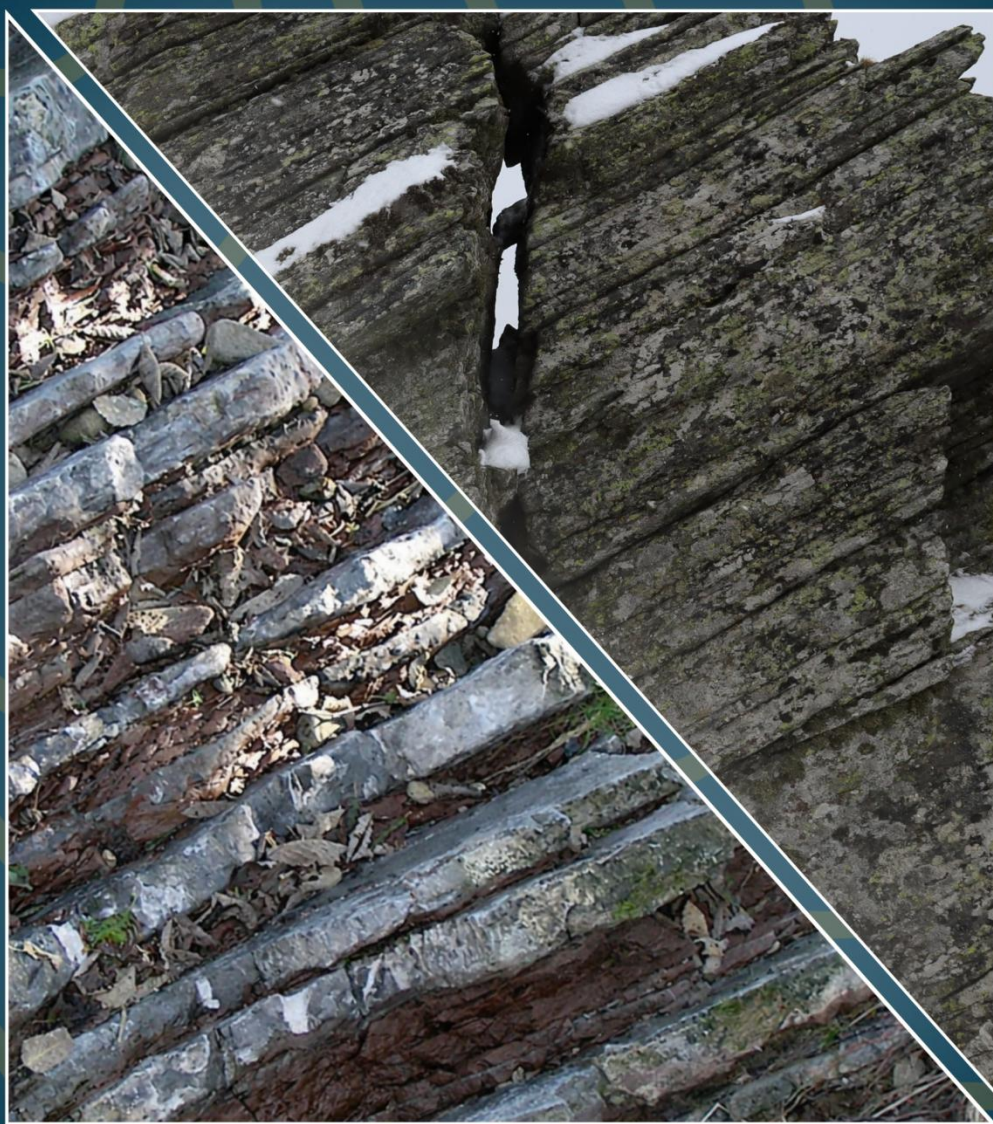


22ND MEETING OF THE CENTRAL EUROPEAN TECTONIC STUDIES GROUPS

APRIL 22 – 25, 2026

CETEG 2026

BOOK OF ABSTRACTS
FIELD GUIDES



Tomáš Potočný
editor



COMENIUS
UNIVERSITY
BRATISLAVA

Tomáš Potočný

editor

CETEG 2026
Book of Abstracts & Field Guides

22nd Meeting of the Central European Tectonic Studies Groups

April 22 – 25, 2026

2026

Comenius University Bratislava

**Field guides authors:**

Marián Putiš, Rastislav Vojtko, Ondrej Nemec, Ján Madarás, Martin Ondrejka, Jiří Sláma,
Alexandra Molnárová, Chrisfanel Eurode Kianguebene-Koussingounina
Dušan Plašienka, Marína Molčan Matejová, Tomáš Potočný

Editor:

Tomáš Potočný

Cover photo:

sandstones and marls of the Malinowa Fm., Kyjov (Dušan Plašienka);
metatonalites, Vápenica Nappe, Kráľova Skala (Marián Putiš)



This publication is distributed under the license Creative Commons CC BY-SA 4.0. This license enables reusers to distribute, remix, adapt, and build upon the material in any medium or format, so long as attribution is given to the creator. The license allows for commercial use. If you remix, adapt, or build upon the material, you must license the modified material under the same or a compatible license. More information about the license: <https://creativecommons.org/licenses/by-sa/4.0/>



https://stella.uniba.sk/texty/PRIF_zba_CETEG_2026.pdf

Publisher:

Comenius University Bratislava, 2026

ISBN 978-80-223-6288-7 (online)

THE MEETING IS ORGANISED BY

Slovak Geological Society

In cooperation with

Department of Geology and Paleontology, Faculty of Natural Sciences,
Comenius University Bratislava

Earth Science Institute of the Slovak Academy of Sciences

Department of Mineralogy, Petrology and Economic Geology, Faculty of
Natural Sciences, Comenius University Bratislava



UNDER THE FINANCIAL SUPPORT OF

Slovak Commission for UNESCO



United Nations
Educational, Scientific and
Cultural Organization

Under the patronage of
Slovak Commission
for UNESCO

ORGANISING COMMITTEE

doc. Mgr. Rastislav Vojtko, PhD.

RNDr. Ján Madarás, PhD.

prof. RNDr. Dušan Plašienka, DrSc.

Mgr. Marína Molčan Matejová, PhD.

prof. RNDr. Marián Putiš, DrSc.

Mgr. Tomáš Potočný, PhD.

RNDr. Igor Broska, DrSc.

RNDr. Monika Kováčiková

RNDr. Milan Kohút, CSc.

RNDr. Silvia Antolíková, PhD.

Table of content

<i>L. Ádám</i>	
Exploration of fractured geothermal resources in the Pannonian Basin	8
<i>J. Andrzejak, P. Strzelecki</i>	
Geometrical Analysis of LiDAR-derived Fault Network in the Bieszczady Mountains (Outer Carpathians, Poland).....	10
<i>E. Balkanska</i>	
Low-temperature thermochronological studies in Bulgaria – a review.....	11
<i>P. Birošáková, P. Závada, F. Tomek, V. Kusbach, J. Semerád</i>	
Magnetic fabric development in ring dykes propagating from sill-like magma chambers	13
<i>I. Broska, S. Georgiev, A. Lazarova, M. Kubiš, S. Kurylo, E. Balkanska, T. Vladinova</i>	
Permian Gemeric granites and their regional scale correlation	14
<i>I. Bystraninová, P. Gedl, M. Molčan Matejová, D. Plašienka</i>	
All that is black is not anoxia.....	16
<i>L. De Doliwa Zieliński, K. Kościńska, M. Janák, M. Bukala, E. Kooijman, M. J. Whitehouse, S. Mazur, J. Majka</i>	
Inverted Metamorphism and Nappe Tectonics in the Variscan Tatra Mountains: A Geochronological Perspective	17
<i>A. Dey, K. Sen</i>	
Unravelling the tectono-metamorphic history of the Tso Moriri Crystalline Complex, NW Himalaya: integrating thermodynamic modelling and EBSD	18
<i>L. Fodor, O. Fernandez, M. Molčan Matejová, D. Plašienka, T. Potočný, R. Aubrecht, Á. Csicssek, B. Grasmann, G. Manatschal, R. Vojtko, Sz. Kövér</i>	
Hyperextension, mantle exhumation, subduction: reconstruction of the Western Carpathian margin of the Neotethys: a new model.....	20
<i>S. Georgiev, A. Lazarova, E. Balkanska, T. Vladinova, I. Broska, S. Kurylo</i>	
Post-collisional (late Carboniferous-early Permian) and rift-related (late Permian-Early Triassic) magmatic stages – a response of tectonic regime shifting, basement of the External Balkanides, Bulgaria	22
<i>A. Guy, I. Soejono</i>	
Geophysical and geological constraints for the crustal structures of the Mongolian Orocline and the adjacent sutures	24
<i>P. Hanžl, Z. Krejčí, P. Budil, K. Hrdličková, P. Čáp, J. Franců, J. Undayria</i>	
Geological map of the Upper Mesozoic strata in the Shiliin Nuruu Syncline, Mongolia	25
<i>G. Héja, T. Budai, M. Palotai, Gy. Maros</i>	
The role of Upper Permian evaporites in the Mesozoic structural evolution of the northeastern part of the Transdanubian Range Unit.....	26
<i>V. Janoušek, M. Kohút, I. Broska, I. Soejono, P. Hanžl</i>	
Variscan magmatism in the Western Central Carpathians and Bohemian Massif: comparing the incomparable	27
<i>P. Jeřábek, J. Sláma, R. Vojtko</i>	
Eo-Alpine Metamorphic Event in the Permian Cover of the Vepor Unit, Western Carpathians: Lu-Hf Garnet Geochronology and PT Conditions	29
<i>E. Klamová, R. Vojtko, M. Reiser</i>	
Apatite and zircon fission-track thermochronology of the High Tatras Mountains (Western Carpathians)....	30
<i>M. Kohút, I. Soejono, J. Míková, M. Zieger-Hofmann, D. Laurinc</i>	
Provenance of the Lower Triassic quartzites from the Western Carpathians - Separation myths from facts ..	31
<i>B. Kronome, L. Hraško, M. Olšovský, O. Pelech</i>	
Complex inner structure of the Murán Nappe (Western Carpathians, Slovakia) based on geological mapping	33

<i>O. Krýza, M. Staněk, P. Závada, J. Doubravová, J. Burjáněk, F. Zwaan</i> Magma Ascent and Fracture Growth in the Oblique Rift of the Reykjanes Peninsula: Insights from Analogue Experiments	34
<i>O. Krýza, P. Maierová, P. Závada, M. Machek, V. Kusbach, Z. Roxerová, K. Schulmann, H. Čížková</i> Dynamics of partially molten lower crust in hot orogens: Coupled insights from numerical and analogue modelling	36
<i>K. Kucharz, A. Świąder</i> Streamlining Structural Analysis: An Automated Workflow for Calculating Intersection Lines and Layer Thickness in ArcGIS Pro.....	37
<i>J. Kulháněk, M. Racek, P. Jeřábek, O. Lexa, T. Ildžová, B. Paddon</i> Lithium in subduction zone: From lithology-scale distribution to mineral-scale coupled substitutions at high pressure	38
<i>S. Kurylo, R. Zurbriegen, M. Janák, I. Broska, P. Konečný</i> Metamorphic P-T conditions of mylonitic orthogneiss from the Strona-Ceneri zone, Southern Alps	40
<i>V. Kusbach, M. Machek, Z. Roxerová, P. Závada, M. Staněk</i> Crystal Mush Dynamics: Analogue Modeling with Plaster of Paris and Micro-CT Visualization	41
<i>A. Lechner, A. Guy, K. Schulmann</i> Geophysical and structural study of the Permian Uranium mineralization in the north-eastern part of the Moldanubian Zone (Bohemian Massif, Czech Republic)	42
<i>M. Machek, Z. Roxerová, V. Kusbach, A. Schöpa, M. de Saint Blanquat, C. Annen, A. Vávrová</i> Flow and deformation microstructure of crystal mush constrained by anisotropy of magnetic susceptibility in Lago della Vacca pluton, Adamello igneous complex.....	43
<i>J. Majka, C.J. Barnes, M. Janák</i> Eo-Alpine metamorphism recorded in the Veporic Superunit of the Western Carpathians – new insights from garnet Lu/Hf and mica Rb/Sr geochronology	44
<i>J. Majka, S. Mazur, C. Schiffer</i> Peculiarities and oddities of the North Atlantic Caledonides	45
<i>M. Maraszewska, M.A. Kusiak, S.A. Wilde, M.J. Whitehouse, H. Jeon, K.Yi, S.Lee</i> Neoproterozoic-Paleoproterozoic Indo-Australo-Antarctic connections evaluated by zircon U-Pb geochronology, $\delta^{18}\text{O}$ & trace elements in the meta-igneous/sedimentary (U)HT complex of SW Bunger Hills (East Antarctica)	46
<i>M. Maraszewska, I. Broska, J. Majzlan</i> Accessory phosphates from ore-bearing granites: an archive of magmatic- hydrothermal evolution (Nízke Tatry pluton, Tatric Unit, the Western Carpathians).....	48
<i>B. Matoš, J. Maslač Soldo, M. Herak, J. Stipčević, B. Kordić, I. Pavičić, I. Vlahović</i> Structural architecture and fault kinematic properties of the SE part of the External Dinarides (Croatia): Seismotectonic implications to ongoing seismicity along the Dalmatian coastline	50
<i>S. Mazur, I. Munteanu, M. Tilita, S. Stovba, R. Stephenson, C. Schiffer, E. Ak</i> Tectonic architecture of the Western Black Sea Basin: insights from integrated 2-D gravity and magnetic forward modelling along the BS-50 seismic profile	53
<i>M. Mikołajczak, S. Mazur</i> Crustal Architecture and Tectonic Inheritance in the Outer Western Carpathians Revealed by Integrated Geophysical Modelling.....	55
<i>M. Molčan Matejová, T. Potočný, D. Plašienka, L. Fodor, S. Kövér, O. Fernandez</i> Permian to Cretaceous evolution of the Neotethyan margin of the Western Carpathians: composition, age and tectono-metamorphic history of the Meliata Unit	57
<i>A. Nasiri, S. Stovba, R. Stephenson, S. Drachev, S. Mazur, L. Slonka</i> Tectonic Evolution of the Dniepr–Donets Basin: An Integrated Geophysical Perspective on Rift Mechanisms	59

O. Nemec, M. Putiš

Thermodynamic P–T estimates in Alpine tectonometamorphic zones of Southern Veporic–Northern Veporic–Subautochthonous Fatric–Infratatic wedge (Inner Western Carpathians)..... 60

A. Obertová, V. Šimonová, J. English

Kinematic analysis of fault structures in Mníchova Lehota quarry..... 62

L.V. Pacheko Shmotkina, P. Hasalová, K. Schulmann, G. Ruffet, P. Štípská

Deciphering the emplacement timing of the Třebíč pluton and the associated thermal implications through $^{40}\text{Ar}/^{39}\text{Ar}$ and U/Pb dating 64

B. Paddon, P. Jeřábek, M. Racek, O. Lexa, T. Ildžová, J. Kulháněk

Prograde Metamorphism in HP Micaschist of the Erzgebirge: Constraints on P–T evolution of the Orogenic Wedge 65

I. Pavičić, Ž. Duić, J. Orešković, I. Pavlin, B. Balaž, S. Kolar, L. Šembera, B. Matoš

Danube Sediment Restoration: River sediment monitoring and research for sustainable sediment management in the Middle Danube 67

O. Pelech, F. Teták, M. Olšavský, J. Madzin

Tectonics of the Pieniny Klippen Belt in the Orava region based on results of regional geological mapping 69

I. Pešková, M. Sentspeter, O. Pelech, J. Hók, M. Olšavský, M. Potfaj

NonOravic units as the key structural elements of the Pieniny Klippen Belt structure (western part). 71

D. Plašienka, P. Gedl, M. Molčan Matejová, T. Potočný

Composition, stratigraphy and structure of the Čergov sector of the Pieniny Klippen Belt in eastern Slovakia 73

T. Potočný, M. Ondrejka, M. Putiš, D. Plašienka, J. Sláma

Zircon U–Pb LA-ICP-MS dating and geochemistry of Early–Middle Triassic acid volcanites with blueschist facies metamorphic overprint (Meliata Unit Bôrka Nappe, Western Carpathians)..... 75

M. Putiš, J. Sláma, Q-L. Li, D. Chew, X-H. Li, O. Nemec, M. Ondrejka, Z. Németh, J. Madarás, P. Siman, J. Spišiak, P. Ružička

Pre-Permian evolutionary history of the West-Carpathian basement based on geochronology data..... 76

M. Racek, O. Lexa, P. Jeřábek, P. Štípská, B. Paddon, P. Závada, M. Svojtka, P. Hasalová

How to reveal the record of (U)HP metamorphic conditions in quartzofeldspathic rocks: mineral composition and phase preservation 78

M. Sentspeter, J. Bučová, I. Slaninka

Current state of knowledge on prospective locations for siting a deep geological repository in Slovakia (the Tribeč Mountains and the Rimava Basin) 80

C. Schiffer, T. Soni, S. Mazur, L. Petrescu

Receiver Function analysis reveals new insight into the geodynamic evolution of the Alpine-Tethys closure in the Western Carpathians..... 82

M. Słotwiński, M. Adamuszek, A. Gluszyński, M. Jarosiński, W. Wiesławska, M. Olkiewicz, K. Durkowski, M. Dąbrowski

Salt beds deposited over high-relief sulphates – observations from the margin of Zechstein Basin, Łeba Elevation, northern Poland..... 83

I. Soejono, J. Konopásek, S. Collett, J. Sláma, K. Schulmann, J. Míková, V. Janoušek

Mixed Moldanubian zircon provenance patterns: journey from Columbia to northern peri-Gondwana 84

T. Soni, C. Schiffer, S. Mazur, L. Fodor, K. Ustaszewski, P. Balling, L. Petrescu

What do we know about the Alpine-Tethys closure in the Western Carpathians? : results from geophysical and geological joint venture 86

J. Soták, S. Antolíková, J. Sláma

An interbasinal connectivity between wedge-top basin and fore-arc basin in weakening zone of the Central Western Carpathians: non-erosional transition between the Domaníža and Sub-Tatra Paleogene basins..... 88

P. Strzelecki

Automated extraction of local geological surface orientations from mapped traces and DEM data 90

<i>F. Tešák, O. Pelech, M. Olšovský, D. Laurinc, L. Vitovič, J. Maglay, K. Fekete, A. Nagy, R. Demko, K. Korábová, J. Madzin</i>	
Geological structure at the contact between the Outer and Inner Western Carpathians – implications from geological mapping of the Oravská Magura Mts.	91
<i>L. Uhrová, J. Rez, P. Hanžl, A. Zachař, K. Hrdličková</i>	
Microstructures and AMS analysis of granite dykes in the Třebíč Pluton	93
<i>M. Velki, E. Márton, D. Prelević, G. Imre, N. Stanković, V. Cvetkov</i>	
Magnetic mineralogy and paleomagnetism of the Western Vardar ophiolitic unit: first results and implications for the age of magnetization	95
<i>R. Vojtko, A. Lačný, J. Brčková, P. Koděra, F. Bakos, I. Pešková, S. Gašper, M. Molčan</i>	
The Veporic–Gemic Contact Zone near the Ochtiná–Rochovce W–Mo Deposit, Western Carpathians: Implications from geological, structural, and mineralogical analyses	97
<i>W. Włodarski, L. Marks, J. Forysiak, R. Wasiluk</i>	
Young tectonic activity of the Kłodawa–Łęczycza anticline (the Kujavian segment of the Mid-Polish Swell): evidence from recent topography and geometry of the Quaternary strata.....	99
<i>A. Zachař, L. Uhrová, D. Buriánek, P. Hanžl</i>	
Subvolcanic dyke rocks in durbachites of the Variscan Třebíč Pluton; Moldanubian zone, Czech Republic	101
<i>P. Závada, O. Krýza, V. Kusbach, M. Boulanger, M. Machek, Z. Roxerová, C. Annen, P. Fiannacca, D. Russo, E. Fazio</i>	
Magma Mingling Dynamics in Mushy Reservoirs Revealed by Analogue Modeling	103
<i>P. Závada, O. Krýza, V. Kusbach, M. Machek, Z. Roxerová</i>	
Tracking deformation and melt migration in the crust using paraffin-wax analogues	104
<i>M. Zielińska, K. Spunda, D. Plašienka, D. Botor</i>	
Sequential 1D Modelling as a Tool for Reconstructing the Multi-stage Thermal History of the Collisional Zone in the Western Carpathians (Pieniny Klippen Belt, Slovakia)	105
<i>M. Putiš, R. Vojtko, O. Nemec, J. Madarás, M. Ondrejka, J. Sláma, A. Molnárová, Ch. E. Kianguebene – Koussingounina</i>	
PRE-CONFERENCE EXCURSION	
Pre-Alpine and Alpine magmatic and tectono-metamorphic evolution of the eastern Nízke Tatry Mts.	107
<i>D. Plašienka, M. Molčan Matejová, T. Potočný</i>	
POST-CONFERENCE EXCURSION	
Composition, stratigraphy and structure of the Pieniny Klippen Belt (Čergov sector, eastern Slovakia)	152

Exploration of fractured geothermal resources in the Pannonian Basin

L. Ádám

Arctic Green Engineering Services Ltd., Alíz u. 4., Budapest, Hungary, laszlo@arcticterv.hu

During the last 15 years significant achievements were made by successful exploration of fractured geothermal resources in the Pannonian Basin. Some of them are fruits of successful professional cooperation between local and Icelandic geothermal experts with which an approach, or rather a method was developed based on gained experiences of exploratory activities, which increased the success rate of geothermal explorations.

The main ingredients of the method over the course of a geothermal exploration are data collection, data evaluation, proposal and decision on reprocessing of vintage data and/or on new geophysical surveys, data re-evaluation, conceptual model, well siting, drilling program and completion of drilling and testing. These items are combined with intense and transparent communication between the experts and the project owner to justify a well thought and responsible decisions on the continuation of the project, when the project arrives to a predefined decision gate. The development of the method is presented through three project examples.

The first example at town of Szentlőrinc, where the geothermal heating system (~3 MW) is up and running since 2011 producing approximately 23.000 GJ energy annually. This geothermal field is located at SW Hungary, along the seismologically active South Mecsek line, which is an E-W to NE-SW oriented deformation zone, where metamorphic rocks of Palaeozoic age and sequences of Permian and Mesozoic age juxtaposed to Late Miocene towards south direction. The line has a complex tectonic development, presumably the latest right-lateral shear during the late Pannonian gave an indispensable precondition to develop the geothermal field. The rock of aquifer is medium grade metamorphic rocks of Palaeozoic age, mainly gneiss.

Geothermal fluid is produced from the highly fractured part of the crystalline rocks. There were two observations during preparation which indicated the dynamic character of the geothermal system. One was a failed drilling activity at XII well, where uncontrolled flow of thermal water with 66°C was observed without clear proof on the infiltration zone. The other one is the elevated temperature of shallow, few hundreds meter deep water wells along the South Mecsek line.

For the setting up of the conceptual model well data, reprocessed vintage 2D seismic data and data of new AMT/MT and gravity surveys were evaluated together for locating site of geothermal exploration well and for designing a drilling program, which proved to be successful

The second example is connected to town of Miskolc, NE Hungary. The drilling of wells of Miskolc Geothermal Field at the vicinity of Bükk Mountains (NE Hungary) started in 2010. Since 2013 the geothermal heating system (~60 MW) is operating 2 production, and 3 injection wells and producing approx. 700.000 GJ thermal energy annually. Based on the original conceptual model all five wells are operating in the same karstified thermal aquifer, which's carbonate formations of Triassic age are outcropping in Bükk Mountains, where the recharge of the system takes place.

The area of town of Miskolc was a known geothermal field, because of the natural phenomena of Miskolc-Tapolca thermal spring and the thermal wells drilled in the town during 20th century. The location of deep thermal wells for heating purposes was designed in the wider vicinity of the town, this way higher outflow temperature was forecasted due to larger distance from the recharge area, and less effect was expected on the existing springs and wells, which receptors enjoyed certain privilege and protection against new developments.

The first exploratory drilling (MAL-PE-01) was made in the outskirt of town of Mályi. The well is 2311 m deep, and it produces thermal water of 105,3 °C from the 2275-2311 m depth interval. The drilling explored a 0,8 m long open fissure at 2275 m, which triggered a total mud loss resulting the complete lack of cuttings. Unfortunately, the attempt of getting cuttings by junk basket tool was failed, so the rock of aquifer is not known accurately. The expected rock of aquifer is Bükkfennsík Limestone Formation (BLF) of Triassic age (rock of lagoonal facies, Less et al. 2005). Above the aquifer Répáshuta

Limestone Formation of Triassic age (pelagic basin and slope facies, Less et al. 2005), Lökvolgy Shale Formation of Jurassic age and Szépvölgy Limestone Formation of Eocene age were recognized.

A year later in 2011, the first injection well (KIS-PE-01) was drilled near town of Kistokaj. The distance between the two wells (MAL-PE-01 and KIS-PE-01) is 1,9 km. The KIS-PE-01 well drilled into the BLF right under the tuff of Miocene age at 1065 m depth. If one compares the drilled sequences of the two wells, the missing cap rocks of Triassic, of Jurassic and of Eocene age above the water-bearing fissure at KIS-PE-01 are observable. In 2012, the second production well (MAL-PE-02) was completed at 600 m distance from MAL-PE-01. The drilling interestingly explored very similar layers as at KIS-PE-01, the water-bearing BLF was right under the tuff of Miocene age at 1395 m.

In this area well data, surface geology and reprocessed vintage 2D seismic data were used for evaluation of subsurface properties for locating well site and designing well program.

The third example is located at town of Nyíregyháza, NE Hungary, where the development of the surface system is still ongoing. In 2024 a resource in volcanic rocks of Miocene age was successfully explored by a geothermal drilling. Previously the volcanic series was explored by 2D seismic survey, and the drilling aimed the most fractured part of the resource. On the seismic data it was observable a young tectonic event and the fractures inside the volcanic series of Miocene age, see **Error! Reference source not found.**

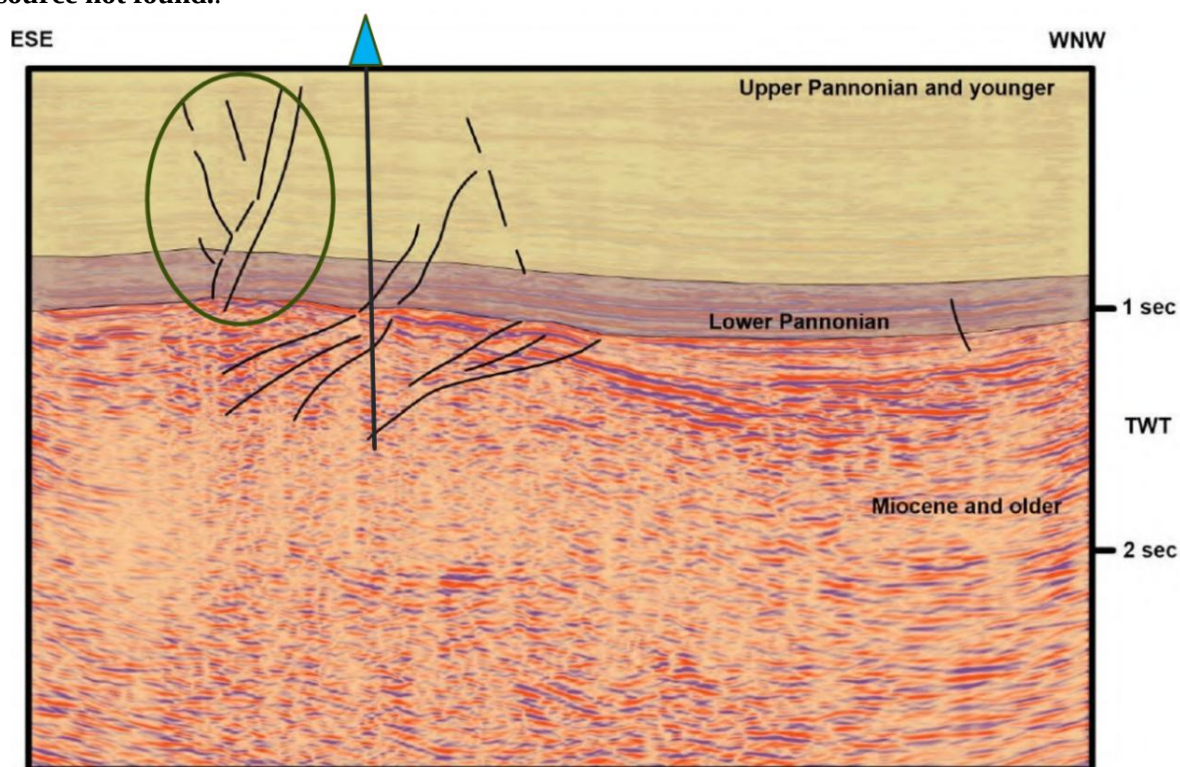


Fig. 1: 2D seismic line exploring a flower structure in Pannonian layers and fractures within the volcanic rocks of Miocene age, area of Nyíregyháza

Based on the production tests of the two wells the resource could provide significant direct heat for the local user. The yield of the production well is close to 50 l/s, the productivity index is in the range of 10-12 l/s/bar, and the resource temperature is around 88-90°C.

Amongst the three above mentioned examples the successful exploration of gneiss of Palaeozoic age and volcanic rocks of Miocene age are novelties, as these were not utilized, nor explored as geothermal resource in the Pannonian Basin previously.

References

- Gyalog L. & Sikhegyi F. (editors) 2005. Geological Map of Hungary, 1:100.000, published by Geological Institute of Hungary, Budapest, <https://map.mbfisz.gov.hu/fdt100/>
- Less Gy., Kovács S., Pelikán P., Pentelényi L. & Sásdi L. 2005. Geology of the Bükk Mountains, issued by Geological Institute of Hungary, Budapest, 284.

Geometrical Analysis of LiDAR-derived Fault Network in the Bieszczady Mountains (Outer Carpathians, Poland)

J. Andrzejak¹, P. Strzelecki²

1 AGH University of Krakow, Faculty of Geology, Geophysics and Environmental Protection, Student Scientific Association of Geological and Computer Cartography "Azymut"

2 AGH University of Krakow, Faculty of Geology, Geophysics and Environmental Protection

High-resolution Digital Elevation Models (DEMs) derived from LiDAR data enable the visualization of geological structures that remain undetectable in other remote sensing datasets, such as satellite imagery and aerial orthophotomaps, as well as in field observations. This approach provides exceptionally valuable data, particularly in areas with dense vegetation cover, including the Outer Carpathians. Fault analysis was conducted within the Central Carpathian Synclinorium of the Silesian Nappe, in a study area extending from the Wetlina River in the west to the Ukrainian border in the east, south of the Otryt Mountain Range. Faults crosscutting folds were identified predominantly within the lithology of the Otryt sandstones of the Lower Krosno Beds, which consist of competent, thick-bedded sandstones, thereby providing an excellent host rock for faults traceable in LiDAR data.

Faults were mapped based on digital elevation model derivatives – hillshade, Topographic Position Index (TPI) and curvature. The analysis focused on determining the orientation and length of individual faults, as well as establishing spatial relationships between fault sets and fold structures.

A total of 893 faults within the two major folds of the study area: the Połoniny–Ustrzyki Górne Syncline and the Terebowiec Syncline were mapped. Several fault sets with distinct geometric characteristics were identified. In the northwestern part of the study area, faults are predominantly N–S oriented and exhibit dextral offsets, whereas in the southeastern part, faults with sinistral offsets and NEE–SWW orientation are common. The fault length range extends from 33 m to 3274 m, with a mean value of 522 ± 405 m, and the data follow a lognormal distribution. Length cumulative frequency diagrams indicate that displacement is dispersed across numerous faults of varying scales. The spatial pattern of faults seems to be controlled by the orientation of folds.

The conducted analysis demonstrates the effectiveness of LiDAR data in resolving the structural geological framework of mountainous regions, particularly for the detection of faults ranging from several hundred metres to several kilometres in length. The identified faults provide a basis for further, more comprehensive structural analyses.

Low-temperature thermochronological studies in Bulgaria – a review

E. Balkanska

Department of Geology, Paleontology and Fossil Fuels, Sofia University, 1504 Sofia, Bulgaria; e-mail balkanska@gea.uni-sofia.bg

Fission-track (FT) analysis is one of the most popular low-temperature thermochronological methods developed very fast during the last fifty decades. In Bulgaria the method is revealed and applied successfully in the last 20 years that contributed significantly to the understanding of the Alpine evolution of several tectonic zones.

The initial attempts to apply FT dating in Bulgaria date back to the 1980s when some experimental analysis of micas from the Rhodope and Sredna Gora Zones was performed (Monchev, 1985 and references therein). These early studies produced inconclusive results due to incomplete theoretical understanding but played an important role for the revelation of the Late Alpine processes in the evolution of the Balkanides.

The conventional method of FT analysis has been successfully applied since the beginning of the new century providing the first quantitative estimates on the exhumation rates and the thermotectonic evolution of several tectonic units. In the Kraishte Zone, FT data was used to constrain the timing of the main thrusting event in the Early Cretaceous and the original thickness and extent of the thrust sheets (Kounov et al., 2010). This compressional event was followed by Cenozoic extension that led to the exhumation of the deeper crustal units proven by the zircon and apatite FT data (Kounov et al., 2004; 2010). The application of the FT analysis for the Central Balkan Zone resulted in estimation of the time of the Early and Late Alpine thrusting events (Balkanska et al., 2015; Kounov et al., 2018). It is suggested that the initial Late Alpine thrusting occurred in Late Paleocene. Kounov et al. (2018) reported apatite FT combined with (U/Th)/He analyses revealing at least two extensional phases of rapid uplift and denudation during the Cenozoic. The Rhodope Zone represents one of the most complex geological areas studies using FT analysis. Combined with other low- and high-temperature geochronological methods, FT data revealed multiple phases of extension, high exhumation rates and significant crustal thinning during the Cenozoic for the Central, Western and Southern Rhodope metamorphic complexes (Kounov et al., 2023 and the references therein). Cattò et al. (2018) provided the first apatite FT dating results for the Strandzha massif indicating limited post-Jurassic deformation and metamorphism, suggesting that the region has remained unaffected by the Late Alpine tectonic processes. The Early Alpine thrusting was followed by slow cooling/exhumation driven by post-orogenic erosion in the region.

In the last few years, after establishing the first Low-Temperature Thermochronological Laboratory in Bulgaria (Balkanska et al., 2021), new FT analysis using LA-ICP-MS contributed significantly to the better understanding of the Alpine evolution and exhumation history of the Sredna Gora and the Rhodope Zones. Balkanska et al. (2022) provided the first constraints on the thermal and tectonic evolution of the pre-Mezozoic basement and the volcano-sedimentary cover of the central parts of the Sredna Gora Zone combining FT dating using LA-ICP-MS with $^{40}\text{Ar}/^{39}\text{Ar}$ dating. New thermochronological data for the Cenozoic tectonic evolution of the Rhodope Metamorphic Complex gave evidence for the existence of a compressional event in latest Oligocene to early Miocene time (Tacheva et al., 2024).

Fission-track analysis has proven to be a powerful method for deciphering the thermal and tectonic history of the Alpine orogen in Bulgaria. Its application across various tectonic zones has led to significant advances in understanding the evolution of the Balkanides. Future studies should focus on expanding the FT analyses and integrating additional datasets, continued development of analytical techniques and combining FT analysis with other low and high temperature geochronological methods.

Acknowledgements: This work has been carried out in the framework of the National Science Program "Critical and strategic raw materials for a green transition and sustainable development", approved by the Resolution of the Council of Ministers № 508/18.07.2024 and funded by the Ministry of Education and Science (MES) of Bulgaria.

References

- Balkanska, E., Kounov, A., Gerdjikov, I. 2015. Fission-track dating applied for reconstruction of tectonic processes in the Balkanides. *Advances in ESR Applications* 31, p. 17.
- Balkanska, E., Georgiev, S., Kounov, A., Tagami, T., Sueoka, S. 2021. Fission-track analysis using LA-ICP-MS: techniques and procedures adopted at the new Low-Temperature Thermochronology Laboratory in Bulgaria. *Comptes rendus de l'Académie bulgare des Sciences* 74 (1), 102–109, <https://doi.org/10.7546/CRABS.2021.01.13>.
- Balkanska, E., Georgiev, S., Kounov, A., Antić, M., Tagami, T., Sueoka, S., Wijbrans, J., Peytcheva, I. 2022. Low-temperature constraints on the Alpine thermal evolution of the central parts of the Sredna Gora Zone, Bulgaria. *Geologica Carpathica* 73 (1), 3–23, <https://doi.org/10.31577/GeolCarp.73.1.1>.
- Cattò, S., Cavazza, W., Zattin, M., Okay, A.I. 2018. No significant Alpine tectonic overprint on the Cimmerian Strandja Massif (SE Bulgaria and NW Turkey). *International Geology Review* 60 (4), 513–529, <https://doi.org/10.1080/00206814.2017.1350604>.
- Kounov, A., Seward, D., Bernoulli, D., Burg, J.-P., Ivanov, Z. 2004. Thermotectonic evolution of an extensional dome: The Cenozoic Osogovo-Lisets core complex (Kraishte Zone, W Bulgaria). *International Journal of Earth Sciences* 93 (6), 1008–1024, <https://doi.org/10.1007/s00531-004-0435-2>.
- Kounov, A., Seward, D., Burg, J.-P., Bernoulli, D., Ivanov, Z., Handler, R. 2010. Geochronological and structural constraints on the Cretaceous thermotectonic evolution of the Kraishte Zone, Western Bulgaria. *Tectonics* 29, TC2002, <https://doi.org/10.1029/2009TC002509>.
- Kounov, A., Gerdjikov, I., Vangelov, D., Balkanska, E., Lazarova, A., Georgiev, S., Blunt, E., Stockli, D. 2018. First thermochronological constraints on the Cenozoic extension along the Balkan fold-thrust belt (Central Stara Planina Mountains, Bulgaria). *International Journal of Earth Sciences* 107 (4), 1515–1538, <https://doi.org/10.1007/s00531-017-1555-9>.
- Kounov, A., Gerdjikov, I., Antić, M.D., Georgiev, N., Spikings, R.A. 2023. Late Alpine multistage exhumation of the northwestern Rhodope Metamorphic Complex (northern Rila Mountains, Bulgaria). *International Journal of Earth Sciences* 112, 1635–1660, <https://doi.org/10.1007/s00531-023-02321-6>.
- Monchev, P. 1985 Application of the fission-track method in age determination of micas from pegmatites in South Bulgaria. *Review of the Bulgarian Geological Society* 46 (1), 103–107 (in Bulgarian, with English abstract).
- Tacheva, V., E. Balkanska, K. Naydenov, S. Georgiev, A. Lazarova, N. Georgiev. 2024. Thermochronological constraints on the Cenozoic tectonic evolution of the northeast Rila-West Rhodopes batholith. *Review of the Bulgarian Geological Society* 85, 3, 35–38, <https://doi.org/10.52215/rev.bgs.2024.85.3.35>.

Magnetic fabric development in ring dykes propagating from sill-like magma chambers

P. Birošáková, P. Závada, F. Tomek, V. Kusbach, J. Semerád

Institute of Geophysics CAS, Boční II 1401, Praha 4, Faculty of Sciences, Charles University, Albertov 6, Praha 2

The emplacement of magma into ring dikes represents a key process in the evolution of caldera volcanic systems, closely linked to the deformation of the host rock during caldera collapse. This study focuses on the experimental investigation of the relationship between the formation of ring faults and subsequent magma migration using analogue modelling. The aim is to understand the specific conditions under which these intrusive structures form, how their geometry is affected by the host rock, and to reconstruct their internal flow kinematics.

The analogue experiments simulated the mechanical behaviour of a brittle host rock using various granular materials (dry sand, flour, and stratified mixtures), while a gypsum-based mixture with magnetite powder served as the magma analogue. Caldera collapse and pressure decrease within the reservoir were simulated by injection of the liquid plaster into a fine-grained flour or a multilayer of the flour and sand. Two types of experiments were conducted. In the first one, liquid plaster was injected into a large box shaped container with flour. In the second type, we injected the liquid plaster into granular layers confined between two glass plates. In the first type of the experiments, the surface deformation was continuously monitored using time-lapse photography and optical deformation analysis processed via the DaVis software (LaVision). After solidification, the bodies were exhumed for 3D morphological analysis, and oriented samples were extracted to investigate the internal fabric using the Anisotropy of Magnetic Susceptibility (AMS). In the second type of experiments, particle image velocimetry was employed to track the propagation of the dyke in a progressively deforming granular host.

The results indicate that while ring faults act as preferential pathways for magma ascent, the resulting intrusion geometry is highly variable. Instead of classic symmetrical ring dikes, the experiments frequently produced asymmetrical, laccolith-like bodies propagating along only one side of the subsiding block. Furthermore, the AMS analysis successfully mapped the internal magnetic fabric of these intrusions, revealing the complex magma flow dynamics and structural evolution during emplacement.

AMS data reveal a clear kinematic zonation across the dike conduits, with more strongly developed magnetic fabrics along the intrusion margins compared to the central parts. In these marginal domains, the minimum susceptibility axes (K3) are not strictly perpendicular to the conduit margins but display a systematic inclination, forming a geometrically consistent pattern across opposite walls that is compatible with shear-driven magma transport, while the maximum susceptibility axes (K1) are relatively well clustered and are interpreted to reflect the dominant magma flow direction.

These findings suggest that the development of ideal ring dikes is strictly limited by reservoir depth, host rock rheology, and the local stress field. By combining morphological observations with AMS flow kinematic data, this study provides a comprehensive new perspective on asymmetrical magma emplacement, applicable to the interpretation of eroded volcanic complexes.

Permian Gemic granites and their regional scale correlation

I. Broska¹, S. Georgiev², A. Lazarova², M. Kubiš³, S. Kurylo¹, E. Balkanska⁴, T. Vladinova²

1 Earth Science Institute SAS, Dúbravská cesta 9, 841 04 Bratislava, Slovakia; E-mail: igor.broska@savba.sk, sergii.kurylo@gmail.com

2 Geological Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev Str., Bl. 24, 1113 Sofia, Bulgaria, E-mail: kantega@abv.bg

3 DPP Žilina Ltd, Legionárska 8203, 010 01 Žilina, Slovakia, E-mail: michal.kubis.sk@gmail.com

4 Sofia University "St. Kliment Ohridski", Dept. of Geology, Paleontology and Fossil Fuels; 15 Tzar Osvoboditel Bld., 1504 Sofia; E-mail: balkanska@gea.uni-sofia.bg

The Permian S-type Gemic granites, by their geophysical and geochemical characteristics, have no clear temporal and petrology analogies in Central Europe. The geophysical 3D density modeling of the Gemic granites, except for several outcrops, shows a large hidden granite pluton (intrusives) with an average thickness of 5-8 km, with many apexes/stocks intruded near the surface in the Lower Paleozoic meta-sedimentary-volcanic Gelnica Group. The geochemical data show that the Gemic granites originated from the melting of a clay-rich source, forming a composite magmatic system: (1) rare metal altered granites are placed in cupolas, (2) porphyritic granites are barren in deep, sharp contacts (Malachovský et al., 1983; Kubiš and Broska, 2015; Broska and Kubiš, 2021). The enrichment of altered granitic apexes in e.g. Li, Nb, Ta, W, Sn resulted from the high activity of fluorine, boron, and phosphorus, which depolymerized low viscous fractionated melt (Petrík et al., 2011; Breiter et al., 2015). The Gemic granites have a dominant age of 264 Ma and were linked to a post-collisional extension in the initial Alpine rifting stage (Radvanec et al., 2009; Vilaseñor et al., 2021). According to Vilaseñor et al. (2022) during the Permian period, the European Variscan post-orogenic magmatic activity occurred in response to a thermal surge following extension, and the lower-crustal melting involved the upward movement of the Moho, thinning the Variscan crust. However, the Gemic granites show geochemical signatures of origin from a thick crust above a subduction zone, probably from the Paleotethys. In this view, they differ from typical rift-related A-type granites known in the Western Carpathians, which have formed in extensionally thinned crust (Ondrejka et al., 2021), and some of which are almost contemporaneous with Gemic granites. Some Gemic granitic rocks contain garnets, which indicate granite formation depth (melting sources) of 21 km at 850 MPa (Faryad and Dianiška, 1989).

In general, the Permian felsic granite magmatism is widely distributed across Central Europe and the Balkan Peninsula. According to Leitner et al. (2024), magmatism in the early and middle Permian in the Eastern Alps was dominantly granitic and crustal; mafic magmatism formed at the end of the Permian, reflecting the break-up of Pangea crust. After the Devonian-Tournaisian-Visean Variscan magmatic activity, the area of central Europe experienced Permian-Triassic extension associated with continental rifting on the Pangea continent, resulting in crustal thinning and large-scale A-type magmatism. The closest Permian tin-bearing granites rich in boron are in the Meseta (Morocco), which resemble the Gemic granites geochemically and mineralogically (Mahjoubi et al., 2016). However, due to the large ALCAPA Tertiary tectonic displacement of the present area of the Western Carpathians, seeking a tectonic solution for the origin of the Gemic granites can be expected in the Balkan area. One possible analogy is part of the post-collisional Late Carboniferous to Permian magmatic activity (Georgiev et al., this volume and refs. therein), which shaped the External Balkanides and the Central Srednogorie. The north-westward subduction of the Paleotethys resulted in an active continental margin with a large magmatic granitoid activity in the Strandzha-Sakar Zone (Bonev et al., 2019; Sałacińska et al., 2022, and ref. therein). The age relationship and the evolved S-type geochemical character of the Gemic granites could place them in a single lineage within this tectonic activity, as the final magmatic pulse of a common Upper Carboniferous–Permian continental arc magmatic system along Paleotethys.

Acknowledgments: This study was financially supported by bilateral cooperation SK-BG-23-0016 and KII-06-Slovenia/10.

References

- Breiter, K., Broska, I. & Uher, P. (2015). Intensive low-temperature tectono-hydrothermal overprint of peraluminous rare-metal granite: a case study from the Dlhá dolina valley (Gemicum, Slovakia). *Geologica Carpathica* 66, 19-36.
- Bonev, N., P. Filipov, R. Raicheva, R. Moritz. 2019. Timing and tectonic significance of Paleozoic magmatism in the Sakar unit of the Sakar-Strandzha Zone, SE Bulgaria. – *International Geology Review*, 61, 16, 1957–1979; <https://doi.org/10.1080/00206814.2019.1575090>.
- Broska, I. & Kubiš, M. (2018). Accessory minerals and evolution of tin-bearing S-type granites in the western segment of the Gemic Unit (Western Carpathians). *Geologica Carpathica* 69, 483-497.
- Faryad, S. & Dianiška, I. (1989). Garnets from granitoids of the Spišsko-Gemerské Rudohorie Mts. *Geologica Carpathica* 40, 715–734.
- Leitner, C., Hauzenberger, C.A., Gilg, H.A., Friedl, G., von Hagke, C. & Finger, F. (2024). The geochemical character of synsedimentary volcanism in the Permian Haselgebirge Formation of the Eastern Alps (Austria): Implications for paleogeographic models. *Geologica Carpathica* 75, 359–374.
- Kubiš, M., & Broska, I. (2010). The granite system near Betliar village (Gemic Superunit, Western Carpathians): evolution of composite silicic reservoir. *Journal of Geosciences* 55, 2, 131–148.
- Mahjoubi, El. M., A. Chauvet, L. Badra, S. Sizaret, L. Barbanson, A.E. Maz, Y. Chen, M. Amann. 2016. Structural, mineralogical, and paleoflow velocity constraints on Hercynian tin mineralization, the Achmmach prospect of the Moroccan Central Massif. – *Mineralium Deposita*, 51, 431–451; <https://doi.org/10.1007/s00126-015-0613-0>.
- Malachovský, P., Dianiška, I., Matula, I., Kamenický, J., Kobulský, J., Hodermarský, J., Fabián, M., Radvanec, M., Kozáč, J., Vlasák, M., Mihalič, A., Ščerbáková, A., Seliga, J., Novoveský, M. (1983). SGR high-temperature mineralization, Sn, W, Mo. Final report. Manuscript - Geofond, Bratislava, 1–248 (in Slovak).
- Petrik, I., Kubiš, M., Konečný, P., Broska, I. & Malachovský, P. (2011). Rare phosphates from the Surovec topaz-Li-mica microgranite, Gemic Unit, Western Carpathians, Slovak Republic: role of F/H₂O of the melt. *The Canadian Mineralogist* 49, 521-540.
- Ondrejka, M., Uher, P., Putiš, M., Kohút, M., Broska, I., Larionov, A., Bojar, A.V. & Sobocký T. (2021). Permian A-type granites of the Western Carpathians and Transdanubian regions: products of the Pangea supercontinent breakup. *International Journal of Earth Sciences*, 110, 2133–2155.
- Radvanec, M., Konečný, P., Ondrejka, M., Putiš, M., Uher, P. & Németh, Z. (2009). The Gemic granites as an indicator of the crustal extension above the Late-Variscan subduction zone and during the Early Alpine riftogenesis (Western Carpathians): an interpretation from the monazite and zircon ages dated by CHIME and SHRIMP methods. *Mineralia Slovaca*, 41, 381–394 (in Slovak with English summary).
- Sałacińska, A., I. Gerdjikov, A. Gumsley, K. Szopa, D. Chew, A. Gawęda, I. Kocjan. 2021. Two stages of Late Carboniferous to Triassic magmatism in the Strandja Zone of Bulgaria and Turkey. – *Geological Magazine*, 158, 12, 2151–2164; <https://doi.org/10.1017/S0016756821000650>.
- Šefara, J., Bielík, M., Vozár, J., Katona, M., Szalaiová, V., Vozárová, A., Pánisová, J. Šimonová, B., Schmidt, S. & Götze H.J. (2017). 3D density modelling of Gemic granites of the Western Carpathians. *Geologica Carpathica* 68, 177–192. <https://doi.org/10.1515/geoca-2017-0014>.
- Villaseñor, G., Catlos, E.J., Broska, I., Kohút, M., Hraško, L., Aguilera, K., Etzel, T., Kyle, R. & Stockli, D. (2021). Evidence for widespread mid-Permian magmatic activity related to rifting following the Variscan orogeny (Western Carpathians). *Lithos* 390, 106083.

All that is black is not anoxia

I. Bystraninová¹, P. Gedl², M. Molčan Matejová¹, D. Plašienka¹

¹ Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University, Mlynská dolina, Ilkovičova 6, 842 15 Bratislava, Slovakia; bystraninov1@uniba.sk

² Institute of Geological Sciences, Polish Academy of Sciences, Senacka 1, 31-002 Kraków, Poland

Palynofacies analysis provides valuable insight into past marine environments particularly in reconstructing palaeoecological conditions and understanding evolutionary processes of sedimentary sequences. One of these environmental aspects that can be reconstructed by this method is determining the level of water oxygenation.

Here, we present preliminary results of palynological analysis of Cretaceous black shales of the Koňhora Formation from two localities in the Pieniny Klippen Belt: one from the Koňhora Formation belonging to the Kysuca Succession (Pieniny Unit) from the locality Capova skalka, near the village of Kyjov (Čergov segment of the Pieniny Klippen Belt), second from the type locality of this lithostratigraphic unit near the village of Koňhora (Varín segment of the Pieniny Klippen Belt). Analysis of the lithologically similar material from both sites revealed various results.

Samples from the Capova skalka yielded large amounts of amorphous organic matter (Fig. 1) interpreted as indicative for anoxic conditions of the bottom waters. Moreover, palynomorphs, including dinoflagellate cysts, spores and pollen grains show signs of degradation.

In contrast, samples from the type locality of the Koňhora Formation (also lithologically represented by black shales) show no evidence of anoxic conditions. Instead, they yielded palynofacies dominated by black opaque phytoclasts and well-preserved palynomorph assemblages, including dinoflagellate cysts and sporomorphs (Fig. 2).

These preliminary findings highlight significant variability within seemingly similar lithologies. Demonstrating that black shales do not necessarily indicate uniform depositional conditions, especially with respect to oxygen levels. Further research will focus on palynological analysis of other black Cretaceous deposits from various localities in the Pieniny Klippen Belt.

Acknowledgements: This work is supported by the Grant Agency for Science, Slovakia project VEGA 2/0012/24.

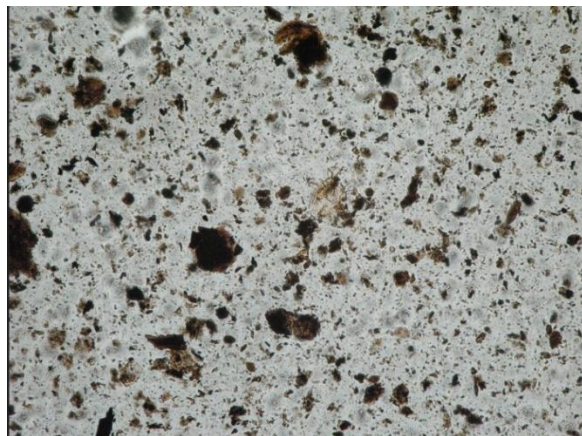


Fig. 1: Palynofacies of the Koňhora Fm. from Capova Skalka locality.

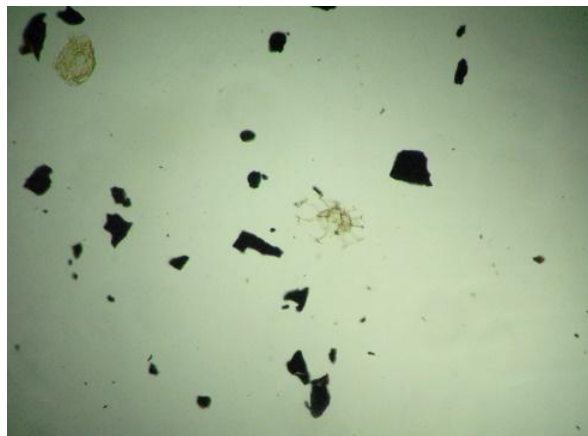


Fig. 2: Palynofacies of the Koňhora Fm. from type locality

Inverted Metamorphism and Nappe Tectonics in the Variscan Tatra Mountains: A Geochronological Perspective

L. De Doliwa Zieliński¹, K. Kościńska¹, M. Janák², M. Bukata^{3,4}, E. Kooijman⁵, M. J. Whitehouse⁵, S. Mazur⁴, J. Majka^{1,6}

¹ Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow, Kraków, Poland lzilins@agh.edu.pl

² Earth Science Institute, Slovak Academy of Sciences, Bratislava, Slovakia

³ Instituto Andaluz de Ciencias de la Tierra (IACT-CSIC), CSIC, Armilla, Granada, Spain

⁴ Institute of Geological Sciences, Polish Academy of Sciences, Kraków Research Centre, Kraków, Poland

⁵ Department of Geosciences, Swedish Museum of Natural History, Stockholm, Sweden

⁶ Department of Earth Sciences, Uppsala University, Uppsala, Sweden

The Variscan basement of the Tatra Mountains (Western Carpathians) preserves a classic example of nappe tectonics and inverted metamorphic zonation, reflecting the complex tectonometamorphic evolution of the Late Paleozoic continental collision. This study integrates phase equilibrium modeling, zirconium-in-rutile geothermometry, and in situ LA-ICP-MS Th–U–Pb monazite geochronology of metapelites from the Lower Unit, combined with new U–Pb zircon ages from the Upper Unit granitoids, to reconstruct the metamorphic and tectonic history of the Variscan Tatras.

In the Lower Unit, the staurolite–kyanite (St–Ky) zone is characterized by a peak metamorphic assemblage of garnet + muscovite + biotite + staurolite + kyanite + plagioclase + rutile + quartz, while the structurally higher kyanite–fibrolite (Ky–Fib) zone is marked by the loss of staurolite and the presence of abundant kyanite, often replaced by fibrolitic sillimanite. Pressure–temperature (P–T) conditions increase from 600–640 °C and 6–8 kbar in the St–Ky zone to 640–655 °C and 6.5–8.5 kbar in the Ky–Fib zone. Monazite geochronology reveals a downward-younging trend, with ages ranging from 342–332 Ma in the Ky–Fib zone to 323–318 Ma in the underlying St–Ky zone, indicating a temporally and structurally inverted metamorphic sequence. These ages are younger than zircon ages from Upper Unit granitoids (353–346 Ma), suggesting that prograde metamorphism in the Lower Unit overlapped with late granitoid intrusion in the Upper Unit.

The inverted metamorphic zonation and spatially decoupled thermal histories of the Upper and Lower Units suggest that nappe stacking played a dual role: accommodating crustal shortening and driving crustal re-equilibration through partial melting and melt migration. These processes are critical for understanding the long-term rheological evolution of orogenic belts and the coupling between deformation, metamorphism, and plutonism in thickened continental crust.

Altogether, this study provides new quantitative constraints on the metamorphic architecture of the Tatra Mountains, demonstrating that metamorphic inversion was maintained and sharpened during progressive Variscan nappe emplacement. The downward-younging monazite ages in the Lower Unit, combined with the older granitoid ages in the Upper Unit, document footwall heating during nappe emplacement, consistent with thrust-driven burial and channelized heat redistribution in thickened crust. The distinct P–T–t trajectories of the two units further underscore the heterogeneous crustal evolution, comparable to other Variscan and Alpine collisional belts where metamorphic inversion developed through progressive stacking.

Unravelling the tectono-metamorphic history of the Tso Morari Crystalline Complex, NW Himalaya: integrating thermodynamic modelling and EBSD

A. Dey^{1,2}, K. Sen²

¹ Institute of Geological Sciences, Polish Academy of Sciences, Senacka 1, 31-002 Krakow, Poland, e-mail: deyalosree@gmail.com

² Wadia Institute of Himalayan Geology, 33 GMS road, Dehradun, Uttarakhand, e-mail: koushik.geol@gmail.com

The India-Eurasia collision zone in eastern Ladakh, India, is marked by the Tso Morari Crystalline Complex (TMCC), which experienced continental subduction, eclogite-grade metamorphism, and rapid exhumation during the Himalayan orogeny. The TMCC consists of orthogneisses and paragneisses mostly of Paleozoic age, characterized by metabasic enclaves that underwent high-pressure (HP eclogites) to ultrahigh-pressure (UHP coesite) metamorphism (Steck et al., 1998; Guillot et al., 2000; Epard and Steck, 2008). TMCC is bounded by two fault zones: the Karzok fault to the southeast and the Zildat fault to the northeast. Previous studies have extensively examined the TMCC in terms of its metamorphic evolution, exhumation mechanisms, and tectonics (St. Onge et al., 2013; Palin et al., 2014, 2017; Wilke et al., 2015). However, these studies focused on samples from the same outcrop, specifically in the core of the complex, which surprisingly have yielded varied results (O'Brien et al., 2019a). In this study, the metamorphic evolution of the eclogites is assessed in terms of breakdown reactions, symplectite formation, and carbonate metasomatism. The variation in strain regime from continental subduction to subsequent exhumation phases, corresponding to different stages of TMCC's metamorphic evolution, has also been analyzed using Lattice Preferred Orientations (LPO) and slip-system analysis of phases obtained from EBSD (Electron Backscatter Diffraction) data, which were further processed with MTEX. To better understand upper crustal tectonics or the final stage of emplacement of the TMCC, EBSD analysis of quartz from Puga gneiss samples collected across the strike of the complex was also conducted. The study suggests that the TMCC experienced a constrictional strain regime indicated by Type-1 omphacite LPO at a peak P-T of $\sim 2.75 \pm 0.1$ GPa and $\sim 550 \pm 50^\circ\text{C}$, followed by plane strain deformation at P-T conditions of $\sim 1.50 \pm 0.1$ GPa and $\sim 580 \pm 50^\circ\text{C}$ (Types-2 & 3 omphacite). High-temperature metamorphism resulting from collisional thickening at $\sim 0.85 \pm 0.1$ GPa and $\sim 680 \pm 50^\circ\text{C}$ coincides with {m}<c> slip of quartz (Dey et al., 2022, 2023a). Metamorphic analysis further indicates that the exhumation of TMCC eclogites was facilitated by omphacite breakdown, with no significant involvement of lawsonite, and by the infiltration of carbonaceous fluids in the final stage. The study also finds that recrystallized quartz grains, especially near the fault zones bounding the TMCC, exhibit simple shear or non-coaxial deformation. Additionally, misorientation analysis of these recrystallized quartz grains reveals the presence of Dauphiné twins and prism and rhomb <a> slip during recrystallization and grain size reduction (Dey et al., 2023b).

References

- Dey, A., Sen, K., Sen, A., & Choudhary, S. 2023a, Omphacite breakdown, symplectite formation and carbonate metasomatism in a retrograded continental eclogite: implications for the exhumation of the Tso Morari Crystalline Complex (Trans-Himalaya, NW India). *Physics and Chemistry of the Earth, Parts A/B/C*, 131, 103453.
- Dey, A., Sen, K., & Mamtani, M. A. 2023b, Lattice preferred orientation of quartz in granitic gneisses from Tso Morari Crystalline Complex, Eastern Ladakh, trans-Himalaya: evaluating effect of Dauphiné twin in dynamic recrystallization during exhumation. *Geological Magazine*, 160(8), 1556-1577.
- Dey, A., Sen, K., & Mamtani, M. A., 2022, Electron Backscatter Diffraction Study of Ultrahigh-Pressure Tso Morari Eclogites (Trans-Himalayan Collisional Zone): Implications for Strain Regime Transition from Constrictional to Plane Strain during Exhumation. *Lithosphere*, 2022(1).
- Epard, J.-L., Steck, A., 2008, Structural development of the Tso Morari ultra-high pressure nappe of the Ladakh Himalaya. *Tectonophysics* 451, 242–264.
- Guillot, S., Hattori, K.H., de Sigoyer, J., 2000, Mantle wedge serpentinization and exhumation of eclogites: Insights from eastern Ladakh, northwest Himalaya.

- O'Brien, P.J., 2019a, Tso Morari coesite eclogite: pseudosection predictions v. the preserved record and implications for tectonometamorphic models. Geological Society London, Special Publications, v. 474(1), p. 5–24.
- Palin, R.M., Reuber, G.S., White, R.W., Kaus, B.J.P., and Weller, O.M., 2017, Subduction metamorphism in the Himalayan ultrahigh-pressure Tso Morari massif: an integrated geodynamic and petrological modelling approach: *Earth and Planetary Science Letters*, v. 467, p. 108–119.
- Palin, R.M., St. Onge, M.R., Waters, D.J., Searle, M.P., and Dyck, B. 2014, Phase equilibria modelling of retrograde amphibole and clinozoisite in mafic eclogite from the Tso Morari massif, northwest India: constraining the P-T-M(H₂O) conditions of exhumation. *Journal of Metamorphic Geology*, v. 32(7), p. 675–693.
- St. Onge M.R., Rayner N., Palin R.M., Searle M.P., and Waters D.J., 2013, Integrated pressure–temperature–time constraints for the Tso Morari dome (northwest India): implications for the burial and exhumation path of UHP units in the western Himalaya. *Journal of Metamorphic Geology*, v. 31, p. 469–504.
- Steck, A., Epard, J., Vannay, J., Hunziker, J., Girard, M., Morard, A., Robyr, M., 1998, Geological transect across the Tso Morari and Spiti areas: The nappe structures of the Tethys Himalaya.
- Wilke, F.D.H., O'Brien, P.J., Schmidt, A., Ziemann, M.A., 2015, subduction, peak and multi-stage exhumation metamorphism: Traces from one coesite-bearing eclogite, Tso Morari, western Himalaya: *Lithos*, v. 231, p. 77–91.

Hyperextension, mantle exhumation, subduction: reconstruction of the Western Carpathian margin of the Neotethys: a new model

L. Fodor^{1,2}, O. Fernandez³, M. Molčan Matejová⁴, D. Plašienka⁴, T. Potočný⁴, R. Aubrecht⁴, Á. Csicssek², B. Grasemann³, G. Manatschal⁶, R. Vojtko⁴, Sz. Kövér^{1,2}

1 HUN-REN Institute of Earth Physics and Space Science, Sopron, Hungary, fodor.laszlo@epss.hun-ren.hu, kover.szilvia@epss.hun-ren.hu

2 Eötvös Loránd University, Institute of Geography and Earth Sciences, Department of Geology, Budapest, Hungary

3 University of Vienna, Department of Geology, Vienna, Austria, oscar.fernandez.bellon@univie.ac.at, bernhard.grasemann@univie.ac.at

4 Comenius University, Department of Geology and Paleontology, Bratislava, Slovak Republic, marina.matejova@uniba.sk,

dusan.plasienka@uniba.sk, potocny9@uniba.sk, aubrecht@fns.uniba.sk, rastislav.vojtko@uniba.sk

5 Universidad de Granada, Departamento de Geodinámica, Spain, adamcsicssek@gmail.com

6 University of Strasbourg, Institute of Earth and Environment, Strasbourg, France, manat@unistra.fr

The inverted northern margin of the Neotethys between the Vepor unit and the Szendrő Hills represents a complex structure within the Inner Western Carpathians. Despite of the long research history and considerable advancements (Grill et al., 1984; Less 2000; Lexa et al. 2003; Plašienka et al. 2019; Fodor et al. 2023), several fundamental questions remain unresolved. In this presentation, we address some of these outstanding problems and aim to contribute a milestone toward the long-term reconstruction of the original geometry of this rifted margin.

We redefine certain tectonic terms and units to avoid confusion with earlier publications, focusing on the tectonic elements that compose the nappe stack and clarifying their specific roles during extensional deformation. We use the term “Meliata domain” to encompass all units and/or palaeogeographical locations between the Gemer and Silica domains. This term is applied in a Triassic palaeogeographic sense, without addressing whether the domain represented a fully developed ocean with newly formed oceanic crust. The Bôrka high-pressure unit represents the Middle Jurassic to earliest Cretaceous subduction channel which divides the early nappe pile into a lower (Gemer, Vepor units) and an upper plate (low-grade units and the Silica nappe) (Mello et al. 1998; Faryad 1995; Potočný et al. 2023). The Držkovce unit consists of variably composed tectono-sedimentary mélanges related to the subduction process; the origin and age of clasts were clarified recently (Molčan-Matejová et al. 2025). It forms a coherent nappe unit although a tectonic mixture with the Bôrka nappe is present in places (Dobšiná). In a broader sense, the Silica domain represents the upper, flat-lying orogenic lid emplaced over the units of the Meliata domain. As a first-order approximation, the Bódva development can be assigned to this domain, although differences in Triassic palaeogeographic position and Cretaceous nappe stacking distinguish it from the Silica unit *sensu stricto* (Kövéř et al. 2009).

Serpentinite bodies of variable size occur at multiple locations and are associated with different tectonic units. We interpret these rocks not as fragments of a dismembered ophiolite sequence formed during Cretaceous nappe emplacement, but as exhumed portions of continental mantle derived from beneath the pre-Alpine basement. Their presence beneath several units of both the Meliata and Silica domains indicates a high degree of extension, locally reaching hyperextension. At least at one location (Bretka) the serpentinite is overlain by mylonitic marble of the formerly Middle Triassic platform carbonate. Crystalplastic deformation and thermal alteration decreasing rapidly from the contact. We interpret the mylonitisation and heating as consequences of the exhumation of hot mantle rocks, combined with the latent heat released during the exotherm process of serpentinitization although this hypothesis needs detailed investigation. Sedimentary cover of the exhumed serpentinite was observed in one borehole (Bódvárakó Br-4). The scarcity and narrow age range of the volcanic rocks within the detached units support the magma-poor character of the entire domain (Réti 1985; Ivan 2002; Faryad et al. 2005; Putiš et al. 2019). Several units of the Meliata domain are interpreted as extensional allochthons formed above a major detachment fault.

The Silica domain is interpreted as a large-scale extensional block rifted away from the northern margin. The persistence of platform carbonate sedimentation until the Carnian or Rhaetian suggests that it remained attached to continental crust until that time. However, the occurrence of serpentinite bodies at its base indicates that the domain was subsequently juxtaposed the exhumed mantle rocks in the latest Triassic to earliest Jurassic. We propose that the original basement of the Silica domain corresponded to the Szendrő Unit or a similar crustal block.

The subduction interface likely reactivated earlier extensional shear zones formed during mantle exhumation. Detached tectonic units, including former extensional allochthons, experienced variable degrees of burial within the subduction channel and were mostly exhumed during the Early Cretaceous. Large-scale, thin-skinned northward nappe emplacement occurred during the Late Cretaceous to Paleocene, accompanied by out-of-sequence thrusting and back-thrusting. Despite these contractional overprints, the original rift-related architecture remained relatively well preserved, allowing for meaningful reconstruction of the margin.

References

- Faryad, W. 1995. Phase petrology and P-T conditions of mafic blueschists from the Meliata unit, Western Carpathians, Slovakia. — *Journal of Metamorphic Geology* 13, 701–714.
- Faryad S.W., Spišiak J., Horváth P., Hovorka D., Dianiška I. & Józsa S., 2005: Petrological and geochemical features of the Meliata mafic rocks from the sutured Triassic oceanic basin, Western Carpathians. *Ophioliti*, 30, 1, 27–35.
- Fodor, L., Oravecz, É., Less, Gy., Kövér, Sz. (2023): Structure and evolution of the Aggtelek and Rudabánya Hills, north-east Hungary. Guidebook for pre- and post-conference excursions related to the CETEG 2023 Meeting, Kazincbarcika, Hungary. — *Acta Mineralogica-Petrographica Field Guide Series* 34, 66 p., Univ. of Szeged, Department of Mineralogy, Geochemistry and Petrology.
- Grill J., Kovács S., Less Gy., Réti Zs, Róth L. & Szentpétery I. 1984: Geological constitution and history of evolution of the Aggtelek-Rudabánya range. — *Földtani Kutatás* 27, 49–56.
- Ivan P., 2002: Relics of the Meliata Ocean crust: geodynamic implications of mineralogical, petrological and geochemical proxies. *Geologica Carpathica*, 53, 4, 245–256.
- Kövé, Sz., Fodor, L., Judik, K., Németh, T., Balogh, K. & Kovács, S. 2009: Deformation history and nappe stacking in Rudabánya Hills (Inner Western Carpathians) unravelled by structural geological, metamorphic petrological and geochronological studies. — *Geodinamica Acta* 22, 3–29.
- Kozur H. & Mock R. 1997: New palaeographic and tectonic interpretations in the Slovakian Carpathians and their implications for correlation with the Eastern Alps and other parts of the Western Tethys. Part II: Inner Western Carpathians. *Mineralia Slovaca*, 29, 3, 164–209.
- Less Gy. 2000: Polyphase evolution of the structure of the Aggtelek-Rudabánya Mountains (NE Hungary), the southernmost element of the Inner Western Carpathians – a review. *Slovak Geological Magazine* 6 (2-3), 260–268.
- Lexa, O., Schulmann, K. & Jezek, J. (2003). Cretaceous collision and indentation in the West Carpathians: View based on structural analysis and numerical modelling. *Tectonics*, 22 (6), 1066–1071.
- Mello J., Reichwalder, P. & Vozárová, A. 1998: Bôrka Nappe: high-pressure relic from the subduction-accretion prism of the Meliata ocean (Inner western Carpathians, Slovakia). *Slovak Geological Magazine* 4, 4, 261–273.
- Molčan Matejová, M., Potočný, T., Plašienka, D. & Aubrecht, R. 2025. Palaeoenvironmental interpretation of chaotic complexes of the Meliata Unit (Western Carpathians, Slovakia): new data from biochronology, lithostratigraphy and geochemistry. *Ophioliti*, 51, 17–36.
- Plašienka D., Méres Š., Ivan P., Sýkora M., Soták J., Lačný A., Aubrecht R., Bellová S. & Potočný T., 2019: Meliatic blueschists and their detritus in Cretaceous sediments: New data constraining tectonic evolution of the West Carpathians. *Swiss Journal of Geosciences*, 112, 1, 55–81.
- Potočný, T., Jeřábek, P. & Plašienka, D. 2023. Subduction–exhumation cycle recorded by calcite deformation microstructures: blueschist facies metacarbonates and kinematic implications for deformation of the Meliata Unit (West Carpathians). *International Journal of Earth Sciences*, 112, 2097–2117.
- Putiš M., Soták J., Qiu-Li L., Ondrejka M., Xian-Hua L., Zhaochu H., Xiaoxiao L., Nemec O., Németh Z. & Ružička P., 2019: Origin and age determination of the Neotethys Meliata basin ophiolite fragments in the Late Jurassic – Early Cretaceous accretionary wedge mélange (Inner Western Carpathians, Slovakia). *Minerals*, 9, 652.
- Réti, Zs. 1985: Triassic ophiolite fragments in an Evaporitic Melange, Northern Hungary. *Ophioliti*, 10/2-3, 411–422.

Post-collisional (late Carboniferous-early Permian) and rift-related (late Permian-Early Triassic) magmatic stages – a response of tectonic regime shifting, basement of the External Balkanides, Bulgaria

S. Georgiev¹, A. Lazarova¹, E. Balkanska², T. Vladinova¹, I. Broska³, S. Kurylo⁴

¹ Geological Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev Str., Bl. 24, 1113 Sofia, Bulgaria; E-mail: kantega@abv.bg

² Sofia University “St. Kliment Ohridski”, Department of Geology, Paleontology and Fossil Fuels; 15 Tzar Osvoboditel Bld., 1504 Sofia; E-mail: balkanska@gea.uni-sofia.bg

³ Earth Science Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 840 05 Bratislava, Slovakia; E-mail: igor.broska@savba.sk

⁴ Earth Science Institute, Slovak Academy of Sciences, Ďumbierska 1, 974 11, Banská Bystrica, Slovakia; E-mail: kurylo@savbb.sk

The Variscan orogenic belt formed during the late Paleozoic, resulted of the convergence and subsequent collision of the two major paleocontinents Laurasia and Gondwana, including a number of smaller microplates and fragments of magmatic arcs (e.g., Edel et al., 2017). During the final stages of the Variscan orogeny, late- to post-collisional magmatism was broadly manifested with an emplacement of large granitoid plutons (with minor mafic component), which delineate a long and well-pronounced magmatic belt. Subsequently, at the transition from Permian to Triassic, Eurasia was a locus of a widespread mafic to acidic magmatism and rifting thus causing the Pangea breakup (Nikishin et al., 2002, and references therein).

In the External Balkanides, several late Variscan to post-Variscan magmatic episodes are geochronologically well constrained (e.g., Carrigan et al., 2005; Dyulgerov et al., 2018; Georgiev et al., 2024), which culminated at late Carboniferous to early Permian. After an interval of absence of magmatic activity of 30–35 million of years, in late Permian–Early Triassic a new episode of “A-type” magmatism started, assumed to reflect a rift-related setting (e.g., Georgiev et al., 2022, and references therein). This magmatic event is attributed to crustal melting due to incorporation of mantle melts, which penetrated or underplated the crust in a post-orogenic environment, during the initial stage of extension and rifting, and further opening of the Vardar-Meliata Ocean (as proposed by Poli et al., 2009).

In the external Balkanides (including Balkan and Sredna Gora), the syn-orogenic to post-orogenic Variscan magmatic stage generally follows the main stage of convergence and subsequent collision of the two major paleocontinents, Laurasia and fragments of Gondwana respectively. An important compressional ductile Variscan shear zone with an orogenic-scale significance (e.g., Gerdjikov et al., 2023) probably marks a suture and traces the contact between the high- and low-grade metamorphic complexes along the southern foot of the Central Stara Planina Mountains in Bulgaria. The zone was initiated shortly after the thermal peak of the metamorphism in amphibolite facies in the Sredna Gora high-grade metamorphic complex (~337 Ma, Carrigan et al., 2006) and predated the stage of the late syn-tectonic to post-tectonic voluminous orogenic-scale magmatism in late Carboniferous to early Permian in the Balkan region. The initial high-K-alkaline magmatism, reflecting melting of an enriched mantle source, was revealed at 330 to 310 Ma (Dyulgerov et al., 2018), followed by a voluminous calc-alkaline to high-K calc-alkaline magmatism, evidenced by several plutonic bodies (with ages in the interval 309 to 306 Ma) and remnants of contemporaneous volcanic rocks (307.4±2.2 Ma) (e.g., Georgiev et al., 2024). There are sporadic coeval K-alkaline events (Dyulgerov, Stoylkova, 2022). The final stage of the late Variscan magmatic activity is marked by the intrusion of predominantly acid subvolcanic bodies and dikes in the interval of 288–286 Ma up to 260 Ma. In the Central Sredna Gora Mountain, two suits of granitoids (e.g., Carrigan et al., 2005 and references therein) are known – I-type (c. 312–304 Ma) and later S-type (c. 290 Ma). The I-type granodiorite-dominated plutons show many indicators of magma mixing and mingling processes as well as typical to I-type granites accessory minerals (e.g., titanite, low-Mn apatite, zircon and typical zoned allanite-(Ce)). This magmatic activity is finalized with the emplacement of S-type muscovite granites (Strelcha type granites), where mafic input is practically absent. The typical accessory minerals are apatite, zircon, and monazite.

During the late Permian–Early Triassic, a new magmatic episode started with the emplacement of small granitoid bodies (Kalofer and Klissura/Rozino plutons; Balkanska et al., 2021; Lazarova et al.,

2021) as well as numerous subvolcanic and volcanic bodies in the Central Balkan and Sinite kamani areas (e.g., Georgiev et al., 2022). All these rocks are formed in a close time span between 255 to 251 Ma. Geochemical data from several of the bodies show trends of A-type granitoids and can be classified as A2-type granites formed as a result of crustal melting induced by mantle melts in a post-orogenic setting.

Acknowledgements: This study is funded by the National Science Fund, bilateral cooperation (Bulgaria–Slovakia) via contracts KII-06-Словакия/10 and SK-BG-23-0016.

References

- Balkanska, E., Gerdjikov, I., Georgiev, S., Lazarova, A., Dörr, W., Kounov, A. 2021. Structural and geochronological constraints on the magmatic and tectonic events in the pre-Alpine basement of the central parts of the Balkan fold–thrust belt (Central Stara Planina Mountains, Bulgaria). – *International Journal of Earth Sciences*, 110, 3, 1181–1211; <https://doi.org/10.1007/s00531-021-02011-1>.
- Carrigan, C.W., S.W. Mukasa, I. Haydoutov, K. Kolcheva. 2005. Age of Variscan magmatism from the Balkan sector of the orogen, central Bulgaria. – *Lithos*, 82, 1–2, 125–147; <https://doi.org/10.1016/j.lithos.2004.12.010>.
- Carrigan, C.W., S.W. Mukasa, I. Haydoutov, K. Kolcheva. 2006. Neoproterozoic magmatism and Carboniferous high-grade metamorphism in the Sredna Gora Zone, Bulgaria: An extension of the Gondwana-derived Avalonian–Cadomian belt? – *Precambrian Research*, 147, 404–416; <https://doi.org/10.1016/j.precamres.2006.01.026>.
- Dyulgerov, M., M. Ovtcharova, M. Schaltegger, A. Ulianov, U. Schaltegger. 2018. Timing of K alkaline magmatism in the Balkan segment of southeast European Variscan edifice: ID TIMS and LA ICP MS study. – *International Journal of Earth Sciences* 107, 1175–1192; <https://doi.org/10.1007/s00531-017-1527-0>.
- Dyulgerov, M., T. Stoylkova. 2022. Mineralogical and geochemical characteristics of the Sedemte Prestola potassic alkaline pluton. – *Geologica Balcanica*, 51, 3, 57–59; <https://doi.org/10.52321/GeolBalc.51.3.57>.
- Edel, J.B., K. Schulmann, O. Lexa, J. M. Lardeaux. 2018. Late Palaeozoic palaeomagnetic and tectonic constraints for amalgamation of Pangea supercontinent in the European Variscan belt. – *Earth-Science Reviews*, 177, 589–612; <https://doi.org/10.1016/j.earscirev.2017.12.007>.
- Georgiev, S., A. Lazarova, E. Balkanska. 2022. Permian–Triassic A-type rhyolites from the Central Balkanides (Stara Planina Mountains), Bulgaria. – *Review of the Bulgarian Geological Society*, 83, 3, 77–80; <https://doi.org/10.52215/rev.bgs.2022.83.3.77>.
- Georgiev, S., A. Lazarova, E. Balkanska, K. Naidenov, I. Broska, S. Kurylo. 2024. Time constraints on the Variscan magmatism along Iskar River Gorge and Botevgrad basin, Bulgaria. – *Review of the Bulgarian Geological Society*, 85, 2, 159–162. <https://doi.org/10.52215/rev.bgs.2024.85.2.159>.
- Gerdjikov, I., A. Kounov, A. Lazarova, S. Georgiev, D. Vangelov. 2023. Lower Paleozoic low-grade metamorphic units from the Central Balkan Zone, Bulgaria: tectonic relationships, framework and geodynamic significance. – *Geologica Balcanica*, 52, 1, 65–86; <https://doi.org/10.52321/GeolBalc.52.1.65>.
- Lazarova, A., Broska, I., Svojtka, M., Naydenov, K. 2021. Klisura/Rozino granite, Central Sredna Gora: a part of the story of Late Permian–Early Triassic extensional magmatic event. – *Review of the Bulgarian Geological Society*, 82, 3, 87–90; <https://doi.org/10.52215/rev.bgs.2021.82.3.87>.
- Nikishin, A.M., P.A. Ziegler, D. Abbott, M.–F. Brunet, S. Cloetingh. 2002. Permo–Triassic intraplate magmatism and rifting in Eurasia: implications for mantle plumes and mantle dynamics. – *Tectonophysics*, 351, 3–39; [https://doi.org/10.1016/S0040-1951\(02\)00123-3](https://doi.org/10.1016/S0040-1951(02)00123-3).
- Poli, G., G. Christofides, A. Koroneos, T. Soldatos, D. Perugini, A. Lagone. 2009. Early Triassic granitic magmatism – Arnea and Kerkini granitic complexes – in the Vertiskos unit (Serbo-macedonian massif, north-eastern Greece) and its significance in the geodynamic evolution of the area. – *Acta Vulcanol.*, 20/21, 47–70; <https://doi.org/10.1400/146011>.

Geophysical and geological constraints for the crustal structures of the Mongolian Orocline and the adjacent sutures

A. Guy, I. Soejono

Czech Geological Survey, Klarov 3 11800 Praha 1, Czech Republic, Alexandra.guy@geology.cz

Magnetic and gravity analyses combined with a synthesis of high-pressure metamorphic and arc-related magmatic rocks characterize the crustal structures of the Mongolian Orocline and its adjacent sutures. The spatial distribution and the orientation trend of the geophysical fabrics are specific to the defined tectonic zones. Furthermore, the magnetic and gravity signatures, associated with the deep-seated continuity of the lineaments at the crustal-scale of the Precambrian blocks and the Mongol-Okhotsk oceanic domain, unveil the 3D geometry of the Mongolian Orocline. Thus, its distinct U-shape is observable in lithospheric magnetic and gravity fields, implying the involvement of the entire crust and possibly the upper mantle in the Mongolian Orocline's bending processes. Moreover, the examination of adjacent sutures, using conventional geophysical and geological markers, tends towards the absence of sutures between Precambrian blocks, suggesting therefore a single curved ribbon composed of microcontinents around the Mongol-Okhotsk oceanic domain. In contrary to previous interpretations, the study proposes separate traces for the Mongol-West Sayan and Baikal-Sayan sutures and enhances the predominance of the northern northward-dipping Mongol-Okhotsk suture. Finally, geophysical and geological data from the Mongolian Collage are consistent with the occurrence of an oroclinal bending at the lithospheric-scale of an originally near-linear Precambrian continental ribbon during late Palaeozoic to Mesozoic.

Geological map of the Upper Mesozoic strata in the Shiliin Nuruu Syncline, Mongolia

P. Hanzl¹, Z. Krejčí¹, P. Budil¹, K. Hrdličková¹, P. Čáp¹, J. Franců¹, J. Undayria²

¹ Czech Geological Survey, Klárov 3, 118 21 Prague, Czech Republic, pavel.hanzl@geology.cz

² School of Geology and Mining Engineering, Mongolian University of Science and Technology, Ulaanbaatar 14191, Mongolia

The Mesozoic cover in Mongolia is a part of widespread intracontinental extensional basins of Central and South-eastern Asia. In the western Mongolia, the Upper Mesozoic sedimentary belt is exposed along the northern slopes of the Mongolian and Gobi-Altai in the Valley of Lakes. The Shiliin Nuruu Syncline is located in the central part of this belt, to the west of Boon Tsagaan Lake and along the northern piedmont of the Zamtyin Nuruu mountain range. The Upper Jurassic to Lower Cretaceous formations, which have both lateral and vertical transitions with local wash-outs, reach a total thickness of up to 1000 metres.

The **Toromkhon Formation** (Upper Jurassic) represents the lowermost sequence of Mesozoic strata in the area. It consists of poorly sorted red conglomerates, breccias, sandy conglomerates and rare siltstone horizons. The **Undurukhin Formation** (Berriasian to Valanginian) is formed by first tens of meters thick sedimentary cycles consisting of conglomerates fining upward into sandstones. The **Anday Khudag Formation** (Hauterivian to Barremian, locally also Aptian) is exposed as fine-grained, dark-coloured, relatively thin (first tens of meters) sedimentary horizons locally developed between the Khulsan Gol and Undurukhin formations. The uppermost **Khulsan Gol Formation** (Aptian–Albian) is built by cycles of sandstones, mudstones, siltstones, marls and limestones as well as bituminous mudstones. Breccias are common in the Arslan Khayrkan mountain area in the east. Extrusive volcanic rocks dominate in the upper part of the Khulsan Gol Formation.

The rocks contain relics of terrestrial plants, indicating an origin in a warm desert-like environment with short periods of humidity. The coalification corresponds to early brown coal. The rich Hauterivian–Aptian palaeontological associations containing conchostracans, larvae of giant mayflies, gastropods, bivalves, and fishes are related mainly to the Anday Khudag and the Khulsan Gol formations. This assemblage could be compared with the **Jehol Biota** in north-east China.

The sedimentary sequence of the Shiliin Nuruu Syncline developed in a continental environment within the Mesozoic Gobi-Altai rift, as a part of a fluvial-lacustrine deltaic system.

Acknowledgments: *The primary field data were collected in the frame of the project “Geological mapping of selected parts of Mongolia at a scale of 1:50,000”, which was an integral part of the Program of the Development Assistance Project of the Czech Republic in 2003–2007. The preparation of the map and text was supported by the Strategic Research Plan of the Czech Geological Survey DKRVO/ČGS 2023–2027, internal task No. 311560.*

The role of Upper Permian evaporites in the Mesozoic structural evolution of the northeastern part of the Transdanubian Range Unit

G. Héja¹, T. Budai², M. Palotai¹, Gy. Maros¹

¹ SZTFH Geological Survey, gabor.heja@sztfh.hu

² University of Pécs, Department of Geology and Meteorology

The Transdanubian Range Unit (TRU) forms a thick-skinned nappe within the Eastern Alpine–Western Carpathian orogenic wedge. It is composed of Variscan low-grade metamorphic formations overlain by a Permian to Cenozoic non-metamorphic succession. The northeastern part of the TRU displays several distinctive features: (1) the base of the Permian–Mesozoic succession includes Upper Permian evaporites, which are absent in the central and southwestern parts of the unit; (2) Upper Triassic platform carbonates, deposited along the Neotethyan passive margin, are disrupted by narrow, long-lived intra-platform basins in the northeast of the area; and (3) the Cretaceous fold-and-thrust structures in this region exhibit different orientations and geometries compared to those in the central and southwestern TRU.

Our work is based on field geology, borehole and geophysical data and archive studies. Based on this dataset, the pre-Cenozoic geological map of the study area and six geological cross-sections were constructed, providing new insights into the structural evolution of the region.

According to our model, the Upper Permian evaporites played a key role in the Mesozoic structural evolution of the study area. The narrow Late Triassic basins of the north-eastern TRU developed in the hanging walls of NW–SE-striking normal faults that detached within the Permian evaporites. The development of these faults is interpreted to be related to gravity-driven gliding along the passive margin of the Neotethys Ocean.

We suggest that a south-vergent thin-skinned fold-and-thrust belt developed in the northeastern part of the Transdanubian Range Unit above a relatively shallow detachment level within the Permian evaporites during the Cretaceous (Barremian–Cenomanian). We propose that the local, oblique, NW–SE-striking thrusts formed due to oblique inversion of Triassic normal faults.

The general E–W strike of thrusts and fault-related folds observed in the study area differs from the NE–SW strike typical for the central part of the Transdanubian Range Unit. We interpret this curvature of the compressional structures as a detachment-controlled salient. Based on this model, the thrust sheets underwent larger tectonic transport in the northeastern part of the TRU where Permian evaporites provided a basal detachment, compared to the central and southwestern parts of the unit where such ductile detachment was absent. This interpretation implies vertical axis rotation of the northeastern part of the TRU compared to its central part. The different rotation of the two parts of the unit is supported by Jurassic and Cretaceous paleomagnetic data compiled by Márton et al. (2025), while Late Triassic paleomagnetic data are inconsistent with it, highlighting the need for further investigation. Due to the Late Cretaceous growth of the Western Carpathian orogenic retro-wedge, the thin-skinned fold-and-thrust belt of the study area was re-folded by thick-skinned structures that also deformed the Variscan basement.

References

Márton, E., Haas, J., Imre, G., Velki, M., & Fodor, L. 2025: New Mesozoic APWP for Adria aided by data from the Transdanubian Range Unit – Tectonic interpretation in the Europe–Africa geodynamic system. – *Gondwana Research* 137, 274–298. DOI: 10.1016/j.gr.2024.09.006

Variscan magmatism in the Western Central Carpathians and Bohemian Massif: comparing the incomparable

V. Janoušek¹, M. Kohút², I. Broska², I. Soejono¹, P. Hanzl¹

¹ Czech Geological Survey, Klárov 3, 118 21 Prague 1, Czech Republic;
e-mail: vojtech.janousek@geology.cz, igor.soejono@geology.cz, pavel.hanzl@geology.cz

² Earth Science Institute SAS, Dúbravská cesta 9, 840 05 Bratislava, Slovakia;
e-mail: milan.kohut@savba.sk, igor.broska@savba.sk

The first serious attempt on correlation of Variscan magmatic associations from the Bohemian Massif (BM) and Central Western Carpathians (CWC) (Cambel *et al.*, 1980, Klomínský *et al.*, 1981) faced two main problems: general scarcity of precise ages and strong Alpine overprint in dismembered Variscan massifs occurring in the latter. Still, there were noted some major differences – most importantly, CWC granitoids tend to have on average a more leucocratic character, a higher Na₂O/K₂O, and (ultra-)K magmatic rocks, common in the BM (Janoušek *et al.*, 2025), are absent.

The rapid advancement of statistical and analytical techniques, in particular isotope geochemistry and geochronology, motivated us to revisit this issue. For this reason, we compiled a large database of geochronological and whole-rock geochemical data for plutonic rocks that intruded in the critical time period (Mid-Devonian to early Visean, < 330 Ma) and evaluated it using the R environment (Janoušek *et al.*, 2016). To date, the database includes representative U–Pb ages, mainly on zircon (BM: 110 and CWC: 309), as well as major- and trace-element (277/252) and Sr–Nd isotopic (150/111) data. The main conclusion from our comparison is that the magmatic rock inventories, timing and evolution of magmatism in BM and CWC did differ profoundly.

In the BM, much of this period (at least c. 390–360 Ma) was characterized by magmatic activity of an arc developed due to subduction of the Saxothuringian Ocean beneath the Teplá–Barrandian/Moldanubian domain (Schulmann *et al.*, 2009, Žák *et al.*, 2014). In Tournaisian, the magmatism migrated eastward, and the Peri-Moldanubian Arc formed. The evolution of this enormous structure was terminated by the Visean (~340 Ma) continental collision and slab break-off. The Visean activity in the BM was characterized by voluminous (ultra-)K magmatism (durbachitic and related rocks) derived from metasomatized mantle (Janoušek *et al.*, 2025). Unlike in the rest of the Variscan belt (Moyen *et al.*, 2025), practically missing are syn- to early post-collisional S-type granitoids. The bulk of Moldanubian S-type magmas was produced only in Serpukhovian, or later (Verner *et al.*, 2025).

In the CWC, the evolution started somewhat later but proceed faster from subduction-related through syn- to post-collisional magmatism. Still, genuine arc-related rocks are lacking. The Mid-Devonian (~380–361 Ma) gabbros–diorites and diatexites were probably generated in a back-arc setting of an unknown arc system (Ivan *et al.*, 2001, Putiš *et al.*, 2009). The subduction was short-lived, and ended by the late Famennian (~360 Ma) collision, slab break-off and asthenospheric upwelling (Broska *et al.*, 2022). This heat pulse is recorded by dioritic rocks, followed in Tournaisian (357–345 Ma) by mostly syn- to late-collisional I- and immature S-type (Bt-only) granitoids. They gave way to the Visean post-collisional, Bt–Ms granites derived from mature metasedimentary sources (Kohút *et al.*, in print).

Contrasting magmatic histories of the BM vs. CWC reflect distinct geodynamic and, consequently, paleogeographic settings. We propose that the early slab break-off in the CWC prevented the continental crust to be dragged into the subduction zone, and to metasomatize the local mantle. Visean (ultra-)K rocks, ubiquitous in the BM, Vosges, Schwarzwald, Alps and on Corsica (Moyen *et al.*, 2025), are absent in the CWC as are the spatially and temporally associated felsic (U)HP–HT granulites. The BM vs. CWC crustal segments had to be located far from each other, probably along two unconnected sutures in different branches of the Variscan orogenic collage. The BM forms a complete vestige of the collisional orogen's interior. In contrast, the CWC is a fragmented and displaced crustal section derived from a specific, so far unidentified part of the Variscan belt.

Acknowledgements: This study was financially supported by GAČR 22-34175S, APVV-22-0092, VEGA-2/0002/24, VEGA-1/0028/24 as well as the internal project of the Czech Geological Survey (311330).

References

- Broska, I., Janák, M., Svojtka, M., Yi, K., Konečný, P., Kubiš, M., Kurylo, S., Hrdlička, M. & Maraszewska, M. (2022). Variscan granitic magmatism in the Western Carpathians with linkage to slab break-off. *Lithos* 412–413, 106589.
- Cambel, B., Kamenický, L., Klomínský, J. & Palivcová, M. (1980). Petrochemical correlation of granitoids of the Bohemian Massif and the West Carpathians. *Geologický Zborník Geologica Carpathica* 31, 3–26.
- Ivan, P., Méres, Š., Putiš, M. & Kohút, M. (2001). Early Paleozoic metabasalts and metasedimentary rocks from the Malé Karpaty Mts. (Western Carpathians): evidence for rift basin and ancient oceanic crust. *Geologica Carpathica* 52, 67–78.
- Janoušek, V., Moyen, J. F., Martin, H., Erban, V. & Farrow, C. (2016). *Geochemical Modelling of Igneous Processes – Principles and Recipes in R Language. Bringing the Power of R to a Geochemical Community*. Berlin: Springer.
- Janoušek, V., Magna, T., Tabaud, A. S., Vennemann, T., Hora, J. M. & Holub, F. V. (2025). Infracrystal reworking and cryptic crustal growth during the Variscan Orogeny: stable isotopic evidence from (ultra-) potassic magmatic rocks of the Moldanubian Zone, Bohemian Massif. *Lithos* 510–511, 108115.
- Klomínský, J., Palivcová, M., Cambel, B. & Gurbanov, A. G. (1981). Petrochemical correlation and I/S classification of Variscan granitoids from the Czech Massif, West Carpathians (Czechoslovakia) and the Caucasus Mts. (USSR). *Geologický Zborník Geologica Carpathica* 32, 307–315.
- Kohút, M., Broska, I., Konečný, P., Kurylo, S. & Yi, K. (in print). The Staré mesto granite: its dating and genetic implications for the Variscan magmatism of the Western Carpathians. *Mineralogy and Petrology*.
- Moyen, J.-F., Guy, A., Fiannacca, P., Janoušek, V., Villaseca, C. & Ayarza Arribas, P. (2025). Granites and the nature of the Variscan crust. *Elements* 21, 415–421.
- Putiš, M., Ivan, P., Kohút, M., Spišiak, J., Siman, P., Radvanec, M., Uher, P., Sergeev, S., Larionov, A., Méres, Š., Demko, R. & Ondrejka, M. (2009). Meta-igneous rocks of the West-Carpathian basement, Slovakia: indicators of Early Paleozoic extension and shortening events. *Bulletin de la Société Géologique de France* 180, 461–471.
- Schulmann, K., Konopásek, J., Janoušek, V., Lexa, O., Lardeaux, J. M., Edel, J. B., Štípská, P. & Ulrich, S. (2009). An Andean type Palaeozoic convergence in the Bohemian Massif. *Comptes Rendus Géoscience* 341, 266–286.
- Verner, K., Megerssa, L., Buriánek, D. & Kalinová, R. (2025). The Moldanubian units – a broad insight into deeper parts of the Variscan Orogen. In: Linnemann, U. (ed.) *The Variscan Orogen of Central Europe: Geodynamics – Geochronology – Geobiology*. Cham: Springer Regional Geology Reviews, 527–550.
- Žák, J., Verner, K., Janoušek, V., Holub, F. V., Kachlík, V., Finger, F., Hajná, J., Tomek, F., Vondrovic, L. & Trubač, J. (2014). A plate-kinematic model for the assembly of the Bohemian Massif constrained by structural relationships around granitoid plutons. In: Schulmann, K., Martínez Catalán, J. R., Lardeaux, J. M., Janoušek, V. & Oggiano, G. (eds.) *The Variscan Orogeny: Extent, Timescale and the Formation of the European Crust*: Geological Society London Special Publications 405, 169–196.

Eo-Alpine Metamorphic Event in the Permian Cover of the Vepor Unit, Western Carpathians: Lu-Hf Garnet Geochronology and PT Conditions

P. Jeřábek¹, J. Sláma², R. Vojtko³

¹ Institute of Petrology and Structural Geology, Faculty of Science, Charles University, Albertov 6, 12800 Praha 2, Czechia; jerabek.petr@natur.cuni.cz

² Institute of Geology, Czech Academy of Sciences, Rozvojová 269, 16500 Praha 6, Czechia; slama@gli.cas.cz

³ Department of Geology and Palaeontology, Faculty of Natural Sciences, Comenius University, Ilkovičova 6, Bratislava, Slovakia; rastislav.vojtko@uniba.sk

The peak metamorphic conditions related to the Cretaceous Eo-Alpine event have been reached in a narrow time span in both the Eastern Alps and Western Carpathians, however the two domains show contrasting, subduction and collisional, geothermal gradients, respectively. In the Western Carpathians, the highest metamorphic conditions of Cretaceous age occur in the Vepor Unit. Here the previous peak PT estimates of 11 kbar and 620 °C (Janák et al. 2001; Jeřábek et al. 2008) have been recently shifted to slightly higher pressures of 12–14 kbar and 580–600 °C and dated by monazite EPMA geochronology to ~96 Ma (Janák et al. 2025). In the Eastern Alps, the highest metamorphic conditions of Cretaceous age occur in the Silvretta-Seckau Nappe System with the peak PT conditions reaching UHP at ≥35 kbar and 800–850 °C (e.g. Janák et al. 2004). Recent Lu-Hf garnet dating of garnets from various eclogites of the Silvretta-Seckau Nappe System confirmed peak metamorphic ages for the Eo-Alpine event between ~102–90 Ma (Miladinova et al. 2021).

In this work, we report the first Lu-Hf garnet age, and associated PT estimates, related to the Eo-Alpine event in the West Carpathians. Dated garnet comes from a quartzite sample collected from the Permian cover sequence in the southern part of the Vepor Unit (Slavošovce area). The quartzite contains quartz, garnet, muscovite intergrowths with paragonite, chlorite, sporadic albite, and ilmenite overgrown by rutile. The garnet shows a honeycomb microstructure with numerous quartz inclusions and its chemical composition is dominated by almandine and grossular (Xalm 0.72–0.76, Xgrs 0.18–0.21) with a slight rimward decrease in spessartine and increase in pyrope (Xsps 0.04 → 0.01, Xprp 0.04 → 0.07). Muscovite has Si ranging between 3.15–3.2 atoms per formula unit and chlorite has XMg between 0.44–0.45. Plagioclase is albite with Xan ranging between 0.05–0.11. Thermodynamic modelling performed in MAgEMin suggests an increase in PT conditions from ~7.5 kbar at ~540 °C to ~13 kbar at ~580 °C, based on the mineral assemblage and core to rim compositional zoning of garnet. The Lu-Hf garnet age will be provided on the poster.

References

- Janák, M., Froitzheim, N., Lupták, B., Vrabec, M., Ravna, E.J.K., 2004. First evidence for ultrahigh-pressure metamorphism of eclogites in Pohorje, Slovenia: Tracing deep continental subduction in the Eastern Alps. *Tectonics* 23, 2004TC001641.
- Janák, M., Petřík, I., Plašienka, D., Froitzheim, N., Konečný, P., 2025. Allanite to monazite transition and dating of prograde Eo-Alpine metamorphism in the Veporic Unit, Western Carpathians (Slovakia). *Geologica Carpathica* 76.
- Janák, M., Plašienka, D., Frey, M., Cosca, M., Schmidt, S.Th., Lupták, B., Méres, Š., 2001. Cretaceous evolution of a metamorphic core complex, the Veporic unit, Western Carpathians (Slovakia): P – T conditions and in situ ⁴⁰Ar/³⁹Ar UV laser probe dating of metapelites. *Journal of Metamorphic Geology* 19, 197–216.
- Jeřábek, 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.
- Miladinova, I., Froitzheim, N., Nagel, T.J., Janák, M., Fonseca, R.O.C., Sprung, P., Münker, C., 2022. Constraining the process of intracontinental subduction in the Austroalpine Nappes: Implications from petrology and Lu-Hf geochronology of eclogites. *Journal of Metamorphic Geology* 40, 423–456.

Apatite and zircon fission-track thermochronology of the High Tatras Mountains (Western Carpathians)

E. Klamová¹, R. Vojtko¹, M. Reiser^{2,3}

¹ Department of Geology and Palaeontology, Faculty of Natural Sciences, Comenius University Bratislava, Ilkovičova 6, SK-842 15 Bratislava, Slovakia; rastislav.vojtko@uniba.sk; klamova13@uniba.sk

² Geosphere Austria, Hohe Warte 38, 1190 Vienna, Austria; martin.reiser@geosphere.at

³ Department of Geology, University of Innsbruck, Innrain 52f, 6020 Innsbruck, Austria

The Tatras Mountains, located in the northernmost part of the Central Western Carpathians, experienced a complex Alpine tectonic evolution. To constrain the timing of this evolution and the cooling history of the crystalline basement, we analysed zircon and apatite fission-track ages. Zircon central (or peak) ages were obtained from four samples (PPVTA01–04) and range from 157 ± 26 Ma to 29 ± 9 Ma. Two analyses (PPVTA02 and PPVTA04) passed the χ^2 test ($P(\chi^2) > 5\%$), indicating that the single-grain ages are statistically drawn from a single population. The remaining two analyses (PPVTA01, PPVTA03) failed the test; therefore, their ages are interpreted as peak ages.

Apatite central ages are significantly younger than the zircon ages, ranging from 17 ± 2 Ma to 14 ± 4 Ma. All apatite samples passed the χ^2 test. The confined track-length distributions of horizontally confined fission tracks are unimodal and negatively skewed, with relatively broad standard deviations ranging from $1.9 \mu\text{m}$ (PPVTA01) to $2.6 \mu\text{m}$ (PPVTA03). Mean horizontally confined track lengths are short, ranging from $12.3 \mu\text{m}$ (PPVTA01) to $11.2 \mu\text{m}$ (PPVTA03).

Based on these data, the older zircon fission-track ages likely reflect a thermal overprint that caused significant annealing of zircon fission tracks. This heating event is interpreted as a consequence of Jurassic rifting along the northern Tatric margin, related to the Alpine Atlantic, or along the southern margin associated with the Zliechov Basin (Fatric sedimentary domain). Subsequently, during the late Early Cretaceous (~ 110 – 80 Ma), the Tatric crystalline basement was buried beneath the Eo-Alpine Fatric and Hronic nappes, coeval with regional nappe stacking. Fully annealed zircon samples indicate metamorphic temperatures exceeding ~ 300 °C. This major compressional phase was followed by orogenic collapse during the Late Cretaceous to Paleogene (~ 70 – 55 Ma), as recorded by younger zircon fission-track ages.

The Late Eocene to Early Miocene was marked by the formation of a marginal sea within the Magura Ocean – the Central Carpathian Paleogene Basin. This basin represents a fore-arc setting developed along a destructive plate margin behind the External Western Carpathian accretionary wedge. During deposition of the Paleogene sedimentary succession (~ 45 – 20 Ma), the Tatric crystalline basement resided within the apatite–zircon partial annealing zones (~ 200 – 100 °C). Final cooling of the Tatra Massif resulted from asymmetric exhumation associated with activity along the Subatric Fault. Apatite fission-track data indicate that exhumation of the Tatric crystalline basement from depths of ~ 5 km occurred from the Early Miocene.

Acknowledgements: This work was supported by the Slovak Research and Development Agency under contract No. APVV-21-0281 “Alpine geodynamical evolution of the Western Carpathian inner zones” and VEGA 1/0021/25 “Neotethys (Meliaticum) and Alpine Atlantic (Vahicum) – what has happened with two oceans which influenced evolution of the Western Carpathians?”. This article was also funded by the EU NextGenerationEU through the Recovery and Resilience Plan for Slovakia under the project No. 09I03-03-V05-00012.

Provenance of the Lower Triassic quartzites from the Western Carpathians - Separation myths from facts

M. Kohút¹, I. Soejono², J. Miková², M. Zieger-Hofmann³, D. Laurinc⁴

¹ Earth Science Institute, SAS Bratislava, Slovakia; milan.kohut@savba.sk

² Czech Geological Survey Prague, Czech Republic; igor.soejono@geology.cz

³ Senckenberg Naturhistorischen Sammlungen Dresden, Germany

⁴ Dionýz Štúr State Institute of Geology Bratislava, Slovakia

The Lower Triassic quartzites form important sedimentary and metamorphic rock formations found worldwide, which usually represent the erosional product of Variscan and older orogeneses. Generally, due to their transgressive character they often form the onset of new Mesozoic depositional cycles in the Alpine-Himalayan Orogen. In the Western Carpathians (CWC) they are attracting at first glance with their pronounced petrification (having even metamorphic character at elevated pressure and temperature) exceeding the usual lithification or diagenesis. Their designation was often changed due to development of knowledge, from analogous naming such as: "*Rothliegendes*", "*älterer Quarzit*", "*Permotrias*", "*Quartzsandstein*", "*basal Triassic*", "*Werfener sandstones*", "*Seis sandstones*", "*Scythian quartzites*", "*basal conglomerates and quartzites*" to the codified labelling the Lúžná Fm. (Fejdiová, 1980 and citations therein). The Lúžna F. (LF) occurs in the Tatric, Fatric, Veporic, Hronic and Zemplinic units in the Western Carpathians, where they deposited in fluvial (continental) to shallow marine environments. The LF can be divided into 3 members: 1) - medium- to coarse-grained quartz sandstones to conglomerates, less arcose and cherts; most often brown, but sometimes pink or grey in colour; 2) - fine-grained to medium-grained quartzites with frequent cross-bedding, in places with green claystone; 3) - fine-grained purple to red micaceous arcose sandstones, red and purple silty shales. Psammitic sediments of the LF are composed mainly of quartz (polycrystalline, monocrystalline), feldspars, locally also carbonates and clay-silica-sericite groundmass (fraction below 0.02 mm) (Fejdiová, 1985). In accessory quantities there are micas, zircon, rutile, tourmaline, pyrite, leucoxene and apatite. There were identified following lithoclasts in the LF: the most common are acid magmatites (granites ± rhyolites), gneisses, phyllites, lydites, tourmaline rocks and metaquartzites. The controversy of the sedimentary environment features e.g.: short, fast transport within a pronounced relief, poorly rounded clasts, unsorted grain size, as well as the mineralogical immaturity of the arenite fraction, terrestrial-lake environment and arid area, versus long transport with well-abraded sand grains and sorting of sand grains, removal of the clay fraction, abundant exotics, peneplenized relief with a humid marine environment, have long led to the idea that the source area of the LF was the area north to north-west of the Carpathian - area between the Bohemian Massif and the Armorican Massif (Fejdiová, 1985; Mišík & Jablonský 2000, and citations therein); of course, the contribution of a local source was not excluded.

We selected, in this study, one sample of the Lower Triassic quartzite from the Tatric Unit envelope taken on the southern slopes of the Nízke Tatry Mts. in the Krupová area (labelled as UT-70) near the underlying crystalline basement, formed by migmatized orthogneisses. The second sample of the LF quartzite (ZKP-3/08) comes from the base of the Fatric Unit (Křížna nappe) from the Belianska Valley of the Veľká Fatra Mts., where these quartzites are tectonically overlying a Cretaceous (Albian–Cenomanian) member of the Tatric Unit envelope of the Veľká Fatra Mts., well exposed in tectonic window. Generally, on the basis of their chemical composition, the mineral clasts and/or lithoclasts presence, maturity of sediments, and pour-rounded character of sand grains, studied quartzites can be classified as massive (isotropic) quartz arenite to sublithic arenite, and as weakly foliated subarcose. Chemical alteration index values are CIA = 49 – 67 showing a low to moderate alteration, while plagioclase alteration index values varying in the range PIA = 63 – 96 indicate mild to total plagioclase weathering. The chemistry and mineral composition of the LF, clearly document that these mechanical-clastic sediments were deposited in an extensional rift basin on the Passive Continental Margin (PM).

Most of the analysed detrital zircons (DZ) from sample UT-70 have Ordovician age from 474 to 446 Ma (35% of the total number of concordant grains), the second most abundant group is formed by Carboniferous zircons (358–307 Ma, 30%), over 10% of total are Neo-Proterozoic grains (964–542 Ma, 15%), other age groups (Permian, Devonian, Silurian, Cambrian and Paleo-Proterozoic) are represented

in numbers of 2–9 pieces. The youngest population of DZ gives the concordia age of 274 Ma, which corresponds to the maximum depositional age (MDA). In contrast, in the sample from the Fatric base of the ZKP-3/08, the Carboniferous zircons dominate (356–310 Ma, 40%), followed by Neo-Proterozoic grains (684–545 Ma, 36 %), other age groups, including the Archean, are represented in a minority with a number of grains of 1–3; and with MDA = 316 Ma. Naturally, the older the zircon grains, the more abraded they are, becoming perfectly oval, while young Carboniferous zircons are poorly-rounded, what indicates their short transport. Detrital zircons in sandstones serve as a “fingerprint” of the parent rocks. According to the Hf data, we can assign zircon grains to the type of crust and the development of individual orogens forming the source of sediments. The epsilon Hf values $\epsilon\text{Hf}_{(i)}$ of the analysed zircons vary in a wide interval from +11 to –17, while their two-stage model ages $T_{\text{DM2st}} = 725\text{--}1800$ Ma mirroring the long time spent in the crust before final crystallization. It is evident that these zircons originate from multiple recycled metamorphic rocks, but also from young intermediate to acidic magmatites.

The presence of clastic tourmaline in the LF quartzites was one of the main mythical arguments for the origin of sedimentary material outside the CWC in the past (Uher 1999; Mišík & Jablonský 2000). However, Havrila & Kohút (2006) identified clastic tourmaline not only in the quartzites themselves, and in the biotite phyllites forming lithoclasts’ pebbles in the so-called “*Zlatý vrch conglomerate*”, but also directly in the underlying phyllites of the Tatric Unit basement in the Považský Inovec Mts., from which these pebbles were derived. Noteworthy, the distribution of DZ ages in the studied samples agrees in many aspects with the distribution of zircon ages in rocks from the crystalline basement of the CWC, although there in the LF is missing a prominent maximum with an age of 352 Ma in the probability plot. Similarly, the new Hf isotopic data from analysed detrital zircons more or less coincide with the data from the crystalline basement of the CWC (Soejono et al. 2024).

Comprehensive mineralogical-petrological data together with modern data from the DZ confirm the polygenic origin of the studied LF quartzites, showing signs of both long and short transport and reworking of clastic material. It is obvious that the source was a crystalline basement proximate to the CWC basement, but some contribution from a distant crystalline basement is very likely, although this basement also originated on the northern margin of Gondwana. Preliminary we exclude the transport of clastic material from the north - from the Baltica, because of distinct Meso-Proterozoic gap in the detrital zircon’s distribution in the LF.

References

- Fejdiová, O. 1980: Lúžna Formation – formal Lower Triassic lithostratigraphic unit. *Geologické práce, Správy* 74, 95-101. (*in Slovak*)
- Fejdiová, O. 1985: New information on Lower Triassic Liptovská Lúžna Clastic Formation in the Central West Carpathians. *Západné Karpaty, Series Miner. Petrogr. Geoch. Metalog.* 10, 111-160. (*in Slovak with English summary*)
- Havrila, M. & Kohút, M. 2006: Polymictic conglomerates of the Zlatý vrch in the Považský Inovec Mts. - basis of the Lúžna Formation: lithology and source of material. *Mineralia Slovaca* 38/2, *Geovestník*, 14-15. (*in Slovak*)
- Mišík, M. & Jablonský, J. 2000: Lower Triassic quartzites of the Western Carpathians: transport directions, source of clastics. *Geologica Carpathica* 51(4), 251-264.
- Soejono, I., Collett, S., Kohút, M., Janoušek, V., Schulmann, K., Bukovská, Z., Novotná, N., Zelinková, T., Míková, J., Hora, J.M. & Veselovský, F. 2024: Paleogeography of the Gondwana passive margin fragments involved in the Variscan and Alpine collisions: Perspectives from metavolcanic-sedimentary basement of the Western Carpathians. *Earth-Science Reviews* 253, 104763
- Uher, P. 1999: Clasts of tourmaline-rich rocks in Lower Triassic quartzites, the Tatric Unit, Central Western Carpathians: Tourmaline composition and problem of source areas. *Geologica Carpathica, Spec. Issue* 50, 140-141.

Complex inner structure of the Muráň Nappe (Western Carpathians, Slovakia) based on geological mapping

B. Kronome¹, E. Hraško¹, M. Olšavský², O. Pelech¹

¹ State Geological Institute of Dionýz Štúr, Mlynská dolina 1, Bratislava, Slovakia

² State Geological Institute of Dionýz Štúr, Zelená 5, Banská Bystrica, Slovakia

The Muráň Nappe is generally considered a relatively simple superficial nappe overthrust directly on the Veporic unit. Formerly the Muráň Nappe was considered to be a part of the Hronic, later the Silicic or partly Vernaric units, however its lithological and stratigraphical characteristics show both Silicic and Hronic affinity, thus it could be interpreted as a transitional tectonic element between the Silicic and Hronic nappes.

Our earlier geological mapping between 2010-20 as well, as our ongoing mapping since 2024, shows also a much-complicated multi-phase and multi-style structural evolution of the Muráň Nappe. The main tectonic phases, their sense and map-scale effects can be deciphered as follows:

- 1) The Upper Jurassic – Lower Cretaceous nappe stacking caused:
 - a) Strong deformation of the underlying Veporic Unit, creating duplexes in the Federata-type cover sequence and causing strong mylonitisation in the crystalline basement
 - b) Formation of a massive *rauhwacke* horizon with variable thickness from almost 0 to hundreds of metres, mostly from the disintegrated Federata cover sequence
 - c) Deformation of the dominantly shaley-sandy Lower Triassic complex (“Werfen”) of the Muráň Nappe of variable thickness; in some places (zones?) with duplex structures as well as incorporated and discontinuous slices of Carboniferous shales and sandstones, or Permian rhyolitic bodies.
 - d) The formation of lower and upper Muráň Nappe. By our opinion they are also partial structures in the same nappe body, developed by diagonal partial overthrust during the main nappe stacking phase or a later event.
- 2) the Middle Cretaceous uplift and subsequent unroofing of the southern Veporic domain is not directly detectable, however we can't exclude, that some internal deformation structures of the nappe stack as a whole can be originated by the unroofing.
- 3) Cenozoic fault activity
 - a) probably Paleogene activation of the Muráň Line itself as a main normal fault and forming of antithetic parallel lesser normal faults; similarly oriented fault zones with strike-slip + normal fault character are known – however less evident – in the surrounding Veporic crystalline massifs south and also north of the Muráň Line; the emplacement of the later Miocene volcanics in the western part of the study area, in the recent stage observed only as the former stratovolcano's magma channels (as dykes), seemingly preferred these fault structures
 - b) probably Paleogene NE-SW faults, mostly of strike-slip character
 - c) Neogene NW-SE of several generations, mostly of normal fault character combined with strike-slip movements dipping to the SW with sense changing according the changes of the Miocene stress field
- 4) Pliocene to Recent neotectonics is the youngest observed, but often underestimated process in forming the recent structure, causing large scale slope movements (e.g. rock slides, landslides), terraces and deeply eroded valleys.

Magma Ascent and Fracture Growth in the Oblique Rift of the Reykjanes Peninsula: Insights from Analogue Experiments

O. Krýza^{1,2}, M. Staněk¹, P. Závada¹, J. Doubravová¹, J. Burjáněk¹, F. Zwaan^{3,4,5}

1 Institute of Geophysics of the Czech Academy of Sciences, Prague, Czechia

2 Department of Geophysics, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, 180

3 GFZ Helmholtz Centre for Geosciences, Telegrafenberg, 14473 Germany

4 Institute of Earth Sciences, University of Lausanne, Géopolis, 1015 Lausanne, Switzerland

5 Department of Geosciences, University of Fribourg, Chemin du Musée 7, 1700 Fribourg, Switzerland

The Reykjanes Peninsula (RP) in southwest Iceland marks a zone of highly oblique rifting with magmatic activity distributed along belt-like volcanic systems aligned in an en-echelon pattern with respect to the plate boundary between the North American and European plates. These volcanic systems of the RP display cyclic activity that recurs approximately every 800 years. Since 2021, a series of eruptions has occurred within the Svartsengi and Fagradalsfjall systems. Erupted lava compositions and seismic tomography suggest their common magma source is located near the Moho.

To investigate how transcrustal magma pathways and eruptive fissures form at Reykjanes Peninsula, we conducted scaled analogue experiments with a silicone magma chamber at the base of a gelatin crust subjected to deformation related to oblique extension. Pig-skin gelatin represents the brittle upper crust and a high-viscosity PDMS body simulates a semi-solidified “mushy” magma reservoir. A low-viscosity silicone oil reproduces buoyant basaltic magmas rising through the mush and the overlying crust. The photoelasticity of the gelatin visualizes the stress field, while digital image correlation quantifies surface deformation, allowing us to track the nucleation and propagation of brittle fractures in the vicinity of sub-crustal magma reservoirs.

In experiments with active magma injection, first a sill-like, U-shaped, silicone-filled fracture propagated from the point source of the analog magma injection. Its geometry and propagation are analogous to WSW–ENE-trending seismic clusters interpreted as magma-filled fractures or pathways migrating along the plate boundary during the 2020–2021 unrest. Two NE-striking, subparallel fractures in our models resemble seismic clusters directly underlying the Fagradalsfjall and Sundhnúkur eruption sites, and when one such fracture reached the surface, its continued propagation was accompanied by uplift of adjacent wall segments. In follow-up experiments, we tested the effects of pre-developed mushy reservoir (geometry), pure oblique extension without magma presence (Fig. 1), and several other combinations of such settings to inversely derive the effect of magmatic sources on large-scale fracture dynamics and geometry.

Our experiments demonstrate that a mushy reservoir can indeed act as a structural and rheological link between deep magma accumulation zones and eruptive fissures, controlling both the path and geometry of ascending magma. These results provide new insights into the feedbacks between magmatic intrusion, brittle failure, and surface deformation that govern eruption initiation in oblique rift environments such as the Reykjanes Peninsula.

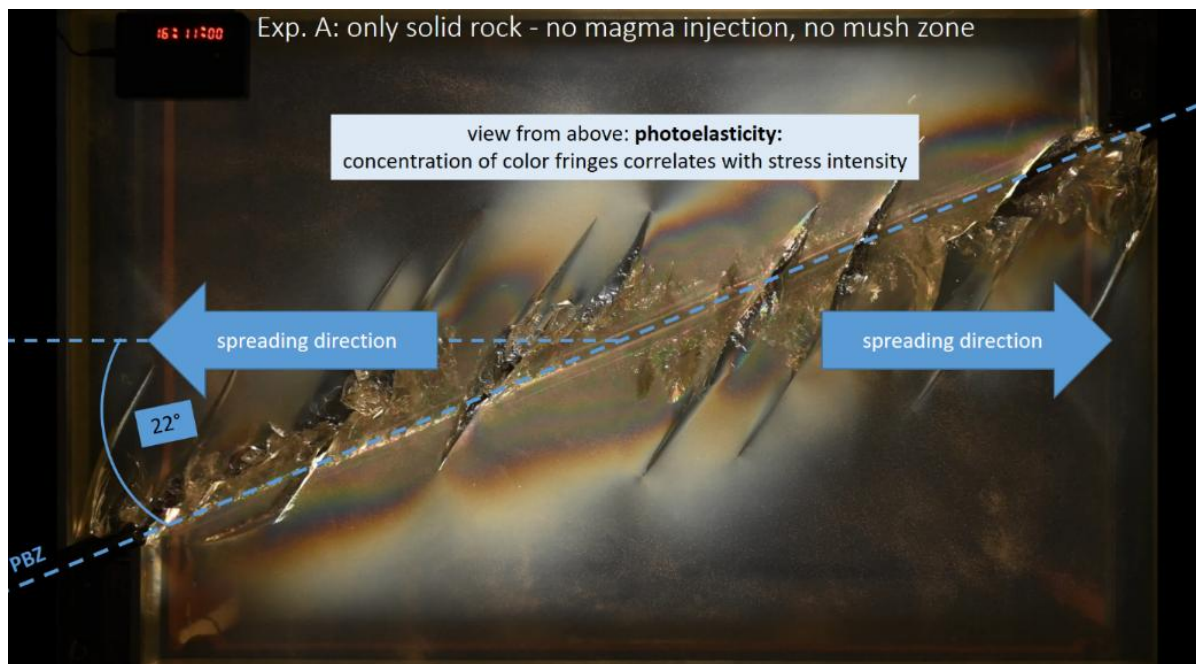


Fig. 1: Example from the oblique-extension experiment without a magma chamber (top view). The rainbow aureole indicates the stress pattern within the jelly layer representing the upper crust.

Dynamics of partially molten lower crust in hot orogens: Coupled insights from numerical and analogue modelling

O. Krýža^{1,2}, P. Maierová^{2,3}, P. Závada^{1,3}, M. Machek¹, V. Kusbach¹, Z. Roxerová¹, K. Schulmann^{3,4}, H. Čížková²

¹ Institute of Geophysics, Czech Academy of Sciences, Boční II/1401, 141 31 Prague 4, Czech Republic.

² Department of Geophysics, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, 180 00 Prague 8, Czech Republic.

³ Centre for Lithospheric Research, Czech Geological Survey, Klárov 131/3, 118 00 Prague 1, Czech Republic.

⁴ Université de Strasbourg, EOST–IPGS, CNRS/Université de Strasbourg UMR 7516, 5 rue René Descartes, 67084 Strasbourg Cedex, France

Partially molten lower-crustal domains are key features of large hot orogens such as the Altai tract, Tibet, and the Altiplano–Puna, where seismic imaging reveals extensive low-velocity, high-temperature zones interpreted as crustal mush regions. These form through the combined effects of crustal thickening, lithospheric removal, and thermally driven weakening, which together promote melt generation, rheological softening, and mechanical decoupling between crustal levels. Yet, the feedbacks between melt migration, deformation, and mechanical anisotropy in layered partially molten systems remain poorly constrained.

To address this, we compare semi-scaled thermal analogue experiments using paraffin wax with visco-plastic finite-element numerical models, developed in the ASPECT code, that reproduce the experimental rheologies and geometries. Complementary orogen-scale models explore natural-scale consequences under comparable parameter ranges. The setups explicitly investigate how crustal strength, basal heating, and shortening rate affect strain distribution, melt coalescence, and the architecture of crustal plumbing systems.

The analogue experiments reproduce melt localization within folds, shear zones, and developing permeability pathways, suggesting transitions from dominantly lateral to buoyancy-driven melt transfer as deformation evolves. However, limited control of the thermal field and incomplete rheological scaling constrain quantitative interpretation. Numerical simulations replicate many of these features, offering precise control over thermal structure and temperature–melt coupling. While single-layer models tend to produce homogenized crustal thickening without strong buckling, two-layer configurations (upper and lower crust) successfully generate localized folding and buckling of the lower crust. These arise from the ductile continuation of brittle faults into the deep crust, which act as initial perturbations promoting vertical redistribution of partially molten material.

The combined results highlight a complex rheological interplay between deformation and melt connectivity that neither approach captures individually. Future improvements should focus on refining the thermal and rheological scaling of analogue models and implementing porous flow and anisotropic permeability in numerical formulations to bridge experimental and natural system behavior.

Streamlining Structural Analysis: An Automated Workflow for Calculating Intersection Lines and Layer Thickness in ArcGIS Pro

K. Kucharz¹, A. Świąder²

¹ Faculty of Space Technologies, AGH University of Krakow, Poland, kakucharz@student.agh.edu.pl

² Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow, Poland, andrzej.swiader@agh.edu.pl

High-resolution digital elevation models (DEMs), obtained using LiDAR technology, provide a record of terrain topography with unprecedented accuracy. They enable the identification of surface symptoms of geological structures and allow for a much more accurate interpretation of these features than traditional geological mapping methods alone. However, there is still a lack of analytical tools integrated with GIS software to support this process, forcing users to rely on manual, time-consuming, and error-prone workflows.

In order to address the identified gap, the Geological Mapping Toolbox (GMTB) has been developed. It is an open-source Python Toolbox for ArcGIS Pro, designed to automate and streamline key tasks in digital geological mapping. The toolbox features two complementary modules: "Generate Intersection Lines" and "Calculate Thickness". The first module implements both a deductive 1-point method (for known orientations) and an inductive 3-point method (for calculating unknown orientations) to model geological planes and their intersection lines with the terrain. The second module provides a comprehensive workflow for calculating apparent and true layer thickness, offering local, pessimistic, and optimistic global modes, with the latter incorporating a robust angular filtering algorithm. This multi-variant approach enables users to conduct both rapid point-based checks and comprehensive statistical analyses across the entire study area.

The results of the functional testing demonstrated the complementary nature of the implemented methods. Furthermore, the results confirmed the critical nature of analytical filtering for obtaining reliable statistical estimates of layer thickness. In conclusion, GMTB provides a practical and flexible extension for ArcGIS Pro, enhancing the efficiency and reliability of digital structural mapping.

References

- Allmendinger, R. W. (2012). *GMDE (Desktop) v. 10.1*.
- Hasbargen, L. E. (2012). A test of the three-point vector method to determine strike and dip utilizing digital aerial imagery and topography. *Special Paper of the Geological Society of America*, 492, 199–208. [https://doi.org/10.1130/2012.2492\(14\)](https://doi.org/10.1130/2012.2492(14))
- Świąder, A. (2021). Metodyczne studium wykorzystania wysokorozdzielczych numerycznych modeli terenu LiDAR do rozpoznania budowy geologicznej na przykładzie wybranego fragmentu Karpat zewnętrznych; PhD thesis defence; AGH University of Krakow.

Lithium in subduction zone: From lithology-scale distribution to mineral-scale coupled substitutions at high pressure

J. Kulháněk, M. Racek, P. Jeřábek, O. Lexa, T. Ildžová, B. Paddon

Institute of Petrology and Structural Geology, Faculty of Science, Charles University, Albertov 6, 12800 Praha 2, Czech Republic

Lithium is a powerful tracer of a wide range of geological processes. Lithium contents and isotopic compositions are widely used to track material redistribution and element mobility in subduction zones, owing to the significant isotopic fractionation of Li during metamorphism and devolatilization of the subducting slab (e.g., Brenan et al., 1998; Magna et al., 2006).

Lithium occurs in rocks over a broad range of concentrations, typically from ~1 to ~200 ppm, with the highest abundances commonly found in (meta-)pelitic rocks and S-type granites (Tomascak et al., 2016). Variations in Li concentration and isotopic composition can be used to characterize rock protoliths, identify metasomatic processes related to fluid–rock interaction (Penniston-Dorland et al., 2010), and trace Li fractionation associated with dehydration during prograde metamorphism (Marschall et al., 2007; Zack et al., 2003).

In this project, we aim to conduct a comprehensive and detailed study of a well-defined suite of rocks representing a range of lithologies and continuous metamorphic trajectories, from the initial stages of metamorphism to UHP conditions. These rocks preserve, in many cases, exceptionally well-developed peak mineral assemblages from a continental subduction setting in the Saxothuringian Domain of the Bohemian Massif (Jouvent et al., 2023).

To assess Li concentrations in subducted rocks from low-grade metamorphic conditions to ultra-high-pressure metamorphism, we compared whole-rock Li contents from an initial dataset, which presently includes only 3–6 samples per lithotype. The analysed samples show Li concentrations within the expected range of up to ~200 ppm, with distinct variations among lithologies: phyllite 20–133 ppm, micaschist 21–77 ppm, metabasalt-to-greenschist 11–46 ppm, amphibolite 21–71 ppm, eclogite 15–33 ppm, orthogneiss 38–97 ppm, and felsic granulite 28–49 ppm. Although the dataset is still limited, the preliminary results indicate that subducted rocks may retain broadly comparable amounts of Li even at deep subduction levels relative to lower-grade equivalents.

Lithium concentrations in the major minerals of metapelitic and metabasic rocks show marked differences between lithologies and mineral phases. In metapelitic rocks, the highest Li concentrations are found in phyllosilicates, including prograde phengite and paragonite (~50–180 ppm), retrograde chlorite (~200–300 ppm), and biotite (~400–500 ppm). In contrast, kyanite contains only very low Li concentrations (up to 3 ppm), and chloritoid contains up to 20 ppm. Another important Li-bearing phase in metapelitic rocks is garnet, which contains approximately 50–200 ppm Li. Garnet commonly displays core-to-rim zoning, locally accompanied by annular fluctuations in concentration. Similar zoning patterns are also observed in garnet from metabasic samples, although with significantly lower Li contents, generally up to 10 ppm. In metabasic rocks, most Li is hosted by amphibole (~800–1400 ppm) and clinopyroxene (up to 130 ppm).

Because garnet appears to be one of the principal Li hosts, particularly in metapelitic samples, and shows pronounced zoning in Li concentration, the mechanism of Li incorporation into the garnet structure requires explanation, as Li is not generally considered highly compatible in garnet. Correlations with other trace elements suggest that Li is initially incorporated through the coupled substitution $^{\text{VIII}}\text{Y}^{3+} + ^{\text{VIII}}\text{Li}^{+}$, particularly during the early stages of garnet growth, when garnet consumes much of the trivalent Y and REE budget from the surrounding rock matrix. At later stages, under higher-pressure conditions, Li occurs in concentrations notably exceeding those of Y and REE, indicating incorporation via the coupled substitution of $^{\text{VIII}}\text{Li}^{+} + ^{\text{IV}}\text{P}^{5+}$. This interpretation is consistent with previously published work (Kulháněk & Faryad, 2023; Racek et al., 2025) and opens the way for further investigation of Li redistribution along the P–T path of garnet growth, including the potential role of fluctuating availability of fluid media during subduction and the effects on lithium variation in isotopic composition.

Acknowledgments: This research was supported by the Czech Science Foundation (Grant No. 24-12845S), and by Charles Uni. Cooperatio Geological Sciences program (COOP/9207024).

References

- Brenan, J. M., Ryerson, F. J., & Shaw, H. F. (1998). The role of aqueous fluids in the slab-to-mantle transfer of boron, beryllium, and lithium during subduction: Experiments and models. *Geochimica et Cosmochimica Acta*, 62(19–20), 3337–3347. [https://doi.org/10.1016/S0016-7037\(98\)00224-5](https://doi.org/10.1016/S0016-7037(98)00224-5)
- Jouvent, M., Peřestý, V., Jeřábek, P., Lexa, O., & Kylander-Clark, A. R. C. (2023). Assembly of the Variscan Orogenic Wedge in the Bohemian Massif: Monazite U-Pb Geochronology of the Tectonic Events Recorded in Saxothuringian Metasediments. *Tectonics*, 42(4), 1–29. <https://doi.org/10.1029/2022TC007626>
- Kulhánek, J., & Faryad, S. W. (2023). Compositional changes in garnet: trace element transfer during eclogite-facies metamorphism. *Contributions to Mineralogy and Petrology*, 178(10). <https://doi.org/10.1007/s00410-023-02050-8>
- Magna, T., Wiechert, U., Grove, T. L., & Halliday, A. N. (2006). Lithium isotope fractionation in the southern Cascadia subduction zone. *Earth and Planetary Science Letters*, 250(3–4), 428–443. <https://doi.org/10.1016/j.epsl.2006.08.019>
- Marshall, H. R., Pogge von Strandmann, P. A. E., Seitz, H. M., Elliott, T., & Niu, Y. (2007). The lithium isotopic composition of orogenic eclogites and deep subducted slabs. *Earth and Planetary Science Letters*, 262(3–4), 563–580. <https://doi.org/10.1016/j.epsl.2007.08.005>
- Penniston-Dorland, S. C., Sorensen, S. S., Ash, R. D., & Khadke, S. V. (2010). Lithium isotopes as a tracer of fluids in a subduction zone mélange: Franciscan Complex, CA. *Earth and Planetary Science Letters*, 292(1–2), 181–190. <https://doi.org/10.1016/j.epsl.2010.01.034>
- Racek, M., Jeřábek, P., Štípská, P., Závada, P., Svojtka, M., Lexa, O., Hasalová, P., & Veselovský, F. (2025). (Li,Na)-P substitution in garnet: an indicator of ultra-high pressure conditions in subducted continental crust. *American Mineralogist*. <https://doi.org/10.2138/am-2025-9836>
- Tomascak, P. B., Magna, T., & Dohmen, R. (2016). Advances in Lithium Isotope Geochemistry. In *Springer*. <http://link.springer.com/10.1007/978-3-319-01430-2>
- Zack, T., Tomascak, P. B., Rudnick, R. L., Dalpé, C., & McDonough, W. F. (2003). Extremely light Li in orogenic eclogites: The role of isotope fractionation during dehydration in subducted oceanic crust. *Earth and Planetary Science Letters*, 208(3–4), 279–290. [https://doi.org/10.1016/S0012-821X\(03\)00035-9](https://doi.org/10.1016/S0012-821X(03)00035-9)

Metamorphic P-T conditions of mylonitic orthogneiss from the Strona-Ceneri zone, Southern Alps

S. Kurylo¹, R. Zurrbruggen², M. Janák¹, I. Broska¹, P. Konečný³

¹ Earth Science Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 840 05 Bratislava, Slovakia, kurylo@savbb.sk

² Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, 3012 Bern, Switzerland, roger-zurrbruggen@bluewin.ch

³ Dionýz Štur Geological Institute, Mlynská dolina 1, Bratislava

The Strona-Ceneri Zone (SCZ) forms a SW-NE striking, pre-Alpine basement unit in the western part of the Southern Alps. This zone shows a polymetamorphic evolution, which comprises gneisses and schists of sedimentary origin, metagranitoids such as the Ceneri gneisses, banded amphibolites and eclogites. The Ceneri gneiss is a peraluminous S-type metagranitoid intruding metagreywackes and metapelites. It is rich in gneiss and schist xenoliths, calc-silicate nodules and restitic quartz lumps. (Zurrbruggen, 2017). Such Ceneri gneiss-like lithologies are typical for early Paleozoic basement units in the Alps, formed during the “Cenerian orogeny”. In this study we investigated a mylonitic Ceneri gneiss to constrain the metamorphic P–T evolution and the timing of peak metamorphism using thermodynamic modelling, zirconium in rutile thermometry and chemical (Th-U-Pb) dating of monazite. The samples were collected north of Cannobio from a Ceneri gneiss body known as Monte-Giove-Schlinge (Zurrbruggen et al. 1998).

The peak metamorphic assemblage in the strongly sheared Ceneri gneiss consists of an assemblage of garnet + kyanite + plagioclase + K-feldspar + muscovite + biotite + rutile + quartz. Garnet occurs as idioblastic crystals, slightly elongated parallel to the rock foliation, and typically contains kyanite needle inclusions. Garnet is zoned, showing decreasing Ca ($X_{\text{Grs}} = 0.11\text{--}0.04$), Mg ($X_{\text{Prp}} = 0.13\text{--}0.1$), and increasing Mn ($X_{\text{Sps}} = 0.1\text{--}0.14$) from core to rim. Thermodynamic modelling suggests that the metamorphic P-T path reflects granite mylonitisation at 7–8 kbar and 550–580 °C, during exhumation from deep to middle crustal level, followed by retrograde cooling down to 5 kbar and 530 °C. Peak metamorphic conditions are consistent with Zr-in-rutile thermometry (606 °C at 8 kbar). Polygonal aggregates of plagioclase display reverse zoning, indicating recrystallisation during subsolidus shearing. A relation of this microtexture to the anatectical origin, as suggested earlier (Zurrbruggen, 1996), cannot be shown. These P-T conditions reflect the Barrovian-type (D2) metamorphism in the SCZ, similar to those obtained from the garnet mica schists (570–630 °C and 7–9 kbar) by Romer and Franz (1998). The monazite yielded an Ordovician age of 460 ± 3.7 Ma, recording the metamorphic recrystallization of the Ceneri gneiss. This age coincides with previous geochronological data (Romer and Franz, 1998; Zurrbruggen et al. 1998; Pinarelli et al., 2008) documenting both, the Ordovician (450–466 Ma) metamorphism and granitoid magmatism in the SCZ.

Acknowledgments: Support from the VEGA-2/0002/24 and APVV-22-0092 is greatly appreciated.

References

- Romer, R. L. & Franz, L. (1998). Ordovician Barrovian-type metamorphism in the Strona–Ceneri Zone (northern Italy) dated by U–Pb on staurolite. *Schweizerische Mineralogische und Petrographische Mitteilungen*, 78, 383–395.
- Pinarelli, L., Bergomi, M. A., Boriani, A. & Giobbi, E. (2008). Pre-metamorphic melt infiltration in metasediments: Geochemical, isotopic (Sr, Nd, and Pb), and field evidence from Serie dei Laghi (Southern Alps, Italy). *Mineralogy and Petrology*, 93(3–4), 213–242.
- Zurrbruggen, R. (2017). The Cenerian orogeny (early Paleozoic) from the perspective of the Alpine region. *International Journal of Earth Sciences*, 106(2), 517–529.
- Zurrbruggen, R., Kamber, B. S., Händy, M. R. & Nægler, T. F. (1998). Dating synmagmatic folds: a case study of Schlingen structures in the Strona-Ceneri Zone (Southern Alps, northern Italy). *Journal of Metamorphic Geology* 16, 403–414.

Crystal Mush Dynamics: Analogue Modeling with Plaster of Paris and Micro-CT Visualization

V. Kusbach, M. Machek, Z. Roxerová, P. Závada, M. Staněk

Institute of Geophysics v.v.i., Academy of Sciences of the Czech Republic, Boční II/1401, 141 31, Praha 4, Czech Republic

Crystal mush can be defined as a super-solidus rock with a largely interconnected melt phase within a continuous crystal framework and variable fluid content. The chemical and physical properties of a crystal mush - such as temperature, melt composition, density, tensile strength and seismic velocity - change dramatically with crystal fraction. In volcanological contexts, crystal mushes are found in two main settings: deep magma reservoirs, where large volumes of nearly-solid magma reside quasi-stably over long periods, and shallow conduits and lava domes, where rapidly degassing magma crystallizes quickly during ascent, producing the dense, sluggish lavas that are the focus of the CRUSH project. The bulk rheology of crystal mush is controlled by the mechanical properties of the solid crystal framework, and flow occurs primarily through self-organized sliding of crystals along domain boundaries.

To investigate deformational processes in crystal mushes at the meso-scale, we carried out shear analogue experiments in the laboratory using plaster of Paris. The rheological analogy is based on shear-thinning behavior and a well-defined yield strength exhibited by plaster suspension, which closely mimics the rheology of crystal mushes. The components of the analogue material - large unsolved beta-hemihydrate relics, a liquid phase increasingly enriched in Ca^{2+} and SO_4^{2-} from which small new gypsum crystals grow, and pores filled with excess mixing water (if present) and air entrapped during mixing - mimic the principal constituents of a crystal mush: large crystals, solidifying melt, and an optional fluid phase. Moreover, the addition of a small fraction of magnetite grains enables assessment of the evolving microstructure through magnetic fabric analysis (AMS). An additional advantage of this approach is the ability to produce samples of comparable composition subjected to systematically varying amounts of shear strain.

X-ray micro-computed tomography (μCT) provides non-destructive, three-dimensional data on the internal architecture of solidified plaster models. While thin sectioning yields destructive two-dimensional images and AMS provides only volume-averaged magnetic fabric, μCT resolves the full spatial distribution of solid relics, newly crystallized matrix, and pores at resolutions down to approximately 5 μm . Shear zone analogue experiments using plaster of Paris have revealed that the localization and partitioning of deformation are essential factors governing crystal mush flow (Roxerová et al., 2023). These processes lead to self-organized slip of particles, forming conjugated microshear planes of aligned particles and domains in which particles retain either a primary fabric or one or more synkinematic subfabrics. Together, the plaster analogue approach and μCT visualization are a powerful experimental approach that bridges the scale gap between micro-scale laboratory deformation experiments and field-scale observations of igneous bodies.

References

- Roxerová, Z., Machek, M., Kusbach, V. K., & Vávrová, A. (2023). Strain localization: Analog modeling and anisotropy of magnetic susceptibility. *Geochemistry, Geophysics, Geosystems*, 24, e2022GC010630. <https://doi.org/10.1029/2022GC010630>
- Catastrophic ductile to brittle Shifts in crystal-rich magmas, MSMT grant project, 2026-2029, <https://www.ig.cas.cz/en/research/projects/crush/>

Geophysical and structural study of the Permian Uranium mineralization in the north-eastern part of the Moldanubian Zone (Bohemian Massif, Czech Republic)

A. Lechner, A. Guy, K. Schulmann

Center for Lithospheric Research, Czech Geological Survey, Klárov 3, 11821, Prague 1, Czech Republic
E-mails : aurelien.lechner@geology.cz ; alexandra.guy@geology.cz ; karel.schulmann@geology.cz

The Moldanubian Zone (MZ) of the Bohemian Massif hosts significant hydrothermal uranium (U) deposits associated with shear zones within Variscan high-grade metamorphic units. These structures were subsequently reactivated under brittle conditions. The tectono-metamorphic evolution of the MZ culminated at ~340 Ma and was accompanied by extensive plutonic activity from the Late Devonian to the Carboniferous, during which an episode of ultrapotassic magmatism gave rise to the durbachite series. The Třebíč pluton (~335 Ma), located in the northeastern part of the MZ, represents the largest intrusion of this suite and has recently been recognized as a potential U-fertile source. Permian post-collisional tectonics related to changes in the European stress regime led to the structural reactivation, likely facilitating fluid circulation and significant U mobilization. The role of reactivated Variscan structures in controlling fluid circulation and the timing of mineralizing events in the Třebíč area remains poorly constrained. In particular, it is still unclear whether these structures controlled primary U mineralization or were only associated with later U remobilization.

The basement mapping is based on geophysical analyses, lithological and structural datasets. Aeromagnetic data were acquired along flight line spacing of 250 m and reduced to the pole. Bouguer anomalies were obtained from gravity data using a reduction density of 2670 kg m⁻³. Residual isostatic gravity anomalies were not considered, as isostatic variations are negligible. The geophysical fabrics are obtained by two semi-automated depth-estimation methods (Euler deconvolution and matched filtering) and edge-detection filters (tilt derivative, horizontal gradient, and multiscale edge detection). The results of these processing techniques are integrated to generate lineament maps highlighting major geophysical fabrics. These maps combined with geological information enable us to deduce the major structures, the assessment of regional tectonic controls, and the delineation of potential fluid pathways that may host unidentified U mineralization. This integrated approach ultimately aims to produce a predictive map highlighting key exploration parameters and prospective zones for U exploration.

The patterns of magnetic anomalies reveal a predominant NW–SE orientation of lineaments, whereas gravity-derived lineaments display two main fabrics (NE–SW to NNE–SSW and NW–SE to NNW–SSE). These results are consistent with two superimposed stages of accretion in the eastern Variscan belt recently proposed in the literature : an initial W–E convergence which led to the NNE–SSW-trending structures dominating the southern Bohemian Massif ; followed by an important N–S shortening event that generated WNW–ESE-oriented structures. These structural patterns indicate crustal-scale reactivation of major shear zones, exerting a strong control on the Třebíč area and suggesting favorable conditions for significant U mineralization.

Flow and deformation microstructure of crystal mush constrained by anisotropy of magnetic susceptibility in Lago della Vacca pluton, Adamello igneous complex

M. Machek¹, Z. Roxerová¹, V. Kusbach¹, A. Schöpa², M. de Saint Blanquat³, C. Annen¹, A. Vávrová¹

¹ Institute of Geophysics v.v.i., Academy of Sciences of the Czech Republic, Boční II/1401, 141 31, Praha 4, Czech Republic

² School of Earth Sciences, University of Bristol, Wills Memorial Building, BS81RJ Bristol, United Kingdom

³ GET, Observatoire de Midi-Pyrénées, Université de Toulouse, CNRS, IRD, 14 avenue Edouard Belin, F-31400 Toulouse, France

Crystal mush represents a porous and permeable framework of closely packed crystals, with interstitial melt occupying pore spaces. Found across a variety of magmatic environments and at multiple scales, crystal mushes play an important role in melt extraction and migration, as well as in magma storage, evolution, and eruption. Dense crystal mush exhibits a strong power-law rheological behavior driven by frequent grain-to-grain interactions. Flow and deformation within the mush are accommodated by the self-organized slip of crystals of varying orientations, coupled with the development of microstructural subfabrics, defined by the shape and crystallographic preferred orientations of the phenocryst framework. Under continuous shear, this leads to transient liquefaction, allowing mush mobilization despite high crystallinity. The anisotropy of magnetic susceptibility (AMS) reflects an integrated magnetic signal of the crystallographic and shape preferred orientation of all mineral grains constituting the rock microstructure. Consequently, the relative proportion and orientation of these subfabrics reflects the symmetry and conditions of deformation.

The Lago della Vacca Complex (LVC) forms part of the Re di Castello pluton in the southern Adamello Batholith (northern Italy), representing a Middle Eocene–Early Oligocene intrusion into Southern Alpine basement and its Permo-Mesozoic cover. The LVC is a small, elliptical intrusion formed by a series of magmatic pulses in the following sequence: high-potassium marginal unit; low-potassium marginal unit; Vacca Tonalite; and Galliner Granodiorite at the core. Magmatic foliations - defined by the planar alignment of igneous plagioclase, amphibole and biotite, as well as by mafic enclaves - form steeply inward-dipping concentric trajectories that broadly parallel the marginal contact (John & Blundy, 1993). The pluton structure has been interpreted as the result of sequential forceful emplacement of the core units, accommodated by radial expansion (John & Blundy, 1993; Schoene et al., 2012).

AMS measurements across the LVC reveal a significant discrepancy between the magnetic foliation and field measurements of magmatic foliation across the intrusion, particularly within the youngest granodiorite core. To investigate this unexpected feature, AMS data and rock microstructure were subjected to detailed analysis. Flow and deformation of the crystal mush under submagmatic conditions led to the formation of microstructural subfabrics including crystal alignment domains, microshears and small-scale shear zones. The scale, relative proportion and orientation of these structures are reflected in AMS parameters and in the distribution and clustering of AMS ellipsoid principal axes. Detailed analysis of orientation and AMS parameters at individual sampling localities provides a diagnostic indicator of magma flow and deformation in the submagmatic mushy state.

References

- John, B.E. & Blundy, J.D., 1993. Emplacement-related deformation of granitoid magmas, southern Adamello Massif, Italy. *Geol. Soc. Am. Bull.*, 105. 1517-1541.
- Schoene, B., Schaltegger, U., Brack, P., Latkoczy, C., Stracke, A., & Günther D., 2012. Rates of magma differentiation and emplacement in a ballooning pluton recorded by U–Pb TIMS-TEA, Adamello batholith, Italy. *Earth Planet. Sci. Lett.*, 355-356, 162-173.

Eo-Alpine metamorphism recorded in the Veporic Superunit of the Western Carpathians – new insights from garnet Lu/Hf and mica Rb/Sr geochronology

J. Majka^{1,2}, C.J. Barnes^{2,3,4}, M. Janák⁵

1 Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow, Kraków, Poland jmajka@agha.edu.pl

2 Department of Earth Sciences, Uppsala University, Uppsala, Sweden

3 Department of Earth, Environmental and Geographic Sciences, University of British Columbia Okanagan, Kelowna, Canada

4 Institute of Geological Sciences, Polish Academy of Sciences, Kraków Research Centre, Kraków, Poland

5 Earth Science Institute, Slovak Academy of Sciences, Bratislava, Slovakia

Eo-Alpine metamorphism in the Western Carpathians is chiefly recorded in the low- to medium-grade rocks of the Veporic Superunit. In situ garnet Lu/Hf and mica Rb/Sr geochronology constrains both the prograde and retrograde evolution of these rocks. Garnet yields an imprecise but geologically robust age of ~116 Ma, interpreted as reflecting subduction-related metamorphism. Biotite Rb–Sr ages of ~91 Ma and ~75 Ma document isotopic resetting during near-peak conditions at the onset of exhumation and later fluid-assisted re-equilibration. A white-mica Rb–Sr age of ~58 Ma records continued fluid activity during the final stages of exhumation. Combined with previously published data, these results support a coherent intracontinental subduction–exhumation model for the Veporic Superunit, with a continental fragment of Adria acting as the upper plate. We propose that the studied rocks were subducted following significant crustal thinning—analogue to the Eastern Alps, where the Lower Central Austroalpine units were subducted beneath Adria. These temporal and tectonic parallels suggest that the major allochthonous units of the Western Carpathians may indeed correspond to those of the Eastern Alps.

Peculiarities and oddities of the North Atlantic Caledonides

J. Majka^{1,2}, S. Mazur³, C. Schiffer²

¹ Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow, Kraków, Poland jmajka@agha.edu.pl

² Department of Earth Sciences, Uppsala University, Uppsala, Sweden

³ Institute of Geological Sciences, Polish Academy of Sciences, Kraków Research Centre, Kraków, Poland

The North Atlantic Caledonides extend from the British Isles to the High Arctic, with their most extensive and continuous exposures occurring across the Scandinavian Peninsula, northeastern Greenland, and the western and northern margins of Svalbard. This orogenic system represents a classic example of a Himalayan-style collisional belt. Its geology and tectonothermal evolution—particularly in Scandinavia, Greenland, and Svalbard—have been thoroughly documented over several decades.

In this contribution, we present a broad, integrative framework for the North Atlantic Caledonides. We begin with the well-established architecture of the Scandinavian segment and then compare it with the High Arctic and the German–Polish Caledonides. Rather than reiterating the conventional model of this archetypal collisional orogen, we focus on distinctive and commonly underemphasized occurrences of rock units across the entire system. These include a series of seemingly disparate, yet potentially interconnected, lithotectonic assemblages: (1) units of the Middle, Upper, and Uppermost allochthons in the Scandinavian Caledonides; (2) the Hagar Bjerg Allochthon and parautochthonous units of Greenland; (3) Caledonian basement provinces of Svalbard; and (4) Caledonian thrust sheets in southern Norway and in northern Germany.

We use these examples to critically evaluate existing tectonic models and to highlight unresolved issues. In doing so, we pose a set of key questions aimed at stimulating renewed discussion on the evolution of the North Atlantic Caledonides and, more broadly, on the dynamics of collisional orogens worldwide.

Neoarchean-Paleoproterozoic Indo-Australo-Antarctic connections evaluated by zircon U-Pb geochronology, $\delta^{18}\text{O}$ & trace elements in the meta-igneous/sedimentary (U)HT complex of SW Bunge Hills (East Antarctica)

M. Maraszewska¹, M.A. Kusiak¹, S.A. Wilde², M.J. Whitehouse³, H. Jeon³, K. Yi⁴, S. Lee⁴

¹ Institute of Geophysics, Polish Academy of Sciences ul. Księcia Janusza 64 01-452 Warsaw maria.maraszewska@igf.edu.pl

² School of Earth and Planetary Sciences, Curtin University, Kent St, Bentley, Western Australia 6102, Australia

³ Department of Geosciences, Swedish Museum of Natural History, SE-10405 Stockholm, Sweden.

⁴ Korea Basic Science Institute (KBSI), Ochang Campus, Republic of Korea.

The Precambrian basement of East Antarctica (EA) comprises of collage of terranes, each with its own stratigraphic, magmatic and tectono-thermal record. These terranes can be correlated with cratons and orogens of Australia, India, China, and Southern Africa, making EA a crucial component in global paleogeographic reconstructions. Bunge Hills (BH) is situated in Australo-Antarctica in the Gondwana supercontinent (Sheraton et al. 1993; Tucker et al. 2017, 2018), and some reconstructions suggest its proximity to a suture between Australo-Antarctica and Indo-Antarctica. The nature and primary spatial relations of Archean-Paleoproterozoic igneous and sedimentary rocks in the SW BH were largely obscured by 1.25-1.1 Ga (U)HT metamorphism, deformation and magmatism (Tucker et al. 2018). This reworking, together with scarcity of geochronological data, means the pre-metamorphic history of the BH is largely unknown (Tucker et al. 2017). However, due to zircon's resistance to the extremes of metamorphism, zircon U-Pb geochronology, $\delta^{18}\text{O}$ and trace elements can reveal the ancestry of high-grade terranes. Here, we focus on zircon from a suite of rocks collected from Taylor Island (TI) in the W and from Gantela Lake (GL) in the SSW of BH. These exposures are tentatively assigned to the oldest portion of the basement (Association 1. *cf* Tucker et al. 2017) and include meta-mafites, opx-orthogneisses, and migmatitic paragneiss.

Opx-orthogneisses are tonalitic-granodioritic in composition. TI orthogneiss is weakly foliated and moderately altered, whereas GL samples are extensively brecciated and altered. Both are sodic, with high Sr/Y (>63) and La/Yb (>54) what indicate a TTG precursor. Zircon in TI samples preserves prismatic shape and oscillatory zonation, but is variably resorbed and recrystallised. The highly discordant $^{207}\text{Pb}/^{206}\text{Pb}$ ages range ~2.6 Ga-1.9 Ga. Only one zircon core yielded a concordant age of ~2.54 Ga whereas the isochron upper intercept is ~2.62 Ga. These ages record the timing of parental magmatism. The lower intercept of ~1.15 Ga indicates syn-metamorphic partial Pb loss at this time. Similar Neoarchean discordant dates (2.6-2.5 Ga) and isochron upper intercept ages of ~2.67 Ga were obtained from GL orthogneiss. Total zircon resetting and/or metamorphic crystallisation during the UHT event is indicated by a predominance of Mesoproterozoic dates recording lower intercept ages of ~1.2 Ga.

Metabasic rocks from GL vary from unaltered two-pyroxene gabbro to banded and altered amphibolite. Both show transitional tholeiitic to calc-alkaline character with trace element signatures of MORB/IAT. Gabbro zircon is anhedral with banded or weak oscillatory zonation typical for mafic igneous rocks and yielded an age of 1.77 Ga as the time of magmatism. Metamorphic recrystallisation is limited to grain rims, which yielded scattered ages between 1.6-1.1 Ga.. Zircon $\delta^{18}\text{O}$ is partly in the mantle range (6.1-6.9‰) but too elevated for a juvenile primitive mantle source. Crustal influence is shown by zircon U/Yb-Th/U and Hf-Y signatures, transitional between continental intra-plate/arc setting. Zircon in amphibolite has patchy zonation, and is microporous due to pervasive reaction with metamorphic fluids when it was reworked during high-grade metamorphism at 1.2-1.1 Ga.

1.85-1.65 Ga magmatic activity is recorded by a dominant population of detrital zircons in Grt-Crd-Bt-Pl-Opx-Sp paragneiss from GL. Predomination of prismatic, oscillatory zoned grains often enclosing antecrystic and inherited cores indicate a derivation from granitoids and limited input from mafic sources. Such provenance is also indicated by elevated $\delta^{18}\text{O}$ ranging from 7.0-9.0 ‰, rarely less than 6.6‰, and Y-Hf, Th-U, and Eu*/Eu-Ce*/Ce ratios. However, more irregular habit, cloudy zonation and very low U/Th of some zircons of this age point to their metamorphic provenance. Older ages of ca. 2.35-1.9 Ga are preserved either in whole grains or as inherited cores in younger zircon. They are

characterised by variable but high $\delta^{18}\text{O}$ (6.2-9.6‰) and lower Y and Hf contents. Only two zircon grains recorded Archean ages: ~2.62 Ga with 8.02‰ $\delta^{18}\text{O}$, interpreted as granitoid-derived, and discordant data of ~3.15 Ga with less evolved 6.3‰ $\delta^{18}\text{O}$.

The generally accepted scenario assigns the BH as equivalent to the composite, long-living Albany-Fraser Orogen (AFO) developed on and partly involving the southern margin of Yilgarn Craton (YC) in Western Australia (Sheraton et al. 1993; Tucker et al. 2017). The oldest portions of BH crust are orthogneisses of age 2.75-2.7 Ga (Tucker et al. 2017), identifying them as displaced portions of fragmented YC crust. The slightly younger ages of 2.66-2.62 Ga of TTG in this study can be correlated with the youngest magmatism in the YC (Champion&Smithies 2001). However, late-Neoproterozoic TTGs are also well-known from the Indian cratons e.g. Dharwar Craton (Ranjan et al. 2020).

Mafic magmatism at ca. 1.77 Ga parental to the GL metagabbro corresponds well with the timing of bimodal magmatism within the Biranup zone (BZ) of the AFO. The BZ magmatism was associated with prolonged continental rifting, and was dominated by juvenile mantle sources (Smithies et al. 2015). In contrast, the BH meta-basite zircons show elevated $\delta^{18}\text{O}$ and high U/Yb which can be explained as a crustal influence from a subduction-enriched mantle source. The 1.85-1.65 Ga granitoid-derived zircons that dominate the detrital population in BH imply the BZ intrusions or their temporal equivalents were rapidly uplifted, exhumed and eroded after emplacement. Further, the detrital record of ca. 2.35-1.9 Ga zircon correlates with recently-discovered episodes of rift-related magmatism found in the E AFO and E YC margin (Hartnady et al. 2019, Tucker et al. 2023; Clarke et al. 2024). However, record of that event is very restricted. The presence of ~2.35-1.9 Ga inherited cores in 1.85-1.65 Ga zircon from the BH metasediments indicates reworking of Paleoproterozoic crust. However, only the Lu-Hf signature of zircons bears evidence of much more extensive igneous activity of this age in W Australia (Tucker et al. 2023, Clarke et al. 2024 and refs. therein). Therefore, these zircons may be exotic to Australo-Antarctica, as bimodal anorogenic magmatism at this time is omnipresent in the Dharwar Craton (Belica et al. 2014).

Our preliminary data show that evolution of the BH shares similarities with the eastern and not the southwestern domains of the YC and AFO. However, the geodynamic control of AFO formation during the early Paleoproterozoic is ambiguous. Some early concepts postulated its connection with a back-arc setting linked with convergence and subduction of the South Australia-East Antarctic cratons beneath Western Australia (Kirkland et al. 2011, Hartnady et al. 2019). But, the generally accepted model excludes significant (if any) arc influence and points to the AFO being remote from any subduction zone (Smithies et al. 2015). In summary, our preliminary data provide evidence that the BH terrane was situated more proximal to an inferred arc and could indeed represent the back-arc system. On the other hand, 1.85-1.7 Ga arc magmatism is well known from the Eastern Ghats Mobile Belt (Vijaya Kumar et al. 2011). This, together with a possible correlation with the 2.65-1.9 Ga record in the Dharwar Craton provide clues to possible Archean-Paleoproterozoic relations of BH with India.

Acknowledgements: This work was funded by the grant UMO-2023/50/A/ST10/00046 (MAK)

References

- Champion & Smithies 2001: AGSO-Geoscience Australia, Record 2001/37, 134-136. Belica et al. 2014: Precamb. Res. 244, 100-122; Clarke et al. 2024: Precamb. Res. 404, 107680; Hartnady et al. 2019: Precamb. Res. 332, 105400; Kent et al. 1996: Geology 24, 879-882; Kirkland et al. 2011: Precamb. Res. 187, 223-247; Kirkland et al. 2015: Precamb. Res. 266, 260-268; Ranjan et al. 2020: Precamb. Res. 340, 105630; Sheraton et al. 1993: Antarct. Sci. 5, 85-102; Smithies et al. 2015: Geol Surv AusReport; Tucker et al. 2017: Precamb. Res. 298, 16-30; ; Tucker et al. 2018: Precamb. Res. 314, 194-220; Tucker et al. 2023: Precamb. Res. 397, 107192. Vijaya Kumar et al. 2011: Intern. Geol.Rev. 53, 1297-1311.

Accessory phosphates from ore-bearing granites: an archive of magmatic- hydrothermal evolution (Nízke Tatry pluton, Tatric Unit, the Western Carpathians)

M. Maraszewska¹, I. Broska², J. Majzlan³

¹ Institute of Geophysics Polish Academy of Sciences ul. Księcia Janusza 64 Warszawa, Poland

² Earth Science Institute, Slovak Academy of Sciences, Dúbravská cesta 9, P.O. Box 106, 840 05 Bratislava, Slovakia

³ Institute of Geosciences, Friedrich-Schiller University, Burgweg 11, D-07749 Jena, Germany

Granitoid suites are important sources of a wide range of magmatic-hydrothermal ore deposits. The ore-controlling parameters of magmas (fO_2 , H_2O , fS , fCO_2 and metal budget) are dictated by their entire history. It includes the nature of the source (mantle, crustal - igneous or sedimentary), differentiation processes (including magma mixing and fractional crystallisation), emplacement and devolatilization. The convergent plate boundaries are favourable places for granitic magmatism and composite polymetallic systems. However, a superimposition of multiple tectono-thermal and hydrothermal events in subduction-collision zones often hinders the origin of igneous rocks and ore mineralisation. These hidden links between magmatism and ore mineralisation can be traced by accessory minerals as excellent archive of petro- and metallogenic processes.

The Nízke Tatry Pluton (NTP) is a product of Variscan multi-source magmatism in Tatric Unit of the polyorogenic basement of Western Carpathians (Maraszewska et al. 2022). The NTP hosts Mo, W, Au-As mineralization (Majzlan et al. 2020a, b). The Mo and W stages are inferred to be of magmatic-hydrothermal origin and coeval with NTP formation (Kohút et al. 2024), but their genetic model is uncertain. Here, we focus on the NW part of NTP built by I- to S-type Prašivá granitoid (Pr-gr). I-type magmas are represented by diorites (Di) and as variously hybridized mafic microgranular enclaves (MMEs) hosted by the Pr-gr. Most geochemically evolved, two-mica or muscovite leucogranites (Lg) are found as smaller bodies emplaced in ore mineralised regions. Beyond typical textural assemblages of interactions of melts and transfer of phenocrysts found elsewhere in I-S type suites (e.g. Kurylo & Broska 2025), the interface of MME - Pr-gr boundary recorded syn-mixing transfer of magmatic fluid. Presence of fluids is exhibited also by the fabric of Lg. Their “two-phase microtexture” (Štemprok et al. 2008) documents their derivation from residual, volatile-rich magmas which underwent shallow level devolatilization. In an aim to decipher, how magmas and their fluids evolved and formed ore mineralisation, we use microtextures and chemical composition of phosphate minerals found in the NTP rocks - apatite, monazite and xenotime.

Apatite and monazite in hybrid rocks evidence for syn-mixing H_2O -S- CO_2 -NaCl transfer. Presence of S and Cl in volatiles transferred from the oxidized I-type melt is recorded in the elevated F/OH, F/Cl, low in Mn in MME's apatite (Pan et al. 2016), and difference of sulfur content between the high- SO_3 , zoned pre- to syn-mixing apatite and low- SO_3 acicular, almost pure fluorapatite crystallized rapidly during devolatilization. Relatively low S content in apatite in less affected by hybridisation Di is linked to the presence of highly resorbed relics of sulfides. Mixing with S-type melt, fluid loss, and changes of fO_2 caused sulfide dissolution (Georgatou et al. 2022) and final liberation of sulfur. The influxes of I-type melt and its fluids are reflected by oscillatory zonation in SO_3 shown by apatite in Pr-gr. Unlike apatite, igneous monazite crystallised prior to mixing in S-type melt and underwent reaction with magmas and fluids during mixing. In Pr-gr, monazite underwent limited alteration along grain margins. However, the phenocrysts situated along boundary of the Pr-gr and MME were pervasively metasomatized due to focused fluid flow in this zone. The melt+fluid-monazite interaction via dissolution-precipitation resulted in complex secondary textures due to redistribution of Th, Si, U, and Y-Ca-S enrichment. Such modifications of monazite indicate the presence of dissolved SO_4^{2-} but also NaCl and CO_2 in magmatic fluids (Broom-Fendley et al. 2020).

Residual magmas and magmatic-hydrothermal transition. Besides phenocrysts inherited from a less evolved Pr-gr precursor, accessory minerals in Lg enhance the highly evolved and fluid-rich character of the host. Monazite in the Lg is rich in U, Y and HREE, pointing to extreme differentiation of magma. Rare antecrystic grains are metasomatized and enriched in S and Ca in analogy to Pr-gr monazite. However, in some bodies, xenotime prevails. Xenotime in Lgs coexists with destabilised

zircon. Their textural relations indicate growth of xenotime in expanse of zircon. The association of zircon replaced by xenotime is known from ore-bearing granites and pegmatites (Pettke et al. 2005; Rene 2014). Xenotime morphology varies from euhedral and oscillatory-zoned igneous crystals to anhedral aggregates precipitated from fluids. Thus, its crystallisation proceeded through a transition from magmatic to hydrothermal environment and indicates a halogen- and alkali-bearing environment (Rene 2014). A common feature of xenotime is enrichment in As_2O_5 up to 3 wt%. Apatite in Lg is late-stage and S-poor, but exceptionally rich in MnO (up to 3wt%) indicating high peraluminosity but also rapid drop of fO_2 (Broska et al. 2004). That enabled sulfide saturation and, in turn, ore minerals precipitation, evidenced by igneous pyrite that is widespread in Lg.

How did the evolution of magmas and fluids control metallogeny? Molybdenum and tungsten enrichment in magma is enhanced in H_2O -, S- and F-rich oxidised hybrid melts (Audétat et al. 2011), whereas CO_2 and NaCl are key agents responsible for metal complexing in ore forming fluids, including ones constrained as parental for Variscan ore formation in the NTP (Majzlan et al. 2020a). In other words, mixing of magmas from fertile sources (enriched mantle for I- and early Paleozoic crust for S-type end member) and associated fluid exchange led to enrichment of I-S type Pr-gr magma. Extensive fractional crystallisation of volatile-rich hybrid melts led to formation of highly evolved, residual magmas – Lg – concentrated fluids and complexed metals (Wang et al. 2014). Subsequently, a shallow devolatilization of these magmas under decrease of fO_2 enabled the formation of hydrothermal Mo and W vein system and ore minerals crystallisation.

References

- Audétat et al. 2011: J. Petrol. 52, 891-904. Broom-Fendley et al. 2020: Mineral Mag 84, 35-48. Broska et al. 2024: Chem. Geol. 205, 1–15. Georgatou et al. 2022: Geochem. Geophys. Geosyst. 23, e2021GC010161. Kohút et al. 2024: Geol. Carpath. 75, 303-315. Kurylo & Broska 2025: Chem Geol. 677, 122625. Majzlan, et al. J. 2020a: Geol. Carpath. 71, 85–112; Majzlan et al. 2020b: Geol. Carpath. 71, 113–133. Maraszewska et al. 2022: Geol. Carpath. 73, 273–291. Pan et al. 2016: Lithos 254–255, 118-130. Pettke et al. 2005 Chem. Geol. 220, 191-213. Piccoli & Candela 2002: Rev. Min. & Geochem. 48, 255–292. Rene 2004: Miner. Petrol. 108, 551-569. Štemprok et al. 2008: Contrib. Mineral. Petrol. 155, 93–109. Wang et al. 2014: Lithos 206–207, 147–163.

Structural architecture and fault kinematic properties of the SE part of the External Dinarides (Croatia): Seismotectonic implications to ongoing seismicity along the Dalmatian coastline

B. Matoš¹, J. Maslač Soldo², M. Herak³, J. Stipčević³, B. Kordić², I. Pavičić¹, I. Vlahović¹

¹ University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, Zagreb - Croatia,

bojan.matos@rgn.unizg.hr; ivica.pavicic@rgn.unizg.hr; igor.vlahovic@rgn.unizg.hr

² Croatian Geological Survey (HGI-CGS), Department of Geology, M. Sachsa 2, Zagreb – Croatia,

jmaslac@hgi-cgs.hr; bkordic@hgi-cgs.hr

³ University of Zagreb, Faculty of Science, Department of Geophysics, Horvatovac 95, Zagreb – Croatia,

mherak@gfz.hr; jstipcevic.geof@pmf.hr

The External Dinarides, a NW–SE striking orogenic system along the eastern Adriatic Sea coastline, were uplifted by Late Cretaceous–Palaeogene collision of Adria–Europe plates. Approximately 700 km long, from the Slovenian to Montenegrin coast, the External Dinarides incorporate predominantly SW-verging stacked structures formed by oblique collision and repeatedly reactivated under compression and transpression/transension. The counterclockwise rotation of Adria and its ongoing collision with Europe (<5 mm/year) yield differential stress distribution along the Adria coast, characterised by moderate seismicity and occasional strong earthquakes (see e.g. Herak, 2024). The most prominent seismically active regions along the Croatian coast are the *Rijeka region* and *Central Adriatic–Southern Dalmatia region* (Fig. 1A). The *Rijeka epicentral region*, covering Croatia–Slovenia border area, Kvarner area and Velebit Mt. area, is mainly characterized by NW–SE striking strike-slip faults accommodating dextral displacement/transpressional and oblique reverse/compressional regimes. Seismic hazard here is rather high (Herak et al., 2011), and several strong earthquakes exceeding $I_0 = VII^\circ$ MSK have occurred in the past (e.g., in years 1750, 1776, 1838, 1870, 1904). The *Central Adriatic–Southern Dalmatia epicentral region* extends for approximately 350 km, from Ravni Kotari in Northern Dalmatia to Montenegro, and is characterised by NW–SE striking structures dominated by thrust tectonics (e.g. Herak, 2024). Its southeasternmost part exhibits the highest levels of seismic activity in Croatia, with historical and instrumental records documenting several strong earthquakes with magnitudes $M > 6.0$ (e.g., in 1667, 1942, 1962, 1979, 1996). The distribution of maximum horizontal stress (S_{Hmax}) orientations (Fig. 1B) further highlights tectonic complexity of External Dinarides. These analyses suggest that *Rijeka* and *Central Adriatic regions* are affected by N–S to NNE–SSW orientated S_{Hmax} and transpressional/compressional regimes, whereas toward *Southern Dalmatia* S_{Hmax} progressively rotates to NE–SW orientation, accompanied with compressional stresses (Fig. 1B).

To complement existing knowledge of seismogenic hazard, i.e., seismogenic source model of the area (see Basili et al., 2022), in this study we focused on detailed identification and parameterizations of the potential onshore seismogenic sources in the southeasternmost part of Dalmatia and its immediate hinterland (Fig. 1). Based on available geological and seismicity data, as well as previous field observations, ten regional geological cross-sections were constructed (Figs. 1A and C). These cross-sections, with total length of c. 550 km, were used to develop a 3D geological model covering an area of c. 4500 km² (Fig. 1C). This conceptual model primarily focuses on fault architecture and identification of fault geometrical and kinematic properties, constrained by their kinematic evolution and tectonic history. Results show that tectonic activity of more than 40 modelled NW–SE striking fault surfaces is mainly associated with a stacked nappe system composed of six nappes, formed above Permian–Early Triassic ductile deposits, accommodating horizontal shortening between 25 and 50% i.e., 17 to 55 km in length, respectively. In addition to NW–SE striking low angle listric-shaped fault planes, several N–S oriented, subvertical dextral/sinistral faults with lengths between 24 and 50 km show substantial horizontal displacement between 1 and 5 km with slight rotations, hindering lateral continuation of Dinaric nappe system. Empirical magnitude and maximal coseismic displacement computations of modelled fault segments (Wells & Coppersmith, 1994) suggest that maximal M_w values are between 6.3 and 7.0, while the average displacements and maximal displacements are $0.23 \leq AD \leq 0.91$ m and $0.29 \leq MD \leq 2.37$ m, respectively.

The distribution of hypocenters suggests an additional level of seismotectonic complexity. According to Dasović et al. (2024), HRCS004 and HRCS001 (see Basili et al., 2022 for details) could

be considered the primary composite seismogenic sources in the area, rooted to the deep basal thrust of Dalmatian tectonic unit (≥ 12 km depth). In this context, our fault-surface modelling results, which identify both NW–SE and general N–S orientated fault systems in the study area, may have significant importance for future local to regional hazard and risk assessments. Consequently, modelled NW–SE oriented fault planes, interpreted as potential second–order seismogenic structures, may influence near-surface stress redistribution and stress release, whereas the modelled N–S oriented dextral/sinistral faults, perpendicular to the Dinaric orogen, could promote both (i) segmentation of existing nappe system and (ii) localised stress accumulation/release, thereby limiting along-strike stress transfer within Dinaric orogen or acting as a secondary seismogenic source.

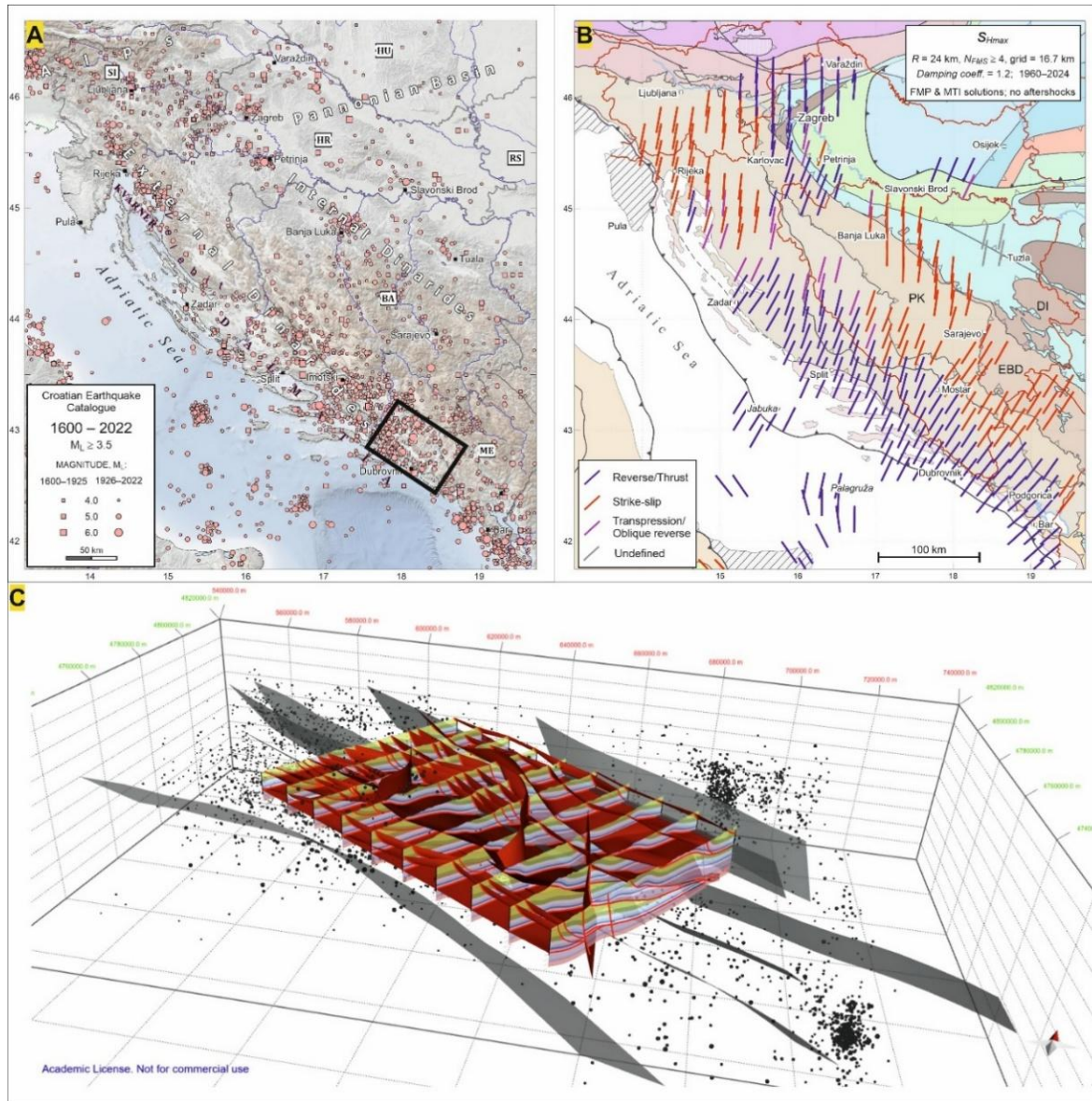


Fig. 1: A. Croatian Earthquake Catalogue (CEC, 1600–2022) with the local magnitude $M_L \geq 3.5$ for the Croatia and surrounding regions (from Herak, 2024). Study area is outlined by a black polygon. B. The orientation of maximal horizontal stress (S_{Hmax}) based on formal stress inversion of available focal mechanisms (for details see Herak, 2024). C. Constructed 3D geological model of the southernmost Dalmatia area showing NW–SE and general N–S striking fault systems, stratigraphic-geological units, and earthquake hypocentres. Gray surfaces show composite seismogenic sources in the area (see Basili et al., 2022).

References

- Basili R., et al. (2022): European Fault-Source Model 2020 (EFSM20): online data on fault geometry and activity parameters [Data set]. Istituto Nazionale di Geofisica e Vulcanologia (INGV). <https://doi.org/10.13127/efsm20>
- Dasović, I., Herak, M., Herak, D., Latečki, H., Sečanj, M., Tomljenović, B., Cvijić- Amulić, S., Stipčević, J. (2024): The Berkovići (BIH) M =6.0 earthquake sequence of 22 April 2022 – seismological and seismotectonic analyses. *Tectonophysics* 875, 230253. <https://doi.org/10.1016/j.tecto.2024.230253>.
- Herak, M., Allegretti, I., Herak, D., Ivančić, I., Kuk, V., Marić, K., Markušić, S., Sović, I. (2011): Republika Hrvatska, Karta potresnih područja, available at <http://seizkarta.gfz.hr/hazmap/> (last accessed March 2026) (in Croatian).
- Herak, M., 2024. Croatian catalogue and database of focal mechanism solutions, characteristic mechanisms, and stress field properties in the Dinarides and the surrounding regions. *Geofizika* 41 (1), 79–123. <https://doi.org/10.15233/gfz.2024.41.5>.
- Sečanj, M., Tomljenović, B., Herak, M., Dasović, I., Latečki, H., Stipčević, J. (2025): Pliocene-Quaternary activity of the Dalmatian unit basal thrust – a potential seismogenic source in the Dubrovnik epicentral area (Croatia), *Journal of Structural Geology*, 199,105485, <https://doi.org/10.1016/j.jsg.2025.105485>.
- Serpelloni, E., Faccenna, F., Spada, G., Dong, D., Williams, S. D. P. (2013): Vertical GPS ground motion rates in the Euro-Mediterranean region: New evidence of velocity gradients at different spatial scales along the Nubia-Eurasia plate boundary, *J. Geophys. Res. Solid Earth*, 118, 6003–6024, doi:10.1002/2013JB010102.
- Wells, D. L. & Coppersmith, K. J. (1994): New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement. *Bulletin of the Seismological Society of America*, Vol. 84, No. 4, 974-1002.

Tectonic architecture of the Western Black Sea Basin: insights from integrated 2-D gravity and magnetic forward modelling along the BS-50 seismic profile

S. Mazur¹, I. Munteanu², M. Tilita³, S. Stovba^{1,4}, R. Stephenson⁵, C. Schiffer⁶, E. Ak¹

1 Institute of Geological Sciences, Polish Academy of Sciences, Kraków Research Centre, Poland, ndmazur@cyf-kr.edu.pl

2 Faculty of Geology and Geophysics, University of Bucharest, Romania,

3 Repsol Exploración S.A., Madrid, Spain

4 S.I. Subbotin Institute of Geophysics of NAS of Ukraine, Kyiv, Ukraine

5 School of Geosciences, University of Aberdeen, King's College, United Kingdom

6 Department of Earth Sciences, Uppsala University, Sweden

The origin and crustal architecture of the Black Sea remain among the most debated problems in the tectonics of the Alpine–Tethyan domain. In particular, the nature of the crust underlying the deepest depocentres of the Western Black Sea Basin (WBSB) is still unresolved, with competing models invoking (i) true oceanic crust formed during Cretaceous back-arc spreading, (ii) strongly attenuated continental crust, or (iii) exhumed and serpentinised subcontinental mantle generated during extreme lithospheric stretching. Resolving this ambiguity is critical not only for regional geodynamic reconstructions, but also for understanding the timing of basin formation, subsidence history, and the potential preservation of pre-Neogene sedimentary successions.

The WBSB constitutes one of the two main deep-water domains of the Black Sea, separated from the Eastern Black Sea Basin by the Mid-Black Sea High. It is bounded by the Pontides to the south and the Odesa Shelf to the north and is commonly interpreted as a back-arc basin related to the northward subduction of the Neotethys beneath Eurasia during the Late Cretaceous. Some geodynamic models propose that seafloor spreading initiated in the Cenomanian–Turonian, leading to the formation of oceanic crust subsequently buried beneath a thick Cenozoic sedimentary cover. However, more recent studies have questioned this paradigm, suggesting instead that large portions of the basin may be underlain by hyper-extended continental lithosphere, similar to magma-poor rifted margins observed in the North Atlantic.

In this study, we present new constraints on the deep structure of the WBSB derived from integrated interpretation of seismic reflection data and potential field modelling. We focus on a NNW–SSE-oriented seismic profile acquired by ION Geophysical (line BS-50), which runs from the Turkish margin across the deepest part of the basin towards the Odessa Shelf. The seismic data provide high-quality imaging of the sedimentary cover and the top of the crystalline basement, but do not uniquely constrain the composition and physical properties of the crystalline crust and upper mantle. To address this limitation, we performed 2-D forward modelling of gravity and magnetic anomalies along the profile, integrating available density–velocity relationships and magnetic susceptibility constraints.

The modelling strategy tests three end-member scenarios: (1) a classical oceanic crustal model with layered gabbroic composition and relatively high densities; (2) a thinned continental crust scenario characterised by progressive crustal attenuation but preservation of felsic to intermediate compositions; and (3) a hyper-extended system involving partial to complete crustal excision and exhumation of serpentinised mantle at the basin centre. Particular attention is paid to the geometry of the Moho, the presence or absence of high-density lower crust, and the magnetic signature expected from serpentinised peridotites.

Preliminary results indicate that models invoking typical oceanic crust fail to reproduce the observed gravity field without introducing unrealistic crustal thicknesses or density contrasts. In contrast, models incorporating extreme crustal thinning and mantle exhumation provide a significantly better fit to both gravity and magnetic data. These results support a tectonic scenario in which the WBSB developed through hyper-extension of continental lithosphere rather than through steady-state oceanic spreading. Such a model is consistent with analogues from magma-poor rifted margins and implies a more complex, diachronous evolution of the basin.

The implications of this interpretation are substantial. First, hyper-extension suggests that the transition from continental to mantle domains may be more gradual and structurally complex than previously assumed. Second, the absence of fully developed oceanic crust raises questions about the

timing and extent of Cretaceous magmatism in the basin. Finally, this scenario increases the likelihood that pre-Neogene sedimentary sequences are preserved within the deep-water basin, with important implications for regional stratigraphy and petroleum systems.

Overall, our integrated geophysical approach demonstrates that potential field modelling, when tightly coupled with seismic interpretation, provides a powerful tool for discriminating between competing tectonic models in deeply buried basins. The results call for a re-evaluation of the geodynamic evolution of the Western Black Sea and highlight the broader significance of hyper-extension processes in shaping marginal basins within the Alpine–Tethyan realm.

Crustal Architecture and Tectonic Inheritance in the Outer Western Carpathians Revealed by Integrated Geophysical Modelling

M. Mikołajczak, S. Mazur

Institute of Geological Sciences, Polish Academy of Sciences, Senacka 1, 31-002 Kraków, Poland, ndmikoła@cyf-kr.edu.pl

The deep structure and geodynamic evolution of the Outer Western Carpathians in Poland remain only partially resolved, despite decades of geological and geophysical investigation. Previous interpretations have commonly relied on limited datasets or single-method approaches, resulting in simplified or locally constrained models of the crustal architecture.

Here, we present a comprehensive, integrated analysis combining magnetic and gravity data, seismic reflection and refraction profiles, and borehole constraints to derive a robust, multi-scale model of the subsurface structure. This multidisciplinary approach enables the construction of regionally consistent structural maps of three key horizons: (1) the top of the crystalline basement, (2) the top of the pre-Miocene basement, and (3) the basal detachment of the Carpathian thrust system.

Within the pre-Carpathian basement, two principal structural trends are identified. The first, parallel to the Carpathian thrust fronts, is expressed as a pronounced basement depression beneath the Outer Carpathians, interpreted as flexural bending of the foreland lithosphere in response to nappe loading. The second, older structural grain is oriented approximately perpendicular to the thrust belt and extends to depths of up to ~24 km below sea level, suggesting inheritance from pre-Alpine tectonic phases.

The pre-Miocene basement surface exhibits a regional southward dip towards the Inner Carpathians, reaching depths of 7.5–8 km below sea level. Superimposed on this trend is a distinct NNE–SSW-oriented structural high in the vicinity of Krosno, indicating localised uplift or differential subsidence.

The geometry of the crystalline basement beneath the Carpathian nappes broadly mirrors that of the pre-Miocene basement, but with important modifications related to thrust tectonics. In particular, a shallow detachment beneath the Magura Nappe along the Slovakian border is clearly resolved, refining previous interpretations of nappe emplacement.

A notable feature of the crustal architecture is a narrow, NNE–SSW-trending “neck” characterised by significant crustal thinning, with crystalline crust reduced to approximately 13 km in thickness (Fig. 1). This structure likely represents a zone of enhanced lithospheric stretching and elevated heat flow, potentially linked to earlier extensional or passive-margin processes. In contrast, crustal thinning parallel to the Carpathian front is comparatively subdued.

Overall, this integrated study provides a significantly improved and internally consistent model of the deep structure of the Outer Western Carpathians. The results highlight the combined influence of inherited tectonic fabrics and Cenozoic compressional processes, offering new constraints on the geodynamic evolution of the Carpathian orogenic system and its foreland.

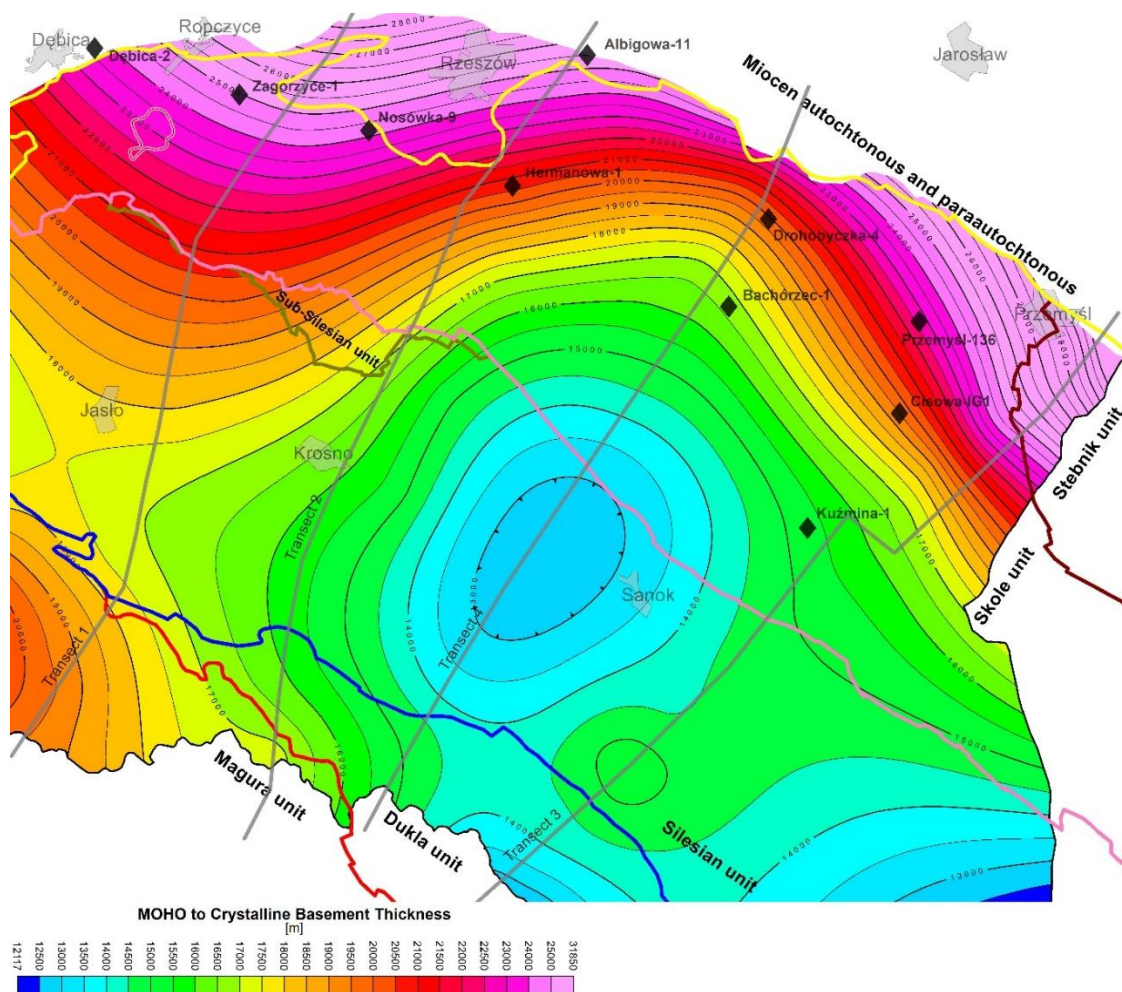


Fig. 1: Thickness map of the crust from the MOHO to the crystalline basement.

Permian to Cretaceous evolution of the Neotethyan margin of the Western Carpathians: composition, age and tectono-metamorphic history of the Meliata Unit

M. Molčan Matejová¹, T. Potočný¹, D. Plašienka¹, L. Fodor², S. Kövér², O. Fernandez³

¹ Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University, Mlynská dolina, Ilkovičova 6, 842 15

Bratislava, Slovakia; marina.matejova@uniba.sk

² HUN-REN Institute of Earth Physics and Space Science, Csatka Endre utca 6-8, Sopron, Hungary

³ Department of Geology, University of Vienna, Josef Hlaubek-Platz 2, 1090 Vienna, Austria

The Meliata Unit of the Inner Western Carpathians represents a key remnant of the Neotethyan domain, preserving a complex record of Permian to Cretaceous geodynamic evolution associated with the opening, subduction and closure of the Meliata oceanic domain. The Meliata Unit is composed of a heterogeneous assemblage of high-pressure metamorphic rocks, ophiolite-bearing mélanges, and Jurassic sedimentary complexes, reflecting a polygenetic origin and multi-stage tectonic evolution. The Meliatic was subdivided on the basis of rock composition and tectono-metamorphic overprint into three distinct types of units (Plašienka et al., 2019): (1) the HP–LT Bôrka Nappe (Mello et al., 1998), situated in the lower structural position partly imbricated with (2) /serpentine-bearing mélanges and (3) a sedimentary complex consisting of olistostrome bodies that are largely devoid of magmatic material – Meliata Unit s.s.

The evolution of the Meliata Unit began with Permian clastics and volcanics (ca. 266 Ma, Vozárová et al., 2012) lithologically correlated with the sedimentary cover of Austroalpine basement Gemer Unit (Gemicum), followed by thick complex of Early-Middle Triassic carbonates and mostly basic volcanites (ca. 248 Ma; Potočný et al., this book of abstracts; Fig. 1). During the Middle–Late Triassic, the area evolved into a passive continental margin following the rifting and breakup of the Neotethyan domain. Sedimentation was characterized by the deposition of radiolarites, pelagic shales, and slope-related facies with intercalations of basalts, indicating marine conditions with intermittent input from the adjacent continental margin (Molčan Matejová et al., 2025; Fig. 1). At the Triassic–Jurassic boundary, a major geodynamic transition occurred with the onset of subduction and progressive consumption of the Meliata domain. This led to the formation of Jurassic sedimentary complexes (Molčan Matejová et al., 2025), including turbidites, radiolarites, and olistostromes containing blocks of Triassic carbonates, radiolarites, and oceanic crustal fragments/exhumed continental mantle (Fodor et al., this book of abstracts; Fig. 1). The Permian clastics and volcanics, together with Triassic carbonate clastics and metavolcanics, were incorporated into the subduction channel and underwent subduction-related metamorphism under blueschist facies conditions (Bôrka Nappe; Fig. 1). Peak metamorphic conditions were reached during the Middle–Late Jurassic (ca. 155 Ma; Faryad and Henjes-Kunst, 1997). Following peak metamorphism, the high-pressure rocks underwent exhumation accompanied by retrograde metamorphism (Fig. 1). The Jurassic sedimentary complexes of the Meliata Unit s.s. experienced only low-grade metamorphism, corresponding to the anchizone or sub-greenschist facies. Subduction at the Triassic–Jurassic boundary resulted in the development of an accretionary wedge, within which complex polygenous mélanges were formed (Fig. 1). These mélanges consist of blocks derived from multiple sources, including high-pressure metamorphic rocks, serpentinite and basalt fragments, and sedimentary successions, embedded in a predominantly Jurassic radiolaritic–siliciclastic matrix of both sedimentary and tectonic origin. Their formation reflects a combination of mass-transport processes and tectonic mixing during accretion.

In contrast to other Neotethyan segments, the Meliata Unit lacks typical supra-subduction ophiolite nappes and Late Jurassic carbonate platforms sealing thrust structures. Instead, deformation persisted into the Late Jurassic and Early Cretaceous, indicating a prolonged and possibly diachronous closure of the Triassic oceanic domain. The presence of extensive blueschist-facies units and the absence of classical obduction features support a collisional rather than obductional model of ocean closure.

Final emplacement of the Meliatic accretionary complex occurred during the Cretaceous, when it was thrust over the Gemeric Unit and incorporated into the Alpine–Carpathian orogenic wedge (ca.

140–120 Ma; Fig. 1; e.g. Putiš et al., 2014). Subsequent tectonic processes, including nappe stacking, out-of-sequence thrusting, and collapse-related deformation, shaped the present-day architecture of the Inner Western Carpathians.

Overall, units derived from the Meliata domain records the complete evolution of a Neotethyan oceanic margin, from Permian rifting through Triassic passive margin development, Jurassic subduction and accretion, to final Cretaceous collision and orogenic incorporation.

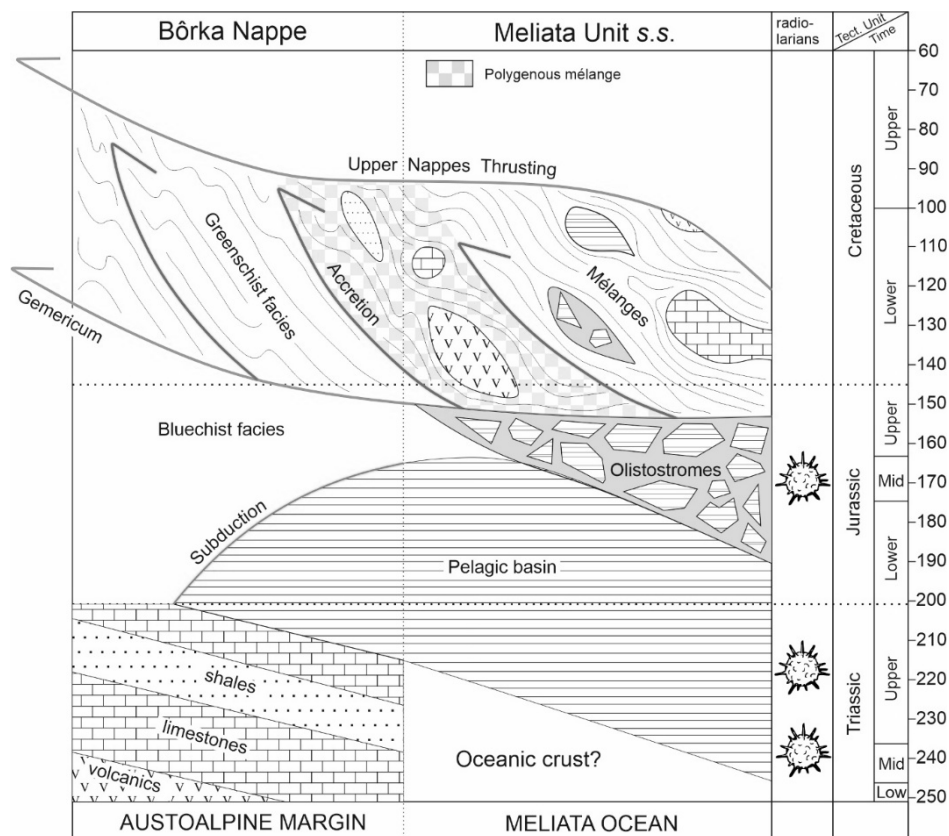


Fig. 1: Triassic to Cretaceous tectonostratigraphic evolution of the Meliata Unit (Molčan Matejová et al., 2025).

Acknowledgements: This work is supported by the Slovakian-Hungarian bilateral research project SK-HU-24-0016, Slovak Research and Development Agency project APVV-21-281, and by the Grant Agency for Science, Slovakia project VEGA 1/0021/25

References

- Faryad S.W. and Henjes-Kunst F. 1997. Petrological and K–Ar and ^{40}Ar – ^{39}Ar age constraints for the tectonothermal evolution of the high-pressure Meliata unit, Western Carpathians (Slovakia). *Tectonophysics*, 280, 141–156.
- Mello J., Reichwalder P. and Vozárová A. 1998. Bôrka Nappe: high-pressure relic from the subduction–accretion prism of the Meliata ocean (Inner Western Carpathians, Slovakia). *Slovak Geological Magazine*, State Geological Institute of Dionyz Štúr, 4, 261–273.
- Molčan Matejová, M., Potočný, T., Plašienka, D., & Aubrecht, R. (2025). Palaeoenvironmental interpretation of chaotic complexes of the Meliata Unit (Western Carpathians, Slovakia): new data from biochronology, lithostratigraphy and geochemistry. *Ofioliti*, 50, 1.
- Plašienka, D., Méres, Š., Ivan, P., Sýkora, M., Soták, J., Lačný, A., ... & Potočný, T. (2019). Meliatic blueschists and their detritus in Cretaceous sediments: new data constraining tectonic evolution of the West Carpathians. *Swiss Journal of Geosciences*, 112, 1, 55–81.
- Putiš M., Danišík M., Ružička P. and Schmiedt I. 2014. Constraining exhumation pathway in accretionary wedge by (U–Th)/He thermochronology – case study on Meliatic nappes in the Western Carpathians. *Journal of Geodynamics*, 81, 80–90.
- Vozárová, A., Šmelko, M., Paderin, I., & Larionov, A. (2012). Permian volcanics in the Northern Gemericum and Bôrka Nappe system: U–Pb zircon dating and the implications for geodynamic evolution (Western Carpathians, Slovakia). *Geologica Carpathica*, 63, 3, 191–200.

Tectonic Evolution of the Dniepr–Donets Basin: An Integrated Geophysical Perspective on Rift Mechanisms

A. Nasiri¹, S. Stovba^{1,2}, R. Stephenson³, S. Drachev⁴, S. Mazur¹, L. Slonka¹

¹ Polish Academy of Sciences, Institute of Geological Sciences, Warsaw, Poland

² S.I. Subbotin Institute of Geophysics of NAS of Ukraine, Kyiv, Ukraine

³ School of Geosciences, University of Aberdeen, King's College, Aberdeen, United Kingdom

⁴ ArcGeoLink Ltd., Caterham, Surrey, United Kingdom

The Dniepr–Donets Basin (DDB) is the largest and best-preserved intracontinental rift systems in Europe, yet the mechanisms governing its formation and evolution remain debated. Two end-member models are commonly invoked: (1) passive rifting driven by far-field tectonic stresses and lithospheric stretching, and (2) active rifting associated with mantle upwelling and thermal anomalies, potentially linked to plume-related processes. Discriminating between these scenarios is critical not only for reconstructing the evolution of the DDB but also for understanding the broader controls on intracontinental rifting and its potential transition to oceanic spreading.

This study presents an ongoing re-evaluation of the tectonic evolution of the DDB through the integration of diverse geophysical and geological datasets within a unified interpretative framework. The analysis is based on an extensive dataset comprising approximately 40 regional seismic reflection and refraction profiles, including key surveys such as DOBRE'99 and Georift-2013, which provide robust constraints on crustal structure and basin architecture. These data are systematically calibrated using information from nearly 1,900 boreholes, offering high-resolution constraints on stratigraphy, lithology, and seismic velocity structure, and enabling reliable correlation between seismic reflections and geological units.

As part of this work, fourteen regionally significant stratigraphic horizons—spanning pre-rift, syn-rift, and post-rift stages—have been identified and are being mapped across an area of ~76,900 km². Preliminary results demonstrate that major stratigraphic boundaries and unconformities can be traced across large portions of the basin, providing improved constraints on the timing and spatial distribution of tectonic phases. At the same time, pronounced lateral variations in sediment thickness and structural style point to significant along-strike heterogeneity in basin development.

To complement the seismic interpretation, gravity and magnetic data are incorporated to better resolve the geometry of major fault systems and to image deeper crustal features not directly constrained by seismic data. These datasets provide additional insight into variations in crustal density, magnetic susceptibility, and the possible presence of mafic intrusions or lower crustal heterogeneities.

Initial reconstructions reveal marked variability in deformation style along the basin, with some segments displaying pronounced asymmetry consistent with simple-shear deformation and the development of large-scale detachment systems. Such features are typically associated with passive rifting processes, although their regional significance requires further validation.

A three-dimensional structural model of the basin is currently under development, integrating seismic horizons with borehole and velocity data to capture the full spatial complexity of the system. Early results indicate substantial variability in sediment thickness, fault segmentation, and structural architecture, suggesting that the evolution of the DDB cannot be explained by a single, uniform geodynamic mechanism.

The role of mantle processes is further assessed using gravity and magnetic anomaly data, which are analysed to identify signatures of magmatic activity and thermal perturbations within the lithosphere. Preliminary observations suggest that such features are present but spatially restricted, implying that magmatic processes likely played a secondary or localized role during rift evolution.

Overall, the emerging results tentatively support a model in which the DDB developed predominantly through passive rifting driven by far-field tectonic forces, with localized thermal effects contributing to lithospheric weakening in specific segments. This study highlights the importance of integrated, multi-dataset approaches in resolving the complexity of intracontinental rift systems and provides new constraints on the processes controlling their development and ultimate fate.

Thermodynamic P–T estimates in Alpine tectonometamorphic zones of Southern Veporic–Northern Veporic–Subautochthonous Fatric–Infratatic wedge (Inner Western Carpathians)

O. Nemec, M. Putiš

Department of Mineralogy, Petrology and Economic Geology, Faculty of Natural Sciences, Comenius University, Ilkovičova 6, 842 15 Bratislava, Slovakia, ondrej.nemec@uniba.sk, marian.putis@uniba.sk

The Cretaceous tectono-metamorphic evolution of the Inner Western Carpathians (IWC) was investigated in the Southern Veporic Unit, which underwent deep syn-collisional burial in the frontal segment of the developing Southern Veporic–Gemic–Meliatie orogenic wedge. This phase followed the closure of the Neotethyan oceanic Meliatie Basin. As the orogenic wedge have prograded towards north, it progressively incorporated the Northern Veporic–Fatric domain of an Albian–Eocene orogenic system in the northern sector of the IWC, including the Tatic and Infratatic basement–cover structural complexes, exhibiting variable grades of Alpine tectono-metamorphic overprint (Putiš et al., 2021 and references therein). The investigated rock complexes have yielded thermodynamic pressure–temperature (P–T) conditions using several methods, including chlorite–phengite multi-equilibria geothermobarometers by Vidal et al., (2006), chlorite and paragonite–muscovite thermometers (Yavuz et al., 2015; Blencoe et al., 1994), phengite barometers (Massone & Schreyer, 1987), and Perple_X pseudosection modelling (Conolly, 2005).

Alpine overprint for a granodiorite-mylonite sample from the northern margin of the Southern Veporic Kráľova Hoľa Nappe (Fabova Hoľa Massif) shows upper greenschist facies conditions of 480 °C at 630 MPa calculated by Perple_X modelling. This suggests burial to a minimum of 20 km depth within the frontal part of the Southern Veporic–Gemic–Meliatie wedge, which originated by collisional shortening of the oceanic Meliatie Basin passive continental margin.

For the IWC northern wedge, the next Alpine metamorphic overprint conditions were distinguished. The Chl–Phg geothermobarometry for the Permian meta-dacite and meta-granite porphyry (Northern Veporic Nízke Tatry Mts. Krakľová Nappe) yielded 500–600 MPa at 290–327 °C.

Perple_X modelling of subautochthonous Fatric Vápenica Nappe Permian meta-basalts in the eastern Nízke Tatry Mts. yielded greenschist-facies metamorphic overprint at 350–410 °C and 375–480 MPa. Similar pressures were detected from host meta-sediments in the 500–600 MPa range at estimated 300 °C temperature. The Chl–Ph geothermobarometry for the basement tonalite blastomylonites yielded 400–700 MPa at the calculated 300–350 °C.

Pseudosection modelling of subautochthonous Fatric Permian meta-basalts (Tribeč Mts. Razdiel Nappe) estimated 370–400 °C at 580–700 Ma. Similar pressures were detected from host meta-sediments at 400 MPa and approximately 300 °C, while the Chl–Ph P–T conditions of the basement tonalite blastomylonites show 400–550 MPa at 308–365 °C.

Infratatic Hlohovec Block (Hlohovec Nappe, southernmost part of the Považský Inovec Mts.) Lower Triassic quartzites exhibit 280–283 °C at 600 MPa (Ms–Pg thermobarometry) and 245 °C at 500 MPa using the Chl–Ph pairs of a meta-aplite. Perple_X modelling of meta-basalt from the Infratatic Považský Inovec Mts. (Selec Block, Inovec Nappe, Hôrčanská Valley) yielded P–T conditions of 330–345 °C at 460–580 MPa, consistent with 290–323 °C at 400–600 MPa obtained from Chl–Ph pairs. The lower anchi-metamorphism of the Couches-Rouges type marly slates of the Hlohovec Block in the southernmost Považský Inovec Mts. with P–T conditions of 269–278 °C and 510–620 MPa (Chl–Phg).

These compiled P–T estimates reflect mostly syn-collisional burial stage during the closure of Jurassic–Early Cretaceous basins and incorporation of sedimentary infill and thinned basement into the accretionary wedge. To summarise, the frontal part of the southern Southern Veporic–Gemic–Meliatie wedge underwent the Alpine metamorphic overprint of upper greenschist facies at 480 °C and 630 MPa, while northern wedge, including the Northern Veporic, subautochthonous Fatric structural units, and the higher Infratatic (Inovec) nappes, achieved lower metamorphic conditions of ca. 250–400 °C and 400–700 MPa during ca. 100–80 Ma (by Ar–Ar dating).

Despite overlapping P–T fields, a temperature and pressure decrease is registered from the southern towards the northern wedge. However, within the northern wedge, the temperature decrease occurred at similar pressures from the rear Northern Veporic and subautochthonous Fatric structural units towards the wedge front Infrataticum at ca. 90–70 Ma. Figure 1 highlights P–T conditions of all accretionary wedge investigated structural units.

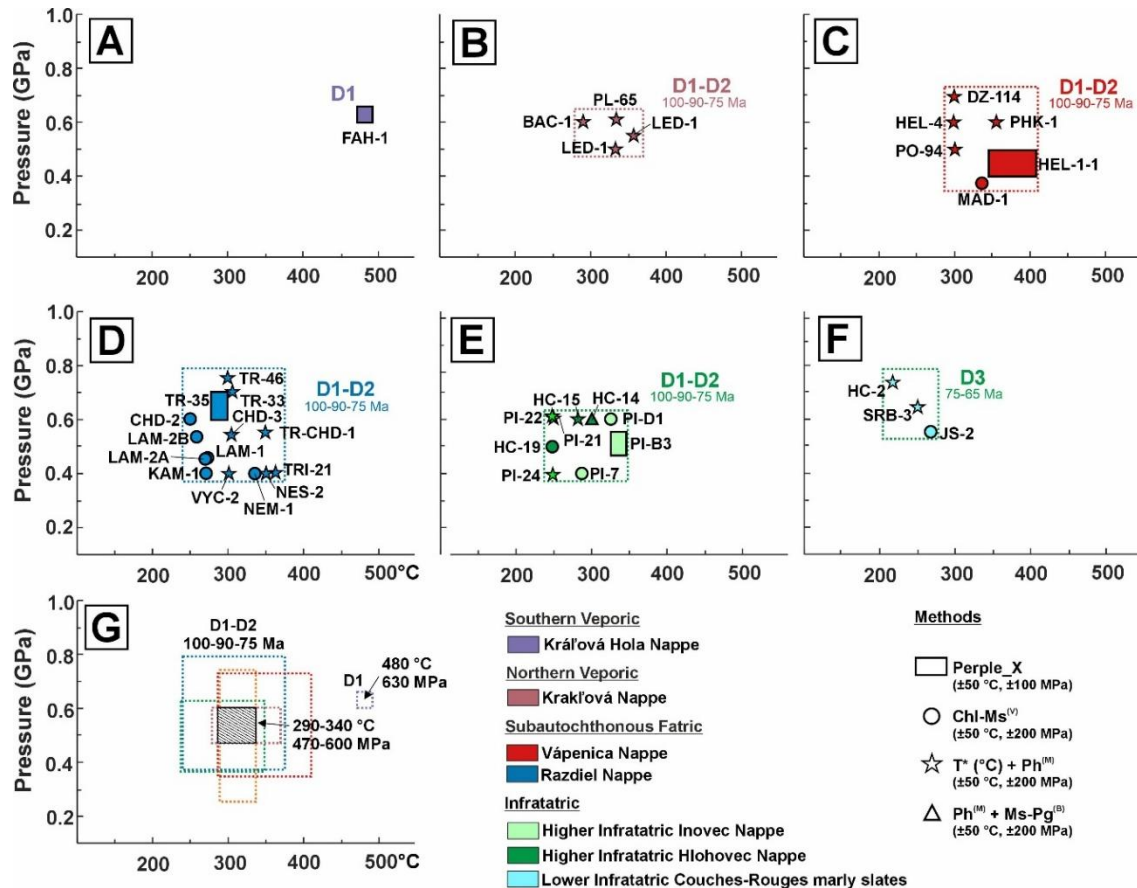


Fig. 1: Review diagrams of P–T estimates from the Southern Veporicum (A), Northern Veporicum (B), subautochthonous Fatricum (C–D) and Infrataticum (E–F) structural units; (G) Summary of all estimated P–T conditions from investigated units. Shown ages were done by Ar–Ar dating (modified after Putiš et al., 2021).

Acknowledgements: Funded by the EU NextGenerationEU through the Recovery and Resilience Plan for Slovakia under the project No. 09I03-03-V04-00071.

References

- Blencoe, J.G., Guidotti, C.V., Sassi, F.P., 1994. The paragonite-muscovite solvus: II. Numerical geothermometers for natural, quasibinary paragonite-muscovite pairs. *Geochim. Cosmochim. Acta* 58, 2277–2288.
- Connolly, J.A.D., 2005. Computation of phase equilibria by linear programming: A tool for geodynamic modeling and its application to subduction zone decarbonation. *Earth Planet. Sci. Lett.* 236, 524–541.
- Massonne, H.-J., Schreyer, W., 1987. Phengite geobarometry based on the limiting assemblage with K-feldspar, phlogopite, and quartz. *Contrib. Mineral. Petrol.* 96, 212–224.
- Putiš, M., Nemec, O., Danišík, M., Jourdan, F., Soták, J., Tomek, Č., Ružička, P., Molnárová, A., 2021. Formation of a Composite Albian–Eocene Orogenic Wedge in the Inner Western Carpathians: P–T Estimates and ⁴⁰Ar/³⁹Ar Geochronology from Structural Units. *Minerals* 11, 988.
- Vidal, O., Andrade, V.D.E., Lewin, E., Munoz, M., Parra, T., Pascarelli, S., 2006. P–T-deformation Fe³⁺/Fe²⁺ mapping at the thin section scale and comparison with XANES mapping: Application to a garnet-bearing metapelite from the Sambagawa metamorphic belt (Japan). *J. Metamorph. Geol.* 24, 669–683.
- Yavuz, F., Kumral, M., Karakaya, N., Karakaya, M.Ç., Yıldırım, D.K., 2015. A Windows program for chlorite calculation and classification. *Comput. Geosci.* 81, 101–113.

Kinematic analysis of fault structures in Mníchova Lehota quarry

A. Obertová, V. Šimonová, J. English

Department of Geography and Geology, Faculty of Natural Sciences, Matej Bel University, Tajovského 40, 974 01 Banská Bystrica, Slovak Republic; angelika.obertova@umb.sk

Our investigation focused on the kinematic analysis and paleostress reconstruction of the brittle structures of the Hronic Unit in the Strážovské vrchy Mountains. The Hronic nappe system represents the structurally highest tectonic unit in the Late Cretaceous thrust stack of the Central Western Carpathians. Structurally, the Hronic Unit is an internally complex nappe system with numerous partial nappes. It consists mainly of a Permian volcano-sedimentary sequence and Triassic carbonate sediments.

The Mníchova Lehota quarry is located on the western margin of the Strážovské vrchy Mountains. It is an extensive multi-level quarry exposing Middle to Upper Triassic carbonate sediments. The Middle Triassic is represented by massive dark-gray to black limestones of the Gutenstein Formation, which are overlain by white organodetrital Wetterstein limestones and dolomites (Anisian–Carnian). The upper part of the carbonate complex consists of gray, layered dolomites of the Hauptdolomite Formation.

Based on kinematic analyses of mesoscale faults (slickensides), several brittle deformation stages characterized by distinct properties of the reconstructed stress field were identified. We employed the Win Tensor program to calculate stresses and to separate the faults into homogeneous groups. The relative superposition of individual palaeostress states was derived from field structural relationships. Their stratigraphic age was estimated mainly by comparison with previously published data from the adjacent south-western parts of the Western Carpathians (e.g., Kováč et al., 1994; Králiková et al., 2010; Obertová, 2025; Pešková et al., 2009; Vojtko et al., 2010). The observed chronology of deformation phases can be divided into five different palaeostress fields. The evolution is characterised by a continuous change in the orientation of the maximum principal stress axis σ_1 , from W–E through N–S to NE–SW. The kinematic analysis of fault-slip data confirmed predominant strike-slip nature of the fault during the entire deformation history.

The oldest recorded deformation event is characterized by W–E oriented compression during a transpressional tectonic regime. Brittle deformation structures include sinistral strike-slip faults with NW–SE orientation, dextral strike-slip faults trending NE–SW, and reverse faults oriented predominantly N–S. This stage took place during the Paleocene to Oligocene (Obertová, 2025; Vojtko et al., 2010; Sůkalová et al. 2011). The second deformation phase represents a direct continuation of the transpressional tectonic regime during the Early Miocene (Obertová, 2025; Pešková et al., 2009; Sůkalová et al. 2011). The maximum compressional stress axis was oriented NW–SE. This resulted in the formation of sinistral strike-slip faults trending mainly NNW–SSE and dextral strike-slip faults oriented WNW–ESE to WSW–ENE. Reverse faults trending ENE–WSW were also recorded. During the subsequent third deformation stage, the transpressional tectonic regime persisted and compression remained in a N–S orientation. This stage is assigned to the Middle Miocene (Obertová, 2025; Pešková et al., 2009; Sůkalová et al. 2011). Only strike-slip faults are present in this phase, with sinistral faults oriented NE–SW and dextral faults trending NW–SE. The fourth deformation event, characterized by NE–SW-oriented compression, represents the final stage of the transpressional tectonic regime. It involves sinistral strike-slip faults with a predominantly W–E orientation and dextral strike-slip faults trending NNW–SSE to NNE–SSW. Paired reverse faults oriented NW–SE are also present. Structures formed during this stage are dated to the Late Miocene (Obertová, 2025; Pešková et al., 2009; Sůkalová et al., 2011). During the youngest deformation stage, the tectonic regime shifted to an extensional one. The maximum compressional stress axis was replaced by an extensional stress component, leading to the formation of normal faults. Extension oriented WNW–ESE and NNW–SSE falls within the Late Miocene to Pliocene (Obertová, 2025; Pešková et al., 2009; Vojtko et al., 2010). The tectonic evolution culminated by NE–SW extension during the Quaternary (Obertová, 2025; Pešková et al., 2009; Vojtko et al., 2010; Sůkalová et al., 2011).

AGE OF DEFORMATION EVENTS	CENOZOIC					
	PALEOGENE	NEOGENE				QUATERNARY
	PALEOCENE TO OLIGOCENE	EARLY MIOCENE	MIDDLE MIOCENE	LATE MIOCENE	LATE MIOCENE TO PLIOCENE	
	1. EVENT	2. EVENT	3. EVENT	4. EVENT	5. EVENT	
MNÍCHOVA LEHOTA QUARRY						
TECTONIC REGIME	TRANSPRESSIONAL REGIME				EXTENSIONAL REGIME	

Fig. 1: Chronological summary of deformation events in the study area.

Acknowledgements: This work was supported by the Slovak Research and Development Agency under the contracts APVV-22-0092 and VEGA 1/0574/25.

References

- KOVÁČ, M., KRÁČ, J., MÁRTON, E., PLAŠIENKA, D. & UHER, P., 1994. Alpine uplift history of the Central Western Carpathians: geochronological, paleomagnetic, sedimentary and structural data. *Geologica Carpathica*, 45: 83–96.
- KRÁČKOVÁ, S., HÓK, J. & VOJTKO, R. 2010., Reorientácia napätového poľa odvodená z morfoštruktúr a zlomového porušenia pliocénnych sedimentov Hronskej pahorkatiny (Západné Karpaty). *Acta Geologica Slovaca*, 2 (1): 17–22.
- OBERTOVIÁ, A., 2025: Kinematic analysis and structural development of the Ipolitica Group (Hronic Unit, Western Carpathians). Master thesis. Matej Bel University Banská Bystrica, 95p.
- PEŠKOVÁ, I., VOJTKO, R., STAREK, D., SLIVA, L., 2009: Late Eocene to Quaternary deformation and stress field evolution of the Orava region (Western Carpathias). *Acta Geologica Polonica*, 59 (1), 73-91. Warszawa.
- SŮKALOVÁ, E., VOJTKO, R. & PEŠKOVÁ, I., 2011: Cenozoic deformation and stress field evolution of the Kozie chrbty Mountains and the western part of Hornád Depression (Central Western Carpathians). *Acta Geologica Slovaca*, 4 (1), 2011, 73-91.
- VOJTKO, R., TOKÁROVÁ, E., SLIVA, E. & PEŠKOVÁ I., 2010: Reconstruction of Cenozoic palaeostress fields and revised tectonic history in the northern part of the Central Western Carpathians (the Spišská Magura and Východné Tatry Mountains). *Geologica Carpathica*, 61, 3, 211-225.

Deciphering the emplacement timing of the Třebíč pluton and the associated thermal implications through $^{40}\text{Ar}/^{39}\text{Ar}$ and U/Pb dating

L. V. Pacheko Shmotkina¹, P. Hasalová², K. Schulmann², G. Ruffer³, P. Štípská²

¹ Ecole et Observatoire des Sciences de la Terre, Université de Strasbourg, 1 Cr des Cigarières, 67000 Strasbourg, France, laura.pacheko-shmotkina@etu.unistra.fr

² Czech Geological Survey, Klárov 3, 118 21 Prague 1, Czech Republic, pavlina.hasalova@geology.cz

³ Géosciences Rennes, Université de Rennes, Rue du Thabor, 35000 Rennes, 35000 Rennes, France

The Třebíč Pluton, represents a Variscan intrusion into the orogenic root of the Bohemian Massif at ca. 338 Ma (e.g. Janoušek et al., 2020). The pluton belongs to the “durbachite series”, which are ultra-potassic biotite-amphibole quartz melasyenites-melagranites. The petrogenesis of these rocks is generally considered to be controversial, and further investigation into their origins is needed to better understand the geodynamic processes occurring in the deep roots of the Variscan Orogen.

U/Pb zircon ages reveal magmatic ages of 340 ± 5 Ma (Kotková et al. 2010) and 335 ± 3 Ma (Janoušek et al., 2020, 2021).

In our study we focus on the cooling and deformation history of the Třebíč pluton. We have collected 12 samples from the durbachite as well as from the surrounding migmatite units and performed biotite and amphibole $^{40}\text{Ar}/^{39}\text{Ar}$ dating (Univeristy of Rennes, France). Furthermore we have collected 15 samples from pegmatitic dykes in the durbachite and performed U-Pb geochronology on titanites and monazites.

The results show two main ages (i) 332 Ma - 336 Ma and (ii) ca. 340 Ma -. The biotites in the migmatites reveal younger ages of 332-335 Ma. While the durbachites shows either both ages or the older ages of ca. 340Ma.

These ages seem to be perfectly correlated to with the deformation evolution of the area, with older vertical exhumation fabric dated at ca. 340 Ma (U-Pb zircon and monazite ages) and the younger horizontal flow fabric dated at cca. 335 Ma (U-Pb zircon and monazite ages).

Therefore we suggest that the Ar ages could actually date these two deformation events rather than the cooling history of the pluton. To further explain this peculiar age distributions of the Třebíč pluton and its surrounding, a detailed petrography study is in progress.

References

- Janoušek, V., Hanžl, P., Svojtka, M., Hora, J. M., Kochergina, Y. V. E., Gadas, P., Holub, F. V., Gerdes, A., Verner, K., Hrdličková, K., Daly, J. S., & Buriánek, D. (2020). Ultrapotassic magmatism in the heyday of the Variscan Orogeny: the story of the Třebíč Pluton, the largest durbachitic body in the Bohemian Massif. *International Journal of Earth Sciences*, 109(5), 1767–1810. <https://doi.org/10.1007/s00531-020-01872-2>
- Janoušek, V., & Svojtka, M. (2021). How old is the Třebíč durbachitic Pluton? Reply to comment on “Ultrapotassic magmatism in the heyday of the Variscan Orogeny: the story of the Třebíč Pluton, the largest durbachitic body in the Bohemian Massif” by Schaltegger et al. *International Journal of Earth Sciences*, 110(3), 1133–1136. <https://doi.org/10.1007/s00531-020-01977-8>
- Kotková, J., Schaltegger, U., & Leichmann, J. (2010). Two types of ultrapotassic plutonic rocks in the Bohemian Massif — Coeval intrusions at different crustal levels. *Lithos*, 115(1–4), 163–176. <https://doi.org/10.1016/j.lithos.2009.11.016>

Prograde Metamorphism in HP Micaschist of the Erzgebirge: Constraints on P-T evolution of the Orogenic Wedge

B. Paddon, P. Jeřábek, M. Racek, O. Lexa, T. Ildžová, J. Kulháněk

Institute of Petrology and Structural Geology, Faculty of Science, Charles University, Albertov 6, 12800 Praha 2, Czech Republic

The Erzgebirge represents a key high-pressure domain of the Variscan orogenic system (e.g. Collett et al., 2017; Jouvent et al., 2022, 2023; Willner et al., 2000), however important questions remain about the pressure-temperature evolution of metasedimentary units and their significance for regional tectonic architecture. This study investigates garnet-bearing micaschists from the Gneiss-Eclogite Unit (GEU) and Micaschist-Eclogite Unit (MEU) to reconstruct their prograde evolution, peak metamorphic conditions and retrograde overprint, and to assess the implications for subduction and exhumation processes.

Phase-equilibria modelling combined with petrographic observations reveals a coherent prograde P-T evolution from c. 14–19 kbar and 470–530 °C to peak conditions of c. 24–28 kbar and 570–590 °C. Peak assemblages are characterised by garnet + muscovite + paragonite + quartz + rutile ± kyanite, with no evidence of ultrahigh-pressure conditions. Peak P-T conditions increase generally eastward across the study area, with GEU samples recording slightly higher pressures and temperatures (c. 27–28 kbar and 580–590 °C for samples SX274D and TD7) than those from the MEU (c. 26 kbar and 580 °C for TD6B and c. 24–25 kbar and 560–570 °C for TD1) (Fig. 1).

The prograde evolution is documented by garnet growth zoning and mineral inclusions. Garnet cores formed within the Grt-Ms-Pg-Chl-Cld-Qz-Rt stability field and commonly contain chlorite, chloritoid and paragonite inclusions, whereas chlorite is absent from garnet rims. This pattern indicates progressive chlorite consumption during burial and heating. Chloritoid is widespread in garnet cores, but absent from outer-rim domains at peak conditions, demonstrating its destabilisation along the prograde path. In TD6B and TD7, textural relationships indicate that kyanite developed at the expense of chloritoid during the late prograde to peak stages through the reaction chloritoid + quartz = garnet + kyanite + H₂O. In TD7, this transition is especially well preserved, with inclusion textures recording chloritoid consumption and a final matrix assemblage containing kyanite but no remaining chloritoid.

A notable feature of all samples is the presence of quartz-rich bands within garnet, locally developed into a pervasive honeycomb texture. These microstructures are interpreted to record syn-growth garnet crystallisation preferentially advancing along an intergranular quartz grain-boundary network. In this model, garnet occupies former interstitial space while quartz grains were progressively trapped and engulfed as inclusions, consistent with grain-boundary-controlled growth during subduction-zone metamorphism. Comparable honeycomb garnet textures have been described from high-pressure metasedimentary rocks in the Tauern Window and were interpreted to reflect fluid-assisted processes during subduction (Hawkins et al., 2007). Several garnets also contain healed fractures and channel-like features filled by rim-composition garnet, and some inclusions are entirely replaced by late garnet. Phosphorus is generally low in garnet cores and increases toward the rims, broadly mirroring the major-element zoning and indicating that P enrichment may be linked to prograde growth rather than retrograde diffusional modification. Although P behaviour in garnet can be complex, P has been shown to increase in (U)HP conditions (Racek et al., 2026).

Retrograde evolution is expressed by hydration textures, including replacement of garnet by biotite and chlorite, and late fractures are infilled by retrograde phases. In TD7, a low-Si muscovite population overgrows the main foliation at an angle and is compositionally distinct from the earlier high-Si phengitic muscovite, pointing to a later re-equilibration event. Partial replacement of kyanite by kaolinite provides further evidence for a late H₂O-rich overprint.

These results support interpretation of the GEU and MEU micaschists as products of relatively cool subduction-zone metamorphism within an orogenic wedge. The eastward increase in peak pressure-temperature conditions is consistent with a stacked wedge architecture developed during eastward subduction and subsequent exhumation. The study shows that garnet textures, especially honeycomb quartz-rich domains and dissolution-precipitation features, preserve a record of prograde growth dynamics and fluid activity during burial to high-pressure conditions.

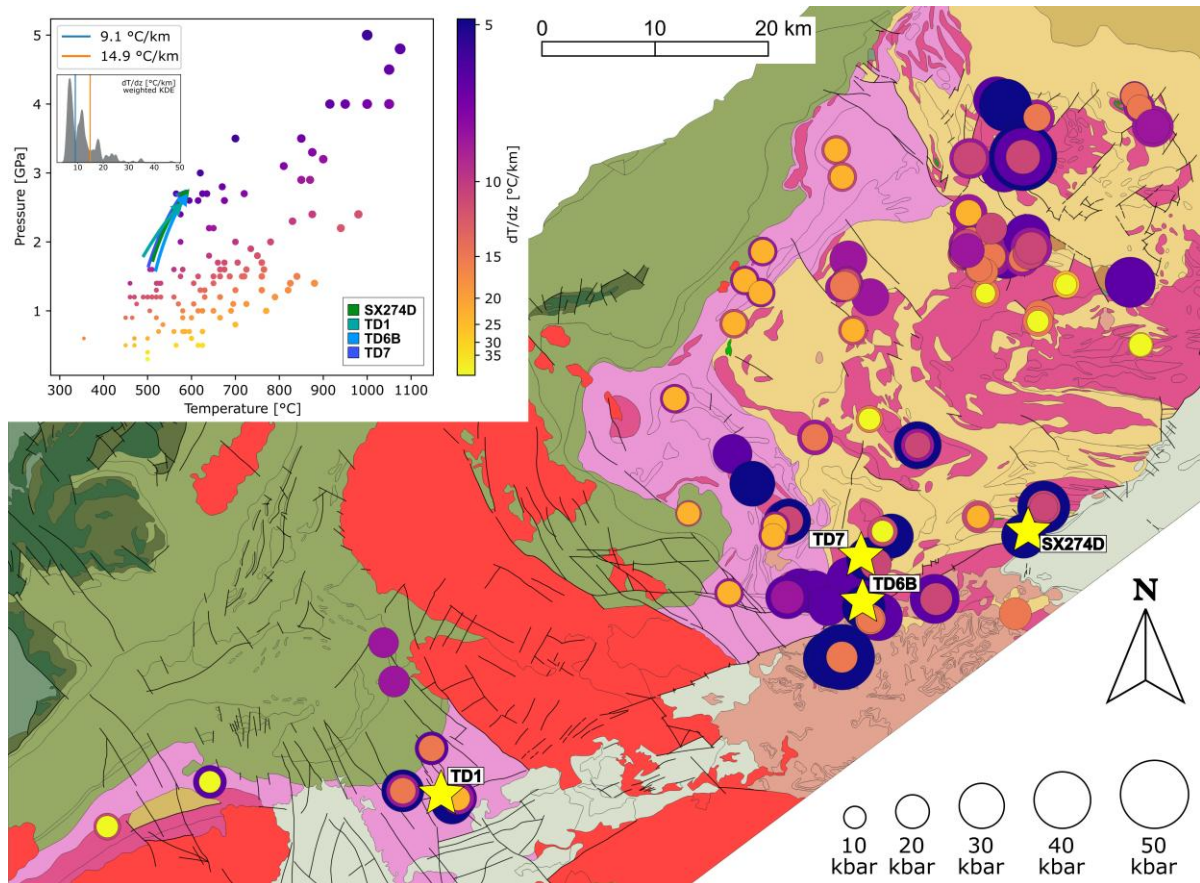


Fig. 1: Geological map of the Erzgebirge, showing the location of published P-T estimates. Inset: Compilation of published peak P-T estimates for Erzgebirge rocks, plotted as Pressure (GPa) versus Temperature (°C). Colours denote the corresponding apparent geothermal gradient (dT/dz , °C/km), with lower gradients (cooler geotherms) shown in purple and higher gradients (warmer geotherms) shown in yellow.

References

- Collett, S., Štípská, P., Kusbach, V., Schulmann, K., & Marciniak, G. (2017). Dynamics of Saxothuringian subduction channel/wedge constrained by phase-equilibria modelling and micro-fabric analysis. *Journal of Metamorphic Geology*, 35(3), 253–280. <https://doi.org/10.1111/jmg.12226>
- Hawkins, A. T., Selverstone, J., Brearley, A. J., Beane, R. J., Ketcham, R. A., & Carlson, W. D. (2007). Origin and mechanical significance of honeycomb garnet in high-pressure metasedimentary rocks from the Tauern Window, Eastern Alps. *Journal of Metamorphic Geology*, 25(5), 565–583. <https://doi.org/10.1111/j.1525-1314.2007.00714.x>
- Jouvent, M., Lexa, O., Peřestý, V., & Jeřábek, P. (2022). New constraints on the tectonometamorphic evolution of the Erzgebirge orogenic wedge (Saxothuringian Domain, Bohemian Massif). *Journal of Metamorphic Geology*, 40(4), 687–715. <https://doi.org/10.1111/jmg.12643>
- Jouvent, M., Peřestý, V., Jeřábek, P., Lexa, O., & Kylander-Clark, A. R. C. (2023). Assembly of the Variscan Orogenic Wedge in the Bohemian Massif: Monazite U-Pb Geochronology of the Tectonic Events Recorded in Saxothuringian Metasediments. *Tectonics*, 42(4), e2022TC007626. <https://doi.org/10.1029/2022TC007626>
- Racek, M., Jeřábek, P., Štípská, P., Závada, P., Svojtka, M., Lexa, O., Hasalová, P., & Veselovský, F. (2026). (Li,Na)-P substitution in garnet: An indicator of ultrahigh-pressure conditions in subducted continental crust. *American Mineralogist*, 111(3), 509–517. <https://doi.org/10.2138/am-2025-9836>
- Willner, A. P., Krohe, A., & Maresch, W. V. (2000). Interrelated P-T-t-d Paths in the Variscan Erzgebirge Dome (Saxony, Germany): Constraints on the Rapid Exhumation of High-Pressure Rocks from the Root Zone of a Collisional Orogen. *International Geology Review*, 42(1), 64–85. <https://doi.org/10.1080/00206810009465070>

Danube Sediment Restoration: River sediment monitoring and research for sustainable sediment management in the Middle Danube

I. Pavičić, Ž. Duić, J. Orešković, I. Pavlin, BI. Balaž, S. Kolar, L. Šembera, B. Matoš

Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Pierottijeva 6, Zagreb Croatia, ivica.pavicic@rgn.unizg.hr

Sediment dynamics and water quality and quantity underpin channel-floodplain morphology, habitat diversity, and the transport and storage of nutrients and pollutants within the Danube River system. Anthropogenic pressures (e.g., hydropower dams, channelisation/embankments, sediment/gravel extraction), together with climate-driven shifts in the hydrological regime, have disrupted sediment supply and channel connectivity, triggering incision in some reaches and accelerated infilling and rapid riparian succession growth of side arms and wetlands in others. The Horizon Europe project DANSER (GA 101157942, 2025-2028) addresses these basin-scale challenges across ~95% of the Danube Basin by combining state-of-the-art monitoring and modelling with stakeholder-engaged sediment co-management, including a transnational sediment task force, to restore sediment balance, improve sediment quality/flow, and support resilient river-society interactions.

We present practical monitoring and research examples from the Middle Danube DEMO in NE Croatia (Drava-Danube corridor), where regulation works, upstream hydropower dams, and frequent low-water periods promote oxbow and wetland infilling. The updated research baseline (DANSER D2.4) integrates long-term national hydrometric records (15 stations) with DEMO-scale monitoring (10 measuring stations and new piezometers), i.e., mean daily Danube discharge ranges at Batina (c. 2,291.8 m³/s) and Aljmaš, Dalj and Vukovar locations (between 2,800.7 and 2,870.3 m³/s), while on Drava river mean daily discharge ranges are observed at Donja Dubrava (c.305.3 m³/s) and Belišće locations (c.543.4 m³/s). The wider Osijek-Kopački Rit sector recorded 31 flood events in 1921-2013 time period (18 Danube, 13 Drava), with major floods in 1965, 1966 and 1972.

The DEMO targets the Novi Gradac-Stara Drava oxbow/side-channel complex near Virovitica (DS1) and the Danube-associated wetlands of Kopački Rit Nature Park (Ramsar/Natura 2000) (DS2). At the DS1, geomorphological and lithofacies mapping along ~1.75 km long Stara Drava channel documents dominant fine-grained sand-silt infill, bar formation up to ~1.5 m, and partial channel drying (~40% of mapped segments), providing a quantitative baseline for restoration design. Bathymetry and UAV/LiDAR surveys, fixed sediment stations, undisturbed coring (seven boreholes to 10 m) and geophysical surveys (ERT, GPR, shallow seismic refraction) support a 3D reconstruction of sediment bodies and channel evolution.

At DS2 (Kopački Rit), recent sedimentation is quantified by a network of 50 in-situ sedimentation/erosion stations distributed across canals, side channels, lakes and marshes. Eight campaigns (2021-2023) indicate dominant accretion across the park, peaking at 15 cm in Lake Kopačevo; cumulative sedimentation across all stations totals 43.85 cm (mean 0.89 cm; median 0.45 cm), while erosion is restricted to a few sites.

Building on the D2.4 baseline, the DEMO monitoring concept follows a nested design: basin-scale hydrometric and suspended-sediment archives are coupled with process-based measurements at DS1 and DS2. At DS1, repeated bathymetric surveys along fixed transects, ten fixed sediment stations (bed pins, staff gauges and repeated depth profiles), and multi-temporal Copernicus imagery/historical orthophotos quantify shoaling, bar growth and vegetation encroachment and help identify priority reconnection corridors.

Undisturbed coring and complementary geophysics (ERT, GPR, shallow seismic refraction) constrain the thickness and geometry of infill and support 3D reconstruction of channel evolution. Planned radionuclide dating (¹³⁷Cs, ²¹⁰Pb, ¹⁴C) and geochemical screening (PAHs, PCBs, DDT and heavy metals) will provide accumulation-rate histories and a contamination baseline, supporting nature-based sediment management and safe sediment handling.

In Kopački Rit, the monitoring network was originally established in the Naturavita programme (January-March 2021) Field surveys repeated several times per year, supported by GIS/Tableau-based spatial analysis, enable rapid detection of sedimentation/erosion “hotspots” and provide inputs for

hydraulic-connectivity modelling of the wetland network. First-year results (January-November 2021) already documented rapid sediment redistribution in the wetland's hydraulic connectors. Net accretion reached 16.5 cm into Kopačko Lake within nine months, forming an elongate sandbar that partly restricts the inlet and reduces navigability during low water (Pavičić et al., 2022). Along the Renovo canal, sand deposition peaked at 8.2 cm, whereas the Vemelj side channel showed dynamic bed adjustment with local erosion of 13.8 cm alternating deposition/erosion consistent with downstream migration of dunes and ripples (Pavičić et al., 2022).

Because Kopački Rit is a Ramsar/Natura 2000 site and its Quaternary sands host regional groundwater resources, DANSER couples geomorphological monitoring with river-aquifer exchange measurements (piezometers and continuous loggers) and standardised ecological surveys (fish, amphibians, macroinvertebrates, macrophytes and waterbirds). Early analyses confirm strong anthropogenic controls on Drava hydro-sedimentary dynamics (dam-driven sediment deficit and hydropeaking) and highlight critical gaps in bedload transport data, reinforcing the need for integrated monitoring to restore sediment and hydrological connectivity, improve water quality and sustain wetland habitat diversity.



Fig. 1: Location of the Middle Danube DEMO sites and sedimentation/erosion monitoring network in Kopački Rit Nature Park (modified after Pavičić et al., 2022).

References

- DANSER Consortium (2025). Deliverable D2.4: Integrated baseline assessment and plan for impact assessment (GA 101157942).
- Pavičić, I., Pavelić, D., Duić, Ž., Pavlin, I., Urumović, K., & Tot, I. (2022). First results of recent sediment deposition monitoring in the Nature Park Kopački Rit. *Hrvatske vode*, 30(122), 321-330.
- Tadić, L., Bonacci, O., & Dadić, T. (2016). Analysis of Drava and Danube floods in Osijek (Croatia). *Environmental Earth Sciences*, 75(18), 1238.

Tectonics of the Pieniny Klippen Belt in the Orava region based on results of regional geological mapping

O. Pelech¹, F. Tet'ák¹, M. Olšavský², J. Madzin³

¹ State Geological Institute of Dionýz Štúr, Mlynská dolina 1, 817 04, Bratislava, ondrej.pelech@geology.sk

² State Geological Institute of Dionýz Štúr, Zelená 5, SK-97404, Banská Bystrica

³ Earth Science Institute, Slovak Academy of Sciences, Ľuberská 1, 974 01 Banská Bystrica

The Pieniny Klippen Belt (PKB) represents a zone 0.5–10 km wide along the southern edge of the Carpathian Flysch Belt. Based on the significant differences in the geological structure, the PKB is laterally divided into several segments (Andrusov, 1938). The studied area of Orava and east part of Varín sector is located between the Zázrivá village and Trstená town in Northern Slovakia. Recent regional geological mapping aimed at creating a new geological map 1:50,000 facilitated detailed study of this area (Tet'ák et al., in press).

The PKB in this region is predominantly composed of the “klippen cover” successions of Late Cretaceous age, mostly represented by sandy flysch of the Snežnica and Sromowce fms. (locally with conglomerate bodies) and variegated marlstones of the Púchov Fm. Another type of thin-bedded flysch is represented by the Upper Cretaceous Pupov Fm. west of Zázrivá village. Third type of distinctive flysch formation is represented by the massive-bedded greywacke-like and quartz-carbonate sandstones alternating with variegated Malinowa-type thin-bedded flysch which are referred to here as the Pavláškova skala Fm. The Pavláškova skala Fm. is often neighbouring with the quartz-carbonate sandstones and conglomerates of the Maastrichtian Jarmuta and Paleocene–Eocene Proč fms. However, the latter are also overlying Snežnica, Sromowce and Púchov fms. in certain locations.

Rigid, mostly limestone klippen are of Oravic origin, and based on characteristic lithostratigraphic units can be assigned into deep-water (Kysuca and Orava), transitional (Czertezik, Niedzica and Nižná) and shallow-water (Czorsztyn) successions (e.g., Gross et al., 1993, Plašienka et al., 2021). The klippen of the Kysuca and Orava successions dominate in the region. The largest klippe connecting elevation points Polom-Banské-Holica-Príboj-Lukáčiková-Biela skala situated on the southern flank of the PKB is approximately 8 km long and belongs to the Kysuca succession. Other large klippen with well-preserved sedimentary successions are represented by the Havranský vrch-Kozinec, Skalka (NW of Oravský Podzámok), the Orava Castle klippe and Červená skala near Podbiel, all of which are assigned to the Orava (former Podbiel) succession. The Nižná succession differs from the Kysuca succession due to occurrence of Aptian-Albian organodetritic limestone (Nižná Fm.) and forms Ostražica Hill near Nižná and several smaller klippen. The Czertezik or Niedzica successions are known from only a few klippen, such as Plešivský Žiar near Zázrivá. Klippen of the Czorsztyn succession are relatively small and rare (e.g., Erdúdsy kostol, Skalka in the Dlžňiansky Cickov valley and small klippen in the wider area of Podbiel, the Hlodočín area, and Stráň NE of Tvrdosín town).

A special feature of the studied region is the zone of Babín Klippen, a narrow strip of PKB rocks (approx. 200 m wide and 8 km long) emerging on the northwestern slopes of the Oravská Magura Mts. in the Prípor Hill massif (1,106 m a.s.l.), SE of Babín village. It consists of Upper Cretaceous flysch formations, variegated marls of the Púchov Fm. and small klippen of Allgäu, Czajakowa and Pieniny fms. as well as the Krupianka and Czorsztyn limestones. Therefore, corresponds mostly to the rocks of the Orava and Czorsztyn successions (Tet'ák et al., 2025).

Exposures of the Pavláškova skala Fm. occurring with Jarmuta and Proč fms. represent the Šariš succession. It appears in the Zázrivá area and become more widespread in a several kilometers long thrust slices east of the Racibor valley west of Oravský Podzámok village. Smaller occurrences are located west of Trstená town.

A separate Upper Cretaceous thin-bedded flysch of the Pupov Fm. in the area west of Zázrivá village represents the analogue of the Klappe Unit (Potfaj et al. 2003) or has been recently correlated with the Gosau Group sediments (Madzin & Plašienka, 2022).

The studied area is significantly affected by the post-Oligocene fold-and-thrust tectonics, which resulted in the formation of reverse and thrust faults with south vergence. The Krynica Unit is backthrust over the PKB successions, and latter are backthrust to the south over Central Carpathian Paleogene Basin formations (Andrusov, 1938; Pešková et al. 2009). In the east, the Flysch Belt and Pieniny

Klippen Belt structure is covered by the Sarmatian to Pliocene and Quaternary sedimentary fill of the Orava-Nowy Targ Basin which post-dates the back-thrusting.

In the area between Zázrivá and Istebné villages a significant regional bend of the PKB and Flysch Belt, traditionally referred to as the Zázrivá or Párnica fault (or sigmoid) is present. This area is characterized by complex structural evolution that is beyond the scope of this work.

The geological mapping confirmed the high quality of Andrusov's early maps (1931a, b) of the region and provides a comprehensive picture of complex geological structure in this area.

Acknowledgements: The study was financially supported by the Ministry of Environment of the Slovak Republic project no. 02 20 Geological map of the Oravská Magura Mts. at scale 1:50,000.

References

- Andrusov, D., 1931a: Geologická mapa útesového pásma v údolí Oravy 1 : 25 000. Díl východní. In: Matějka, A. & Andrusov, D. (eds.): Guide des excursions dans les Carpathes occidentales. Praha, Státní geologický ústav Československé republiky, 397 pp.
- Andrusov, D., 1931b: Geologická mapa útesového pásma v údolí Oravy 1 : 25 000. Díl západní. In: Matějka, A. & Andrusov, D. (eds.): Guide des excursions dans les Carpathes occidentales. Praha, Státní geologický ústav Československé republiky, 397 pp.
- Andrusov, D., 1938: Geologický výskum vnútorného bradlového pásma v Západných Karpatech III. Tektonika. Rozpravy státného geologického ústavu ČSR 9, 135 pp.
- Gross, P., Köhler, E. (eds.), Mello, J., Haško, J., Halouzka, R., Nagy, A., Kováč, P., Filo, I., Havrila, M., Maglay, J., Salay, J., Franko, O., Zakovič, M., Pospíšil, L., Bystrická, H. & Snopková, P., 1993: Geológia južnej a východnej Oravy. GÚDŠ, Bratislava, 320 s.
- Madzin J. & Plašienka D., 2022: Petrographic and heavy mineral analysis of the Upper Cretaceous – Paleocene turbiditic deposits of the Pupov Formation (Western Carpathians, Pieniny Klippen Belt, Terchová-Zázrivá area). Acta Geologica Slovaca, 14, 2, 115–130.
- Pešková I., Vojtko R., Starek D. & Sliva L. 2009: Late Eocene to Quaternary deformation and stress field evolution of the Orava region (Western Carpathians). Acta Geologica Polonica 59, 73–91.
- Tefák, F., Pelech, O. & Potfaj, M., 2025: The Babín Klippen – a peculiar branch of the Orava sector of the Pieniny Klippen Belt (Slovakia). Miner. Slov., 57, 2, 97 – 109.
- Tefák, F. (ed.), Pelech, O., Laurinc, D., Olšovský, M., Vitovič, L., Maglay, J., Fekete, K., Nagy, A., Madzin, J. & Dananaj, I., *in press*: Geological map of the Oravská Magura Mts. 1:50,000. State Geol. Inst. of Dionýz Štúr, Bratislava.

NonOravic units as the key structural elements of the Pieniny Klippen Belt structure (western part).

I. Pešková¹, M. Sentpetery², O. Pelech³, J. Hók¹, M. Olšavský³, M. Potfaj^{3†}

¹ Department of Geology and Palaeontology, Faculty of Natural Sciences, Comenius University Bratislava, Ilkovičova 6, SK-842 15 Bratislava, Slovakia; ivana.peskova@uniba.sk

² Nuclear and Decommissioning Company, plc., Jaslovské Bohunice 360, 919 30, Slovakia

³ State Geological Institute of Dionýz Štúr, Mlynská dolina 1, 817 04 Bratislava, Slovakia, @geology.sk

The Pieniny Klippen Belt represents a distinctive morphotectonic phenomenon of the Western Carpathians. Due to its structural independence and recent tectonic position, the Klippen Belt is considered to mark the surface course of the contact between the External and Internal Western Carpathians. The present-day configuration of the Klippen Belt is the result of transpressional and transtensional tectonics (Nemčok and Nemčok, 1994; Ratschbacher et al., 1993; Kováč and Hók, 1996). An integral part of the Pieniny Klippen Belt consists of the Oravic units (e.g., Andrusov, 1938; Birkenmajer, 1984; Mahel', 1986; Mišík, 1997). These are characterized by the absence of pre-Mesozoic lithostratigraphic members. Within the present structural framework, these units are preserved as various developments of Jurassic and Cretaceous rocks that were detached from their substratum. During tectonic structuring, additional elements—most probably derived from the nappe system of the Internal Western Carpathians—were incorporated into the Pieniny Klippen Belt structure.

Lithotectonic units adjacent to the Klippen Belt and showing affinity to the Internal Western Carpathians were defined by Mahel' (1980) as the Periklippen Zone. Interpretation of the lithostratigraphic extent, tectonic affiliation, as well as the spatial distribution of rock complexes of the Periklippen Zone in the Biele Karpaty-north region has undergone significant conceptual evolution, evolving from being assigned to the Drietoma, Klappe, Manín, and Dúbravka units."

The most recent results based on detailed geological mapping and biostratigraphic research were presented by Pešková & Teťák (2021). It indicates the structurally highest and southernmost structural unit in the wider area the Hronic Unit. It is overthrust onto the rock complexes of the Fatric Unit represented by deep-water facies with a stratigraphic range from the Lower Jurassic to the Middle Cretaceous. Part of these rock assemblage exposed near Bošáca was previously considered to belong either to the Manín Unit or to the shallow-water facies of the Fatric Unit.

To the north, the Fatric units is in tectonic contact with Lower Jurassic sediments of the Drietoma Unit. The stratigraphic succession of the Drietoma Unit can be demonstrated within the range of Upper Triassic to Lower Jurassic. Stratigraphically higher members previously considered as a part of the Drietoma Unit, together with the Vrzávka zone, are currently classified as tectonically unassigned units. These unassigned units are represented by a belt of Upper Jurassic to Lower Cretaceous limestone klippen embedded within Middle Cretaceous flysch deposits.

Further north, the Middle Cretaceous unassigned flysch complexes are in contact with prominent massive klippen that have been previously attributed to the Kysuca, Drietoma, or Klappe units. However, detailed lithostratigraphic and structural analysis do not support their assignment to any of these units, and their tectonic affiliation remains a subject of ongoing discussion. At present, they are tentatively interpreted as units with affinity to the Internal Western Carpathians.

Typical Oravic shallow-water successions of the Pieniny Klippen Belt occur at the contact with the Biele Karpaty Unit of the External Western Carpathians. These are represented by small klippen of Jurassic crinoidal limestones tectonically incorporated into the Upper Cretaceous marls of the Ondrášovec Formation (External Western Carpathians).

Acknowledgements: This work was supported by the Ministry of Environment of the Slovak Republic and also by the Slovak Research and Development Agency under contracts No. APVV-21-0281 "Alpine geodynamical evolution of the Western Carpathian inner zones" and VEGA 1/0021/25 "Neotethys (Meliatum) and Alpine Atlantic (Vahicum) – what has happened with two oceans which influenced evolution of the Western Carpathians?".

References

- Andrusov, D., 1938: Geologický výzkum vnútorného bradlového pásma v Západných Karpatech. Část III.: Tektonika. Rozpr. St. geol. ústavu ČSR, 9, 1–135.
- Birkenmajer, K., 1984: Interrelation of Neogene tectonics and volcanism in the Pieniny Klippen Belt of Poland. Acta Geodaet. Geophys. Montan. Hung., 19, 37–48.
- Kováč, P. & Hók, J., 1993: The Central Slovak Fault System – field evidence of a strike slip. Geol. Carpath., 44, 155–159.
- Mahel', M., 1980: Pribradlové pásmo, charakteristika a význam. Mineralia Slov., 12, 193–207.
- Mahel', M., 1986: Geologická stavba československých Karpát. 1 – Paleoalpínske jednotky. Veda, Bratislava, 503 s.
- Mišík, M., 1997: The slovak part of the Pieniny Klippen Belt after the pioneering works of D. Andrusov. Geol. Carpath., 48, 4, 209–220.
- Nemčok, M. & Nemčok, J. 1994: Late Cretaceous deformation of the Pieniny Klippen Belt, West Carpathians. Tectonophysics, 239, 81–109.
- Pešková, I. (ed.), Teťák, F., Pelech, O., Sentpetery, M., Olšavský, M., Kováčik, M., Maglay, J., Vlačíky, M., 2021: Geological map of the Biele Karpaty Mts. (northern part). Štátny geologický ústav Dionýza Štúra, Bratislava. ISBN 978-80-8174-055-8.
- Ratschbacher, L., Frisch, W., Linzer, H.G., Sperner, B., Meschede, M., Decker, K., Nemčok, M., Nemčok, J. & Grygar, R. 1993: The Pieniny Klippen Belt in the Western Carpathians of northeastern Slovakia: structural evidence for transpression. Tectonophysics, 226, 471–483.

Composition, stratigraphy and structure of the Čergov sector of the Pieniny Klippen Belt in eastern Slovakia

D. Plašienka¹, P. Gedl², M. Molčan Matejová¹, T. Potočný¹

¹ Department of Geology and Palaeontology, Faculty of Natural Sciences, Mlynská dolina, Ilkovičova 6, 842 15 Bratislava, Slovakia;
dusan.plasienka@uniba.sk, marina.matejova@uniba.sk, potocny9@uniba.sk

² Institute of Geological Sciences, Polish Academy of Sciences, Research Centre in Kraków, Senacka 1, 31-002 Kraków, Poland; ndgedl@cyf-kr.edu.pl

The Čergov sector of the Pieniny Klippen Belt (PKB) in eastern Slovakia is relatively poorly known, but remarkable from both its geological structure and morphological-touristic beauties. Numerous spectacular klippen of different origin embedded in various soft matrix formations occur in laterally tapering belt about 25 km long and 3–4 km wide. The belt is bounded by subvertical faults from both sides against the Paleogene complexes of the Magura units to the NE and the Central Carpathian Paleogene Basin (CCPB) in the SW, where it is followed by the peculiar Šambron–Kamenica anticlinal zone a few km SW of PKB. Within these limits, the Oravic PKB elements include the Šariš, Subpieniny and Pieniny thrust units from bottom to top, which are all only composed of detached Jurassic to Eocene sedimentary successions.

The Šariš Unit involves deep-water Middle Jurassic through Lower Eocene sedimentary formations. The Jurassic–Cretaceous pelagic deposits are rather thin, condensed, but form a continuous, though often strongly tectonically reduced and dismembered succession. The key section in a ravine NE of Kyjov village includes black shales intercalated by beds of turbiditic micaceous sandstone (Aalenian–Bajocian Szlachtowa Fm., a.k.a. “black flysch”) followed by greenish-grey siliceous and spotted marly shales (Bajocian–Bathonian Opaleniec Fm.), dark siliceous shales (Bathonian Sokolica Fm.), red ribbon radiolarites (Callovian–Kimmeridgian Czajakowa Fm.), aptychi-bearing variegated marlstones (Tithonian Palenica Mb.), and grey bioturbated marly limestones (Tithonian–Hauterivian Pieniny Fm.). This sequence is imbricated with red abyssal claystones of the Malinowa Fm. (Turonian–Campanian). Elsewhere exposed mid-Cretaceous strata consist of dark spotted marlstones and siliceous shales (Kapuśnica, Wronine and Hulina Fms). The Maastrichtian? to Lower Eocene synorogenic wildflysch complex consists of marly shales and turbiditic or massive calcareous sandstones (Proč Fm.) grading to thick breccia bodies carrying huge olistoliths of Jurassic–Lower Cretaceous limestones derived from the overriding Subpieniny nappe (e.g. at the Milpoš type locality).

The Subpieniny Unit comprises several partially differing lithostratigraphic successions (Czorsztyn, Niedzica, Czertezik) derived from the occasionally emerged submarine elevation known as the Czorsztyn Ridge and its rifted slopes. The most typical members are represented by the lower Middle Jurassic black shales (Skrzypny Fm.) abruptly overlain by sandy-crinoidal limestones (Smolegowa and Krupianka Fms), red nodular limestones (Czorsztyn Fm.), Oxfordian radiolarites (Czajakowa Fm. in the Niedzica and Czertezik successions), and Tithonian–Valanginian bioclastic limestones (e.g. Dursztyn Fm.). After a considerable hiatus and erosion, Albion to Campanian variegated “Púchov” marls (Jaworki Fm.) and Maastrichtian synorogenic flysch were deposited (Jarmuta Fm. including Gregorianka-type breccias composed of material from the Pieniny Unit).

Oldest exposed formations of the Pieniny Unit are represented by the Bajocian dark spotted marls (Harcygrund Fm.) and limestones (Podzamcze Fm.), which are overlain by the Bathonian–Oxfordian radiolarites (Sokolica and Czajakowa Fms), Kimmeridgian reddish nodular limestones (Czorsztyn Fm.) and Tithonian–Barremian well-bedded cherty limestones (Pieniny Fm.). The mid-Cretaceous dark (Tissalo or Kapuśnica Fm.) and variegated marls (Jaworki and Lalinok Fms) are followed by turbiditic sandstones of the Snežnica Fm. and conglomerates of the Sromowce Fm.

The Jurassic up to Eocene tectonostratigraphic evolution of the Oravic PKB successions is well documented by their sedimentary record (e.g. Plašienka et al., 2020). The most important events embrace the sudden and short-term uplift of the central Oravic elevation – Czorsztyn Ridge – during the Late Bajocian. This is ascribed to the thermal uplift of the upper plate of an asymmetric rift zone of the formerly uniform basinal area before breakup of the South Penninic oceanic domain. Following the post-rift thermal subsidence, the ridge was elevated again during the oppositely oriented North Penninic (Magura) asymmetric rifting period in mid-Cretaceous times. In the meantime, the Western Carpathian

orogenic wedge progressing from the SE grew by incorporation units from its foreland and finally reached the Oravic domain during the Late Cretaceous. Sequential accretion of Oravic units is recorded by the synorogenic, coarsening-upward flysch deposits terminated by coarse olistostrome breccia bodies composed of material derived from fronts of the overriding thrust units. The compressional structural development then included four main deformation stages: (1) consecutive emplacement of the Oravic nappes (Maastrichtian and Early Eocene); (2) out-of-sequence folding and thrusting of the nappe stack with NW- to N-vergency (Eocene); (3) dextral transpression along the NW–SE trending wrench zone (Late Eocene); (4) after the Oligocene collapse of the CCPB, the earliest Miocene SSW-directed backthrusting produced the Šambron–Kamenica anticlinal zone SW of the PKB and accentuated the PKB boundary faults. All these processes shaped the final structural pattern of the Čergov sector.



Fig. 1: The authors' team at a rocky window in the Sokol' klippe near Kyjov. From left to right: T. Potočný, P. Gedl, M. Molčan Matejová, D. Plašienka.

Acknowledgements: Financial support from the research projects funded by the Slovak Research and Development Agency (project APVV-21-0281) and by the Grant Agency for Science, Ministry of Education of the Slovak Republic (VEGA 1/0021/25) is gratefully acknowledged.

References

Plašienka D., Bučová J. & Šimonová V., 2020: Variable structural styles and tectonic evolution of an ancient backstop boundary: the Pieniny Klippen Belt of the Western Carpathians (+supplement). *International Journal of Earth Sciences*, 109, 4, 1355–1376.

Zircon U–Pb LA-ICP-MS dating and geochemistry of Early–Middle Triassic acid volcanites with blueschist facies metamorphic overprint (Meliata Unit Bôrka Nappe, Western Carpathians)

T. Potočný¹, M. Ondrejka², M. Putiš², D. Plašienka¹, J. Sláma³

¹ Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University, Mlynská dolina, Ilkovičova 6, 842 15 Bratislava, Slovakia; potocny9@uniba.sk

² Department of Mineralogy, Petrology and Economic Geology, Faculty of Natural Sciences, Comenius University, Mlynská dolina, Ilkovičova 6, 842 15 Bratislava, Slovakia

³ Institute of Geology, Czech Academy of Sciences, Rozvojová 269, Prague, Czech Republic

Blueschist-facies complexes represent important records of subduction-related processes in ancient orogenic belts, although their original geological features are commonly obscured by intense metamorphic overprinting. Fragments of the ancient Meliata oceanic basin (Meliata Unit/Meliatic) occur in limited tectonic windows and slices in southern Slovakia and partly in northern Hungary. The Meliata Unit exhibits lithologies commonly observed in oceanic sutures, such as ophiolites, blueschist facies rocks, mélanges and oceanic sediments. The Bôrka Nappe represents one of the key subunits of the Meliata Unit and constitutes a typical high-pressure/low-temperature (HP/LT) metamorphic complex interpreted as a subducted fragment of the Meliata oceanic basin margin. The Bôrka Nappe comprises three main lithostratigraphic complexes: Permian volcano-sedimentary complex, a Triassic volcano-sedimentary Hačava sequence, and Jurassic pelagic sediments. Although the Permian volcanic activity has previously been dated, the age of the Triassic volcanic complex has remained poorly constrained due to the absence of direct geochronological data. This study presents new zircon U–Pb LA-ICP-MS ages and whole-rock geochemistry from rare felsic metavolcanic rocks discovered within the blueschist-facies Hačava sequence of the Bôrka Nappe. The studied rocks occur as a small body associated with metabasites (glaucophanites) and marbles and are interpreted as metamorphosed rhyolitic volcanics. Petrographically, they display a grano-lepidoblastic metamorphic texture with a mineral assemblage consisting of phengitic muscovite, albite, quartz, epidote, titanite, jadeite, and garnet, along with relic magmatic aegirine. Zircon U–Pb dating yielded a concordia age of 248.5 ± 1.3 Ma, corresponding to the Early–Middle Triassic boundary (Olenekian–Anisian). This age provides the first direct evidence for Triassic acid volcanic activity within the Hačava sequence of the Bôrka Nappe. Whole-rock geochemistry indicates an aluminous subalkaline rhyolite–rhyodacite composition with calc-alkaline affinity. Trace-element patterns and tectonic discrimination diagrams suggest a transitional tectonomagmatic setting between volcanic-arc and within-plate environments. The coexistence of felsic and mafic volcanic rocks within the Hačava sequence indicates bimodal volcanism, characteristic of extensional tectonic regimes. These results support the interpretation that the Bôrka Nappe records syn-rift magmatism related to an advanced stage of continental rifting and transition to the opening of the oceanic Meliata Basin during the Early–Middle Triassic. The volcanic rocks were subsequently subducted and metamorphosed under blueschist-facies conditions during the Late Jurassic. The new geochronological and geochemical data thus provide important constraints on the timing and geodynamic context of the early evolution of the Meliata oceanic domain in the Western Carpathians.

Acknowledgments: The research was supported by the Slovak Research and Development Agency (APVV-19-0065, APVV-21-0281, APVV-22-0092) and the Slovak scientific grant agency VEGA (VEGA 1/0435/21, VEGA 2/0012/24, VEGA 1/0028/24, and VEGA 1/0021/25).

Pre-Permian evolutionary history of the West-Carpathian basement based on geochronology data

M. Putiš¹, J. Sláma², Q-L. Li³, D. Chew⁴, X-H. Li³, O. Nemec¹, M. Ondrejka¹, Z. Németh[†], J. Madarás⁵, P. Siman⁵, J. Spišiak⁶, P. Ružička

1 Department of Mineralogy, Petrology and Economic Geology, Faculty of Natural Sciences, Comenius University, Ilkovičova 6, 842 15 Bratislava, Slovakia, marian.putis@uniba.sk, Ondrej.nemec@uniba.sk, martin.ondrejka@uniba.sk, peter.ruzicka@uniba.sk

2 Institute of Geology, Czech Academy of Sciences, Rozvojová 269, 165 00 Prague 6, Lysolaje, Czech Republic, slama@gli.cas.cz

3 Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China, liqili@mail.iggcas.ac.cn, lixh@gig.ac.cn
Department of Geology, School of Natural Sciences, Trinity College Dublin, Ireland, chewd@tcd.ie

5 Earth Science Institute, Slovak Academy of Sciences, Dúbravská 9, 840 05 Bratislava, Slovakia, j.madaras@savba.sk, pavel.siman@savba.sk

6 Department of Geography and Geology, Faculty of Natural Sciences, Matej Bel University, Tajovského 40, 974 01 Banská Bystrica, Slovakia, jan.spisiak@umb.sk

The Inner Western Carpathian (IWC) Mesozoic–Cenozoic Orogen contains extensive areas of partly reworked crystalline basement rocks. The investigated rock complexes have yielded petrological, geochemical, and geochronological data (SIMS and LA–ICP–MS U–Pb zircon ages) providing evidence for their peri-African Gondwana origin and evolution (Putiš et al., 2008, 2009, 2024, 2026, and references therein). The IWC Variscan basement is a unique segment of Cadomia, encompassing both the northern, Prototethys-related and the southern, Paleotethys-related domains of the Galatia terrane.

The late- to post-Cadomian kilometre-thick passive-margin Hron Complex metasediments contain detrital zircon populations derived from two Ediacaran sources at ca. 620 and 570 Ma, with minor ages at 3100–2700 Ma, 2400–1900 Ma, and 1000–750 Ma. These age spectra indicate a foreland setting adjacent to an eroded Ediacaran magmatic arc and the Saharan Metacraton, thus positioning the IWC basement in the western part of Cadomian Galatia (east of Cadomian Armorica). The rift-related Koleso Valley Complex, tectonically overlying the Hron Complex, preserves late Cadomian metasediments with dominant Ediacaran detrital zircons, intruded by early to middle Cambrian tonalitic orthogneisses (~540–520 Ma; av. Th/U 0.23). Together with the middle Cambrian granitic orthogneisses (511–507 Ma) in the Jarabá Complex paragneisses, this evidence suggests a late Cadomian magmatic arc above the inferred Prototethys subduction zone. Late Cambrian to Early Ordovician metamorphic zircon ages (~500–475 Ma; Th/U 0.01–0.1) in gneisses of the Koleso Complex indicate the transformation of this arc into a supra-subduction arc–backarc basin system during ongoing subduction of the Prototethys oceanic slab (Fig. 1). The WP and E-MOR type mafic rocks of this complex, dated ~480 Ma on zircon, indicate an early extensional stage of this incipient basin system.

These processes initiated the gradual growth of the Galatian terrane through accretion of underplated upper mantle mafic–ultramafic and supra-subduction ensialic sedimentary–magmatic suites of the Cenerian Orogen (~500–420 Ma). The Layered amphibolite Complex (~490–440 Ma) contains juvenile N-MORB and VAB-C rocks representing an incipient ensialic arc–backarc domain, separating the Koleso Valley Complex from the foreland Jarabá Complex, both intruded by numerous granitic arc-type orthogneisses (~500–450 Ma). Closure of the Prototethys Ocean led to termination of the supra-subduction basin system, northward intra-continental subduction of the Layered amphibolite and Koleso Valley complexes (~390–380 Ma), collision (~380–370 Ma), and formation of an early orogenic arc (~370–360 Ma). Meanwhile, the Lower to Middle Devonian rift-related volcanic–sedimentary Pezinok Complex evolved into the Upper Devonian oceanic Pernek Complex (~370 Ma) within the Prototethyan forearc of the Jarabá Complex. These complexes are exposed in Cretaceous Tatric and Veporic zones.

Prototethys slab rollback, potentially aided by a mantle plume, drove rifting of the inboard northern Gondwana margin, comprised of the late Cambrian–Silurian volcanic–sedimentary Gelnica Complex, and the formation of oceanic Paleotethys. The Lower to Middle Devonian (~400–380 Ma) rift-related ensialic Rakovec Complex and the evolved oceanic Klátov Complex formed on the Gondwana margin, and these complexes are exposed in the Late Cretaceous Gemeric zone. Northward subduction of the Paleotethys Ocean (including the Rakovec–Klátov Basin) from ~370 Ma caused the

collapse of the early Variscan orogenic arc of Northern Galatia (Tatric–Veporic basement). This event was accompanied by Late Devonian to Early Carboniferous anatexis and emplacement of granitic–tonalitic–dioritic intrusions (~365–340 Ma) in the Tatric–Veporic basement complexes (Fig. 1).

Continued closure of Paleotethys resulted in the accretion of the Rakovec–Klášov (~350 Ma) and Gelnica complexes of Southern Galatia to the Variscan orogen of Northern Galatia, culminating in the formation of late Variscan southvergent (~340–320 Ma) tectonic structures in the IWC basement.

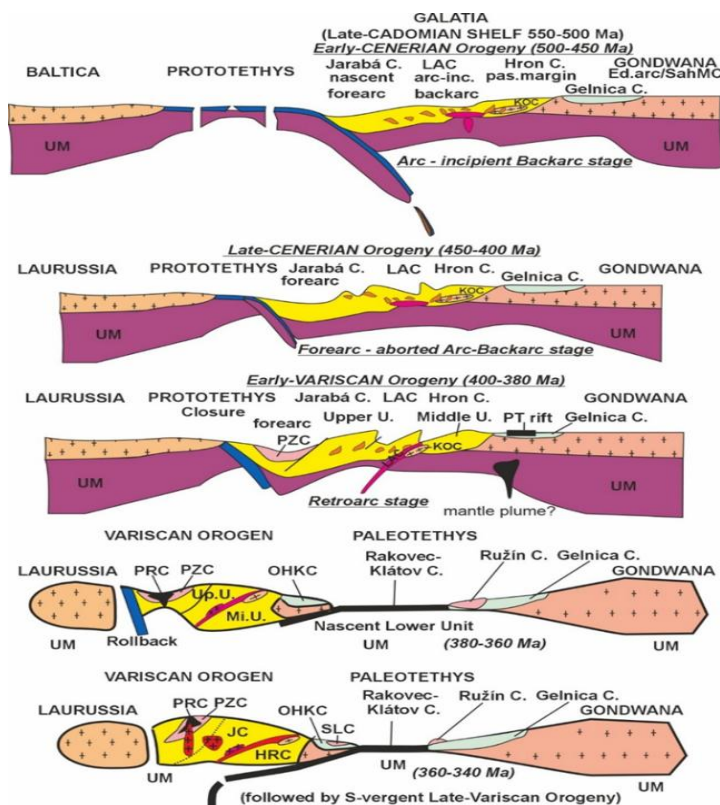


Fig. 1: Evolutionary scheme of pre-Permian basement of the Western Carpathians (not to scale). Ed.arc – Ediacaran arc, SahMC – Saharan Metacraton, JC – Jarabá Complex, HRC – Hron Complex, LAC – Layered amphibolite Complex, KOC – Koleso Valley Complex, OHKC – Ostrá-Hlalomorná Valley-Klenovec Complex, SLC – Sinec-Lovinobaňa Complex, PZC – Pezinok Complex, PRC – Pernek Complex, PT – Paleotethys, Up.U – Upper Unit, Mi.U. – Middle Unit, UM – Upper mantle (updated model scheme from Putiš et al., 2009, 2024).

Acknowledgements: This research finalization was funded by the Slovak APVV-19-0065, APVV-22-0092 projects, VEGA-1/0028/24 project, the Chinese 2016YFE0203000 project, the EU NextGenerationEU project 09I03-03-V04-00071, the Czech RVO67985831 grant, the Science Foundation Ireland research grants 12/IP/1663, 13/RC/2092, and 13/RC/2092_P2.

References

- Putiš, M., Sergeev, S., Ondrejka, M., Larionov, A., Siman, P., Spišiak, J., Uher, P., Paderin, I., 2008. Cambrian–Ordovician metaigneous rocks associated with Cadomian fragments in the West-Carpathian basement dated by SHRIMP on zircons: A record from the Gondwana active margin setting. *Geologica Carpathica* 59, 3–18.
- Putiš, M., Ivan, P., Kohút, M., Spišiak, J., Siman, P., Radvanec, M., Uher, P., Sergeev, S., Larionov, A., Méres, S., Demko, R., Ondrejka, M., 2009. Meta-igneous rocks of the West-Carpathian basement, Slovakia: Indicators of Early Paleozoic extension and shortening events. *Bulletin de la Société Géologique de France* 180, 461–471.
- Putiš, M., Ondrejka, M., Nemec, O., Li, Q-L., Chew, D., Li, X-H., Madarás, J., Németh, Z., Spišiak, J., Siman, P., Ružička, P., 2024. The Western Carpathians Variscan Orogen: A collage of post-Cadomian, Cenerian, and Paleotethyan complexes from the Gondwana-derived terranes (a new concept). 13th ESSEWECA Conference, Bratislava, Abstract Book, 57–61.
- Putiš, M., Sláma, J., Li, Q-L., Chew, D., Nemec, O., Li, X-H., Ondrejka, M., Németh, Z.†, Madarás, J., Ackerman, L., Strnad, L., Spišiak, J., Siman, P., Ružička, P., 2026. Peri-Gondwanan evolution of the Western Carpathians pre-Permian basement: Petrological–geochemical and geochronological evidence of Proto- and Paleo-Tethys related assemblage of Galatia terrane in Variscan orogen (being submitted to ESR).

How to reveal the record of (U)HP metamorphic conditions in quartzofeldspathic rocks: mineral composition and phase preservation

M. Racek¹, O. Lexa¹, P. Jeřábek¹, P. Štípská², B. Paddon¹, P. Závada³, M. Svojtka⁴, P. Hasalová²

¹ Institute of Petrology and Structural Geology, Faculty of Science, Charles University, Prague, Czech Republic

² Czech Geological Survey, Prague, Czech Republic

³ Institute of Geophysics of the Czech Academy of Science, Prague, Czech Republic

⁴ Institute of Geology of the Czech Academy of Science, Prague, Czech Republic

Quartzofeldspathic rocks represent a major component of the continental crust and their subduction to (U)HP conditions has been documented in multiple cases. Despite of that, the preservation of unequivocal evidence for (U)HP metamorphism in these lithologies remains rare often leading to doubts about shared or separate P-T evolution of such lithologies and coexisting mafic eclogites.

The direct proof is the presence of the UHP index minerals, namely diamond and coesite. Where preserved, coesite typically occurs as inclusions in refractory phases as garnet, making its identification challenging, especially in the case of very small inclusions and/or the absence of the diagnostic back-reaction textures to quartz. Unequivocal identification of coesite is mainly achieved by the Raman spectroscopy or EBSD. In addition to that, we propose the use of the cathodoluminescence (CL) spectrometry. Considering the distinct wavelengths emitted by coesite (c. 550 nm) and quartz (c. 660 nm), application of the CL spectrometry coupled with SEM-EDS proved itself as a rapid and unambiguous method for detection of coesite inclusions, even at micron scale.

In the absence of UHP index minerals, quartzofeldspathic rocks commonly retain stable mineral assemblages over a wide P–T range, limiting their usefulness for peak pressure estimates. In such cases, other UHP indicators need to be searched, including trace-element substitutions in major minerals. Investigation of garnet with coesite inclusions from subducted metagranites of the Eger Crystalline Complex, Bohemian Massif (Racek et al. 2026) revealed chemically distinct concentric domains with minor amounts of P, Na, and Li, that systematically coincide with coesite locations. From the correlation of these elements, $(\text{Na,Li})_1\text{P}_1\text{M}^{2+}_{-1}\text{Si}_{-1}$ substitution was inferred. Its clear connection to UHP conditions in the studied natural samples is in line with experimental data (e.g. Thompson 1975; Hanrahan et al. 2009) and therefore, identification of such substitution can be considered as a UHP conditions indicator.

A further peculiarity of (U)HP quartzofeldspathic rocks is the frequent absence of jadeite-rich clinopyroxene, despite its predicted stability by experiments and thermodynamic modelling. This absence has been attributed either to complete retrograde decomposition or to its non-participation in the peak assemblage. Recently discovered quartzofeldspathic gneiss from Erzgebirge is composed of quartz, garnet, plagioclase, K-feldspar, muscovite, and kyanite and contains relics of jadeite included in kyanite and garnet (the latter also with coesite). Observed domains up to 3 mm in size of fine-grained plagioclase-muscovite symplectite present in the matrix, surrounded by plagioclase-muscovite mosaic and occasionally associated with small garnet grains are interpreted as pseudomorphs after jadeite. Peak P-T conditions estimated to >28 kbar and 600–800 °C are consistent with the coexistence of jadeite, coesite and Ca-poor garnet. The subsequent decompression led to jadeite breakdown into plagioclase-muscovite symplectite and Ca redistribution, reflected by increasing Ca content in newly formed garnet. Based on our observations, we propose that jadeite/omphacite should be considered as a part of the HP mineral assemblage in quartzofeldspathic rocks, and the presence of muscovite-plagioclase assemblage associated with Ca-poor garnet may indicate its former presence.

Acknowledgements: This work was funded by the Czech Science Foundation grant GACR 24-12845S.

References

Hanrahan M., Brey G., Woodland A., Altherr R., Seitz H.-M. (2009) Towards a Li barometer for bimineralic eclogites: Experiments in CMAS. *Contributions to Mineralogy and Petrology*, 158, 169–183, <https://doi.org/10.1007/s00410-009-0376-7>.

- Racek M., Jeřábek P., Štípská P., Závada P., Svojtka M., Lexa O., Hasalová P., Veselovský F. (2026) (Li,Na)-P substitution in garnet: An indicator of ultrahigh-pressure conditions in subducted continental crust. *American Mineralogist*, 111 (3), 509–517, <https://doi.org/10.2138/am-2025-9836>.
- Thompson R.N. (1975) Is upper-mantle phosphorus contained in sodic garnet? *Earth and Planetary Science Letters*, 26, 417–424, [https://doi.org/10.1016/0012-821X\(75\)90017-5](https://doi.org/10.1016/0012-821X(75)90017-5).

Current state of knowledge on prospective locations for siting a deep geological repository in Slovakia (the Tribeč Mountains and the Rimava Basin)

M. Sentpetery, J. Bučová, I. Slaninka

Nuclear and Decommissioning Company, plc., Jaslovské Bohunice 360, 919 30 Jaslovské Bohunice, Slovakia

GOAL: Slovakia is required to ensure the safe and long-term management of radioactive waste. The majority of this waste originates from the operation and decommissioning of nuclear power plants, while smaller amounts arise from applications in medicine, industry, and scientific research. The central challenge lies in guaranteeing that radioactive materials remain effectively isolated from humans and the environment over extended timescales, taking into account both present-day conditions and future geological and societal developments.

PROPOSED SOLUTION: Experts broadly agree that the most reliable and long-term solution for managing spent nuclear fuel, high-level and long-lived intermediate-level radioactive waste is its disposal in a deep geological repository (DGR). This type of facility is constructed at great depths underground and consists of a system of access tunnels and disposal chambers designed for the final emplacement of the waste. It relies on a multi-barrier system comprising the engineered barrier system (waste form, canister, and bentonite-based buffer and backfill materials) and the surrounding host rock, which acts as the natural geological barrier. Together, these components ensure the long-term isolation of radioactive substances from the biosphere and significantly reduce the risks associated with their potential release.

The host rock represents the most important natural barrier surrounding the underground disposal zone. Based on preliminary geological data such as tectonic, hydrogeological and geomechanical conditions, the granitic massif of the Tribeč Mountains and the sedimentary formations of the Rimava Basin emerge as the most suitable host-rock settings for the potential siting of a DGR in Slovakia.

CURRENT STATUS IN SLOVAKIA: The investigation and assessment of potential sites for a DGR has been the responsibility of JAVYS a. s. since 2010. Preliminary site investigations were carried out in the past within earlier research programs. The evaluation of the sites focused primarily on geological structure, tectonic conditions, neotectonic and geomorphological evolution, and hydrogeological and geochemical characteristics. A new phase of site investigations is currently being prepared for the two most promising candidate areas. The objective is to evaluate and compare these areas to identify the site that demonstrates the highest overall suitability for the development of the future repository.

TRIBEČ MOUNTAINS: Geological mapping and the exploratory borehole RAO-3 (drilled in 2001, 250 m depth) confirmed that the crystalline core of the mountain range is composed predominantly of medium- to coarse-grained biotite granodiorite to tonalite (the Tatric Unit: Hercynian post-kinematic intrusions of Late Carboniferous age). Based on the geological documentation from the RAO-3 borehole, tectonic disturbance within the upper 250 m of the massif is generally low to moderate, while the Rock Quality Designation (RQD) values indicate an improvement in rock quality with depth. The potential repository host rock is therefore expected to occur outside mylonite zones and major discontinuities within the lower structural level of the crystalline basement. Surface-based structural analysis shows that tectonic deformation in the area is mainly expressed through mylonitization and jointing, whereas faults are relatively rare. Geomorphological analysis indicates long-term landscape stability, with no evidence of recent neotectonic activity affecting the central part of the massif. Geophysical surveys likewise suggest a relatively homogeneous geological environment at greater depths.

Initial hydrogeological investigations, including staged hydraulic testing in the RAO-3 borehole, indicate that groundwater circulation within the granitoid massif does not preclude the potential use of this geological structure for deep waste disposal. However, additional investigations are required to further characterize the hydraulic properties of the rock mass and the regional groundwater flow regime. Based on the current state of knowledge, the central part of the Tribeč Mountains represents the most prospective crystalline candidate site identified to date. Future research will focus on the south-western

sector near the Veľký Tribeč peak and will include additional geophysical surveys and deep exploratory drilling to depths of at least 750 m in order to better constrain tectonic structures, hydrogeological conditions, and host rock properties.

RIMAVA BASIN: The geological setting is dominated by calcareous siltstones of the Lučenec Formation, the so-called *Szecsény Schlier*, which represents the dominant lithology of the formation and forms a relatively homogeneous sedimentary sequence with properties favorable for a potential repository host rock. The thickness of this unit decreases northwards but remains substantial across the entire study area, reaching approximately 500 m even in the northernmost sector and locally up to 700 m, as confirmed by previous drilling. Exploratory core boreholes RAO-5 (drilled in 2001, 250 m depth) and GOR-1 (drilled in 2011, 100 m depth) encountered a continuous, lithologically uniform succession of calcareous siltstones of Egerian age.

From a tectonic and geomorphological perspective, the area is relatively stable. The main structural feature is the Čierny Potok fault zone, which divides the study area into two structural blocks. However, there is no evidence of recent seismic activity, and the dominant tectonic development was completed during the Miocene. Compared to the other nearby candidate area in the Cerová vrchovina region, the western Rimava Basin exhibits lower morphostructural differentiation, lower erosion rates, and overall, more favourable geomorphological conditions.

Hydrogeological investigations, including hydrodynamic testing in borehole RAO-5, indicate that the sedimentary environment of the *Szecsény Schlier* siltstones may be hydrogeologically more favourable than crystalline settings due to their low permeability and limited infiltration of precipitation. The key uncertainty relates to the distribution and hydraulic significance of fault zones that may locally enhance groundwater flow and potentially host CO₂-bearing fluids. Additional uncertainties concern the magnitude of vertical movements in the area and the potential reactivation of volcanic activity, which occurred in the wider region during the Quaternary.

Based on the current state of knowledge, the western Rimava Basin represents a highly prospective sedimentary candidate site. Upcoming investigations will focus on detailed geophysical surveys, particularly 2D seismic imaging, and additional exploratory boreholes to depths of at least 900 m (preferably reaching the pre-Tertiary basement) to verify the thickness and homogeneity of the host formation, exclude the presence of permeable sandy interlayers, and further characterize regional hydrogeological conditions.

MAIN ACTIVITIES OF THE PLANNED RESEARCH: The next stage of site investigation will focus on reducing the key geological and hydrogeological uncertainties identified during the preliminary evaluation. Planned activities will include additional geophysical surveys (2D seismic reflection, gravimetric and magnetometric measurements, magnetotelluric sounding, profile gamma-ray spectrometry, and radon emanation measurements) aimed at improving the structural model of the subsurface and identifying potential fault zones.

Deep exploratory drilling will be carried out to obtain continuous core samples from the potential host formations and to verify their lithological homogeneity, mechanical properties, and thickness. The boreholes will also enable in situ testing, including hydraulic testing, geophysical logging, and long-term groundwater monitoring.

Further studies will focus on the regional hydrogeological framework, including groundwater flow gradients, recharge and discharge areas, and the hydraulic connectivity of deeper formations. Complementary investigations will also address neotectonic activity, geomorphological stability, volcanism (Rimava Basin) and the long-term geological evolution of the study areas.

The results of these investigations will provide key input data for a refined geological model and for the preliminary safety assessment of potential deep geological repository sites.

Receiver Function analysis reveals new insight into the geodynamic evolution of the Alpine-Tethys closure in the Western Carpathians

C. Schiffer¹, T. Soni², S. Mazur², L. Petrescu³

¹ Department of Earth Sciences, Uppsala University, 752 36 Uppsala, Sweden

² Polish Academy of Sciences, Institute of Geological Sciences, Kraków, Poland

³ National Institute for Earth Physics, Magurele, Ilfov, Romania

The Alpine–Tethys suture in the Western Carpathians records the collision between the northern European passive margin and the Adria-derived Alps–Carpathians–Pannonian (AlCaPa) block, and is exposed at the surface as the ~600 km long, narrow, sub-vertical Pieniny Klippen Belt (PKB). This sub-vertical unit consists of shallow-marine limestone klippen embedded in a flysch matrix containing exotic clasts. These characteristics previously led to the hypothesis of a Briançonnais-type continental ribbon, the Czorsztyn Ridge, within the Alpine-Tethys Ocean, now located at lower crustal levels beneath the Tatra mountains.

To investigate the crustal architecture and the processes of Alpine-Tethys closure, 18 broadband seismometers were deployed from summer 2023 to summer 2026 along a north–south profile from southern Poland to northern Hungary. This regional deployment formed part of the AdriaArray initiative, covering Central, Eastern and Southern Europe with over 400 temporary stations in addition to the existing network of more than 1000 permanent stations. The 18 temporary seismometers complement 3 conveniently positioned permanent stations, and 6 other temporary AdriaArray stations, forming a north-south oriented profile of 27 seismic stations. Using nearly 2.5 years of continuous recordings, we performed receiver-function (RF) analysis to image crustal velocity structure. Receiver functions utilise teleseismic P-to-S conversions at subsurface discontinuities.

Common-conversion-point (CCP) stacking of thousands of RFs along the profile provides high-resolution images of the crustal architecture beneath the Western Carpathians. The CCP images place the Moho at ~30–35 km depth with distinct steps beneath the PKB and the Darnó Fault. They show crustal-scale wedging between the European and AlCaPa plates, together with a south-dipping upper-mantle interface interpreted as the base of underthrust attenuated European crust, analogous to the Pyrenean double-wedge system. No distinct crustal block or microcontinental fragments are observed beneath the Tatra nappe, where subduction of the Czorsztyn basement had previously been proposed.

Joint inversion of RFs, apparent S-wave velocities, and Rayleigh-wave dispersion curves yields 1D shear-wave velocity models beneath each station. Estimated Moho depths are ~30 km in the northern part of the profile, increasing to ~35 km towards the PKB. Beneath the PKB, the Moho signature disappears and is replaced by a gradual transition from crustal to mantle velocities. South of this zone, the expected Moho at 30–35 km is accompanied by a second sub-horizontal discontinuity at ~50 km depth, which spatially coincides with the south-dipping upper-mantle interface seen in the CCP images, although appearing slightly shallower.

The velocity discontinuity at ~30 km corresponds to an increase from V_s ~3.7–3.9 km/s to ~4.0–4.3 km/s (equivalent to V_p ~6.5–6.8 km/s to ~7.0–7.5 km/s). Typical mantle velocities (V_s 4.5–4.6 km/s; V_p 8.0–8.1 km/s) only appear at ~50 km depth, below the deeper discontinuity. Surface-wave tomography indicates relatively low velocities in the uppermost mantle in this area, but whether this is the effect of the transitional crust-upper mantle layer remains to be tested. Its isostatic consequences and implications for the density of the layer will also be tested in future work.

Our models reveal a ~20 km thick transitional zone between typical crustal and mantle velocities that extends to the southern end of the profile, south of the PKB. We interpret this feature as attenuated, metamorphosed European lower crust that underthrust and relaminated beneath the AlCaPa crust. This supports a model involving significant late-stage continental underthrusting during Alpine-Tethys collision, either as the final phase after oceanic subduction or as purely continental underthrusting. The observed geometries are compared with models of flat subduction and continental underthrusting documented in other orogenic settings worldwide.

Salt beds deposited over high-relief sulphates – observations from the margin of Zechstein Basin, Łeba Elevation, northern Poland

M. Słotwiński¹, M. Adamuszek¹, A. Głuszyński², M. Jarosiński³, W. Wiesławska¹, M. Olkowicz¹, K. Durkowski⁴, M. Dąbrowski¹

1 Polish Geological Institute – National Research Institute, Computational Geology Laboratory

2 Polish Geological Institute – National Research Institute, Geophysics Department

3 Polish Geological Institute – National Research Institute, Regional Geology Department

4 KGHM CUPRUM sp. z o.o. – Research and Development Centre

Evaporite successions are known for their cyclical nature, with repeating pattern of layers starting from the least to most soluble rocks – in the typical setup beginning with non-evaporite clastics, then progressing through carbonates, sulphates, rock salt and potash deposits. In such sequences, complementarity of thickness between sulphates (usually anhydrite) and rock salt was observed in several localities, i.e. despite variance in the thickness of both the lithologies their combined thickness remained roughly constant. One such case that is particularly well documented is located in the area of Łeba Elevation in northern Poland. This area was subjected to intense geological exploration for rock salt, potash, and hydrocarbons, with numerous boreholes and rich seismic data, including 3D. This surveying revealed a high-relief morphology of the top surface of Lower Anhydrite (A1d), forming highs and low differing by up to over 150 m. This relief is filled by rock salt – Oldest Halite (Na1). The 3D seismic data in particular reveal a network of small basins bounded by elevated ridges in a polygonal pattern. As the origin of such geometry is unclear, with several competing hypotheses, studying the internal structure of the salt bed could provide some hints about the evolution of these structures.

Hence, several hundred metres of borehole core material were surveyed, photographically documented and analysed. All specific features (interlayers, faults, grain size changes, etc.) were recorded in a database. An attempt to discriminate between those of sedimentary and deformational origin was conducted, and then extended to divide the deformational features into syn-sedimentary and post-sedimentary groups. Through synthesis and correlation of these observations, a handful of possible scenarios for the geological evolution of local evaporite strata were proposed.

Mixed Moldanubian zircon provenance patterns: journey from Columbia to northern peri-Gondwana

I. Soejono¹, J. Konopásek¹, S. Collett¹, J. Sláma², K. Schulmann¹, J. Míková¹, V. Janoušek¹

¹ Czech Geological Survey, Klárov 3, 118 21 Prague 1, Czech Republic, igor.soejono@geology.cz

² Institute of Geology of the Czech Academy of Sciences, Rozvojová 269, 165 00 Prague 6, Czech Republic

The European Variscan belt is composed of crustal blocks derived mostly from the northern Gondwana (Nance and Murphy 1994). The basement of the Moldanubian Zone in central Bohemian Massif represents one of the so-called Armorican peri-Gondwanan terranes, traditionally assumed to be of West African origin (Tait et al. 1997; Samson et al. 2005). Although the Moldanubian Zone has been extensively studied, detrital zircon isotopic data from this unit are scarce (Košler et al. 2014; Sorger et al. 2020). Therefore, its age, pre-orogenic relationships with adjacent crustal domains and original paleogeographic position are still uncertain. Despite having been intensively reworked during the Variscan orogeny, basement of the Moldanubian Zone still provides important information on pre-collisional evolution and paleogeography of the Bohemian Massif and the peri-Gondwanan terranes. In this study, we use U–Pb and Hf isotopic data of zircons from metavolcanic–sedimentary successions (Varied and Monotonous units) in the southern Moldanubian Zone for provenance analysis and to address the above-mentioned issues.

Based on the contrasting zircon age and Hf isotopic patterns, the studied samples are assigned to three sedimentary sequences: late Paleoproterozoic, late Mesoproterozoic and Ediacaran–Cambrian. Zircon age spectra of one metarhyolite and three metasedimentary samples of the oldest sequence uniformly show a prominent Paleoproterozoic peak (c. 2.1 Ga) and only rare Archean ages, with a range of $\epsilon_{\text{Hf}(t)}$ values (–9 to +7). The maximum depositional or crystallization ages, determined by the youngest age groups, range from c. 2084 to 1779 Ma. Five metasedimentary samples from the late Mesoproterozoic sequence contain broad Paleoproterozoic to Mesoproterozoic age populations (c. 2.2–1.1 Ga) and minor Archean ages, all with similar $\epsilon_{\text{Hf}(t)}$ values (–8 to +7). The youngest age groups yielded maximum depositional ages from c. 1460 to 1190 Ma. In contrast, five samples of the Ediacaran–Cambrian sequence show a dominant late Neoproterozoic age peak at c. 600 Ma with a wide range of $\epsilon_{\text{Hf}(t)}$ values (–25 to +10), Paleoproterozoic ages are rare and have generally negative $\epsilon_{\text{Hf}(t)}$ values (–21 to +0) and Mesoproterozoic ages are essentially absent. The maximum depositional or crystallization ages of the youngest samples range from c. 582 to 507 Ma.

The age and isotopic patterns of the late Paleoproterozoic sequence are interpreted as detritus derived exclusively from intraformational volcanic rocks and local magmatic sources (c. 2.1 Ga Světlík Gneiss; Wendt et al. 1993; Kröner et al. 1988; Soejono et al. 2025), without significance in terms of provenance. The late Mesoproterozoic sequence was sourced, in addition to the same late Paleoproterozoic gneisses, from local rift-related magmatic sources (c. 1.27 Ga orthogneisses; Soejono et al. 2025) and an Archean–Mesoproterozoic cratonic basement, characterized by significant c. 2.7, 1.8, and 1.5 Ga material derived from mixed mantle – crustal sources. This late Mesoproterozoic basement has not yet been documented in any other Armorican block outside of the Moldanubian Zone. A high proportion of the Mesoproterozoic detritus likely rules out the late Mesoproterozoic affinity of the Moldanubian Zone to the West African Craton. Time of deposition coincided with the break-up of the Columbia supercontinent (Evans and Mitchell 2011) and the similarities with data from the possible source cratons point to a connection to Baltica. Completely different age patterns of the Ediacaran–Cambrian sequence are considered as clastic material dominantly derived from the Neoproterozoic magmatic arc with very limited input of recycled cratonic crust. Such age spectra with conspicuous late Paleo- to Mesoproterozoic (c. 1.7–1.2 Ga) gap typically indicate affinity to the northern African part of northern Gondwana (Nance and Murphy 1994; Friedl et al. 2000; Samson et al. 2005).

We interpreted the change in the late Mesoproterozoic and Ediacaran provenance signals as result of the Stenian–Ediacaran plate tectonic relocation from the Columbia supercontinent to northern Gondwana. It is proposed that the Moldanubian Zone and potentially other peri-Gondwanan terranes were rifted-off the Baltican part of Columbia’s margin and accreted to their ‘traditional’ Ediacaran–early Paleozoic position on the northern margin of Gondwana. Moreover, identical contrasting pre-Ediacaran vs. Ediacaran–early Paleozoic provenance of the Moldanubian Zone and Brunia Block

implies that these domains originally formed a single pre-Variscan crustal unit. Therefore, our data complicate an existence of the Rheic oceanic suture (Finger et al. 1998) proposed to be located between the central and eastern parts of the Bohemian Massif (Moldanubian domain and Brunia).

Acknowledgements: The study was supported by GACR (25-18370S) and Strategic Research Plan of the Czech Geological Survey – DKRVO/ČGS 2023–2027 (Internal Project 311300).

References:

- Evans, D.A.D. & Mitchell, R.N. (2011). Assembly and breakup of the core of Paleoproterozoic-Mesoproterozoic supercontinent Nuna. *Geology* 39, 443–446
- Finger, F., von Quadt, A., Pin, C. & Steyrer, H.P. (1998). The ophiolite chain along the western Moravo-Silesian plate margin - A trace of the Rheic suture? *Acta Universitatis Carolinae, Geologica* 42, 744–745.
- Friedl, G., Finger, F., McNaughton, N.J. & Fletcher, I.R. (2000). Deducing the ancestry of terranes: SHRIMP evidence for South America-derived Gondwana fragments in central Europe. *Geology* 28, 1035–1038
- Košler, J., Konopásek, J., Sláma, J. & Vrána, S. (2014). U–Pb zircon provenance of Moldanubian metasediments in the Bohemian Massif. *J. Geol. Soc. London* 171, 83–95.
- Nance, R.D. & Murphy, J.B. (1994). Contrasting basement isotopic signatures and the palinspastic restoration of peripheral orogens: Example from the Neoproterozoic Avalonian-Cadomian belt. *Geology*, 22, 617–620.
- Kröner, A., Wendt, I., Liew, T.C., Compston, W., Todt, W., Fiala, J., Vaňková, V. & Vaněk, J. (1988). U–Pb zircon and Sm–Nd model ages of high-grade Moldanubian metasediments, Bohemian Massif, Czechoslovakia. *Contrib. to Mineral. Petrol.* 99, 257–266.
- Samson, S.D., D’Lemos, R.S., Miller, B.V. & Hamilton, M.A. (2005). Neoproterozoic palaeogeography of the Cadomia and Avalon terranes: constraints from detrital zircon U–Pb ages. *J. Geol. Soc. London* 162, 65–71.
- Soejono, I., Janoušek, V., Trubač, J., Konopásek, J., Sláma, J., Míková, J., Collett, S., Schulmann, K., & Vrána, S. (2025). Ancient magmatic basement of the Bohemian Massif as a possible paleogeographic tracer. In: Lexa, O., Jeřábek, P., Hasalová, P., (Eds.), *CETEG 2025 — 21th Meeting of the Central European Tectonic Groups*, Nové Hamry, 23–26 April, 2025, Abstract Volume. p. 74.
- Sorger, D., Hauzenberger, C.A., Finger, F. & Linner, M. (2020). Two generations of Variscan garnet: Implications from a petrochronological study of a high-grade Avalonia derived paragneiss from the Drosendorf unit. *Bohemian Massif. Gondwana Res.* 85, 124–148.
- Tait, J.A., Bachtadse, V., Franke, W. & Soffel, H.C. (1997). Geodynamic evolution of the European Variscan fold belt: palaeomagnetic and geological constraints. *Int. J. Earth Sci.* 86, 585–598.
- Wendt, J.I., Kröner, A., Fiala, J. & Todt, W. (1993). Evidence from zircon dating for existence of approximately 2.1 Ga old crystalline basement in southern Bohemia, Czech Republic. *Int. J. Earth Sci.* 82, 42–50.

What do we know about the Alpine-Tethys closure in the Western Carpathians? : results from geophysical and geological joint venture

T. Soni¹, C. Schiffer², S. Mazur¹, L. Fodor^{3,4}, K. Ustaszewski⁵, P. Balling⁵, L. Petrescu⁶

1 Institute of Geological Sciences, Polish Academy of Sciences, Senacka 1, 31-002 Kraków, Poland

2 Department of Earth Sciences, Uppsala University, Villavägen 16, 75236 Uppsala, Sweden

3 Hun-REN Institute of Earth Physics and Space Science, 9400 Sopron, Csatskai Endre u. 6-8, Hungary

4 Institute of Geography and Earth Sciences, Department of Geology, Eötvös Loránd University, 1117 Budapest, Pázmány P. sétány 1/C, Hungary

5 Friedrich-Schiller University Jena, Germany

6 National Institute for Earth Physics, Magurele, Ilfov, Romania

The closure of the Alpine Tethys in the Western Carpathians, marked by the Pieniny Klippen Belt (PKB), represents the suture between the European plate and the Alps–Carpathian–Pannonian (AlCaPa) domain. Despite extensive study, the nature of this closure remains debated, particularly the role of oceanic subduction versus continental collision. Here, we present new constraints on the lithospheric structure from a passive seismic experiment, integrated with kinematic restoration and potential field analysis.

Common Conversion Point (CCP) migration of Receiver Functions imaged a N–S profile reveal a well-defined, wedge-shaped suture geometry. The European lower crust is imaged as underthrusting beneath the AlCaPa mantle, while the AlCaPa lower crust is emplaced as a wedge between the European upper and lower crust. This configuration defines a classical double-wedge architecture, comparable to that of the Pyrenees.

We interpret this geometry as a clear expression of crustal wedging, in which the lower crust of the overriding plate is mechanically inserted into a mid-crustal decoupling horizon within the underthrusting plate. This process leads to vertical partitioning of deformation, with upper crustal shortening accommodated independently from deeper underthrusting of dense lower crust. In this framework, the European lower crust—likely corresponding to the mafic, high-density basement of the Precambrian Brunovistulia block—remains sufficiently dense and strong to continue submerging beneath AlCaPa, while facilitating the development of a doubly vergent wedge structure.

The observed architecture provides a direct structural analogue to the Pyrenees, where Iberian lithosphere underthrusts beneath Europe and crustal wedging is well established. Importantly, our results demonstrate that such geometries can develop without the necessity of preserving a large oceanic domain.

Two end-member scenarios may explain the present-day structure: (1) closure involving oceanic subduction followed by slab break-off and rebound of an attenuated passive margin, or (2) progressive shortening of a hyper-extended continental margin, with crustal wedging as the dominant mechanism.

Kinematic restoration of the seismic section indicates ~180 km of shortening. These results provide new evidence that continental crustal wedging, rather than classical oceanic subduction, may have played a primary role in shaping the Western Carpathian orogen.

Acknowledgements: This work is sponsored by the National Science Center (Poland) grant number 2021/43/B/ST10/02312.

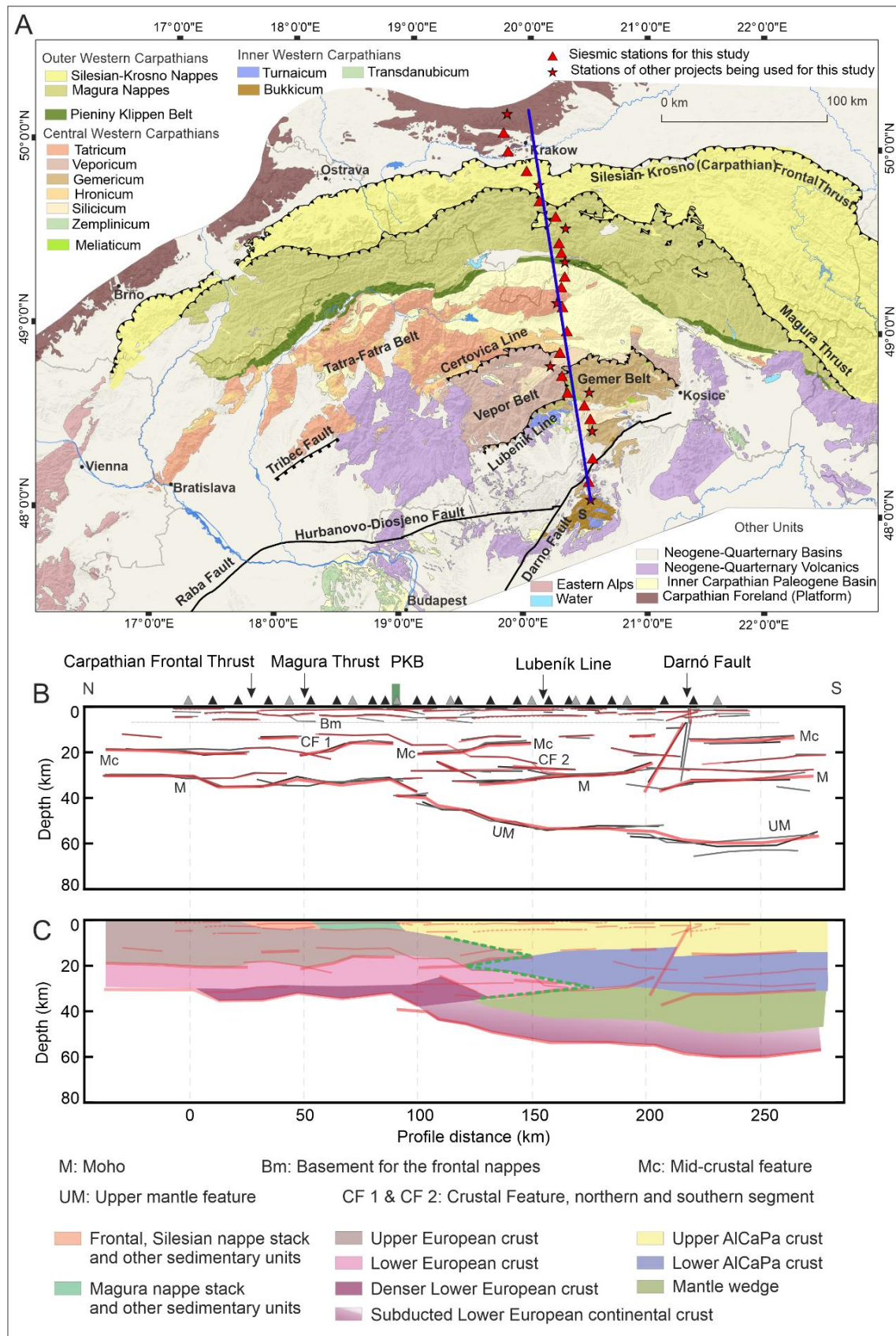


Fig. 1: A: Geological map of the Western Carpathians (www.geology.sk) B: Overlay of interpretation from CCP sections, E: Geological interpretation of the features observed in the CCP images

An interbasinal connectivity between wedge-top basin and fore-arc basin in weakening zone of the Central Western Carpathians: non-erosional transition between the Domaníža and Sub-Tatra Paleogene basins.

J. Soták^{1,2}, S. Antolíková³, J. Sláma⁴

¹ Earth Science Institute of the Slovak Academy of Sciences, Ďumbierska 1, 974 11, Banská Bystrica Slovakia

² Faculty of Education, Catholic University in Ružomberok, Hrabovská cesta 1, 03 401 Ružomberok, Slovakia

³ Earth Science Institute of the Slovak Academy of Sciences, Dúbravská cesta 9, 840 05 Bratislava, Slovakia

⁴ Institute of Geology of the Czech Academy of Sciences, Rozvojová 269, 165 00, Prague 6, Czech Republic

The weakening zone of the CWC follows the Žilina Basin, which is filled with Middle Eocene sediments of the Domaníža Basin (Myjava–Hričov Group) and Upper Eocene to Oligocene sediments of the Central-Carpathian Paleogene Basin (CCPB, Podtatranská Group). The Domaníža Formation consists of deep-water claystones with distal turbidites that are weakly calcareous and rich in agglutinated foraminiferal fauna. Higher up, the deep-water sequence abruptly pass into Nummulites-bearing limestones and pelagic marlstones, which form the basal formation of the CCPB. The transitional sequence between the Domaníža Fm. and the basal formations of the CCPB was studied in the Turie TR-1 borehole.

The Domaníža Basin attained a deep-water conditions in the Middle Lutetian revealing by bathyal assemblages of calcareous benthic foraminifera such as *Cibicidoides*, *Nuttallides*, *Stilostomella*, *Oridorsalis*, and others. Gradual deepening of the basin is evidenced by fully non-calcareous agglutinated foraminifera like *Ammodiscus*, *Trochamminoides*, *Reophax*, *Repmantina*, and others in the upper part of the Domaníža Fm. The middle Lutetian age of this formation is evidenced by the occurrence of the species *Ammodiscus latus* (Waskowska & Kaminski 2017). The Bartonian age is also indicated by rare planktonic foraminifera *Orbulinoides backmanni* (E 12 Zone), abundance of discoasters and nannofossil species *Reticulofenestra umbilicus*, *Helicosphaera compacta* (zone NP16), *Coronocyclus nitescens* (zone NP15) and species *Isthmolithus recurvus* providing a lowest occurrence in the Bartonian zone NP17 (Young et al. 2022).

The Domaníža basin reveals an increase of pelagification during the Late Eocene, considering a more frequent appearance of planktonic foraminifera like globigerinathekids, subbotinids, globoturbotalids, and others. The most common species is *Globigerinatheka index*, known mainly from the Late Eocene (zone E15), occurs in the upper part of the Domaníža Fm., and there still accompanied by species of *Acarinina*. The Middle / Upper Eocene boundary in the Domaníža Fm. is marked by the last occurrence of *Acarinina topilensis* and the first occurrences of the nannofossil species *Criboecentrum* the Turie-1 section. This boundary is also dated by the presence of tuffaceous admixture of zircons and apatites in the Domaníža Fm., providing the age of 40.91 Ma (Fig. 1A). During the Late Eocene inversion, the Domaníža basin ceased under shallowing a progradation of the CCPB.

The CCPB basin began to develop from basal beds of nummulitid limestones and eupelagic calcareous marlstones. These basal beds are rich in large foraminifera such as *Nummulites*, *Discocyclina*, *Heterocyclina*, and others. Overlying marlstones contain a numerous large-sized specimens of *Globigerinatheka index*, which abundance maximum corresponds to the Late Priabonian E15 Zone (Berggren & Pearson, 2006).

Higher up in the Turie TR1 section, the microfauna of basal marlstones markedly changes at the Eocene/Oligocene boundary in response of climatic cooling and deterioration of environmental conditions. Upper Eocene foraminifers like *Globigerinatheka*, *Hantkenina* and *Turbotalia* disappear, and were replaced by small opportunistic forms of chiloquembelinids, tenuitellids, pseudohastigerinids and dentoglobigerinids. Rich calcareous plankton indicated a carbonate oversaturation at the Eocene/Oligocene boundary. Calcareous nannoplankton from the upper beds of the TR-1 section mainly consists of the species *Cyclicargolithus floridanus*, *Coccolithus pelagicus*, and *Coccolithus formosus*, indicating eutrophic conditions (de Kaenel & Villa 1996; Bown & Dunkley, 2012). Nannofossils in the uppermost sequences increase in cold-water taxa, especially representatives of *Reticulofenestra* and *Isthmolithus*. The Eocene/Oligocene boundary is defined by the occurrence of

species *Isthmolithus recurvus*, which occurred in NP19/20 Zone and disappeared in NP22 Zone (*sensu* zonation by Martini 1971, revised by Young et al. 2022). Tuffite-bearing horizons at the Eocene/Oligocene transition provide the U-Pb zircon age 32.98 Ma (Fig. 1B). Oligocene formations of the Žilina Basin are developed like those in the Sub-Tatra Group of the CCPB (*sensu* Gross et al. 1984).

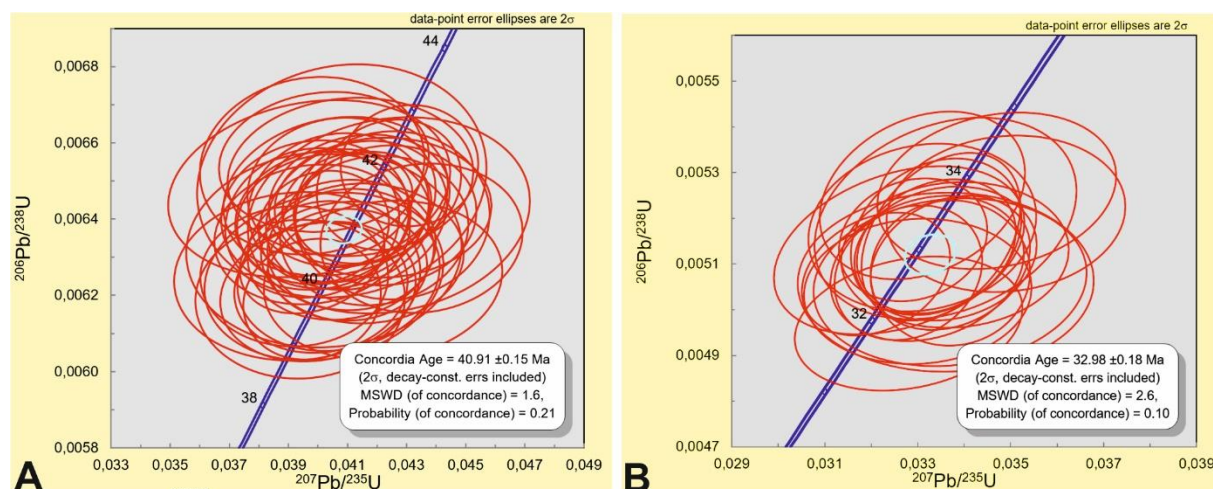


Fig. 1: The U-Pb zircon dating of tuffite beds providing the age of 40.1 Ma for upper formation of the Domaníža Basin (A) and 32.98 Ma for lower formation of the CCPB (B).

Acknowledgements: The research was supported by the Slovak Research and Development Agency project (APVV-20-0079) and the Scientific Grant Agency (VEGA 2/0012/24).

References

- Berggren, W.B. & Pearson, P.N., 2006: Tropical to subtropical planktonic foraminiferal zonation of the Eocene and Oligocene. In: Pearson, P.N., Olsson, R.K., Huber, B.T., Hemleben, Ch., Berggren, W.: Atlas of Eocene Planktonic Foraminifera. Cushman Foundation Special Publication No 41, 41-46.
- Bown, P. R. & Dunkley Jones, T., 2012: Calcareous nannofossils from the Paleogene equatorial Pacific (IODP Expedition 320 Sites U1331-1334). *Journal of Nannoplankton Research*. 32(2): 3-51.
- de Kaenel, E. & Villa, G., 1996: Oligocene-Miocene calcareous nannofossil biostratigraphy and paleoecology from the Iberian Abyssal Plain. *Proceedings of the Ocean Drilling Program, Scientific Results*. 149: 79-145.
- Gross P., Köhler E. And Samuel O., 1984: A new lithostratigraphic subdivision of the Central Carpathian Paleogene. *Geol. Práce, Správy*, 81: 103-117.
- Martini, E., 1971: Standard Tertiary and Quaternary Calcareous Nannoplankton Zonation. *Proceedings of the 2nd Planktonic Conference, Roma, 1970*, 739-785.
- Waśkowska, A. & Kaminski, M.A., 2017: “*Ammodiscus*“ *latus* Grzybowski, 1898: its taxonomy, variability, and affinity to the genus *Trochamminoides* Cushman, 1910. In: Kaminski, M.A. & Alegret, L., (eds.): *Proceedings of the Ninth International Workshop on Agglutinated Foraminifera*. Grzybowski Foundation Special Publication, 22, 229-238.
- Young, J.R., Bown P.R., Lees J.A., 2022: Nannotax3 website. International Nannoplankton Association. Accessed 21 Apr. 2022. URL: www.mikrotax.org/Nannotax3

Automated extraction of local geological surface orientations from mapped traces and DEM data

P. Strzelecki

AGH University of Krakow, Faculty of Geology, Geophysics and Environmental Protection; pjsrzl@agh.edu.pl

High-resolution topographic data, particularly LiDAR-derived digital elevation models (DEMs), have become an essential resource for structural mapping. However, while geological interpretation commonly yields mapped surface traces or lineaments, the conversion of such features into spatially explicit and quantitatively constrained orientation data remains non-trivial. This study presents an automated ArcGIS-based workflow for deriving local orientation parameters of geological surfaces directly from mapped surface traces integrated with topographic information.

The method converts interpreted traces into DEM-constrained three-dimensional point sets through systematic sampling along the mapped geometry. Local best-fit planes are then estimated within moving spatial neighbourhoods using principal component analysis (PCA), allowing the calculation of standard structural parameters, including dip and dip direction. In parallel, eigenvalue-based geometric descriptors are used to characterise the robustness of each local solution and to identify segments where the sampled geometry is poorly planar, overly linear, or otherwise unreliable. This permits not only the extraction of orientation data, but also the assessment of their internal consistency and spatial variability along the trace.

The workflow is designed to support efficient, reproducible, and scalable analysis of long and geometrically heterogeneous traces, for which a single global plane solution may be inadequate. By linking automated orientation extraction with quality assessment, the approach provides a practical framework for the quantitative evaluation of fault-related and stratigraphic surfaces from topographic data. The tool is intended to complement conventional structural interpretation by enabling rapid screening of mapped features, objective comparison with field observations, and more systematic identification of structurally complex or uncertain zones.

Geological structure at the contact between the Outer and Inner Western Carpathians – implications from geological mapping of the Oravská Magura Mts.

F. Teťák¹, O. Pelech¹, M. Olšovský¹, D. Laurinc¹, L. Vitovič¹, J. Maglay¹, K. Fekete¹, A. Nagy¹, R. Demko¹, K. Korábová¹, J. Madzin²

¹ State Geological Institute of Dionýz Štúr, Mlynská dolina 1, 817 04, Bratislava, frantisek.tetak@geology.sk

² Earth Science Institute of the Slovak Academy of Sciences, Ďumbierska 1, 974 11 Banská Bystrica

The aim of the geological mapping and research of the Oravská Magura Mts., conducted since 2020 at the State Geological Institute of Dionýz Štúr, is the preparation of a regional geological map at a scale of 1:50,000 and its explanations (Teťák et al., in press). The region comprises the Pieniny Klippen Belt (PKB) between Zázrivá village and Trstená town; the more northerly occurring Flysch Belt forming the ridge of the Oravská Magura Mts. and the Hruštín Basin; the Orava–Nowy Targ Basin filled with Neogene sediments, and is bordered to the south by the Inner Carpathian Paleogene (Fig. 1).

Geological mapping was carried out using a digital terrain model DMR 5.0 (LiDAR), which, together with GNSS positioning and processing in QGIS, enabled more efficient planning of fieldwork, prediction of bedrock exposure sites, and identification of klippen occurrences. Based on the high-resolution DMR, we were able to interpret with high accuracy the strike of bedding in flysch sequences, several tectonic lines, and the boundaries of landslides. A geological map of the region at a scale of 1:25,000 was compiled, with maximum accuracy of structural representation, locally exceeding the limits of visualization at this scale. Extensive landslides were depicted as exposed, with the underlying bedrock indicated where interpretable. The result is a number of new significant findings regarding the geological structure of the region.

Knowledge of the surface expression of bedding in flysch sequences allowed precise delineation of lithostratigraphic boundaries and tectonic lines. Geological mapping confirmed larger extent of the Malcov Formation near Vasil'ov which was indicated by the DMR. North–south faults in the zone of the Zázrivá sigmoid cutting the flysch complexes are also evident from the DMR, as is transverse tectonics across the ridge of the Oravská Magura Mts. Most mapped structural elements of the Flysch Belt represent refinements of earlier works (e.g., Potfaj et al., 1991), but a key finding is the occurrence of the Biele Karpaty Unit over an area of approximately 40 km² northwest of Tvrdošín town. In the past, this area was variably assigned either to the PKB (due to its Campanian–Maastrichtian age and quartz-carbonate sandstones) or to the Magura Nappe (due to misinterpretation of massive greywacke sandstones of Paleocene–Early Eocene age). The Biele Karpaty Unit shows a typical Vlára sequence of the Javorina Nappe (here defined as Štefanov Nappe) of Campanian to the early Eocene age, with Ondrášovec Mb. at the base, overlain by Javorina Mb., and terminated by the Svodnica Fm.

In addition to the main course of the PKB in the region, its anomalous occurrence also appears in a narrow tectonic zone north of the Oravská Magura Mts. ridge (the Babín Klippen). The authors interpret its origin similarly to Marschalko and Potfaj (1982), i.e., as a result of south-vergent backthrusting of the southern part of the Krynica Unit over the PKB. The remarkable accuracy and lasting value of the geological maps by Andrusov (1931) must be acknowledged within the PKB. Besides significant refinement of geological boundaries and the finding of dozens of previously unknown occurrences of Jurassic klippen, attention was focused on the subdivision of their Cretaceous flysch cover. Thanks to orthophotomaps from 1950, older geological maps, and a low water level of the Orava Reservoir, the documentation of extensive outcrops of the Neogene sediments and interpretation of the geology beneath the Orava Reservoir was possible. The latter are overlain by the Čimhová Fm. and glaci-fluvial gravels and terraces of the Čierna Orava River. In the valley of the meandering Orava River, an extensive system of river terraces was documented. Specialist studies complemented the field research by dating flysch sediments based on nannoplankton and by providing modal petrographic characterization of clastic sediments. Electron microanalyses, among other results, identified the composition of detrital garnets in sandstones and dated monazites from exotic rhyolitic material from the Krivá and Nižná localities to 278 ± 4.9 Ma.

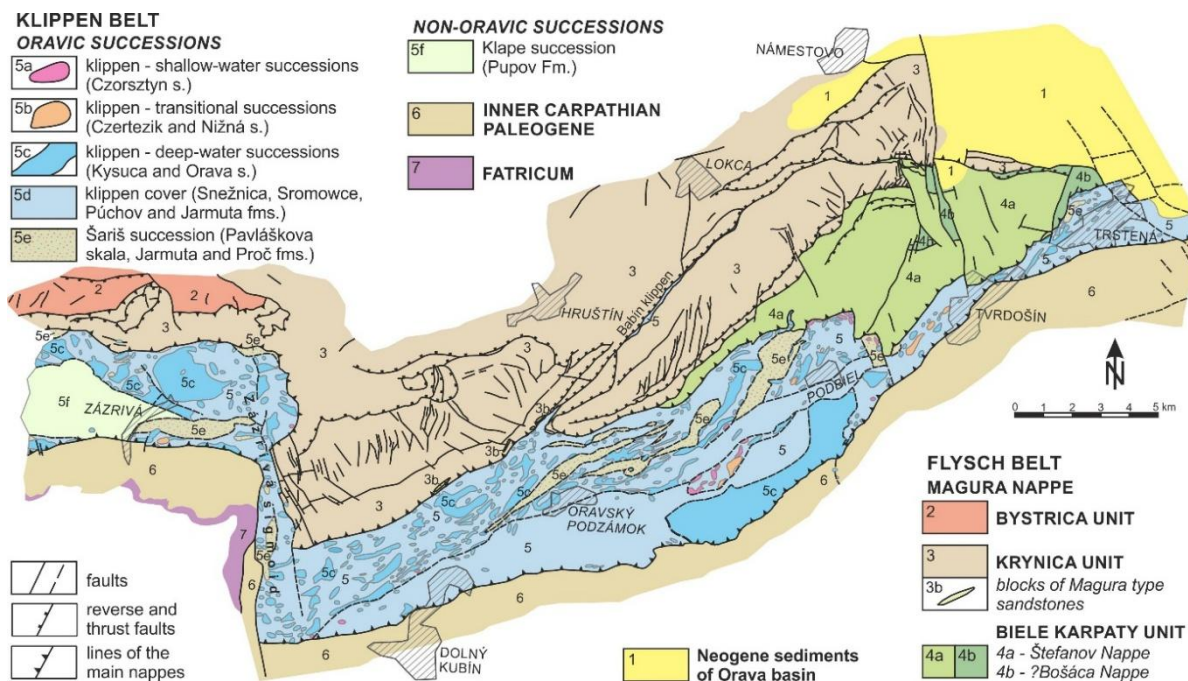


Fig. 1: Tectonic sketch of the Oravská Magura region.

Acknowledgements: The study was financially supported by the Ministry of Environment of the Slovak Republic project no. 02 20 Geological map of the Oravská Magura Mts. at scale 1:50,000.

References

- Andrusov, D., 1931: Geologická mapa útesového pásma v údolí Oravy 1 : 25 000. Díl východní a Díl západní. In: Matějka, A. & Andrusov, D. (eds.): Guide des excursions dans les Carpathes occidentales. Praha, Státní geologický ústav Československé republiky, 397 pp.
- Marschalko, R., Potfaj, M., 1982: Sekvenčná analýza, paleoprúdenie a prostredie uloženia spodnoeocénneho flyšu Oravskej Magury a bradlového pásma. Geologické práce, Správy, 78, 97–122.
- Potfaj, M., Samuel, M., Raková, J., Samuel, O., 1991: Geologic structure of Kubínska hoľa range (Orava). Západné Karpaty, sér. geológia, 15, 25–66.
- Teťák, F. (ed.), Pelech, O., Laurinc, D., Olšavský, M., Vitovič, L., Maglay, J., Fekete, K., Nagy, A., Madzin, J. & Dananaj, I., *in press*: Geological map of the Oravská Magura Mts. 1:50,000. State Geol. Inst. of Dionýz Štúr, Bratislava.

Microstructures and AMS analysis of granite dykes in the Třebíč Pluton

L. Uhrová, J. Rez, P. Hanžl, A. Zachař, K. Hrdličková

Czech Geological Survey, Czech Republic, lucie.uhrova@geology.cz

The Třebíč Pluton represents the largest intrusive body of the “durbachite series” in the Bohemian Massif, composed of several textural and mineralogical varieties of coarse-grained melasyenites to melagranites. According to zircon (LA-ICP-MS) dating, its crystallisation age is ~ 336 Ma (Janoušek et al. 2020). The pluton is intruded by numerous granitic dykes, which are steep and dominantly NW–SE trending, with thickness ranging from decimetres up to several tens of metres. Granitic dykes are characteristic of the western part of the pluton and adjacent Moldanubian rocks. They occur both within durbachite outcrops of the Třebíč Pluton and in migmatitic rocks near the pluton margin, as well as in smaller migmatitic septa within the pluton. Structural analysis was carried out on dykes with visible contact with host rocks to constrain better the conditions of dyke intrusion and possible subsequent deformation. At each locality, sampling was performed by drilling at a minimum of three positions across the dyke. Sampling was carried out on both sides of the endocontact within the host rock and, where possible, perpendicular to the contact as well as within the dyke itself. The number and distribution of samples within the dyke depended on its thickness and accessibility.

Microscopic analysis of thin sections confirmed weak deformation of the granitic dykes, consistent with macroscopic field observations. A weak preferred mineral orientation (magmatic fabric) was observed in three samples, and in one sample, an older foliation overprinted by a younger fabric was identified. Samples were therefore collected for anisotropy of magnetic susceptibility (AMS) analysis to detect structural fabrics of dykes, since both magmatic and deformational structures are commonly observable in durbachites. In contrast, deformation in granitic dykes is only rarely expressed macroscopically. The AMS data were subsequently compared with compass measurements of dyke orientation in the field at each locality.

In this study, AMS was used to constrain the conditions of intrusion of granitic dykes within the Třebíč Pluton. Comparison of parameters describing the magnetic susceptibility ellipsoid (Jelínek 1977; Hroudá 1982) provides further insight into the rock's structural characteristics and allows interpretation of its deformation history (Chadima 2003).

The AMS results indicate that the relationship between the magnetic structure of granitic dykes and the surrounding host rocks is not uniform across all studied localities. A significant difference between these two groups is reflected in the values of mean magnetic susceptibility (K_{mean}), with the surrounding rocks consistently showing higher values than the granitic dykes. This contrast primarily reflects differences in mineralogical composition, particularly a higher proportion of ferromagnetic minerals in the host rocks, whereas the granitic dykes are characterised by lower susceptibility corresponding to a predominance of paramagnetic minerals. K_{mean} variability reflects differences in mineralogical composition, particularly the proportions of magnetite and biotite, as well as alteration processes such as magnetite oxidation, and contrasts between granitic dykes and surrounding durbachites and migmatites. At two localities, the orientation of magnetic foliation in the dykes approaches that of the surrounding host rocks, suggesting that the original magmatic fabric of the dykes was subsequently overprinted to varying degrees by later deformation. This overprinting is not equally pronounced and varies in both intensity and degree of preservation of the original fabric. A specific case is represented by a locality within the Třebíč Pluton, located in proximity to the Třebíč Fault, where the magnetic fabric does not appear to be clearly overprinted at first glance; however, microscopic observations reveal two foliations, older and younger, whose mutual angle corresponds to the distribution observed in the AMS data. It can therefore be assumed that deformation-related overprinting also occurred at this locality, although it is expressed differently compared to other localities. Jelínek diagrams seem to be sensitive to the readability of overprinting fabric in dykes.

AMS data, in combination with microscopic observations and additional outcrop and drilled core data, suggest that deformation affecting the Třebíč Pluton had a significant impact on the internal structure of the granitic dykes, leading to partial overprinting of their original magmatic fabric. The

varying degree of overprinting between localities indicates a spatially variable character of deformation. These findings open further discussion on the relationship between the emplacement of granitic dykes and deformation within the Třebíč Pluton. Study of granitic dykes, interpreted as late- to post-magmatic relative to the host durbachites, suggests that the Třebíč Pluton was affected by inhomogeneous and localised deformation.

Acknowledgements: Project is supported by the Strategic Research Plan of the Czech Geological Survey DKRVO/ČGS 2023–2027, internal task No. 311560, and Horizontal Cooperation project between the Czech Geological Survey and SÚRAO for financial support of this study.

References

- Hrouda, F. 1982. Magnetic anisotropy of rocks and its application in geology and geophysics. *Geophysical surveys*, 5 (1), 37–82.
- Chadima, M. 2003. Magnetická Anizotropie Deformovaných Sedimentů. MS, rešerní práce, Masarykova univerzita, Brno.
- Jelínek, V. 1977. Statistical Theory of Measuring Anisotropy of Magnetic Susceptibility of Rocks and Its Application. – *Geofyzika*. Brno.
- Janoušek, V., Hanžl, P., Svojtka, M., Hora, J.M., Kochergina, Y.V.E., Gadas, P., Holub, F. V., Gerdes, A., Verner, K., Hrdličková, K., Daly, J.S. & Buriánek, D. 2020. Ultrapotassic magmatism in the heyday of the Variscan Orogeny: the story of the Třebíč Pluton, the largest durbachitic body in the Bohemian Massif. *International Journal of Earth Sciences* 109 (5), 1767–1810.

Magnetic mineralogy and paleomagnetism of the Western Vardar ophiolitic unit: first results and implications for the age of magnetization

M. Velki^{1,2}, E. Márton^{*1}, D. Prelević³, G. Imre¹, N. Stanković³, V. Cvetkov³

¹ SARA, Department of Geophysics, Paleomagnetic Laboratory, 1123 Budapest, Alkotás 50, Hungary, velki.mate@gmail.com

² ELTE, Department of Geophysics and Space Sciences, 1117 Budapest, Pázmány Péter 1/C, Hungary

³ University of Belgrade, Faculty of Mining and Geology, Belgrade, Djusina 7, Serbia

A new integrated paleomagnetic and mineralogical research aims to compare the Late Jurassic Western and Eastern Vardar ophiolites in Serbia. The Western Vardar ophiolitic unit forms a 100–150 km wide belt of obducted ophiolites, whereas the Eastern Vardar belt is much narrower, particularly in its portions south of Belgrade.

Here we present the initial results, focusing on the Western Vardar ophiolitic unit. Oriented samples were collected from a total of 18 localities, representing different lithologies, including serpentized peridotites, diabases, gabbros, amphibolites and eclogites.

Laboratory work consisted of standard paleomagnetic analysis, as well as the investigation of the magnetic properties and mineralogical composition of the sampled rocks. In serpentized peridotites, we furthermore examined possible correlations between the degree of serpentization and the magnetic susceptibility, natural remanent magnetization (NRM) and grain size of magnetite [1].

Magnetic mineralogy suggests that magnetite is the dominant ferromagnetic mineral in the studied rocks, with minor to intermediate amounts of ferritchromite in serpentinites and titanomagnetite in serpentinites and diabases. The grain size of the magnetite varies between the pseudo-single domain and multidomain ranges. Susceptibilities and NRMs mostly depend on the magnetite content of the rocks. In the serpentized peridotites (serpentization degree: 40–90%), magnetite formed during the serpentization, and can preserve the magnetization acquired at the time of this process. The degree of serpentization does not correlate well with the susceptibility and NRM values, nor with the estimated grain size.

Well-defined paleomagnetic directions were obtained for 12 localities and can be divided into two groups. For one group, the directions cluster close to the present-day magnetic field, representing a very recent remagnetization. The other group shows an approximately 30° clockwise rotation, which is consistent with previously observed Oligocene–Miocene results in the wider area (Fig. 1). The similarity of these directions and the inclination value of the mean direction from the ophiolites raise the possibility of a remagnetization during the late Paleogene–Neogene; however, an earlier study of the Mirdita ophiolites suggests that the magnetization, characterized by a very similar direction, could be of pre-obduction age [2].

Acknowledgements: This study is supported by the bilateral project between Serbia and Hungary with reference numbers of 2023-1.2.4-TÉT-2023-00088 and 001908878 2025 13440 003 000 000 001 02 003.

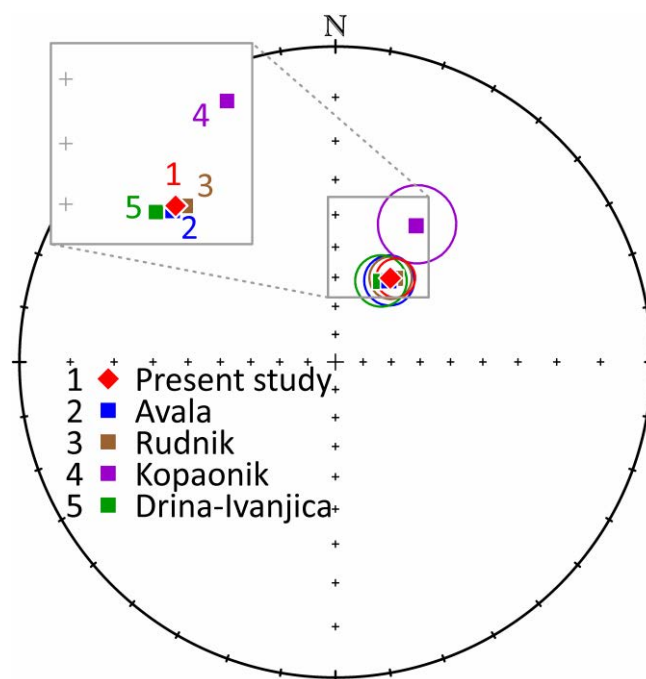


Fig. 1: Comparison of paleomagnetic results from the Western and Eastern Vardar zones on a stereographic projection. Published results from the Avala [3] and Kopaonik [4] regions are Oligocene in age, whereas those from the Rudnik [4] and Drina-Ivanjica [5] areas are early Miocene.

References

- [1] Maffione, M., Morris, A., Plümper, O., van Hinsbergen, D.J.J. (2014): Magnetic properties of variably serpentinized peridotites and their implication for the evolution of oceanic core complexes. *Geochem. Geophys. Geosyst.* 15, 923–944. <https://doi.org/10.1002/2013GC004993>
- [2] Maffione, M., Morris, A., Anderson, M.W. (2013): Recognizing detachment-mode seafloor spreading in the deep geological past. *Sci. Rep.* 3, 2336. <https://doi.org/10.1038/srep02336>
- [3] Márton E., Toljić M., Cvetkov V. (2022): Late and post-collisional tectonic evolution of the Adria-Europe suture in the Vardar Zone. *Journal of Geodynamics* 149. 101880. <https://doi.org/10.1016/j.jog.2021.101880>
- [4] Lesić, V., Márton, E., Gajić, V., Jovanović, D., Cvetkov, V. (2019): Clockwise vertical-axis rotation in the West Vardar zone of Serbia: tectonic implications. *Swiss Journal of Geosciences* 112, 199–215. <https://doi.org/10.1007/s00015-018-0321-8>
- [5] Velki, M., Márton, E., Cvetkov, V., Kövér, Sz. (2023): Paleomagnetic contribution to resolving the tectonic evolution of the Drina–Ivanjica Unit, Internal Dinarides. *Geologica Carpathica* 74, 5, 423–440. <https://doi.org/10.31577/GeolCarp.2023.22>

The Veporic–Gemic Contact Zone near the Ochtiná–Rochovce W–Mo Deposit, Western Carpathians: Implications from geological, structural, and mineralogical analyses

R. Vojtko¹, A. Lačný^{1,2}, J. Brčková³, P. Koděra³, F. Bakos⁴, I. Pešková¹, S. Gašper¹, M. Molčan¹

¹ Department of Geology and Palaeontology, Faculty of Natural Sciences, Comenius University Bratislava, Ilkovičova 6, SK-842 15 Bratislava, Slovakia; rastislav.vojtko@uniba.sk

² State Nature Conservancy of the Slovak Republic, Little Carpathians Protected Landscape Area, Štúrova 115, 900 01, Modra, Slovakia

³ Department of Mineralogy, Petrology and Economic Geology, Faculty of Natural Sciences, Comenius University Bratislava, Ilkovičova 6, 842 15 Bratislava, Slovakia

⁴ Green View, s.r.o., Nevädzová 5, 821 04 Bratislava, Slovakia

The Ochtiná–Rochovce W–Mo deposit is the only known deposit of this type in the Western Carpathians. It was discovered in the 1980s during a government-funded drilling campaign, which was subsequently followed by detailed exploration (Václav et al., 1988; Lörincz et al., 1993). The deposit is located in the contact zone of the Gemic and Veporic tectonic units of the Central Western Carpathians and is genetically linked to an Upper Cretaceous monzodiorite to granodiorite intrusive complex emplaced near the Lubeník Shear Zone (Václav et al., 1988). SHRIMP U–Pb zircon data from the monzogranite and Re–Os molybdenite ages indicate that both are of similar age (81.5 ± 0.7 Ma and 81.4 ± 0.3 Ma, respectively; Kohút et al., 2013).

The Gemic Unit is represented by Lower Carboniferous mylonitised schists with intercalated conglomerates and frequent metamorphosed basalts and basaltic pyroclastics (Ochtiná Group). The Veporic Unit comprises Carboniferous metamorphosed sandstones/graywackes and phyllites (Slatviná Formation) and overlying Permian metasandstones and metaconglomerates (Rimava Formation). The deposit consists of two partly overlapping zones. The lower Mo zone is approximately 400 m thick and occurs at depths of 200–600 m, mainly in the country rocks of the Veporic Unit and partly in the granitoid endocontact. It is represented by molybdenite hosted in a stockwork of quartz veinlets. The upper W zone is approximately 100 m thick and extends from the surface to depths of up to 300 m. It is represented by disseminated-stockwork mineralisation and less frequent quartz veins in both the Veporic and Gemic metamorphosed rocks. Principal ore minerals are scheelite and, less commonly, wolframite in a quartz gangue (Lörincz et al., 1993; Bakos et al., 2016).

Both the Veporic and Gemic units were incorporated into the Lower Cretaceous Eo-Alpine structural framework as south-dipping, thick-skinned basement–cover imbricates. Eo-Alpine tectonometamorphic events (135–95 Ma) produced low- to medium-grade metamorphism and a pronounced subhorizontal mylonitic fabric overprinting earlier Variscan structures (Janák et al., 2001; Lexa et al., 2003; Jeřábek et al., 2012). The orientation of the Alpine mylonitic foliation changes from NE–SW in the eastern part to E–W in the western part of the study area, seemingly circumventing the Upper Cretaceous granitic intrusion.

The compressional fabric was subsequently overprinted during Late Cretaceous unroofing of the Veporic metamorphic dome (cf. Vojtko et al., 2016). As a result of this exhumation, a gently ESE-dipping detachment shear zone developed at the basement–cover contact, facilitating the eastward unroofing of the Veporic dome from beneath the overlying Gemic Unit, as indicated by E–W-trending stretching lineations.

This unroofing must have been completed before emplacement of the Rochovce granite intrusion, as the W–Mo mineralisation clearly cuts across the Lubeník shear zone (representing the contact between the Veporic and Gemic units) and is therefore younger. Structures related to the unroofing process were subsequently modified by the intrusion.

A next exhumation phase, mainly recorded by zircon and apatite fission-track data, occurred between ~80 and 45 Ma and was associated with regional uplift and denudation (Vojtko et al., 2016). Data on exhumation within the Veporic–Gemic contact zone remain scarce. The only notable exception is two isolated zircon fission-track ages from the small A-type Turčok granite, 71–74 Ma (Plašienka et al., 2007). Boreholes KV–3, RO–3 and RO–6 (250–1400 m depth) provide the only relevant data from the central study area, revealing unexpectedly young cooling ages for the Rochovce

granitic intrusion: apatite fission-track (AFT) 17.5–12.9 Ma, and apatite (U–Th)/He (AHe) 12.9–11.3 Ma (Danišík et al., 2008).

Acknowledgements: This work was supported by the Slovak Research and Development Agency under contracts No. APVV-21-0281 “Alpine geodynamical evolution of the Western Carpathian inner zones”, No. APVV-22-0134 “Complex model of the W-Mo deposit Ochtiná–Rochovce and environmentally acceptable possibilities of its exploitation”, and VEGA 1/0021/25 “Neotethys (Melaticum) and Alpine Atlantic (Vahicum) – what has happened with two oceans which influenced evolution of the Western Carpathians?”.

References

- Bakos F., Jánošík M., Sýkora M., 2016: Final report with reserves calculations – Ochtiná W, Mo, Re mineralisation. GreenView report. (in Slovak)
- Danišík, M., Kohút, M., Dunkl, I., Hraško, E., Frisch, W., 2008: Apatite fission track and (U–Th)/He thermochronology of the Rochovce granite (Slovakia) – implications for the thermal evolution of the Western Carpathian-Pannonian region. *Swiss Journal of Geosciences* (Supplement 1) S225–S233.
- Hraško, E., Hataár, J., Huhma, H., Mäntäri, I., Michalko, J., Vaasjoki, M., 1999: U/Pb zircon dating of the Upper Cretaceous granite (Rochovce type) in the Western Carpathians. *Krystalinikum* 25, 163–171.
- Janák, M., Plašienka, D., Frey, M., Cosca, M., Schmidt, S.T., Lupták, B., Méres, Š., 2001: Cretaceous evolution of a metamorphic core complex, the Veporic unit, Western Carpathians (Slovakia): P–T conditions and in situ Ar-40/Ar-39 UV laser probe dating of metapelites. *Journal of Metamorphic Geology* 19, 197–216.
- Jeřábek, 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, TC5002. <http://dx.doi.org/10.1029/2012TC003097>
- Kohút M., Stein H., Uher P., Aimmerman A., Hraško L., 2013: Re–Os and U–Th–Pb dating of the Rochovce granite and its mineralization (Western Carpathians, Slovakia). *Geologica Carpathica* 64, 1, 71–79.
- Lexa, O., Schulmann, K., Ježek, J., 2003: Cretaceous collision and indentation in the West Carpathians: view based on structural analysis and numerical modeling. *Tectonics* 22, 1066–1081.
- Lörincz L., Švantnerová E., Bachňák M., 1993: Final report: Ochtiná–Rochovce Mo, W, exploration survey, status at 30.9.1993. Geofond Bratislava, 225 p. (in Slovak)
- Plašienka, D., Broska, I., Kissová, D. & Dunkl, I., 2007: Zircon fissiontrack dating of granites from the Vepor–Gemer Belt (Western Carpathians): constraints for the Early Alpine exhumation history. *Journal of Geosciences* 52, 113–123.
- Václav J., et al., 1988: Prognostic evaluation of Mo–W mineralization south of Rochovce. Final report, Geofond Bratislava, 386 p. (in Slovak)
- 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.

Young tectonic activity of the Kłodawa-Łęczycza anticline (the Kujavian segment of the Mid-Polish Swell): evidence from recent topography and geometry of the Quaternary strata

W. Włodarski¹, L. Marks², J. Forysiak³, R. Wasiluk⁴

¹ Institute of Geology, Adam Mickiewicz University, Krygowskiego 12, 61-680 Poznań, Poland, wojtek.w@amu.edu.pl

² Department of Climate Geology, Warsaw University, Żwirki i Wigury 93, 02-089 Warsaw, Poland, l.marks@uw.edu.pl

³ Department of Geology and Geomorphology, University of Łódź, Narutowicza 88, 90-139 Łódź, Poland, jacek.forysiak@geo.uni.lodz.pl

⁴ Polish Geological Institute, Rakowiecka 4, 00-975 Warsaw, Poland, rwas@pgi.gov.pl

The Kłodawa salt structure is the largest tectonic feature in the Kujavian segment of the Mid-Polish Swell (Krzywiec, 2004). Its evolution was mainly influenced by the extension and normal faulting of the sub-Zechstein basement and by salt withdrawal processes during the Triassic and Jurassic periods (Krzywiec, 2012). This is evident from the significant variation in the Triassic-Jurassic cover thickness on the NE and SW sides of the Kłodawa salt structure. Uneven withdrawal processes to the NE of the salt structure influenced subsidence migration, thereby forming a rim syncline. Enhanced normal faulting of the sub-Zechstein basement also affected strata covering the SW flank of the Kłodawa salt structure (Krzywiec, 2004). Additionally part of the salt from the Kłodawa structure extruded onto the floor of the rim syncline as a submarine salt glacier. The resulting large, asymmetric salt overhang was overlapped by the youngest Triassic and Jurassic strata (Krzywiec, 2012). The Late Cretaceous tectonic inversion led to the uplift of the NE side of the Kłodawa salt structure (Krzywiec, 2012). This process was driven by reactivation of the aforementioned fault. As a result, the asymmetric Kłodawa-Łęczycza anticline was formed. Moreover, the entire Cretaceous cover was eroded across the gently inclined NE limb of the anticline up to the reactivated fault.

The tectonic activity of the Kłodawa- Łęczycza anticline during the Quaternary is evident in the terrain topography, where elongated elevation trending NW-SE can be observed (Molewski, 2014). This elevation, with gentle slopes rising to ca. 30 m, dominates the topography relative to the more local glacial and fluvial landforms developed within the Kutno moraine and the adjacent morainic plateaus. It continues southeastwards as a watershed across the Warsaw-Berlin ice-marginal spillway (Jewtuchowicz, 1967), reaching a maximum height of ca. 4.5 m. The presence of this watershed currently prevents east-to-west river flow. Consequently, the Bzura and Ner rivers, which flow into the bottom of the ice-marginal spillway from the south near Łęczycza, display separate watercourses that drain into the Vistula and Odra river basins.

Interpretation of the 3D GIS modelling results indicates that the geometry and thickness of the Quaternary strata vary across the SW and NE limbs of the Kłodawa-Łęczycza anticline. As shown in Fig. 1, the Quaternary strata with reduced thickness predominate above the SW limb and partly above the anticline's hinge zone, whereas increased thickness is evident above the NE limb. The glacial tills of the Late Saalian age form strata with a double convex lens shape and a maximum thickness of 42 m, while the Early Saalian till has a maximum thickness of ca. 37 m and a rather flat, convex-downward lens shape. Notably, these lateral thickness changes generally coincide with the terrain topography where the elongated elevation was determined. However, the zone where the till strata gradually change in thickness is ca. 10 km wide, about half the width of the rim syncline in the Mesozoic basement. By comparison, the size of the salt overhang is too small to be considered a tectonic element controlling deposition of glacial tills. When analysing discrepancies between these sizes, it is important to consider the local depocentres recorded in the Early to Middle Triassic sedimentary sequence, which demonstrate lateral migration towards the SE within the rim syncline. Therefore, the zone of lateral thickness changes in the till strata more closely corresponds to the size of the youngest recognisable depocenter within the Triassic strata.

The spatial variability of the examined features indicates that vertical movements of the NE limb of the Kłodawa-Łęczycza anticline were reactivated during the Quaternary. This reactivation was driven by vertical loading from Pleistocene ice sheets. In this context, localised subsidence—caused by salt withdrawal below the rim syncline—may have played a significant role (Liszkowski, 1993; Lang et al., 2014). Notably, this process was likely most pronounced during syn-kinematic deposition of the Saalian

tills, which resulted in gradual changes in strata thickness and lens-shaped geometries. Following this stage, vertical uplift influenced the formation of the transverse watershed across the Warsaw-Berlin ice-marginal spillway and the elongated elevation to the NW. Synkinematic erosion likely played an important role during east-to-west meltwater runoff across the uplifting watershed. Thus, the deformation mechanism involved the remobilisation of salt from the Kłodawa structure, triggered by vertical loading of its northern part during prolonged ice-sheet margin standstills in the Late Saalian and Weichselian.

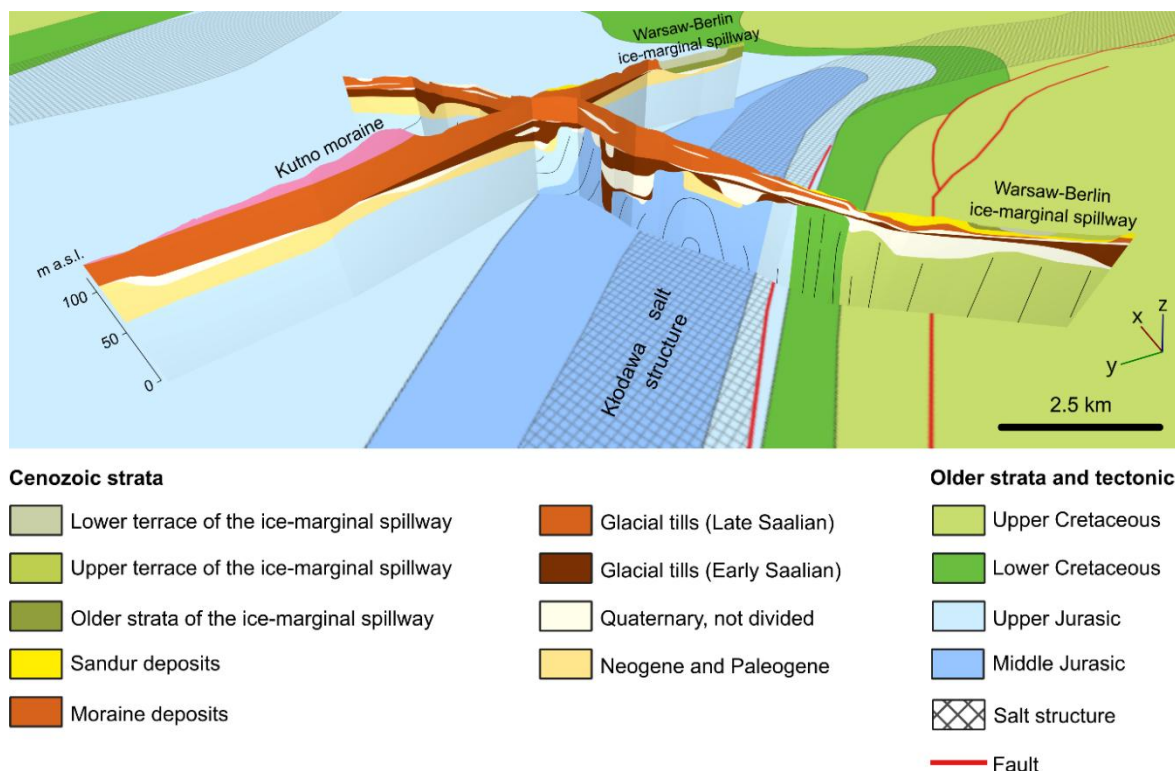


Fig. 1: 3D GIS model created from digital borehole data and interpreted geological cross-sections. The NE-SW cross-section was converted into a 3D mesh using archival data from the Detailed Geological Map of Poland, scale 1:50,000, sheet Łęczyca (Kucharska and Krawczyk, 2017). The NW-SE cross-section was developed using borehole data from the Central Geological Database of the Polish Geological Institute.

References

- Jewtuchowicz, S., 1967. Geneza pradoliny warszawsko-berlińskiej między Nerem i Moszczenicą. *Prace Geograficzne IG PAN* 62, 1–102.
- Krzywiec, P., 2004. Triassic evolution of the Kłodawa salt structure: basement-controlled salt tectonics within the Mid-Polish Trough (Central Poland). *Geological Quarterly*, 48, 123–134.
- Krzywiec, P., 2012. Mesozoic and Cenozoic evolution of salt structures within the Polish Basin – an overview. In: Alsop, G.I., Archer, S.G., Hartley, A.J. Grant, N.T., Hodgkinson, R. (Eds.), *Salt Tectonics, Sediments and Prospectivity*. Geological Society of London, Special Publications, 363, 381–394.
- Kucharska, M., Krawczyk, M., 2017. Detailed Geological Map of Poland in a scale of 1:50 000, Łęczyca sheet (552). Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy, Warszawa.
- Lang, J., Hampel, A., Brandes, C., Winsemann, J., 2014. Response of salt structures to ice-sheet loading: implications for ice-marginal and subglacial processes. *Quaternary Science Reviews*, 101, 217–233.
- Liszkowski, J., 1993. The effects of Pleistocene ice-sheet loading-unloading cycles on the bedrock structure of Poland. *Folia Quaternaria*, 64, 7–23.
- Molewski, P., 2014. Paleogeographical conditions of the outflow from the Warsaw ice-dammed lake through the Bachorza valley and the Warsaw-Berlin pradolina during the Main Stage of the Weichselian Glaciation. *Landform Analysis* 25, 105–114.

Subvolcanic dyke rocks in durbachites of the Variscan Třebíč Pluton; Moldanubian zone, Czech Republic

A. Zachař, L. Uhrová, D. Buriánek, P. Hanžl

Czech Geological Survey, Leitnerova 22, Brno, 602 00 Czech Republic; adam.zachar@geology.cz

Variscan Třebíč Pluton is predominantly composed of ultrapotassic amphibole-biotite melamonzogranites ($ASI = 0.7\text{--}1.0$). These coarse-grained, porphyritic mafic rocks, also known as durbachites, are formed by a mineral association $Kfs + Phl + Pl + Amp + Qz \pm Px$ as main rock-forming minerals. The Třebíč Pluton, a tabular mid-crustal body emplaced at $\sim 8\text{--}15$ km depth, intruded the Moldanubian unit at ca. 340–335 Ma during or slightly after peak metamorphism (Schulmann et al. 2005, Leichmann et al. 2017, Janoušek et al. 2020). Commonly SE–NW trending subvolcanic dykes occur in a several-hundred-meter wide zone in the central part of the Třebíč Pluton. These microgranitic to micromonzonitic bodies are typically a few meters thick and up to 200 m long. They form either isolated bodies or dyke swarms. At a single outcrop, the subvolcanic rock intrudes foliated durbachite along an irregular but lithologically sharp contact.

LA-ICP-MS U–Pb zircon dating of this rock yielded an age of 343.5 ± 2.2 Ma. Temperature and pressure conditions were estimated using machine-learning-based thermobarometry applied to clinopyroxene compositions (Ágreda-Lopéz et al., 2024). The calculated temperatures range from 988 to 1002°C, while the corresponding pressures vary between 1.3 and 1.8 kbar, indicating crystallization under relatively shallow crustal conditions. The presence of granophyric texture documents a subvolcanic level of intrusions, which took place in a cold host-rock.

Microgranites and microgranodiorites contain K-feldspar phenocrysts up to 5 mm in diameter. The fine-grained matrix is characterized by granophyric intergrowths of K-feldspar, plagioclase, and quartz. Both feldspars are typically euhedral with sharp crystal boundaries, whereas quartz is commonly rounded and locally affected by magmatic corrosion. “Anti-rapakivi” textures, with K-feldspar mantling plagioclase (core An_{24-34} , rim $Ab_{77}An_0$), have also been observed. Phlogopite ($X_{Fe} = 0.40\text{--}0.43$) forms pseudo-hexagonal flakes, often strongly chloritized. High amounts of Ti (0.21–0.23 apfu) and F (< 0.28 apfu), respectively, are typical. Diopside ($X_{Fe} = 0.21\text{--}0.33$) occurs locally as euhedral zoned crystals with Fe increasing from the core to the rim. Rare actinolite ($X_{Fe} = 0.2$) replaces diopside. Accessory minerals include fluorapatite and cheralitic monazite-(Ce). Zircon, Sn-rich titanite and chromite are much rarer.

Micromonzonites contain K-feldspar phenocrysts up to 4 cm in size, with phlogopite, actinolite, plagioclase, and quartz in a fine-grained granophyric matrix. K-feldspar is strongly perthitic and zoned with Ba-enriched cores (< 0.03 apfu). Plagioclase (An_{32-43}) is locally replaced by albite/prehnite. Ti-rich phlogopite ($X_{Fe} = 0.33\text{--}0.39$) and diopside ($X_{Fe} = 0.25\text{--}0.27$) are less common and partly replaced by actinolite ($X_{Fe} = 0.24\text{--}0.35$).

Similar pattern of dykes and host durbachites in spider REE a NMORB normalised spider diagrams indicate similar origin of magmas (Boynton 1984, Pearce et al. 1984, Sun and MacDonough 1989). Durbachites and micromonzonites ($K_2O/Na_2O \sim 2.3$) both fit to shoshonitic series, whether microgranites/microgranodiorites are of more high-K calc-alkaline character with $K_2O/Na_2O \sim 1.4$. These compositions are in agreement with pre-existing data of Němec (1978, 1993) and Janoušek et al. (2020).

NW–SE trending belt rich in subvolcanic dykes documents the presence of local extensional domain in Třebíč Pluton during its cooling. The zircon concordia age (343.5 ± 2.2 Ma) of micromonzonite is older than the age span of published data from the TP durbachites (340–335 Ma), which is in contrast with the field observation. This could be caused by interaction with the late fluids, which have distorted the original isotopic ratio. Also, the incorporation of older zircon growth zones within the analytical volume is plausible. Marginal rims of the zircon grains, representing a younger age, could not be resolved or dated separately.

Considering the chemical composition, micromonzonites are well comparable with durbachites from central parts of pluton. More acidic microgranites and microgranodiorites show slightly higher A/CNK, and, in contrast, lower Ba, HFSE and REE than durbachites. Nevertheless, we can assume the

magmatic source of both dyke rocks and durbachites was the same one. Dyke rocks emplaced after solidification and deformation of durbachites in shallow crustal level.

References:

- ÁGREDÁ-LÓPEZ, M., PARODI, V., MUSU, A., JORGENSEN, C., CARFÌ, A., MASTROGIOVANNI, F., CARICCHI, L., PERUGINI, D. AND PETRELLI, M., 2024. Enhancing machine learning thermobarometry for clinopyroxene-bearing magmas. *Computers & Geosciences*, 193, p.105707.
- BOYNTON, W.V., 1984: Geochemistry of the Rare Earth Elements: Meteorite Studies. In: Henderson, P., (ed.) Rare Earth Element Geochemistry. – Elsevier, Amsterdam, 63–114.
- BREITER K., 2008. Durbachity třebíčského masivu ve vrtu Poždátky V-5-genetické implikace. *Geoscience research reports for 2007, Czech geology survey*, pp.143-147.
- JANOUSEK, V., HANŽL, P., SVOJTKA, M., HORA, J.M., KOCHERGINA, Y.V.E., GADAS, P., HOLUB, F.V., GERDES, A., VERNER, K., HRDLÍČKOVÁ, K. AND DALY, J.S., 2020. Ultrapotassic magmatism in the heyday of the Variscan Orogeny: the story of the Třebíč Pluton, the largest durbachitic body in the Bohemian Massif. *International Journal of Earth Sciences*, 109(5), pp.1767-1810.
- LEICHMANN, J., GNOJEK, I., NOVÁK, M., SEDLÁK, J. AND HOUZAR, S., 2017. Durbachites from the Eastern Moldanubicum (Bohemian Massif): erosional relics of large, flat tabular intrusions of ultrapotassic melts—geophysical and petrological record. *International Journal of Earth Sciences*, 106(1), pp.59-77
- NĚMEC D. 1978: Ganggesteine auf der Störung von Třebíč (als Beispiel einer an eine Tiefenstörung gebundenen Gangschar). *Z. geol. Wiss*; Berlin 6, 10; S. 1211-1217. (In German with Czech and English summaries).
- NĚMEC, D., 1993. Žilné horniny v okolí Třebíče. *Přírodověd. Sbor. Západomor. Muz. v Třebíči*, 19, pp.13-31.
- PEARCE, J.A., HARRIS, N.B. AND TINDLE, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of petrology*, 25(4), pp.956-983.
- SCHULMANN, K., KRÖNER, A., HEGNER, E., WENDT, I., KONOPÁSEK, J., LEXA, O. AND ŠTÍPSKÁ, P., 2005. Chronological constraints on the pre-orogenic history, burial and exhumation of deep-seated rocks along the eastern margin of the Variscan orogen, Bohemian Massif, Czech Republic. *American Journal of Science*, 305(5), pp.407-448.
- SUN, S.S. AND McDONOUGH, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *Geological Society, London, Special Publications*, 42(1), pp.313-345.

Magma Mingling Dynamics in Mushy Reservoirs Revealed by Analogue Modeling

P. Závada^{1,2}, O. Kryža¹, V. Kusbach¹, M. Boulanger³, M. Machek¹, Z. Roxerová¹, C. Annen¹, P. Fiannacca⁴, D. Russo⁴, E. Fazio⁴

¹ Institute of Geophysics CAS, Boční II 1401, 14101, Prague

² Centre for Lithospheric Research, Czech Geological Survey, Klárov 3, 11800, Praha

³ Magmas and Volcanoes Laboratory, 6 Avenue Blaise Pascal, 63170 Aubière, France

⁴ Department of Biological, Geological and Environmental Sciences, University of Catania, Corso Italia, 57 - 95129 – Catania

Magma mingling structures and textural changes in the surroundings of interacting magma portions reflect exchange of heat and chemical components, including fluids, in the magmatic reservoirs. Understanding the sources and budget of interacting magmas that exchange the fluid phase decreasing their solidus temperature, and viscosity of host magmas - can later inform working models simulating volcanic eruptions sourced from over-pressurized magma chambers. Field evidence from the different levels of magmatic arc systems suggest that intrusion of less evolved, but volatile-rich magmas (tonalite, gabbro) into more evolved host magma (granodiorite), promotes crystallization of the host, development of cumulates (crystal mushes) and production of a new, potentially eruptible low-density melt that percolates to shallower levels of the magmatic system. We present two field examples of magma mingling structures in magmatic-arc settings that illustrate the feedbacks of the mingling process and deformation. This is all visualized and discussed using analogue modeling experiments with molten paraffine waxes.

The field examples represent magma mingling domains from two different levels of a continental magmatic arc system – at paleodepths ~35 km from the Serre Batholith (~295 Ma, Calabria, Italy), and middle-crustal paleodepths of ~10 km from the Adamello Batholith (~42 Ma, Southern Alps, Italy). Mingling structures from the felsic MASH (Melting-Assimilation-Storage-Homogenization) zone in the Serre Batholith reveal hybridized lense to bulbous shaped tonalite bodies embedded in granodiorite abundant in K-feldspar megacrysts. Field mapping of the outcrop and the surrounding units of the lower crustal domain suggests that this MASH zone was laterally shortened during the Variscan orogenesis, still in magmatic/submagmatic state, producing steep contacts between the magmatic portions and isolated, lozenge to rhomb shaped domains of megacrystic feldspar cumulates. This deformation was likely associated with further melt migration along the steep new fabrics to the shallower portions of the deformed arc.

Another example presents a horse-shoe shaped map domain in the core of the Adamello Batholith, called the Listino Ring structure. This structure reveals arrays of gabbroic enclaves with irregular blobby to cauliflower shapes embedded in a phenocryst-rich (mushy) granodiorite. Rhyolite porphyry forms wedge-like veins intruding the chilled enclaves and forms dykes inside the Listino Ring structure. Some of these dykes shoot outwards from the Listino Ring structure. Rhyolite porphyry here represents a product of interaction of both – the volatile-rich gabbro and residual granodiorite mush and represents eruptible magma draining the over-pressurized caldera-type magma system.

The analogue experiments consist of two layers representing the mushy, residual granodiorite magma at the bottom of a magma chamber (~800°C, ~2.6g/cm³), and overlying felsic magma, respectively, intruded hot and relatively dense gabbro (~1200°C, ~2.8g/cm³). The mushy part and overlying melt are simulated by low-melting point wax (40-50°C), representing the granodiorite mush and overlying magma, respectively. Intrusion of a 90°C modelling clay and ceresin wax mixture – an analog of the gabbro magma – creates sill-like intrusions at the interface of the mushy and liquid part of the host wax. These experiments display the typical blobby, convoluting and highly irregular interfaces with the surrounding host wax very similar to natural arrays of enclaves in the Listino structure. We suggest that instrumentation and quantification of these experiments might offer new clues for the complex feedbacks between mingling dynamics and melt percolation in mushy reservoirs, increasing the internal pressures and culminating in magma chamber-wall failure and escape of eruptible rhyolite porphyries.

Tracking deformation and melt migration in the crust using paraffin-wax analogues

P. Závada^{1,2}, O. Krýza¹, V. Kusbach¹, M. Machek¹, Z. Roxerová¹

¹ Institute of Geophysics CAS, Boční II 1401, 14101, Prague

² Centre for Lithospheric Research, Czech Geological Survey, Klárov 3, 11800, Praha

Paraffin wax is an ideal analogue material for simulating grain-scale to lithospheric-scale deformation, because its strength is thermally dependent. Historically, paraffins have been popular in the analogue modelling community for more than a century. Paraffin is a highly versatile and practical material as it can be colored and recycled. Besides the heat, the properties of paraffin can be decreased using turpentine or mineral oils or vaseline; the density is modulated by the addition of mineral powders. In contrast, mixtures of paraffin and resin deformed at low temperatures produce cross-cutting fractures. Paraffin was successfully used for the demonstration of oceanic crust formation at divergent boundaries or the impact of mechanical anisotropy on the style and wavelength of folding, complex hydrocarbon mixtures (paraffin, $T_m \sim 50^\circ\text{C}$, ceresin – higher-grade wax, $T_m \sim 80^\circ\text{C}$; vaseline, mineral oils, mineral powders) scaled well in lithosphere-scale models of Alexander Shemenda.

In the laboratory of Tectonic modelling of the Institute of Geophysics, we employ different experimental setups and develop analogue models, in which partially molten paraffin and ceresin multilayers are deformed to simulate their deformation from grain- to lithospheric-scale. We focus on tracking melt migration from a scale of a mineral grain to the outcrop-scale using progressively deformed honeycomb aggregates of paraffins or multilayers. These are greatly instructive for understanding the textures and melt-escape dynamics in partially-molten rocks (migmatites) or crystal mushes (cumulates with residual melt). Our current lithosphere-scale models with paraffin focus on understanding the oblique divergence and partial melting of the lower crust on the surface deformation patterns at the Reykjanes peninsula (Iceland). Recently, we tested mixtures of waxes and modelling clay, which proved to be excellent analogues of primitive magmas. We employ these mixtures in intrusion experiments into low-melting-point paraffin mush to simulate mingling processes in magma chambers.

Sequential 1D Modelling as a Tool for Reconstructing the Multi-stage Thermal History of the Collisional Zone in the Western Carpathians (Pieniny Klippen Belt, Slovakia)

M. Zielińska¹, K. Spunda², D. Plašienka³, D. Botor⁴

¹ Faculty of Natural Sciences, Institute of Earth Sciences, University of Silesia in Katowice, Będzińska 60, 41-200 Sosnowiec, Poland
magdalena.zielinska@us.edu.pl

² Oil and Gas Institute-National Research Institute, Lubicz 25A, 31-303 Krakow, Poland, spunda@inig.pl

³ Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University, Mlynská dolina
Ilkovičova 6, 842 15 Bratislava 4, Slovakia, dusan.plasienka@uniba.sk

⁴ Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow, Mickiewicza Av. 30, 30-059 Krakow, Poland, botor@agh.edu.pl

The thermal evolution of collisional orogens reflects the coupled effects of tectonic stacking, burial, erosion, and transient thermal perturbations. In structurally complex suture zones such as the Pieniny Klippen Belt (PKB) —a major tectonic boundary separating the Central Western Carpathian domain from the Outer Western Carpathians (OWC), a key challenge is to separate true regional boundary heat-flow variations from **effective** thermal signals produced by rapid burial, fault-zone processes, and structural reworking.

Here we reconstructed the paleothermal evolution of the northern Western Carpathian suture zone using data from the Hanušovce-1 borehole (eastern PKB, Slovakia), which intersects the **PKB–Magura contact** (Proč Formation over Strihovce Formation) at ~4 km depth (Zielińska et al. 2026).

The objective was to constrain the timing and magnitude of thermal changes through the Mesozoic–Cenozoic and to evaluate how they relate to sequential deformation of the PKB structural elements and progressive incorporation of the southern Magura domain into the evolving accretionary wedge. We combined vitrinite reflectance data and present-day temperature measurements with calibrated 1D PetroMod burial–thermal modelling constrained by stratigraphic thicknesses, alternative erosion scenarios, and time-dependent basal heat-flow boundary conditions. A central methodological element was a suite of sequential 1D paleo-models representing successive thrusting stages and tectonic stacking of the main structural units intersected by the borehole. We systematically tested alternative burial/erosion–heat-flow scenarios, selected the best-calibrated model against the maturity–temperature constraints, and used the ensemble of solutions to quantify the trade-off between burial/erosion and basal heat-flow histories under internally consistent lithological and petrophysical properties. The preferred model required a multi-stage thermal evolution with (i) a moderate Late Cretaceous increase in effective basal heat flow and (ii) a short-lived Middle Eocene thermal pulse. Rather than being interpreted as unique mantle-driven signals, these heat-flow transients were treated as effective proxies for the combined thermal consequences of time-dependent boundary conditions and collisional-stage thrust kinematics, dominated by rapid thrust-related burial/exhumation and localized fault-zone processes during initiation and early development of the PKB–Magura shear zone in the southern Magura domain. Maximum paleotemperatures differ strongly between structural units, reflecting differential burial and stacking histories: in the Šariš Unit temperatures locally reached ~160–180 °C (late oil to wet-gas stages), whereas structurally higher or less deeply buried units (Czorsztyn and Magura) remained within the early to main oil window. The results show that thermal maturity patterns across the PKB–OWC transition were primarily controlled by thrust stacking and variable burial–exhumation trajectories, while time-dependent basal heat flow provided an effective boundary-condition parameterization of transient thermal states during suture-zone deformation.

References

Zielińska, M., Spunda, K., Plašienka, D., Botor, D., 2026. Thermal records of Mesozoic and Cenozoic heat flow peaks as an expression of structural evolution interplay in the Western Carpathian northern suture. *Marine Geosciences and Energy Resources*, 184, 207654, <https://doi.org/10.1016/j.marger.2026.207654>

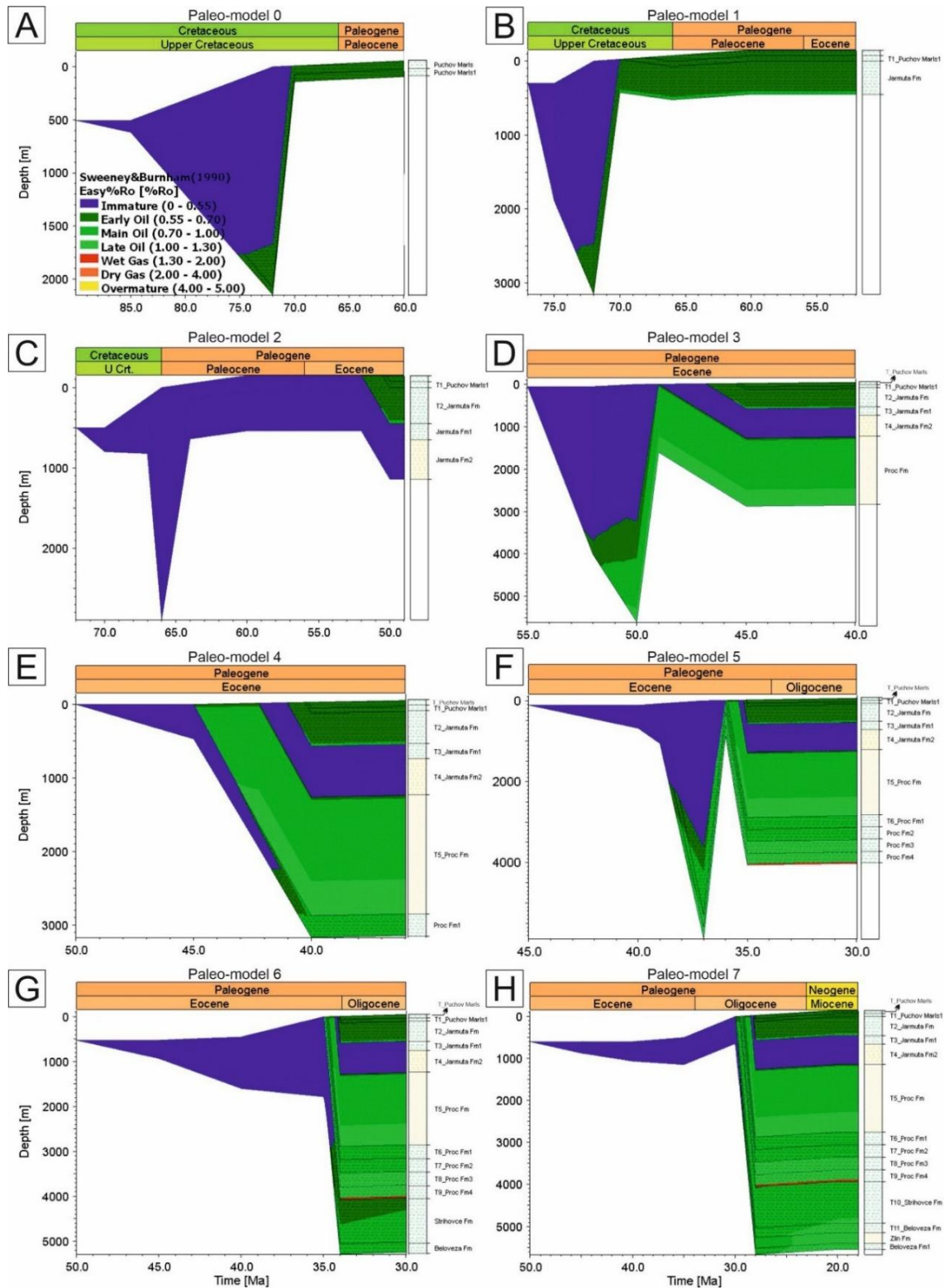


Fig. 1: Paleo models depicting burial plots for individual thrust units (notations such as “T1_Púchov Marls1” in Figure 1B indicate the same lithostratigraphic unit after it has been transported by thrusting from a previous paleogeometric configuration. Similar notation is consistently applied to other units in the subsequent panels to track the structural reworking and inheritance of tectonic slices through time): A. Paleo-model 0 for Púchov Marls; B. Paleo-model 1 for Púchov Marls and Jarmuta Fm1; C. Paleo-model 2 after Jarmuta Fm2 deposition; D. Paleo-model 3 after Proč Formation deposition; E. Paleo-model 4 after burial of the Proč Formation; F. Paleo-model 5 after Proč Fm. inversion; G. Paleo-model 6 after the Strihovce and Beloveža formations burial; H. Paleo-model 7 after the Zlín and Beloveža formations burial

PRE-CONFERENCE EXCURSION

Pre-Alpine and Alpine magmatic and tectono- metamorphic evolution of the eastern Nízke Tatry Mts.

*M. Putiš, R. Vojtko, O. Nemec, J. Madarás, M. Ondrejka, J. Sláma, A. Molnárová, Ch. E.
Kianguebene – Koussingounina*

Preface to Pre-Conference Excursion

(Evolutionary milestones of the Inner Western Carpathians)

Pre-Mesozoic evolution (ca. 550–250 Ma) of the Inner Western Carpathians basement with focus on the Nízke Tatry Mts.

The Inner Western Carpathians (IWC) Alpine (Mesozoic–Cenozoic) Orogen contains large areas of partly reworked pre-Alpine crystalline basement rocks, which provide petrological–geochemical and geochronological constraints on their peri-African Gondwana origin and evolution. The IWC Variscan basement is a unique part of the Cadomia, encompassing both the northern, Prototethys-related and the southern, Paleotethys-related domains of the Galatia terrane. The eastern part of the Nízke Tatry Mts. consists of kilometre-thick late- and post-Cadomian metasedimentary suites. The late- to post-Cadomian passive margin Hron Complex metasediments contain detrital zircon populations derived from two Ediacaran sources at ca. 620 and 570 Ma, with minor ages at 3100–2700 Ma, 2400–1900 Ma, and 1000–750 Ma. These age spectra indicate a foreland setting adjacent to the eroded Ediacaran magmatic arc and the Saharan Metacraton, thus positioning the IWC basement in the western part of Cadomian Galatia. The rift-related Koleso Valley Complex, tectonically overlying the Hron Complex, preserves late Cadomian metasediments with dominant Ediacaran detrital zircons, intruded by early to middle Cambrian tonalitic orthogneisses (~540–520 Ma; av. Th/U 0.23). Together with the middle Cambrian orthogneisses (~511–507 Ma) in the Jarabá Complex paragneisses, this evidence suggests a late Cadomian magmatic arc above the inferred Prototethys subduction zone. Late Cambrian to Early Ordovician metamorphic zircon ages (~500–475 Ma; Th/U 0.01–0.1) in gneisses of the Koleso Valley Complex indicate the transformation of this arc into a supra-subduction late Cambrian to Silurian arc-backarc basin system during ongoing subduction of the Prototethys oceanic slab beneath the northern Gondwana margin (Fig. 1). The WP and E-MOR type mafic rocks of this complex dated at ~480 Ma, indicate an early extensional stage of this basin system. These processes initiated the gradual growth of the Galatian terrane through accretion of underplated upper mantle mafic–ultramafic and supra-subduction ensialic sedimentary–magmatic suites of the Cenerian Orogen (~500–420 Ma). The Layered amphibolite Complex (~490–440 Ma) contains juvenile N-MORB and VAB-C rocks representing an incipient ensialic arc–backarc domain, separating the Koleso Valley Complex and the foreland Jarabá Complex, both intruded by numerous granitic orthogneisses (~500–450 Ma) from an ensialic arc setting. Closure of the Prototethys Ocean led to termination of the supra-subduction basin system, northward intra-continental subduction of the Layered amphibolite and Koleso Valley complexes (~390–380 Ma), collision (~380–370 Ma), and formation of an early orogenic arc (~370–360 Ma). Meanwhile, the Lower to Middle Devonian rift-related volcanic–sedimentary Pezinok Complex evolved into the Upper Devonian oceanic Pernek Complex (~370 Ma) within the Prototethyan forearc of the Jarabá Complex. These complexes are exposed in the Late Cretaceous Tatric and Veporic zones. Prototethys slab rollback, potentially aided by a mantle plume, drove rifting of the inboard northern Gondwana margin, comprised of the late Cambrian–Silurian volcanic–sedimentary Gelnica Complex, and the formation of oceanic Paleotethys. The Lower to Middle Devonian (~400–380 Ma) rift-related ensialic Rakovec Complex and the evolved oceanic Klátov Complex formed on the Gondwana margin, and these complexes are exposed in the Late Cretaceous Gemeric zone. Northward subduction of the Paleotethys Ocean (including the Rakovec–Klátov Basin) from ~370 Ma caused the collapse of the early Variscan orogenic arc of Northern Galatia (Tatric–Veporic basement). This event was accompanied by Late Devonian to Early Carboniferous anatexis and emplacement of granitic–tonalitic–dioritic intrusions (~365–340 Ma) in the Tatric–Veporic basement complexes. Continued closure of Paleotethys resulted in the accretion of the Rakovec–Klátov (~350 Ma) and Gelnica complexes of

Southern Galatia to the early Variscan orogen of Northern Galatia, culminating in the formation of late Variscan southvergent (~340–320 Ma) tectonic structures in the IWC basement (Figs. 1–3).

Permian event

It is detected mainly in the eastern part of the Nízke Tatry Mts. and adjoining domains. This event has a distinct record in sedimentary–magmatic suites and metamorphic impact on the basement rocks. This event is generally associated with the breakup of the Pangea supercontinent. Typical intra-plate rift-related sediments with continental tholeiites occur in the basal part of the Hronic Unit (Choč Nappe). The main period of volcanic activity is represented by Cisuralian to Guadalupian (~270–260 Ma) acid subvolcanic porphyries, rhyolites, trachyrhyolites, rhyodacites, basalts or dykes with A-type affinity and calc-alkaline basalts, andesites with within-plate riftogeneus geochemical signatures in the Infratatic, Tatric, Fatric, Northern Veporic, Southern Veporic, Gemeric and Meliatic units and the Muráň Nappe as well. Lamprophyre dykes were reported from the Tatric crystalline basement rocks. All these rocks are contemporaneous with S-type Gemeric granites (~280–250 Ma). The latter seems to be a product of Variscan post-collision and/or orogenic collapse. In general, they are timely overlapping with pre-orogenic continental rifting heralding the Pangea break-up and opening of the Neotethys, including the Meliatic Basin. The Permian metamorphic event is recorded by U–Pb dated Zrn, Mnz and Rt in the Northern Veporic domain.

Alpine evolution (ca. 135–35 Ma) of the IWC with focus on the eastern Nízke Tatry Mts.

The eastern part of the Nízke Tatry Mts. includes the Northern Veporic Unit, separated from the Tatric Unit by the Late Cretaceous Čertovica thrust zone, and being overridden by the Southern Veporic Unit along the Pohorelá Late Cretaceous sinistral shear zone. The eastern part of the Nízke Tatry Mts. also includes the southern, called subautochthonous Fatric Unit, represented by the Vápenica Nappe, composed of thinned mylonitised granodiorite–tonalite basement with the Veľký Bok-type Permian to Lower Cretaceous cover. This nappe is southvergently overlying the Northern Veporic Ľubietová and Kráľová basement–cover nappes and even the frontal part of the Southern Veporic Kráľova Hoľa Nappe in the Kráľova Hoľa Massif. The Fatric Unit was paleogeographically (during Jurassic–Cretaceous) placed between the Tatric Unit and Northern Veporic Unit, characterised by a large intra-continental Zliechov Basin with the southern, Northern Veporic and the northern, Tatric margins, respectively. The Fatric Unit thus divergently overthrusts the Tatric (Křížna Nappe s. l.) and Northern Veporic units, being overlain by the Hronic Unit (Choč Nappe s. l.).

The IWC basement–cover units of the eastern part of the Nízke Tatry Mts. are composed of Variscan crystalline basement and Permian–Mesozoic cover, the latter, although differing in the stratigraphic extent and the sedimentary basin origin. The complex Cretaceous tectono-metamorphic evolution of this area started in the Southern Veporic Unit by its deep syn-collisional burial in the frontal part of the developing Southern Veporic–Gemic–Meliatic orogenic (southern) wedge, resulting in low- to lower medium-grade (up to higher medium-pressure) metamorphism of the basement and cover rocks and associated deformation related to thrusting and collisional thickening (AD1 of southern wedge, ~135–100 Ma; in-situ EPMA Mnz and Ar–Ar Phg ages) following the closure of the Neotethyan oceanic Meliatic Basin. The progressively growing orogenic wedge subsequently incorporated the foreland Northern Veporic–Fatric domain, which caused the closure of the intra-continental Fatric Jurassic–Cretaceous Zliechov Basin. Gradual underthrusting of the thinned Fatric–Northern Veporic basement (due to Permian and Middle Jurassic to Early Cretaceous extensions) beneath the Neotethyan Southern Veporic–Gemic–Meliatic wedge (AD1 of northern wedge, ~100–80 Ma; Ar–Ar Phg ages) brought about the detachment of the main (unmetamorphosed) part of the Fatric Mesozoic cover nappes (the Křížna and analogous nappes) northwards thrust over the Tatric Unit (~95–85 Ma), whereas metamorphosed South-Fatric subautochthonous Vápenica Nappe thrust southwards over the Northern Veporic Unit (~80–60 Ma). The underthrusting of the thinned Fatric–Northern Veporic basement below the Southern Veporic–Gemic–Meliatic wedge initiated the top-to-the-SE/E structural unroofing and

orogen-parallel stretching of the Southern Veporic Unit (AD2–AD3 of southern wedge, ~100–85 Ma; Ar–Ar Phg ages) and sinistral Lubeník and Pohorelá shear zones formation. The exhumed low-grade metamorphosed (low- to medium-pressure) Northern Veporic Unit, southvergently overthrust by the subautochthonous-Fatric Vápenica Nappe (AD2 of northern wedge, ~80–60 Ma; Ar–Ar Phg ages), can be traced from the eastern Nízke Tatry Mts. in the SW direction to the Tribeč Mts. northern Rázdiel Block, where these units overlie the less metamorphosed South-Tatric Zobor Block (72–62 Ma; Ar–Ar Ms ages). This event was timely, already overlapping with the post-Santonian closure of the foreland Infratatric Belice Basin (~South-Penninic supra-subduction forearc ~85–70 Ma), syn-collisional very low-grade (lower to medium-pressure) metamorphism and thrusting (AD3 of northern wedge, ~70–50 Ma, Ar–Ar Phg ages), thus completing the northern Albian–Eocene Infratatric–Tatric–Fatric–Northern Veporic wedge (~100–50 Ma). Some Upper Cretaceous–Paleogene smaller wedge-top depressions formed on the N-ward thrusting nappes. The Infratatric and the Tatric hanging wall exhumation (AD4 of northern wedge, ~50–35 Ma; Ar–Ar Phg and ZFT ages) is most likely related to the collapse of the Eocene wedge and the development of the Central Carpathian Paleogene Basin in response to subduction of the North-Penninic Magura Basin of the Outer Western Carpathians beneath the Inner Western Carpathians (Figs. 3–6).

M. Putiš and R. Vojtko

1 Introduction – review of the IWC tectonic units

Pre-Permian origin and tectonic structure of the IWC basement complexes

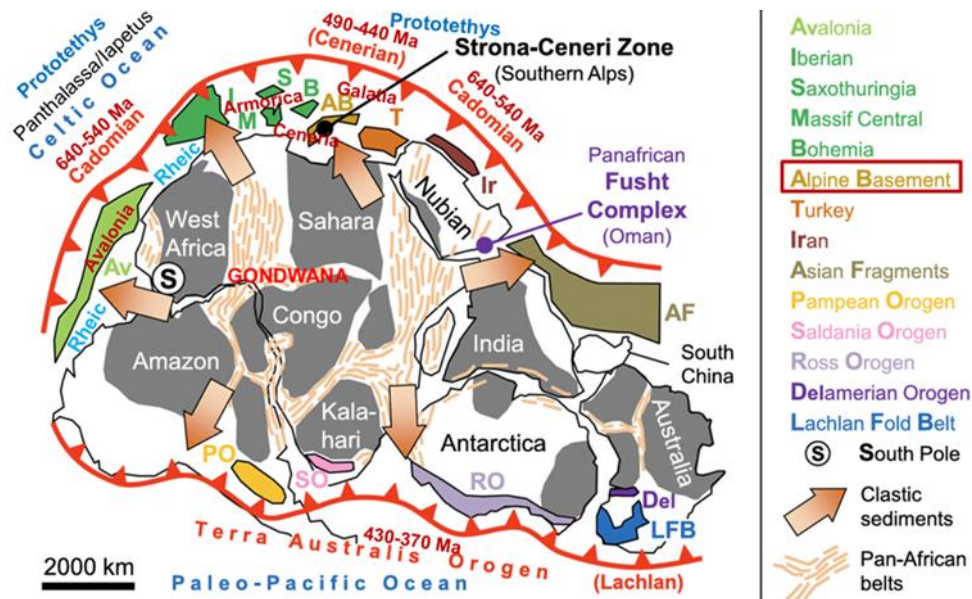


Fig. 1: Position of the IWC basement on the Gondwana Supercontinent map (after Zurrbruggen, 2020) in relationship to the Cadomian Armorican and Galatian (with the Alpine Basement, incl. the IWC basement) terranes.

The Inner Western Carpathians (IWC) pre-Variscan basement rocks bear the signatures of post-Cadomian Cenerian Orogeny, followed by the Variscan Orogeny. In this concept, we distinguish post-Cadomian (~550–500 Ma) and Prototethyan subduction–accretion (Cenerian; ~500–420 Ma) forearc–arc-incipient backarc complexes, as well as Paleotethyan and other Devonian rift-related complexes (~420–360 Ma), all sited on the northern Gondwana margin Galatian terrane (von Raumer et al., 2013). A model for the evolution of the IWC basement complexes (Putiš et al., 2009a, 2024b) shows their tight connection with the Gondwana Supercontinent in the early Paleozoic. The prevailing Neoproterozoic detrital zircon populations in the metasediments of the Tatric, Veporic and Gemeric basement (Vozárová et al., 2017; Kohút et al., 2022; Putiš et al., 2023a, 2024a, b, c; Soejono et al., 2024) suggest a proximity to the Cadomian Ediacaran magmatic arc and the Saharan Metacraton (Linnemann et al., 2008) (Fig. 1).

Variscan basement of the IWC can be basically subdivided into the composite Upper, Middle and Lower Variscan tectono-stratigraphic (nappe) units (Putiš, 1992; Bezák, 1994; Bezák et al., 1997; Putiš et al., 2008a, 2021) composed of characteristic lithological complexes (Fig. 2). Despite the Cadomian basement rocks being obscured, kilometre-thick post-Cadomian sedimentary sequences in all three Variscan units can be viewed as the response to late Cadomian closure and exhumation of the Cadomian Ediacaran arc due to late Neoproterozoic to early Cambrian Cadomian Orogeny (Linnemann et al., 2007). The main evolutionary milestones of the IWC basement complexes are reviewed in the Preface. Horizontal zonation of the basement complexes, and even their vertical tectono-stratigraphy, remained prominent features of the Variscan southward prograding orogeny in the territory of the IWC (Putiš, 1992; Putiš et al., 2008a). This structure formed due to the closure of the Prototethyan and Paleotethyan basins.

The southvergent early Variscan structure (~400–350 Ma) of the IWC basement (Fig. 2) formed due to closure of Prototethyan arc-backarc system and shows this top-to-bottom tectono-stratigraphy:

- (1) the higher-grade metasedimentary and metamagmatic rocks of the Jarabá Complex (Krist et al., 1992 and references therein; Madarás et al., 1999; Moussallam et al., 2012; Janák et al., 2022).

(2) the Layered amphibolite (or Leptyno–amphibolite) Complex and associated gneisses and serpentinites (Putiš, 1992; Krist et al., 1992; Hovorka and Méres, 1993; Janák et al., 1996; Hovorka et al., 1997; Putiš et al., 1996, 1997a, b, 2008a, 2009a; Ivan et al., 2007).

(3) the gneiss–metamafic–ultramafic Koleso Valley Complex (redefined, previously considered a part of the Layered amphibolite Complex by Ivan, 1996; Korikovskiy and Putiš, 2002; Janák et al., 2007, 2020; Putiš et al., 2008a; Michálek and Putiš, 2009, 2011).

(4) the micaschist–gneiss Hron Complex (Putiš, 1992; Krist et al., 1992; Putiš et al., 2008a, 2009a).

The previously mentioned complexes occur in the Cretaceous Infratatic, Tatic, Northern Veporic and Southern Veporic tectonic zones of the IWC (Fig. 3).

The late Variscan (~350–300 Ma) orogenic basement structure, which formed after the closure of the Paleotethyan basins, consists of: (5) Ostrá–Hladomorná Valley–Klenovec Complex phyllites to micaschists, rare metabasic and carbonatic rocks (newly defined; after Krist et al., 1992; Bezák, 1994; Bezák et al., 1997), (6) Gelnica Complex metasediments with acidic, intermediary, and less basic metavolcanics (Vozárová et al., 1998, 2010, 2017), (7) Rakovec Complex metabasites, less acidic metavolcanics, and phyllites (Bajaník, 1973; Bajaník et al., 1981; Grecula, 1982; Hovorka et al., 1988; Ivan, 1997; Putiš et al., 2009a; Radvanec et al., 2017), (8) Klátov Complex serpentinites, metabasites, metaplagiogrinites, rare metacarbonates and calc-schists (Rozložník, 1965; Grecula, 1982; Hovorka et al., 1984; Radvanec, 1994; Hovorka and Spišiak, 1997; Putiš et al., 2009a), (9) Zlatník Complex of metamafic rocks (Ivan and Méres, 2012) in Carboniferous *mélange* (Németh, 2002), and (10) Ružín Complex metatonalites, metadiorites and rare siliciclastic metasediments (newly defined). These complexes occur in the Late Cretaceous South-Veporic (5) and Gemeric (6–10) IWC tectonic zones. In addition, (11) Pezinok Complex metasediments with rare basic metavolcanics (Cambel, 1954; Putiš, 1987a, 1992; Putiš et al., 2004; Ivan and Méres, 2006), and (12) Pernek Complex deepwater metasedimentary and thicker metabasic rocks (Cambel, 1954; Putiš, 1987a, 1992; Ivan et al., 2001; Putiš et al., 2004; Ivan and Méres, 2006), and some further analogous complexes, overlie the early Variscan (pre-granitoid) basement in the Late Cretaceous Tatic zone (Putiš, 1992; Putiš et al., 2004, 2009a; Kohút et al., 2006; Ivan and Méres, 2015).

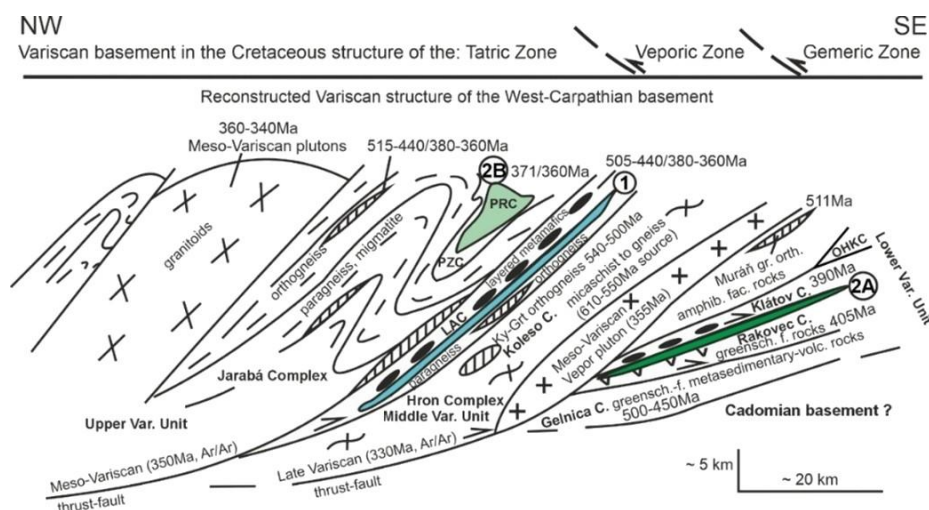


Fig. 2: Scheme of southvergent Variscan structure of the IWC basement complexes with Proto- and Palaeotethyan sutures (modified from Putiš et al., 2008a). **Suture 1** indicates the early Variscan closure of the Ordovician–Silurian (Prototethyan) arc-backarc basin system, whereas **Suture 2A** is left after the late Variscan closure of the Devonian (Paleotethyan) basin system. **Suture 2B** contains relics of the oceanic Pernek Complex (PRC) infolded to the Pezinok Complex (PZC) in the upper (forearc) part of the Jarabá Complex in the Tatic basement. The protolith ages are shown before the slash, while the metamorphic–anatectic ages are shown after the slash. Other abbreviations: LAC = Layered amphibolite Complex, OHKC = Ostrá–Hladomorná Valley–Klenovec Complex. The redefined part of the Layered amphibolite Complex – Koleso Valley Complex is tectonically included in the Hron Complex.

The Nízke Tatry Mts. crystalline basement complexes

The **Hron Complex** represents the Variscan Middle Unit and occupies the basal part of the Tatric and Veporic basement exposed in the eastern Nízke Tatry (Low Tatra), High Tatra, Považský Inovec, Tribeč, Veporské Vrchy, and Čierna Hora Mts. in the footwall of the Variscan Upper Unit Layered amphibolite and Jarabá complexes (Figs. 2, 3, 5, 6). In the eastern Nízke Tatry Mts., it is included in the Cretaceous **Northern Veporic Krakľová Nappe**. Kilometre-thick monotonous micaschist–gneisses contain thin bodies of amphibolites and rare tiny orthogneiss bodies (only in the northern Považský Inovec Mts.). The Hron Complex St–Grt and Ky–Grt micaschists to gneisses are products of the Variscan metamorphism (e.g., Krist et al., 1992). The St–Grt–And micaschist–gneisses north of the village of Pohorelá (Putiš, 1989) revealed the Permian thermal overprint of the Variscan St–Grt micaschists according to dated (~275 Ma) Mnz inclusions in And porphyroblasts (Jeřábek et al., 2008a).

The **Koleso Valley Complex (KOC)** is a relatively small tectonic block that overlies the Hron Complex in the Northern Veporic Krakľová Nappe (Figs. 2, 3, 5). Previously, it was considered to be a part of the LAC (Ivan, 1996; Korikovsky and Putiš, 2002; Janák et al., 2007, 2020; Putiš et al., 2008a; Michálek and Putiš, 2009, 2011). It is composed of Ky–Grt paragneisses, which host metaperidotites, massive metagabbros, metabasalts?, metamorphosed in amphibolite to eclogite facies, and Cambrian to Ordovician tonalitic to granitic orthogneisses. The gneisses exhibit signatures of Variscan partial melting and migmatitisation in higher-T and P amphibolite facies (Michálek and Putiš, 2009). Metabasites of mostly Ordovician magmatic age are originally WPT, less E-MORB, and rare N-MORB types ($\epsilon\text{Nd}_{(500)} = +7.7$ to 0.0, $\text{TDM}_{(2\text{st})} = 0.58\text{--}1.18$ Ga), derived from predominant enriched mantle sources (Putiš et al., 2023a, 2024a, b, c). An early Ordovician metamorphic event was detected on Zrn in a Cambrian orthogneiss (Putiš et al., 2008a), or from Mnz and Xnt inclusions in an orthogneiss Bt (Ondrejka et al., 2016) and Grt (Petrik et al., 2024). Metabasic and metaultramafic rocks are metamorphosed mostly in eclogite facies (Janák et al., 2007, 2020; Michálek and Putiš, 2009, 2011). These rocks are crosscut by Carboniferous granites, (Tur) pegmatites and aplites (age database of M. Putiš). The Hron Complex and Koleso Valley Complex represent the **Variscan Middle Unit** (Figs. 2, 3).

The **Layered amphibolite Complex**, also termed the Leptyno–amphibolite Complex or banded amphibolites (e.g., Putiš, 1992; Krist et al., 1992; Hovorka and Méres, 1993; Janák et al., 1996; Hovorka et al., 1997), occupies the basal part of the gneissic Jarabá Complex in the **Variscan Upper Unit** (Figs. 2, 5, 6) in association with rare serpentinites or orthogneisses. This complex lies on the top of the **Krakľová Nappe**. It is composed of 200–300 m of MORB-type layered metagabbros ($\epsilon\text{Nd}_{(480)} = +10.1$ to +5.5, $\text{TDM}_{(2\text{st})} = 0.37\text{--}0.73$ Ga), which originated by fractionation of juvenile and isotopically quite homogeneous depleted mantle sources, emplaced in the lower crust of an incipient backarc basin (Putiš et al., 2023a, 2024a, b, c). Both differentiated mafic and felsic layers provided late Cambrian to Late Ordovician magmatic Zrn ages (Putiš et al., 2008a, 2009a). Variscan metamorphic conditions achieved amphibolite (Putiš et al., 1997b; Hovorka et al., 1997) to eclogite facies conditions (Janák et al., 1996).

The **Jarabá Complex** metasediments of the Variscan Upper Unit are kilometre-thick post-Cadomian Cambrian to Devonian deposits separated into a Cambrian to Early Devonian arc part with numerous Ordovician orthogneiss bodies, and an upper Late Devonian forearc part, the latter exposed only in the northern margin of the Tatric basement. There, Neoproterozoic (concordia ages between 572 and 552 Ma; Putiš et al., 2023a) and older detrital zircon populations are complemented by the Cambrian–Ordovician zircon population derived from the aborted late Cambrian–Ordovician arc-incipient backarc system, which was disrupted by an early Variscan orogenic event (Putiš et al., 2024b). The pre-Devonian part of the Jarabá Complex is exposed in the Cretaceous Northern Veporic **Ľubietová Nappe**, indicated by the emplacement of the granitic protoliths of orthogneisses dated 485–462 Ma (Putiš et al., 2008a, 2009a) in host higher amphibolite-facies paragneisses. The peraluminous granitic protoliths of the orthogneisses have a calc-alkaline character (e.g., Hovorka et al., 1987), indicating arc-type magmatism. The next evolutionary stage is consistent with an outboard-directed supra-subduction

compression, exhumation and erosion of the acidic (orthogneisses) and mafic (metagabbros) type magmatic rocks, from which the released zircon was transported to the forearc.

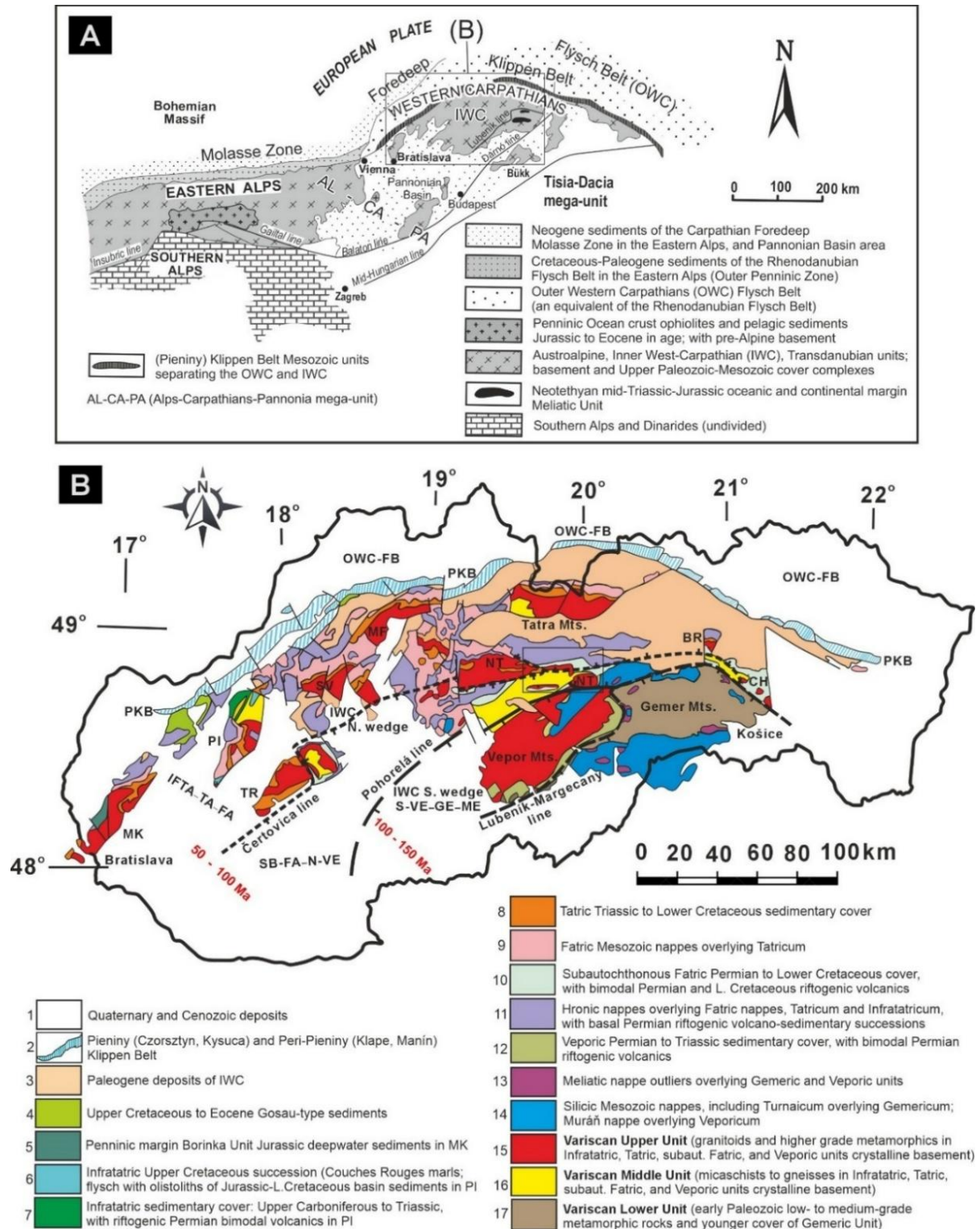


Fig. 3: (A) Tectonic sketch of the Eastern Alps and Western Carpathians in Cenozoic AL-CA-PA microplate (modified from Putiš et al., 2021, 2023a, b). (B) Alpine structure of the IWC with included Variscan basement (map compiled from Lexa et al., 2000; tectonic zonation modified from Putiš et al., 2021, 2023a, b). MK = Malé Karpaty Mts., PI = Považský Inovec Mts., TR = Tribeč Mts., SV = Strážovské vrchy Mts., MF = Malá Fatra Mts., NT = Nízke Tatry (Low Tatra) Mts., BR = Branisko Mts., CH = Čierna hora Mts., OWC-FB = Outer Western Carpathians Flysch Belt, PKB = Pieniny Klippen Belt, IFTA-TA-FA = Infratatic-Tatric-Fatric Belt, SB-FA-N-VE = Subautochthonous Fatric Unit (in-situ exhumed metamorphosed basement and cover rocks from the root

zone of Fatric nappes at ca. 95–80 Ma; Putiš et al., 2021) and Northern Veporic Unit, S-VE–GE–ME = Southern-Veporic–Gemerik–Meliatic Belt. Red time intervals are related to the formation of the southern Neotethyan (S-VE–GE–ME) and northern Atlantic or Alpine Tethys (IFTA–TA–FA) wedge, respectively. Close-up of the framed area in Figs. 5, 6.

Basaltic and felsic bimodal magmatism in the Hron Complex (rare), Koleso Valley Complex, Layered amphibolite Complex, and Jarabá Complex lasted from the late Cambrian up to the Late Ordovician and was likely initiated by magmatic underplating and melting of the overheated continental crust in the Prototethys-related supra-subduction zone developed on the northern Gondwana active margin (Putiš et al., 2008a, 2024b). These complexes may have thus experienced an Alaskan-type subduction–accretion orogeny during the Cenerian event, as reported by Zurbriggen (2020 and references therein) from the Strona–Ceneri Zone of the Southern Alps for the period of 490–440 Ma.

Review of the IWC Mesozoic and Cenozoic tectonic units with the Variscan basement rocks

The Pieniny Klippen Belt is a Cenozoic structure separating the Outer (OWC) and Inner (IWC) Western Carpathians. The IWC, south of the Pieniny Klippen Belt, comprise two principal orogenic wedges separated by the Pohorelá Master Thrust-Fault, which formed due to closure of two oceanic (Meliatic and Penninic) and a few intra-continental Jurassic–Cretaceous basins: (1) the southern, called Meliatic–Gemerik–Southern Veporic wedge of Late Jurassic–Early Cretaceous age, derived from the Neotethys Ocean (Meliata Basin) and its northern passive continental margin (Gemerik, Southern Veporic), and (2) the northern, called Northern Veporic–Fatric–Tatric–Infratatic wedge derived from the Atlantic (Alpine) Tethys Ocean southern continental domain (Figs. 3, 4) (Plašienka, 2018; Putiš et al., 2009b, 2021, 2023b, and references therein).

In general, the northern wedge is characterised by rare Upper Carboniferous (only in the Považský Inovec Mts.), Permian–Lower Triassic intra-continental sequences and Permian magmatism, Triassic platform sediments, continental-lagoonal Carpathian Keuper, Jurassic to Cretaceous shallow and deepwater successions, and Paleogene–Oligocene post-tectonic sediments. The southern wedge is characterised by Upper Carboniferous to Permian volcanic–sedimentary sequences, Permian acidic magmatic bodies, Triassic–Jurassic sediments, with the tendency of deepening towards the Meliatic continental margin (e.g., Plašienka et al., 1997). The principal Alpine tectonic units of the IWC (Fig. 3) are briefly characterised as follows:

The IWC northern Albian–Eocene wedge (Fig. 4) south of the Pieniny Klippen Belt is composed from south to north of the Northern Veporic, Fatric, Tatric, Infratatic and peri-Pieniny Klippen Belt basement–cover structural complexes (Putiš et al., 2019a, 2021, and references therein), which are structural equivalents of the Lower Austroalpine units. The IWC southern Late Jurassic–Early Cretaceous Meliatic, Gemerik, and Southern Veporic wedge units are structural equivalents of the Upper Austroalpine units in the Austrian Eastern Alps (Tollmann, 1980; Maheľ, 1986; Putiš, 1992; Dallmeyer et al., 1996; Plašienka et al., 1997; Putiš et al., 2009b, 2021).

An intra-continental basin of the Atlantic Tethys (or Alpine Tethys after Schmid et al., 2008) called the Fatric Basin (Andrusov et al., 1973) was located between the Tatric and Northern Veporic units. The Fatric nappes are presumed to have formed from a Jurassic to Lower Cretaceous sedimentary infill of the Fatric (Zliechov) Basin, which originated on an extensionally thinned basement (~Variscan crystalline basement with a Permian–Triassic pre-rift cover) in a transitional area of the present-day Tatric and Northern Veporic units. The Fatric (Zliechov) Basin was closing from the late Albian to Cenomanian at ca. 100–95 Ma, and the Fatric nappes were thrust onto the Tatric Unit during the Turonian to Santonian (Plašienka, 2018 and references therein) and overlain by the Hronic nappes (Maheľ, 1986; Plašienka et al., 1997).

The Late Cretaceous Čertovica thrust-fault separates the Tatric from the subautochthonous Fatric–Northern Veporic area, the structural complexes of the latter showing a distinct Alpine tectono-

metamorphic overprint (e.g., Korikovsky et al., 1997a, b; Putiš et al., 2021). The central Tatric sliver consists of the relatively thicker basement rocks (Tomek, 1993) with the Variscan granitic plutons intruded in the higher-grade metamorphics, such as gneisses, amphibolites and migmatites (Krist et al., 1992), and covered by the Triassic platform and Jurassic–Cretaceous deep-water Šiprúň or shallow-water Tatra successions of the Tatric Basin. The closure of this basin occurred in the Cenomanian to Turonian as documented by the termination of sedimentary successions by pelagic “flysch” sediments (e.g., Plašienka et al., 1997 and references therein).

The Infratatic Unit (Putiš, 1992; Plašienka et al., 1997) developed from the deep-water Middle Jurassic to Lower Cretaceous successions, which were deposited on a distant thinned continental margin basement (Putiš et al., 2008b, 2019a). The Infratatic deep-water Orešany and Humienec successions appear to have been formed in a transitional area to the South-Penninic oceanic basin, while the Borinka Unit represents the South-Penninic oceanic margin (Plašienka et al., 1997). The southward subduction of the South-Penninic Ocean opened the Infratatic forearc Late Cretaceous (Belize) basin system on the upper plate (Putiš et al., 2008b, 2019a; Plašienka, 2012; Plašienka and Soták, 2015; Pelech et al., 2017).

A wide range of the blastomylonitic white mica $^{40}\text{Ar}/^{39}\text{Ar}$ ages from ca. **100 to 50 Ma** have been reported from the northern IWC wedge (Hók et al., 2000; Král' et al., 2002; Putiš et al., 2009b, 2019a, 2021; Etzel et al., 2018). Zircon (U–Th)/He and apatite fission-track ages between ca. **50 and 40 Ma** are interpreted as erosional and tectonic exhumation of the basement units due to the extensional collapse of the Carpathian orogenic wedge (Danišík et al., 2011; Králiková et al., 2016).

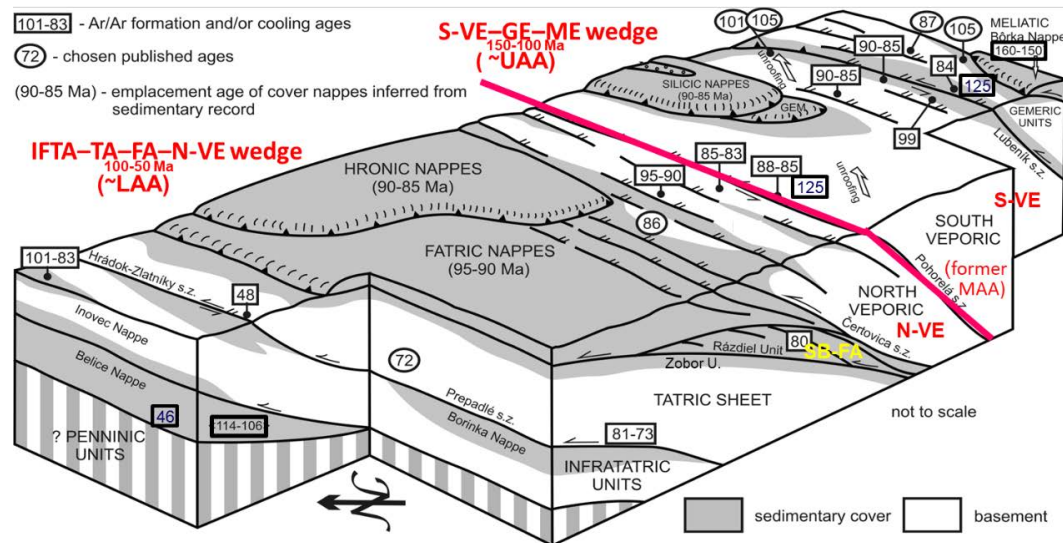


Fig. 4: Evolutionary scheme of the IWC Orogenic Wedge (~150–50 Ma), limited by oceanic – the Meliatic and Penninic-equivalent units, following the Meliatic subduction (160–150 Ma) and exhumation (150–130 Ma), constrained by the WhM ^{40}Ar – ^{39}Ar ages from the shear zones mylonites/phylionites (modified from Putiš et al. 2009b) using also data of Dallmeyer et al. (1993, 1996, 2005) and Putiš et al. (2019a, 2021). ME = Meliatic, GE = Gemic, S-VE = Southern Veporic, N-VE = Northern-Veporic, SB-FA = Subautochthonou Fatric, FA = Fatric, TA = Tatric, IFTA = Infratatic, UAA = Upper Austroalpine structural equivalents, LAA = Lower Austroalpine structural equivalents.

The IWC southern Southern Veporic–Gemic–Meliatic wedge (Fig. 4) formed due to closure of the Middle Triassic–Late Jurassic Neotethyan oceanic Meliata Basin and southward subduction of its oceanic and continental margin crust at ca. **160–150 Ma** (Dallmeyer et al., 1993, 1996, 2005; Maluski et al., 1993; Faryad and Henjes-Kunst, 1997; Putiš et al., 2019b; 2023b; Nemec et al., 2020). This wedge also comprises a decoupled part of the Gemic and Veporic thinned continental margin, which accreted to the Meliatic subduction-related accretionary wedge at ca. **140–110 Ma** (Putiš et al., 2014, 2015; Li et al., 2014). Contemporaneous exhumation and cooling of the overthrusting high-pressure

metamorphosed Meliatic fragments is constrained by the zircon (U–Th)/He thermochronology (Putiš et al., 2014) and the monazite in-situ EPMA dating in the underlying Gemic Unit (Vozárová et al., 2014; Hurai et al., 2015). The Meliatic Unit overlies the Gemic Unit and is overlain by Silicic nappes (Plašienka et al., 1997; Plašienka, 2018). Whereas the U–Pb SIMS metamorphic Rt age of **100±10 Ma** from a metabasalt sample at Jaklovce (Putiš et al., 2019b) most likely indicates reburial/overheating of the Meliatic fragments within the orogenic wedge in the late Early Cretaceous (Fig. 4).

Geological setting of the wider area of the Nízke Tatry Mts.: Variscan–Alpine structure

We use the following principal Late Cretaceous structural units of the IWC with the Variscan basement participation: Infratatic Zone (N of the Hrádok–Zlatníky thrust-fault), Tatic Zone (between the Hrádok–Zlatníky and Čertovica thrust-faults), Northern Veporic Zone (between the Čertovica and Pohorelá thrust-faults), Southern Veporic Zone (between the Pohorelá and Lubeník–Margecany thrust-faults), and Gemic Zone (between the Lubeník–Margecany and Rožňava thrust-faults), overlain by the Hronic, Muráň, Meliatic and Silicic rootless nappes.

In the area of question, the detached Mesozoic Fatic nappes are divergently overriding the Tatic and Northern Veporic units. Paleogeographically, there was a large domain of the Jurassic–Early Cretaceous extension and the basin formation between the Tatic and Northern Veporic units. This Fatic domain, after the syn-collision inversion, transformed into the Late Cretaceous structural units overlying the Tatic Unit (Krížna and other nappes; Andrusov et al., 1973). However, the buried, metamorphosed, and nearly in-situ exhumed part of the Fatic basement-cover (Veľký Bok) succession is called the subautochthonous Fatic Unit (Putiš et al., 2021), southvergently thrust over the Northern Veporic basement-cover nappes of a former continental margin (Figs. 5, 6). This type of distinctly metamorphosed subautochthonous Fatic Unit is exposed in the eastern Nízke Tatry Mts. (and the Rázdiel Block in the Tribeč Mts.), where the subautochthonous Fatic Vápenica Nappe was backthrust over the Northern Veporic Ľubietová and Krakľová nappes. Whereas the northern Fatic margin basement–cover rocks are exposed in the southern Tribeč Mts. Zobor Block (Figs. 3, 4). The detached Fatic shallow-water successions of the south-Tatic/Fatic continental margin are Vysoká (in the Malé Karpaty Mts.) and Manín (a Fatic nappe in the Infratatic foreland) successions (Putiš et al., 2021 and references therein). Altogether, these Fatic successions suggest a large, at least first-hundred-km wide intra-continental Fatic Basin (Mahel', 1986; Plašienka et al., 1997).

Fig. 5A: Geological map of the eastern termination of the Nízke Tatry Mts. (modified from Putiš, 1989, 1991a; Putiš in Biely et al., 1992). Subautochthonous Fatic (SB-FA) Vápenica Nappe overlies the Northern-Veporic Krakľová Nappe and the Southern-Veporic Kráľova Hoľa Nappe in Late Cretaceous southvergent structure, overlain by the Muráň Nappe front (Silicium?). 1—Quaternary and Cenozoic deposits; 2—Muráň Nappe (from Biely et al., 1992); 3a—SE-vergent FA Vápenica Nappe on the northern slopes of the Nízke Tatry Mts. overlying the Northern-Veporic Krakľová Nappe; 3b—Vápenica Nappe in the Upper Hron Valley synform; 4—Permian siliciclastic sediments of the Veľký Bok Succession (a part of the Vápenica Nappe – SB-FA); 5—Triassic Föderata cover Succession of the Southern Veporicum; 6—Permian–Triassic Föderata succession overlain by black schists of the Gemic Ochťiná Group; 7—Variscan tonalites to granodiorites of the Vápenica Nappe (SB-FA basement); 8—Variscan granites to granodiorites of the Southern-Veporic Kráľova Hoľa Nappe; 9—Gneisses of the Var. Jarabá Complex (JC) in the Cretaceous Kráľova Hoľa Nappe; 10—Cretaceous phyllonites; 11—Amphibolites of the Var. LAC and HRC in the Cretaceous Krakľová Nappe; 12—Var. Koleso Valley Complex (KOC, undivided); 13—Leucocratic granites, aplites and pegmatites; 14—Micaschist gneisses of the Krakľová Nappe (Var. HRC); 15—Thrust plane of the Mesozoic Muráň Nappe (Silicium?); 16—Thrust plane of the SB-FA Vápenica Nappe over the N-VE Krakľová Nappe; 17—Important thrust planes subsequent to subhorizontal nappe thrusting; 18—Thrust planes influenced by gravitational sliding; 19—Faults, strike-slips (a) and geological boundaries (b); 20—Pre-Alpine metamorphic schistosity/foliation (a) or lineation (b); 21—Alpine schistosity (a) or lineation (b); 22—Joint cleavage. SB-FA—Subautochthonous Fatic (Vápenica Nappe). Close-up of the KOC in Fig. 5B.

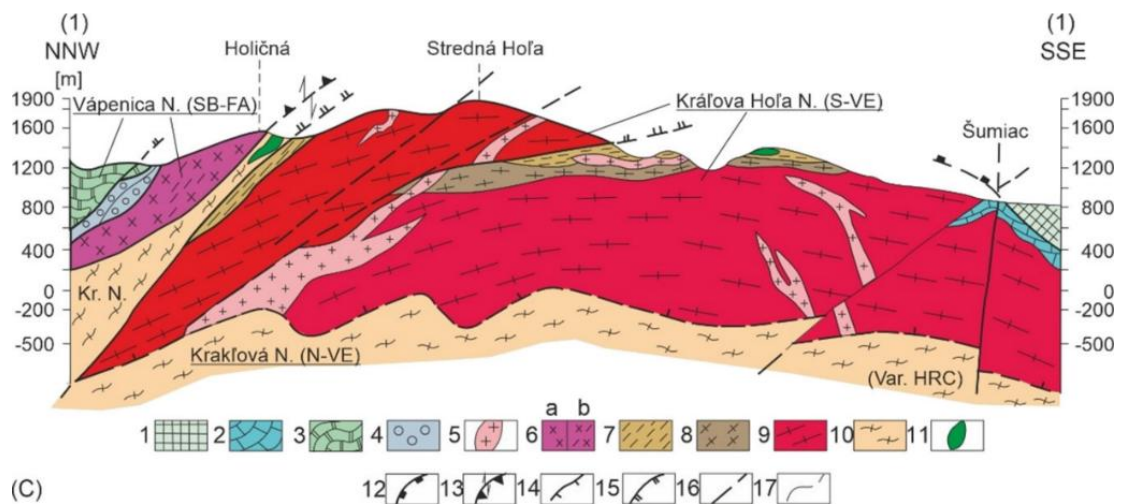
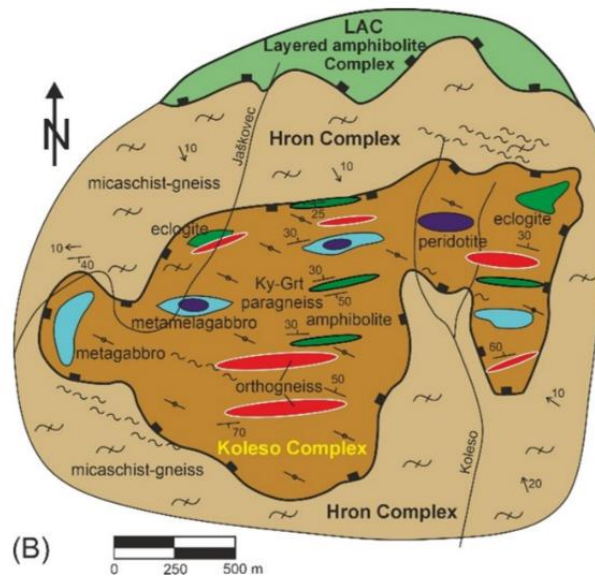
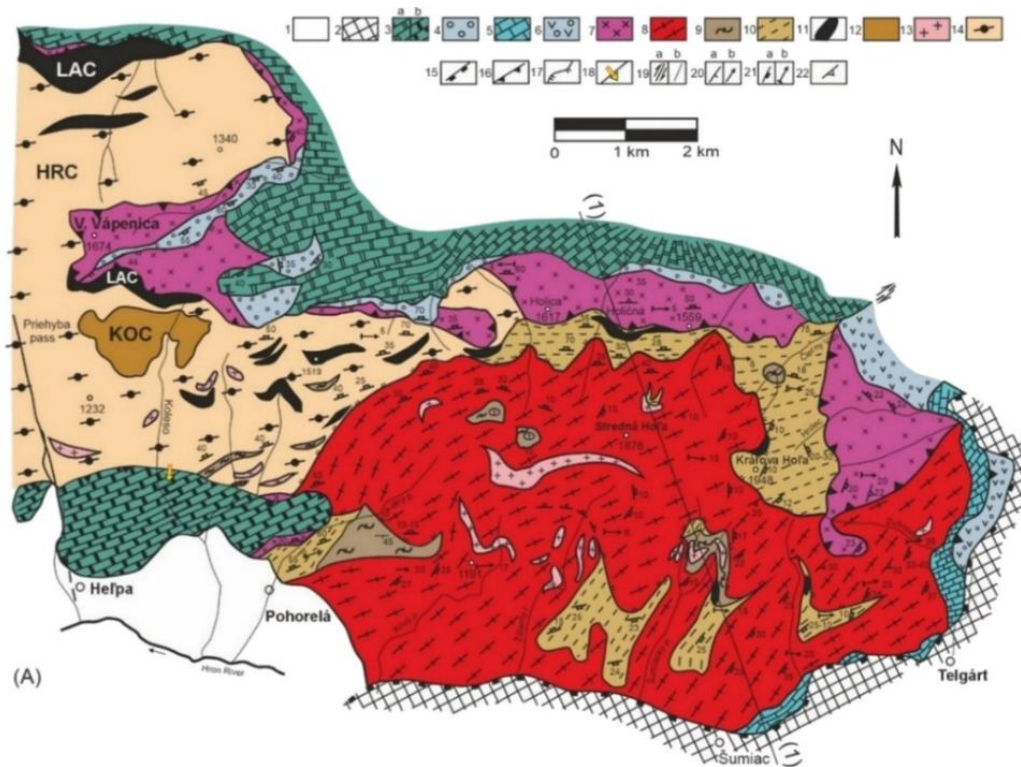


Fig. 5B: Schematic geological map of the Variscan Koleso Valley Complex (KOC in Fig. 5A) overlying the micaschists of the Variscan Hron Complex (HRC), both overlain by the Variscan Layered amphibolite complex (LAC). HRC and KOC represent the Middle Variscan Unit, whereas LAC represents the base of the Upper Variscan Unit JC (original figure of M. Putiš).

Fig. 5C: Geological profile (1-1) across the Kráľova Hoľa Massif in the eastern termination of the Nízke Tatry Mts. (modified from Putiš, 1989, 1991a). 1—Muráň Nappe, undivided (from Biely et al., 1992); 2—Triassic Föderata cover Succession of the Southern Veporicum; 3—Triassic to Lower Cretaceous Veľký Bok Succession of subautochthonous Fatric SE-vergent Vápenica Nappe; 4—Permian siliciclastic sediments of the Veľký Bok Succession (a part of the Vápenica Nappe); 5—Leucocratic granites, aplites and pegmatites of unknown age; 6a—Variscan tonalites to granodiorites of the Vápenica Nappe mylonitised to blastomylonitised hanging wall (b); 7—Cretaceous phyllonites of the Variscan metamorphics; 8—Gneisses of the Southern-Veporic Kráľova Hoľa Nappe; 9—Variscan granites to granodiorites of the Southern-Veporic Kráľova Hoľa Nappe, mylonitised; 10—Micaschist gneisses of the Krakľová Nappe; 11—Amphibolites; 12—Thrust plane of the Mesozoic Muráň Nappe; 13—Thrust plane of the Vápenica Nappe over the Northern-Veporic Krakľová Nappe with indicators of dextral shearing; 14—Thrust plane of Kráľova Hoľa Nappe over Krakľová Nappe; 15—Secondary thrust planes; 16—Faults, strike-slips; 17—Geological boundaries.

Following the Fatric (Zliechov) Basin closure, the thinned underlying basement and the Northern Veporic continental margin were underthrust southward beneath the Southern Veporic–Gemic–Meliatic (Neotethyan) wedge. The exhumed tectono-metamorphosed basement–cover structural units from this suture zone are collectively termed subautochthonous Fatric–Northern Veporic domain (Putiš et al., 2021, 2023b) to emphasise their close relationship to allochthonous detached Fatric Mesozoic cover nappes (*sensu* Andrusov et al., 1973). This area is the homeland or the root zone of the Fatric nappes, including the southvergent Vápenica Nappe (Putiš, 1989, 1991a). Their characteristic feature is a distinct Cretaceous greenschist facies tectonometamorphic overprint (Putiš et al., 2021).

The Vápenica Nappe consists of a metamorphosed Veľký Bok-type Permian–Lower Cretaceous succession overlying the tectonically reduced and sheared-off 200–300 m thick granitoid basement. Blastomylonitised granodiorites to tonalites and the sedimentary cover show the same low-grade tectono-metamorphic overprint in the whole area of the eastern Nízke Tatry Mts. and the Upper Hron Valley. The thrust plane of the Vápenica Nappe may also be a reactivated originally north-dipping extensional fault of the southern Fatric (Zliechov) Basin continental margin. The SE/ESE-vergency of the Vápenica Nappe, still under ductile conditions over the Northern Veporic Ľubietová and Krakľová nappes (Buday et al., 1962), is indicated by the WNW–ESE- to E-striking stretching lineation of granitoid blastomylonites. Similarly, the Krakľová Nappe is back-thrust over the Southern Veporic front in the Kráľova Hoľa Massif south-vergent duplex structure (Putiš, 1989; 1991a; Putiš in Krist et al., 1992; Putiš in Biely et al., 1992; Hrouda et al., 2002) (Figs. 5, 6). The flatly lying Vápenica Nappe overlying the compressed WSW–ESE striking and mostly steeply south-dipping structure of the Northern-Veporic phyllonite zones indicates postponed back-thrusting in relationship to the northward Fatric nappes formation. The Late Cretaceous sinistral transpression zone between the Čertovica and Pohorelá thrust-faults formed during and after the expulsion of the Fatric nappes over the Tatric Unit. The Čertovica thrust-fault separates the sutured Northern-Veporic–subautochthonous Fatric domains from the Tatric Unit in the footwall (Fig. 3). The Staré Hory Nappe in the western Nízke Tatry Mts., and the Rázdiel (an equivalent of the Vápenica Nappe overlying Northern Veporic-type basement–cover rocks) and Zobor nappes in the Tribeč Mts. are thrust over the Tatric sliver, and thus the Čertovica thrust-fault is inferred to continue to the Tribeč Mts. (Putiš et al., 1991a; Hók et al., 2000; Hók and Vojtko, 2011; Plašienka, 2018; Putiš et al., 2021; Petřík et al., 2024) (Figs. 3, 4).

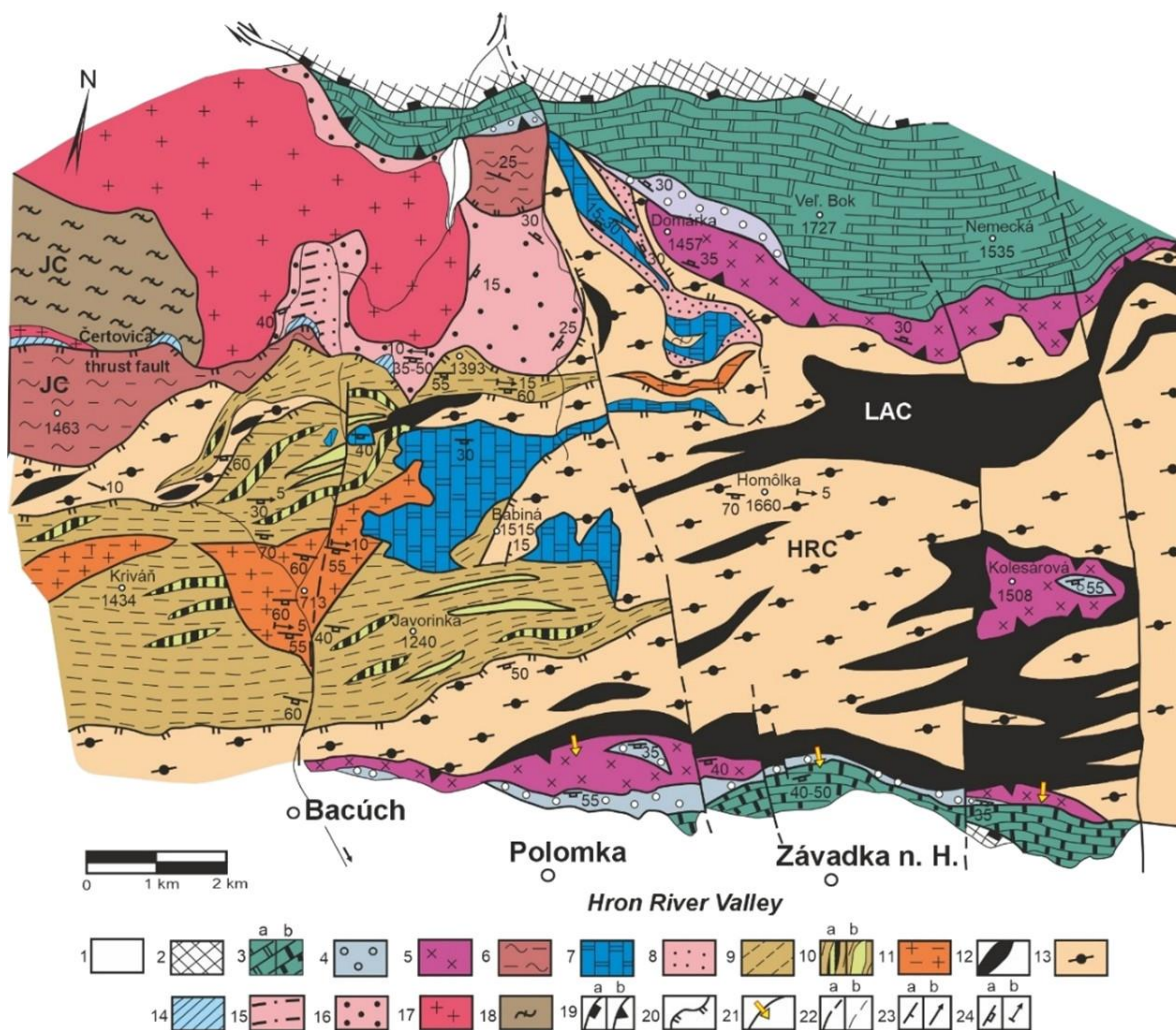


Fig. 6: Geological map of the western part of the eastern Nízke Tatry Mts. (modified from Putiš, 1989, 1991a; Putiš in Biely et al., 1992). Contact of the Tatricum and the Northern-Veporic Ľubietová and Krakľová nappes at the Čertovica thrust-fault, and southvergent subautochthonous Fatric Vápenica Nappe. 1—Quaternary and Cenozoic deposits; 2—Hronic Choč Nappe undivided (from Biely et al., 1992); 3a—SE-vergent Vápenica Nappe on the northern slopes of the Nízke Tatry Mts. overlying the Krakľová Nappe; 3b—Vápenica Nappe in the Upper Hron Valley synform; 4—Permian siliciclastic sediments of the Veľký Bok Succession (a part of the Vápenica Nappe); 5—Variscan tonalites to granodiorites of the Vápenica Nappe mylonitised hanging wall; 6—Ľubietová basement-cover nappe; 7—Triassic carbonates of the Krakľová Nappe; 8—Lower Triassic quartzites of the Krakľová Nappe; 9—11—Permian: low-grade metamorphosed siliciclastic sediments (9), acidic (10a) and basic (10b) volcanics, and granite porphyry (11); 12—Amphibolites (LAC) overlying the micaschist gneisses (13) in the Cretaceous Krakľová Nappe; 14—16—Triassic cover of the Tatricum: carbonates (14), shales (15), and quartzites (16); 17—18—Variscan basement of the Tatricum: granites to tonalites (17), gneisses to migmatites (18); 19a—Thrust plane of the Choč Nappe (Hronicum); 19b—Thrust plane of the subautochthonous Fatric Vápenica Nappe over the Northern-Veporic Krakľová Nappe; 20—Important thrust planes subsequent to subhorizontal nappe thrusting; 21—Thrust planes probably influenced by gravitational sliding; 22—Faults, strike-slips (a) and geological boundaries (b); 23—Pre-Alpine metamorphic schistosity/foliation (a) and lineation (b); 24—Alpine schistosity (a) and lineation (b). JC—Variscan Jarabá Complex, LAC—Variscan Layered amphibolite Complex, HRC—Variscan Hron Complex.

Locality No. 1: An outlook to Kráľova Skala Hill in Kráľova Hoľa Massif

GPS: 48°52'24.50"N; 20°09'21.64"E; 1641 m a.s.l. (Kráľova Skala Hill)

Position: Nižné/Predné Saddle, GPS: 48°51'49.80"N; 20°08'02.00"E; 1448 m a.s.l., 4 km NNE of the village of Šumiac, Kráľova Hoľa Massif, southern slope

Tectonic Unit: Vápenica Nappe of the subautochthonous part of the Fatric Unit (Figs. 5, 6 in Introduction)

Structure: The hanging wall of the S-vergent Vápenica Nappe overlying the S-vergent structure of the Northern Veporic Krakľová Nappe and the Southern Veporic Kráľova Hoľa Nappe duplex structure

Rocks: tonalite, mylonite and blastomylonite

The Vápenica Nappe (Putiš, 1989, 1991a), belonging to the subautochthonous part of the Fatric Unit, is characterised by a sheared and strongly tectonically thinned granitic sole (reduced to 300–150 m in thickness), macroscopically exhibiting variable degrees of deformational recrystallisation of granodioritic to tonalitic protomylonites, mylonites and schistose hanging wall blastomylonites. The mylonitic foliation dips 30–50° to the north, with subhorizontal W–E to WNW–ESE stretching lineations observed on the northern slopes of the eastern Nízke Tatry Mts. ridge, from the Domárka Hill in the west to the Holica and Dzurová Hills in the east. However, on the eastern slopes of the Kráľova Hoľa Massif, the foliation dips 20–25° towards the ENE to ESE. The southern termination of the Vápenica Nappe is located at the Kráľova Skala Hill site, where the mylonitic foliation dips to the SE and the stretching lineations are shallowly ESE-dipping. The nappe also forms the northern and southern limbs of the Upper Hron River synform between the villages of Pohorelá and Bacúch (Figs. 5, 6 in Introduction).

The original Variscan granodiorites to tonalites are peraluminous and belong to the calc-alkaline series. They display I-type affinities and are associated with magmatic arc and post-collisional extension settings. Whole-rock initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.706542–0.707581 and $\epsilon\text{Nd}_{(350)}$ ranging from 0.05 to –1.9 (with the exception value of –4.89 in the KS-1 sample from Kráľova Skala locality) indicate mixed lower-crustal- and mantle-dominated sources. Variscan tonalite (Pl, Bt, Qz, Ttn) from Kráľova Skala locality was dated on zircon at 351 ± 1 Ma by LA–ICP–MS U/Pb geochronology, whereas a tonalite from Domárka Hill yielded an age of 343 ± 2 Ma (Kianguebene-Koussingounina et al., 2025, 2026 in press).

During the Cretaceous orogeny, this Variscan tonalite underwent significant deformation and recrystallisation, resulting in the formation of protomylonite, mylonite and blastomylonite (Fig. 1.1A–D). Pronounced crystal-plastic deformation is observed in quartz and, to a lesser extent, in plagioclase. The mylonitic schistosity contains macroscopically visible fine-grained aggregates of white mica, Chl, Qz, Ab, Ep, Cal and the elongated Qz–Fsp porphyroclasts parallel to the WNW–ESE striking stretching lineation (Putiš, 1989). Alpine mylonitisation destabilised the primary magmatic minerals, resulting in the formation of diverse deformation–recrystallisation textures and newly formed secondary phases, including quartz, albite, chlorite, celadonite-rich muscovite ('phengite'), Fe-rich and Ti-poor biotite, sagenitic titanite, Ca-rich garnet, minerals of the epidote–clinozoisite group, tourmaline, calcite, and rare stilpnomelane. Characteristics include breakdown microtextures of primary allanite-(Ce) to epidote–clinozoisite (Ondrejka et al., 2022; Kianguebene-Koussingounina et al., 2025, 2026 in press). The metamorphic P–T conditions of the tonalite mylonite were estimated to 330–340 °C and 350 MPa (Fig. 1.1, right) at the Domárka Hill area (Putiš et al., 2021) using the Chl–Ph–Qtz–H₂O geothermobarometry (after Vidal et al., 2006).

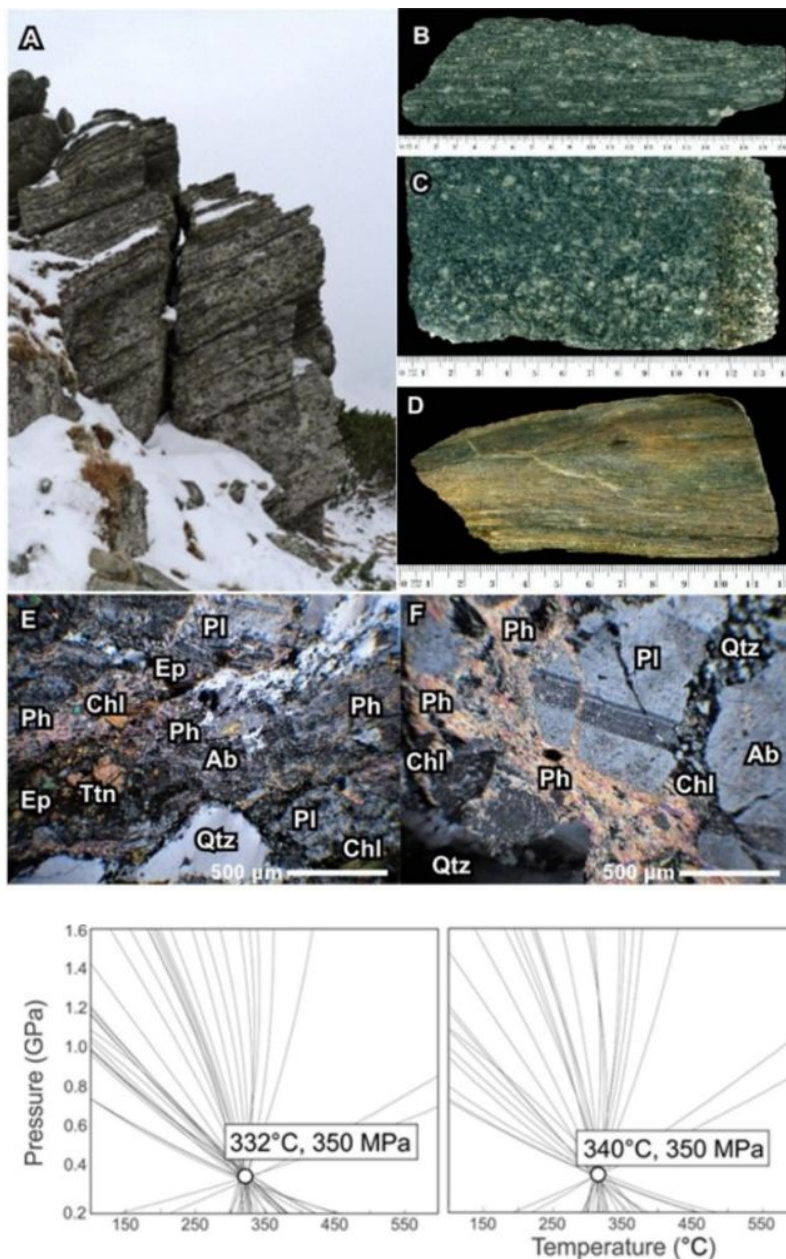


Fig. 1.1: Up: Tonalite mylonite to blastomylonite (sample KS-1) from Kráľova Skala Hill. (A) Mylonitic foliation in tonalite; (B) XZ cut; (C) YZ cut; (D) Blastomylonite from the nappe thrust plane; (E–F) Mylonitic textures (Putiš et al., 2021). **Down:** P–T diagrams showing univariant curves and their intersections defined by equilibrium Chl–Ph pairs, indicating P–T conditions for the tonalite mylonite from the Domárka Hill area of the Vápenica Nappe (Putiš et al., 2021).

Locality No. 2: Skalička Saddle (southern ridge of Mt. Král'ova Hoľa)

GPS: 48°51'07.03"N; 20°08'18.47"E; 1162 m a.s.l.

Position: 1.4 km NNE of the village of Šumiac

Tectonic Unit: Southern Veporic Unit (Fig. 5 in Introduction)

Structure: The Král'ova Hoľa Nappe S-vergent duplex structure

Rocks: Porphyritic granite mylonites

The main part of the Král'ova Hoľa Massif is composed of granites and granodiorites of the Variscan Vepor Pluton, intruded into paragneisses of the Variscan Upper Unit Jarabá Complex. This large granitic plutonic body continues southwards to the Fabova Hoľa, Tresník and Stolica massifs, which are composed of (meta)granites, (meta)granodiorites, and (meta)tonalites, overlain by low-grade metamorphosed Permian–Triassic Föderata sedimentary cover rocks (e.g., Putiš, 1987b, 1989, 1991a; Krist et al., 1992).

These excursion localities (Fig. 2.1A, B) yielded magmatic zircon ages of 350 ± 1 Ma (Skalička, sample SKA–1) and 352 ± 1 Ma (Šumiac, sample SUM–1) (Molnárová et al., new age data). The steep slopes of the Stolično and Šumiac canyon-shaped valleys expose phyllonitic metapelites along a sub-horizontal thrust plane separating the lower and upper granitoids within the S-vergent frontal duplex structure of the Král'ova Hoľa Nappe (Fig. 5A, C in Chapter 1), which is overlain by the Krakľová and Vápenica nappes (Putiš et al., 1989, 1991a).

The Skalička locality Vepor-type metagranite mylonite exhibits SE-dipping metamorphic–mylonitic foliation, whereas the stretching lineations are shallowly E–SE dipping. The Alpine metamorphic mineral assemblage (Fig. 2.1C) consists of Qz, Ab, Chl, low-Ti Bt₂, Ph, Rt, Ttn $\pm$ Grs-rich Grt (Putiš, 1989, 1991a, 1994), defining maximum AD1 burial P–T conditions within the garnet zone. Phengite yielded Ar–Ar ages of 100–85 Ma (AD2 exhumation stage), whereas the oldest phengite aggregates gave ages of ~ 124 Ma (from a S-Veporic orthogneiss) and monazite dated by EPMA (from a S-Veporic Permian metarhyolite) yielded ~ 128 Ma, corresponding to the AD1 burial stage (ca. 130 to 100 Ma) in the Fabova Hoľa Massif (Putiš et al., 2009b, 2019b, 2021).

Using the GeoPS modelling software, conditions of 480 °C at 630 MPa (Fig. 2.2, left) were estimated from the Fabova Hoľa Massif metagranitoids (Nemec, new data), indicating AD1 burial conditions in the frontal part of the Early Cretaceous Southern Veporic–Gemic–Meliatic wedge. This temperature is consistent with the fully ductile behaviour of dynamically recrystallised Qz and a semi-ductile behaviour of Fsp during AD2 exhumation associated with top-to-the-ESE structural unroofing. This stage is recorded in Qz and Cal textural patterns (Fig. 2.2, right) from extensional shear zones (Putiš et al., 1999).

The Variscan granitoids of the Vepor Pluton in the Král'ova Hoľa Massif, together with those of the Fabova Hoľa and Tresník massifs, belong to the Král'ova Hoľa Nappe (Klinec, 1976). They comprise granites to granodiorites of the Vepor and Ipeľ types and tonalites of the Sihla type. Zircon saturation thermometry indicates crystallisation temperatures in the range of 780–680°C. A systematic decrease in temperature with increasing SiO₂ content reflects fractional crystallisation towards more evolved peraluminous hybrid S/I-type varieties. The less fractionated Sihla type exhibits a higher Zr/Hf ratio (32–63), whereas the Vepor and Ipeľ types show a Zr/Hf ratio ranging from 18 to 64. The initial $\epsilon_{\text{Nd}(t)}$ values are lower in the Vepor and Ipeľ types of granitoid rocks (–1.9 to –2.7) and higher in the Sihla type (–0.8). The U–Pb zircon dating yielded ages of 357 ± 1 Ma for the Vepor-type granitoids and 345 ± 3 Ma or 359 ± 1.5 Ma for the Ipeľ-type granitoids. An age of 355 ± 2 Ma was obtained by in-situ U–Pb chemical dating of monazite-(Ce) from the Vepor and Ipeľ types of granitoids (Molnárová et al., 2024a, b). The emplacement ages of these granitoids indicate a Variscan arc-related anatectic event (Broska et al., 2013, 2022) within the Upper Variscan Unit Jarabá Complex, related to the northward

subduction of the Layered amphibolite and Koleso Valley complexes (ca. 390–380 Ma) and the Rakovec–Klátov Complex (ca. 370–360 Ma) (Putiš et al., 2023a, 2024a, b; 2026).

The deformation–recrystallisation characterisation of the Vepor Pluton metagranitoids in the Fabova Hol'a Massif continues at the locality No. 5A (the Pohorelá Shear Zone).

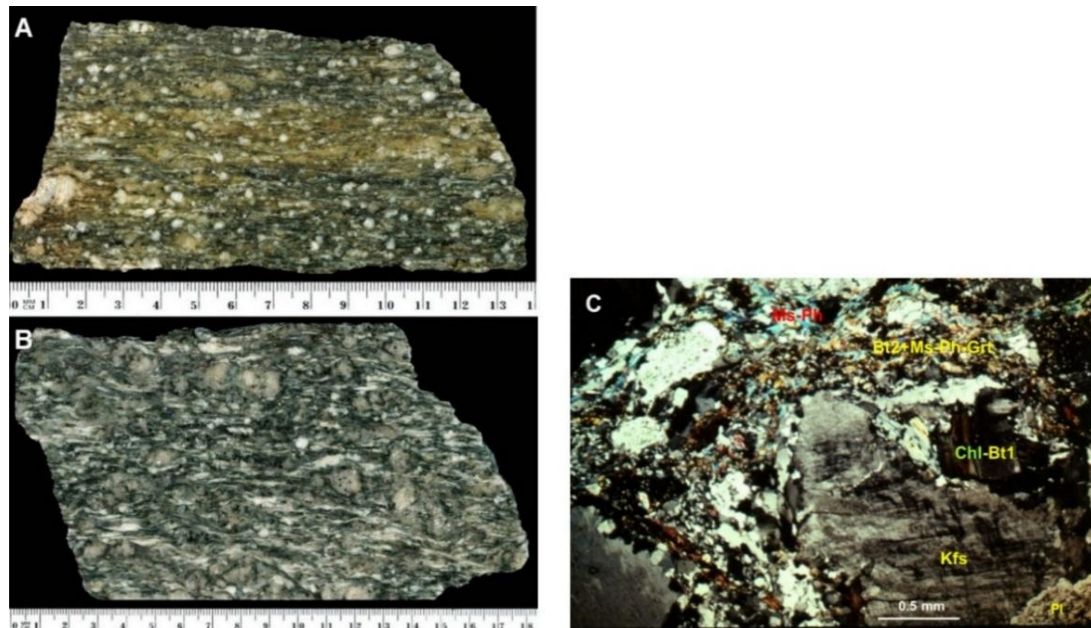


Fig. 2.1: (A) XZ section of medium-grained porphyritic granite from the Skalička locality. The mylonitic foliation dips SE-wards, whereas the stretching lineation is shallowly E-ward dipping. (B) XZ section of coarse-grained porphyritic granite (typical so-called Vepor-type) from an outcrop near the village of Šumiac. Subhorizontal S-planes are cross-cut by SE-dipping C'-planes bearing distinct stretching lineations. (C) Mylonitic texture of the Vepor-type porphyritic granite.

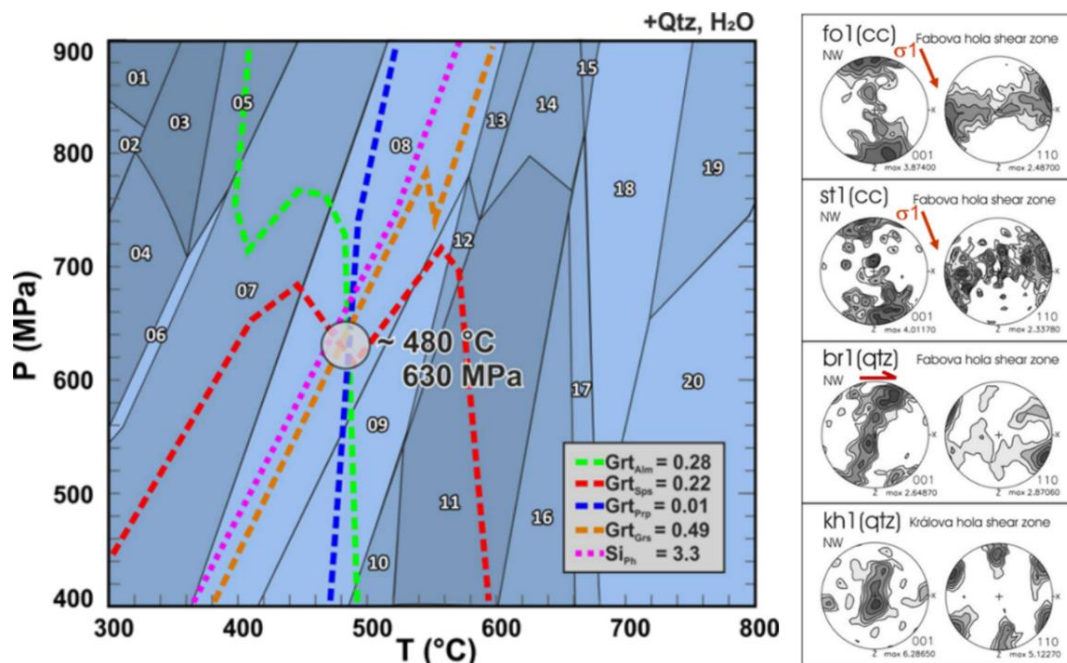


Fig. 2.2: Left: P–T diagram (pseudosection) for granodiorite sample FAH-1 (AD1 stage), calculated using the GeoPS ver. 3.3 software package (Xiang and Connolly, 2021) by Nemec (new data). Right: AD2 extensional exhumation (top-to-the-ESE structural unroofing) of the Southern Veporic basement–cover complex recorded in X-ray reflection texture goniometer patterns of quartz (qtz) and calcite (cc) (Putiš et al., 1999).

Locality No. 3: Krivul'a–Jaškovec Valley (south of Priehyba Pass)

GPS: 48°53'21.98"N; 19°58'47.09"E; 1040 m a. s. l.

Position: 3 km NNE of the village of Heľpa

Tectonic Unit: Northern Veporic Unit (Figs. 5, 6 in Introduction)

Structure: Variscan Middle Unit Hron and Koleso Valley complexes in the Cretaceous Krakľová Nappe

Rocks: Micaschist, Orthogneiss, Metagabbro, Paragneiss

Micaschists of the Hron Complex

Variscan St–Grt micaschists (Fig. 3.1) with And (Putiš, 1989) of the Middle Variscan Unit (Hron Complex), derived from late- to post-Cadomian passive margin sediments, contain detrital Zrn exclusively from two Ediacaran sources of ca. 620 and 570 Ma (Putiš et al., 2023a, 2024a, b). This complex rarely registers the Cenerian (late Cambrian to Ordovician) metamorphic–magmatic event, while Variscan granitoid magmatism is unclear (rare pegmatitic veins). In places, they are overlain by Permian volcanic–sedimentary suites (Kotov et al., 1996; Putiš et al., 2019b), or these micaschists show Permian reheating dated on Zrn, Rt (unpublished age data of M. Putiš), and Mnz (Jeřábek et al., 2008a). The Alpine mineral assemblage in phyllonitised micaschists (Fig. 3.1, right) consists of Cld, Ph, Qz, Chl, Ab $\pm$ Grs-rich Grt (Putiš, 1994; Putiš et al., 2021). These phengite (Phg, Ph) aggregates, dated at 91.9 ± 2.3 Ma by the ^{40}Ar – ^{39}Ar method, formed during the AD1 burial/underthrusting of the Northern Veporic and adjoining Fatric basement–cover rocks beneath the Southern Veporic Unit (Putiš et al., 2009b, 2021). The extensive Hron Complex is overlain by the Variscan Koleso Valley Complex and the Variscan Upper Unit hanging wall Layered amphibolite Complex (Figs. 5, 6 in Chapter 1).

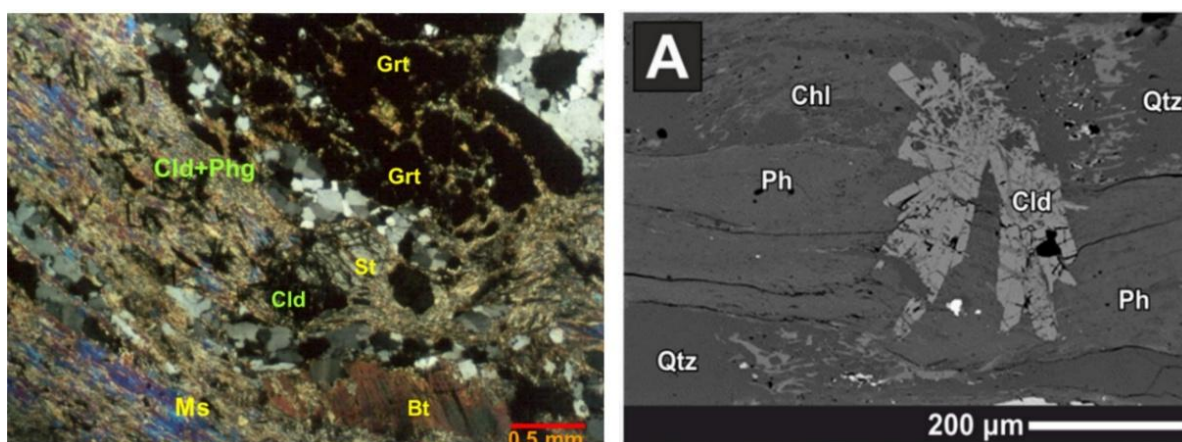


Fig. 3.1: Variscan St–Grt–Ms–Bt micaschist of the Hron Complex from Priehybka pass, with Alpine overprint Cld–Ph/Phg–Chl–Qz assemblage (Putiš et al., 2021).

Tonalitic to granitic orthogneiss of the Koleso Valley Complex

The largest orthogneiss body has a tonalitic composition (sample KO-2A-24; former KO-1), whereas its marginal parts (sample KO-1-24 and KO-5,6-25) are granitic in composition. The core of the (meta)tonalite body still has well-preserved early to middle Cambrian magmatic zircons but also displaying textural overprints related to the Cenerian, Variscan and Alpine orogenies.

The tonalitic orthogneiss (KO-2A-24) contains zircons with inherited partly dissolved Ediacaran (rarely older) cores overgrown by euhedral oscillatory zoned early to middle Cambrian rims (av. Th/U 0.23), which provided concordia ages between 540–520 Ma (Fig. 3.2). The youngest Zrn core population, with a concordia age of ~ 570 Ma, is consistent with the youngest detrital Zrn population (~ 570 Ma) identified in the host paragneisses. These orthogneisses may have thus formed by melting of late- to

post-Ediacaran (Cambrian) sedimentary sources within a late Cadomian magmatic (fore)arc setting. Early to middle Cambrian ages were not detected in the Zrn cores of the host metasediments, which is consistent with contemporaneous felsic magmatism within the host metasediments (Putiš et al., 2008a, 2023a, 2024a, b).

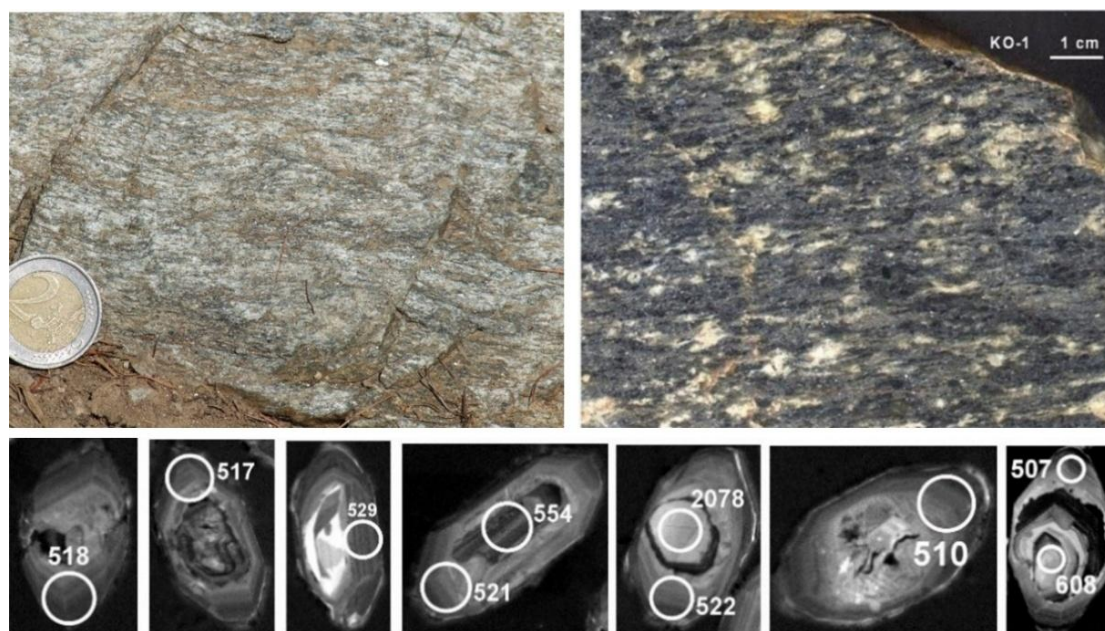


Fig. 3.2: Tonalitic orthogneiss KO-2A-24 (KO-1 from Putiš et al., 2008a; Michálek and Putiš, 2009) contains early to middle Cambrian magmatic Zrn with inherited Ediacaran and older cores (Putiš et al., 2008a, 2023a, 2024a, b, and new age data).

In addition, they contain a newer generation of late Cambrian to Ordovician (Cenerian) metamorphic–anatectic zircons (Fig. 3.3), often overgrowing inherited cores (av. Th/U 0.04), yielding concordia ages from 492 to 480 Ma. They also contain millimetre-size Grt1 porphyroblasts with Early Ordovician Mnz (Fig. 3.4, left) and Ilm inclusions, as well as Qz, Pl, Kfs, Bt1 (hosting Ordovician Mnz and Xnt inclusions), and Ms (Fig. 3.4, right). Variscan metamorphic assemblage consists of fine-grained Ky–Grt aggregates (tiny Grt2 grains with Rt and Ky inclusions), Rt, Qz, Bt2/Phg and Ms–Mrg–Phg aggregates (Fig. 3.5, left). A Late Variscan dextral shear zone records top-to-the-SE thrusting, as documented by Grt (Fig. 3.5, right). The Alpine assemblage of Qz, Phg, Ab, Chl, Ep, Czo, Grs-rich Grt3, Fe-Bt3, Ttn, Mag and Cal occurs in micro-shears (Michálek and Putiš, 2009).

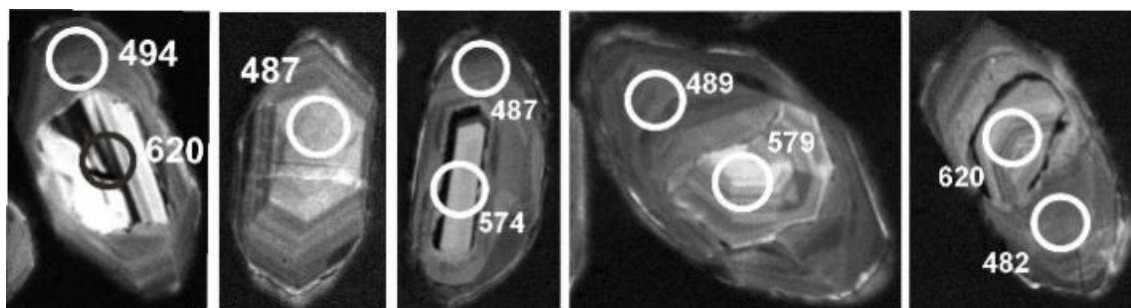


Fig. 3.3: Tonalitic KO-2A-24 (KO-B in Fig. 3.4) orthogneiss (sample KO-1 in Putiš et al., 2008a). Newly formed late Cambrian to Early Ordovician zircons or Zrn rims have extremely low Th/U due to their metamorphic–melting (Cenerian) origination (Putiš et al., 2024a, b, and new age data).

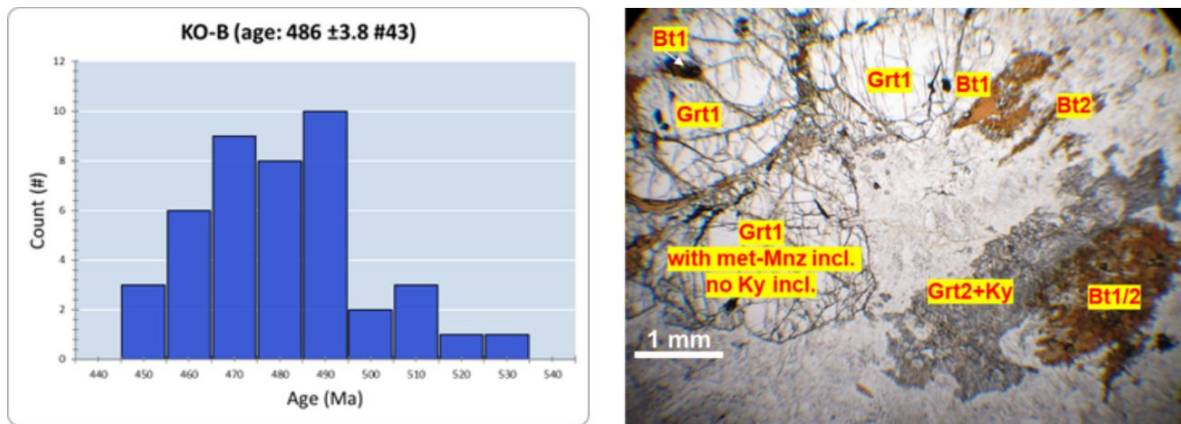


Fig. 3.4: Early Ordovician metamorphic Mnz (left age diagram) inclusions in Grt1 porphyroblasts and Bt1 (right) (KO-2A-24, KO-B). The Ordovician metamorphic peak is characterised by Grt1, Pl, Bt1, Qz, Ilm, Zrn, Mnz at $\geq 700^\circ\text{C}/\text{MP}$? Grt2+Ky+Bt2/Ph indicates a Variscan overprint (Putiš et al., 2008a, and new data).

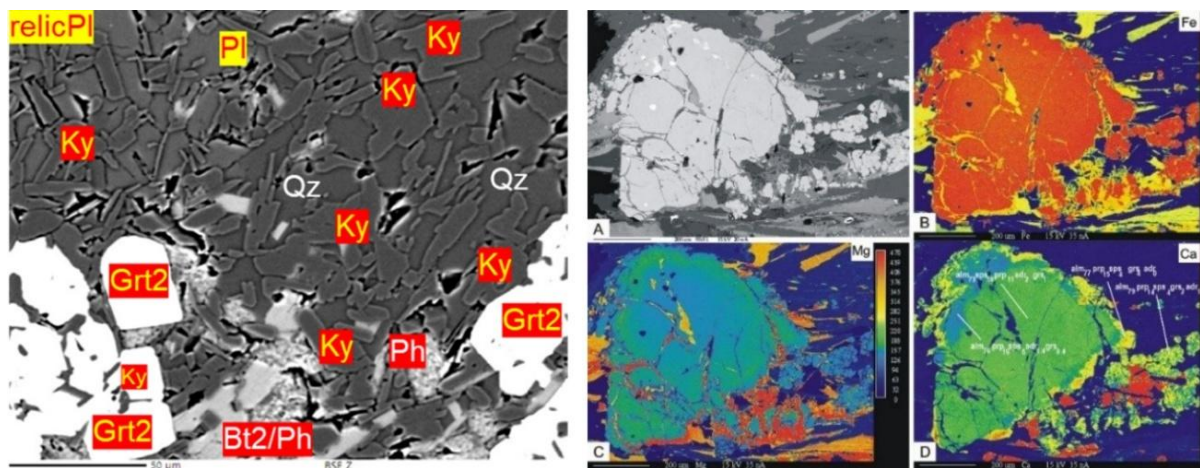


Fig. 3.5: Left: Variscan metamorphic assemblage (KO-2A-24 sample). Variscan metamorphic peak is characterised by Grt2, Ky, Rt, Bt2/Ph, Qz, $\pm\text{Zrn}$ and Mnz at $640\text{--}660^\circ\text{C}$ and $0.78\text{--}0.9\text{ GPa}$ (Perple_X modelling), Ph (Si 3.35): $\sim 1.2\text{ GPa}$ based on Ph-barometry (Putiš et al., 2024a, b, and new data). **Right:** Late Variscan southeast-ward thrusting of the Koleso Valley Complex over the Hron Complex. Syn-kinematic recrystallisation of Grt1 into snowball-type δ structure with tails of tiny Grt aggregates (both Alm-rich) in the tonalitic orthogneiss (KO-1) mylonite (Michálek and Putiš, 2009).

Other homogeneous to porphyritic orthogneisses (Fig. 3.6) appear to represent a direct product of the Cenerian magmatic event, and these do not contain such a (Cenerian) metamorphic mineral assemblage like the tonalitic orthogneiss KO-2A-24. Part of them may have formed by remelting of the tonalitic orthogneiss (KO-1-24; av. Th/U 0.05; $\sim 480\text{ Ma}$; KO-6-25; av. Th/U 0.02; $\sim 487\text{ Ma}$) or represent newer intrusions (KO-5-25).

The granitic orthogneiss (sample KO-5-25; av. Th/U 0.51; $\sim 490\text{ Ma}$) yields newly formed late Cambrian to Ordovician magmatic Zrn grains (av. Th/U 2.01), as well as inherited magmatic early to middle Cambrian (rare older) Zrn cores (Fig. 3.6). This type of orthogneisses likely formed by melting of metasediments together with the early to middle Cambrian felsic magmatic rocks (as indicated by the inherited cores) during the late Cambrian to Ordovician (Cenerian) event. Although Ordovician metamorphic textures are absent, in contrast to the KO-2A-24 type, the Variscan metamorphic overprint and ductile deformation are well-developed.

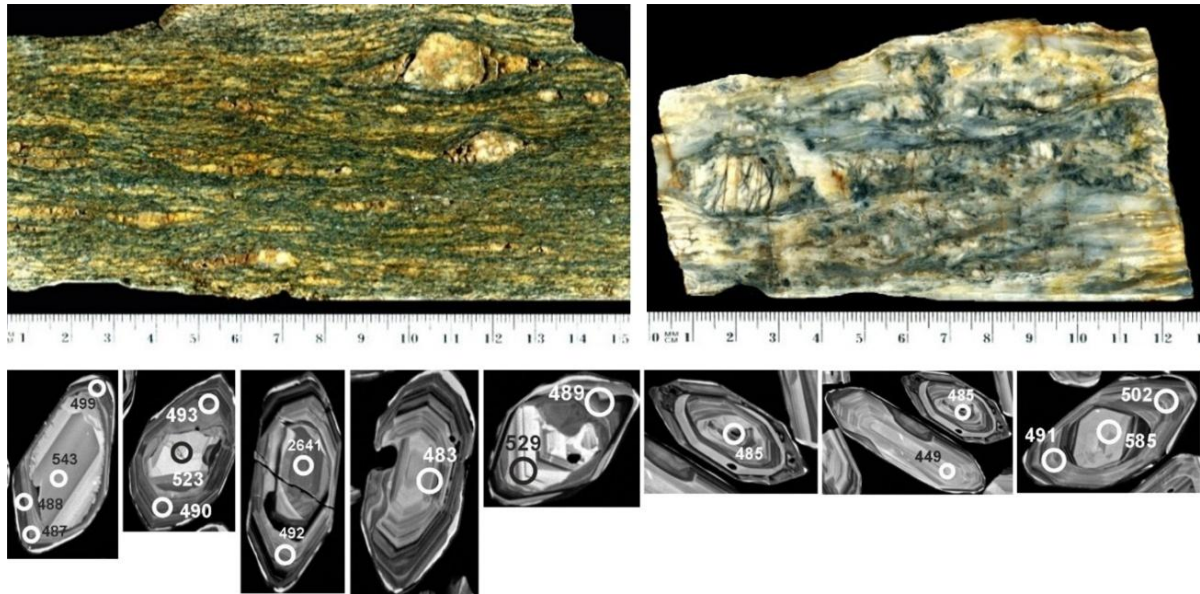


Fig. 3.6: The KO-5-25 (left) and KO-6-25 (right) late Cambrian to Ordovician granitic orthogneiss mylonites. The sample KO-5-25 contains inherited early to middle Cambrian (rare older) Zrn cores (Putiš et al., 2024a, b and new age data).

Metagabbro and metaperidotite of the Koleso Valley Complex

Originally, troctolitic Ol-Pl gabbro (samples KO-56, 100, 101, KO-20-25) has well-developed metamorphic reaction-corona texture between Ol and Pl, composed of Cpx-Di, brown Ti-Prg-Amp, and Cpx-Amp symplectites, partly replaced by Srp, Mag, Tr/Act, Ab, Ep, Czo and Qz (Fig. 3.7).

Similarly, carbonate-silicate metaperidotite lenses (samples KO-6, 21, KO-20-25) have locally well-preserved magmatic textures indicated by original magmatic reaction coronas between carbonate (Dol-Mgs oikocrysts) and silicate (Ol1, Opx1, Spl) melts (Fig. 3.8). Metamorphic overprint is indicated by partial breakdown of Dol to C and Mag, and by Ol1 (X_{Fo} 0.74) and Opx1 (X_{En} 0.76, CaO 0.33–0.39 wt%), and metamorphic matrix composed of Ol2, Opx2, Cpx, and Grt, overgrown by retrograde Ti-Prg.

Magmatic concordia Zrn ages of the metagabbros (KO-25A-25) and associated eclogites (JAS-10) are approximately 480 Ma, whereas Rt from the eclogite lens (JAS-10) provided a post-metamorphic cooling age of ~330 Ma and Permian reheating at ~277 Ma (unpublished age data of M. Putiš).

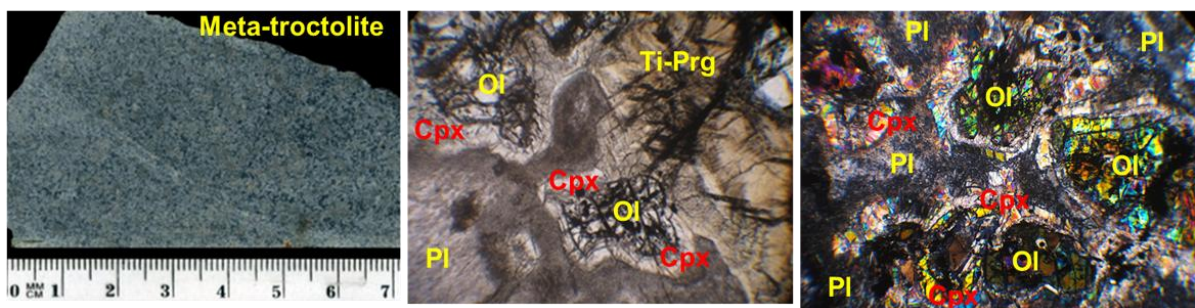


Fig. 3.7: Massive troctolitic metagabbro (KO-100c) has a well-preserved magmatic texture of Ol and Pl. Metamorphic Cpx-bearing reaction coronas between Ol and Pl are conspicuous, overgrown by Ti-Prg-Amp.

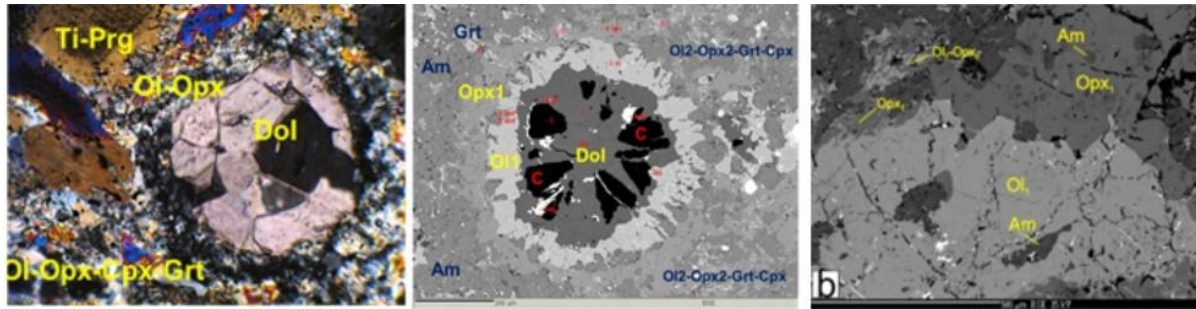


Fig. 3.8: Massive carbonate–silicate metaperidotite (sample KO-6) has a well-preserved magmatic texture with reaction corona of Dol–Mgs oikocrysts with Ol1 and Opx1 with Spl inclusions. Fine-grained metamorphic matrix, composed of Ol2–Opx2–Cpx–Grt, is overgrown by Ti–Prg (Michálek and Putiš, 2009, 2011).

Paragneiss of the Koleso Valley Complex

Variscan Ky–Grt paragneisses (Ky, Grt, Rt, Bt, Ms–Phg, Pl, Qz) form the host rocks of the orthogneisses. They contain partly dissolved dominant Ediacaran detrital zircons overgrown by late Cambrian to Ordovician euhedral rims. The newly formed Zrn population of indistinctly oscillatory zoned to mosaic grains (av. Th/U 0.05) yielded 492–480 Ma (Fig. 3.9), providing evidence for a (Cenerian) metamorphic–melting event (Putiš et al., 2008a, 2023a, 2024a, b).

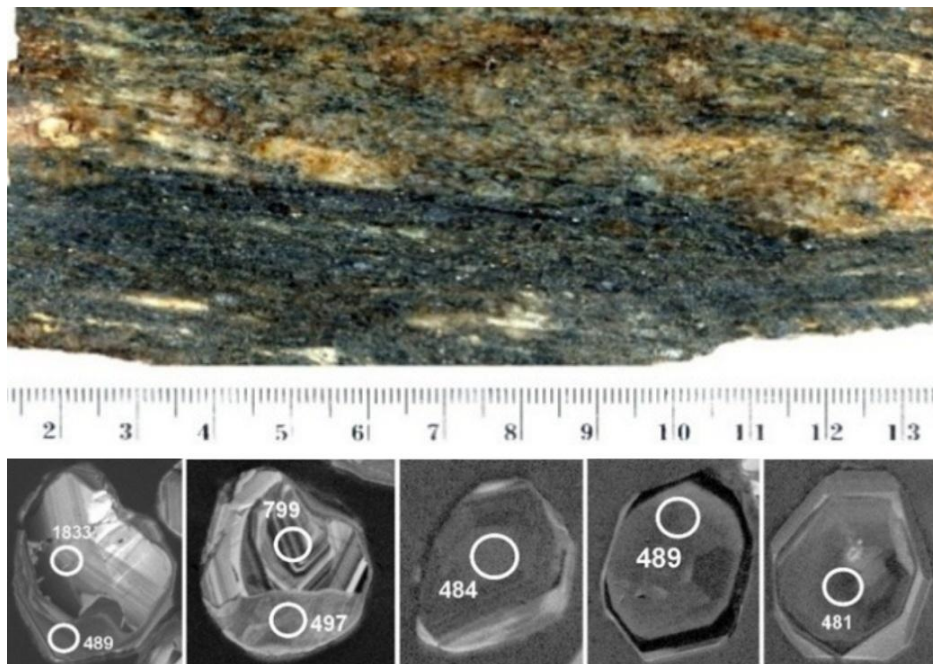


Fig. 3.9: Migmatitic (Variscan) paragneiss (samples KO-58 and KO-21-25) contains newly formed late Cambrian to Early Ordovician metamorphic–anatexitic Zrn grains and outer Zrn rims on older cores due to the Cenerian metamorphic event.

Locality No. 4: Heľpa – Hájníca

GPS: 48°51'09.89"N; 19°57'55.59"E; 645 m a.s.l.

Position: 1 km SW of the village of Heľpa

Tectonic Unit: Northern Veporic Unit, Vápenica Nappe

Structure: Hron Valley synform southern margin

Rocks: Permian cover of tonalites: arkoses with basalt interlayers

This locality exposes Permian arkosic metasandstones (Fig. 4.1A, C) with intercalation of Hem-rich metabasalt (Fig. 4.1 B, D) in a quarry in the Heľpa – Hájníca area (Fig. 4.2). Syn-metamorphic, medium- to coarse-grained Qtz–Phg–Ab veins, oriented sub-parallel to the metamorphic schistosity, occur within the metaarkoses.

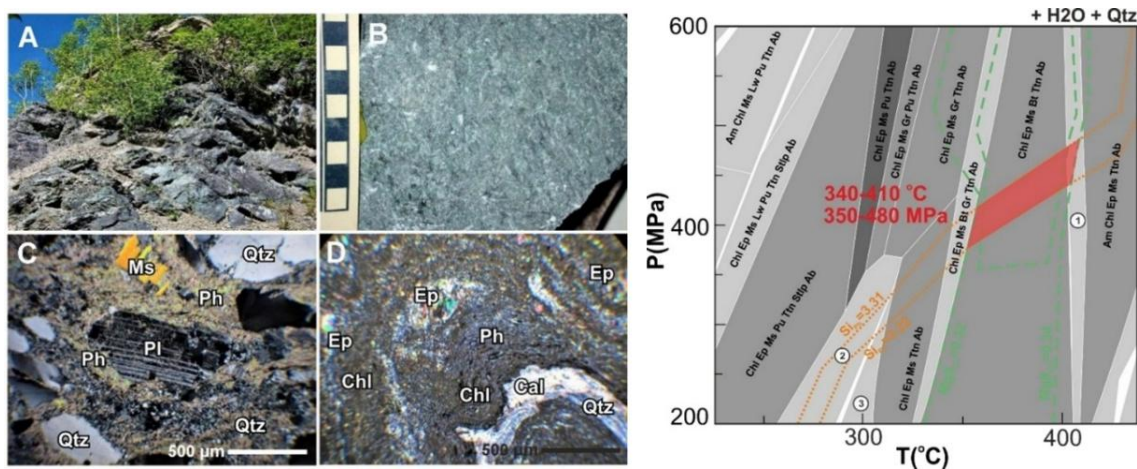


Fig. 4.1: Left – Permian arkosic metasandstone (A, C, sample HP-22, from the top of the quarry; and pale debris) with a metabasalt intercalation (B, D, sample HEL-1) in a quarry south of Heľpa. **Right** – P–T pseudosection calculated using Perple_X thermodynamic software (Connolly and Petrini, 2002; Connolly, 2005) for the Permian metabasalt (sample HEL-1) of the Vápenica Nappe, using isopleth intervals of Si-in-Ph 3.22–3.31 p.f.u. and $Chl_{Mg\#}$ 0.32–0.34. Numbers refer to mineral assemblage: 1: Amp, Ch, Ep, Ms, Bt, Ttn Ab 2: Chl, Ms, Ep, Pum, Stp, Ttn, Ab, 3: Chl, Ms, Ep, Pum, Prh, Ttn, Ab (Putiš et al., 2021).

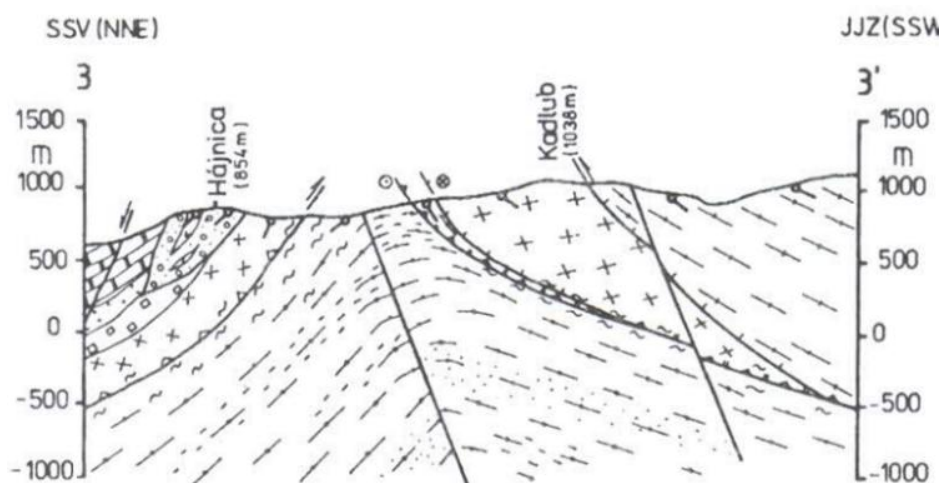


Fig. 4.2: A cross-section through Permian metaarkoses and metabasalts of the Hájníca Hill area, representing the cover of the Vápenica Nappe metatonalites overlying the micaschists of the Krakľová Nappe (Variscan Middle Unit – Hron Complex). The sinistral Pohoreľá Shear Zone separates the granitoids and paragneisses of the Kráľova Hoľa Nappe (Variscan Upper Unit) from the Krakľová Nappe west of Kadlub Hill (Madarás et al., 1994). The map and legend are the same as at the next locality (No. 5).

Locality No. 5A: Hronec Valley (Závadka nad Hronom) and 5B: Petříkovo Valley (Polomka)

GPS (5A): 48°49'47.21"N; 19°55'56.31"E; 670 m a.s.l.

Position: 2.7 km SSE of the village of Závadka nad Hronom, a quarry in the Hronec Valley

Tectonic Unit: Northern/Southern Veporic Units boundary

Structure: Pohorelá shear zone

Rocks: Cretaceous mylonite of a Variscan tonalite

GPS (5B): 48°49'35.45"N; 19°50'47.44"E; 705 m a.s.l.

Position: 2.9 km SSW of the village of Polomka, Petříkovo Valley

Tectonic Unit: Northern/Southern Veporic Units boundary

Structure: Pohorelá shear zone

Rocks: Cretaceous phyllonites of a Variscan micaschist from the Hron Complex

The Pohorelá and Lubeník shear zones in the Slovenské rudohorie Mts. are interpreted as Early Alpine footwall-propagation thrust-faults (Hók and Hraško, 1990; Putiš, 1991a, b, 1994; Hók et al., 1993; Madarás et al., 1994; Sulák et al., 2009; Hók and Vojtko, 2011) developed within the Meliatic passive continental margin (~135–105 Ma, Phg Ar–Ar and Mnz EPMA ages; Putiš et al., 2009b, 2019b; Vozárová et al., 2014; Hurai et al., 2015). The AD1 thick-skinned compressive regime changed to AD2 transpressive–extensional tectonics during the rise of the Vepor Dome (Plašienka and Putiš, 1993; Madarás et al., 1996; Janák et al., 2001; Jeřábek et al., 2007, 2012) in the time interval between 105 and 85 Ma (Phg Ar–Ar and Bt2 Rb–Sr ages; Bibikova et al., 1990; Dallmeyer et al., 1993, 1996; Maluski et al., 1993; Putiš et al., 2009b), and was followed by cooling at ~80–55 Ma (Vojtko et al., 2016). The upper crustal rheology of the shear zones, whether in Grt or the Ky–Cld structural levels, is indicated by the fully ductile behaviour of quartz and calcite, contrasted with the semi-ductile behaviour of feldspars (Putiš, 1994).

Locality 5A (Hronec Valley)

The metatonalite mylonites of the Kráľova Hoľa Nappe (Fabova Hoľa Massif) at this excursion locality contain relic magmatic Pl and Bt1, ±Ttn. The south-dipping (~45°) mesoscopic mylonitic foliation is defined by flattened aggregates of Pl and Bt1, whereas subhorizontal stretching lineations striking W–E are indicated by the oriented, newly formed Alpine metamorphic aggregates of Ab, Ep, Bt2, Chl, and Qz. This fabric is cut at an acute angle to the north by the ENE–WSW-striking Pohorelá thrust-fault zone. About 100 m wide zone of tonalite blastomylonites (Chl–Phg schists) along the boundary with the Hron Complex micaschist-gneisses of the Kráľová Nappe (Figs. 5.1–4) indicates the Pohorelá shear zone.

In the opposite direction, further to the south, the mylonitic S-type foliation in granitoids dips southwards, the stretching lineations dip 10–25° towards the ESE to SE, and the extension C'-planes dip 30–40° towards the ESE (Putiš, 1991a, 1994; Putiš et al., 1997a). While the S-planes and subhorizontal C-planes (Fig. 5.5a–c) record the AD1 compressional tectonic regime, the C'-planes (Fig. 5.5d) reflect the AD2 core top-to-the-ESE structural unroofing (Plašienka and Putiš, 1993; Putiš, 1994; Madarás et al., 1996; Plašienka et al., 1999; Janák et al., 2001; Jeřábek et al., 2007, 2012).

Deformation analysis of feldspar and quartz porphyroclasts in sheared granitic mylonites (Figs. 5.1–2, 5.5–6) and Lower Triassic quartzitic metaconglomerates suggested the deformation regimes according to K-values in the diagram of Flinn (1962). These vary around $K \approx 1$ in the central parts of the shear

zones, indicating a plane strain type of non-coaxial deformation. Towards the shear zone boundaries, K-values decrease to about 0.5, within the dominant flattening field. In the innermost parts of shear zones, K-values increase to 2–10 and characterise the transition to a constrictional field of deformation. The shear factor γ , calculated from R_{fXZ} , converges to a value of ~ 1 in the central parts of the shear zones and to around 2 in the inner parts. γ -values derived from shear angle Θ are approximately twice as high (Fry, 1979). The values obtained by these two methods are therefore only broadly comparable. This indicates that the true simple shear (in the plane-strain regime) was not dominant. Instead, the mode of shearing was influenced by a transpressive or transtensive deformation regime (Putiš et al., 1997a, 1999).

Locality 5B (Petrikovo Valley)

This locality represents the northern margin of the Pohorelá ENE–WSW striking sinistral transpression shear zone, indicating the Late Cretaceous interaction of the Southern Veporic (being part of the southern wedge) and the Northern Veporic (being part of the northern wedge) units, or the Kráľova Hol'a and Krakľová nappes, respectively.

Subhorizontal original (pre-Alpine) position of metamorphic schistosity of phyllonitised micaschist-gneisses (Figs. 5B.3–4) is cut by SSE-dipping transpressional cleavage planes with subhorizontal ENE–WSW striking stretching lineation.

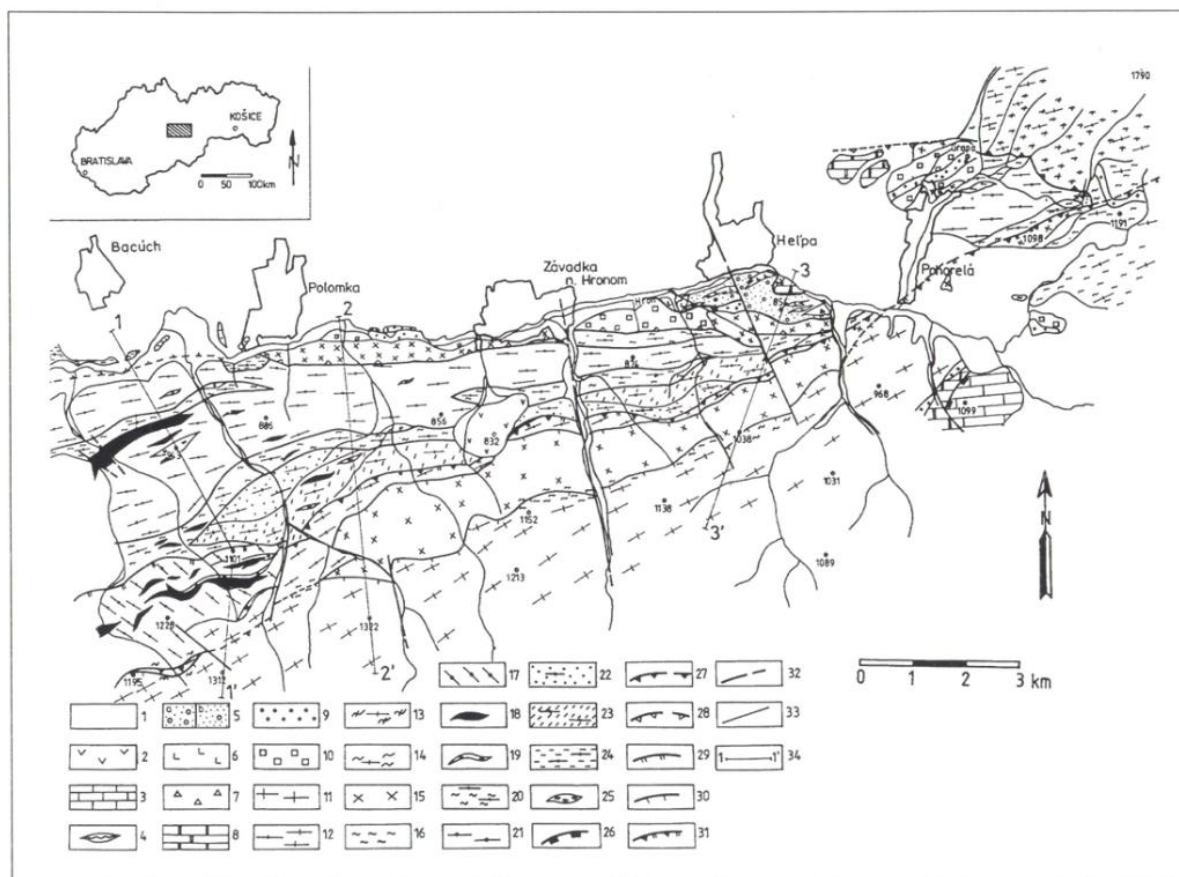


Fig. 5.1: Geological map of the middle part of the Pohorelá tectonic zone (after Madarás et al., 1994). 1 – Quaternary and Cenozoic rocks, 2 – Neogene andesite, 3 – Muráň Nappe (Silicic), 4 – metacarbonate (Triassic, Predná Hol'a type), 5 – metasandstone (Permian), 6 – metabasalt (Permian), 7 – Diorite (? age), 8 – Metacarbonates (Middle-Upper Triassic, Foederata type), 9 – Quartzites (Lower Triassic), 10 – Arkose, conglomerate, shale (Permian to Lower Triassic), 11 – Granite to granodiorite (Variscan) mylonite (Alpine), 12 – Granite blastomylonite, 13 – Migmatite, 14 – Migmatite blastomylonite, 15 – Tonalite (Variscan) mylonite (Alpine), 16 – Blastomylonite zone, 17 – Gneiss Qz rich, 18 – Amphibolite, Amp gneiss, 19 – Pegmatite, aplite, 20 – Phyllonite, 21 – Micaschist, 22–24 – Gneiss Qz- and mica-rich, 25 – Migmatitic gneiss, 26 – Thrust plane of the Muráň

Nappe, 27 – Thrust plane of the Kráľova Hoľa Nappe, 28 – Trust plane of the Vápenica Nappe, 29 – Reverse fault of the Pohorelá shear zone, 30 – Reverse fault of the second order, 31 – Pohorelá thrust-fault, 32 – Fault, 33 – Geological boundary.

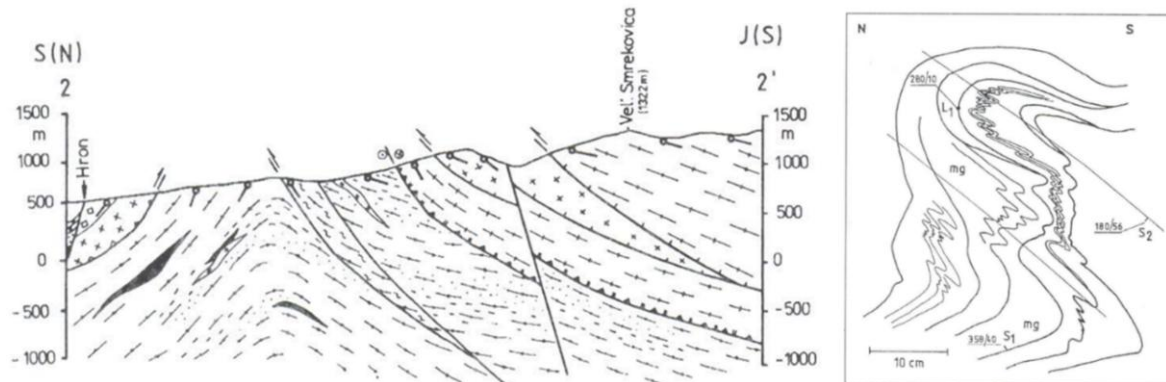


Fig. 5.2: **Left:** Cross-section across the sinistral Pohorelá shear zone north of the Fabova Hoľa Massif. **Right:** Transposition of the Variscan northward-dipping metamorphic schistosity in micaschist-gneisses (Hron Complex of the Kráľová Nappe) into Alpine southward-dipping axial-plane fold cleavage within the Pohorelá shear zone (Madarás et al., 1994). Transpressional harmonic-type fold axes are parallel to the ENE–WSW stretching lineations of the Pohorelá shear zone system.

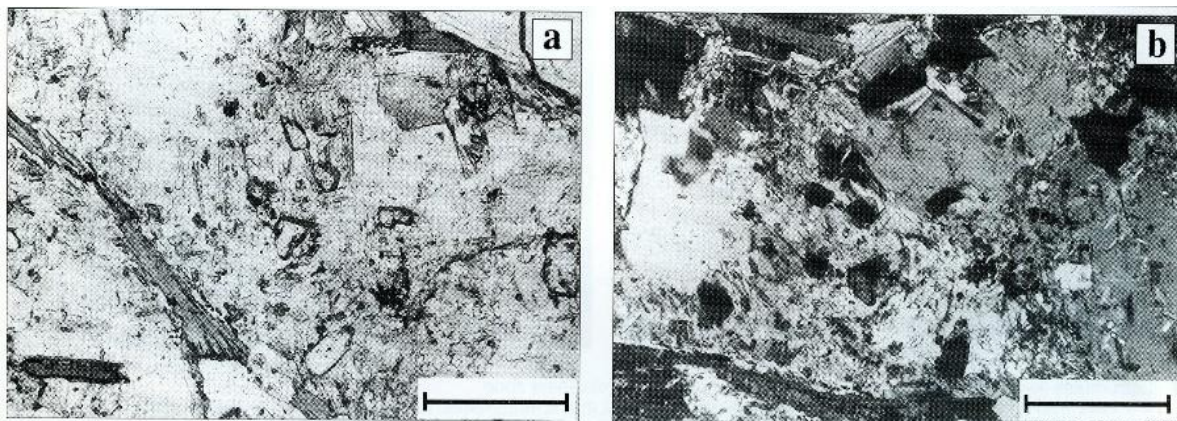


Fig. 5B.3: Micaschist-gneiss Pl porphyroblast of Hron Complex within Pohorelá shear zone (Hronec Valley) replaced by Cretaceous Ab, Grs-Grt, and Phg (Putiš, 1994). Scale bar 1 mm.



Fig. 5B.4: Phyllonite (Qz–Ab–Chl–Phg/Ms shist) of a micaschist-gneiss within the Pohorelá sinistral transpression shear zone in the middle part of the Petříkovo Valley (photo by M. Putiš). Subhorizontal original

(pre-Alpine) position of metamorphic schistosity is cut by 40–50° SSE-dipping transpressional cleavage planes with subhorizontal ENE-WSW striking stretching lineation.

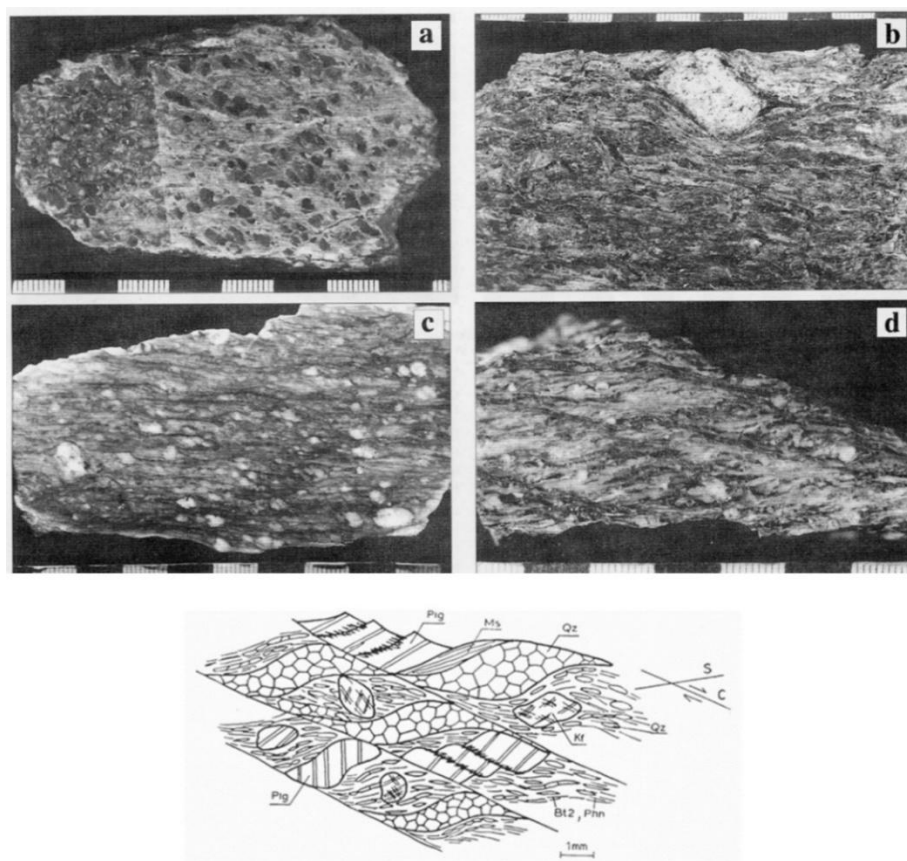


Fig. 5A.5. Cretaceous granitic mylonites from the Fabova Hol'a Massif (Putiš, 1994). (a) Granite blastomylonite with Qz grains in blastomylonitic Phg–Chl-rich matrix; (b–c) Mylonites of the porphyritic granites with dominant AD1 subhorizontal C-planes; (d) S–C' mylonite of porphyritic granite of the AD2 exhumation stage S of the Pohorelá shear zone, and a schematic texture sketch (C is C').

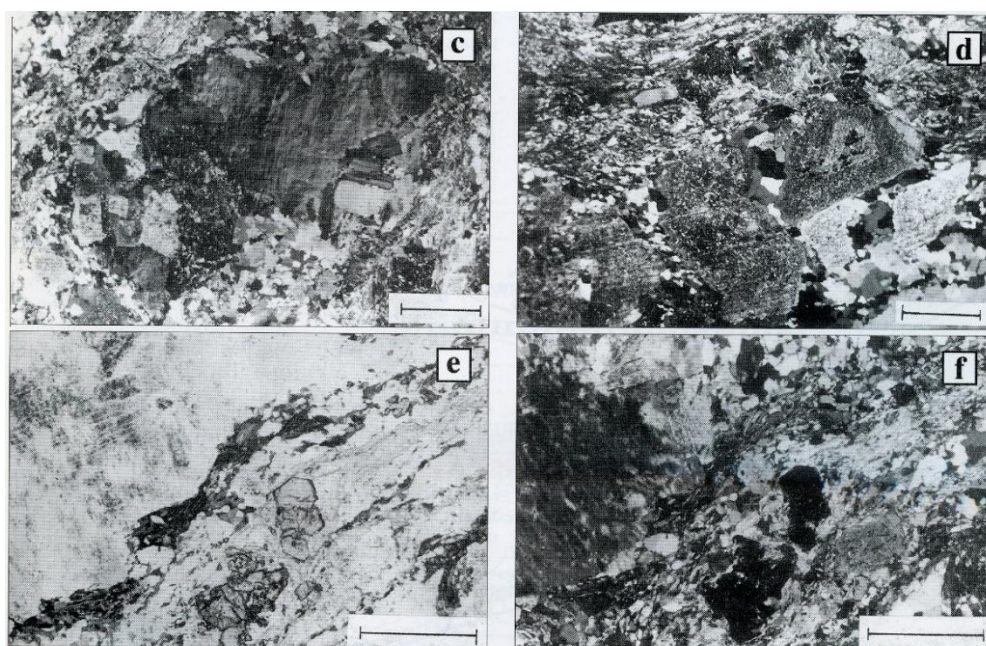


Fig. 5A.6: Microtextures of granitic mylonites from the Fabova Hol'a Massif documenting the Grt zone of the Cretaceous tectono-metamorphic overprint (Grs–Grt in e–f). Tension fractures of semi-ductile stretched Pl and Kfs porphyroclasts healed by Qz–Ab–Phg metamorphic aggregates (Putiš, 1994).

Locality No. 6: Závadka and Hronom, Hotel Vršky

GPS: 48°52'50.57"N; 19°54'49.76"E; 810 m a.s.l.

Position: 2 km north of the village of Závadka nad Hronom.

Tectonic Unit: Northern Veporic Unit (Fig. 6 in Introduction)

Structure: Layered amphibolite Complex within the Krakľová Nappe

Rocks: Layered amphibolite with signatures of Alpine overprint

The Layered amphibolite Complex (LAC) forms the base of the Upper Variscan Unit, overlying micaschist-gneisses of the Variscan Middle Unit Hron Complex (Fig. 6.1). The name of this complex reflects the internal magmatic layering of fractionated gabbroic intrusions (Fig. 6.2). An analogous term is „leptyno-amfibolite complex“, traditionally used in France, and introduced in Slovakia by Hovorka and Méres (1993). It is representative of an immature arc–backarc setting (Putiš et al., 2008a, 2009a), now ascribed to the Cenerian-type orogeny (Putiš et al., 2024b).

The layers or bands show different textures: relic, originally magmatic with a superimposed metamorphic overprint, newly formed anatectic–magmatic, and mylonitic. These textures imply a polystage petrogenesis represented by:

- pre-metamorphic magmatic, originally Cpx–Amp cumulates, gabbro, diorite, tonalite (trondhjemite) to leucotonalite layers, decametric to metric in thickness, with straight, sharp boundaries and internal metamorphic textures.
- migmatitic layering, preferably developed in the layer-parallel shear domains of decametric to milimetric width, displaying magmatic textures, or in-situ-formed magmatic (remelted) dioritic to leucotonalitic (trondhjemitic) sub-layers, including crosscutting pegmatitic to aplitic dykes.
- exhumation-related ductile mylonitic textures with dynamic recrystallisation of amphibole, plagioclase and quartz ribbons (Putiš et al., 1996, 1997a, b).

The original (oldest) magmatic layers were subsequently subjected to amphibolite- (Putiš et al., 1996) to eclogite-facies (Janák et al., 1996), or locally granulite-facies, metamorphic overprint. Some thicker metapelitic interlayers are represented by Ky–Grt paragneisses.

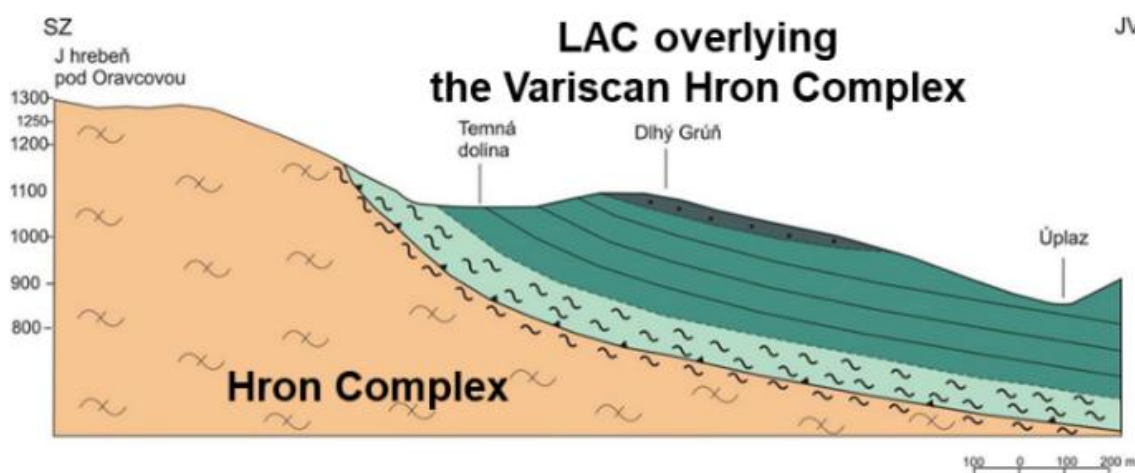


Fig. 6.1: NW–SE (Úplaz Valley, near the village of Závadka nad Hronom) profile across the contact between the LAC and the Hron Complex, showing an Alpine overprint (Filová and Putiš, 2004).

Pre-metamorphic magmatic compositional layering of the LAC was dated to ~497–476 Ma in dark metagabbro to metadiorite layers, and to ~494–477 Ma in pale metatonalite to metaleucotonalite layers

(Putiš et al., 2001, 2008a, 2009a, 2018, 2023a). A Late Cambrian to Early Ordovician metamorphic event, like that recorded in the Koleso Valley Complex, was not detected in the LAC. Variscan metamorphic overprint was dated on Zrn at 390 Ma (Putiš et al., 2023a, 2024a, b).

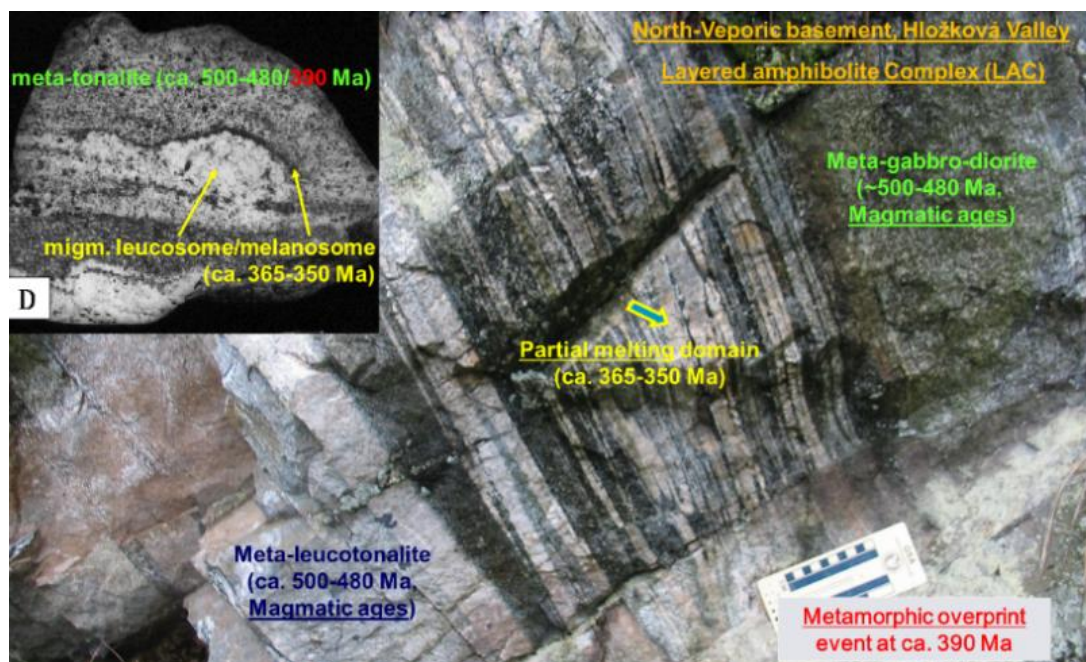


Fig. 6.2: An LAC outcrop in the Hložková Valley, north of the eastern Nízke Tatry Mts. ridge, yielding late Cambrian to Ordovician magmatic, Middle Devonian metamorphic, and Late Devonian to Early Carboniferous partial melting ages (Putiš et al., 1997b, with ages from Putiš et al., 2008a, 2009a, and new data).

The primary compositional layering may have formed through fractionation of juvenile, depleted mantle N-MORB-type sources ($\epsilon\text{Nd}_{(480)} = +10.1$ to $+5.2$ and $\text{TDM}_{(2\text{st})} = 0.37\text{--}0.76$ Ga). The alternating leucotonalitic layers ($\epsilon\text{Nd}_{(480)} = +6.8$ to $+5.5$ and $\text{TDM}_{(2\text{st})} = 0.64\text{--}0.73$ Ga) were derived from an isotopically uniform fractionated gabbroic mantle source (Putiš et al., 2024a–c). A smaller group of interlayers exhibits an affinity to VAB-C with $\epsilon\text{Nd}_{(480)} = +0.6$ to -2.9 and $\text{TDM}_{(2\text{st})} = 1.12\text{--}1.40$ Ga. Newly formed (remelted) leucotonalitic to dioritic layers were dated at $\sim 365\text{--}350$ Ma ($\epsilon\text{Nd}_{(350)} = +2.0$ to $+0.3$ and $\text{TDM}_{(2\text{st})} = 0.92\text{--}1.04$ Ga) (Fig. 6.3).

The Alpine greenschist-facies metamorphic assemblage consists of Ab, Grs-rich Grt, Act, Chl, and Ep–Czo (Putiš, 1994; Putiš et al., 1997b) (Fig. 6.4).

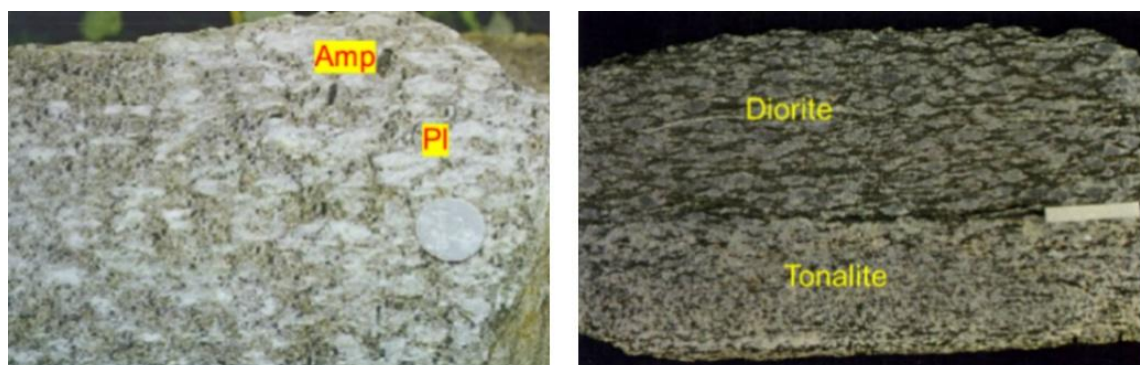


Fig. 6.3: Newly formed (remelted) Late Devonian to Early Carboniferous dioritic to tonalitic ($\sim 365\text{--}350$ Ma) layers of the LAC in the Velký Zelený Potok Valley (Fabova Hoľa Massif), preserving Variscan post-metamorphic magmatic structures (Putiš et al., 1997b, 2001, 2008a, 2009a, and new age data).

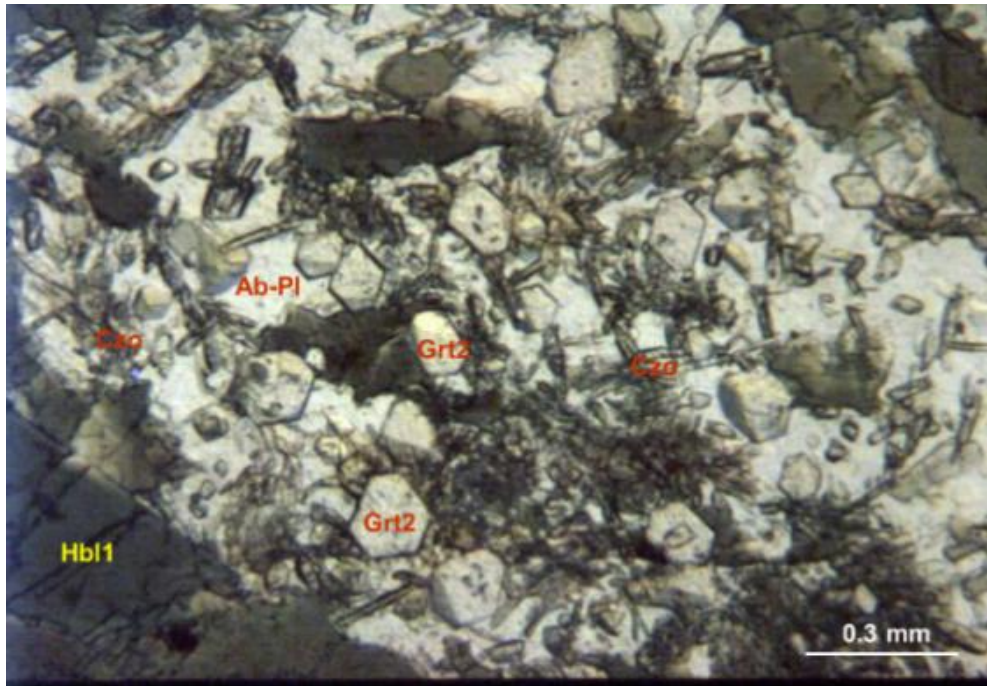


Fig. 6.4. Cretaceous greenschist-facies metamorphic overprint assemblage of the LAC in shear zones. Detail of Pl in a Hbl–Pl amphibolite, showing a Variscan Pl porphyroblast replaced by an Alpine Ab, Grs-rich Grt2, and Ep–Czo aggregate (Putiš, 1994; Putiš et al., 1996, 1997a, b).

Locality No. 7: Bacúch Valley

GPS: 48°52'59.78"N; 19°47'54.47"E; 735 m a. s. l.

Position: 2.5 km NNW of the village of Bacúch

Tectonic Unit: Northern Veporic Unit (Fig. 6 in Introduction)

Structure: Jánov Grúň Complex of the Krakľová Nappe, Alpine deformation

Rocks: Permian granite porphyry with Alpine metamorphic overprint

The locality occurs within the inferred root zone of the Fatric (Križna) Nappe. A complicated fold–thrust tectonic zone related to the Čertovica thrust–fault and associated shear zone is characteristic of this area. Common recumbent folds of the basement micaschists (Variscan Middle Unit, Hron Complex) and the Permian–Triassic cover are overlying the para- and orthogneisses of the Northern Veporic Lubietová Nappe (Figs. 7.1, 7.2; Buday et al., 1962; Putiš, 1989, 1991a; Biely et al., 1992; Putiš et al., 2021; Vojtko and Kriváňová, 2024).

The Northern Veporic crystalline basement was predominantly affected by high- to medium-grade Variscan metamorphism followed by a generally low-grade Alpine overprint. Variscan deformation (VD) is characterised by a pervasive metamorphic foliation (VS1) developed throughout the crystalline basement of the study area. This Variscan fabric provides a suitable marker for identifying the Alpine deformation.

Alpine deformation (AD1) was accompanied by lower greenschist-facies metamorphism (AM1). However, complete transposition of the earlier fabric occurred only locally, allowing the relationships between the preserved deformation phases to be recognised. The Alpine tectonic fabric (AS1) is mainly localised within the shear zones and developed during the Cretaceous deformation. The average orientation of Alpine fold axes and intersection lineations (AL1c) associated with Alpine deformation (AD1) is AF1 81/05°. Top-to-the-NNW thrusting is also documented by a recumbent syncline, which is up to 3 km long, with a maximum thickness of Mesozoic strata is up to 400 m (Figs. 7.1, 7.2). The syncline is filled with a typically overturned sequence of Lower Triassic meta-quartzites and Middle- to Upper-Triassic meta-carbonates. The recumbent fold has an unusual structure because its overturned limb has a completely preserved sedimentary succession, whereas the normal limbs are strongly reduced and on the sole of thrust sheared (Fig. 7.2).

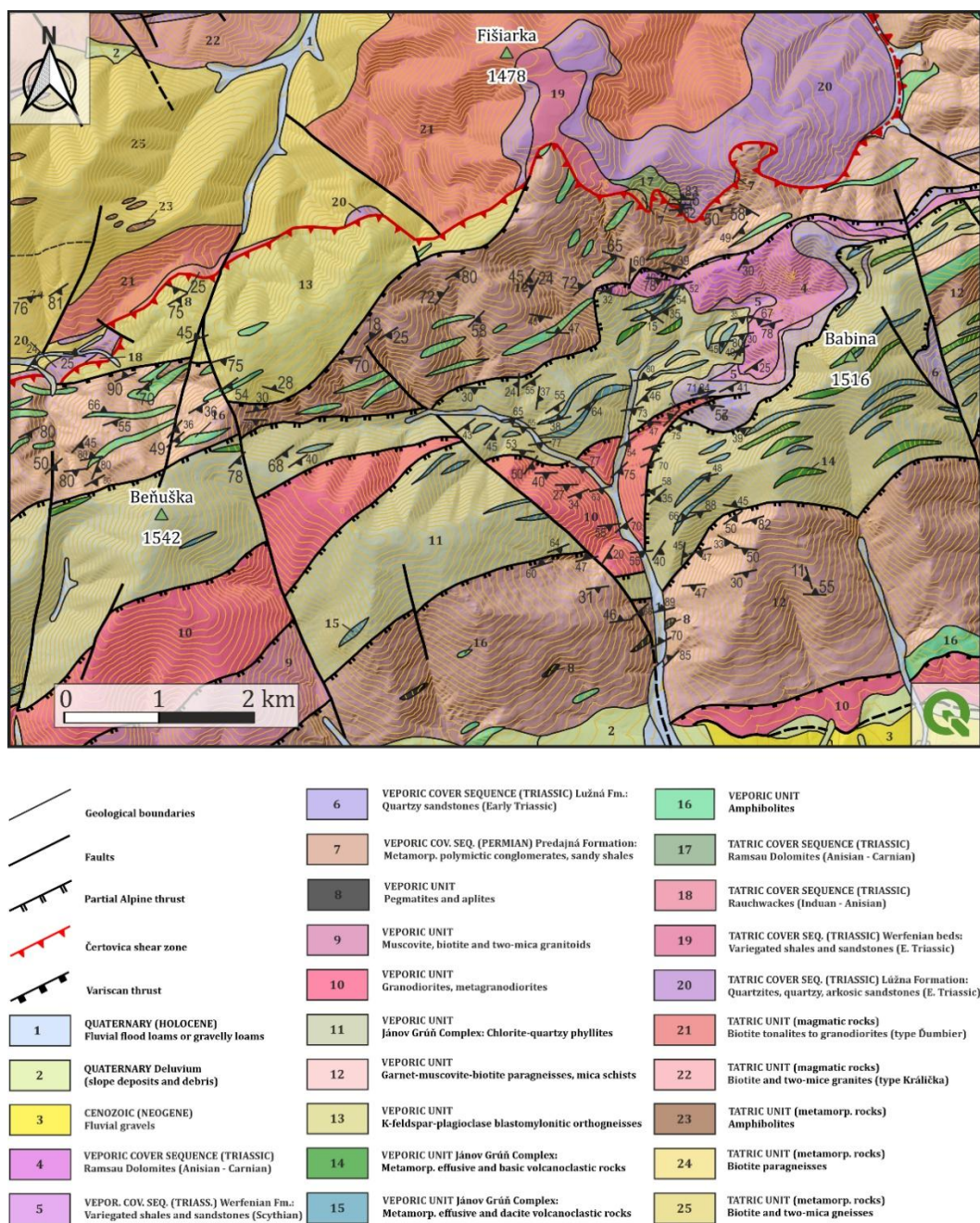


Fig. 7.1: Geological map of the study area north of the village of Bacúch (according to Biely et al., 1992).

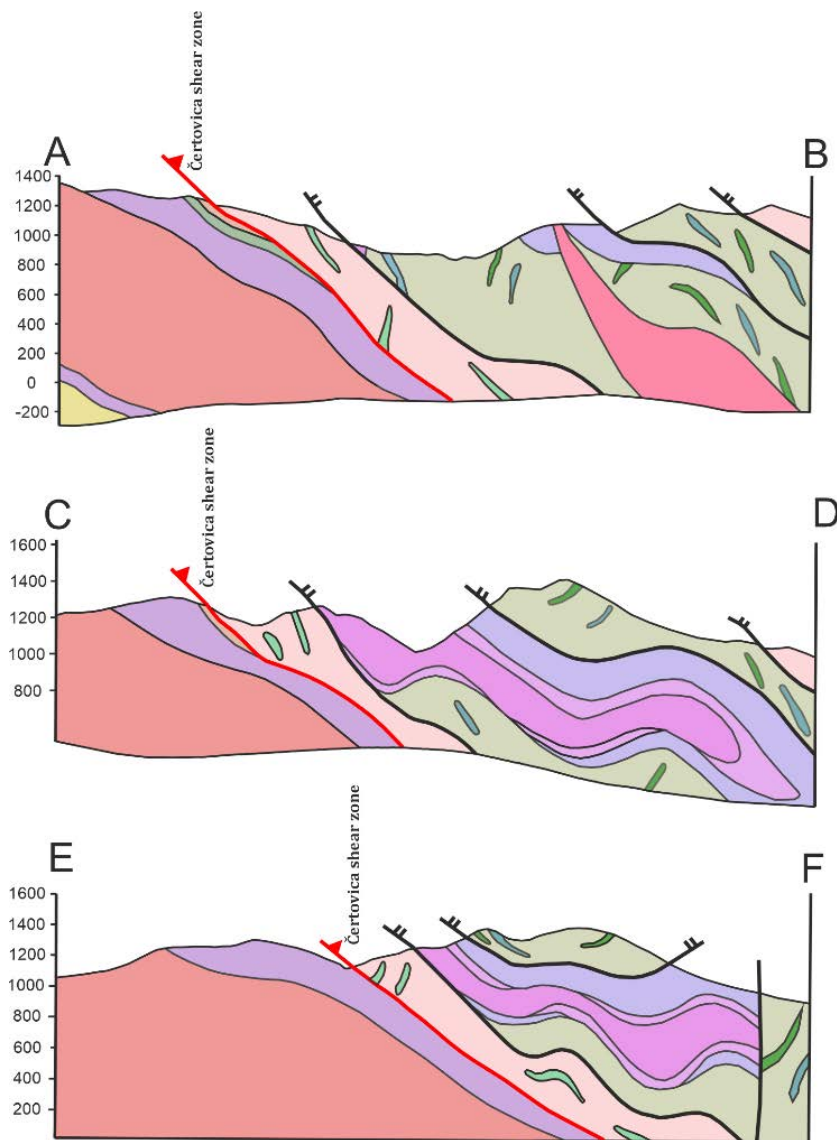


Fig. 7.2: Geological cross-sections in the study area, showing large-scale Alpine recumbent fold structure. Note: for the legend, see Fig. 7.1 (Vojtko and Kriváňová, 2024).

The U–Pb zircon dating of the Northern Veporic acid to intermediate volcanic and subvolcanic rocks in Ľubietová and Bacúch areas (Jánov Grúň Complex by Miko, 1981) first determined a Permian age of this volcano–sedimentary complex using multi-zircon grain method (258 ± 2 , 263 ± 3 , 272 ± 10 Ma; Kotov et al., 1996).

Dacites to trachyandesites from the Brusno Fm. in the Ľubietová Nappe yielded ages of ~ 273 and ~ 279 Ma (Kungurian) obtained by U–Pb SHRIMP dating. These volcanic rocks were contemporaneous with the sedimentation of the associated Brusno Fm. arkoses, confirming that the Northern Veporic Permian sedimentary basin was established during the latest Kungurian (Vozárová et al., 2016).

A rhyodacite body from the Northern Veporic Permian volcano-sedimentary succession near the village of Bacúch was dated at 267 ± 2 Ma (BAC-1 sample) by U–Pb SIMS. A rhyolite dyke in the Permian siliciclastic cover of the Southern Veporic Unit from a quarry at the Burda Pass, S of the village of Závadka nad Hronom (Fabova Hoľa Massif), yielded ages of 267 ± 2 Ma (BUR-1 sample) and 266 ± 2 Ma (BUR-1 sample retested by nano-SIMS from 10 μm Zrn rims) (Putiš et al., 2019c, 2021). The Hrončok A-type granite from the Veporic basement was dated at 267 ± 2 Ma (HK-1 sample), whereas the Turčok

A-type granite from the Northern Gemeric basement was dated at 262 ± 4 Ma (TU-3 sample) (Ondrejka et al., 2021).

The granite porphyry at the Bacúch locality forms part of a large body about 8 km long, with the maximum thickness of a few hundred metres in the Leňušská Valley near the village of Beňuš. It yielded a magmatic age of 266 ± 1 Ma (LED-1 sample; unpublished database of M. Putiš). This body was emplaced within the host volcano–sedimentary succession of a similar age, determined from a rhyodacite intercalation (267 ± 2 Ma) in phyllitic metasediments.

At both localities, the rocks show metamorphic microstructures characterised by crenulation microfolds (Fig. 7.3). Isotopically, the samples LED-1 and BAC-1 show mixed crust–mantle sources with $\epsilon\text{Nd}_{(266, 267)}$ around zero ($+0.3$ to -0.1 , respectively) and $\text{TDM}_{(2\text{st})}$ ca. 1 Ga (unpublished data of M. Putiš). Basaltic intercalations are also characteristic.

These bimodal volcanics are calc-alkaline, and together with A2-type rare granitic bodies (Hrončok type) represent within-plate riftogeneious processes. They provide a distinct LREE enrichment and a positive Eu anomaly (Ondrejka et al., 2021).

These rocks show low-temperature and medium-pressure metamorphic overprint (Korikovsky et al., 1997b) with T 330–370°C and P 500–600 MPa estimated from the BAC-1 and LED-1 samples (Putiš et al., 2021) by Chl–Ms thermobarometry (Vidal et al., 2006). Metamorphic Cel–Ms (“phengitic”) yielded the Late Cretaceous ages according to $^{40}\text{Ar}/^{39}\text{Ar}$ dating (~ 90 –80 Ma; Putiš et al., 2009b).

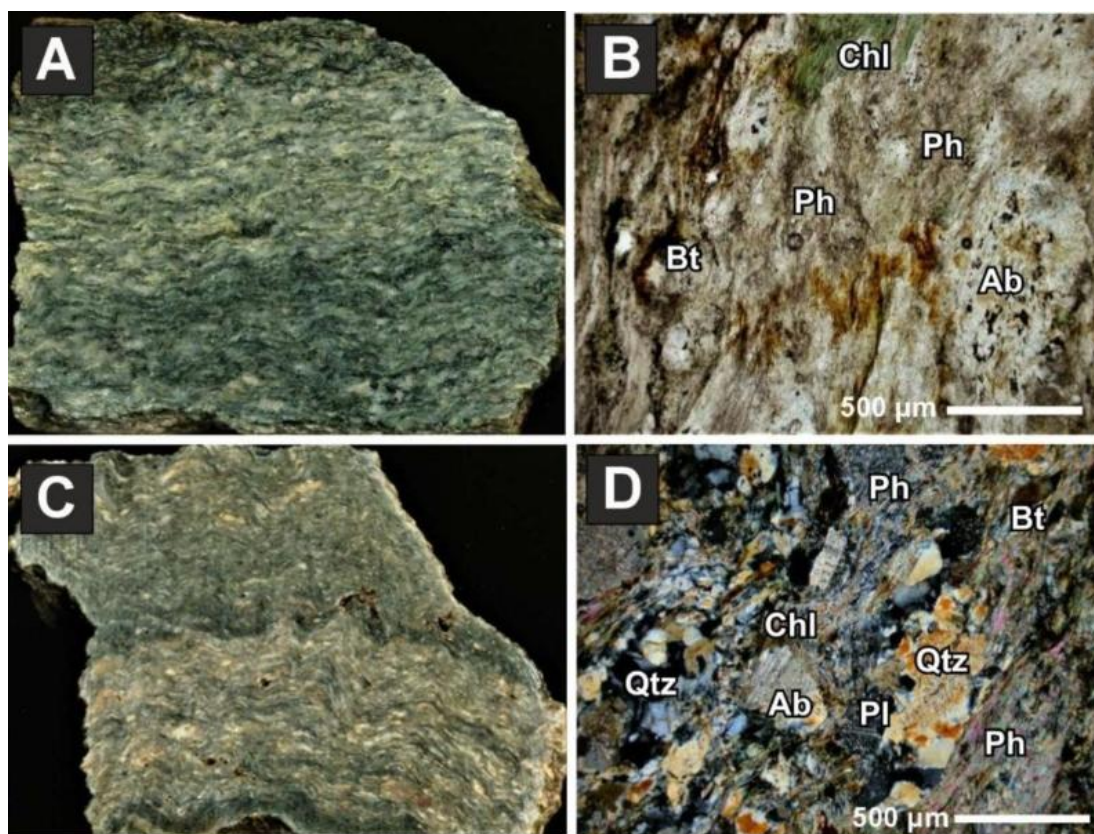


Fig. 7.3: Macroscopic (A, C) and microscopic (B, D) textures from the Permian Jánov Grúň Complex of the Krakľová Nappe in the eastern Nízke Tatry Mts. (A, B) Permian meta-dacite (BAC-1, Bacúch Valley); (C, D) Permian meta-granite porphyry with tiny Fsp porphyroclasts within the metamorphic matrix with crenulation microfolds (LED-1, Leňušská Valley at the village of Beňuš). B picture at II N. D picture at X N (from Putiš et al., 2021).

Locality No. 8: Čertovica Pass

GPS: 48°54'10.96"N; 19°44'5.61"E; 1256 m a. s. l.

Position: 2.25 km SSW of the village of Vyšná Boca

Tectonic Unit: Tatric/Northern Veporic tectonic contact (Fig. 6 in Introduction)

Structure: Čertovica Shear Zone

Rocks: remnants of the Tatric Triassic cover overthrust by the Northern Veporic (Lubietová Nappe) orthogneisses

The Nízke Tatry Mountains form a range in the central part of the Western Carpathians. They are divided into two major subunits, both geomorphologically and geologically distinct. The western section consists of the Tatric crystalline basement, while the eastern section is formed by the Veporic crystalline basement (Figs. 8.1, 8.2). The geographical and geological boundary between these tectonic units roughly follows the Čertovica shear zone, visible on the surface between the villages of Mýto pod Ďumbierom and Nižná Boca, near the Čertovica Pass (1,238 m a.s.l.). This basement is exposed within both the Tatric and Northern Veporic thick-skinned tectonic units, which record a polyphase magmatic and metamorphic history including pre-Variscan, Variscan, Permian and Alpine events (e.g., Matějka and Andrusov, 1931; Siegl, 1976a, b, 1981; Krist et al., 1992; Bezák et al., 1997; Putiš, 1989, 1991a; Janák et al., 2001; Jeřábek et al., 2008a; Plašienka, 2018; Putiš et al., 2021; Kriváňová et al., 2023; Vojtko and Kriváňová, 2024).

This locality documents a contact of Ďumbier type tonalite cataclasite and rhauwackised mid-Triassic carbonates of the Tatric Unit with the overthrust granitic orthogneisses of the Northern Veporic Lubietová Nappe. The orthogneiss provided a magmatic protolith age of 485 ± 6 Ma and represents a lower part of the Variscan Jarabá Complex paragneisses with orthogneisses and thin bodies of amphibolites (Putiš et al. (2009a, 2024a, b).

Two main deformation groups were distinguished. The older group of deformations (VD) is related to Variscan higher-grade metamorphism, and the younger deformation group (AD) is characterised by deformation under low-grade (retrograde) metamorphic conditions. Variscan deformation can be divided into three phases. The VD1 deformation is only sporadically recognisable in low-strain domains and is characterised by tight, isoclinal, and sheath folds (VF2) that fold limbs (VS1), which are conformable with the VS2 foliation – clearly confirming its oldest age. The fold axes (VF2) show considerable spatial variation, but, in general, they are E–W-oriented. We cannot exclude that the VD1 deformation may be pre-Variscan and potentially related to the Cenerian Orogeny.

Deformation VD2 was accompanied by progressive metamorphosis and represents the most complex and significant process, producing pervasive metamorphic foliation (VS2) throughout the study area. This foliation (VS2) determines the anisotropy of most observed metamorphosed rocks. Mineral and stretching lineations (VL2t), oriented ENE – WSW, are also associated with VD2 deformation but are not as pervasive as VS2 foliations.

The VS2 foliation is folded by VF2 non-penetrative folds with E–W-oriented fold axes. The new fabric is represented by VS3 non-penetrative cleavage and by intersection and crenulation lineations (VL3c). The last observed Variscan deformation (VD4) is accompanied by the formation of aplites, pegmatites, or quartz veins (VS4), which are predominantly oriented in two directions — $VS2 \parallel VS4$ and $VS2 \perp VS4$ – and associated linear structures were observed.

The Alpine deformation (AD1) was accompanied by retrograde metamorphism, and the evolution of the deformation fabric was more strongly localised within shear zones, developing during the Cretaceous orogeny (Eo-Alpine deformation). The P–T conditions of metamorphism were lower during AD1 than during VD2, and complete transposition of the VS2 fabric into AS1 occurred only very

locally. The AD1 deformation is characterised by the development of crenulation cleavage that grades into mylonitic foliation (AS1) within shear zones. The AS1 foliation has an average NE–SW strike and dips shallowly to moderately towards the SE. The AD1 deformation is also associated with NE–SW-oriented intersection lineations (AL1c) and AF1 folds, which are commonly asymmetric. These structures are younger than, and conformably superimposed on, the VL2t lineations and VF2 folds. Based on these observations, the kinematics of the Alpine thrust deformation can be unambiguously interpreted as having a top-to-the-NNW vergence.

The last identified Alpine deformational stage (AD2) is related to an extensional tectonic regime, particularly within the Čertovica shear zone. Extensional structures such as en-échelon veins (AS2) and stretching lineation (AL2t) indicate top-to-the-east transport, with the orientation of the principal minimum palaeostress axis in the E–W direction. The AD2 structures are not pervasive and were observed mainly in Lower Triassic metaquartzites and in the crystalline basement around the Čertovica shear zone (Figs. 8.1, 8.2).

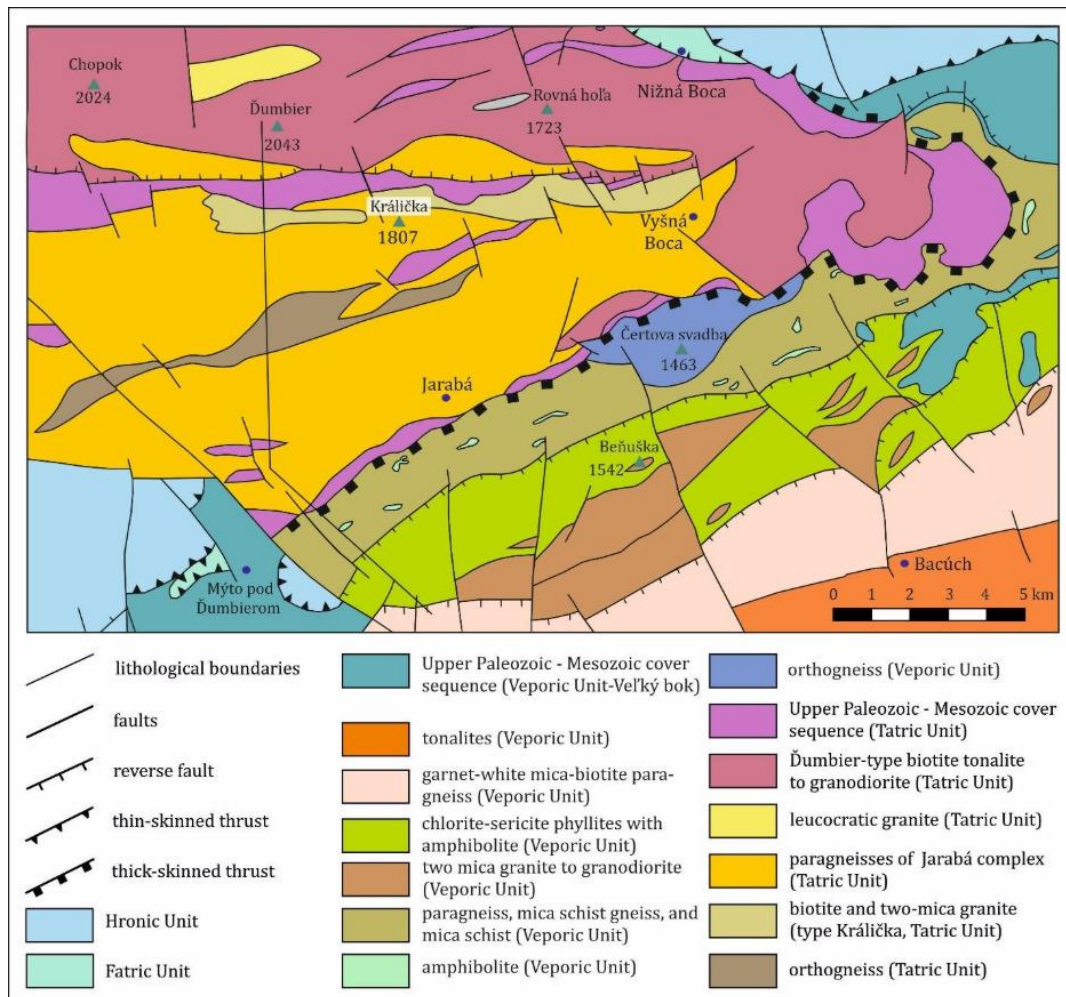


Fig. 8.1: Tectonic map of the study area (Krivánová et al., 2023, according to Bezák et al., 2004).

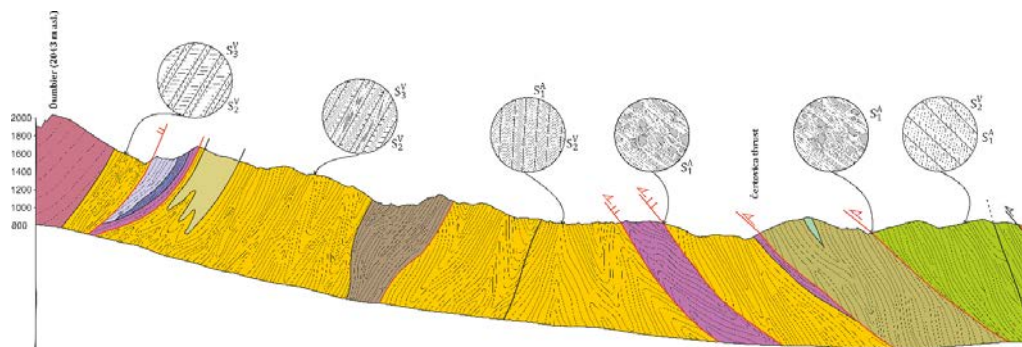


Fig. 8.2: Geological cross-section through the Tatric and Veporic crystalline complexes separated by the Čertovica shear zone (Kriváňová et al., 2023).

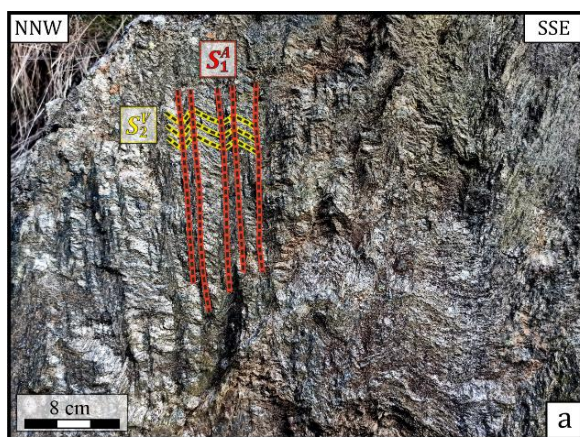


Fig. 8.3: Field photographs of the Variscan and Alpine fabrics: (a) symmetric Alpine crenulation cleavage (AS1) with folded Variscan pervasive metamorphic foliation (VS2) in paragneiss (Veporic Unit); (b) nicely developed symmetric Alpine crenulation cleavage (AS1) in Lower Triassic quartzites (Early Triassic, Veporic cover sequence); (c) the Variscan foliation (VS2) forms in the orthogneiss (Veporic Unit) close to the narrow shear zones (AS1) and it is deflected and parallelised to the mylonitic foliation (subhorizontal). In the shear zone, the orthogneiss has been almost completely transformed into a mylonite (top-to-the-NNW tectonic transport); (d) High amplitude 'V-shaped' kink fold with the Alpine axial plane cleavage (AS1). Pervasive foliation is related to the Variscan fabric (VS2) in paragneiss (Veporic Unit); (e) cross-section of the mylonitic paragneiss (Veporic Unit) perpendicular to S planes and parallel with stretching lineation with well-developed C' planes with macroscopic shear band cleavage and asymmetric bending of the foliation (top-to-the-ESE transport); (f) ductile deformation in the marbles with kinematic indicators which refers to tectonic transport top-to-the-ESE (Triassic, Veporic cover sequence) (Vojtko and Kriváňová, 2024).

References

- Andrusov, D., Bystrický, J. & Fusán, O., 1973: Outline of the Structure of the West Carpathians. In Congress of Carpathian-Balkan Association X; Geological Survey of the Slovak Republic: Bratislava, Slovakia, 1–44.
- Bajaník, Š., 1973: Pillow lavas of the Rakovec Group in the Spišsko-Gemerské rudohorie Mts. *Geologický Zborník Geologica Carpathica* 26, 2, 341–348.
- Bajaník, Š., Vozárová, A. & Reichwalder, P., 1981: Litostratigrafická klasifikácia rakoveckej skupiny a mladšieho paleozoika v Spišsko-gemerskom rudohorí. *Geologické Práce. Správy* 75, 27–55. In Slovak with English summary.
- Bezák, V., 1994: Návrh nového členenia kryštalinika Západných Karpát na základe rekonštrukcie hercýnskej tektonickej stavby. *Mineralia Slovaca* 26, 1–6. In Slovak with English summary.
- Bezák, V., Jacko, S., Janák, M., Ledru, P., Petřík, I. & Vozárová, A., 1997: Main Hercynian lithotectonic units of the Western Carpathians. In: Grecula, P., Hovorka, D., Putiš, M. (Eds.): Geological evolution of the Western Carpathians. *Mineralia Slovaca – Monograph.*, 261–268.
- Bezák, V., Broska, I., Elečko, M., Havrila, M., Ivanička, J., Janočko, J., Kaličiak, M., Konečný, V., Lexa, J., Mello, J., Plašienka, D., Polák, M., Potfaj, M. & Vass, D., 2004: Tectonic map of Slovak Republic, 1:500 000. ŠGÚDŠ, Bratislava, ISBN 80-88974-62-3
- Bibikova, E.V., Korikovskiy, S.P., Putiš, M., Broska, I., Golzman, Y.V. & Arakeliants, M.M., 1990: U/Pb, Rb/Sr and K/Ar dating of Sihla tonalites of Vepor pluton (Western Carpathians). *Geol. Zbor. Geol. Carpath.*, 41, 427–436.
- Biely, A., Beňuška, P., Bezák, V., Bujnovský, A., Halouzka, R., Ivanička, J., Kohút, M., Klinec, A., Lukáčik, E., Maglay, J., Miko, O., Pulec, M., Putiš, M. & Vozár, J., 1992: Geologická mapa Nízkych Tatier 1:50 000. Štátny geologický ústav Dionýza Štúra, Bratislava. (Geological Map of the Nízke Tatry Mts. 1:50,000. State Geological Institute of Dionýz Štúr, Bratislava, Slovakia).
- Broska, I., Petřík, I., Be'eri-Shlevin, Y., Majka, J. & Bezák, V., 2013: Devonian/Mississippian I-type granitoids in the Western Carpathians: A subduction-related hybrid magmatism. *Lithos* 162–163, 27–36.
- Broska, I., Janák, M., Svojtka, M., Keewook, Yi, Konečný, P., Kubiš, M., Kurylo, S., Hrdlička, M. & Maraszewska, M., 2022: Variscan granitic magmatism in the Western Carpathians with linkage to slab break-off. *Lithos* 412–413, 106589.
- Buday, T., Kodým, O., Mahel', M., Máška, M., Matějka, A., Svoboda, J. & Zoubek, V., 1962: Tectonic Development of Czechoslovakia. ČSAV, Prague, p. 249.
- Cambel, B., 1954: Geologicko-petrografické problémy severovýchodnej časti kryštalinika Malých Karpát. *Geologické práce – Zošit* 36, 3–74. In Slovak with English summary.
- Connolly, J.A.D., 2005: Computation of phase equilibria by linear programming: A tool for geodynamic modeling and its application to subduction zone decarbonation. *Earth and Planetary Science Letters* 236, 524–541.
- Connolly, J.A.D. & Pettrini, K., 2002: An automated strategy for calculation of phase diagram sections and retrieval of rock properties as a function of physical conditions. *J. Metamorph. Geol.* 20, 697–708.
- Dallmeyer, R.D., Neubauer, F. & Putiš, M., 1993: ⁴⁰Ar/³⁹Ar mineral age controls for the Pre-Alpine and Alpine tectonic evolution of nappe complexes in the Western Carpathians. In: Pitoňák, P., Spišiak, J. (Eds). Pre-Alpine Events in the Western Carpathians' Realm; Conference in Stará Lesná, Excursion Guide; Slovak Academy of Sciences: Bratislava, Slovakia, pp. 11–20.
- Dallmeyer, R.D., Neubauer, F., Handler, R., Fritz, H., Müller, W., Pana, D. & Putiš, M., 1996: Tectonothermal evolution of the internal Alps and Carpathians: Evidence from ⁴⁰Ar/³⁹Ar mineral and whole-rock data. *Eclogae Geologicae Helveticae* 89, 203–227.

- Dallmeyer, R.D., Németh, Z. & Putiš, M., 2005: Regional tectonothermal events in Gemericum and adjacent units (Western Carpathians, Slovakia): Contribution by the $^{40}\text{Ar}/^{39}\text{Ar}$ dating. *Slovak Geological Magazine* 11, 155–163.
- Danišík, M., Kadlec, J., Glotzbach, C., Weisheit, A., Dunkl, I., Kohút, M., Evans, N.J., Orvošová, M. & McDonald, B.J., 2011: Tracing metamorphism, exhumation and topographic evolution in orogenic belts by multiple thermochronology: A case study from the Nízke Tatry Mts., Western Carpathians. *Swiss J. Geosci.* 104, 285–298.
- Etzel, T.M., Catlos, E.J., Kohút, M. & Yin, H.Z., 2018: Dating the High Tatra Mountains, Slovakia: Tectonic Implications. In: Proceedings of the 5th Central-European Mineralogical Conference (CEMC) and 7th Mineral Sciences in the Carpathians Conference (MSCC), Banská Štiavnica, Slovakia, 26–30.
- Faryad, S.W., Henjes-Kunst, F., 1997: Petrological and K–Ar and ^{40}Ar – ^{39}Ar age constraints for the tectonothermal evolution of the high-pressure Meliata unit, Western Carpathians (Slovakia). *Tectonophysics* 280, 141–156.
- Filová, I. & Putiš, M., 2004: Litologicko-petrografické štúdium metamafitov severného veporika. *Miner. Slovaca*, 36, 195–204.
- Flinn, D., 1962: On folding during three dimensional progressive deformation. *Q. Jl. Geol. Soc. Lond.* 118, 385–428.
- Fry, N., 1979: Random points distributions and strain measurements in rocks. *Tectonophysics* 60, 89–105.
- Grecula, P., 1982: Gemerikum – segment riftogénneho bazénu Paleotetýdy. *Mineralia Slovaca monograph*, 263 p. (in Slovak with English summary)
- Hók, J. & Hraško, L., 1990: Deformačná analýza západnej časti pohorelskej línie. *Miner. Slovaca* 22, 69–80.
- Hók, J. & Vojtko, R., 2011: Interpretácia pohorelskej línie v podloží stredoslovenských neovulkanitov (Západné Karpaty). *Acta Geologica Slovaca* 3, 1, 13–19 (in Slovak with English summary).
- Hók, J., Kováč, P. & Madarás, J., 1993: Extenzná tektonika západného úseku styčnej zóny gemerika a veporika. *Miner. Slovaca* 25, 172–176. (in Slovak with English summary)
- Hók, J., Siman, P., Frank, W., Král, J., Kotulová, J. & Rakús, M., 2000: Origin and exhumation of mylonites in the Lúčanská Malá Fatra Mts. (the Western Carpathians). *Slovak Geol. Mag.* 6, 325–334.
- Hovorka, D. & Méres, Š., 1993: Leptynitovo-amfibolitový komplex Západných Karpát: vystupovanie a litologická náplň. *Mineralia Slovaca* 25, 1–9. (in Slovak with English summary)
- Hovorka, D. & Spišiak, J., 1997: Medium grade metamorphics of the Gemeric unit. In: Grecula, P., Hovorka, D., Putiš, M. (Eds.): Geological evolution of the Western Carpathians, *Mineralia Slovaca – Monograph*, 315–332.
- Hovorka, D., Ivan, P. & Spišiak, J., 1984: Nappe with amphibolite facies metamorphites in the Inner Western Carpathians – its positions, origin and interpretation. *Miner. Slovaca* 16, 73–86.
- Hovorka, D., Dávidová, M.J., Fejdi, P., Gregorová, Z., Határ, J., Kátlovský, V., Pramuka, S. & Spišiak, J., 1987: The Muráň gneisses of the Kohút Crystalline Complex. *Acta Geologica et Geographica Universitatis Comenianae* 42, 5–101.
- Hovorka, D., Ivan, P., Jilemnická, I. & Spišiak, J., 1988: Petrology and geochemistry of metabasalts from Rakovec (Paleozoic of Gemeric unit, Inner Western Carpathians). *Geol. Carpath.* 39, 395–425.
- Hovorka, D., Ivan, P. & Méres, Š., 1997: Leptyno-amphibolite complex of the Western Carpathians: Its definition, extent and genetical problems. In: Grecula, P., Hovorka, D., Putiš, M. (Eds.): Geological evolution of the Western Carpathians. *Mineralia Slovaca monograph*, 269–280.
- Hrouda, F., Putiš, M. & Madarás, J., 2002: The Alpine overprints of the magnetic fabrics in the basement and cover rocks of the Veporic Unit (Western Carpathians, Slovakia). *Tectonophysics* 359, 271–288.
- Hurai, V., Paquette, J.-L., Lexa, O., Konečný, P. & Dianiška, I., 2015: U–Pb–Th geochronology of monazite and zircon in albitite metasomatites of the Rožňava-Nadabula ore field (Western Carpathians, Slovakia): implications for the origin of hydrothermal polymetallic siderite veins. *Mineral. Petrol.* 109, 519–530.
- Ivan, P., 1996: Gabroidy v severnom veporiku Nízkyh Tatier. *Miner. Slovaca* 28, 38–44. (in Slovak with English summary)
- Ivan, P., 1997: Rakovec and Zlatník Formations: two different relics of the pre-Alpine back-arc basin crust in the inner Western Carpathians. In: Grecula, P., Hovorka, D. & Putiš, M. (Eds.): Geological evolution of the Western Carpathians. *Mineralia Slovaca – Monograph*, 281–288.
- Ivan, P. & Méres, Š., 2006: Litostratigrafické členenie a pôvod spodnopaleozoického kryštalinického podložia Malých Karpát (centrálne Západné Karpaty). *Miner. Slovaca* 38, 165–186 (in Slovak with English summary)
- Ivan, P. & Méres, Š., 2012: The Zlatník Group—Variscan ophiolites on the northern border of the Gemeric Superunit (Western Carpathians). *Miner. Slovaca* 44, 39–56.
- Ivan, P. & Méres, Š., 2015: Geochemistry of amphibolites and related graphitic gneisses from the Suchý and Malá Magura Mountains (central Western Carpathians) – evidence for relics of the Variscan ophiolite complex. *Geol. Carpath.* 66, 5, 347–360.
- Ivan, P., Méres, Š., Putiš, M. & Kohút, M., 2001: Early Paleozoic metabasalts and metasedimentary rocks from the Malé Karpaty Mts. (Western Carpathians): evidence for rift basin and ancient oceanic crust. *Geol. Carpath.* 52, 1–10.

- Ivan, P., Méres, Š. & Janák, M., 2007: Intraplate origin of some retrogressed eclogites from the Early Paleozoic of the Veporic Unit (western Carpathians): evidence from geochemical data. *Géol. Fr.* 2, 109.
- Janák, M., O'Brien, P. J., Hurai, V. & Reutel, C., 1996: Metamorphic evolution and fluid composition of garnet-clinopyroxene amphibolites from the Tatra Mountains, Western Carpathians. *Lithos* 39, 75–79.
- Janák, M., Plašienka, D., Frey, M., Cosca, M., Schmidt, S.Th., Lupták, B. & Méres, Š., 2001: Cretaceous evolution of a metamorphic core complex, the Veporic unit, Western Carpathians (Slovakia): P-T conditions and in situ $^{40}\text{Ar}/^{39}\text{Ar}$ UV laser probe dating of metapelites. *J. Met. Geol.* 19, 197–216.
- Janák, J., Méres, Š. & Ivan, P., 2007: Petrology and metamorphic P-T conditions of eclogites from the northern Veporic Unit (Western Carpathians, Slovakia). *Geol. Carpath.* 58, 2, 121–131.
- Janák, M., Méres, Š. & Medaris, G. (Jr.), 2020: Eclogite facies metaultramafite from the Veporic Unit (Western Carpathians, Slovakia). *Geol. Carpath.* 71, 3, 209–220.
- Janák, M., Petrik, I., Konečný, P., Kurylo, S., Kohút, M. & Madarás, J., 2022: Variscan metamorphism and partial melting of sillimanite bearing metapelites in the High Tatra Mts. constrained by Th–U–Pb dating of monazite. *Geol. Carpath.* 73, 97–122.
- 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. *J. Struct. Geol.* 29, 1722–1743.
- Jeřábek, P., Janák, M., Faryad, S.W., Finger, F. & Konečný, P., 2008a: Polymetamorphic evolution of pelitic schists and evidence for Permian low-pressure metamorphism in the Vepor Unit, West Carpathians. *J. Met. Geol.* 26, 465–485.
- Jeřábek, P., Faryad, S.W., Schulmann, K., Lexa, O., & Tajčmanová, L., 2008b: Alpine burial and heterogeneous exhumation of Variscan crust in the West Carpathians: insight from thermodynamic and argon diffusion modelling. *J. Geol. Soc.* 165, 479–498.
- Jeřábek, 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, TC5002.
- Kianguebene–Koussingounina, Ch.E., Ondrejka, M., Chew, D., Putiš, M., Nemec, O. & Ružička, P., 2025: Variscan granitoids with Cretaceous tectonometamorphic overprint in the Western Carpathians. GeoTolosa Conference, Toulouse, June 2025, Abstract Book, p. 148.
- Kianguebene–Koussingounina, Ch.E., Ondrejka, M., Putiš, M., Nemec, O., Ružička, P., Chew, D. & Sláma J., 2026: Geochronology and geochemistry of Variscan granitoids of the Fatric basement with Alpine tectonometamorphic overprint (Inner Western Carpathians). ICYG Conference 2026, Prague, Czech Republic, Abstract Book.
- Klinec A., 1976: Geologická mapa Slovenského Rudohoria a Nízkych Tatier. Geologický Ústav Dionýza Štura, Bratislava.
- Kohút, M., Konečný, P. & Siman, P., 2006: The first finding of the iron Lahn-Dill mineralization in the Tatric unit of the Western Carpathians. *Mineralogia Polonica, Special Papers* 28, 112–114.
- Kohút, M., Linnemann, U. & Hofmann, M. 2022: Provenance and detrital zircon study of the Tatric Unit basement (Western Carpathians, Slovakia). *International Journal of Earth Sciences (Geologische Rundschau)* 111, 2149–2168.
- Korikovsky, S.P. & Putiš, M., 2002: Olivine-orthopyroxene-amphibole-talc-chlorite meta-serpentinites in the medium-temperature metamorphic complex of Northern Veporic, Western Carpathians: phase equilibria, metamorphic parameters, comparison with gneiss and amphibolite associations. *Petrology* 10, 3–29.
- Korikovsky, S.P., Putiš, M., Plašienka, D. & Ďurovič, V., 1997a: Cretaceous very low-grade metamorphism of the Infratatic and Supratatic domains: An indicator of thin-skinned tectonics in the central Western Carpathians. In: Grecula, P., Hovorka, D. & Putiš, M. (Eds.). Geological Evolution of the Western Carpathians. Mineralia Slovaca – Monograph, Bratislava, pp. 89–106.
- Korikovsky, S.P., Putiš, M. & Plašienka, D., 1997b: Cretaceous low-grade metamorphism of the Veporic and North-Gemeric Zones: A result of collisional. In: Grecula, P., Hovorka, D. & Putiš, M. (Eds.). Geological Evolution of the Western Carpathians. Mineralia Slovaca – Monograph, Bratislava, pp. 107–130.
- Kotov, A.B., Miko, O., Putiš, M., Korikovsky, S.P., Bereznaya, N.G., Král, J. & Krist, E., 1996: U/Pb dating of zircons of postorogenic acid metavolcanics and metasubvolcanics: a record of Permian – Triassic taphrogeny of the West-Carpathian basement. *Geol. Carpath.*, 47, 73–79.
- Králiková, S., Vojtko, R., Hók, J., Fügenschuh, B. & Kováč, M., 2016: Low-temperature constraints on the Alpine thermal evolution of the Western Carpathian basement rock complexes. *Journal of Structural Geology* 91, 144–160.
- Král, J., Hók, J., Frank, W., Siman, P., Liščák, P. & Jánová, M., 2002: Shear deformation in granodiorite: Structural, $^{40}\text{Ar}/^{39}\text{Ar}$, and geotechnical data (Tribeč Mts., Western Carpathians). *Slovak Geol. Mag.* 8, 235–246.
- Krist, E., Korikovskij, S.P., Putiš, M., Janák, M. & Faryad, S.W., 1992: Geology and Petrology of Metamorphic Rocks of the Western Carpathian Crystalline Complexes. Comenius University Press, Slovakia, p. 324.

- Kriváňová, K., Vojtko, R., Droppa, D.M. & Gerátová, S., 2023: Deformation record and revised tectonic evolution of the Nízke Tatry Mts. in the Tatric–Veporic junction area: Insights from structural analysis. *Geol. Carpath.* 74, 3, 197–211.
- Lexa, J., Bezák, V., Elečko, M., Mello, J., Polák, M., Potfaj, M., Vozár, J., Schnabel, G.W., Pálenský, P. & Császár, G., 2000: Geological Map of Western Carpathians and Adjacent Areas 1: 500,000. State Geological Institute of Dionýz Štúr, Bratislava.
- Li, X.H., Putiš, M., Yang, Y.H., Koppa, M. & Dyda, M., 2014: Accretionary wedge harzburgite serpentinization and rodingitization constrained by perovskite U/Pb SIMS age, trace elements and Sm/Nd isotopes: Case study from the Western Carpathians, Slovakia. *Lithos* 205, 1–14.
- Linnemann, U., Gerdes, A., Drost, K. & Buschmann, B., 2007: The continuum between Cadomian orogenesis and opening of the Rheic Ocean: constraints from LA-ICP-MS U–Pb zircon dating and analysis of plate-tectonic setting (Saxo-Thuringian zone, northeastern Bohemian Massif, Germany). *Geological Society of America Special Papers* 423, 61–96.
- Linnemann, U., Pereira, F., Jeffries, T.E., Drost, K. & Gerdes, A. 2008: The Cadomian Orogeny and the opening of the Rheic Ocean: the diachrony of geotectonic processes constrained by LA-ICP-MS U–Pb zircon dating (Ossa-Morena and Saxo-Thuringian Zones, Iberian and Bohemian Massifs). *Tectonophysics* 461, 21–43.
- Madarás, J., Putiš, M. & Dubík, B., 1994: Štruktúrna charakteristika stredného úseku pohorelskej tektonickej zóny. *Miner. Slovaca*, 26, 177–191. (in Slovak with English summary)
- Madarás, J., Hók, J., Siman, P., Bezák, V., Ledru, P. & Lexa, O., 1996: Extension tectonics and exhumation of crystalline basement of the Veporicum unit (Central Western Carpathians). *Slovak Geol. Mag.* 3–4/96, 179–183.
- Madarás, J., Putiš, M. & Hók, J., 1999: Structural features of the Hercynian tectonics in the southern part of the Dumbier crystalline complex (Low Tatra Mts., Western Carpathians). *Miner. Slovaca* 31, 17–30.
- Mahel', M., 1986. Geologická stavba československých Karpát. Palealpínske jednotky. VEDA, Bratislava, 503 p.
- Maluski, H., Rajlich, P. & Matte, Ph., 1993: ⁴⁰Ar–³⁹Ar dating of the Inner Carpathian Variscan Basement and Alpine mylonitic overprinting. *Tectonophysics* 223, 313–337.
- Matějka, A. & Andrusov, D., 1931: Aperçu de la géologie des Carpathes occidentales de la Slovaquie central et des régions avoisinantes. *Knih. SGÚ* 13A, 19–163.
- Michálek, M. & Putiš, M., 2009: P-T-d evolution of eclogitic metabasite and Neoproterozoic orthogneiss in the North-Veporic basement of the central Western Carpathians. *Miner. Slovaca* 41, 1–22. (in Slovak with English summary)
- Michálek, M. & Putiš, M., 2011: P-T estimates from a meta-ultramafite exhumed with HP/HT metamorphic rocks in a Variscan shear zone, Veporic unit, Slovakia. 9th International Eclogite Conference, Mariánské Lázně, Czech Republic, Abstract Book, p. 47.
- Miko, O., 1981: Strednopaleozojskaja vulkanogennoosadočnaja tolšča Janovogo gruňa v veporidnom kristallinikume Nízkych Tatr. *Geol. Zbor Geol Carpath.* 32, 4, 465–474.
- Molnárová, A., Ondrejka, M., Putiš, M. & Nemec, O., 2024a: Petrológia a geochemia varískych granitoidov veporského plutónu v masíve Fabovej Hole a ich alpínska mylonitizácia. *Geochemia 2024*, Bratislava, Abstracts, 135–139.
- Molnárová, A., Ondrejka, M., Putiš, M. & Nemec, O., 2024b: Accessory zircon as a petrogenetic indicator in granitoid rocks of the Vepor pluton (Fabova hoľa, Western Carpathians, Slovakia). 4th European Mineralogical Conference EMC2024At: Dublin, Ireland: EMC Programme and abstracts, p. 105.
- Moussallam, Y., Schneider, D.A., Janák, M., Thöni, M. & Holm, D.K., 2012: Heterogeneous extrusion and exhumation of deep-crustal Variscan assembly: Geochronology of the Western Tatra Mountains, northern Slovakia. *Lithos* 144–145, 88–108.
- Nemec, O., Putiš, M., Bačík, P., Ružička, P. & Németh, Z., 2020: Metamorphic conditions of Neotethyan Meliatic accretionary wedge estimated by thermodynamic modelling and geothermobarometry (Inner Western Carpathians). *Minerals* 10, 1094, 1–50.
- Németh, Z., 2002: Variscan suture zone in Gemericum: Contribution to reconstruction of geodynamic evolution and metallogenic events of Inner Western Carpathians. *Slovak Geol. Mag.* 8, 247–257.
- Ondrejka, M., Putiš, M., Uher, P., Schmiedt, I., Pukančík, L. & Konečný, P., 2016: Fluid-driven destabilization of REE-bearing accessory minerals in the granitic orthogneisses of North Veporic basement (Western Carpathians, Slovakia). *Miner. Petrol.* 110, 561–580.
- Ondrejka, M., Uher, P., Putiš, M., Kohút, M., Broska, I., Larionov, A. Bojar, A.-V. & Sobocký T., 2021: Permian A-type granites of the Western Carpathians and Transdanubian regions: products of the Pangea supercontinent breakup. *International Journal of Earth Sciences* 110, 2133–2155.
- Ondrejka, M., Molnárová, A., Putiš, M., Bačík, P., Uher, P., Voleková, B., Milovská, S., Mikuš, T. & Pukančík, L., 2022: Hellandite-(Y)–hingganite-(Y)–fluorapatite retrograde coronae: a novel type of fluid-induced

- dissolution–reprecipitation breakdown of xenotime-(Y) in the metagranites of Fabova Hoľa, Western Carpathians, Slovakia. *Min. Mag.* 86, 586–605.
- Pelech, O., Hók, J. & Józsa, S., 2017: Turonian–Santonian sediments in the Tatricum of the Považský Inovec Mts. (Internal Western Carpathians, Slovakia). *Austrian J. Earth Sci.* 110, 19–33.
- Petrík, I., Janák, M., Vaculovič, T., Finger, F., Kurylo, S. & Konečný, P., 2024: Ordovician (Cenerian) metamorphism in the Western Carpathians: Evidence from EMP monazite dating of polymetamorphosed granitoids in the Veporic unit, Slovakia. *Lithos* 476–477, 107600.
- Plašienka, D., 2012: Jurassic syn-rift and Cretaceous syn-orogenic, coarse-grained deposits related to opening and closure of the Vahic (South Penninic) Ocean in the Western Carpathians—An overview. *Geol. Quarterly* 56, 601–628.
- Plašienka, D., 2018: Continuity and episodicity in the early Alpine tectonic evolution of the Western Carpathians: How large-scale processes are expressed by the orogenic architecture and rock record data. *Tectonics* 37, 2029–2079.
- Plašienka, D. & Putiš, M., 1993: Kinematics of Cretaceous uplift of the Veporic dome (Western Carpathians). *Terra Abstr. (Oxford) to Terra nova* 5, Abstr. suppl. 2, 27.
- Plašienka, D. & Soták, J., 2015: Evolution of Late Cretaceous–Palaeogene synorogenic basins in the Pieniny Klippen Belt and adjacent zones (Western Carpathians, Slovakia): Tectonic controls over a growing orogenic wedge. *Ann. Soc. Geol. Pol.* 85, 43–76.
- Plašienka, D., Grecula, P., Putiš, M., Kováč, M. & Hovorka, D., 1997: Evolution and structure of the Western Carpathians: an overview. In: Grecula P., Hovorka D. & Putiš M. (Eds.): *Geological evolution of the Western Carpathians. Mineralia Slovaca – Monograph*, Bratislava, 1–24.
- Plašienka, D., Janák, M., Lupták, B., Milovský, R. & Frey, M., 1999: Kinematics and metamorphism of a Cretaceous core complex: the Veporic Unit of the Western Carpathians. *Phys. Chem. Earth (A)* 24, 651–658.
- Putiš, M., 1987a: Geológia a tektonika juhozápadnej a severnej časti kryštalinika Malých Karpát. *Miner. Slovaca* 19, 135–157. (in Slovak with English summary)
- Putiš, M., 1987b: Some remarks on the metamorphism and tectonics of the Kráľova hoľa and Trestník crystalline complexes (Veporicum, Western Carpathians). *Acta Geol. Geogr. Univ. Comen. Geol.* 43, 67–84.
- Putiš, M., 1989: Štruktúrny a metamorfny vývoj kryštalinika východnej časti Nízkych Tatier. *Miner. Slovaca* 21, 217–224. (in Slovak with English summary)
- Putiš, M., 1991a: Tectonic styles and Late Variscan – Alpine evolution of the Tatric-Veporic crystalline basement in the Western Carpathians. *Zbl. Geol. Paläont.* T. I, H. 1, 181–204.
- Putiš, M., 1991b: Geology and petrotectionics of some shear zones in the West Carpathian crystalline complexes. *Miner. Slovaca* 23, 459–473.
- Putiš, M., 1992: Variscan and Alpidic nappe structures of the Western Carpathian crystalline basement. *Geol. Carpath.* 43, 6, 369–380.
- Putiš, M., 1994: South Tatric – Veporic basement geology: Variscan nappe structures; Alpine thick-skinned and extensional tectonics in the Western Carpathians (Eastern Low Tatra Mts., Northwestern Slovak Ore Mts.). *Mitt. Österr. Geol. Gesell.* 86, 83–99.
- Putiš, M., Madarás, J., Korikovský, S.P., Kotov, A.B. & Filová, I., 1996: Ductile deformation and recrystallization of the Variscan magmatic complex in the hanging wall of Cretaceous thrust (Veporic unit, Central Western Carpathians). *Slov. Geol. Mag.* 3–4, 221–237.
- Putiš, M., Unzog, W., Wallbrecher, E. & Fritz, H., 1997a: Mylonitization and chemical mass - transfer in granitoid rocks of the Vepor pluton near the Cretaceous Pohorelá thrust (Veporic unit, central Western Carpathians). *Mineralia Slovaca – Monograph*, Bratislava, 197–214.
- Putiš, M., Filová, I., Korikovský, S.P., Kotov, A.B. & Madarás, J., 1997b: Layered metaigneous complex of the Veporic basement with features of the Variscan and Alpine thrust tectonics (the Western Carpathians). In: Grecula P., Hovorka D. & Putiš M. (Eds.): *Geological evolution of the Western Carpathians. Mineralia Slovaca – Monograph*, Bratislava, 175–196.
- Putiš, M., Németh, Z., Unzog, W. & Wallbrecher, E., 1999: The quartz and calcite X-ray texture goniometer patterns from the Western Carpathians Cretaceous ductile shear zones used as kinematic indicators. *Geol. Carpath.* 50, Spec. issue, 165–169.
- Putiš, M., Kotov, A.B., Korikovský, S.P., Salnikova, J.B., Yakovleva, S.Z., Berezhnaya, N.G., Kovach, V.P. & Plotkina, J.V., 2001: U-Pb zircon ages of dioritic and trondhjemitic rocks from a layered amphibolitic complex crosscut by granite vein (Veporic basement, Western Carpathians). *Geol. Carpath.* 52, 1, 49–60.
- Putiš, M., Hrdlička, M. & Uher, P., 2004: Litológia a granitoidný magmatizmus staršieho paleozoika Malých Karpát. *Miner. Slovaca* 23, 183–194. (in Slovak with English summary)
- Putiš, M., Sergeev, S., Ondrejka, M., Larionov, A., Siman, P., Spišiak, J., Uher, P. & Paderin, I., 2008a: Cambrian–Ordovician metaigneous rocks associated with Cadomian fragments in the West-Carpathian basement dated by SHRIMP on zircons: a record from the Gondwana active margin setting. *Geol. Carpath.* 59, 1, 3–18.

- Putiš, M., Gawlick, H.J., Frisch, W. & Sulák, M., 2008b: Cretaceous transformation from passive to active continental margin in the Western Carpathians as indicated by the sedimentary record in the Infratatic unit. *Int. J. of Earth Sciences (Geologische Rundschau)* 97, 4, 799–819.
- Putiš, M., Ivan, P., Kohút, M., Spišiak, J., Siman, P., Radvanec, M., Uher, P., Sergeev, S., Larionov, A., Méres, S., Demko, R. & Ondrejka, M., 2009a: Meta-igneous rocks of the West-Carpathian basement, Slovakia: Indicators of Early Paleozoic extension and shortening events. *Bulletin de la Société Géologique de France* 180, 461–471.
- Putiš, M., Frank, W., Plašienka, D., Siman, P., Sulák, M. & Biroň, A., 2009b: Progradation of the Alpidic Central Western Carpathians orogenic wedge related to two subductions: constrained by ⁴⁰Ar/³⁹Ar ages of white micas. *Geodinamica Acta* 22, 1–3, 31–56.
- Putiš, M., Danišík, M., Ružička, P. & Schmiedt, I., 2014: Constraining exhumation pathway in accretionary wedge by (U–Th)/He thermochronology – Case study on Meliatic nappes in the Western Carpathians. *J. Geodyn.* 81, 80–90.
- Putiš, M., Yang, Y.H., Koppa, M., Dyda, M. & Šmál, P., 2015: U/Pb LA-ICP-MS age of metamorphic-metasomatic perovskite from serpentinized harzburgite in the Meliata Unit at Dobšiná, Slovakia: Time constraint of fluid-rock interaction in an accretionary wedge. *Acta Geol. Slovaca* 7, 63–71.
- Putiš, M., Németh, Z., Li, X.-H., Yang, Y.-H., Li, Q.-L., Ling, X., Nemec, O. & Ondrejka, M., 2018: Prototethys, Paleotethys and Neotethys remnants in the Western Carpathians constrained by SIMS and LA-ICP-MS U–Pb zircon ages. EGU Conference, Abstract Book, Vienna, Austria.
- Putiš, M., Danišík, M., Siman, P., Nemec, O., Tomek, Č. & Ružička, P., 2019a: Cretaceous and Eocene tectono-thermal events determined in the Inner Western Carpathians orogenic front Infrataticum. *Geol. Quarterly* 63, 248–274.
- Putiš, M., Soták, J., Li, Q.-L., Ondrejka, M., Li, X.-H., Hu, Z., Ling, X., Nemec, O., Németh, Z. & Ružička, P., 2019b: Origin and Age Determination of the Neotethys Meliata Basin Ophiolite Fragments in the Late Jurassic–Early Cretaceous Accretionary Wedge Mélange (Inner Western Carpathians, Slovakia). *Minerals* 9(11), 652.
- Putiš, M., Koller, F., Li, X.-H., Li, Q.-L., Larionov, A., Siman, P., Ondrejka, M., Uher, P., Németh, Z., Ružička, P. & Nemec, O., 2019c: Geochronology of Permian-Triassic tectono-magmatic events from the Inner Western Carpathian and Austroalpine units. *Geol. Carpath.* 70, 9–11.
- Putiš, M., Nemec, O., Danišík, M., Jourdan, F., Soták, J., Tomek, Č., Ružička, P. & Molnárová, A., 2021: Formation of a Composite Albian–Eocene Orogenic Wedge in the Inner Western Carpathians: P–T Estimates and ⁴⁰Ar/³⁹Ar Geochronology from Structural Units. *Minerals* 11, 988.
- Putiš, M., Nemec, O., Li, Q.-L., Li, X.-H., Ling, X., Ivan, P., Németh, Z., Ackerman, L., Spišiak, J., Ondrejka, M., Siman, P., Demko, R., Madarás, J., Ružička, P. & Sobocký, T., 2023a: Zircon ages and geochemistry of metamafic complexes from the Variscan suture zones of the West-Carpathian basement: Indicators of northern Gondwana breakup and collision events. 5th Bohemian Massif Symposium, Smolenice, Slovakia. Book of Abstracts, VEDA, Publishing House of the Slovak Academy of Sciences, 25–27.
- Putiš, M., Scherer, E.E., Nemec, O., Ackerman, L. & Ružička, P., 2023b: Geochemistry, Lu–Hf garnet ages, and P–T conditions of blueschists from the Meliatic and Fatric nappes, Western Carpathians: Indicators of Neotethyan subduction. *Geosystems and Geoenvironment* 2, 3, 100150.
- Putiš, M., Li, Q.-L., Chew, D., Li, X.-H., Nemec, O., Ondrejka, M., Ackerman, L., Spišiak, J., Madarás, J., Németh, Z. & Ružička, P., 2024a: Origin and age determination of Early Paleozoic mafic complexes from the Variscan basement of the Western Carpathians: Indicators of demised Tethyan oceanic basins (review and new data). Book of abstracts, Geochemistry Conference, April 10–11th, 2024, Bratislava. Slovakia 151–155.
- Putiš, M., Ondrejka, M., Nemec, O., Li, Q.-L., Chew, D., Li, X.-H., Madarás, J., Németh, Z., Spišiak, J., Siman, P. & Ružička, P., 2024b: The Western Carpathians Variscan Orogen: A collage of post-Cadomian, Cenerian, and Paleotethyan complexes from the Gondwana-derived terranes (a new concept). 13th ESSEWECA Conference, Bratislava, Abstract Book. 57–61.
- Putiš, M., Sláma, J., Li, Q. L., Nemec, O., Ondrejka, M., Li, X. H., Koller, F., Ackerman, L., Strnad, L. & Ružička, P., 2024c: Lithology, U–Pb zircon geochronology, and geochemistry of the Austroalpine Siegraben Complex: Pre-Alpine vs. Alpine history. *Lithos* 482–483, 107739.
- Putiš, M., Sláma, J., Li, Q.-L., Chew, D., Nemec, O., Li, X.-H., Ondrejka, M., Németh, Z.[†], Madarás, J., Ackerman, L., Strnad, L., Spišiak, J., Siman, P. & Ružička, P., 2026: Peri-Gondwanan evolution of the Western Carpathians pre-Permian basement: Petrological–geochemical and geochronological evidence of Proto- and Paleo-Tethys related assemblage of Galatia terrane in Variscan orogen (being submitted to ESR).
- Radvanec, M., 1994: Petrológia rulovo-amfibolitového komplexu gemerika na severnom okraji rudnianskeho rudného rájónu. Prvá časť: P–T–x podmienky a zóny metamorfózy. *Miner. Slovaca* 26, 223–238. (in Slovak with English summary)
- Radvanec, M., Németh, Z., Král, J. & Pramuka, S., 2017: Variscan dismembered metaophiolite suite fragments of Paleo-Tethys in Gemeric unit, Western Carpathians. *Miner. Slovaca* 49, 1–48.

- Rozložník, L., 1965: Petrografia granitizovaných hornín rakoveckej série v okolí Dobšinej. Sborník geologických vied Západné Karpaty 4, 95–144. (in Slovak with German summary)
- Schmid, S.M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., Tischler, M. & Ustaszewski, K., 2008: The Alpine Carpathian-Dinaridic orogenic system: Correlation and evolution of tectonic units. *Swiss J. Geosci.* 101, 139–183.
- Siegl, K. 1976a: Vrásové deformácie Ľumbierskeho kryštalinika. *Acta Geol. et Geogr. Universitatis Comenianae, Geologia* 28, 115–125.
- Siegl, K. 1976b: The structure of the Low Tatra pluton (West Carpathians). *Geol. Zbor. – Geol. Carpath.* 27, 149–164.
- Siegl, K. 1981: Structure of the Ľumbier metamorphites (West Carpathians). *Geol. Zbor. – Geol. Carpath.* 32, 113–127.
- Soejono, I., Bukovská, Z., Collett, S., Novotná, N., Kohút, M., Janoušek, V., Zelinková, T., Jitka Míková, J., Schulmann, K., Hora, J.M. & Veselovský, F., 2024: Paleogeography of the Gondwana passive margin fragments involved in the Variscan and Alpine collisions: Perspectives from metavolcanic-sedimentary basement of the Western Carpathians. *Earth-Science Reviews* 253, 104763.
- Sulák, M., Kaindl, R., Putiš, M., Šítek, J., Krenn, K. & Tóth, I., 2009: Chemical and spectroscopic characteristics of potassium white micas related to polystage evolution of the Central Western Carpathians orogenic wedge. *Lithos* 113, 709–730.
- Tollmann, A., 1980: Geology and tectonics of the eastern Alps (middle sector). In *Abhandlungen der Geologischen Bundesanstalt; Abhandlungen der Geologischen Bundesanstalt; Geologische Bundesanstalt: Wien, Austria, Volume 34*, pp. 197–255.
- Tomek, Č., 1993: Deep crustal structure beneath the central and inner West Carpathians. *Tectonophysics* 226, 417–431.
- Vidal, O., Andrade, V.D.E., Lewin, E., Munoz, M., Parra, T. & Pascarelli, S., 2006: P-T-deformation-Fe³⁺/Fe²⁺ mapping at the thin section scale and comparison with XANES mapping: Application to a garnet-bearing metapelite from the Sambagawa metamorphic belt (Japan). *J. Metamorph. Geol.* 24, 669–683.
- Vojtko, R. & Kriváňová, K., 2024: Cretaceous collision and thrusting of the Veporic Unit onto Tatric Unit in the Nízke Tatry Mts. revealed from structural analysis. *Acta Geol. Slovaca* 16, 1, 19–31.
- 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.
- von Raumer, J.F., Bussy, F., Schaltegger, U., Schulz, B. & Stampfli, G.M., 2013: Pre-Mesozoic Alpine basements – their place in the European Paleozoic framework. *Geol. Soc. of America Bulletin* 125, 89–108.
- Vozárová, A., Soták, J. & Ivanička, J., 1998: A new microfauna from the Early Paleozoic of the Gemicum (foraminifera): constraints for another fossils or subfossils. In: Rakús M. (Ed.) *Geodynamic development of the Western Carpathians*. Monogr., State Geological Institute of Dionýz Štúr, Slovakia, 63–74.
- Vozárová, A., Šarinová, K., Larionov, A., Presnyakov, S. & Sergeev, S., 2010: Late Cambrian/Ordovician magmatic arc type volcanism in the Southern Gemicum basement, Western Carpathians, Slovakia: U–Pb (SHRIMP) data from zircons. *International Journal of Earth Sciences (Geologische Rundschau)* 99, 17–37.
- Vozárová, A., Konečný, P., Šarinová, K. & Vozár, J., 2014: Ordovician and Cretaceous tectonothermal history of the Southern Gemicum Unit from microprobe monazite geochronology (Western Carpathians, Slovakia). *Int. J. Earth Sci.* 103, 1005–1022.
- Vozárová, A., Rodionov, N., Vozár, J., Lepekhina, E. & Šarinová, K., 2016: U–Pb zircon ages from Permian volcanic rocks and tonalite of the Northern Veporicum (Western Carpathians). *J. of Geosci.* 61, 221–237.
- Vozárová, A., Rodionov, N., Šarinová, K. & Presnyakov, S., 2017: New zircon ages on the Cambrian–Ordovician volcanism of the Southern Gemicum basement (Western Carpathians, Slovakia): SHRIMP dating, geochemistry and provenance. *Int. J. Earth Sci. (Geologische Rundschau)* 106, 2147–2170.
- Xiang, H. & Connolly, J.A.D., 2022: GeoPS: An interactive visual computing tool for thermodynamic modelling of phase equilibria. *J. of Metamorphic Geology* 40, 243–255.
- Zurbriggen, R., 2020. Banded amphibolites in the Alps: a new interpretation in relation to early Paleozoic peraluminous magmatism. *Swiss J. of Geosci.* 113, 1–24.

POST-CONFERENCE EXCURSION

Composition, stratigraphy and structure of the Pieniny Klippen Belt (Čergov sector, eastern Slovakia)

D. Plašienka, M. Molčan Matejová, T. Potočný

1 Introduction

As a tradition, the CETeG meetings are accompanied by two one-day field trips presenting geological phenomena in the wider surroundings of the conference venue. The pre-conference excursion usually concerns the “hard rock geology” of crystalline basement complexes, while the post-conference trip relates to the “soft rock” issues, such as sedimentary basin evolution, cover nappes, or young volcanism.

During the CETeG events that were held in Slovakia, several post-conference excursions were devoted to the particular Western Carpathian structure, the Pieniny Klippen Belt (PKB). In 2008 (Upohlav, western Slovakia), localities in one of the classical PKB regions – the Middle Váh River Valley – showed some most conspicuous PKB phenomena like the large Czorsztyn-type klippen area at Vršatec, or Cretaceous exotic conglomerates at Stupné. The 2012 meeting took place at Medvedia hora in eastern Slovakia and the PKB tour presented the Slovakian part of the Pieniny segment with an emphasis on the synorogenic sedimentary record and structure of the Oravic units exposed along a section between Jarabina and Litmanová villages. Finally, because of Covid19 several times postponed, the 2021 CETeG conference was organized near Terchová village (Vrátna Valley in the Malá Fatra Mts.). The field trip offered an overview of the very complicated structure at the contact of the Kysuce and Orava PKB segments with relationships to the adjoining external and internal Carpathian zones. All these presented PKB parts share many common features concerning composition and synsedimentary development of the particular units involved, but also important differences in the structure and tectonic evolution along-strike the PKB. This year we shall continue with another part of the eastern PKB branch – the Čergov segment. Being rather small, this region is like an extract of all principal PKB phenomena, both geological and geomorphological. Thus, welcome to the Klippen Belt again!

2 Generalities about the PKB

The very special Western Carpathian tectonic structure, the Pieniny Klippen Belt (PKB), is characterized by its complex internal structure, particular tectonic units and a range of specific lithostratigraphic formations. As a very narrow, but nearly continuous zone, the PKB follows the boundary between the Flysch Belt, which is a Cenozoic accretionary prism of the External Western Carpathians (EWC), and the Cretaceous nappe stack of thick- and thin-skinned thrust sheets of the Central Western Carpathians (CWC; Fig. 1). In this position, the PKB only includes detached sedimentary cover nappes composed of exceptionally variable Jurassic to Eocene formations and successions (e.g. Birkenmajer 1977).

In general, the PKB includes nappe units of two types: 1) the Oravic units, which are exclusive for and limited to the PKB; 2) the “non-Oravic” thrust sheets, presumably frontal elements of the CWC Patric nappe system (see Plašienka et al. 2020 and references therein). However, the along-strike distribution of these units is irregular. The Oravic units create a substantial part of the PKB and occur all along the ca 600 km long PKB as at least a few dozens of metres to some five kilometres wide zone at the contact with the Magura units of the EWC Flysch Belt. On the other hand, the CWC Patric units (such as the Drietoma, Manín and Klapce units) form the so-called Peri-Klippen zone, which intermittently occur along the southern PKB margin, reaching the maximum width of ca 20 km in the Middle Váh River Valley of western Slovakia (e.g. Plašienka 2019). In the Pieniny Mts of the eastern PKB branch, only the small Haligovce Unit might be attributed to the CWC units, which was correlated with the Patric Manín Unit by Matějka (1961a), Nemčok et al. (1990) and Plašienka (2022), or with the Humenné Unit (Janočko et al. 2000) occurring farther east in the Humenské vrchy Mts. (Fig. 1).

In this contribution, we characterize a comparatively short, but remarkable Čergov segment of the eastern PKB branch. Except of a few lithological and biostratigraphic studies of several individual klippen and despite of its remarkable morphological appearance, this area is little known especially from the point of view of regional structure. Henceforth, we describe composition and lithostratigraphy of the Oravic units focused on some key localities, which will be presented during the excursion.

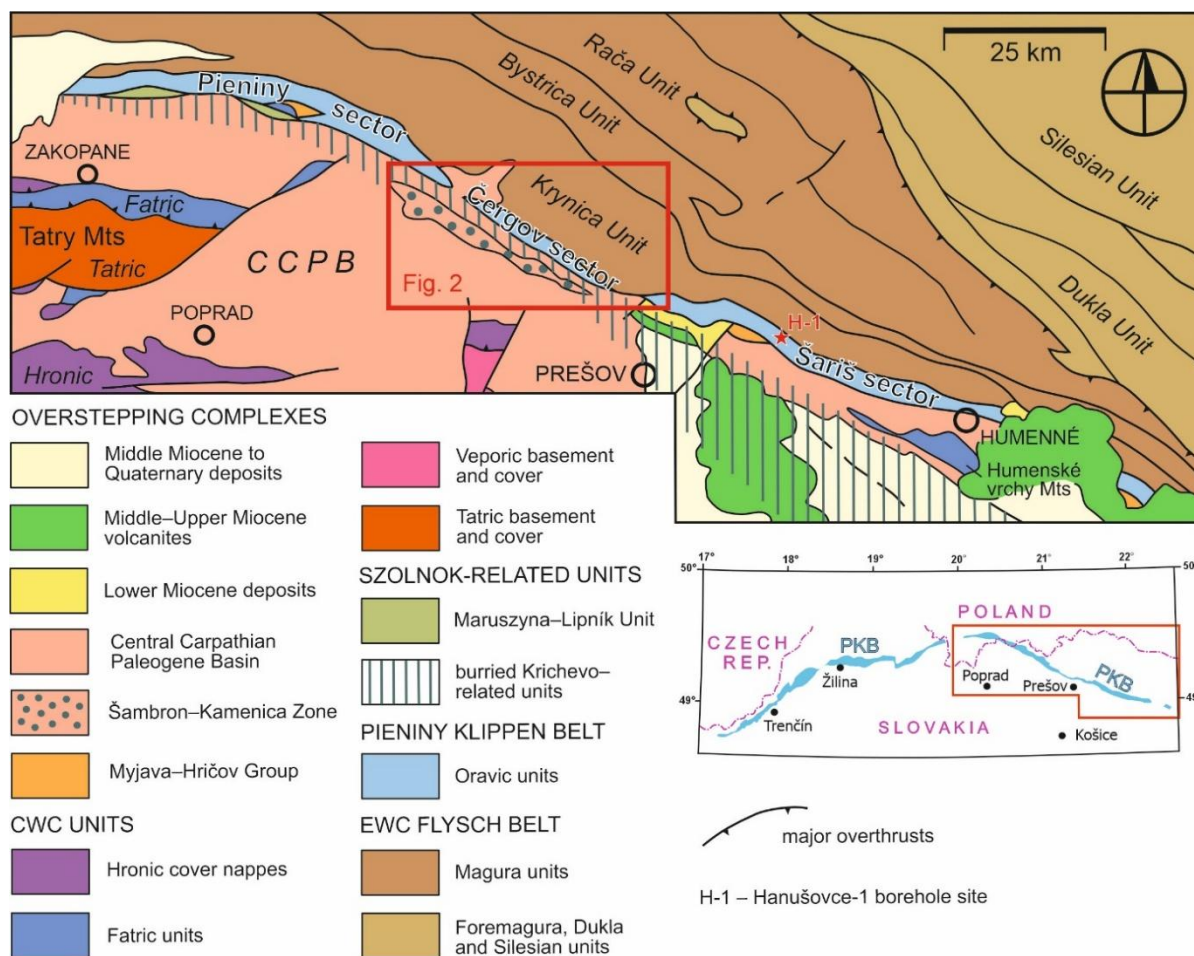


Fig. 1: Tectonic sketch map of the eastern branch of the PKB and surrounding units showing position of the Čergov segment within the red rectangle enlarged in Fig. 2. CCPB – Central Carpathian Paleogene Basin.

3 Geological setting

Geographically, the Čergov PKB segment occurs in north-eastern Slovakia at the boundary between the geomorphological entities of the Čergov Mountains and Spišsko-šarišské medzihorie intramontane depression. Large parts of this area are not forested and constitute one of the most scenic PKB segment with rugged morphology formed by numerous, variously sized klippen of different types surrounded by mildly modelled relief of the “klippen mantle” (e.g. Nemčok 1990; Plašienka 2018a; Plašienka & Novotný 2022).

In earlier divisions (e.g. Scheibner 1968), the PKB Čergov segment was not treated separately, but included in the Šariš sector spreading from the Pieniny Mts far east to the Humenné Mts (Fig. 1). However, there are considerable differences between these two PKB segments – the Pieniny Unit wedges out in the eastern part of the Čergov sector and is absent in the Šariš sector, the Subpieniny Unit is devoid of its characteristic Jurassic – Lower Cretaceous klippen in the Šariš sector and there are also substantial differences in the composition of the Šariš Unit. Moreover, the Čergov segment is individualized by two bordering interruptions, where the PKB is disconnected for a short distance of several hundred meters. In the NW, between the villages of Údol and Plaveč, the Pieniny and Čergov sectors are separated by the transversal structure known as the Plaveč “graben” (Figs 2, 3). However, there is no evidence about the fault-bounded nature of this structure. Instead, it is rather an axial depression filled with transgressive Oligocene deposits of the Údol Succession (Nemčok 1961; Plašienka & Mikuš 2010).

The south-eastern interruption against the Šariš sector between villages Drienica and Babin Potok northeast of Sabinov town is caused by an arcuate, southward convex backthrust of the Krynica Unit of the Magura flysch zone over the PKB units (Fig. 2). Within these limits, the Čergov sector attains the length of around 25 km and the width of several metres to zero at its tapering tips, but reaches 3–4 km across its middle part.

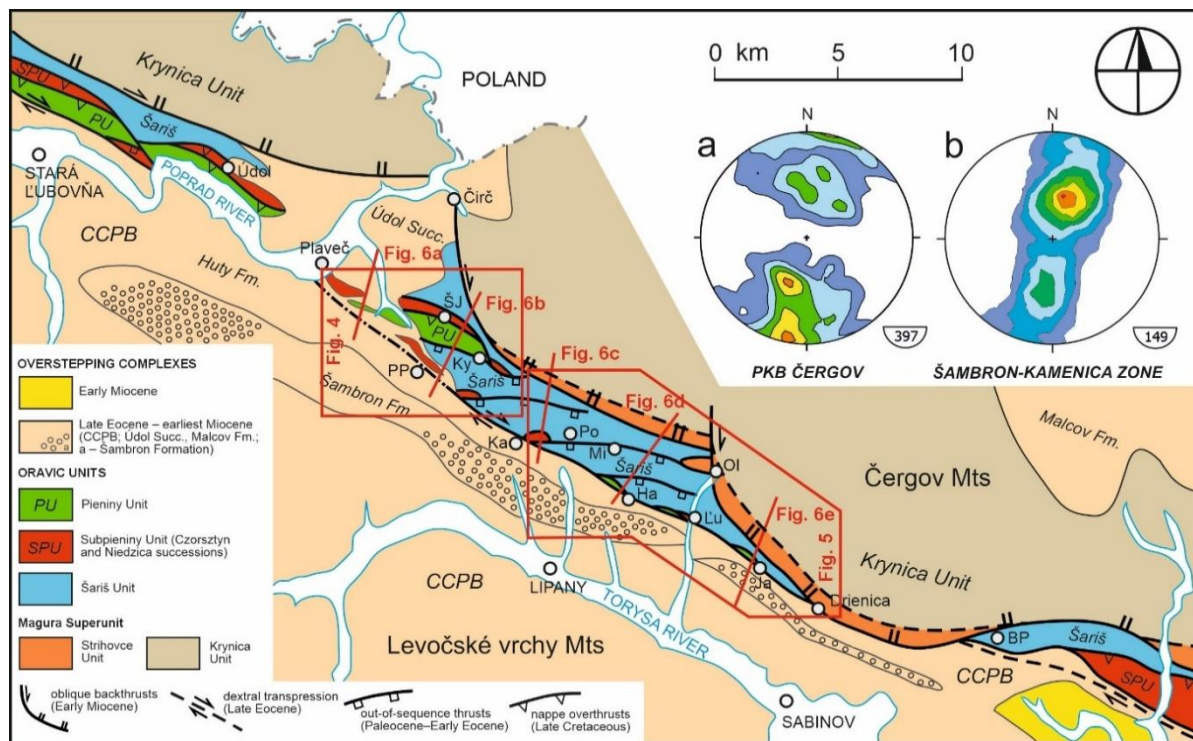


Fig. 2: Simplified tectonic map of the Čergov sector and adjacent units. Modified after Plašienka et al. (2020). Abbreviations of villages mentioned in the text: ŠJ – Šarišské Jastrabie; PP – Pusté Pole; Ky – Kyjov; Ka – Kamenica; Po – Potoky; Mi – Milpoš; Ha – Hanigovce; Lu – Ľutina; Ol – Olejníkov; Ja – Jakovany; BP – Babin Potok. Stereographic projections show poles to bedding from the Čergov PKB segment (a) and from the adjacent Paleogene sediments of the CCPB and Šambron–Kamenica anticlinal zone (b).

The south-western, NW–SE striking boundary of the Čergov PKB sector is formed by a distinct fault against the CCPB sediments named as the Podhale fault by Andrusov (1968). Where occasionally exposed, this fault is represented by a single, discrete subvertical fault plane lacking clear kinematic indicators (Plašienka et al. 2013).

The north-eastern boundary with the Krynica Unit of the Magura Belt is more complicated, although formed by a distinctive fault at the majority of places, too. However, differentiation between the lithologically similar Paleogene flysch sediments of the PKB Šariš Unit (Proč Fm.) and the Krynica Unit (Strihovce and Szczawnica Fms; Fig. 3) is locally problematic due to their mutual imbrication (Bónová et al. 2018). Consequently, the PKB/Magura contact zone can be also described as the “Šariš Transitional Zone”, as it was proposed by Jurewicz (2018) in the Polish Pieniny Mts. On the other hand, lithological differences between the Proč and Strihovce Fms are striking in places, where their contact is clearly tectonic by origin. Sandstones of the Proč Fm. are rich in carbonate clastic material and contain bodies of the Milpoš-type breccias composed dominantly of angular clasts of the PKB units. In contrast, the siliciclastic sandstones of the Strihovce Fm. involve layers of polymict matrix-supported conglomerates (pebbly mudstones) with well-rounded “exotic” pebbles, mostly quartzites, granitoids, crystalline schists and various volcanic rocks, carbonate material being less common (cf. Mišík et al. 1991a, b).

The overstepping Údol Succession, previously known also as the “Ujak (=Údol) facies” (Roth 1957 ex Stráník 1965), is composed of the Middle Eocene variegated shales, Upper Eocene Globigerina marls, and the Oligocene menilitic shales overlain by a thick sequence of turbiditic Malcov Fm. The Údol Succession fills the Plaveč depression (Figs 2, 3, 4), where it was interpreted as unconformably overlying strongly deformed PKB units, itself being less deformed (Roth 1980; Nemčok et al. 1990; Oszcypko et al. 2005; Plašienka & Mikuš 2010). In a similar position, the Malcov Fm. overlies formations of the Krynica Unit in the Čergov Mts. (e.g. Nemčok & Ďurkovič 1989; Nemčok 1971, 1990). At the same time, the Malcov Fm. exhibits close age and lithological analogies with Oligocene deposits of the Central Carpathian Paleogene Basin (CCPB, a.k.a. the Podhale Basin in Poland; Huty or Zakopane Fm.). Therefore, the Údol Succession was interpreted as an interconnecting element of the CCPB and the Magura realms that communicated during the Oligocene (e.g. Książkiewicz & Leško 1959; Stráník 1965).

4 Overview of lithostratigraphy of the Oravic units

The Čergov segment of the PKB is exclusively built up by the Oravic thrust units – the Šariš, Subpieniny and Pieniny from bottom to top (Fig. 2). The general lithostratigraphic composition of these units was described in numerous publications (e.g. Andrusov 1974; Birkenmajer 1977; Mišík et al. 1996; Plašienka et al. 2020+suppl.; Aubrecht in Plašienka et al. 2021; and references in these works), although the age and tectonic affiliations of various sedimentary formations were often differing. In this section, we briefly characterize the lithostratigraphy of the Oravic units in the Čergov PKB sector (Fig. 3).

4.1 The Šariš Unit

Apart from the westernmost portion around the village of Šarišské Jastrabie, the Šariš Unit is dominating the PKB structure farther to the east (Figs 2, 4 and 5). Most of the area is composed of the Maastrichtian – Lower Eocene calcareous turbiditic and olistostrome-bearing (wild)flysch deposits of the Jarmuta and/or Proč Fm. (Nemčok et al. 1990; Plašienka & Mikuš 2010), while older formations are cropping out in narrow imbricated antiformal zones accompanying out-of-sequence reverse fore- and backthrust fault zones.

The Šariš Unit is the name introduced by Plašienka and Mikuš (2010) to replace old, vague terms like “calcareous facies of Magura flysch” (Matějka 1959), “Lackovce resp. Kyjov series” (Stráník 1965), or “Inovce development of the Beňatina flysch” (Leško 1960) used for the Paleogene flysch deposits of the Proč Fm. associated with Jurassic to Cretaceous deep-water formations formerly assigned to the Pieniny Unit. From the point of view of lithostratigraphic content, the Šariš Unit is largely analogous to the Grajcerek Unit distinguished in the Polish Pieniny Mts (e.g. Birkenmajer 1970, 1986).

In the Čergov area, the oldest recognized member of the Šariš Unit is the **Szlachtowa Formation** (Birkenmajer 1977; Birkenmajer & Gedl 2017). The sediments are also informally known as the “black flysch”, the stratigraphic age of which has been controversially interpreted as either Cretaceous, or Jurassic (e.g. Oszcypko et al. 2004, 2012 vs. Birkenmajer et al. 2008; Birkenmajer & Gedl 2017). Nevertheless, the recent data have confirmed the Jurassic (mostly Aalenian–Bajocian) age of the Szlachtowa Fm. from the Pieniny, Orava and Kysuca PKB segments (e.g. Gedl 2008, 2013; Barski et al. 2012; Gedl & Józsa 2015; Segit et al. 2015; Birkenmajer & Gedl 2017; Plašienka et al. 2021). In addition to micaceous black shales and mudstones with common imprints of pelagic bivalves of the genus *Bositra*, it comprises also beds of turbiditic siliciclastic sandstones which are also rich in white mica flakes in places. Beds of calciturbiditic crinoidal limestones occurring in the upper part of the formation indicate input of shallow-marine bioclastic material derived from the adjacent Czorsztyn Ridge uplifting southwards during the late Bajocian (e.g. Krobicki & Wierzbowski 2004). Black shales out of the reach of turbiditic currents are identical with the concomitant Skrzypny Fm. recognized in

the successions of the Subpieniny Unit. As such, the Szlachtowa Fm. is diagnostic of the Šariš and Grajcarek units.

The following **Opaleniec Formation** has only been known from the Grajcarek Unit in the Polish Pieniny Mts. (Birkenmajer 1977; Birkenmajer & Gedl 2017), but we found it also in the Čergov segment. The formation is composed of greenish-grey hemipelagic, often spotted claystones, shales and occasionally marls. They are characterized by the radiolarian and filamentous microfacies (Bositra). Unlike the Szlachtowa Fm., which contains a high amount of terrestrial palynodebris, the purely marine palynofacies rich in dinocysts predominates in the Opaleniec Fm. (Gedl 2008, 2013). Based on dinoflagellate cysts and foraminifers, the age of the Opaleniec Fm. was determined as late Bajocian–Bathonian (e.g. Birkenmajer & Gedl 2017 and references therein).

The Opaleniec Fm. is overlain and in part laterally replaced by dark grey to black argillaceous, Mn-bearing siliceous shales of the **Sokolica Radiolarite Formation** (Birkenmajer 1977). Dinoflagellate cysts point to the late Bajocian to early Oxfordian age of the Sokolica Fm. (Gedl 2008). In the area concerned, in the vicinity of Šarišské Jastrabie village (Stop 5 in Fig. 4), the age of the Sokolica Fm. was determined also by scarce and poorly preserved radiolarian fauna as late Bathonian to early Oxfordian (Ožvoldová & Frantová 1997; Rojkovič et al. 2003). However, these occurrences were placed in the Kysuca Succession of the Pieniny Unit at that time.

Siliceous sediments of the Sokolica Fm. are closely related to the **Czajakowa Radiolarite Formation**. This is composed of red-brown ribbon radiolarites with blackish manganese coatings. In the Čergov segment, the Czajakowa radiolarites of the Šariš Unit were studied near Šarišské Jastrabie and Kyjov villages, where their age was determined as middle Oxfordian – early Kimmeridgian (Ožvoldová & Frantová 1997; Rojkovič et al. 2003; our own data; Stop 5).

During last years, we have gathered new biostratigraphic data about the Lower–Middle Jurassic black dysoxic and siliceous sediments from several sections in the Šariš Unit. In particular, these are organic-walled dinoflagellate cysts (P. Gedl) and radiolarians (M. Molčan Matejová). These data are being prepared for publishing, but will not be presented during this excursion due to a difficult access to the sections.

With a direct contact to underlying red radiolarites of the Czajakowa Fm., the dark red-brown, indistinctly bedded, brittle marlstones correspond to the **Palenica Marl Member** defined by Birkenmajer (1977). At a single known Slovakian locality near Kyjov village, the about 2 m thick Palenica marls contain a rich thanatocoenosis association of aptychi, belemnites and brachiopods indicating, along with the Saccocoma microfacies and foraminifers, the early Tithonian age (Józsa 2019).

The **Pieniny Limestone Formation** (Tithonian–Barremian; Birkenmajer 1977) is a formation characteristic for all deep-water Oravic successions of the PKB (Pieniny s.s., Kysuca, Branisko, Niedzica, Podbiel-Orava). Typically, it is formed by regularly bedded, biancone-type light grey to whitish pelagic limestones with dark-grey chert nodules and lenses. In the Slovak localities of the Šariš Unit, the Pieniny Fm. differs from that of the Pieniny Unit by a lower thickness (a few metres only), thinly-bedded to schistose appearance, darker colours, higher clay content, dense bioturbation and scarcity of chert nodules (Stops 2, 3).

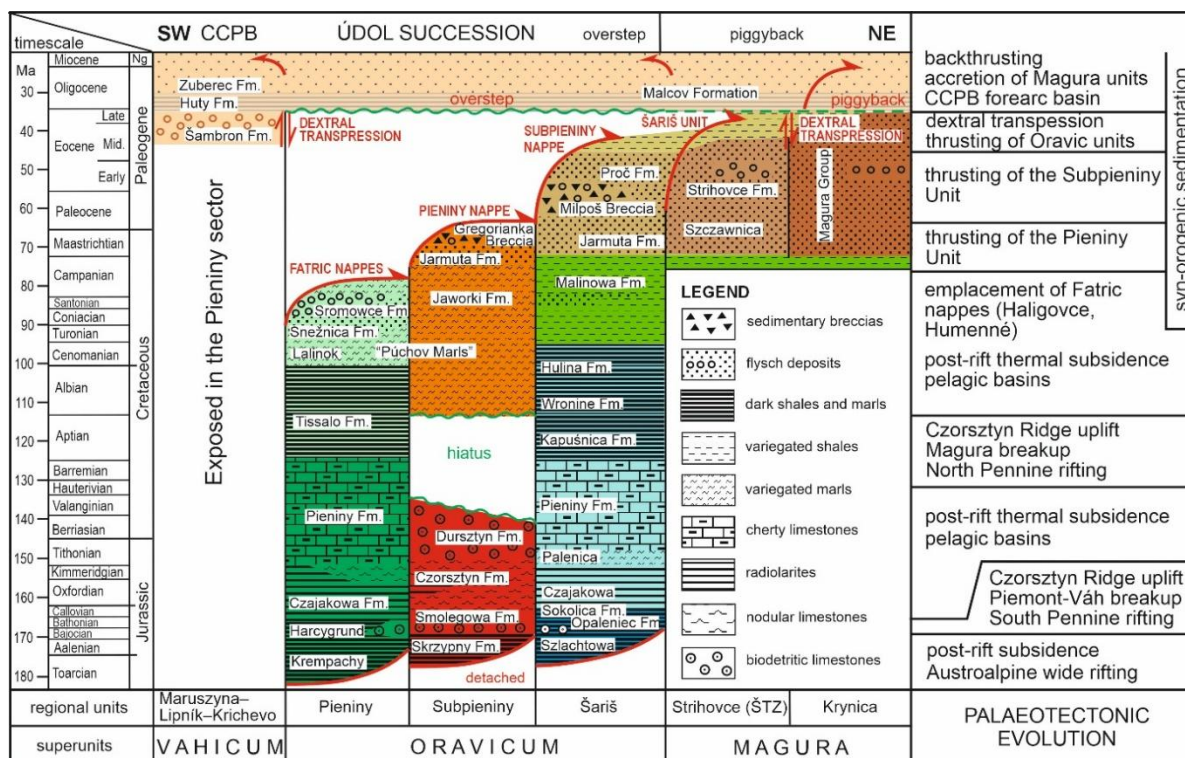


Fig. 3: Simplified litho- and tectonostratigraphy of the Oravic and adjacent Magura units, and overstepping Oligocene deposits in the Čergov sector. ŠTZ – Šariš Transitional Zone (Jurewicz 2018). SW and NE refer to the present coordinates. For the colour code see Fig. 4.

The Pieniny Fm. grades into the Kapuśnica Formation (Aptian in the Grajcarek Unit; Birkenmajer 1977), commonly known also as the Tysalo (Tysalo) Fm. in Slovakia and Ukraine. Dark grey spotty marlstones and marly-siliceous limestones of the Fleckenmergel facies are only a few metres thick in uncovered sections.

Starting from the Albian, sedimentary succession of the Šariš Unit considerably differs from all other PKB units (Grajcarek Group – Birkenmajer 1977), especially by deposition generally below or near the CCD (Fig. 3). Poorly exposed, probably Aptian to early Albian Wronine Formation consists of several metres thick sequence of greenish-grey to black marly and siliceous shales. The overlying Hulina Formation (middle Albian – middle Cenomanian) is composed of black radiolarian cherts and shales with coatings of Mn oxides in the lower portion (Groń Radiolarite Member – Birkenmajer 1977); the upper part (Ubocz Shale Member) is made of dark greenish-grey, calcite-free, laminated argillaceous shales with bentonite intercalations.

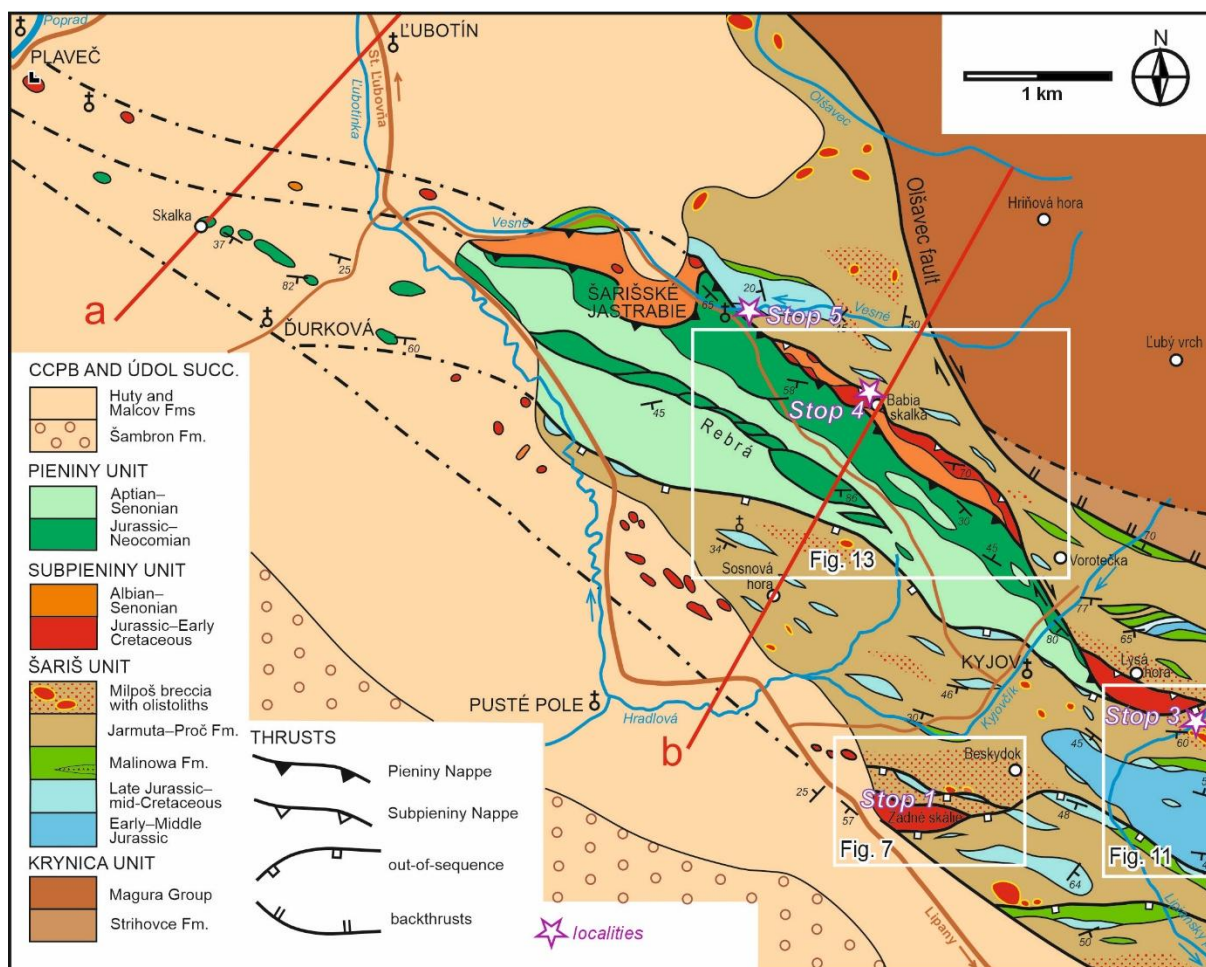


Fig. 4: Detailed tectonic map of the western part of the Čergov sector.

One of the most characteristic, widespread and indicative for the Šariš Unit, is the Malinowa Shale Formation (late Cenomanian to Campanian – Birkenmajer 1977). Variegated, cherry-red to violet, or greenish-grey, mostly non-calcareous shales represent the dominant lithology. There are also passages with siltstone laminae or a few cm thick beds of fine-grained, greenish- or bluish-grey, siliciclastic sandstone turbidites with calcite cement and conspicuous tubular hieroglyphs, usually on both surfaces. Locally, thick beds of greenish-grey quartzitic sandstones prevail over red shales. Thin bands of bentonitized tuffites are present in places, too. The Malinowa Fm. represents the typical Cretaceous Oceanic Red Beds (CORB facies) with distinct abyssal agglutinated foraminiferal (DWAf) associations, including the index species *Uvigerinammmina jankoi* Majzon.

As defined in the Polish Pieniny Mts, the Jarmuta Formation is another typical member of the Šariš/Grajcarek Unit. It represents the synorogenic clastic sequence terminating the Šariš successions in a majority of places. According to Birkenmajer (1977) and Birkenmajer et al. (1987), the Jarmuta Fm. of the Grajcarek Unit is of the Maastrichtian to Paleocene age. The Jarmuta Fm. includes dark calcareous shales intercalated by turbiditic quartz-carbonate sandstones, siltstones and remarkably also coarse-grained sandstones and conglomerates inserted by huge bodies of carbonatic olistostrome breccias. These represent synorogenic, deep-marine mass-flow deposits that carry also large slide blocks and olistoliths, i.e. sedimentary klippen derived from the overriding Subpieniny Nappe (Gregorianka breccias – Nemčok et al. 1989; Milpoš breccias – Plašienka & Mikuš 2010; Plašienka 2012a; Plašienka et al. 2012; Jurewicz 2018; Stop 2 and Stop 3).

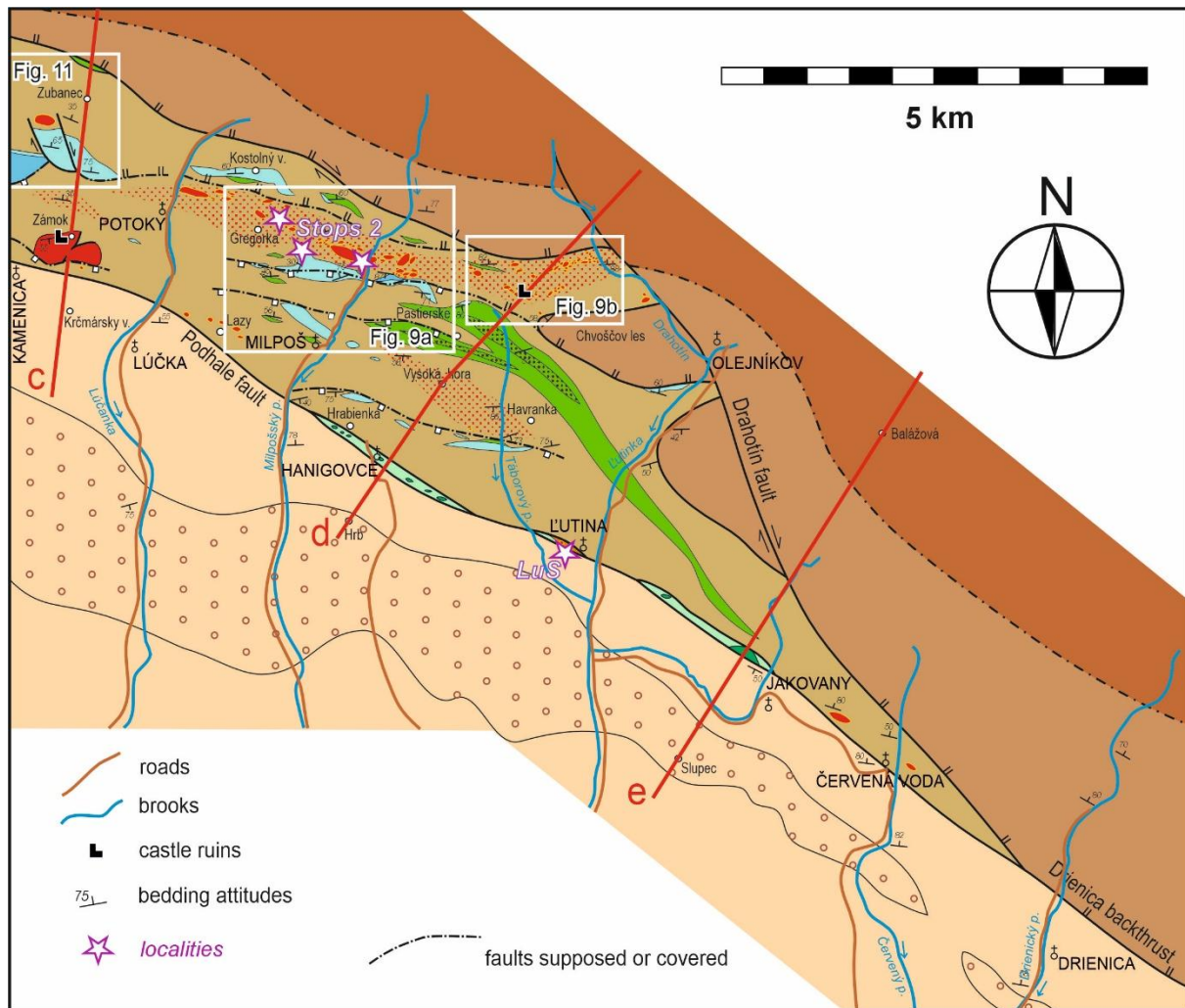


Fig. 5: Detailed tectonic map of the eastern part of the Čergov sector. LuS – Lutina church section (Plašienka et al. 2013). For the legend see Fig. 4.

In easternmost Slovakia, Leško (1960) differentiated the so-called Inovce development of the “Beňatina Flysch” that is predominantly composed of calcareous sandstones of the Proč Formation (Upper Paleocene – Lower Eocene; Leško & Samuel 1968). Because of lithological conformity, Nemčok (1990) and Nemčok et al. (1989, 1990) united the Proč Fm. with the Jarmuta Fm. as the combined Jarmuta–Proč Formation (Maastrichtian – Lower Eocene). Mainly from practical reasons, this term was adopted also by Plašienka & Mikuš (2010), Plašienka (2012a), Plašienka et al. (2012) and Madzin et al. (2019), since both formations are lithologically identical and cannot be distinguished in the field. Judging from the regional distribution, the Jarmuta Fm. (Maastrichtian–?Danian, including the Gregorianka breccias), is confined to the Czorsztyn-type successions of the Subpieniny Unit, whereas the Proč Fm. (Maastrichtian–Paleocene–Lower Eocene, including the Milpoš breccias) is the ubiquitous constituent of the Šariš Unit and forms the substantial part of the surface structure of the Čergov PKB segment (Figs 4 and 5).

4.2 The Subpieniny Unit

In the Čergov sector, sedimentary formations the Subpieniny Unit have a comparatively small areal extent, but form numerous sedimentary klippen of up to a megaolistolith size embedded in the Proč Fm. of the underlying Šariš Unit. The only larger continuous exposure of the Subpieniny Unit occurs around the Šarišské Jastrabie village in the western part of the Čergov segment. In the instructive Babia skalka

klippen area (Stop 4), a narrow, steeply SW-dipping belt of discontinuous Czorsztyn-type Jurassic klippen associated with Upper Cretaceous red marls is in a clear superposition above the Paleogene flysch sandstones (Proč Fm.) of the Šariš Unit and is vice-versa overlain by the Pieniny Nappe (Fig. 4). Scattered outcrops of this belt continue to the WNW to Plaveč village, where it gradually disappears below the overlapping Oligocene deposits of the Huty or Malcov Fm. Inlier of the Plaveč castle rock is located at the western very end of the Čergov sector (Fig. 4).

Another, discontinuous belt of the Czorsztyn and Niedzica klippen occurs along the southern boundary of the Čergov sector around Pusté Pole village (Figs 2, 4, 5). From this area, a unique Czorsztyn klippe with Middle Jurassic syn-rift scarp breccias (Krasín Fm.) and Upper Jurassic neptunian dykes was described by Mišík & Sýkora (1993; KPP in Fig. 4). There, the isolated klippen are surrounded by the Oligocene Huty Fm., but below they probably form olistoliths in the Proč Fm., similarly as the large composite olistolith of the Zadné skálie klippe (Stop 1). It should be noted that, in line with Plašienka & Mikuš (2010) and Plašienka (2018a), we distinguish the tectonic and sedimentary klippen composed of the Czorsztyn-type successions based on the composition of their enveloping matrix. The tectonically separated klippen are usually embedded in sheared soft Púchov-type marls (Jaworki Fm.), whereas olistoliths were emplaced by mass-wasting sedimentary processes in syn-orogenic wildflysch deposits of the Jarmuta-Proč Formation.

In Lutina village farther to the south-east, Plašienka et al. (2013) described a narrow slice of Upper Cretaceous variegated marls with a single Czorsztyn klippe at the direct contacts with the Huty Fm. (Podhale fault) from the SW side and with the variegated shales (Malinowa Fm. of the Šariš Unit) to the NE (LuS in Fig. 5).

Variable sedimentary successions attributed to the Subpieniny Unit and/or to the olistoliths derived from it include standard lithostratigraphic formations of the Czorsztyn, Niedzica or Czertezik successions (Birkenmajer 1977; cf. Fig. 3). However, there are also varieties that combine formations unusually, such as the spectacular Sokol sedimentary klippe near Kyjov (Fig. 4; Stop 3), which comprises sandy-crinoidal limestones (Smolegowa Fm.), red nodular limestones (Czorsztyn Fm.) and bedded cherty limestones (Pieniny Fm.). The problem of the Niedzica vs. Czertezik successions was demonstrated by Wierzbowski et al. (2004) on the example of the Milpoš locality (Stop 3 in Fig. 5).

4.3 The Pieniny Unit

The Pieniny Unit mainly occurs in the western part of the Čergov segment in the Šarišské Jastrabie surroundings (Figs 2 and 4). It is characterized by a distinct NE-vergent fold-thrust structures and is thrust over the narrow strip of the Subpieniny Unit, and both are overriding the Šariš Unit. Yet, the Pieniny Unit is juxtaposed by the Šariš Unit also from the south-western side, which is due to a large-scale WNW–ESE trending and northward verging out-of-sequence thrust oblique to the PKB boundaries. The eastward merging of this thrust with the NNW–SSE directed dextral strike-slip brought about wedging out of the Pieniny Unit near Kyjov village (Fig. 4; see also Fig. 3 in Plašienka 2018a). This is the easternmost large exposure of the Pieniny Unit in the PKB, because further east there are only its small slices present along the southern boundary fault near Hanigovce and Lutina villages (Fig. 2; Plašienka et al. 2013). Afterwards, in the eastern Šariš and Beňatina PKB sectors, and likely also in the Ukrainian PKB, the Pieniny Unit is virtually absent at the surface exposures.

The lithostratigraphic content of the Pieniny Unit corresponds to the deep-water Pieniny s.s. succession (Fig. 3). Oldest exposed formations are represented by the Bajocian dark spotted marls (Harcygrund Fm.) and limestones (Podzamcze Fm.), which are overlain by the Bathonian–Oxfordian radiolarites (Sokolica and Czajakowa Fms), Kimmeridgian reddish cherty limestones (Czorsztyn Fm.) and Tithonian–Barremian well-bedded cherty limestones (Pieniny Fm.). Reduced mid-Cretaceous dark (Tissalo or Kapuśnica Fm.) and variegated “Púchov” marls (Jaworki Fm., Lalinok Fm.) are filling synclinal structures and are in a few places followed by turbiditic sandstones of the Snežnica Fm. and

conglomerates of the Sromowce Fm., which are indicated by the presence of loose pebbles and cobbles in agricultural fields near Šarišské Jastrabie (Fig. 13; Stop 4).

5 Structural elements

Inventories of small-scale structural elements and their kinematic interpretations were presented by Jurewicz (1994) from the Polish and by Plašienka (2012b) from the Slovak part of the Pieniny segment of the PKB. Their results can be fully applied also for the Čergov segment.

All tectonic deformations occurred in the brittle field at palaeotemperatures typically between 110–150°C, but normally not exceeding 200°C, i.e. at higher diagenetic conditions within or above the oil window (e.g. Świerczewska 2005; Zielińska et al. 2021, 2025, 2026). In limestone formations, there is a difference in deformation pattern between the massive sedimentary olistoliths and the tectonic klippen. The former are mostly more coherent with only weak development of anastomosing pressure-solution cleavage and irregular, variously thick veins filled with blocky calcite. On the other hand, the latter are often destroyed by brittle crushing, sometimes forming tectonic breccias cemented by several generations of blocky or fibrous calcite that occasionally forms more than a half of volume of a deformed rock. This is particularly effective in harder rocks of the Šariš Unit.

Except of massive shallow-water limestones and coarse-grained sandstones to breccias, the ubiquitous mesopenetrative structure in the PKB rocks is the foliation, commonly represented by primary sedimentary bedding. In rheologically weak rocks, such as marls and shales, the stratification is frequently intensified by layer-parallel pressure solution foliation formed in diagenetic conditions (Zielińska et al. submitted). This was dominantly achieved by vertical flattening due to sediment loading in the sedimentary basin, later augmented by thrust stacking. Occasionally, within restricted shear zones, the stratification is suppressed by the shearing-related scaly fabric. As a rule, the scaly fabric is accompanied by polished or striated foliation planes and frequently also by intra-foliation slickenfibres.

Extensional bedding-parallel shearing causing stratigraphic omissions in flat-lying, well-bedded Pieniny cherty limestones of the Pieniny Unit was detected near Šarišské Jastrabie village. Together with pre-diagenetic slump folds, they were formed during the Lower Cretaceous extensional processes alongside the unstable southern slopes of the Czorsztyn Ridge (cf. Aubrecht et al. 2022).

Mesoscopic tectonic folds are relatively rare. Low-amplitude, deci- to metric buckle folds with approximately W–E axes were occasionally observed in mid- and Upper Cretaceous soft shales and marls of the Šariš Unit. It would be expected that especially the well-bedded pelagic strata of the Šariš Unit are folded, but this is not the case, partly due to the poor outcrop conditions. An outcrop-scale open fold in red ribbon radiolarites is presented at the first site in Fig. 9a; Stop 2.

6 Regional tectonics

As interpreted in Figs 4, 5 and 6, the generally NW–SE striking faults bounding the Čergov PKB sector exhibit an oblique dextral backthrust character. The south-western Podhale fault juxtaposes the Klippen Belt units against Paleogene deposits of the CCPB. With a unique exception (Plašienka et al. 2013), the fault is not exposed as it is overlapped by Oligocene flysch strata of the Huty and/or Malcov Fm. Nevertheless, outcrops in Oligocene deposits in a close vicinity of the Podhale fault are strongly disturbed, steeply NE-dipping up to vertical or overturned (Fig. 6; railway cuts near Ďurková and Pusté Pole in Fig. 4; exposures in Ľutina, Jakovany and Červená Voda in Fig. 5). From the regional context it follows that the Podhale fault has a polystage kinematic history, first as dextral strike-slip during the Late Eocene (Plašienka et al. 2020), then sealed by Oligocene strata, and reactivated as the oblique-dextral transpressional fault during the Early Miocene. The fault zone is likely subvertical to steeply NE-dipping, accompanied by strongly fractured and cataclastic rocks in places (see also Ludwiniak

2018). In the Čergov sector, the south-western periphery of the PKB is followed by the conspicuous anticlinal Šambron–Kamenica (a.k.a. Hromoš–Kamenica, or Hromovec) zone that exposes thick competent Upper Eocene conglomerates (Šambron Fm.; e.g. Soták et al. 2001), which are supporting macroscopic fold trails (Plašienka et al. 1998, 2020; Jacko 2000).

The northern boundary against the Magura units is more complex. East of the Plaveč axial depression, the Čergov PKB segment is strongly affected by post-Oligocene backthrusting of the Krynica Unit that builds up the Čergov massif (Matějka 1961b; Stráňík 1965; Menčík 1969; Nemčok et al. 1990; Plašienka et al. 2020; Figs 2, 4, 5 and 6). The backthrust has an arcuate, SW-ward convex shape, formed during the post-Oligocene, NE–SW oriented compression. Its north-western limb represents a dextral, oblique-slip fault (Drahotín fault in Fig. 5), while the curvature apex is a NE-dipping reverse fault. As a result, the PKB is completely overridden by the Krynica complexes between Drienica and Babin Potok villages (Fig. 2), where the backthrust merges with the Podhale fault for about 6 km. We name this structure as the Drienica backthrust. It causes also east-ward tightening and ultimately disappearance of the Šambron–Kamenica anticlinal zone from surface east of Drienica.

The kinematically linked Drahotín strike-slip fault and Drienica backthrust have their analogues also westwards. In the western part of the Čergov sector it is the Olšavec dextral strike-slip fault connected with backthrust along the PKB–Magura contact (Figs 2, 4, 5, 6), and in the eastern part of the Pieniny sector it is the system of the Vabec dextral fault zone and the Rozdiel backthrust (see also Plašienka & Mikuš 2010). At the same time, this backward fault-thrust system depicts eastward increasing shortening across the PKB trend until its final tapering near Drienica. The strike-slip and backthrust systems were formed contemporaneously with the anticlinal fold system of the Šambron–Kamenica zone, where it was the only deformation event with the NNE–SSW main compressive axis (Plašienka et al. 2020; Fig. 2b), i.e. oblique to the pre-existing, generally WNW–ESE structural trends of the PKB units (Fig. 2a).

As a whole, the PKB in the Čergov sector is characterized by the fold-and-thrust structure (Fig. 6) that developed during four major deformation phases: 1) D1 nappe thrusting of three Oravic units – Pieniny over Subpieniny and both over Šariš; 2) D2 additional shortening by out-of-sequence thrusting producing tight imbricates of the Oravic units; 3) D3 shearing-dominated dextral transpression along-strike the PKB; 4) D4 post-Oligocene backthrusting associated with slight dextral transpression.

The first three stages D1–3 appear to be closely related and operated in continuity as the Oravic units were detached, stacked and transferred from the frontal to the rear part of the growing accretionary wedge, and finally laterally re-distributed along a wrench zone in the backstop position of the overthickened wedge (Plašienka 2018b; Plašienka et al. 2020). Nappe stacking and subsequent out-of-sequence thrusting were generated in a stable stress field and persisting kinematic framework with orthogonal, generally NW–SE to N–S shortening (Fig. 2a; Jurewicz 1994, 2005; Plašienka 2012a, Plašienka et al. 2020). Thrusting of the Oravic nappes is dated by the age of the youngest syn-orogenic deposits – Maastrichtian Gregoriana breccias in the Subpieniny Unit record thrusting of the overriding Pieniny Unit, whilst the Paleocene–Lower Eocene Milpoš breccias of the Šariš Unit originated during overthrusting by the Subpieniny Unit carrying the piggyback Pieniny Unit (e.g. Plašienka 2012a).

The D2 post-nappe imbrication due to out-of-sequence thrusting is the main deformation process that shaped structures of Oravic units everywhere (Stop 4). In cross-sections (Fig. 6), the macroscopic folds appear to be open to tight, asymmetric, non-cylindrical, north-vergent and closely related to south-dipping listric reverse faults, thus they likely developed as the fault-propagation folds. Supposedly, they are branching from the main detachment thrust fault of the Oravic units superposed above the Magura Strihovce Unit (Fig. 6). The non-cylindricity of macrofolds is unveiled by moderately steep axial plunges of periclinal folds, whereby for instance apical parts of brachyanticlines are often located in topographic elevations and do not continue to adjacent depression. Presumably, periclinal folds developed due to the oblique D2 shortening with respect to the D1 structural trend.

The original overthrust relationships of the Oravic and Magura units is revealed by the situation near Olejníkov village (Fig. 5), where the Strihovce Unit in the Chvoščov les area is overthrust by the Šariš Unit and emerges in a half-window with a periclinal axis plunging to the west. From the north-eastern side, the half-window is then truncated by the Drahotín dextral strike-slip fault. The thrust situation Subpieniny Unit (Púchov marls) over the Šariš Unit (Proč Fm.), over the Magura Krynica Unit (Strihovce Fm.), and over the Magura, Bystrica and Rača units (Beloveža and Zlín Fms.) has been revealed by the Hanušovce-1 deep well (Leško et al. 1984). The borehole was located about 30 km to the east in the Šariš sector (H-1 in Fig. 1). The thermal maturity study of the borehole core material documents a heterogeneous burial and thermal evolution of several partial imbricates of each major unit (Zielińska et al. 2026).

The D3 dextral transpression along the eastern, notably straight PKB branch (east of the PKB arc apex in the Pieniny Mts; Fig. 1), was first documented and kinematically interpreted by Ratschbacher et al. (1993). Data were later extended by Plašienka (2012b), although from localities in the Slovakian Pieniny sector only. Nevertheless, these results are fully applicable also in the Čergov sector. In the map view, all small-scale structures including the kinematic indicators characteristic of the transpressional zones are preferably restricted to the PKB units within its limits made by the bounding faults. Despite being later reactivated as oblique backthrust, the PKB was approximated as a fault-bound, about 120° trending rectangular planar domain, while internal structures – bedding and cleavage strikes and fold axes are oriented in the SW–NE to W–E direction, i.e. obliquely to the PKB boundaries (Ratschbacher et al. 1993; Jurewicz 1994; Plašienka 2012b). Internal synthetic Riedel shears R are then NNW–SSE oriented. This strain pattern complies with the transpressional kinematic model that included pure-shear horizontal shortening, vertical lengthening and dextral simple shearing within the PKB domain (Ratschbacher et al. 1993).

The D2 out-of-sequence thrusting and following D3 dextral transpression ought to have occurred before deposition of the uppermost Eocene – Oligocene sediments of the Údol succession (Huty and/or Malcov Fms.), hence most probably during the late Middle to Late Eocene (Fig. 3). Afterwards, the Oligocene sea covered most of the central and eastern parts of the CWC and EWC areas. The transgressive position of the uppermost Eocene–Oligocene deposits of the Údol Succession above the strongly deformed PKB units was indicated for example by Stráník (1965), Nemčok (1971), Oszczypko et al. (2005) and Plašienka & Mikuš (2010). Then the D4 backthrust event strongly affected also the Oligocene sediments, particularly along the PKB boundaries, where it partly reactivated or obliterated previous transpressional dextral strike-slips. Accordingly, this D4 deformation stage occurred during the latest Oligocene – earliest Miocene times.

7 Field trip localities

While the weathering-resistant limestone klippen provide numerous excellent outcrops, the surrounding soft-rock formations are seldom exposed, usually in deeply incised, but heavily vegetated and badly accessible reached ravines. During this excursion, we shall visit some easily reached outcrops and sections presenting significant phenomena concerning the synsedimentary tectonics, nappe structure, out-of-sequence thrusting and dextral shearing of Oravic units within the Čergov PKB sector.

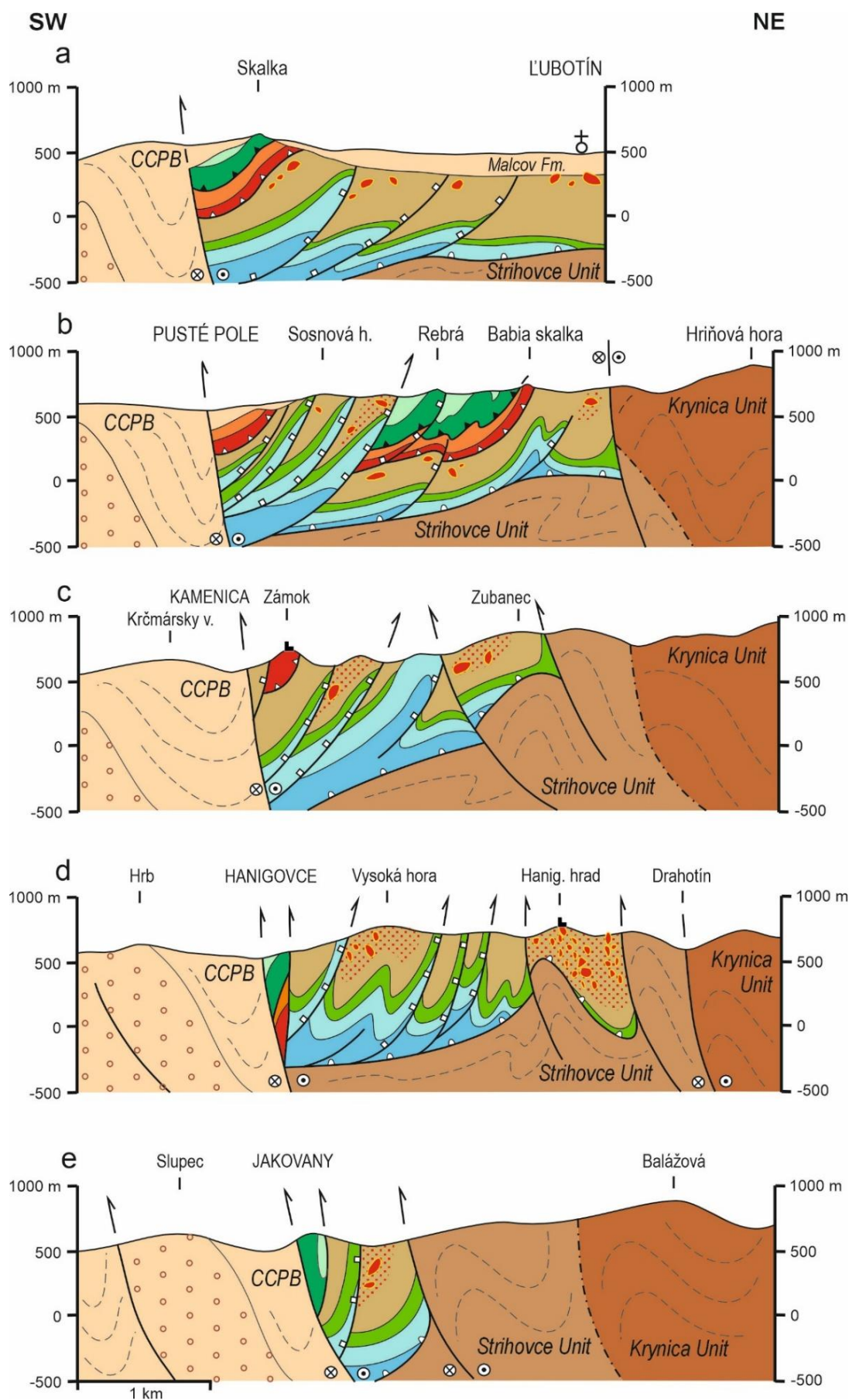


Fig. 7: Cross-sections of the PKB Čergov sector. For their locations and legend see Figs 4 and 5.

Stop 1 – “Sleeping Monk” klippe

Easy access, about 2 km walk (1.5 hour)

The large Zadné skálie klippe (a.k.a. “Sleeping Monk”; Fig. 4; GPS N49.227142, E20.914180) is located above the Pusté Pole Saddle on the watershed divide between the Baltic Sea and Black Sea drainage areas (Figs 7 and 8a, b). It represents a complex slide block or composite megaolistolith formed by at least three individual imbrications, two with the Czorsztyń and one with the Niedzica or Czertezik Succession (Fig. 7). The whole klippe is dominated by various Bajocian sandy-crinoidal limestones (Fig. 8c, d).

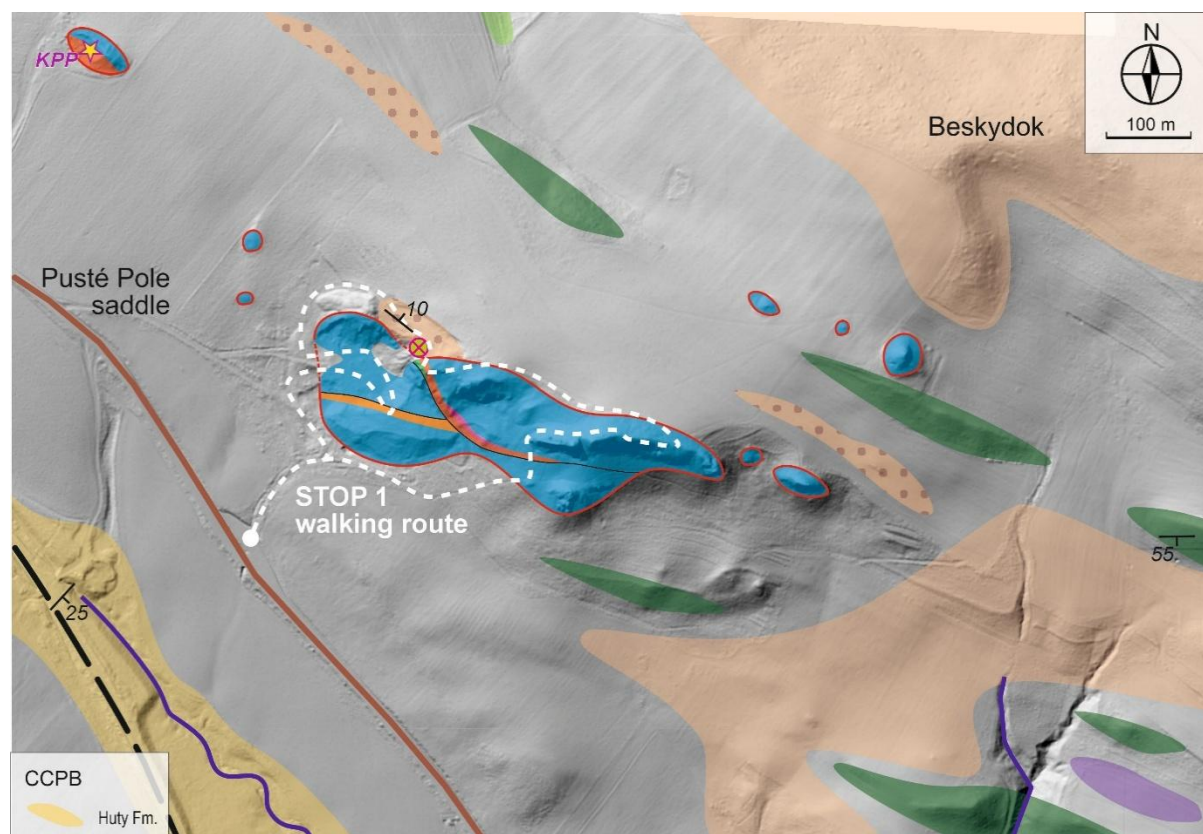


Fig. 7: STOP 1 – Imbricated structure of the Subpieniny Unit in the Zadné Skálie (“Sleeping Monk”) composite klippe (Stop 1 in Fig. 4). KPP – Kyjov–Pusté Pole klippe (Mišík & Sýkora 1993). For the legends see also Figs 9 and 11. All LiDAR-based surface maps depict the relief morphology and especially protracting klippen elevations. The klippen and monomict eluvial scree are coloured, while Quaternary landslides, slope and alluvial deposits, soil and loam are left blank.

A peculiar, metric-sized block of monomict radiolarite breccia occurs in the upper part of this klippe (Fig. 8d). Its apparent transgressive position is suppressed by the lack of clasts of underlying crinoidal limestones and blocky appearance, thus it is interpreted as an olistolith of the Maastrichtian Gregorianka-type breccia derived from the Subpieniny Unit. The whole klippe rests within coarse-grained calcareous sandstones and breccias of the Proč Formation of the Šariš Unit.

A similar, tightly imbricated slide block embedded in coarse-grained Proč sandstones and Milpoš breccias occurs at Lysá hora Hill near Kyjov village (Fig. 11 Plašienka 2018a; his Fig. 3). This block is displaced along a NW–SE trending dextral strike-slip from the stripe of the Subpieniny Unit between Šarišské Jastrabie and Kyjov villages (Fig. 4). Likewise, the massive Kamenica castle rock farther to the SE consists of two or three megablocks of the Czorsztyń Succession (Zámok in Fig. 5; see also Plašienka 2018a; his Fig. 4).

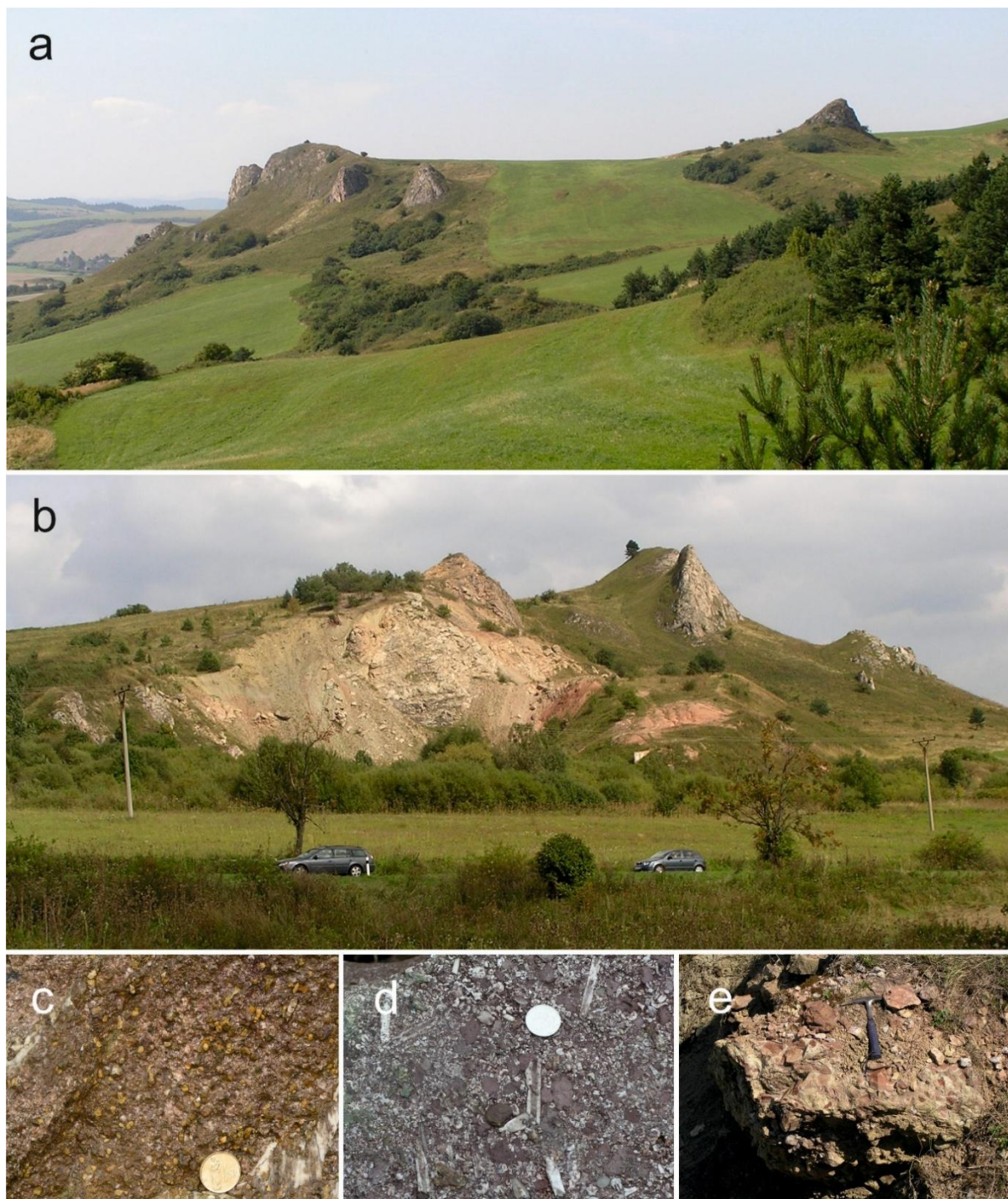


Fig. 8: Zadné Skálie klippen group: a – view from the east; b – view from SW (shot from September 2012; c – sandy-crinoidal limestone with yellow dolomite grains (Smolegowa Fm.); d – bioclastic limestone (Krupianka Fm.); e – olistolith of Gregorianka breccia dominated by clasts of radiolarites (crossed red circle in Fig. 7).

Stop 2 – section of the Šariš Unit with the Milpoš breccia type locality

Moderate difficulty tour (mountain shoes necessary) for about 3.5 km (3 hours with lunch)

The section comprises three partial stops showing the most widespread formations of the Šariš Unit in the area concerned (Figs 5 and 9a). The first stop represents a section through the Upper Jurassic – Lower Cretaceous strata (GPS approx. 49.194528, 21.005750). The lower part is composed of dark red-brown to blackish radiolarites of the Czajakowa Formation.

Radiolarites are overlain by thin-bedded grey, in part cherty limestones of the Tithonian–Barremian of the Pieniny Fm. Radiolarites and limestones are contorted by a system of chevron-type folds, commonly with steeper NW-dipping and shallower SW-dipping limbs indicating their northern vergency. Fold axes are moderately to steeply W to SW-plunging and the whole mesoscale fold track occurs in the core of a large-scale pericline, which represents a fragment of a non-cylindrical macrofold truncated by superimposed out-of-sequence reverse faults of the D2 deformation stage (Fig. 9a).

Going uphill, the Pieniny limestones are covered by pale, structure-less siltstones to fine-grained sandstones of the Proč Fm. Westward (Gregorka Hill), these are grading to coarse-grained calcareous sandstones to breccias revealing the coarsening-and-thickening upward trend of the wildflysch sequence of the Proč Fm.

The second stop presents the Milpoš breccia type locality that occurs along a seldom used field road (Figs 5 and 9a; GPS 49.197139, 21.003306) and shows several types of breccias and associated boulder-sized olistoliths. They were originally described by Nemčok et al. (1989) as a type of the Gregorianka breccias. However, later Plašienka & Mikuš (2010) differentiated the Gregorianka and Milpoš breccias based on their composition, age and tectonic affiliation. The Gregorianka-type breccias are composed of clasts of deep-water sediments, mainly Pieniny limestones, radiolarites and mid-Cretaceous marls that were evidently derived from the Pieniny Unit, which is directly thrust over the breccias at the type locality near Jarabina village (Plašienka et al. 2012). Gregorianka breccia bodies are associated with flysch deposits of the Jarmuta Fm. of Maastrichtian age and belong to the Subpieniny Unit (Fig. 3). In contrast, the Milpoš conglomerates/breccias are dominantly composed of clasts of more shallow-water sediments coming from various successions of the overriding Subpieniny Unit, including huge olistoliths. Milpoš breccias are of Paleocene–Early Eocene age (Nemčok et al., 1989) and represent syn-thrusting deposits associated with the Proč Fm. of the Šariš Unit (Fig. 3; Plašienka & Mikuš 2010; Plašienka 2012a; Plašienka et al. 2012).

Despite of a generally chaotic appearance, the breccias at the Milpoš type locality show some indistinct organization (see also Nemčok et al. 1989). Below and above metre-sized olistoliths composed of crinoidal and red nodular limestones (Fig. 10a), there is a several metres thick layer of polygenous breccia composed of fragments of different carbonates like crinoidal, nodular and micritic limestones with various microfacies, but with prevailing cm-sized angular clasts of red marls (Fig. 10b, c, d, e) that contain globotruncanids of the late Cretaceous age (Coniacian–Campanian–early Maastrichtian). The polymict breccia layer with sandy matrix and angular marlstone fragments rarely contain also cm-sized, well-rounded “exotic” pebbles of polycrystalline quartz, gneisses, low-grade metamorphic rocks, quartzitic sandstones, basic volcanics and granitoids (Fig. 10e). In the upper part of a few metres thick polymict breccia layer, there are also large semi-rounded ellipsoidal cobbles up to 30 cm in diameter of massive grey-green marlstones with hedbergelids and thalmaninellas of the late Albian – early Cenomanian age that resemble sediments of the Tisá or Lalinok Fm. of the Pieniny Unit (Fig. 10b2, f). The matrix of these breccias is formed by fine-grained quartz-carbonate sandstones, from which Nemčok et al. (1989) determined Paleogene foraminifers of genera Globorotalia, Turborotalia and ?Globigerina.

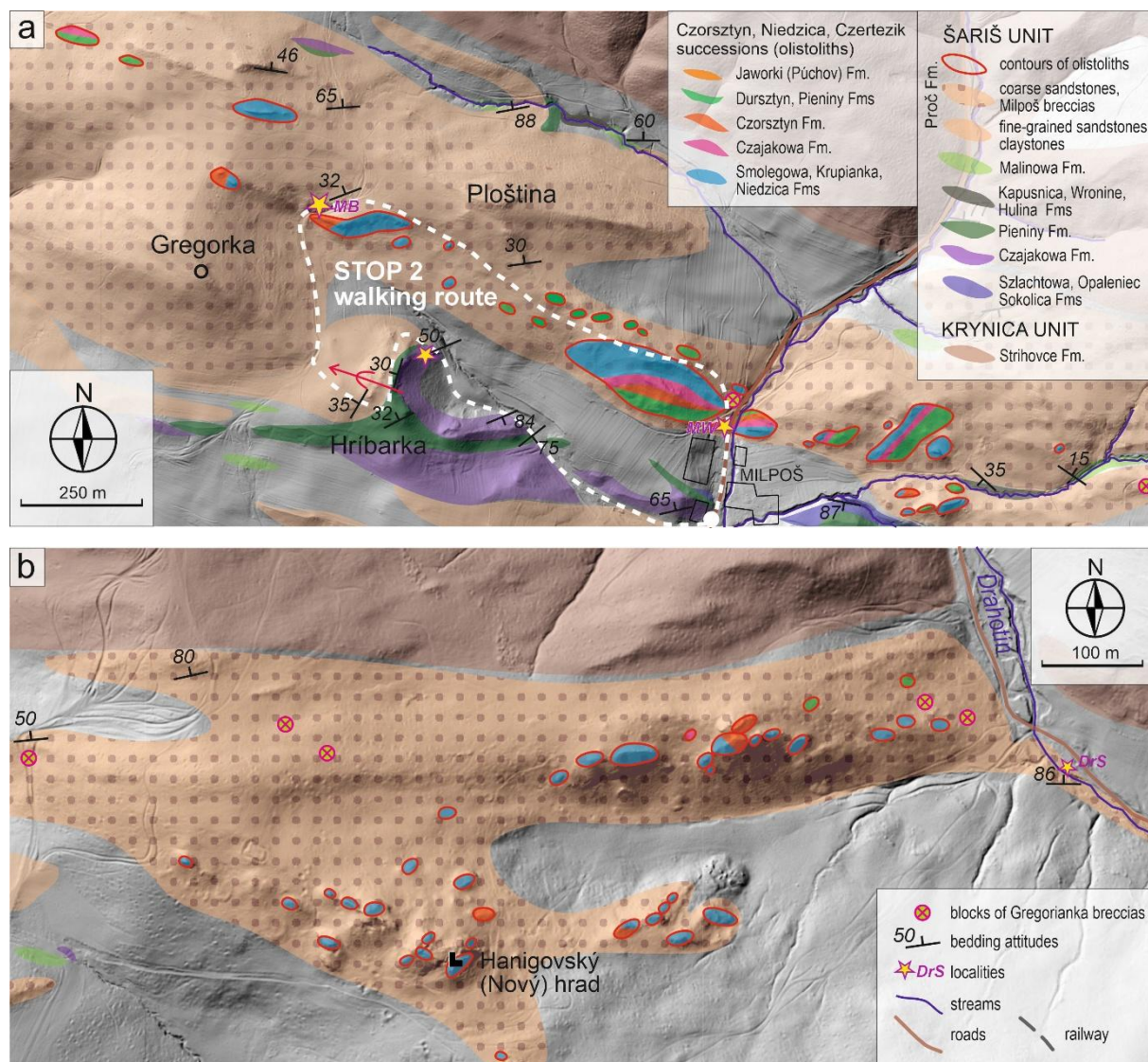


Fig. 9: STOP 2 – The belt of the Milpoš-type breccias with innumerable, variously sized olistoliths of the Czorsztyn-type formations (for the location see Fig. 5); a – surroundings of Milpoš village, MB – Milpoš breccias type locality, MW – Milpoš klippe (Wierzbowski et al. 2004); continuing to b – Hanigovce castle ruins – Drahotín stream area (DrS – Drahotín section).

The upper part of the exposure is represented by monomictic breccia composed of angular cm-dm clasts of red *Globotruncana*-bearing marlstones (Fig. 10b). Nemčok et al. (1989) determined some Coniacian species, but they found also Paleogene foraminifers of the genus *Globorotalia* in the breccia matrix. Our data indicate the late Turonian–Coniacian and Campanian age of the marlstone clasts. The whole complex of polygenous breccias-olistostromes and enclosed olistoliths occurs within the flysch sediments of the Proč Formation of the Paleogene (Paleocene–early Eocene) age.

Other worth visiting localities of the Milpoš breccias in the Čergov sector include the next stop 3 of our route and the remarkable section in the Drahotín stream bedrock (DrS in Fig. 9b; GPS N49.192722, E21.050194). This shows two 2–3 metres thick layers of polymictic Milpoš-type conglomerates with rounded “exotic” pebbles and inserted angular decimetre-sized carbonate clasts that are inserted within coarse-grained, medium-bedded turbiditic sandstones of the Proč Fm.

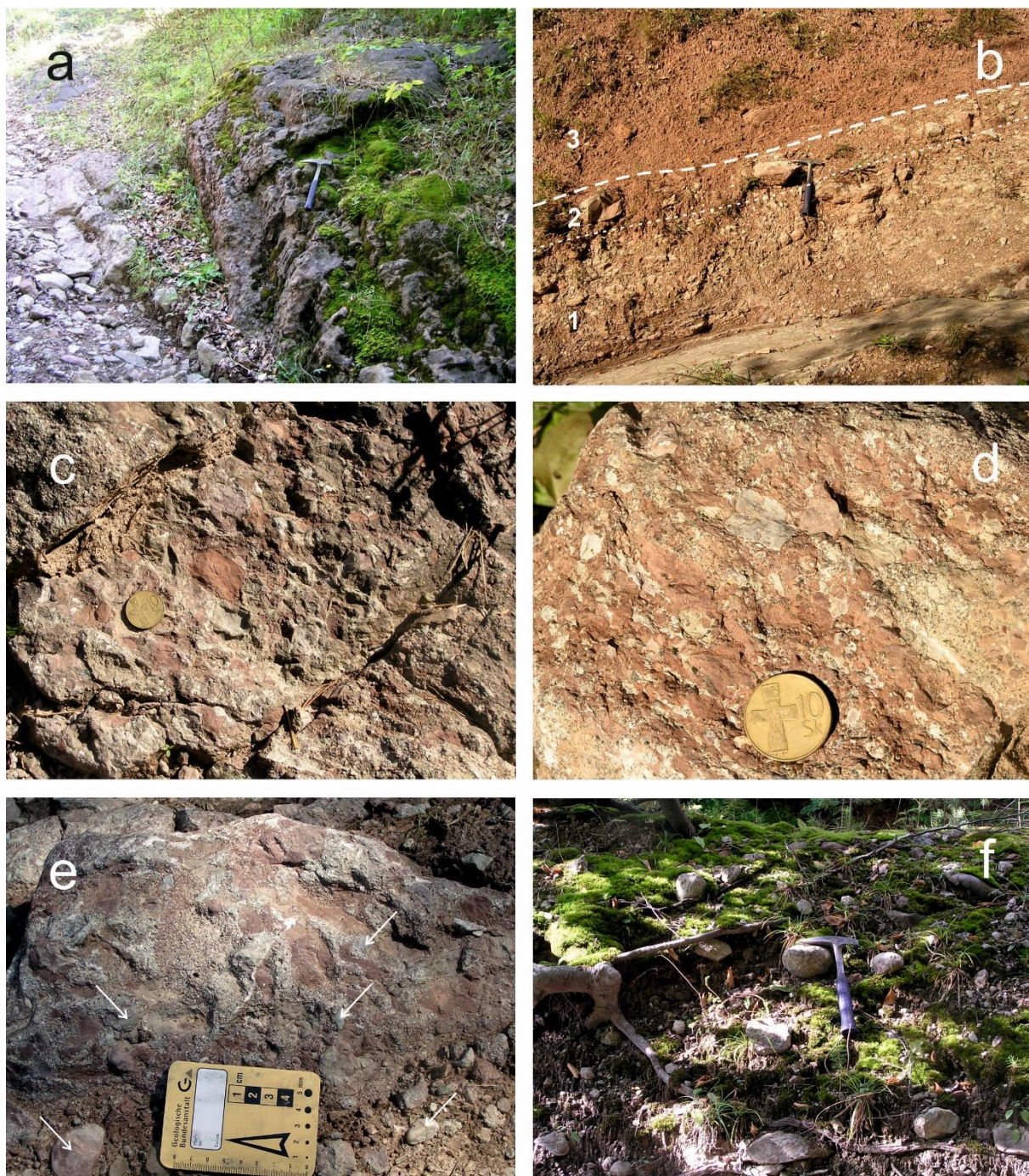


Fig. 10: STOP 4 – Milpoš breccia type locality. All pictures were taken in September 2008; a – boulder olistolith of red nodular limestone; b – layered breccia body (1 – polymict breccia, 2 – with cobbles of rounded marlstones, 3 – monomict breccia composed of red marlstone clasts); c, d – polymict breccia with prevailing red marlstone clasts; e – ditto with dispersed rounded siliciclastic pebbles (arrows); f – rounded marlstone cobbles.

Stop 3 – Sokol' klippe

Easy way, about 3 km walk (ca 1 hour)

Another outcrop of the Milpoš-type conglomerate body is exposed in the Lipiansky potok stream bedrock just below the spectacular Sokol' klippe towering above (Figs 4, 11 and 12a; GPS 49.214250, 20.956333). Some dozens of metres thick polymictic conglomerates/breccias are rich in “exotic” pebbles in places (Fig. 12b). Breccia body is overlain and underlain by steeply SSW-inclined medium-bedded calcareous sandstones of the Proč Fm. (Fig. 12c). The Sokol' klippe is apparently embedded in these breccias. The klippe is composed of an untypical Czorsztyn-type succession comprising thick massive sandy-crinoidal limestones (Smolegowa and Krupianka Fms), reddish nodular limestones (Czorsztyn Fm.) and directly overlying bedded cherty limestones (Pieniny Fm.).

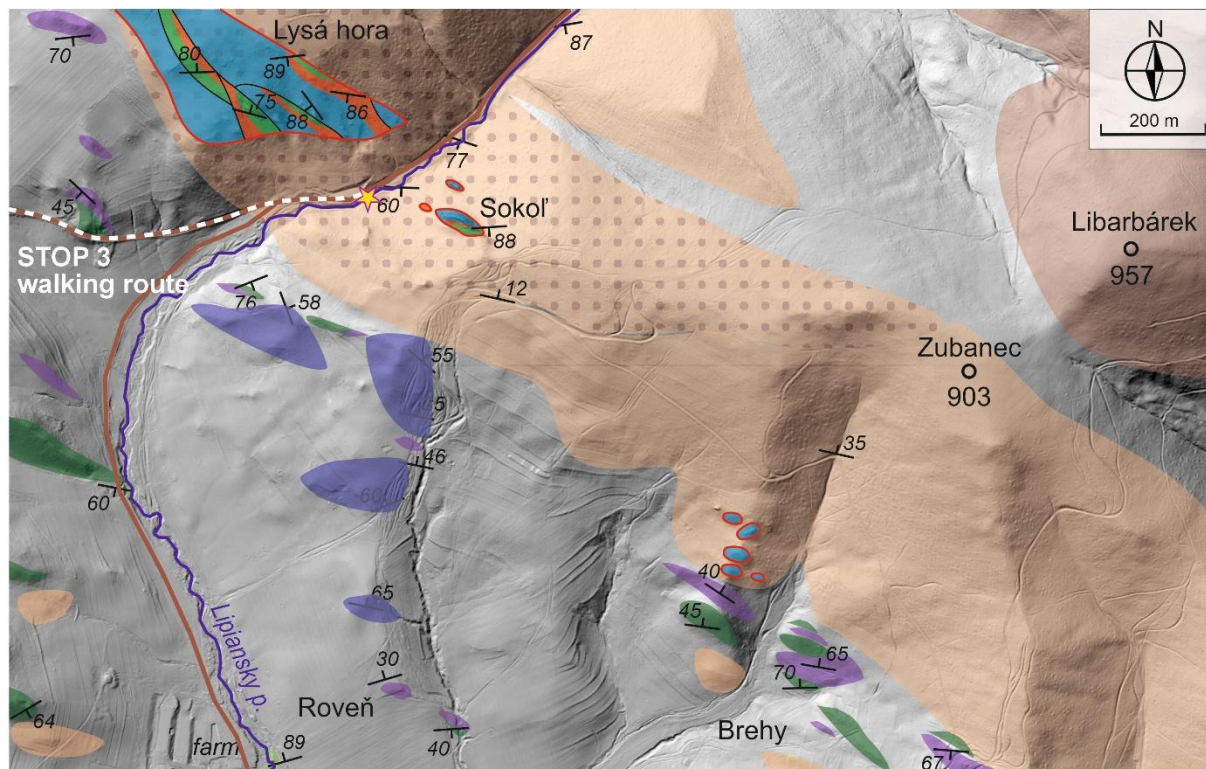


Fig. 11: STOP 3 – Lipiansky potok brook valley, Lysá hora and Sokol' olistolithic klippen.



Fig. 12: STOP 3: a – the Sokol' sedimentary klippe towering above the Lipiansky potok brook composed of crinoidal limestones (Smolegowa Fm.) in this view; b – a variety of the Milpoš breccia/conglomerate forming a matrix of the klippe, in this case dominated by various exotic, well-rounded pebbles, while angular pebbles-cobbles of crinoidal and nodular limestones are infrequent; c – calcareous turbiditic sandstones of the Proč Fm. in which the olistostrome body is inserted.

The immense belt of Milpoš-type olistostromes that occurs in the NE part of the Čergov sector starts east of Kyjov with breccias exposed at Lysá hora Hill, Lipiansky potok stream bedrock and around the Sokol' klippe (Figs 11 and 12) and continues eastward for some 8 km up to the Drahotín stream valley north-west of Olejníkov village (Fig. 4, 5, 9a, b). Within this belt, other remarkable megaolistoliths include several bodies near Milpoš village, or around the Hanigovce castle rock (Figs 9a and 9b, respectively). Judging from the steep north-eastern dip of stratification of matrix sandstones, this gigantic olistostrome layer is up to 1,000 metres thick, although likely composed of several individual bodies separated by pelagic and flysch deposits. Considering the composition of olistoliths that indicates their provenance from the Czorsztyn and/or Niedzica and Czertezik successions, it seems that, during thrusting, a large part of the Subpieniny Nappe was fragmented and transported by mass-wasting mechanisms into the foreland trench-type Proč basin of the later Šariš Unit.

Stop 4 – Babia skalka klippen group

Easy access, about 1.5 km walk (approximately 1 hour)

Stop 4 is a viewpoint of PKB structures in the area east of Šarišské Jastrabie, western part of the Čergov segment (Fig. 4; GPS 49.235111, 20.928694). Here, macroscopic fold-thrust structures can be seen in a plan view, partly in the field, but nicely on the satellite or LiDAR images (Figs 13 and 14). Directly at the viewpoint, the Babia Skalka klippen are composed of red nodular limestones of the Czorsztyn Succession of the Subpieniny Unit, which are thrust over the Proč sandstones of the Šariš Unit (Fig. 6b). On the south-western slopes, the Czorsztyn Succession is imbricated and overridden by Middle–Upper Jurassic formations of the Pieniny Unit (Podzamcze, Czajakowa Fms.) and by the Lower Cretaceous Pieniny Fm. (Fig. 13). Hence, the original nappe succession of Oravic units is preserved here, although affected by the post-nappe out-of-sequence folding and reverse faulting. However, about 1 km more to the south, this nappe stack was truncated by the NW–SE trending regional out-of-sequence thrust that exposed the lowermost Šariš Unit in comparatively large areas (Figs 4, 6b, 13). The belt of the Subpieniny and Pieniny units is tapering eastwards and wedges out near Kyjov village (Fig. 4). There, the north-eastern and south-western belts are merging together and then compose almost exclusively the eastern part of the Čergov sector (Fig. 5).

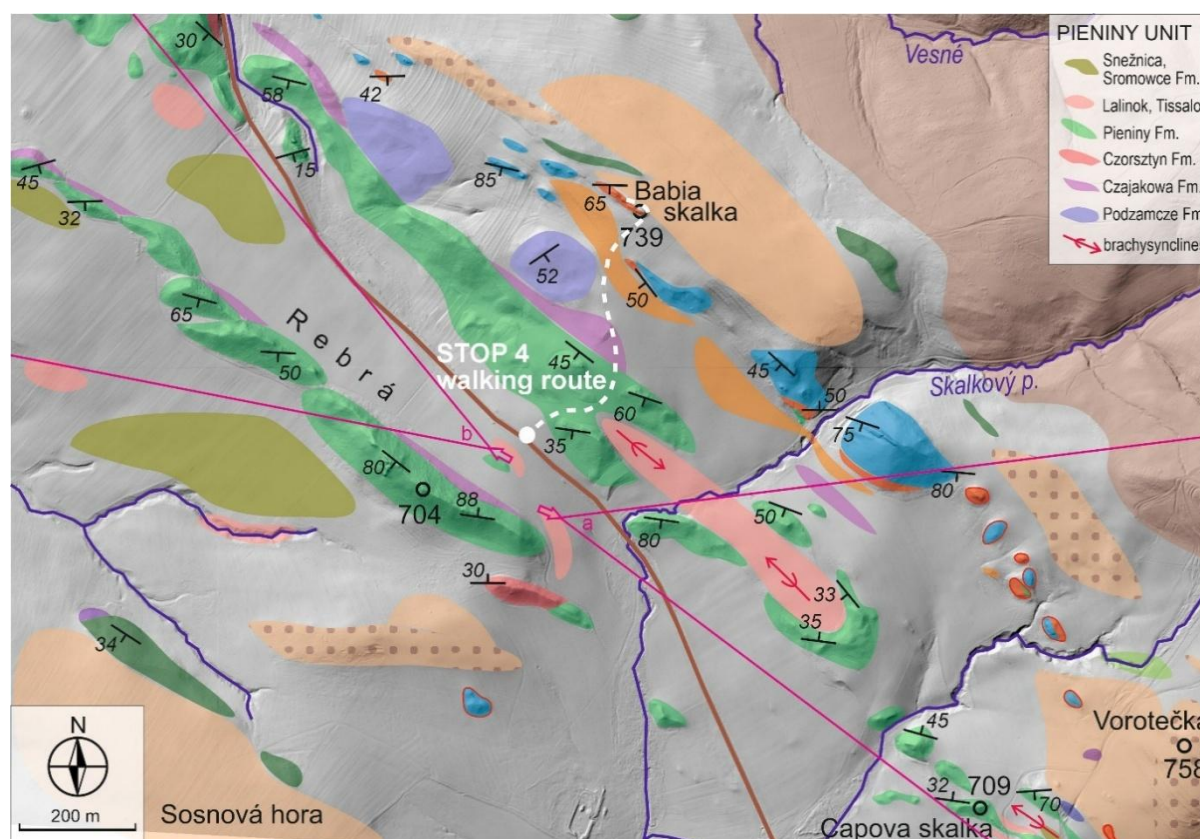


Fig. 13: STOP 4 – LiDAR-based geological map of the area east of Šarišské Jastrabie village. Straight, purple tapering lines indicate the view extent of photographs shown in Figure 14 (a and b).

What is also worth mentioning and nicely recognizable, is a brachysynclinal fold, about 500 metres long and 100 metres wide, which is developed in bedded Pieniny limestones and filled with Upper Cretaceous variegated marls and marked by oppositely plunging axes in Figs 13, 14a. Furthermore, Figure 14b shows a rare example of strike-slip duplex structures formed within the Pieniny Unit. An about 2 km long, narrow and straight belt of the steeply south- to southwest-dipping Pieniny Fm. is stretching parallel to the PKB boundaries and underlain by Jurassic radiolarites from NE and overlain by mid-Cretaceous variegated marls and Upper Cretaceous sandstones (Snežnica and Sromowce Fms)

from the SW side (Fig. 13). Owing to its morphological expressiveness, the belt is accurately named “Rebrá” (Ribs) and forms a weathering-resistant dissected front of a SW-dipping reverse fault. Dextral simple shearing along the pre-existing steep reverse fault then produced an en-echelon array of strike-slip horses within duplex accumulations of laterally alternating with sheared-off thinned extensional segments (Figs 4, 6b, 13, 14b). This is partly in contrast with the more common extensional duplex structures described as the “ribbon-type” klippen by Plašienka (2012b).



Fig. 14: STOP 4 – field views on regional macrostructures of the Pieniny Unit in the area east of Šarišské Jastrabie village (for locations see Fig. 13). a – brachysynclinal closure of limestones of the Pieniny Fm. (traced by the yellow dotted line) filled with mid-Cretaceous variegated marls and surrounded mostly by radiolarites; b – a row of en echelon strike-slip horses within a steeply SW-dipping band of Pieniny limestones (local name Rebrá, i.e. Ribs).

Stop 5 – Vesné stream section

Easy access, 0.5 km walk (half an hour)

This section occurs in Šarišské Jastrabie village, Vesné stream and its surroundings (Fig. 4; GPS N49.241167, E20.916333). There, the Middle Jurassic to Upper Cretaceous strata are cropping out in the core of a broad W–E trending, eastward-plunging anticline. The locality is famous for the manganese ore occurrences attempted to be mined during the WWII and in 1950-ties (Ilavský 1955; Rojkovič et al. 2003). Black siliceous shales are the oldest exposed rocks. They contain oval nodules up to decimetre size of Mn-bearing pelocarbonates. With a tectonic contact, they are overlain by red platy radiolarites, which are in turn overlain by pale thin-bedded limestones of the Pieniny Fm. upstream. Mid-Cretaceous strata are not exposed, and Malinowa-type red shales occur in the scree only. The anticline core is surrounded by coarse-grained calcareous sandstones of the Jarmuta-Proč Fm.

Based on radiolarians, the lower black, Mn-bearing radiolarian shales were dated to the Bathonian–Callovian and attributed to the Sokolica Fm., while the upper red radiolarites represent the Czajakowa Fm. of the Oxfordian–Kimmeridgian age (Ožvoldová & Frantová 1997; Rojkovič et al. 2003).

8 Conclusions

In a relatively restricted area, the Čergov sector concentrates several key phenomena that are essential for understanding the structure and evolution of the PKB. These include the Maastrichtian–Eocene syn-thrusting clastic sedimentation, the huge olistostrome bodies and sedimentary klippen – olistoliths in particular, the nappe contacts of the Oravic units and their subsequent modifications by out-of-sequence folding and thrusting that were later partially disintegrated by the Late Eocene along-strike dextral transpression and formation of the PKB boundary faults. All these structures were sealed by the Oligocene deposits and finally modified by the Early Miocene backthrusting. Although only a fraction of these phenomena can be demonstrated during a short one-day trip, we believe the participants can obtain a comprehensive information about the PKB as a world-wide unique geological marvel.

Acknowledgements: We are grateful for the financial support from the research projects funded by the Slovak Research and Development Agency (project APVV-21-0281) and by the Grant Agency for Science, Ministry of Education of the Slovak Republic (VEGA 1/0021/25).

References

- Andrusov D., 1968: Grundriss der Tektonik der Nördlichen Karpaten. *Verlag Slow. Akad. Wiss.*, Bratislava, 1–188.
- Andrusov D., 1974: The Pieniny Klippen Belt. In Maheľ M. (ed.): *Tectonics of the Carpathian-Balkan regions. Diónýz Štúr Geological Institute*, Bratislava, 145–158.
- Aubrecht R., Józsa Š., Plašienka D. & Wierzbowski H., 2022: Mid-Cretaceous turnover in the Oravic segment of the Pieniny Klippen Belt (Western and Eastern Carpathians): new data and synthesis. *Cretaceous Research*, 140, 105323.
- Barski M., Matyja B.A., Segit T. & Wierzbowski A., 2012: Early to Late Bajocian age of the “black flysch” (Szlachtowa Fm.) deposits: implications for the history and geological structure of the Pieniny Klippen Belt, Carpathians. *Geological Quarterly*, 56, 3, 391–410.
- Birkenmajer K., 1970: Przedeoceńskie struktury fałdowe w pienińskim pasie skałkowym Polski. *Studia Geologica Polonica*, 31, 81 p. (English summary: Pre-Eocene fold structures in the Pieniny Klippen Belt (Carpathians of Poland))
- Birkenmajer K., 1977: Jurassic and Cretaceous lithostratigraphic units of the Pieniny Klippen Belt, Carpathians, Poland. *Studia Geologica Polonica*, 45, 1–158.
- Birkenmajer K., 1986: Stages of structural evolution of the Pieniny Klippen Belt, Carpathians. *Studia Geologica Polonica*, 88, 7–32.

- Birkenmajer K. & Gedl P., 2017: The Grajcarek succession (Lower Jurassic–Mid Paleocene) in the Pieniny Klippen Belt, West Carpathians, Poland: a stratigraphic synthesis. *Annales Societatis Geologorum Poloniae*, 87, 55–88.
- Birkenmajer K., Dudziak J., Jednorowska A. & Kutuba J., 1987: Foraminiferal-nannoplankton evidence for Maastrichtian and Paleocene ages of the Jarmuta Formation: its bearing on dating Laramian orogeny in the Pieniny Klippen Belt, Carpathians. *Bull. Pol. Acad. Sci., Earth Sci.*, 35, 287–298.
- Birkenmajer K., Gedl P., Myczyński R. & Tyszk J., 2008: “Cretaceous black flysch” in the Pieniny Klippen Belt, West Carpathians: a case of geological misinterpretation. *Cretaceous Research*, 29, 535–549.
- Bónová K., Mikuš T. & Bóna J., 2018: Is Cr-spinel geochemistry enough for solving the provenance dilemma? Case study from the Paleogene sandstones of the Western Carpathians (Eastern Slovakia). *Minerals*, 8, 543.
- Gedl P., 2008: Organic-walled dinoflagellate cyst stratigraphy of dark Middle Jurassic marine deposits of the Pieniny Klippen Belt, West Carpathians. *Studia Geologica Polonica*, 131, 7–227.
- Gedl P., 2013: Dinoflagellate cyst from the Szlachtowa Formation (Jurassic) and adjacent deposits (Jurassic–Cretaceous) of the Grajcarek Unit at Szczawnica-Zabniszcze (Pieniny Klippen Belt, Carpathians, Poland). *Geological Quarterly*, 57, 3, 485–502.
- Gedl P. & Józsa Š., 2015: Early?-Middle Jurassic dinoflagellate cysts and foraminifera from the dark shale of the Pieniny Klippen Belt between Jarabina and Litmanová (Slovakia): age and palaeoenvironment. *Annales Societatis Geologorum Poloniae*, 85, 1, 91–122.
- Ilavský J., 1955: Výskyt manganovej rudy v bradlovom pásme pri Šarišskom Jastrabí. *Geologický sborník SAV*, 6, 1-2, 119–130. (German summary: Vorkommen von Manganerz in der Klippenzone bei Šarišské Jastrabie)
- Jacko S. Jr., 2000: Structural research of the NE margin of the Central Carpathian Paleogene Basin: Kamenica railway section, Eastern Slovakia. *Mineralia Slovaca*, 32, 301–302.
- Janočko J. (ed.), Gross P., Polák M., Potfaj M., Jacko S. ml., Rakús M., Halouzka R., Jetel J., Petro L., Kubeš P., Buček S., Köhler E., Siráňová Z., Zlinská A., Halasová E., Hamršíd B., Karoli S., Žec B., Fejdiová O., Milička J., Boorová D. & Žecová K., 2000: Vysvetlivky ku geologickej mape Spišskej Magury 1: 50 000. *ŠGÚDŠ, Vyd. D. Štúra*, Bratislava, 174 s. (English summary: Explanations to geological map of the Spišská Magura region)
- Józsa Š., 2019: Early Tithonian deep-water colonization by benthic foraminifera in the Magura Basin (Pieniny Klippen Belt, Western Carpathians): a clue to the origins of deep-water foraminifera. *Rivista Italiana di Paleontologia e Stratigrafia*, 125, 2, 401–419.
- Jurewicz E., 1994: Analiza strukturalna pienieńskiego pasa skałkowego okolic Jaworek. *Studia Geologica Polonica*, 106, 7–87. (English summary: Structural analysis of the Pieniny Klippen Belt at Jaworki, Carpathians, Poland)
- Jurewicz E., 2005: Geodynamic evolution of the Tatra Mts. and the Pieniny Klippen Belt (Western Carpathians). *Acta Geologica Polonica*, 55, 3, 295–338.
- Jurewicz E., 2018: The Šariš Transitional Zone, revealing interactions between Pieniny Klippen Belt, Outer Carpathians and European platform. *Swiss Journal of Geosciences*, 111, 245–267.
- Krobicki M. & Wierzbowski A. 2004: Pozycja stratygraficzna i paleogeograficzne znaczenie bajoskich wapieni krynowidowych w ewolucji pienieńskiego basenu skałkowego. *Tomy Jurajskie*, 2, 69–82. [English abstract: Stratigraphic position of the Bajocian crinoidal limestones and their palaeogeographic significance in evolution of the Pieniny Klippen Basin]
- Książkiewicz M. & Leško B., 1959: On the relation between the Krosno and Magura-flysch. *Bull. Pol. Acad. Sci., Sér. Chim. Géol. Géogr.*, 7, 10, 773–780.
- Leško B., 1960: Paleogén bradlového pásma na východnom Slovensku. *Geologický sborník*, 11, 1, 95–103. (German summary: Paläogen der Klippenzone in der Ostslowakei)
- Leško B. & Samuel O., 1968: Geológia východoslovenského flyšu. *Vyd. Slov. akad. vied*, 280 s. (English summary: The geology of the East Slovakian Flysch)
- Leško B., Ďurkovič T., Gašpariková V., Samuel O. & Snopková P., 1984: Geologické hodnotenie vrtu Hanušovce-1. *Mineralia Slovaca*, 16, 217–255. (English summary: Geological evaluation of the Hanušovce 1 drill-hole data (Eastern Slovakia))
- Ludwiniak M., 2018: Miocene transpression effects at the boundary of Central Carpathian Paleogene Basin and Pieniny Klippen Belt: examples from Polish-Slovakian borderland. *Geology, Geophysics & Environment*, 44, 1, 91–110.
- Madzin J., Plašienka D. & Méres Š., 2019: Provenance of synorogenic deposits of the Upper Cretaceous – Lower Palaeogene Jarmuta-Proč Formation (Pieniny Klippen Belt, Western Carpathians). *Geologica Carpathica*, 70, 1, 15–34.
- Matějka A., 1959: Šarišský úsek vnitřního pásma bradlového mezi řekou Popradem a Sekčovským potokem. *Zprávy o geologických výzkumech v roce 1957*, ÚÚG Praha, 146–148. (in Czech)
- Matějka A., 1961a: O haligovském mesozoiku a paleogénu. *Zprávy o geologických výzkumech v roce 1959*, ÚÚG Praha, 129–130. (in Czech)

- Matějka A., 1961b: Vnitřní pásmo bradlové na listu geologické generální mapy Vysoké Tatry. *Zprávy o geologických výzkumech v roce 1959*, ÚÚG Praha, 132–134. (in Czech)
- Menčík E., 1969: O některých tektonických problémech v magurské skupině flyšové. *Geologické práce, Správy*, 47, 91–128. (English summary: Tectonics of the Magura flysch group of Czechoslovakia)
- Mišík M. & Sýkora M., 1993: Jurassic submarine scarp breccia and neptunian dykes from the Kyjov – Pusté Pole klippen (Czorsztyn unit). *Mineralia Slovaca*, 25, 411–427.
- Mišík M., Sýkora M., Mock R. & Jablonský J., 1991a: Paleogene Proč conglomerates of the Klippen belt in the west Carpathians, material from Neopieninic exotic ridge. *Acta Geologica et Geographica Universitatis Comenianae, Geologica*, 46, 9–101.
- Mišík M., Sýkora M. & Jablonský J., 1991b: Strihovské zlepenice a juhomagurská kordiléra. *Západné Karpaty, sér. Geológia*, 14, 7–72. (English summary: Strihovce conglomerates and South-Magura exotic ridge)
- Mišík M., Aubrecht R., Sýkora M. & Ožvoldová L., 1996: New lithostratigraphic units in the Klippen Belt. *Slovak Geological Magazine*, 1/1996, 17–19.
- Nemčok J., 1961: Vznik a výplň depresí v magurskom flyši na východnom Slovensku. *Geologický sborník*, 12, 2, 175–190. (German summary: Entstehung und Ausfüllung der Depresionen im Maguraflysch in der Ostslowakei)
- Nemčok J., 1971: Prejavy ilýrskej fázy vrásnenia vo flyši východného Slovenska. *Geologické práce, Správy* 57, 369–378. (English summary: Results of Illyrian folding phase in East-Slovakian Flysch)
- Nemčok J., 1990: Geological map of Pieniny and Čergov Mts., Ľubovnianska vrchovina and Ondavská vrchovina uplands 1:50,000. D. Štúr Inst. Geol., Bratislava.
- Nemčok J. & Ďurkovič T., 1989: Litológia malcovského súvrstvia (magurská jednotka). *Geologické práce, Správy* 89, 39–51. (English summary: Lithology of Malcov Member in Magura Unit (East Slovakia))
- Nemčok J., Kullmanová A. & Ďurkovič T., 1989: Vývoj a stratigrafické postavenie gregoriánskych brekcií bradlového pásma na východnom Slovensku. *Geologické práce, Správy* 89, 11–37. (English summary: Facies- and stratigraphical analyses of Gregorianka breccias in Klippen Belt of East Slovakia)
- Nemčok J. (ed.), Zakovič M., Gašpariková V., Ďurkovič T., Snopková P., Vrana K. a Hanzel V., 1990: Vysvetlivky ku geologickej mape Pienín, Čergova, Ľubovnianskej a Ondavskej vrchoviny v mierke 1: 50 000. Geol. Ústav D. Štúra, Bratislava, 131 s. (English summary: Explanations to the geological map of Pieniny, Ľubovnianska vrchovina Highland and Čergov Mts.)
- Oszczypko N., Malata E., Švábenická L., Golonka J. & Marko F., 2004: Jurassic–Cretaceous controversies in the Western Carpathian Flysch: the "black flysch" case study. *Cretaceous Research*, 25, 89–113.
- Oszczypko N., Oszczypko-Clowes M., Golonka J. & Marko F., 2005: Oligocene–Lower Miocene sequences of the Pieniny Klippen Belt and adjacent Magura Nappe between Jarabina and the Poprad River (East Slovakia and South Poland): their tectonic position and palaeogeographic implications. *Geological Quarterly*, 49, 379–402.
- Oszczypko N., Olszewska B. & Malata E., 2012: Cretaceous (Aptian/Albian–?Cenomanian) age of "black flysch" and adjacent deposits of the Grajcarek thrust-sheets in the Małe Pieniny Mts. (Pieniny Klippen Belt, Polish Outer Carpathians). *Geological Quarterly*, 56, 3, 411–440.
- Ožvoldová L. & Frantová L., 1997: Jurassic radiolarites from the eastern part of the Pieniny Klippen Belt (Western Carpathians). *Geologica Carpathica*, 48, 1, 49–61.
- Plašienka D., 2012a: Jurassic syn-rift and Cretaceous syn-orogenic, coarse-grained deposits related to opening and closure of the Vahic (South Penninic) Ocean in the Western Carpathians – an overview. *Geological Quarterly*, 56, 4, 601–628.
- Plašienka D., 2012b: Early stages of structural evolution of the Carpathian Klippen Belt (Slovakian Pieniny sector). *Mineralia Slovaca*, 44, 1, 1–16.
- Plašienka D., 2018a: The Carpathian Klippen Belt and types of its klippen – an attempt at a genetic classification. *Mineralia Slovaca*, 50, 1, 1–24.
- Plašienka D., 2018b: Continuity and episodicity in the early Alpine tectonic evolution of the Western Carpathians: How large-scale processes are expressed by the orogenic architecture and rock record data. *Tectonics*, 37, 7, 2029–2079.
- Plašienka D., 2019: Linkage of the Manín and Klappe units with the Pieniny Klippen Belt and Central Western Carpathians: balancing the ambiguity. *Geologica Carpathica*, 70, 1, 35–61.
- Plašienka D., 2022: Náčrt geologickej stavby slovenských Pienín. In Krempaská Z. & Števík M. (eds): Vlastivedný zborník Spiš 11, Múzeum Spiša, Spišská Nová Ves, 255–273. (English abstract: Geological structure of the Slovak Pieniny Mountains: an overview)
- Plašienka D. & Mikuš M., 2010: Geologická stavba pieninského a šarišského úseku bradlového pásma medzi Litmanovou a Drienicou na východnom Slovensku. *Mineralia Slovaca*, 42, 2, 155–178. (English summary: Geological structure of the Pieniny and Šariš sectors of the Klippen Belt between the Litmanová and Drienica villages in Eastern Slovakia)

- Plašienka D. & Novotný J., 2022: Limestone klippen belt – atypical landforms in flysch uplands. In Lehotský M. & Boltíziar M. (eds): Landscapes and landforms of Slovakia, Chapter 10. *Springer Nature*, 189–205.
- Plašienka D., Soták J. & Prokešová R., 1998: Structural profiles across the Šambron-Kamenica Periklippen Zone of the Central Carpathian Paleogene Basin in NE Slovakia. *Mineralia Slovaca*, 29, 173–184.
- Plašienka D., Soták J., Jamrichová M., Halášová E., Pivko D., Józsa Š., Madzin J. & Mikuš V., 2012: Structure and evolution of the Pieniny Klippen Belt demonstrated along a section between Jarabina and Litmanová villages in Eastern Slovakia. *Mineralia Slovaca*, 44, 1, 17–38.
- Plašienka D., Józsa Š., Gedl P. & Madzin J., 2013: Fault contact of the Pieniny Klippen Belt with the Central Carpathian Paleogene Basin (Western Carpathians): new data from a unique temporary exposure in Ľutina village (Eastern Slovakia). *Geologica Carpathica*, 64, 2, 165–168.
- Plašienka D., Bučová J. & Šimonová V., 2020: Variable structural styles and tectonic evolution of an ancient backstop boundary: the Pieniny Klippen Belt of the Western Carpathians. *International Journal of Earth Sciences*, 109, 4, 1355–1376. (+supplement)
- Plašienka D., Aubrecht R., Bezák V., Bielík M., Broska I., Bučová J., Fekete K., Gaži P., Gedl P., Golej M., Halášová E., Hók J., Hrdlička M., Jamrich M., Józsa Š., Klanica R., Konečný P., Kubiš M., Madarás J., Majcín D., Marko F., Molčan Matejová M., Potočný T., Schlögl J., Soták J., Suan G., Šamajová L., Šimonová V., Teťák F. & Vozár J., 2021: Structure, composition and tectonic evolution of the Pieniny Klippen Belt – Central Western Carpathian contiguous zone (Kysuce and Orava regions, NW Slovakia). Monograph. *Comenius University*, Bratislava, 148 p.
- Ratschbacher L., Frisch W., Linzer H.-G., Sperner B., Meschede M., Decker K., Nemčok M., Nemčok J. & Grygar R., 1993: The Pieniny Klippen Belt in the Western Carpathians of northeastern Slovakia: structural evidence for transpression. *Tectonophysics*, 226, 471–483.
- Rojkovič I., Ožvoldová L. & Sýkora M., 2003: Manganese mineralization near Šarišské Jastrabie village, Pieniny Klippen Belt, Western Carpathians, Slovakia. *Slovak Geological Magazine*, 9, 1, 51–64.
- Roth Z., 1980: Západní Karpaty – terciérní struktura střední Evropy. *Knih. ÚÚG*, 55, *Geol. Survey*, Prague, 128 p. (The Western Carpathians – a Tertiary structure of Central Europe, in Czech)
- Scheibner E., 1968: Carpathian Klippen Belt. In Mahel' M. & Buday T. (eds): Regional geology of Czechoslovakia. Volume 2, Western Carpathians. *Akademie*, Praha, 304–371.
- Segit T., Matyja B.A. & Wierzbowski A., 2015: The Middle Jurassic succession in the central sector of the Pieniny Klippen Belt (Sprzycne Creek): implications for the timing of the Czorsztyn Ridge development. *Geologica Carpathica*, 66, 4, 285–302.
- Soták J., Pereszlényi M., Marschalko R., Milička J. & Starek D., 2001: Sedimentology and hydrocarbon habitat of the submarine-fan deposits of the Central Carpathian Paleogene Basin (NE Slovakia). *Marine and Petroleum Geology*, 18, 87–114.
- Stráník Z., 1965: Geologie magurského flyše Čerchovského pohoří a západní části Ondavské vrchoviny. *Sborník geologických věd, rad ZK*, 3, 125–178. (German summary: Zur Geologie des Magura-Flysches im Gebirge Čerchovské pohoří und Ondavská vrchovina)
- Świerczewska A., 2005: The interplay of the thermal and structural histories of the Magura Nappe (Outer Carpathians) in Poland and Slovakia. *Mineralogia Polonica*, 36, 2, 91–144.
- Wierzbowski A., Aubrecht R., Krobicki M., Matyja B.A. & Schlögl J., 2004: New data on Jurassic stratigraphy and palaeogeography of the Czertezik Succession, Pieniny Klippen Belt (Western Carpathians) of Poland and Slovakia. *Annales Societatis Geologorum Poloniae*, 74, 237–256.
- Zielińska M., 2021: Thermal maturity of the Grajcarek Unit (Pieniny Klippen Belt): Insights for the burial history of a major tectonic boundary of the Western Carpathians. *Minerals*, 11, 1245.
- Zielińska M., Kus J., Mendonça Filho J.G., Szram E., Blumenberg M. & Fabiańska M., 2025: Middle Jurassic black shale deposits from the Pieniny Klippen belt, Western Carpathians: Insights into organic matter composition, thermal maturity, depositional, and palaeoenvironmental variations. *International Journal of Coal Geology*, 305, 104772.
- Zielińska M., Spunda K., Plašienka D. & Botor D., 2026: Thermal records of Mesozoic and Cenozoic heat flow peaks as an expression of structural evolution interplay in the Western Carpathian northern suture. *Marine Geoscience and Energy Resources*, 184, 207654

Tomáš Potočný

editor

CETEG 2026

Book of Abstracts & Field Guides

22nd Meeting of the Central European Tectonic Studies Groups

April 22 – 25, 2026

Published by Comenius University Bratislava, 2026

Graphic design, cover design: Tomáš Potočný

Manuscript 179 pages, first edition,
published as an electronic publication

ISBN 978-80-223-6288-7 (online)

