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**Geodesy and Geophysics in Slovakia  
2015 – 2018  
Slovak National Report to IUGG**

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Slovak National Committee  
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2019



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# Geodetic, gravimetric and geodynamic research in Slovakia 2015–2018 (Report to IAG)

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## 1. Reference Frames

### 1.1. Vertical reference systems

Majkráková M., Papčo J., Zahorec J., Droščák B., Mikuška J., Marušiak I., 2016: An analysis of methods for gravity determination and their utilization for the calculation of geopotential numbers in the Slovak national levelling network. *Contributions to Geophysics and Geodesy*, **46**, 3, 179–202.

### 1.2 Reference surfaces

Husár L., Švaral P., Janák J., 2017: About the geometry of the Earth geodetic reference surfaces. In *Journal of Geometry and Physics*, **120**, 192–207, doi: 10.1016/j.geomphys.2017.05.016.

## 2. Gravity Field

### 2.1. Determination of geoid, quasigeoid and other functionals of gravity potential in global and regional scale

Bucha B., Bezděk A., Sebera J., Janák J., 2015: Global and regional gravity field determination from GOCE kinematic orbit by means of spherical radial basis functions. *Surveys in Geophysics*, **36**, 6, 773–801.

Sebera J., Pitoňák M., Hamáčková E., Novák P., 2015: Comparative Study of the Spherical Downward Continuation. *Surveys in Geophysics*, **36**, 2, 253–267.

Kostecký J., Klokočník J., Bucha, B., Bezděk A., Förste Ch., 2015: Evaluation of the gravity field model EIGEN-6C4 in comparison with EGM2008 by means of various

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\* IAG National Correspondent

- functions of the gravity potential and by GNSS/levelling. *Geoinformatics*, **14**, 1, 7–27.
- Bucha B., Janák J., Papčo J., Bezděk A., 2016: High-resolution regional gravity field modelling in a mountainous area from terrestrial gravity data. *Geophysical Journal International*, **207**, 2, 949–966.
- Vaniček P., Novák P., Scheng M., Kingdon R., Janák J., Foroughi I., Martinec Z., Santos M., 2017: Does Poisson's downward continuation give physically meaningful results? *Studia Geophysica et Geodaetica*, **61**, 412–428, doi: 10.1007/s11200-016-1167-z.
- Janák J., Vaniček P., Foroughi I., Kingdon R., Sheng M., Santos M. C., 2017: Computation of precise geoid model using UNB Stokes-Helmert's approach: Case study in Auvergne region. *Contributions to Geophysics and Geodesy*, **47**, 3, 201–229, doi: 10.1515/congeo-2017-0011.
- Hábel B., Janák J., 2018: Analysis of local covariance functions applied to GOCE satellite gravity gradiometry data. *Acta Geodaetica et Geophysica*, **53**, 125–138, doi: 10.1007/s40328-017-0208-6.

## **2.2. Gravity data processing, topographical effects, RTM, Bouguer gravity anomalies, hydrological effects**

- Rexer M., Hirt Ch., Bucha B., Holmes S., 2018: Solution to the spectral filter problem of residual terrain modelling (RTM). *Journal of geodesy*, **92**, 6, 675–690.
- Đuričková Z., Janák J., 2016: RTM-based omission error corrections for global geopotential models: Case study in Central Europe. *Studia geophysica et geodaetica*, **60**, 4, 622–643.
- Mikolaj M., Meurers B., Mojzeš M., 2015: The reduction of hydrology-induced gravity variations at sites with insufficient hydrological instrumentation. *Studia geophysica et geodaetica*, **59**, 3, 424–437.
- Zahorec P., 2015: Inner zone terrain correction calculation using interpolated heights. *Contributions to Geophysics and Geodesy*, **45**, 3, 219–235, doi: 10.1515/congeo-2015-0021.
- Zahorec P., Pašteka R., Mikuška J., Szalaiová V., Papčo J., Kušnirák D., Pánisová J., Krajňák M., Vajda P., Bielík M., Marušiak I., 2017: National Gravimetric Database of the Slovak Republic (chapter 7) pp. 113–125, In book: Pašteka Roman, Ján Mikuška and Bruno Meurers (eds.): Understanding the Bouguer Anomaly: A Gravimetry Puzzle, Elsevier, ISBN 978-0-12-812913-5, doi: 10.1016/B978-0-12-812913-5.00006-3.
- Mikuška J., Pašteka R., Zahorec P., Papčo J., Marušiak I., Krajňák M., 2017: Some Remarks on the Early History of the Bouguer Anomaly (chapter 3) pp. 31–62, In book: Pašteka Roman, Ján Mikuška and Bruno Meurers (eds.): Understanding the Bouguer Anomaly: A Gravimetry Puzzle, Elsevier (2017), ISBN 978-0-12-812913-5, doi: 10.1016/B978-0-12-812913-5.00006-3.

- Zahorec P., Marušiak I., Mikuška J., Pašteka R., Papčo J., 2017: Numerical Calculation of Terrain Correction Within the Bouguer Anomaly Evaluation (Program Toposk) (chapter 5) pp. 79–92, In book: Pašteka Roman, Ján Mikuška and Bruno Meurers (eds.): Understanding the Bouguer Anomaly: A Gravimetry Puzzle, Elsevier (2017), ISBN 978-0-12-812913-5, doi: 10.1016/B978-0-12-812913-5.00006-3.
- Pašteka R., Zahorec P., Kušnirák D., Bošanský M., Papčo J., Szalaiová V., Krajňák M., Marušiak I., Mikuška J., Bielik M., 2017: High resolution Slovak Bouguer gravity anomaly map and its enhanced derivative transformations: new possibilities for interpretation of anomalous gravity fields. *Contributions to Geophysics and Geodesy*, **47**, 2, 81–94, doi: 10.1515/congeo-2017-0006.
- Zahorec P., Papčo J., 2018: Estimation of Bouguer correction density based on underground and surface gravity measurements and precise modelling of topographic effects, two case studies from Slovakia. *Contributions to Geophysics and Geodesy*, **48**, 4, 319–336, doi: 10.2478/congeo-2018-0015.

### 2.3. Vertical gravity gradient

- Zahorec P., Mikuška J., Papčo J., Marušiak I., Karcol R., Pašteka R., 2015: Towards the measurement of zero vertical gradient of gravity on the Earth's surface. *Studia geophysica et geodaetica*, **59**, 4, 524–537.
- Zahorec P., Vajda P., Papčo J., Sainz-Maza Aparicio S., Pereda de Pablo J., 2016: Prediction of vertical gradient of gravity and its significance for volcano monitoring, example from Teide volcano. *Contributions to Geophysics and Geodesy*, **46**, 3, 203–220.

### **Significance and application of vertical gradients of gravity and of deformation-induced topographic effects in decomposition and interpretation of time-lapse gravity changes in volcano gravimetry**

We have applied a numerical approach to predicting the vertical gradient of gravity (VGG) based on modelling the contribution (effect) of topographic masses in areas of prominent and rugged topography. By in-situ observations of VGGs we have verified the accuracy of the topographically predicted VGGs. We have compared free-air effects (FAE) computed based on the theoretical (normal) free-air gradient (FAG) with those computed based on the predicted VGGs. We have discussed implications for micro-gravimetric surveys and for the evaluation of deformation-induced topographic effects in volcano gravimetry. The in-situ verification of predicted VGGs was carried out in two field campaigns: in 2016 in the central volcanic complex (surrounding the Teide volcano) on Tenerife, Canary Islands, and in 2018 on Etna, Sicily, Italy.



**Slovak-Italian gravimetric field campaign  
Etna 2018**



**VGG observation at summit craters  
of Etna**



**Slovak gravimetric expedition  
Tenerife 2016**



**VGG observation at Teide summit  
(3718 m a.s.l.)**

Vajda P., Zahorec P., Papčo J., Kubová A., 2015: Deformation induced topographic effects in inversion of temporal gravity changes: First look at Free Air and Bouguer terms. *Contributions to Geophysics and Geodesy*, **45**, 2, 149–171.

Vajda P., 2016: Recent developments and trends in Volcano Gravimetry (chapter in monograph): 81–103, doi: 10.5772/63420, Open Access Book: Németh K. (ed.), Updates in Volcanology, From Volcano Modelling to Volcano Geology, INTECH, eISBN 978-953-51-2623-2, ISBN 978-953-51-2622-5.

Hickey J., Gottsmann J., Mothes P., Odbert H., Prutkin I., Vajda P., 2017: The Ups and Downs of Volcanic Unrest: Insights from Integrated Geodesy and Numerical Modelling (chapter in monograph). In (book): Volcanic unrest: from science to society. Book series: Advances in Volcanology, Springer, Berlin, Heidelberg, doi: 10.1007/11157\_2017\_13.

Zahorec P., Papčo J., Vajda P., Greco F., Cantarero M., Carbone D., 2018: Refined prediction of vertical gradient of gravity at Etna volcano gravity network (Italy). *Contributions to Geophysics and Geodesy*, **48**, 4, 299–317, doi: 10.2478/congeo-2018-0014.



## 2.4 Microgravimetry

Chromčák J., Grinč M., Pánisová J., Vajda P., Kubová A., 2016: Validation of sensitivity and reliability of GPR and microgravimetric detection of underground cavities in complex urban settings: Test case for a cellar. *Contributions to Geophysics and Geodesy*, **46**, 1, 13–32, doi: 10.1515/congeo-2016-0002.

Grinč M., 2015: 3D GPR investigation of pavement using 1 GHz and 2 GHz horn type antenna, comparison of the results. *Contributions to Geophysics and Geodesy*, **45**, 1, 25–39.

Slabej M., Grinč M., Kováč M., Decký M., Šedivý Š., 2015: Non-invasive diagnostic methods for airport Žilina runway's quality investigation. *Contributions to Geophysics and Geodesy*, **45**, 3, 237–254, doi: 10.1515/congeo-2015-0022.

### Near surface geophysics for engineering-geological, geotechnical applications and archaeology

The sensitivity and reliability of microgravimetry and ground penetrating radar (GPR) was validated in complex urban settings on a test case of a known underground cellar. Road pavement quality and airport runway condition were prospected using GPR.



Near surface geophysical survey in urban settings



Deployment of GPR with various antennas

Wilken D., Wunderlich T., Stümpel H., Rabbel W., Pašteka R., Erkul E., Papčo J., Putiška R., Krajňák M., Kušnirák D., 2015: Case history: integrated geophysical survey at Katarínka Monastery (Slovakia). *Near surface geophysics*, **13**, 6, 585–599.

Pánisová J., Murin I., Pašteka R., Haličková J., Brunčák P., Pohánka V., Papčo J., Milo P., 2016: Geophysical fingerprints of shallow cultural structures from microgravity and GPR measurements in the Church of St. George, Svätý Jur, Slovakia. *Journal of Applied Geophysics*, **127**, 102–111.

## 2.5 Development of inversion methodology

Pohánka V., Vajda P., Pánisová J., 2015: On inverting micro-gravimetric signals with the harmonic inversion method: Application to time-lapse gravity changes. *Contributions to Geophysics and Geodesy*, **45**, 2, 111–134, doi: 10.1515/congeo-2015-0016.

### **Development of new inversion approach based on the method of harmonic inversion for interpreting spatiotemporal gravity changes in volcanic areas**

A novel inversion approach based on the method of harmonic inversion, developed by Vladimír Pohánka, was test-applied to the spatiotemporal (time-lapse) gravity changes observed during the 2004/5 volcanic unrest at Teide volcano, Tenerife, Canary islands.

Prutkin I., Vajda P., Jahr T., Bleibinhaus F., Novák P., Tenzer R., 2017: Interpretation of gravity and magnetic data with geological constraints for 3D structure of the Thuringian Basin, Germany. *Journal of Applied Geophysics*, **136**, 35–41, doi: 10.1016/j.jappgeo.2016.10.039.

### **Application of new inversion approach based on Prutkin methodology for interpreting the geological structure of sedimentary basins**

The novel inversion approach based on the Prutkin methodology was applied to invert and interpret gravity and magnetic data with constraints to determine the geological structure of the Thuringian Basin in Germany and its basement.

## 2.6 Absolute gravimetry and metrology

Pálinkáš V., Francis O., Val'ko M., Kostelecký J., Van Camp M., Castelein S., Bilker-Koivula M., Näränen J., Lothhammer A., Falk R., Schilling M., Timen L., Iacovone D., Baccaro F., Germak A., Biolcati E., Origlia C., Greco F., Pistorio A., De Plaen R., Klein G., Seil M., Radinovic R., Reudink R., Dykowski P., Sękowski M., Próchniewicz D., Szpunar R., Mojzeš M., Janák J., Papčo J., Engfeldt A., Olsson P. A., Smith V., Van Westrum D., Ellis B., Lucero B., 2017: Regional comparison of absolute gravimeters, EURAMET.M.G-K2 key comparison. *Metrologia*, **54**, Technical supplement, available online at <http://iopscience.iop.org/article/10.1088/0026-1394/54/1A/07012>

### 3. Earth Rotation and Geodynamics

#### 3.1. Local and regional geodynamics

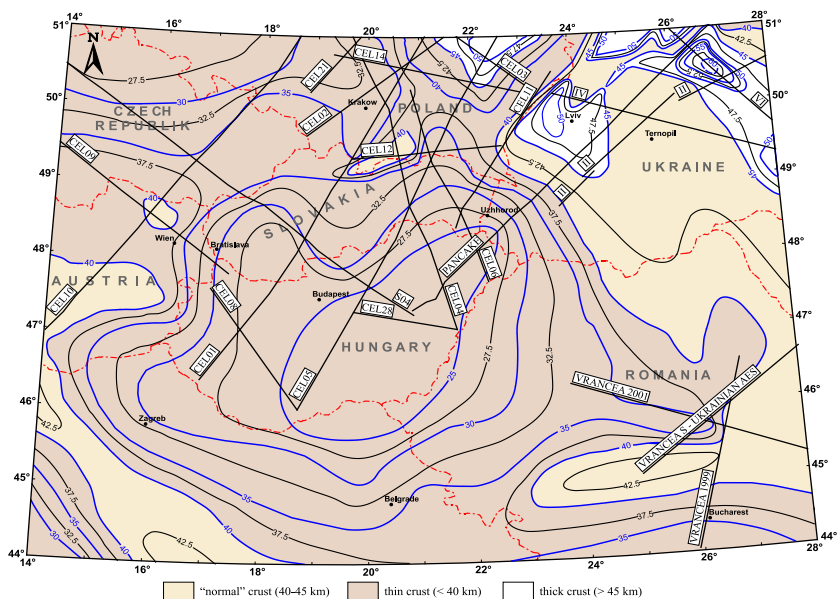
Mojžeš M., Kollár P., Mikolaj M., 2015: Estimation of an effective Young's modulus of elasticity in the locality of the Gabčíkovo hydrology power plant by geometric leveling. *Slovak Journal of Civil Engineering*, **23**, 1, 33–40.

Bednárík M., Papčo J., Pohánka V., Bezák V., Kohút I., Brimich L., 2016: Surface strain rate colour map of the Tatra Mountains region (Slovakia) based on GNSS data. *Geologica Carpathica*, **67**, 6, 509–524.

Bielik M., Makarenko I., Csicsay K., Legostaeva O., Starostenko V., Savchenko A., Šimonová B., Dérerová J., Fojtiková L., Pašteka R., Vozár J., 2018: The refined Moho depth map in the Carpathian-Pannonian region. *Contributions to Geophysics and Geodesy*, **48**, 2, 179–190, doi: 10.2478/congeo-2018-0007.

#### The refined Moho depth map in the Carpathian-Pannonian region

A new digital Moho depth map of the Carpathian-Pannonian region has been created using Moho discontinuity depth data which were obtained by interpretation of seismic measurements that were produced in last 15–20 years together with the results of 2D and 3D integrated geophysical modelling.

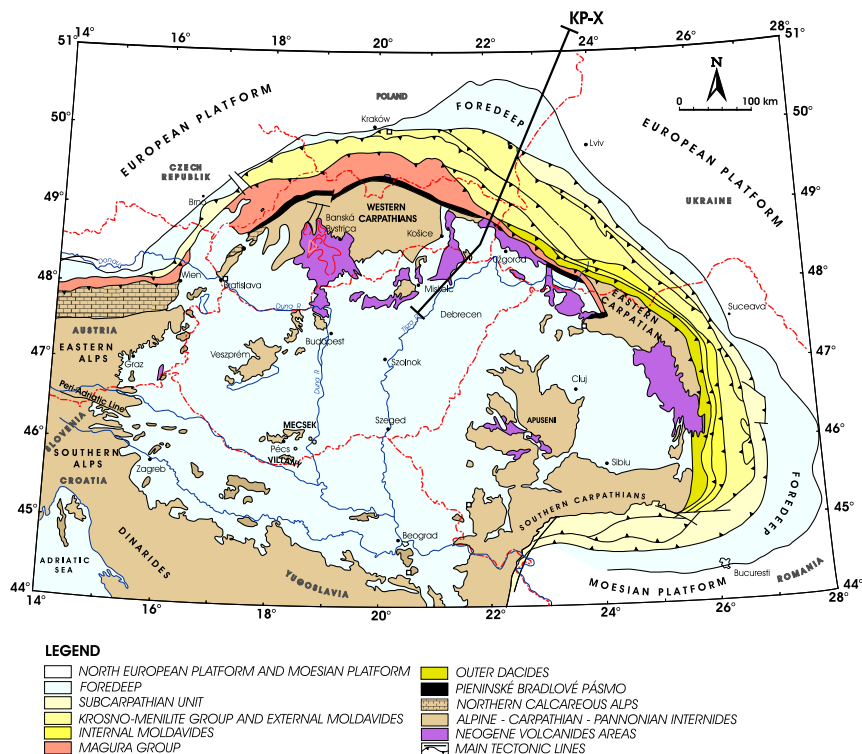


The Moho depth map in the Carpathian-Pannonian region

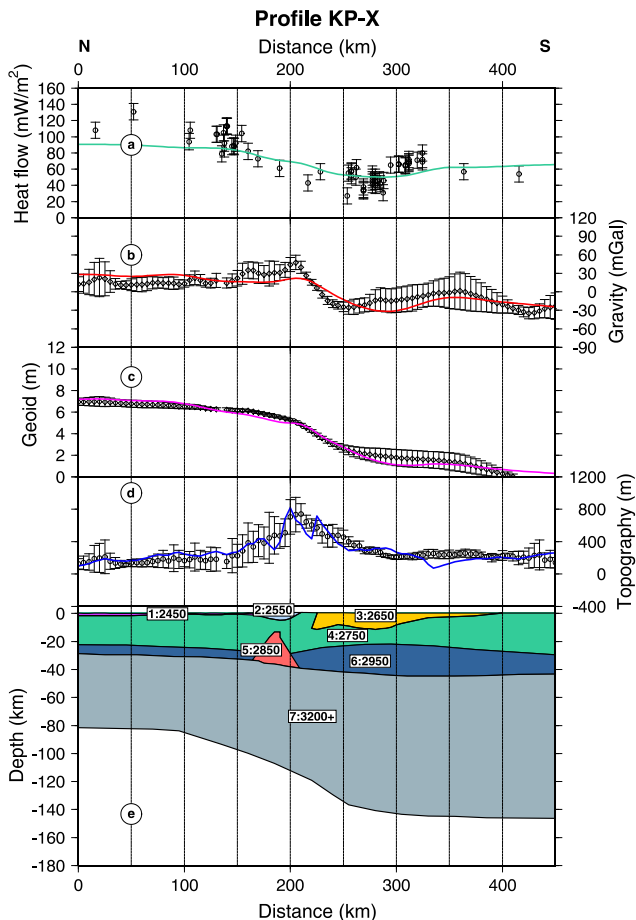
Hlavňová P., Bielik M., Dérerová J., Kohút I., Pašiaková M., 2015: A new lithospheric model in the eastern part of the Western Carpathians: 2D integrated modelling. *Contributions to Geophysics and Geodesy*, **45**, 1, 13–23, doi: 10.1515/congeo-2015-0010.

### 2D integrated modelling

2D integrated geophysical modelling has been used to recalculate older lithospheric model along transect KP-X in the eastern part of the Western Carpathians. Integrated modelling takes into account the joint interpretation of the heat flow, free air anomalies, topography and geoid data. The new model has brought new valuable results about the thickness of the lithosphere and information about the deep seated structures within the lithosphere.



Location of profile KP-X on the map of the Carpathian-Pannonian basin region.



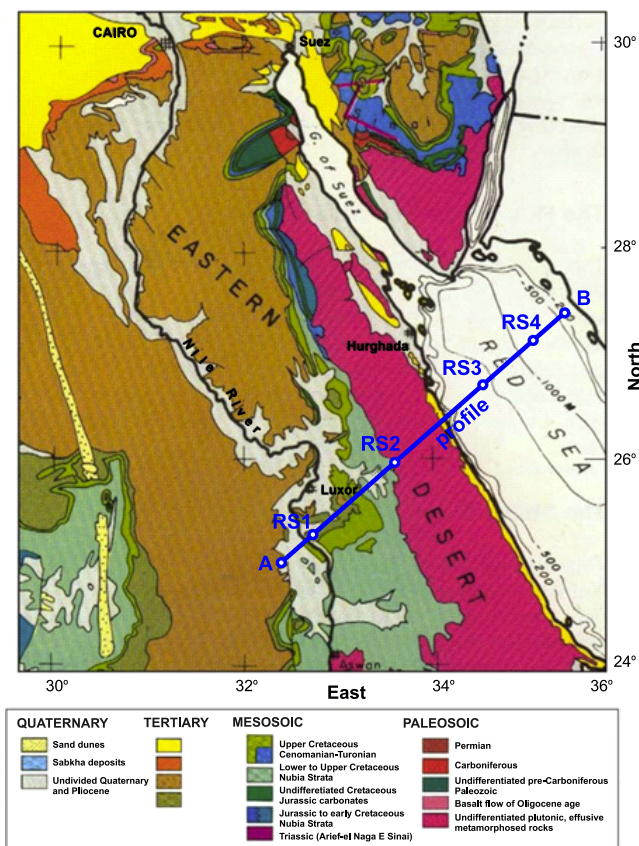
Lithospheric model along transect KP-X. (a) Surface heatflow, (b) free air gravity anomaly, (c) topography with dots corresponding to measured data with uncertainty bars and solid lines to calculated values.

Radwan A. H., Dérerová J., Bielik M., Šimonová B., Kohút I., 2017: Calculation of temperature distribution and rheological properties of the lithosphere along Profile 1 passing through Aswan. *Contributions to Geophysics and Geodesy*, **47**, 1, 69–80, doi: 10.1515/congeo-2017-0005.

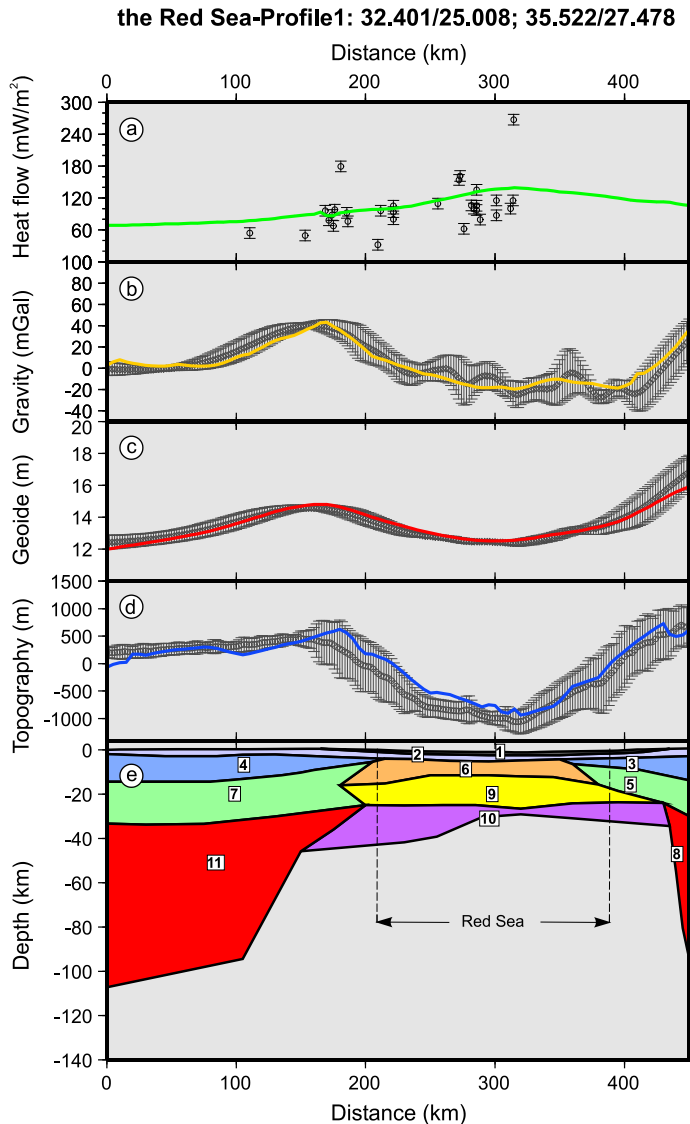
Dérerová J., Kohút I., Radwan A. H., Bielik M., 2017: Calculation of temperature distribution and rheological properties of the lithosphere along geotranssect in the Red Sea region. *Contributions to Geophysics and Geodesy*, **47**, 4, 277–286, doi: 10.1515/congeo-2017-0015.

### Calculation of temperature distribution and rheological properties of the lithosphere

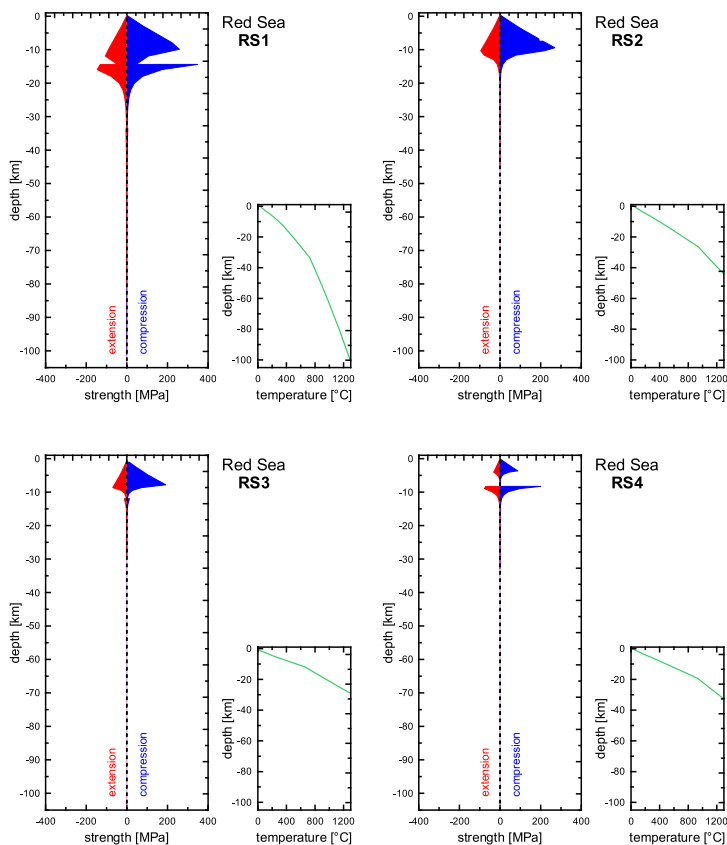
We used 2D integrated geophysical modelling to calculate the temperature distribution in the lithosphere along 2 different profiles in Egypt. One profile was passing through the Aswan area, the other one was located in the Red Sea region. Lithospheric structure in both locations has been previously modelled using 2D integrated modelling. Based on the respective temperature models and the rheological parameters, we have calculated strength distribution in the lithosphere for both profiles. We calculated strength envelopes for both compressional and extensional regimes.



Geology of the Red Sea region (Egyptian Geological Survey, 1994) and location of studied profile in the Red Sea region.



Lithospheric model along profile in the Red Sea (with exact coordinates) (a) surface heat flow, (b) free-air gravity anomaly, (c) geoid, (d) topography with dots corresponding to measured data with uncertainty bars and solid lines to calculated values, (e) lithospheric structures.



Vertical strength distribution for different lithospheric columns RS1–RS4 along profile in the Red Sea. Negative and positive values correspond to extensional and compressional strength respectively.

Majcin D., Bezák V., Klanica R., Vozár J., Pek J., Bilčík D., Telecký J., 2018: Klippen Belt, Flysch Belt and Inner Western Carpathian Paleogene Basin Relations in the Northern Slovakia by Magnetotelluric Imaging. *Pure and Applied Geophysics*, **175**, 3555–3568.

Pánisová J., Balázs A., Zalai Z., Bielik M., Horváth F., Harangi S., Schmidt S., Goetze H. J., 2018: Intraplate volcanism in the Danube Basin of NW Hungary: 3D geophysical modelling of the Late Miocene Pásztori volcano. *International Journal of Earth Sciences*, **107**, 5, 1713–1730, doi: 10.1007/s00531-017-1567-5.



- Godová D., Bielik M., Šimonová B., 2018: The deepest Moho in the Western Carpathians and its respective crustal density model (CEL12 section). *Contributions to Geophysics and Geodesy*, **48**, 3, 255–269, doi: 10.2478/congeo-2018-0011.
- Bezák V., Majcin D., 2018: Lithological composition in deep geothermal source reservoirs of temperature 160°C in the territory of Slovakia. *Contributions to Geophysics and Geodesy*, **48**, 4, 349–363, doi: 10.2478/congeo-2018-0017.
- Fendek M., Grand T., Daniel S., Blanárová V., Kultán V., Bielik M., 2017: The pre-Cainozoic basement delineation by magnetotelluric methods in the western part of the Liptovská kotlina Depression (Western Carpathians, Slovakia). *Geologica Carpathica*, **68**, 4, 318–328, doi: 10.1515/geoca-2017-0022.
- Katona M., Szalaiová V., Vozárová A., Šimonová B., Pánisová J., Schmidt S., Goetze H. J., 2017: 3D density modelling of Gemic granites of the Western Carpathians. *Geologica Carpathica*, **68**, 3, 177–192, doi: 10.1515/geoca-2017-0014.
- Marko F., Andriessen P., Tomek Č., Bezák V., Fojtíková L., Božanský M., Piovarči M., Reichwalder P., 2017: Carpathian Shear Corridor, A strike-slip boundary of an extruded crustal segment. *Tectonophysics*, **703–704**, 119–134, doi: 10.1016/j.tecto.2017.02.010.
- Hrubcová P., Geissler W. H., Bräuer K., Vavryčuk V., Tomek Č., Kämpf H., 2017: Active magmatic underplating in western Eger Rift, Central Europe. *Tectonics*, **36**, 12, 2846–2862, doi: 10.1002/2017TC004710.
- Bednárík M., Papčo J., Pohánka V., Bezák V., Kohút I., Brimich L., 2016: Surface strain rate colour map of the Tatra Mountains region (Slovakia) based on GNSS data. *Geologica Carpathica*, **67**, 6, 509–524, doi: 10.1515/geoca-2016-0032.
- Saleh S., Pamukcu O., Brimich L., 2017: The major tectonic boundaries of the Northern Red Sea rift, Egypt derived from geophysical data analysis. *Contributions to Geophysics and Geodesy*, **47**, 3, 149–199, doi: 10.1515/congeo-2017-0010.
- Alasonati Tašárová Z., Fullea J., Bielik M., Šroda P., 2016: Lithospheric structure of Central Europe: Puzzle pieces from Pannonian Basin to Trans-European Suture Zone resolved by geophysical-petrological modeling. *Tectonics*, **35**, 3, 722–735, doi:10.1002/2015TC003935.
- Šimonová B., Bielik M., 2016: Determination of rock densities in the Carpathian-Pannonian Basin lithosphere: based on the CELEBRATION 2000 experiment. *Contributions to Geophysics and Geodesy*, **46**, 4, 269–287, doi 10.1515/congeo-2016-0016.
- Bezák V., Pek J., Majcin D., Bučová J., Šoltis T., Bilčík D., Klanica R., 2015: Geological interpretation of magnetotelluric sounding in the southern part of seismic profile 2T (Central Slovakia). *Contributions to Geophysics and Geodesy*, **45**, 1, 1–11, doi: 10.1515/congeo-2015-0009.
- Šimonová B., Bielik M., Dérerová J., 2015: 2D density model of Chinese continental lithosphere along a NW-SE transect. *Contributions to Geophysics and Geodesy*, **45**, 2,

135–148, doi: 10.1515/congeo-2015-0017.

Majcin D., Král M., Bilčík D., Šujan M., Vranovská A., 2017: Deep geothermal sources for electricity production in Slovakia: thermal conditions. *Contributions to Geophysics and Geodesy*, **47**, 1, 1–22, doi: 10.1515/congeo-2017-0001.

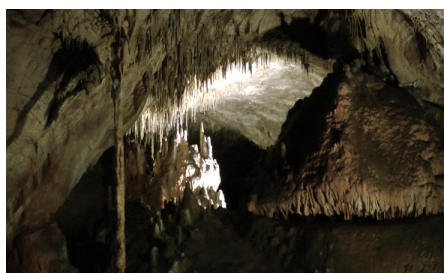
Majcin D., Kutas R., Bilčík D., Bezák V., Korchagin I., 2016: Thermal conditions for geothermal energy exploitation in the Transcarpathian depression and surrounding units. *Contributions to Geophysics and Geodesy*, **46**, 1, 33–49, doi: 10.1515/congeo-2016-0003.

Majcin D., Bilčík D., Klučiar T., 2015: Thermal state of the lithosphere in the Danube Basin and its relation to tectonics. *Contributions to Geophysics and Geodesy*, **45**, 3, 193–218, doi: 10.1515/congeo-2015-0020.

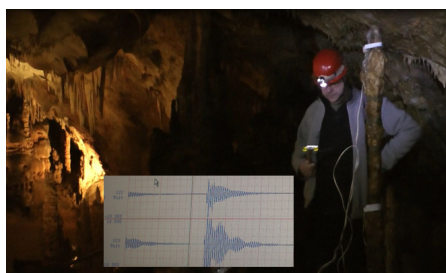
Gribovzski K., Kovács K., Mónus P., Bokelmann G., Konečný P., Lednická M., Moseley G., Spötl Ch., Edwards R. L., Bednárík M., Brimich L., Tóth L., 2017: Estimating the upper limit of prehistoric peak ground acceleration using an in situ, intact and vulnerable stalagmite from Plavecká priepast cave (Detrekői-zsomboly), Little Carpathians, Slovakia, first results. *Journal of Seismology*, **21**, 5, 1111–1130, doi: 10.1007/s10950-017-9655-3.

### Paleo-seismicity estimates based on scinter break-up in caves

Determination of constraints on seismic hazard in adjacent areas to caves based on estimates of peak horizontal acceleration breaking thin long stalagmites in caves.



Paleo-seismicity field work in the Domica cave



Measuring resonance parameters of stalagmites

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## Defended PhD Theses

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Institution: Slovak University of Technology in Bratislava  
Title: Gravity field modelling in terms of spherical radial basis functions  
Student: B. Bucha  
Supervisor: J. Janák  
Year of defence: 2016

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Institution: Slovak University of Technology in Bratislava  
Title: Ground stability monitoring of selected sites in Slovakia using INSAR technology  
Student: M. Bakoň  
Supervisor: J. Hefty  
Year of defence: 2017

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Institution: Slovak University of Technology in Bratislava  
Title: Solution to topographic effect problems in spherical approximation (in Slovak)  
Student: Z. Ďuríčková  
Supervisor: J. Janák  
Year of defence: 2018

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Institution: Slovak University of Technology in Bratislava  
Title: Analysis of relativistic effects and their detection by space techniques (in Slovak)  
Student: P. Letko  
Supervisor: L. Husár  
Year of defence: 2018

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## International Research/grant projects

COST ES1401

### **Time Dependent Seismology (TIDES)**

since 2014

The Action aims at structuring the EU seismological community to enable development of data-intensive, time-dependent techniques for monitoring Earth active processes (e.g., earthquakes, volcanic eruptions, landslides, glacial earthquakes) as well as oil/gas reservoirs.

Project coordinator, Andrea Morelli

National coordinator for Slovak Republic, Peter Moczo, Jozef Kristek

COST ES1206

### **Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe events and climate (GNSS4SWEC)**

since 2013

Global Navigation Satellite Systems (GNSS) have revolutionised positioning, navigation, and timing, becoming a common part of our everyday life. Aside from these well-known civilian and commercial applications, GNSS is now an established atmospheric observing system which can accurately sense water vapour, the most abundant greenhouse gas, accounting for 60-70% of atmospheric warming. Severe weather forecasting is challenging, in part due to the high temporal and spatial variation of atmospheric water vapour. Water vapour is under-sampled in the current meteorological and climate observing systems, obtaining and exploiting more high-quality humidity observations is essential to weather forecasting and climate monitoring. This Action will address new and improved capabilities from concurrent developments in both the GNSS and meteorological communities. For the first time, the synergy of the three GNSS systems (GPS, GLONASS and Galileo) will be used to develop new, advanced tropospheric products, exploiting the full potential of multi-GNSS water vapour estimates on a wide range of temporal and spatial scales, from real-time monitoring and forecasting of severe weather, to climate research. In addition the action will promote the use of meteorological data in GNSS positioning, navigation, and timing services.

National coordinator for Slovak Republic, Ján Hefty

Project of Italian Space Agency ASI for satellite radar images

### **COSMOSkyMed Constellation Open Call For Science 00016/8/416/182**

Detection of underground cavities in environmental and archaeological applications using satellite radar interferometry. 2016. Juraj Papčo, Matúš Bakoň

Project of Italian Space Agency ASI for satellite radar images

**COSMO-SkyMed Open Call for Science proposal ID 655**

InSAR monitoring of landslides with the assessment of surface dynamics due to groundwater level changes, 2017.

Kopecký, Papčo J.

ESA PECS (Programme for European Cooperating States)

**4000123625/18/NL/SC: Retrieval of motions and potential deformation threats using Sentinel-1.**

2018 - 2020

Matúš Bakoň, Juraj Papčo

**Web pages**

<http://www.seismology.sk>

<http://www.nuqake.eu>

<http://www.fyzikazeme.sk>

<http://gnss4swec.knmi.nl/>

[https://www.svf.stuba.sk/en/departments/department-of-theoretical-geodesy/science-and-research/downloads.html?page\\_id=4996](https://www.svf.stuba.sk/en/departments/department-of-theoretical-geodesy/science-and-research/downloads.html?page_id=4996)



# Geomagnetic and aeronomic studies in Slovakia in the period 2015–2018

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## 1. Theories of geomagnetic field generation

### Solidification at the inner core/outer core boundary

(*J. Fluid Mech.*, Guba, Anderson, 2017)

A model for convective transport of heat and solutes in the ternary dendritic zone was studied in our recent paper *Guba & Anderson (2014)*. The model includes the effects of phase transition associated with the release of latent heat, rejection of solutes and background macroscopic solidification (Bridgman-type directional solidification). Applying the asymptotic and numerical techniques, we identified steady and oscillatory phase-change convective instabilities of a novel type. These instabilities may arise in situations where the background stratification of the individual species is statically stable and thus the flow is entirely unexpected from the static point of view. We proposed parcel arguments that explain the physical mechanisms responsible for these statically unexpected convective instabilities.

The linear stability theories (*Anderson et al., 2010; Guba & Anderson, 2014*) applied to the primary solidification of ternary alloys identified an excep-

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\* IAGA National Correspondent

tional class of convective instability in which all components were statically stably stratified. A consistent mathematical model describing the nonlinear regime of compositional convection in ternary dendritic zones was first studied in *Guba & Anderson (2017)*. The main aim was to determine how the initial concentration of the ternary alloy controls the primary bifurcation of nonlinear convection with roll and hexagonal planforms. We found that two-dimensional convection in the form of rolls can bifurcate subcritically or supercritically, depending on the value of Lewis numbers. Three-dimensional convection with hexagonal symmetry bifurcates transcritically. We have proposed a specific ternary system in which these new instabilities can be experimentally verified.

### **Numerical simulations of Geodynamo**

*(Geophys. J. Int., Šimkanin, Kyselica, Guba, 2018)*

In *Šimkanin et al. (2018)* we investigated numerically the thermochemical convection and hydromagnetic dynamos in a spherical shell employing the so-called codensity formulation with various buoyancy sources: the secular cooling from the mantle, the buoyancy sources due to the solidification at the inner core boundary and the combination of the two sources. Numerical simulations of the fully-coupled nonlinear problem were performed using the PARODY code. In the thermochemical regime, we found that inertial convection was preferred at Prandtl numbers lower than Ekman numbers, while the large-scale columnar convection was preferred otherwise. Unlike the large-scale convection, the inertial convection was found to be almost independent of the nature of driving buoyancy sources. Moreover, the codensity field evolved to a new, radially symmetric stationary state. In the dynamo regime, inertial convection was preferred for Prandtl numbers lower than Ekman numbers, with the generated dipolar magnetic fields oscillating from the polar region to the mid-latitudes and back. At the Prandtl numbers greater than Ekman numbers, both dipolar and hemispherical dynamos were found.

## **2. Ground-based observations of the geomagnetic field and physical processes in the near-Earth environment**

### **Monitoring the geomagnetic field and evaluating the geomagnetic activity**

*(Atmos. Sol.-Terr. Phys., Valach, Váczyová, Revallo, 2016; J. Atmos. Sol.-Terr.*

*Phys., Valach, Hejda, Revallo, Bochníček, Váczyová, 2016; Contrib. Geophys. Geod., Valach, Váczyová, Šoltis, Vajkai, 2016)*

Hurbanovo Geomagnetic Observatory of the Earth Science Institute of the Slovak Academy of Sciences is a certified workplace for geomagnetic field measurements in Slovakia. Its geographic and geomagnetic coordinates are (47.874°N; 18.188°E) and (46.67°N; 101.18°E) respectively, and its altitude is 112 meters. Although the observatory was officially established on 30 September 1900, continuous series of the geomagnetic field data from this station has existed since 1893. The historical names of the observatory were successively Ógyalla and Stará Ďala. Since 1998 the Observatory has been participating in INTERMAGNET, which is the global network of real-time working geomagnetic observatories. The variations of the geomagnetic field are continuously recorded with two instruments: torsion photoelectric magnetometer (TPM) and three-axis fluxgate sensor Magson. The absolute measurements are performed once a week; for this purpose DI-flux theodolite (type Lemi) and proton precession magnetometers (types Elsec 820 and PMG 1) are used.

Regular measurements at the observatory were supplemented by geomagnetic observations at 12 temporary observation points evenly distributed throughout Slovakia. The distribution of the geomagnetic elements in Slovakia was expressed in the form of the 1st-degree polynomial model. In addition, regular measurements of the magnetic declination were carried out at selected airports.

Geomagnetic activity is evaluated monthly. Two methods are used to determine the activity expressed by the K indices: the FMI method is used by default and an interactive IM method, which has been developed at our workplace, is used experimentally. Preliminary tests of the IM method were performed on data from Hurbanovo and Budkov observatories. The test results indicated good performance of the IM method for high values of the geomagnetic activity. More specifically, for K indices being at least 5, the IM method provided the values of K indices that satisfactorily matched the K indices obtained by the traditional hand-scaling done by an experienced observer. An unfortunate feature of the method is a certain degree of subjectivity that is introduced when the operator determines the non-K variation. On the other hand, a similar degree of subjectivity was also a part of traditional hand-scaling. This somehow limits the use of the IM method to

producing indices that prolong a homogeneous series of traditional K indices, which were derived from analogue magnetograms in the past.

**Historical records of the geomagnetic field from the context of current knowledge** (*Geophys. J. Int.*, Arneitz, Leonhardt, Schnepf, Heilig, Mayrhofer, Kovacs, Hejda, Valach, Vadasz, Hammerl, Egli, Fabian, Kompein, 2017; *Acta Geod. Geophys.*, Valach, 2017)

Besides recording new data within the INTERMAGNET programme, research on geomagnetic field records in archives that go back to the period before the introduction of digital registrations is also important. We have contributed to the HISTMAG, which is a new database that combines the historical records with archaeo- and paleomagnetic data. The HISTMAG database extends to the 50,000-year-old past and puts together the data from existing databases and newly acquired historical records from Central Europe. It is available via the website of the Conrad Observatory, Austria (Arneitz et al., 2017). We explored the magnetic declination recorded in observation logs and historical mining maps that were found in the archives of the Slovak Mining Museum in Banská Štiavnica. Recent direct measurements of the geomagnetic field in Slovakia have also been included in the study. A detailed examination of the accuracy of the historical data in the database is a part of the published work. We believe that the HISTMAG database might significantly contribute to the modelling of the historical development of the Earth's magnetic field.

Another reason for exploring the historical records of geomagnetic field is the study of transient geomagnetic disturbances. In fact, there are records of extreme magnetic storms that are more than 100 years old in the archives. These data are little known to the geomagnetic and space weather community. An exception is just the Carrington storm of 2 September 1859. However, the occurrence of such extreme phenomena, which represent a serious threat to our technologically advanced society, is rare. Therefore, extending the amount of recorded events is highly desirable. We examined the storm of 8 March 1918, during which auroral oval-related electric currents likely affected the geomagnetic field at mid-latitudes. The auroral oval was then extensively shifted equatorward and the magnetic storm was accompanied by very intense northern lights there. Interestingly, such events usually occur at much higher magnetic latitudes. The study of this event has been more recently followed by research of two other, even more interesting events that were recorded in the

mid-19th century, namely on 17 November 1848 and 4 February 1872 (*Valach et al., 2019*). Pronounced depressions of the horizontal component during these events were recorded at Prague and Greenwich, respectively. In these two mid-latitude magnetic disturbances, the auroral and/or field aligned currents also seemed to play a significant role.

**Numerical modelling of the plasmosphere** (*J. Geophys. Res. Space Phys., Jorgensen, Heilig, Vellante, Lichtenberger, Reda, Valach, and Mandic, 2017*)

The DGCPM is a dynamical model of the flux-tube content in the plasmasphere which is widely used in space physics. The comparison of this model with the results of the observations of the plasma mass density made by means of the field-line resonance technique yielded relatively large disagreement. On the basis of data from the European quasi-meridional magnetometer array (EMMA), three of the parameters of the DGCPM were changed: characteristic time for depletion of the flux-tube, maximum flux from the ionosphere to the flux-tube, and saturation value of the plasma density. The functional form of the equations in the DGCPM as well as the other parameters of the model were preserved. For changing the parameters, only the data observed at the McIlwain L-value equal at 3.24 were used. Nonetheless, it turned out that the modified model well agrees also with the observations at other L-values.

### 3. Electromagnetic and integrated geophysical research

**Geophysical modelling of the Earth's crust and upper mantle in Slovakia** (*Contrib. to Geophys. Geod., Bezák, Pek, Majcin, Bučová, Šoltis, Bilčík, Klanica, 2015; SGEM, Bezak, Pek, Vozar, Bielik, Majcin, 2016; SGEM, Bezák, Majcin, Klanica, Vozár, Bilčík, 2018; Pure Appl. Geophys., Majcin, Bezák, Vozár, Pek, Telecký, 2018*)

The old and newly collected geophysical data and methodology have been used to model a number of small mountain ranges (horsts) separated by small basins (grabens) with Tertiary sedimentary filling, which appeared in the Western Carpathians mostly in their NW and N part. The Tatry Mts. and the Inner Carpathian Paleogene basin, the northernmost horsts from a series of Western Carpathian horsts so called Ruzbachy “island” arc and the nature of its contact

with the Klippen belt units (*Bezák et al., 2018*) have been investigated. Our magnetotelluric measurements focusing particularly on the nature of the Sub-Tatra fault and the interconnection of the Tatry Mts. with the Ruzbachy “island” confirm steep dip of Sub-Tatra fault in the southern border of the Tatry Mts. and connection of Tatra and Ruzbachy horsts to the one transpressional structure. The older measurements from profile MT04 (from MT continuation of the CELEBRATION 2000 project) were combined with the new perpendicular (the SW–NE oriented) MT profile near Stara Lubovna (Northern Slovakia), which passes through the Outer Carpathian Flysch Belt, Klippen Belt and ends in the Inner Western Carpathians Paleogene NW from Ružbachy horst structure.

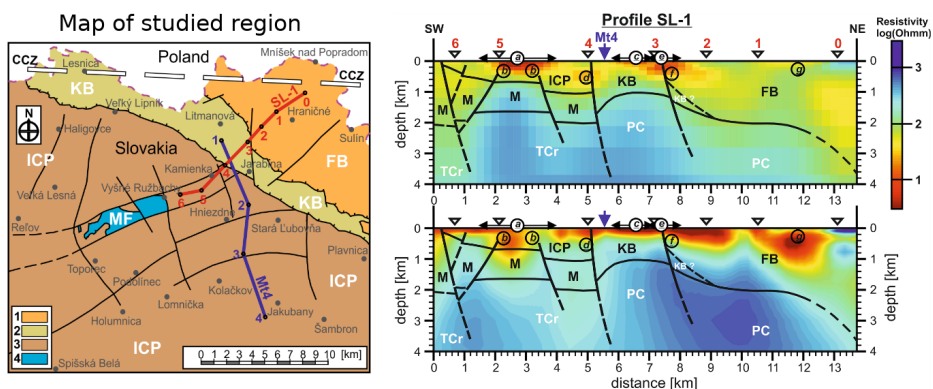


Fig. 1: The map with modelled profiles and data points (left). 2D geoelectrical model along profile SL-1 (upper-right) and section through 3D model along same profile (bottom-right).

The 2-D geoelectrical models were reanalysed by 3-D MT modelling of studied region, which enabled the evaluation of 3D effects in the original 2D modelling and prepare more robust and complex models. The MT data interpretations (Fig. 1) verified the northern inclination of Flysch belt structures and their smaller thickness out of Klippen Belt in direction to the Carpathian electrical conductivity zone axis. We consider this as a consequence of the flower structure – more precisely the southern branch of the suture zone related to mentioned conductivity zone. Northerly from this zone the thickness of the Outer Carpathian Flysch Belt increases and the structures have inclination to the south, i.e. to the subduction zone. The contact of Flysch Belt with Klippen Belt has a fault character and it is subvertical, slightly inclined to the North. The southern boundary between Klippen Belt and Inner Western Carpathians

has also fault character and is very steep. We confirmed the continuation of the Ruzbachy horst to the NE in the basement of Inner Western Carpathian Paleogene. The structural discordance between this horst and Klippen Belt direction is a result of younger tectonic processes. According to our results the depth distribution of the pre-Tertiary basement below the Inner Western Carpathian units is non-uniform; the basement is broken to a number of partial blocks – horsts and grabens (*Majcin et al., 2018*).

The deep crustal and lithospheric studies with goal to characterized Carpathian shear corridor and its relation to the Western Carpathian deep-seated structures have been performed along old deep seismic reflection profile 2T (*Bezák et al., 2016*). The MT, gravimetric and geothermal data were modelled on the section in addition to seismic information and were used for the interpretation (Fig. 2). The advantage of the 2T cut is that it passes from S to J through all the basic tectonic units of the external and internal Carpathians. Additionally to these regional and deep studies, the new detailed MT measurements in Malá Fatra have been carried out. They are focused on the nature of the offset in Klippen belt zone in this area, which may also be correlated with the shift in the Carpathian Conductivity Zone (CCA) in the mid-crustal depths.

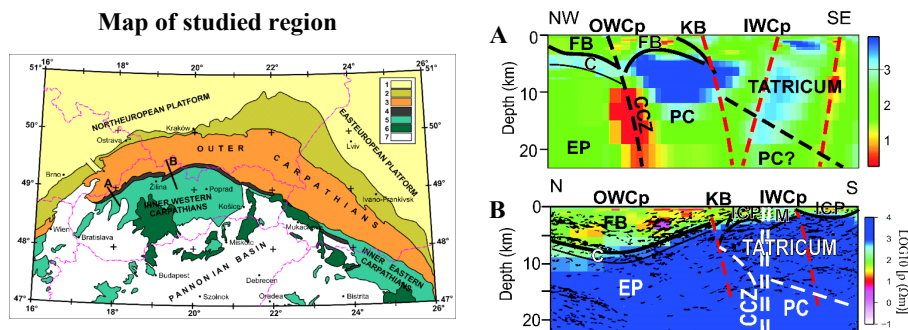


Fig. 2: Tectonic map with approximate positions of profiles (left). 2-D models along profile A and profile B (right).

These methods clearly point to full-length vertical interfaces. They are tectonically interpreted as nealpine lateral shifts at the fractures along which the crustal segments with contrasting physical parameters and the geological composition. Four basic segments can be identified from the north to south. The first block is the European Platform with an overlaying flysch zone and

with notable flexure of the platform towards the south. The next block is the centrally strongly resistive block, which also represents the Carpathian gravitational minimum. The composition of this block is dominated by the granitized complexes of Tatricum. A more distinctive tectonically laminated block emerges, showing a contrast between the resistive granitoid complexes in the overburden and the less resistive metamorphic complexes in the basement (these are residuals of the Hercynian development in the Veporicum, i.e. alpine tectonic unit). The southernmost block is composed from Neogene sediments and vulcanites, metasediments of Gemericum, Veporicum crystalline complexes. The significantly high conductivity of the crust in this area is most probably not related to its lithological composition, but by the abundant supply of fluids in the crust after the Neogene tectonic and volcanic processes (Bezák *et al.*, 2015).

The most important contribution of the interpretation of geophysical measurements from these studies is the detection of whole-crust tectonic boundaries (faults) and identification of geological units in the crust with significant conductivity contrast and their tectonic interpretation.

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## **International Research/Grant Projects:**

### **INTERMAGNET – International Real-time Magnetic Observatory Network**

From 1998

National coordinator: Magdaléna Váczyová (Alan Thomson – chairman of the programme)

Participating institutions: multilateral

CZECH–SLOVAK Bilateral Project

### **Electrical conductivity and geological structure in the West Carpathians and its transition to the Bohemian Massif**

2015–2017

Coordinator: Vladimír Bezák

UKRAINIAN–SLOVAK Bilateral Project

**Low-frequency fluctuations of the geomagnetic field and their bioresponse effects in case of water characteristics, luminescent bacteria and yeast granules**

2017–2019

National coordinator: Magdaléna Váczyová (Yuriy Pavlovich Gorgo – coordinator)

**Defended PhD Theses**

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Institution: Faculty of Natural Sciences, Comenius University, KAEG, Bratislava, Slovak Republic

Title: The reference curve of Slovakia for archaeomagnetic dating purposes

Student: Lenka Kubišová

Supervisor: Peter Vajda

Year of defence: 2016

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**Web pages**

<http://gpi.savba.sk/GPIweb/Projects/Lithores/index.php/sk/>

<https://fns.uniba.sk/pracoviska/geologicka-sekcia/kgf/vedecke-projektyresearch-projects/project-apvv-16-0146-wecafare/>

<http://www.geo.sav.sk/en/structure-of-the-institute/geophysical-division/geomagnetism/>

<http://www.geo.sav.sk/en/structure-of-the-institute/laboratories/geomagnetic-observatory/>



# Catchment and river processes: review of field experiments and mathematical modeling in hydrology in Slovakia from 2015 to 2018

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**Abstract:** This report describes the response of hydrologic research in Slovakia to challenges of global hydrologic research and regional problems. It follows previous reports from 1999, 2004, 2007, 2011 and 2015, and summarises published outcomes of the main research programs in hydrology in Slovakia from 2015 to 2018. The list of referenced papers in English is complemented by a list local and international research projects and defended PhD. theses

**Key words:** catchment processes, hydrological regime, land/use and climate change, floods, droughts

## 1. Introduction

The need to further develop an increased understanding of hydrological processes was stressed in the international scientific community in recent years. The study of hydrological processes on different temporal and spatial scales, land atmosphere interactions, understanding the impact of climate and landuse change on the hydrological cycle and water resources, etc., were increasingly tackled in international science. Interdisciplinarity was seen as one of the drivers of development. This report contains a commented bibliography of papers documenting the response of hydrologic research in Slovakia to these tendencies and challenges. References to most important publications in English from the same period or such with extended English abstracts are given. Main research programs and defended PhD. research theses in hydrology from 2015 to 2018 are listed in the Appendix.

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## 2. Soil-water-plant-atmosphere interactions

The need to develop an increased understanding of the erosion and transport processes on the plot and catchment scales under the specific physiographic conditions of Slovakia was stressed. Research on water and material transport in the soil-water-plant-atmosphere system have been partly focused on quantification of the water balance components in the unsaturated zone of soils in natural, agricultural and forest ecosystems. Field research was conducted and methodological aspects of modelling were tested and verified under lowland conditions of the Ray Island (Zitny ostrov) and the East Slovakian Lowland and in forested experimental mountainous catchments. Estimation of the components of the water balance (including water content of the snowpack), the interpretation of infiltration, evaporation, transpiration, capillary inflow and the seepage of water into lower horizons by means of monitoring and mathematical modeling resulted in an advanced quantitative analysis of the elements of the water balance equation. The spatial and temporal variability of the soil's hydraulic conductivity were also studied. Soil water repellency was studied at several sites on actual real soils. Laboratory and field research on the shrinking and swelling processes in heavy soils was focused on the East Slovakian Lowland. Relationships between the volume changes in these soils and the soil water content, fractions of various soil particle sizes, and density were derived. (Gomboš *et al.*, 2018; Gomboš *et al.*, 2018; Iovino *et al.*, 2018; Kandra *et al.*, 2017; Lichner *et al.*, 2018; Nagy *et al.*, 2018; Orfánus *et al.*, 2016; Pekárová *et al.*, 2015; Šurda *et al.*, 2015).

Several modelling and experimental studies using data from mountainous experimental plots and small catchments tried to venture answers to the questions how to predict the hydrological effects of vegetation and land use change in order to give adequate physical interpretation of the parameters and structures of vegetation in distributed rainfall-runoff models. Measurements and calculation of water and energy transport intensities between plants, soils and atmosphere depending on plants properties and environmental factors were at the basis of this research. Taking into account the two main problems related to determining the water balance in mountainous environments, i.e. the availability/quality of input data and their high spatial variability, phenological problems were also intensively studied by experimental methods at different elevations in complex mountainous terrain taking into account of climatic, meteorological, topographical and astronomical inputs, biological indicators,

slopes, inclinations and aspects. The impact of changes in natural vegetation by climate variability, beetle and wind calamities was observed and estimated. These studies were complemented by studying the ecohydrological aspects of the soil water cycle and connections of these to ecosystem services. (Bartík *et al.*, 2019; Bartík *et al.*, 2016; Mezei *et al.*, 2017; Mind'aš *et al.*, 2016; Mind'aš *et al.*, 2018; Schwilch *et al.*, 2018; Sitko *et al.*, 2016; Škvareninová *et al.*, 2018; Škvareninová, 2016; Škvareninová *et al.*, 2017; Vido *et al.*, 2016).

### 3. Runoff generation processes and rainfall-runoff modelling

With special interest taken in the component of subsurface and groundwater runoff, runoff components were estimated by mathematical rainfall-runoff models, water balance studies, runoff separation methods and experimentally by isotope methods. Tracer techniques were used to study the movement of water in the soil and bedrock and the mean transit times in catchments. Modelling was used for the estimation of the relationship between surface waters and groundwater in the weathered zone of stony soils, where very quick runoff and reaction of groundwater were studied. Based on these, runoff separation methods based on the relationship between stream discharge and the groundwater table were verified. Both the modelling and separation methods have confirmed the important role of subsurface flow during floods. Isotopic response of runoff to forest disturbance in small mountain catchments was assessed. The spatial distribution of precipitation did not seem to strongly affect the response in small mountainous catchments. Rainfall amounts were the most important factor influencing the response. Analysis of the rainfall-runoff events indicated the existence of threshold values in cumulative precipitation, which is important for identification of the catchment's runoff response to rainfall. (Hlaváčiková *et al.*, 2015; Hlaváčiková *et al.*, 2016; Holko, 2016; Holko *et al.*, 2018; Holko *et al.*, 2014; Pfister *et al.*, 2015; Rutkowska *et al.*, 2015; Vystavna *et al.*, 2018).

Research in snow hydrology has a long tradition in Slovakia. Recent re-evaluation of a large database of historical field measurements aided interest in determination of the overall trends in the spatial and temporal distributions of snow density, height and water equivalent in several mountainous catchments. The estimation of snow redistribution by wind was also outlined in snow studies. The modelling of snow accumulation and melt was practically oriented toward distributed simulation of snow accumulation and melt using both

energy-based and temperature-index approaches. Model parameterization including assimilation of remotely sensed data was seen as the most important problem in research of snow accumulation and melt modeling. Spatial and temporal variations of snow water equivalent were therefore also analyzed. The validation of snow models by means of satellite images was tested. Studies focusing on the distribution of snow cover in the forests and ski-slopes were conducted. Implications for ecosystem services were defined. (*Krajčí et al., 2016; Krajčí et al., 2016; Mikloš et al., 2018; Mikloš et al., 2017; Šatala et al., 2017*).

Methods for estimating and transferring model parameters from gauged to ungauged catchments are needed in water resources modelling studies in poorly gauged regions. Although a great deal of experience has been gained from using model parameter estimation methods, there is a continuing need to upgrade these methods and test them against practical requirements, since the problem of parameter estimation still constitutes the largest obstacle to the successful application of models both in gauged and ungauged catchments. Uncertainties in rainfall-runoff model parameter estimation were therefore extensively studied. Modern strategies for the estimation of rainfall-runoff model parameters were discussed and verified. Limitations in the use of distributed models for estimating land use change impacts were discussed. Simulated runoff changes in landuse change studies were confronted with expert judgments and estimates from the literature. A pressing need to increase the standard of forecasts in cases of floods and droughts striking larger territories has been identified in the operation of the Slovak National Flood Forecasting System. The performance of several current forecasting and risk estimation methods was therefore also evaluated, and a number of studies dealt with the development of methods for forecasting extremes and managing risk in water resources systems. (*Danáčová and Szolgay, 2018; Dušek and Velísková, 2017; Mitková et al., 2016; Sleziak and Parajka, 2017; Sleziak et al., 2016; Sleziak et al., 2018; Valent and Paquet, 2017; Peksová et al., 2017; Sleziak et al. 2015; Szolgayová et al., 2017*).

#### **4. Catchment management, water quality and ecosystem services**

Results from experimental catchments and the increase of the availability of spatially distributed data such as digital elevation models, land use and soil information made the use of distributed hydrologic models convenient in



studying relations between catchment management, runoff and ecosystem services. New data from agricultural and mountainous experimental hillslopes and small catchments aided the development of look up tables for the estimation of the parameters of distributed rainfall-runoff models for the estimating hydrological effects of land use change. Long-term changes in the water balance of experimental catchments were investigated with respect to climate, land use and societal changes. Recent extreme flood events in Europe and the public discussion on the issue of whether the frequency and severity of floods have been increasing, stimulated research in the question if such changes happen and could be attributed to anthropogenic influence. The effect of deforestation on runoff was seen as another important issue, which was frequently discussed between environmentalists, hydrologists and water resources managers. In several studies the question has therefore arisen as to how distributed parameter models are suited to predict the hydrological effect of land use change, and if their parameters and structure can have an adequate physical interpretation. The impact of the historical (potential) natural vegetation on runoff formation was estimated. The impact of change in natural vegetation on runoff formation was also estimated; in particular, changes in the water balance and its components were analyzed. (*Fleischer et al., 2017; Hlavčová et al., 2019; Hlavčová et al., 2018; Vitková et al., 2017; Lichner et al., 2010; Lukášová et al., 2019; Rogger et al., 2017; Rončák et al., 2017; Valent et al., 2016*).

Water quality data for the implementation of the EU Water Framework Directive (WFD) were observed by the regular network of the Slovak Hydrometeorological Institute, in experimental basins and in dedicated research projects. The operational data collection and monitoring allowed for the routine analysis of fluctuations in the loads of nitrogen, phosphates, sulphates and chlorides. The characteristics of the water quality regime were determined, as well as the total and specific yields of the pollutants. Empirical relationships and long-term trends have been derived for estimating concentrations and loads for several water quality constituents, which will serve the purpose of the EU WFD implementation in Slovakia. Additionally, various monitoring programs were set up and models were verified in several experimental basins for the simulation of runoff, nutrient and pesticide washout under various land uses during normal and extreme rainfall-runoff situations. The impact of forestry, agriculture and urban activities on the quality of surface water was also assessed. In addition to the routine analysis recently there was also increased

interest in the presence of occurrence of illicit drugs and selected pharmaceuticals in waste waters and sewage sludge. (Hanzelová *et al.*, 2018; Bodík *et al.*, 2016; Fáberová *et al.*, 2017; Ivanová *et al.*, 2018; Mackuľak *et al.*, 2016; Mackuľak *et al.*, 2019; Sokáč and Velísková, 2017; Sokáč *et al.*, 2018).

With regard to bio-indicators for the implementation of the EU WFD numerous qualitative and quantitative investigations on the effect of river morphology on ichthyological fauna in both natural and regulated segments of selected rivers were conducted. Fish species composition, species diversity, the abundance and biomass of particular species, the mean individual weight and the ichthyomass were monitored during the spring and autumn seasons at several experimental river reaches. Factors affecting fish population density were specified. It was shown that in a natural stream segment, the number of species, the diversity of species and equitability indices were higher than in regulated ones. Morphologically stable and environmentally sensitive river training measures were proposed with the aim to support the creation of natural range of instream and bankside habitats for fisheries, flora and fauna, and to protect the wetland ecosystems against successive degradation. (Macura *et al.*, 2016; Macura *et al.*, 2018; Majorošová *et al.*, 2018; Sočuvka and Velísková, 2015; Štefunková *et al.*, 2018; Velísková *et al.*, 2017; Velísková *et al.*, 2018).

## **5. Climate change impact on hydrological processes and water resources management**

Time series of precipitation, air temperature and runoff were analyzed in several studies in order to detect climate change signals in the data series using statistical methods. The long-term variability of Slovak rivers as well as rivers in the temperate zone of the Northern Hemisphere were also analyzed. The analysis detected a time shift in the occurrence of runoff extremes in the regions studied. The analysis did not confirm the hypothesis on the increasing frequency of high flows. Studies of groundwater runoff changes in different geological conditions in the last four decades showed a decrease in groundwater runoff in most of the assessed catchments in Slovakia. Studies of spring yields in the karstic areas of Slovakia showed decreasing trends in almost all the evaluated cases. Local and regional hydrological droughts and the water balance of sensitive areas such as agricultural land and wetlands were studied,

too. Intermittency was observed recently in several rivers and the phenomenon started to be studied.

Several General Circulation Model (GCM) based climate change scenarios were used and the construction of physically plausible downscaled scenarios of daily, monthly and annual time series for air temperature, precipitation and air humidity was also attempted. Attempts to design scenarios of extreme short-term totals for selected time frames began. According to these scenarios, a significant increase in air temperature, small changes in long-term precipitation totals, and a remarkable increase in short-term precipitation extremes are expected in Slovakia in the warm half-years. On the other hand, more frequent and longer periods of drought will occur, mainly in the Slovak lowlands. Higher precipitation and a warmer climate in winter will significantly affect the winter runoff and snow regime on most of the territory of Slovakia. The whole territory of Slovakia could become more vulnerable to drought in the summer and the autumn. (*Blöschl et al., 2017; Fendeková et al., 2018; Halmová et al., 2015; Hlavčová et al., 2015; Jeneiová et al., 2016; Laaha et al., 2017; Pekárová et al., 2016; Rutkowska et al., 2018; Van Lanen et al., 2015; Vilček et al., 2016; Zeleňáková et al., 2017; Zeleňáková et al., 2017*).

## 6. Hydrological extremes

A number of very high flash floods caused by extreme precipitation have occurred in recent years in Slovakia. These events were individually investigated, and the formation of the floods in ungauged basins was reconstructed using data from at site hydrological surveillance and available data from the hydrological and meteorological network together with radar and satellite data (*Bačová Mitková et al., 2018; Hlavčová et al., 2016; Kohnová et al., 2015*).

Catastrophic floods occurred in some regions of Central Europe before and during the period covered by this report. Therefore the most severe recorded events in Slovakia were also analyzed and the flood formation in the catchments of regions, which are known for their extreme floods, was studied. Lumped and distributed rainfall-runoff models were used to model the events. Additionally measured, modelled and historical flows and volumes of flood waves were statistically analysed separately for dry and wet periods. Valuable knowledge of the formation of extreme flood runoff and data on rare events needed for the frequency analysis of peak flows in structural design was gained.

(Blöschl et al., 2017; Blöschl et al., 2016; Hall et al., 2015; Medeiro et al., 2015; Papaioannou et al., 2016; Rutkowska et al., 2017).

Recent research on the bivariate flood peak/volume frequency analysis has mainly focused on the statistical aspects of the use of various copula models. The interplay of climatic and catchment processes in discriminating among these models has attracted less interest. Intensive research in this respect resulted in the analysis of the influence of climatic and hydrological controls on flood peak and volume relationships and their models, which were based on the concept of comparative hydrology in the catchments of a selected region in Austria. Independent flood events have been isolated and assigned to one of the three types of flood processes: synoptic floods, flash floods and snowmelt floods. First, empirical copulas were regionally compared in order to verify whether any flood processes were discernible in terms of the corresponding bivariate flood-peak relationships. Next the types of copulas, which are frequently used in hydrology were fitted, and their goodness-of-fit is examined in a regional scope. The spatial similarity of copulas and their rejection rate, depending on the flood type, region, and sample size were examined, too. In particular, the most remarkable difference is observed between flash floods and the other two types of flood. It was concluded that treating flood processes separately in such an analysis is beneficial, both hydrologically and statistically, since flood processes and the relationships associated with them are discernible both locally and regionally in the pilot region. The studies also inspired new developments in mathematical copula research. (Bacigál et al., 2015; Gaál et al., 2016; Gaál et al., 2015; Kohnová et al., 2016; Komorník et al., 2017; Szolgay et al., 2016; Szolgay et al., 2016; Szolgay et al., 2016; Szolgay et al., 2015).

Several studies were aimed at the development of methodologies for the spatial interpolation of precipitation data and scaling properties of extreme rainfall for hydrological mapping and rainfall runoff modelling. Research into extreme precipitation provided a contribution towards the limited knowledge of possible future changes in the characteristics of sub-daily precipitation extremes that are of great importance for hydrological modelling and other applications. Heavy rainfall event characteristics from data and those projected by an ensemble of Regional Climate Model simulations were analyzed. The scaling exponents of extreme precipitation estimated using the results from the selected RCM simulations were found to be lower than the exponents of the observed historical on average. On the other hand, due to the higher daily

precipitation amounts in the future, as projected by all the scenarios, the downscaled values of the short-term rainfall at all the stations analysed would be considerably higher in the future horizons. These findings show a need for recalculating design short-term rainfall for the engineering practice in the future. (*Kohnová et al., 2018; Molnár et al., 2015; Vasilaki et al., 2017*).

Floods endanger the lives and health of the population, cultural heritage and the environment and cause damage to property while limiting economic activity. While it is not possible to prevent flooding, the amount of flood damage and the estimate the measure of the flood risks can be useful particularly for the proposal of effective flood-protection measures. Such transition from flood protection to complete flood management is implemented in the European Union under the requirements of Directive 2007/60/EC on the assessment and management of flood risk. Therefore efforts were also directed to develop general methodologies for such effective flood protection measures based on objectives of flood risk management. The various risks associated with flooding were characterised by simple relations based on informative numerical values deduced from the actual conditions of the Slovak Republic. (*Solín et al., 2017; Solín et al., 2018; Zeleňáková et al., 2018; Zeleňáková et al. 2017*).

## 7. Conclusions

Attempts to increase the understanding of hydrological processes on various scales have been the focus of the international scientific community in recent years. Signals of changing climate and recent extreme flood and drought events in Europe have stimulated public discussion also on the issue of whether the frequency and severity of these events have been increasing, to what extent such changes could be attributed to anthropogenic influence and how to measure and model processes describing them. Therefore the study of hydrological processes on plot, hillslope, catchment and continental scales, land-atmosphere interactions, the impact of land use and climate change on the hydrological cycle and extreme events has been at centre of interest among environmentalists, hydrologists and water resources managers also in Slovakia.

This report reviewed the response of hydrologic research in Slovakia to challenges of global hydrologic research between 2015 and 2018. It follows previous reports from 1999, 2004, 2007, 2011 and 2015, and summarises results and outcomes of the main research programs in hydrology in Slovakia.

Papers in English and local and international research projects were listed and referenced, list of defended PhD. thesis is also given.

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**International and national research projects**

International Atomic Energy Agency project

**The Role of snow in hydrological cycle of the Upper Vah River basin, Slovakia**

2010–2015

Coordinator: Ladislav Holko

AUSTRIAN – SLOVAK Bilateral Project, SK-AT-2015-0018

**Root uptake modelling with field scale parameters assessment**

2012–2015

Coordinator: Viliam Novák

EC 7<sup>th</sup> FRAMEWORK PROGRAM Grant agreement 269985

**Detection of watercourse contamination in developing countries using sensor networks - enlarged**

2013–2015

National coordinator: Yveta Velísková

EUREKA European research and development funding and coordination organization

**A system of monitoring of selected parameters of porous substances using the EIS method in a wide range of applications**

2012–2017

National coordinator for Slovak Republic: Milan Gomboš

COST project Harnosnow

**An European network for a harmonized monitoring of snow for the benefit of climate change scenarios, hydrology and numerical weather prediction**

2014–2018

National Coordinator: Pavol Nejedlík

MAD SK-PL

**Evaluation of surface soil moisture from satellite and ground-based measurements**

2016–2018

National coordinator: Justína Vítková

MAD SK-Ukraine

**Impacts of global climate changes on water resources in Ukraine estimated by variability of river discharges and hydrograph components**

2017–2019

Coordinator: Pavla Pekárová

UNESCO IHP project

**Flood regime of rivers in the Danube river basin**

2007–2019

International Coordinator: Pavla Pekárová

UNESCO IHP project

**Regional cooperation of the Danube countries**

2014–2021

Coordinator: Pavol Miklánek

UNESCO IHP project

**EUROFRIEND-flow regimes from international experimental and network data**

2014–2021

Coordinator: Pavol Miklánek

UNESCO IHP project

**ERB-European network of experimental and representative basins**

2014–2021

Coordinator: Ladislav Holko

APVV SK-PT-2015-0007

**Risk assessment of the extreme hydrological phenomena**

2016–2018

Coordinator: Martina Zelenakova

APVV SK-PT-18-0008

**Hydrological risk: from excess to scarcity of water**

2018-2020

Coordinator: Martina Zelenakova

APVV SK-PL-18-0033

**Assessment of environmental risk in relation to climate change adaptation**

2018-2020

Coordinator: Martina Zelenakova

BFB-PA7-005 EEA grant

**Adaptation to Climate Change**

2016-2017

Coordinator: Martina Zelenakova

Interreg [V-A Slovakia-Hungary Cooperation Programme](#) SKHU/1601

**Logistic support system for flood crisis management in the Hernád/Hornád catchment. University of Miskolc, Hungary**

2018-2020

Coordinator: Endre Dobos

National coordinator: Peter Blistan, Martina Zelenakova

VEGA 1/0609/14

**Assessment of environmental risks from climate changes and anthropogenic activities in the catchments of water bodies at Eastern Slovakia**

2015-2019

Coordinator: Martina Zelenakova

International Strategy for Disaster Reduction (ISDR) Programme

**Mountain floods – regional joint probability estimation of extreme events.**

2015-2018

National coordinator: Szolgay Ján

EC 7<sup>th</sup> FRAMEWORK PROGRAM No. 603498 RECARÉ

**Preventing and remediating degradation of soils in Europe through land care**

2013-2018

Coordinator: Rudy Hessel, WURL Netherland

National coordinator: Ján Szolgay

CA15113 COST

**Science and management of intermittent rivers and ephemeral streams (SMIRES)**

2016 – 2020

Member of the Management Committee: Silvia Kohnová

ES1306 COST

**Connecting European Connectivity Research**

2014 – 2018

Member of the Management Committee: Kamila Hlavčová

CA16209 COST

**Natural Flood Retention on Private Land**

2017 – 2021

Members of the Management Committee: Silvia Kohnová, Ján Szolgay

APVV-15-0425

**Impact of natural hazards on forest ecosystems in Slovakia under conditions of future climate**

2014-2019

Principal investigator: Jaroslav Škvarenina

VEGA 1/0589/15

**Selected natural hazards as climate change indicators on the example of forest ecosystems in the Slovak republic**

2015-2018

Principal investigator: Jaroslav Škvarenina

APVV-0089-12

**Prognosis of hydrological drought occurrence in Slovakia**

2013 – 2017

Coordinator: Miriam Fendeková

**Defended PhD. Theses**

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Institution:	Department of Hydrogeology, Faculty of Natural Sciences, Comenius University in Bratislava, Slovak Republic
Title:	Analysis of water runoff compounds from the catchment
Student:	Diana Španková
Supervisor:	Miriam Fendeková
Year of defense:	2015

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Institution: Department of Hydrogeology, Faculty of Natural Sciences, Comenius University in Bratislava, Slovak Republic  
Title: Anthropogenic influencing of the chemical composition and water quality in urbanized area of Bratislava  
Student: Alexandra Ďuričková  
Supervisor: Zlatica Ženišová  
Year of defense: 2015

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Institution: Institute of Hydrology, Slovak Academy of Sciences, Slovak Republic  
Title: The water regime of stony soils  
Student: Hana Hlaváčiková  
Supervisor: Viliam Novák  
Year of defense: 2015

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Institution: Institute of Hydrology, Slovak Academy of Sciences, Slovak Republic  
Title: The evaluation of the dynamics of water supply in the soils of Záhorská Lowland in climatic changes conditions  
Student: Peter Stradiot  
Supervisor: Július Šútor  
Year of defense: 2015

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Institution: Institute of Hydrology, Slovak Academy of Sciences, Slovak Republic  
Title: Identification of the hydrological discharge regime changes of the rivers in the Danube basin  
Student: Branislav Pramuk  
Supervisor: Pavla Pekárová.  
Year of defense: 2016

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Institution: Institute of Hydrology, Slovak Academy of Sciences, Slovak Republic  
Title: Impact of surface water bed sediments on interaction with surrounding groundwater  
Student: Valentín Sočuvka  
Supervisor: Yveta Velísková.  
Year of defense: 2017

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Institution: Institute of Hydrology, Slovak Academy of Sciences, Slovak Republic  
Title: Dependence of ground water level oscillation and surface water level in surrounding streams  
Student: Petr Dušek  
Supervisor: Yveta Velísková  
Year of defense: 2017

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Institution: Institute of Hydrology, Slovak Academy of Sciences, Slovak Republic  
Title: Variability of snow accumulation and melt in a mountain catchment  
Student: Pavel Krajčí  
Supervisor: Ladislav Holko

Year of defense: 2017

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Institution: Institute of Hydrology, Slovak Academy of Sciences, Slovak Republic  
 Title: Impact of specific properties of forest soils on hydrological processes in the catchment  
 Student: Anton Zvala  
 Supervisor: Tomáš Orfánus.  
 Year of defense: 2018

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Institution: Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology Bratislava, Slovak Republic  
 Title: The role of Water Authorities in the period of climate change adaptation.  
 Student: Zsolt Lukáč  
 Supervisor: Ján Szolgay  
 Year of defense: 2018

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Institution: Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology Bratislava, Slovak Republic  
 Title: Assessment of snow cover changes during last decades in Slovakia.  
 Student: Katarína Kotríková  
 Supervisor: Kamila Hlavčová  
 Year of defense: 2018

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Institution: Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology Bratislava, Slovak Republic  
 Title: Optimization and analysis of the distribution system of an irrigation system.  
 Student: Ľubomír Čelár  
 Supervisor: Milan Čistý  
 Year of defense: 2017

---

Institution: Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology Bratislava, Slovak Republic  
 Title: Variability of snow accumulation and melting in a mountain catchment.  
 Student: Pavol Krajčí  
 Supervisor: Ladislav Holko  
 Year of defense: 2017

---

Institution: Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology Bratislava, Slovak Republic  
 Title: Modeling of rainfall-runoff processes under a changing climate  
 Student: Patrik Slezziak  
 Supervisor: Ján Szolgay  
 Year of defense: 2017

---

Institution: Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology Bratislava, Slovak Republic  
Title: Impact of bed sediment on the interaction between surface water and groundwater  
Student: Valentín Sočuvka  
Supervisor: Yveta Velísková  
Year of defense: 2017

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Institution: Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology Bratislava, Slovak Republic  
Title: Modeling of erosion and transport processes in the basins of Slovakia  
Student: Zuzana Studvová  
Supervisor: Kamila Hlavčová  
Year of defense: 2017

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Institution: Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology Bratislava, Slovak Republic  
Title: Assessment of the impact of climate on the phenology of woody plants in an Arboretum Mlyňany SAS (Slovak Academy of Sciences)  
Student: Ján Valach  
Supervisor: Silvia Kohnová  
Year of defense: 2017

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Institution: Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology Bratislava, Slovak Republic  
Title: Evaluating quality of aquatic habitat of mountainous rivers  
Student: Peter Ivan  
Supervisor: Viliam Macura  
Year of defense: 2016

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Institution: Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology Bratislava, Slovak Republic  
Title: Soil water regime predictions.  
Student: Miroslava Jarabicová  
Supervisor: Jana Skalová  
Year of defense: 2016

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Institution: Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology Bratislava, Slovak Republic  
Title: Parameterization of rainfall-runoff models for modelling runoff under climate change  
Student: Peter Rončák  
Supervisor: Kamila Hlavčová  
Year of defense: 2016

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Institution: Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology Bratislava, Slovak Republic

Title: Application of multi-regime models for analysis of discharge series  
 Student: Danuše Szökeová  
 Supervisor: Silvia Kohnová  
 Year of defense: 2016

Institution: Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology Bratislava, Slovak Republic  
 Title: Vegetation effect on erosion-sedimentation processes in the floodplain soils of the Schwechat River, Austria  
 Student: Jana Vojtková  
 Supervisor: Viliam Macura  
 Year of defense: 2016

Institution: Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology Bratislava, Slovak Republic  
 Title: Impact of bed sediment on the interaction between surface water and groundwater  
 Student: Katarína Jeneiová  
 Supervisor: Silvia Kohnová  
 Year of defense: 2015

Institution: Faculty of Civil Engineering, Technical University of Košice, Slovak Republic  
 Title: Modelling of meteorological and hydrological drought  
 Student: Tatiana Solakova  
 Supervisor: Martina Zelenakova  
 Year of defense: 2018

Institution: Faculty of Civil Engineering, Technical University of Košice, Slovak Republic  
 Title: The impact of climate change on water management in the country  
 Student: Ibrahim Alkhalaf  
 Supervisor: Martina Zelenakova  
 Year of defense: 2017

Institution: Faculty of Civil Engineering, Technical University of Košice, Slovak Republic  
 Title: Research and solving of drainage of water from surface runoff with emphasis on the retention capacity of the selected area and precipitation intensity  
 Student: Tatiana Solakova  
 Supervisor: Martina Zelenakova  
 Year of defense: 2015

Institution: Faculty of Forestry, Technical University in Zvolen, Slovak Republic  
 Title: Influence of forest decline on precipitation interception process in mountain spruce forest in West Tatra Mts.  
 Student: Martin Bartík  
 Supervisor: Jaroslav Škvarenina  
 Year of defense: 2015



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Institution: Faculty of Ecology and Environmental Science, Technical University in Zvolen, Slovak Republic  
Title: Microbial properties of snow cover in mountain area  
Student: Miriam Hanzelová  
Supervisor: Jaroslav Škvarenina  
Year of defense: 2015

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Institution: Faculty of Forestry, Technical University in Zvolen, Slovak Republic  
Title: The influence of forest growth and select component of the relief on snow water equivalent in river basin of Hučavy –BR Poľana  
Student: Tomáš Šatala  
Supervisor: Jaroslav Škvarenina  
Year of defense: 2015

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Institution: Faculty of Forestry, Technical University in Zvolen, Slovak Republic  
Title: Assessment of artificial (man-made) snow cover impact on vegetation changes in ski resorts and adjacent forests  
Student: Mikloš Michal  
Supervisor: Jaroslav Škvarenina  
Year of defense: 2017

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Institution: Department of Fire Protection, Technical University in Zvolen, Slovak Republic  
Title: Analysis of meteorological conditions of forest and landscape fires in Slovakia  
Student: Katarína Koristeková  
Supervisor: Jaroslav Škvarenina  
Year of defense: 2018

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# Selected achievements in Meteorology and Atmospheric Sciences in Slovakia in 2015–2018 (Report to IAMAS)

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**Abstract:** The Report is based on the selection of the reviewed papers published in international and in Slovak Journals and monographs. Further to that some activities regarding the education and international projects are considered. Number of Institutions were involved both in monitoring and research activities of the processes in the atmosphere and hydrosphere and in the interaction of those two to biosphere including the human but only the major contributors are listed in the text. It is an advantage that except some textbooks, official ministerial documents and papers for education nearly all cited papers and contributions have been published in English language. Only such references are included here where as coauthors are specialists on meteorology, climatology and atmospheric sciences from Slovakia. This involves a list of different European expert journals, at the national level the expert activities are published mostly in the Slovak Meteorological Journal freely available on <http://www.shmu.sk/sk/?page=31>. Many publications on the hydrology and water cycle are included in the Report to IAHS even if contain meteorology and climatology parts, that is why they are not listed in this report.

## 1. Weather forecast, modeling of atmosphere processes

Progress in weather prediction in Slovakia was in recent decades concentrated mostly in the use and application development of the limited area numerical weather prediction system ALADIN denoted as ALADIN/SHMU. It is operationally exploited at the Slovak Hydrometeorological Institute and serves as an input for the routine weather forecasts and warnings as well as for other applications and for the customers oriented products. ALADIN/SHMU system has been ported to the new high performance computing system and substantially upgraded in 2017. It has doubled horizontal resolution and about 40% increase in the number of the vertical levels – the current horizontal step is

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\* IAMAS National Correspondent

4.5 km and there are 63 vertical levels. The higher model resolutions is expected to better represent local weather-related processes mainly thanks to the better description of the local physiographic fields and their interactions with surface and atmospheric processes. Along with the technical update also many new scientific improvements were brought in. The model changes were mostly in the model physics. The operationally introduced package labeled as ALARO-1vB includes namely radiation parameterization upgrade denoted as ACRANEB2, turbulence scheme denoted as TOUCANS, enhancement of the moist deep convection using unsaturated downdraft and sub-grid-scale updraft formulations. All this changes are a part of so called ALARO Canonical Model Configuration of the ALADIN system. New configuration of ALADIN/SHMU has been intensively validated by the computation of the standard statistical verification scores. In parallel, a subjective comparison against the remote sensing measurements was made. In general it was concluded that the new ALADIN/SHMU outperforms the old one in almost every parameter. However, several problematic forecasts were reported, that seem to be associated with particular weather regimes. Apart the operational exploitation of the ALADIN/SHMU system there is ongoing effort in the improvement or new development of the NWP model in general as well as the exploitation of model outputs in other applications like nowcasting systems (INCA) and road weather forecasting.

Further research in atmospheric processes focused on capturing detailed features in deep convection important for severe storm forecasting by using Super Rapid Scan Operations for GOES-R data, radar, and lightning observations.

In close to the ground modelling of atmospheric processes a new model for nowcasting fog events in the coastal desert area was developed for the Dubai conditions which considerably improved fog forecast skill for the first six hours and is used mostly for fog predictions along the highways and for indoor heat exposure during the heat a probabilistic model was developed.

Bartokova I., Bott A., Bartok J., Gera M., 2016: Fog prediction for road traffic safety in a coastal desert region: improved of nowcasting skills by the machine-learning approach. *Boundary Layer Meteorology*, **157**, 3, 501–516, doi: 10.1007/s10546-015-0069-x.

Bedka K. M., Wang C., Rogers R., Carey L. D., Feltz W., Kanak J., 2015: Examining deep convective cloud evolution using total lightning, WSR-88D, and GOES-14 super rapid scan datasets. *Weather and Forecasting*, **30**, 3, 571–590, doi: 10.1175/WAF-D-14-00062.1.

- Belluš M., Wang Y., Meier F., 2016: Perturbing Surface Initial Conditions in a Regional Ensemble Prediction System. *Monthly Weather Review*, **144**, 9, 3377–3390, doi: 10.1175/MWR-D-16-0038.1
- Derková M., Vivoda J., Belluš M., Španiel O., Dian M., Neštiak M., Zehnal R., 2017: Recent improvements in the ALADIN/SHMU operational system. *Meteorological Journal*, **20**, 2, 45–52.
- Kann A., Kršmanc R., Habrovský R., Šajn Slak A., Bujňák R., Schmid F., Tarjáni V., Wang Y., Wastl C., Bica B., Meirold-Mautner I., 2015: High-resolution nowcasting and its application in road maintenance: experiences from the INCA Central European area project. *IET Intelligent Transport Systems*, **9**, 5, 539–546, doi: 10.1049/iet-its.2014.0102. IET Digital Library, <http://digital-library.theiet.org/content/journals/10.1049/iet-its.2014.0102>.
- Sadovský Z., Koronthályová O., Mihálka P., Matiašovský P., Mikulová K., 2015: Probabilistic modelling of extreme indoor heat exposure induced by heat waves. In *Building Simulation*, **8**, 5, 477–485. ISSN 1996-3599.
- Schmalwieser A. W. et al., 2017: UV Index monitoring in Europe. *Photochemical & Photobiological Sciences*, **16**, 9, 1349–1370, doi: 10.1039/c7pp00178a.
- Termonia P., Fischer C., Bazile E., Bouyssel F., Brozkova R., Benard P., Bochenek B., Degrauwe D., Derkova M., El Khatib R., Hamdi R., Masek J., Pottier P., Pristov N., Seity Y., Smolikova P., Spaniel O., Tudor M., Wang Y., Wittmann C., Joly A., 2017: The ALADIN System and its Canonical Model Configurations AROME CY41T1 and ALARO CY40T1. *Geosci. Model Dev.*, **11**, 257–281, <https://doi.org/10.5194/gmd-11-257-2018>.
- Vivoda, J., Smolikova P., Simarro J., 2018: Finite Elements Used in the Vertical Discretization of the Fully Compressible Core of the ALADIN System. *Mon. Wea. Rev.*, **146**, 3293–3310, doi: 10.1175/MWR-D-18-0043.1.
- Wang Y., Meirold-Mautner I., Kann A., Sajn Slak A., Simon A., Vivoda J., Bica B., Bocskor E., Brezkova L., Dantinger J., Giszterowitz M., Heizler G., Iwanski R., Jachs S., Bernard T., Kršmanc R., Merse J., Micheletti S., Schmid F., Steininger M., Haiden T., Regec A., Buzzi M., Derkova M., Kozaric T., Qiu X., Reyniers M., Yang J., Huang Y., Vadislavsky E., 2017: Integrating nowcasting with crisis management and risk prevention in a transnational and interdisciplinary framework. *Meteorologische Zeitschrift*, **26**, 5, 459 – 473.
- Wang Y., Belluš M., Ehrlich A., Mile M., Pristov N., Smolikova P., Spaniel O., Trojakova A., Brozkova R., Cedilnik J., Klaric D., Kovacic T., Masek J., Meier F., Szintai B., Tascu S., Vivoda J., Wastl C., Wittmann C., 2018: 27 years of Regional Cooperation for Limited Area Modelling in Central Europe (RC LACE). *Bulletin of the American Meteorological Society*, **99**, 7, 1415–432, doi: 10.1175/BAMS-D-16-0321.1.

## **2. Upper atmosphere meteorology, ozone, aerosols, atmospheric chemistry, greenhouse gases emission, environmental impacts**

Most of the responsibilities regarding the monitoring and research of upper atmosphere meteorology, aerosols and greenhouse gasses emission is in the hand of specialized departments of the Slovak Hydrometeorological institute. Works emerged within the field of the investigation of optical properties of the atmosphere which is monitored in the mountain area of Northern Carpathians. Total ozone and atmospheric aerosol optical depth measurements based on the detection of ultraviolet solar radiation reaching the Earth's surface showed statistically significant decrease in the total optical depth of the atmosphere. Using this method also some events of the solid particles in the atmosphere (like Sahara sand) being transported over the continent were detected.

The network of the air quality measurements was reconstructed and enlarged to 38 stations with different monitoring programmes out of which 18 is permanently detected ozone and this process is continuing. Further to that specialized measurements and investigations of the impact of surface ozone on the mountain flora is going on in High Tatra mountains. The results brought by Bicarova et al. show further to the elevated levels ground ozone concentration, which is comparable with other European mountains also a high phytotoxic potential of ozone pollution in the forest environment of the highest part of Carpathian Mountains. A special measurement and evaluation of ozone concentrations over the forest area affected smashed by a wind storm indicates moderate but clear increase of ozone means for the period after the wind storm in comparison with the previous period.

Comprehensive evaluation of the climate change issue within the territory of Slovak republic including national circumstances relevant to greenhouse gas emissions and removal is cumulated in The Seventh National Communication of the Slovak Republic on Climate change.

At the wider scale of environmental impacts Slovak exerts contributed to the study on biomass combustion activities on air emissions as well as on effect of climate (temperature and moisture) and land-use on early stage decomposition of litter (selected biomes) .

Bičárová S., Bilčík D., Nejedlík P., Janík R., Kellerová D. 2015: Changes in the surface ozone after the windstorm in 2004, in the High Tatras. *Folia Forestalia Polonica*. Series A, Forestry, **57**, 1, 74–81, doi: 10.1515/ffp-2015-0007.

- Bičárová S., Sitková Z., Pavlendová H., 2016: Ozone phytotoxicity in the western carpathian mountains in Slovakia. *Lesnícky časopis, Forestry Journal*, **62**, 2, 77–88, doi: 10.1515/forj-2016-0008.
- Djukic I., Kepfer-Rojas S., Schmidt I. K., Larsen K. S., Beier C., Berg B., Fleischer P., Humber A. et al., 2018: *Early stage litter decomposition across biomes*. *Science of the total environment*, **628**, 1369–1394, doi: 10.1016/j.scitotenv.2018.01.012.
- Hrabčák P., 2018: Comparison of the optical depth of total ozone and atmospheric aerosols in Poprad-Gánovce, Slovakia, *Atmos. Chem. Phys.*, **18**, 7739–7755, doi: 10.5194/acp-18-7739, 2018.
- Muntean M., Janssens-Maenhout G., Guizzardi D., Crippa M., Schaaf E., Poljanc M., Logar M., Zemko M., Cristea Gasler C., 2017: Impact evaluation of biomass used in small combustion activities sector on air emissions. JRC Technical Report, European Commission, [http://publications.jrc.ec.europa.eu/repository/bitstream/JRC109332/f3\\_impact\\_of\\_fuel\\_used\\_in\\_small\\_comb\\_d2\\_connectivity\\_wpk\\_2017\\_revised\\_by\\_ipo.pdf](http://publications.jrc.ec.europa.eu/repository/bitstream/JRC109332/f3_impact_of_fuel_used_in_small_comb_d2_connectivity_wpk_2017_revised_by_ipo.pdf) EUR 29033 EN, ISBN 978-92-79-77359-4.
- Prikryl P., Bruntz R., Tsukijihara T., Iwao K., Muldrew D. B., Rušin V., Vybanský M., Turňa M., Štastný P., 2018: Tropospheric weather influenced by solar wind through atmospheric vertical coupling downward control. *Journal of Atmospheric and Solar-Terrestrial Physics*, **171** (special issue), 94–110, doi: 10.1016/j.jastp.2017.07.023.
- The Seventh National Communication of the Slovak Republic on Climate change. Bratislava 2017. (contacts, Skultety J., Szemeszova J.)

### 3. Climate, analyses of climatic variability and extreme weather events

Data base for climate evaluation is mostly provided by Slovak Hydrometeorological Institute. The data series start in 1871 with the observations at Hurbanovo, more than 700 stations of different status were established since that time. The research work was supported by the fact that great part of the archived paper data were converted to the digitized form and homogenized for further climatological processing and evaluation. Climatological network of Slovak Hydrometeorological Institute was renovated and almost entirely automatized for the monitoring of all basic climatic elements. Nevertheless, manual observations continued at almost all existing stations (about 90 stations) under unchanged methodology and there is an aim to continue for more years. This brings the data series intact by the changes in methodologies or dramatic changes in instrumentation. Digitalization and homogenization of the sufficient

number of data series for the WMO normal period and further from 1951 up to now led to the elaboration and publishing of a series of different works. Detailed studies on different climatic elements variability and trends in Slovakia continued in systematic way and gave the platform to a number of application works both in the field of climate change assessment as well as in Further to the publishing of climatic 30 years normal for temperature, humidity and precipitation two climate atlases were issued. Climate atlas of Slovakia filled out more than 50 years gap in producing atlas work of this kind and was created as a part of the development of technology of climate system data processing. The atlas itself was prepared in three blocks and represents a comprehensive cartographic work which consists of climatic maps supplemented by graphs and tables and is accompanied by explanatory texts. The first one is built as an interactive web based tool for general use. An interactive instrument for maps interpretation of selected climate parameters for the 50 years period 1961–2010. Second block is constructed by a composition of a series of maps of the particular parts of climatic system in scales from 1:5000000 to 1:1000000. The third block is done in the form of electronic book. Further atlas work is a part of wider project mapping both the abiotic and biotic natural component of the territory of Tatra Mmountains. It was prepared together with polish experts and it abiotic part was published by the Tatra National Park Agency.

Daily range temperature analysis and projection of scenarios in mountainous areas of Slovakia (*Damborska et.al., 2016*) revealed higher increase the minimum daily temperatures than maximum temperatures. The results showed that mainly variations in the regime of precipitation and air humidity can be used as factors of daily temperature range change. They will modify the air temperature daily range probably comparably as the increase of atmospheric greenhouse effect.

Wider assessments of selected climate parameters which included the territory of Slovakia were done based on the outputs of Carpatclim project realized in cooperation of nine countries and JRC. Climatologies and trends of 10 variables in Carpathien region were assessed.

Climatological work formed the basis for further evaluations and possible practical applications in adaptations to climate change in various sectors. The Seventh National Communication on Climate Change in Slovak Republic certified 2°C temperature increase in last 136 years as well as slight increase of annual areal precipitation totals with different trends in different regions



accompanied by 5% increase of potential evapotranspiration. This has brought the decrease of average annual reserve of available water and strong impacts of periods of drought and the necessity to arrange some adaptation strategies. One of the activities in this way was the introduction of drought monitoring system in Slovakia. It is based on three pillars when meteorological, soil and hydrological drought is assessed. Daily calculations of drought indices and parameters are interpreted in weekly maps and graphs and supplemented by subjective evaluation of drought. A network of more than 100 reporters giving their subjective evaluation of drought by using identical methodology, mostly farmers, is growing. The overall operational information on drought gives the opportunity for adaptation activities. The projections of severe drought in the lowlands of Slovakia showed further slight increase in frequency (*Nikolova et al., 2016*). Drought analysis in the mountain areas of Slovakia, *Vido et al. (2015)*, showed that frequency of drought occurrence has cyclic pattern with approximately 30-year period, and the spatial analyses showed that precipitation shadow of the mountains influences the risk of drought occurrence.

Three of several severe droughts which occurred in Europe in the 21<sup>st</sup> century hit also Slovakia (2003, 2012 and 2015). The Standardized Precipitation Index and Standardized Precipitation and Evapotranspiration Index were used for assessment of meteorological drought occurrence; factor and multiple regression analyses were employed to evaluate occurrence and parameters of hydrological drought in respective years, and the relationship among the water balance components. Results showed that drought parameters in evaluated river basins of Slovakia differed in respective years, most of the basins suffered more by 2003 and 2012 drought than by the 2015 one. Water balance components analysis for longer period (1931–2016) showed that because of continuously increasing air temperature and balanced evapotranspiration there is a decrease of runoff in the Slovak territory.

The assessment of the snow line and snow cover area in Slovak basins during 15 years period after 2000 showed a considerable variability in seasonal coverage between the years and periods with larger and smaller snow cover area but rather no significant trend in mean (*Krajci et al., 2015*).

Increasing temperatures are acting as a stress factor for plants and animals and they show their impact on the mortality of Slovak population. The number of tropical days in southern part of Slovakia more than doubled in recent sixty years. The study of long term changes of heat stress (*Svec et al.,*

2016) in the period 1951–2014 shows increasing and statistically significant trend of temperature stress factors accelerating since nineties and widening the period of its occurrence from the end of spring to the early autumn. Specific studies (Vyberci *et al.*, 2015; 2018) showed during the heat events, a non-negligible negative response in mortality. Fatal effects were more pronounced during particularly strong heat events and periods which lasted for two or more days. In general, females and the elderly were the most sensitive groups in the population and mortality was characterized by several specific effects in individual population groups. As there is a prediction for further heat waves rise some adaptation measures should be taken at least to minimize the heat wave impacts and to keep the quality of life.

First climatological observations in Bratislava established by a theologian, scholar and natural scientist Johann Felbiger were investigated and analysed by Melo *et al.* (2016); exceptionally cold winter seasons 1783–84 (as a whole) and 1784–85 (in March) were inferred from these observations. Melo also contributed to an analysis of the most damaging windstorm in nineteenth century and its impacts (and by Brazdil *et al.*, 2017) which hit Czech lands on 7 December 1868. Further to the loss of human lives and many other casualties, as well as to severe damage to buildings and other structures a huge damage was caused on timber (at least 8 million m<sup>3</sup>). The analysis showed that apart from wind forces the reason for this damage was also in increased vulnerability arising out of old, dense and mono-species conifer stands.

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#### 4. Climate change scenarios and impacts of climate change

First general circulation models (GCM) were used in Slovakia at the beginning of nineties. The centre of the activities was moved from Slovak Hydrometeorological Institute to Comenius University in Bratislava. They prepared various climate change scenarios the quality of which was step by step improved. The projections up to the end of the 21<sup>st</sup> century were built on the 1961–90 reference period. The last evaluation showed the series of scenarios as correct. Next use of Regional Circulation Models enabled to produce climatic data in the gridpoint scale with about 25×25 km resolution and further statistical downscaling method enables to prepare data as scenarios for selected locality/station with the projection for the 21<sup>st</sup> century. This has formed the basis for number application in theoretical field as well as in the field of practical applications regarding the adaptations to climate change.

Some of them focussed on the methods of snow cover change scenarios and snow cover trends after 2020. Lapin and Gera found noteworthy reduction of the snow cover in Slovak territory below 800 m a.s.l. while the elevations over 1200 m a.s.l. remained only with little changes. Two methods were prepared to estimate possible scenarios of snow cover development change in

Slovakia up to the end of the 21<sup>st</sup> century. One of them is based on the modified GCMs and RCMs outputs and the second one on the regression (analogue) estimation. By using GCMs (CGCM3.1 and ECHAM5) and RCMs (KNMI and MPI) outputs serious differences among altitudes below 500 m a.s.l., 500 to 1000 m a.s.l. and above 1000 m a.s.l. were found. It appeared that further to the temperature rise liquid precipitation in the lowlands during the winter play and important role in snow cover occurrence and its duration. The comparison of the prepared GCMs and RCMs outputs showed sufficient correspondence to 1951–2017 measured data. Further application of these methodics resulted in possible stable snow conditions over 1000 m a.s.l. while the elevation bellow, and, south slopes even close to this level, show remarkable decrease of snow cover.

Further application of similar concept was used to estimate possible changes in the flood regime in the mountainous regions of Slovakia (*Hlavcova et al., 2015*) and by using GCM ARPEGE in combination with the agroecological DAISY model to assess soil water availability in the future (*Zilinsky et al., 2018*).

The changes shifts in climate parameters bring further changes in the climate regionalization.

*Labudova et al. (2015)* pointed out on the trends in annual, seasonal and monthly air temperature and precipitation totals in Slovakia from 1931 to 2014 and showed the changes which will most probably appear in the next reference period 1991–2020. The results show that the WMO reference periods, 1931–60 and 1961–90, in the past did not show as big differences and sharp trends in between them as they already appear to come for the next one. Climate has become warmer and more arid in the southern part of the Slovak Carpathians, particularly in the adjacent lowlands, while the northern part has become rather warmer and more humid. Changes in the temperature and precipitation in both in the lowlands and mountainous areas result in the changes in climate sub-regions in Slovakia.

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## 5. Agrometeorology, Forestry and Phenology

The development of agrometeorology was in one way directed towards the climate services as described in Climate section in another hand it was oriented to investigate the relations in between the nature, mostly regarding the forestry. Big international effort, to which Slovak experts contributed, was put in identifying trends in the activities in drought research (*Trnka et al., 2018*). The list of 60 questions set and answered by a block of experts covered many aspects of drought and showed the effort to cover the known knowledge gap in this interdisciplinary field. Adaptation strategies for drought, building the integrated drought information structures and consequently drought plans appear the major points in building drought resilience systems. One of the crucial points in drought management identified by experts is the link in between the research community and the stakeholders.

Main component in drought management in the agriculture is irrigation. History and perspective of irrigation of arable land in Slovakia described by *Jurik et al. (2018)* gives a view on the development and decline periods of irrigation in the territory of Slovakia. After agriculture had been intensified after 2<sup>nd</sup> World War, irrigation became an important part of agricultural production. It was a long-term process, and only after 1960, organizations from designing to irrigation's operation were established. After 1990, the situation has changed, area under working irrigation systems has dropped more than four times and nowadays, the need for irrigation is to be resolving again. This point

is in the hands of particular ministries as in Slovakia, the manager and organizer of irrigation constructions have become, and still remains, the state. Irrigation measures of different plants are described by *Rehák et al. (2015)*.

Further to the standard climatological measurements many stations are equipped with the instruments for soil temperature and soil moisture recording. Biological measurements involve 203 phenological stations in a structured network observing plant development and some animals and insects. Data of this network are shared to the European database PEP725 (the successor of the COST Action 725) which is a project funded by Austrian Service for Meteorology and Geodynamics. This database is opened and universally available for the purpose of academic, research, educational, or other not-for-profit professional use. In parallel phenological observations are done at forestry biometeorological network of National Forest Centre. This database serves both for standard and special phenological evaluation.

The investigation of the effect of light pollution on tree phenology (*Škvareninová et al., 2017*) showed that the light pollution is 1–2 times higher during the cloudy weather and under high humidity in comparison to clear sky. Such condition caused delay of the onset of autumn vegetative phenological phases at crown parts of trees by 13 to 22 days and also prolonged these phenological phases. The impact of climatic conditions on the development, physiological response but also the opposite influence of disturbed and dieback spruce forest on rainfall interception snow cover were investigated by various authors (*Bartík et al., 2016, 2018; Mezei et al., 2017; Šustek et al. 2017; Vido et al., 2016*).

Occurrence of thaw–froze cycles along with the high intensity of photosynthetically active radiation were found as stress factors of this harsh environment for different microorganisms by *Hanzelová et al. (2018)*. Despite these facts this investigation confirms potential of Slovak high mountains as suitable place for life of snow microorganisms.

The consequences of large-scale disturbances magnified by climate extremes and land-use changes in Norway spruce forests in the Tatra Mountains (Slovakia) were assessed by *Fleischer et al. (2017)*. The driver-pressure-state-impact-response (DPSIR) framework was applied to evaluate how the ecosystem and its services are affected. The state of the ecosystem and its potential for provisioning ecosystem services before and after disturbances is expressed by a set of indicators derived mostly from long-term ecological research conducted within the investigated area. Ten years after the major

windthrow disturbance in 2004, all ecosystem services were still below the pre-disturbance state. The most pronounced declines were found in cultural and provisioning ecosystem services. Regulating services are recovering faster. Despite a gradual recovery of the ecosystem state and functioning, a serious risk of decline in forest ecosystem benefits according to regional climate change projections can be expected.

The involvement of Slovakia in COST Action ES1106 brought the assessment of water footprint towards the agricultural production at national scale forming a part of European assessment (*Kersebaum et al., 2016; Gobin et al., 2017*).

Some methodological research was dedicated to the impact of various density/destination of climatic data both measured and modeled on further investigation of tree-ring formation (*Sitko et al., 2016*) and to the application of IPCC methodology for greenhouse emissions inventory (*Mind'áš and Škvareninová, 2016*).

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## 6. Hydrometeorology in different aspects

Wide information on hydrology is given in the IAHAS report. Therefore this chapter involves only few activities either connected directly to meteorological evaluations or some special hydrological studies. Monitoring as well as the research works in the field of hydrology are done by quite of number institutes in Slovakia. Monitoring properties reached the current level after finishing the second phase of Flood Warning and Forecasting System project. Further to the enlargement of the number of automated precipitation and hydrological measurement points and higher level of automatization of data collection and quasi on line delivery to specialized data bases, four new meteorological radars were deployed over the territory of Slovakia which strongly contributes to flash flood information system.

Flash flood study by *Hlavčová et al. (2016)* brought the analysis estimating the rainfall-runoff relationships for 3 major flash flood events in Slovakia, which were among the most severe events since 1998 and caused a loss of lives and a large amount of damage.

An analysis of trends and causes of changes of selected hydroclimatic variables influencing the runoff regime in mountain catchments was done by *Blahušíaková and Matoušková (2015)*. Different methods for identifying trends in data series are evaluated by simple mass curve analysis, linear regression, frequency analysis of flood events, for two periods (1931–2010 and 1961–2010). The changes in runoff are significant, especially in terms of lower Q<sub>Max</sub> and 75 percentile values. This fact is also confirmed by the lower frequency and extremity of flood events. The 1980s are considered a turning point in the development of all hydroclimatic variables from when a significant decrease in runoff in the winter period is recognized. A considerable increase in air temperature, the decrease in snow cover depth and changes in seasonal distribution of precipitation amounts are among the main reasons of these changes.

Atmospheric chemistry is influenced differently depending on the circumstances of the particular region. Concentrations of sulphate, nitrate, ammonium, chloride, and base cations and pH of precipitation in the Tatra Mountains (central Europe) back to 1900 were modelled by *Kopáček et al. (201?)* using relationships between the composition of precipitation and emission rates of sulphur and nitrogen compounds and dust from 1978 to 2012. The modelled precipitation chemistry exhibited a high degree of temporal

coherence with the lake water chemistry in 1937 and during the period 1984–2014. Final results indicate that chemical recovery of mountain ecosystems is seriously modified by catchment biogeochemistry and may result not only in elevated dissolved organic carbon leaching but also in an increase of terrestrial export of total organic nitrogen and total phosphorus to the receiving surface waters.

Specific impact of climate change in mountain areas appeared in calcium and magnesium leaching to surface waters (*Holko et al., 2018*). Reverse trends of decreasing calcium and magnesium leaching to surface waters appeared in granitic alpine regions recovering from acidification. Despite decreasing concentrations of strong acid anions during investigated period (2004–2016) in nonacidic alpine lakes in the Tatra Mountains the average concentrations increased together with elevated terrestrial export of bicarbonate. The percentage increase in concentrations in nonacidic lakes was significantly and positively correlated with scree proportion in the catchment area and negatively correlated with the extent of soil cover. Leaching experiments showed that accessory calcite and (to a lesser extent) apatite were important sources of Ca. Different climatic effects on water chemistry are especially strong in catchments where fragmented rocks are more exposed to weathering, and their position is less stable than in soil.

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## **International Research/grant projects**

### **COST-ES1404**

-“A European network for a harmonised monitoring of snow for the benefit of climate change scenarios, hydrology and numerical weather prediction”. HARMOSNOW

2014-2018

The Action focused at the EU climatological community to recognize, compare, evaluate different methods being used in countries for measuring and interpreting the different snow data like snowing days, snow cover depth, water content of snow cover and some others physical data of snow cover.

SK participating Institutes: Earth Science Institute of Slovak Academy of Sciences, Slovak Hydrometeorological Institute, Technical University Zvolen, Slovak Agricultural University Nitra

### **-COST CA15226 Climate-Smart Forestry in Mountain Regions**

SK participating Institutes: Centre of excellence SPECTRA, Institute of Forest Ecology - Slovak Academy of Sciences

### **-FRENCH – SLOVAK Bilateral Project**

**Integrated geophysical modeling of the Carpatho-pannonian region assessment**  
20XX–20YY

SK participating Institutes: Comenius University Bratislava

- The European Aerosols, Clouds, and Trace gases Research Infrastructure (ACTRIS) for providing the calibration of the Cimel sunphotometer. Horizon 2020 research and innovation programme under grant agreement No 654109.

SK participating Institutes: Slovak Hydrometeorological Institute

**-ERASMUS+ „ECOIMPACT: Adaptive learning environment for competence in economic and societal impacts of local weather, air quality and climate,**

SK participating Institutes: University of Central Europe Skalica

**-ALADIN High Resolution Numerical Weather Prediction Project** (<http://www.umr-cnrm.fr/aladin/>)

SK participating Institutes: Slovak Hydrometeorological Institute

**-RC LACE Regional Cooperation for Limited Area modelling in Central Europe**

([www.rlace.eu](http://www.rlace.eu))

SK participating Institutes: Slovak Hydrometeorological Institute

**-DriDanube** (Drought Risk in the Danube Region), under the Danube Transnational Program (DTP), for Priority Area 2: Danube Region Responsible for Environment and Culture

Specific Objective: Improve Disaster Risk Preparedness

The overall objective of the project is to increase the adaptation capacity of the Danube region to climate variability by strengthening drought resilience with the use of newly created tools and data.

Specific goals are:

- New drought monitoring system - creation and implementation;
- Consolidation of risk and drought impact assessment methodologies prepared according to EU regulations and EU directives under the Civil Protection Mechanism;
- Improvement of drought risk management in the Danube region - preparation of the strategy

SK participating Institutes: Slovak Hydrometeorological Institute

## Defended PhD Theses

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Institution: Slovak University of Agriculture in Nitra

Title: Modeling the adaptative strategies to reduce the drought impacts in conditions of changing climate in utilized agricultural land

Student: Ing. Veronika Zuzulová, PhD.

Supervisor: prof. RNDr. Bernard Šiška, PhD.

Year of defense: 2017

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Institution: Comenius University in Bratislava

Title: Climatology of Fog in Coastal Desert Region and its Prediction by Model Based on Data Mining

Student: Ivana Bartoková

Supervisor: Prof. Milan Lapin, PhD.

Year of defense: 2016

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Institution: Technical university in Zvolen

Title: CO<sub>2</sub> fluxes in Norway spruce ecosystems after natural disturbances

Student: Dipl. Ing. Peter Fleischer

Supervisor: Assoc. Prof. Katarína Střelcová, PhD.

Year of defense: 2016

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Institution: Faculty of Forestry, Technical University in Zvolen,  
Title: Influence of forest decline on precipitation interception process in mountain spruce forest  
in West Tatra Mts.  
Student: Martin Bartík  
Supervisor: prof. Dr. Jaroslav Škvarenina  
Year of defense: 2015

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Institution: Faculty of Ecology and Environmental Science, Technical University in Zvolen, Slovakia  
Title: Microbial properties of snow cover in mountain area  
Student: Miriam Hanzelová  
Supervisor: prof. Dr. Jaroslav Škvarenina  
Year of defense: 2015

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Institution: Faculty of Forestry, Technical University in Zvolen,  
Title: The influence of forest growth and select component of the relief on snow water equivalent in river  
basin of Hučavy –BR Poľana  
Student: Tomáš Šatala  
Supervisor: prof. Dr. Jaroslav Škvarenina  
Year of defense: 2015

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Institution: Faculty of Forestry, Technical University in Zvolen,  
Title: Assessment of artificial (man-made) snow cover impact on vegetation changes in ski resorts and  
adjacent forests  
Student: Mikloš Michal  
Supervisor: prof. Dr. Jaroslav Škvarenina  
Year of defense: 2017

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Institution: Department of Fire Protection, Technical University in Zvolen,  
Title: Analysis of meteorological conditions of forest and landscape fires in Slovakia  
Student: Katarína Koristeková  
Supervisor: prof. Dr. Jaroslav Škvarenina  
Year of defense: 2018

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## Seismological and integrated geophysical research in Slovakia 2015–2018 (Report to IASPEI)

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### 1. Numerical modelling of seismic motion and seismic wave propagation

**A no-cost improved velocity-stress staggered-grid finite-difference scheme for modelling seismic wave propagation** (*Geophys. J. Int., Etemadsaeed, Moczo, Kristek, Ansari and Kristekova, 2016*)

We investigated the problem of finite-difference approximations of the velocity–stress formulation of the equation of motion and constitutive law on the staggered grid (SG) and collocated grid (CG). For approximating the first spatial and temporal derivatives, we used three approaches: Taylor expansion (TE), dispersion-relation preserving (DRP), and combined TE-DRP. The TE and DRP approaches represent two fundamental extremes. We derived useful formulae for DRP and TE-DRP approximations. We compared accuracy of the numerical wavenumbers and numerical frequencies of the basic TE, DRP and TE-DRP approximations. Based on the developed approximations, we constructed and numerically investigated 14 basic TE, DRP and TE-DRP finite-difference schemes on SG and CG. We found that (1) the TE second-order in

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time, TE fourth-order in space, 2-point in time, 4-point in space SG scheme (that is the standard (2,4) VS SG scheme, say TE-2-4-2-4-SG) is the best scheme (of the 14 investigated) for large fractions of the maximum possible time step, or, in other words, in a homogeneous medium; (2) the TE second-order in time, combined TE-DRP second-order in space, 2-point in time, 4-point in space SG scheme (say TE-DRP-2-2-2-4-SG) is the best scheme for small fractions of the maximum possible time step, or, in other words, in models with large velocity contrasts if uniform spatial grid spacing and time step are used. The practical conclusion is that in computer codes based on standard TE-2-4-2-4-SG, it is enough to redefine the values of the approximation coefficients by those of TE-DRP-2-2-2-4-SG for increasing accuracy of modelling in models with large velocity contrast between rock and sediments.

### **An orthorhombic representation of a heterogeneous medium for the finite-difference modelling of seismic wave propagation**

*(Geophys. J. Int., Etemadsaeed, Kristek, Moczo Chaljub and Kristekova, 2017)*

The possibility of applying one explicit finite-difference scheme to all interior grid points (points not lying on a grid border) no matter what their positions are with respect to the material interface is one of the key factors of the computational efficiency of the finite-difference modelling. Smooth or discontinuous heterogeneity of the medium is accounted for only by values of the effective grid moduli and densities. Accuracy of modelling thus very much depends on how these effective grid parameters are evaluated. We have developed a new orthorhombic representation of a heterogeneous medium for the finite-difference modelling. We numerically demonstrate its superior accuracy. Compared to the harmonic-averaging representation the orthorhombic representation is more accurate mainly in the case of strong surface waves that are especially important in local surface sedimentary basins. The orthorhombic representation is applicable to modelling seismic wave propagation and earthquake motion in isotropic models with material interfaces and smooth heterogeneities using velocity-stress, displacement-stress and displacement FD schemes on staggered, partly-staggered, Lebedev and collocated grids.

### **On the initiation of sustained slip-weakening ruptures by localized stresses**

*(Geophys. J. Int., Galis, Pelties, Kristek, Moczo, Ampuero and Mai, 2015)*



We investigated conditions for efficient initiation of dynamic ruptures in numerical simulations. For a fixed overstress we found that the initiation is controlled by area of asperity. We developed two new estimates of critical parameters of the asperity for low background stress, which are in excellent agreement with numerical results. Overall, we provide guidelines for optimal initiation of ruptures with minimized undesired numerical effects on the subsequent spontaneous rupture propagation.

**3D numerical simulation and ground motion prediction: Verification, validation and beyond – Lessons from the E2VP project** (*Soil Dyn. and Earth. Eng., Maufroy, Chaljub, Hollender, Bard, Kristek, Moczo, De Martin, Theodoulidis, Manakou, Guyonnet-Benaize, Hollard and Pitilakis, 2016*)

The goals of the EUROSEISTEST Verification and Validation Project (E2VP) were to provide (1) a quantitative analysis of accuracy of the current, most advanced numerical methods applied to realistic 3D models of sedimentary basins (verification) and (2) a quantitative comparison of the recorded ground motions with their numerical predictions (validation). Whereas E2VP phase 1 was focused on detailed comparative verification (*Chaljub et al., 2015*), E2VP phase 2 was focused on validation (*Maufroy et al., 2015*). In both phases the target site was the Mygdonian basin near Thessaloniki, Greece.

The validation phase, based on simulations up to 4 Hz (that is beyond the fundamental frequency 0.7 Hz and covering a frequency range at which EGM is significantly amplified) led, besides other findings, to the following lessons:

- The discrete representation of material heterogeneities, the attenuation model, the approximation of the free surface, and nonreflecting boundaries were identified as the main sources of differences among the numerical predictions.
- The numerical predictions well reproduce some, but not all, features of the actual site effect. The differences between real and predicted ground motions have multiple reasons:
  - the accuracy of source parameters (location, hypocentral depth, and focal mechanism)
  - the uncertainties in the description of the geological medium (attenuation, internal sediment layering structure, and shape of the sediment-basement interface)
- Overall, the agreement reached among synthetics up to 4 Hz despite the complexity of the basin model, with code-to-code differences much smaller

than predictions-to-observations differences, makes it possible to include the numerical simulations in site-specific analysis in the 3D linear case and low-to-intermediate frequency range.

- Similar analyses for other sites are required to indicate whether such observations can be generalized or are specific to the considered site.
- In a deterministic EGM prediction (assuming a scenario earthquake) the uncertainties due to source parameters should be left aside, and only those linked to the wave propagation and site models should be considered. However, for sources of finite extent, an additional cause of variability should be taken into account as the detailed rupture kinematics cannot be deterministically predicted.
- In a probabilistic approach, the use of numerical modelling should focus more on determination of the site amplification – not on extensive modelling with a wide range of source parameters (location and magnitude).
- Consequently, whatever the approach, the main focus is the determination of the site amplification.

**Adjoint Tomography for Predicting Earthquake Ground Motion: Methodology and a Blind Test** (*Bull. Seism. Soc. Am., Kubina, Michlik, Moczo, Kristek and Stripajová, 2018*)

In recent international exercises on numerical prediction of earthquake ground motion (EGM) in local surface sedimentary structures (LSSS), teams with the most advanced numerical-modelling methods reached a very good level of agreement among different methods. The synthetics, however, were not sufficiently close to earthquake records. It was concluded that the structural model must be improved. Here, we applied adjoint tomography to 2D LSSS, aiming to find a model for which EGM characteristics will be sufficiently close to those determined from records. This is an important difference compared to traditional structural inversions. The methodology developed in the exploration, regional, and global scales cannot be directly applied, due to a relatively small amount of data, a relatively large initial waveform misfit, and low frequencies with respect to the size of the structure. We elaborated an inversion procedure specific for the local structures. We presented a verification blind test that is closer to real-data inversion than the standard synthetic inversions. A third party provided (a) seismograms numerically simulated for an undisclosed true structure, (b) source parameters, and (c) a homogeneous half-space as the initial model. We demonstrated the quality of

the inverted model up to the 4.5 Hz target frequency, using seismograms, waveform misfits, waveform goodness of fit (GOF), and mainly GOF for important EGM characteristics. The development of the 2D procedure, requiring much less computational load compared to the 3D procedure, is the first step. We assume that the procedure can be, in principle, applied to 3D structures after refinements, due to a 3D spatial distribution of sources and receivers.

**Computation of Amplification Factor of Earthquake Ground Motion for a Local Sedimentary Structure** (*Bull. Earthquake Eng., Kristek, Moczo, Bard, Hollender and Stripajova, 2018*)

**Key structural parameters affecting earthquake ground motion in 2D and 3D sedimentary structures** (*Bull. Earthquake Eng., Moczo, Kristek, Bard, Stripajova, Hollender, Chovanova, Kristekova and Sicilia, 2018*)

Alluvial valleys generate strong effects on earthquake ground motion (EGM). These effects are rarely accounted for even in site-specific studies because of (a) the cost of the required geophysical surveys to constrain the site model, (b) lack of data for empirical prediction, and (c) poor knowledge of the key controlling parameters. We performed 3D, 2D and 1D simulations for six typical sedimentary valleys of various width and depth, and for a variety of modifications of these 6 “nominal models” to investigate sensitivity of EGM characteristics to impedance contrast, attenuation, velocity gradient and geometry. We calculated amplification factors, and 2D/1D and 3D/2D aggravation factors for 10 EGM characteristics, using a representative set of recorded accelerograms to account for input motion variability (The methodology is presented in the first article). For all investigated sites, there is always an area in the valley for which 1D estimates are not sufficient. 2D estimates are insufficient at several sites. The identified key structural parameters are the shape ratio and overall geometry of the sediment-bedrock interface, impedance contrast at the sediment-bedrock interface, and attenuation in sediments. We showed that the amplification factors may largely exceed the values that are usually considered in GMPEs between soft soils and rock sites.

**Mach wave properties in the presence of source and medium heterogeneity** (*Geophys. J. Int., Vyas, Mai, Galis, Dunham and Imperatori, 2018*)

We investigated Mach wave coherence for kinematic supershear ruptures with spatially heterogeneous source parameters, embedded in 3-D scattering media.

We assessed Mach wave coherence considering: (1) source heterogeneities (variations of slip, rise time and rupture speed); (2) small-scale heterogeneities in Earth structure (variations of medium parameters, parametrized using von Karman power spectral density function); and (3) joint effects of source and medium heterogeneities. We found that Mach wave coherence is slightly diminished at near-fault distances (<10 km) due to source heterogeneity and at larger distances the effects of small-scale heterogeneities in the medium is stronger. Our results for combined effects of heterogeneous source and small-scale heterogeneities in the medium indicate that the levels of peak-ground accelerations due to supershear ruptures are not significantly larger than estimates from GMPEs, suggesting that local supershear ruptures may be more common in nature than reported but are not easily detectable.

## 2. Seismic hazard analysis of the Slovak territory

**A seismic source zone model for the seismic hazard assessment of Slovakia** (*Geologica Carpathica, Hok, Kysel, Kovac, Moczo, Kristek, Kristekova and Sujan, 2016*)

We developed a new seismic source zone model for the seismic hazard assessment of Slovakia based on a new seismotectonic model of the territory of Slovakia and adjacent areas. The seismotectonic model has been developed using a new Slovak earthquake catalogue (SLOVEC 2011), successive division of the large-scale geological structures into tectonic regions, seismogeological domains and seismogenic structures. The main criteria for definitions of regions, domains and structures were the age of the last tectonic consolidation of geological structures, thickness of lithosphere, thickness of crust, geothermal conditions, current tectonic regime and seismic activity. The seismic source zones are presented on a 1:1,000,000 scale map.

## 3. Analysis of earthquakes and explosions

**Compromising polarity and waveform constraints in focal-mechanism solutions; the Mara Rosa 2010 Mw 4 central Brazil earthquake revisited** (*Journal of South American Earth Sciences, Zahradnik, Fojtikova, Carvalho, Barros, Sokos and Jansky, 2015*)

Focal-mechanism determination of weak events recorded in sparse networks is challenging. First-motion polarities are often available at relatively distant stations, and waveforms only at a few near stations can be modeled. A two-step approach of how to combine such data has been suggested recently (Cyclic Scanning of the Polarity Solutions, or CSPS method; *Fojtiková and Zahradník, 2014*). It starts with creating a suite of first-motion polarity solutions, which is often highly non-unique. The next step consists of repeating full waveform inversion for all polarity solutions. Even few stations may efficiently reduce the non-uniqueness of the polarity solutions. Centroid depth, time, scalar moment and uncertainty estimate of the well-fitting double-couple solutions are obtained. The CSPS method has been extended in this paper by adding a new feature, i.e. repeated inversions using multiple first-motion polarity sets. The polarity sets are created by projecting the stations on focal sphere in several available velocity models, thus accounting for the takeoff angle uncertainty. The multiple polarity sets provide assessment of the CSPS solution stability. These ideas are demonstrated on a comprehensive analysis of a rare event in central Brazil. It is the  $M_w \sim 4$  mainshock of the Mara Rosa 2010 earthquake sequence (*Barros et al., 2015; Carvalho et al., 2016*). We employ polarities at 11 stations (distances  $< 730$  km) and invert full waveforms at two stations (CAN3 and BDFB at distances  $\sim 120$  and  $240$  km), for  $0.1\text{--}0.2$  and  $0.05\text{--}0.125$  Hz, respectively. Six polarity sets reflect the takeoff angle uncertainty. The obtained CSPS results are very stable across all the polarity sets (in terms of depth,  $M_w$ , and strike/dip/rake angles). It is found that the Mara Rosa mainshock mechanism deviated from the composite solution of the whole sequence by  $38^\circ$ . The paper also includes a test simulating situations at which just a single waveform is used, and how it negatively affects the solution stability.

**Quantifying capability of a local seismic network in terms of locations and focal mechanism solutions of weak earthquake** (*Journal of Seismology, Fojtikova, Kristekova, Malek, Sokos, Csicsay and Zahradnik, 2016*)

We suggested the combination of suitable methods (including the new one) for quantification of accuracy of earthquake location and determination of focal mechanisms for a given area and seismic station configuration. We also developed the free software. Our analysis was applied to the Malé Karpaty local seismic network (Slovakia). This network enables seismic monitoring of the source zone in the vicinity of a nuclear power plant, important from the

point of seismic hazard. Obtained results clearly demonstrate that suggested network extension remarkably decreases the errors of earthquake location and focal mechanism determination and improves seismic monitoring of the area. The results can also serve as a basis for decision making process when considering financial support of the network extension.

**Tectonic stress regime in the 2003–2004 and 2012–2015 earthquake swarms in the Ubaye Valley, French Alps** (*Pure and Applied Geophysics, Fojtikova and Vavryčuk, 2018*)

We study two earthquake swarms that occurred in the Ubaye Valley, French Alps within the past decade: the 2003–2004 earthquake swarm with the strongest shock of magnitude  $ML = 2.7$ , and the 2012–2015 earthquake swarm with the strongest shock of magnitude  $ML = 4.8$ . The 2003–2004 seismic activity clustered along a 9-km-long rupture zone at depth between 3 and 8 km. The 2012–2015 activity occurred a few kilometres to the northwest from the previous one. We applied the iterative joint inversion for stress and fault orientations developed by Vavryčuk (2014) to focal mechanisms of 74 events of the 2003–2004 swarm and of 13 strongest events of the 2012–2015 swarm. The retrieved stress regime is consistent for both seismic activities. The  $\sigma_3$  principal axis is nearly horizontal with azimuth of  $\sim 103^\circ$ . The  $\sigma_1$  and  $\sigma_2$  principal axes are inclined and their stress magnitudes are similar. The active faults are optimally oriented for shear faulting with respect to tectonic stress and differ from major fault systems known from geological mapping in the region. The estimated low value of friction coefficient at the faults 0.2–0.3 supports an idea of seismic activity triggered or strongly affected by presence of fluids.

#### 4. The monitoring of earthquakes

**A Local Magnitude Scale for Slovakia, Central Europe** (*Bull. Seism. Soc. Am., Chovanová and Kristek, 2018*)

Each country or region should have its own formula for estimating a local magnitude of local earthquakes which consistently reflects the seismic attenuation behaviour of the region. Until now, the Hutton and Boore (1987) scale derived for Southern California was used for local magnitude estimation in Slovakia because of similar attenuation properties of the regions. We have determined the distance correction term and the attenuation term of the local

magnitude scale from collected trace amplitudes of earthquakes recorded by the National Network of Seismic Stations (NNSS) from 2005 to 2016 using linear regression analysis. Additionally, the station corrections for the nine seismic stations of NNSS have been estimated for the first time. Using the newly determined scale reduces error by up to 58% compared to the formula previously used. Since both local magnitude formula and ground motion prediction equation (GMPE) are attenuation relationships, their similarity can be used in seismic hazard analysis

### **Networks of seismic stations**

The Earth Science Institute of Slovak Academy of Sciences (ESI SAS) operates the National Network of Seismic Stations (NNSS) and analyses instrumental and macroseismic data from earthquakes. The seismic stations of NNSS are deployed with the intention to determine seismic source zones on the Slovak territory more precisely and to allow to record and localize any earthquake on the territory of Slovakia and adjacent region with possible macroseismic effects. Map with locations of the NNSS seismic stations is shown in Fig. 1.

The Faculty of Mathematics, Physics and Informatics, Comenius University in Bratislava (FMPI UK) operates the Local Seismic Network Eastern Slovakia (LSNES) since 2007 and analyses instrumental data for the eastern part of Slovakia. The seismic stations of LSNES are deployed with intention to better monitor and understand the seismic regime of this region. Locations of the LSNES seismic stations are also shown in Fig. 1.

Besides the two seismic networks operated by research institutions, there are two local seismic networks on the territory of Slovakia operated by company Progseis, s.r.o.. Seismic stations of these networks are deployed around two nuclear power plants Jaslovské Bohunice and Mochovce (Fig. 1) with intention to monitor in detail local seismic microactivity.

Four additional seismic stations were established for more detailed monitoring of the Malé Karpaty source zone. These stations have been built and are operated in cooperation of ESI SAS, Progseis, s.r.o. and Institute of Rock Structure and Mechanics ASCR (Czech Republic) and are marked in the Fig. 1 by a yellow triangle in red square.

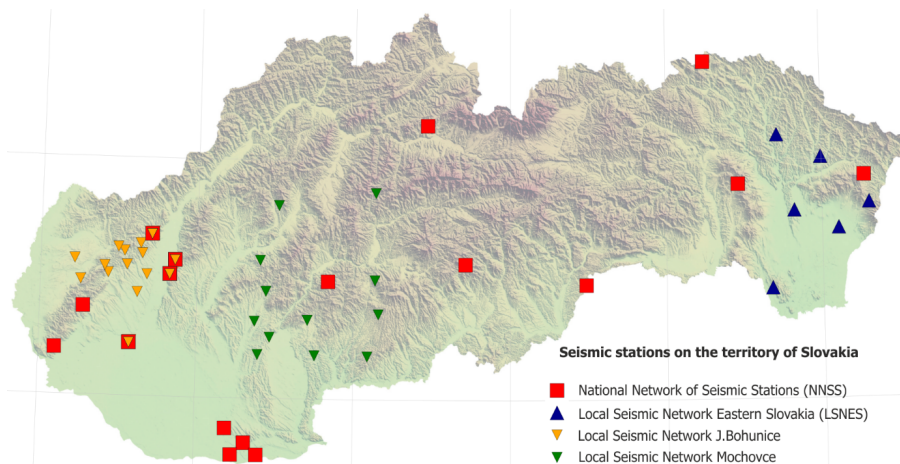


Fig. 1. The seismic stations on the territory of Slovakia.

## Data collection, processing and analysis

The data and the interpretation centers of the national network and of the local network Eastern Slovakia are located in the ESI SAS, Bratislava or in the FMPI UK, Bratislava, respectively. Both data centres are created in the mirror way, equipped with the similar software and functional features. The data centre collects waveforms from all stations of NNSS and LSNES and from selected seismic stations of some other institutions mainly from Central European countries. Data are collected in real time using the SeisComp/SeedLink (*Hanka et al., 2000; Van Eck et al., 2004; Hanka and Saul, 2006*) or SEMS SeedLink software, respectively. The miniSeed format is used for both data collection and data exchange. In total, data from 55 seismic stations are collected in real-time which create Regional Virtual Seismic Network in the ESI SAS (Fig. 2). More information about NNSS and live seismograms from the seismic stations of NNSS are available at <http://ww.seismology.sk> web page. Live seismograms from NNSS seismic stations for 2 days (actual and previous one) are available for public. There is also information about earthquake activity for recent 2 months (earthquakes with epicentre on the territory of Slovakia) available for public at the web page <http://ww.seismology.sk>. Similarly, more information about LSNES can be found at web page [http://www.fyzikazeme.sk/mainpage/index\\_en.htm](http://www.fyzikazeme.sk/mainpage/index_en.htm).



Seismic waveforms are exchanged with all institutions that supply data to the data center in Bratislava. In addition, the seismic waveforms are sent also to the Orfeus Data Center, De Bilt, Netherlands.

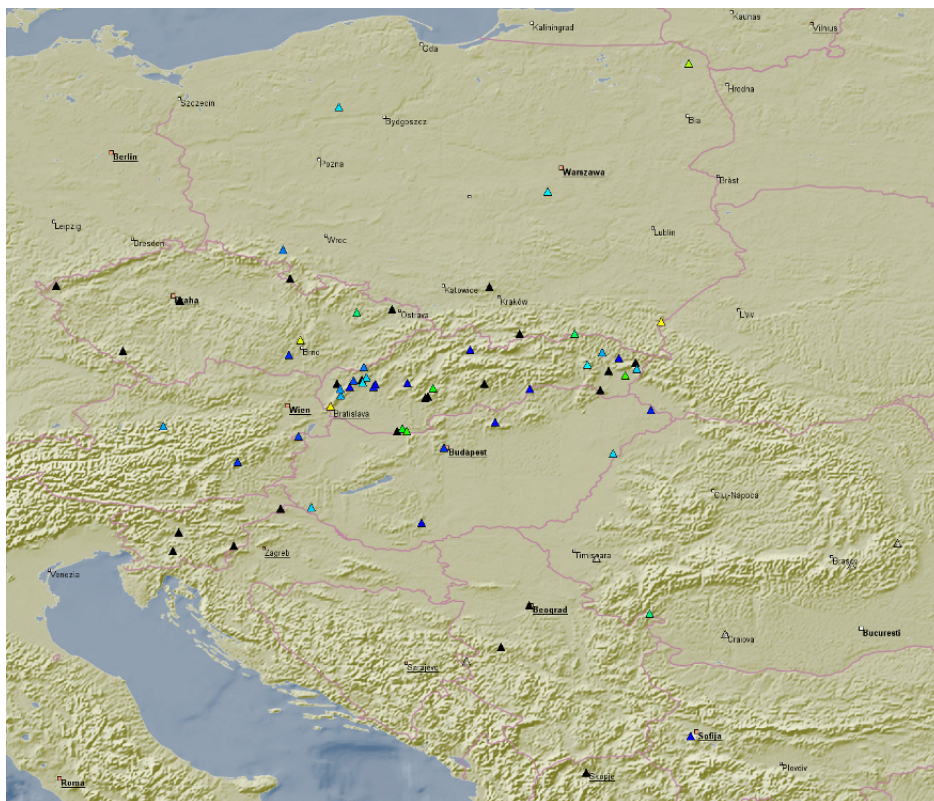


Fig. 2. Virtual Regional Seismic Network in the ESI SAS, Bratislava.

A two-step analysis of seismic events is performed - automatic and manual.

In the first step the automatic analysis and localization is performed in real time by acquisition software SeisComp GFZ Potsdam (*Hanka and Saul, 2006*).

In the second step the manual analysis and localization is performed on daily basis (work days only, weekends and holidays only in emergency cases) using the Seismic Handler package since October 2003 (*Stammler, 1993*). The results of waveform interpretation and earthquake localization are stored in a

database which is in operation since 1996. Fig. 3 shows an example of the macroseismically felt local event interpretation for the August 17, 2018 with estimated  $M_L = 2.9$  and epicentral intensity  $I_0 = 4^\circ$  EMS-98 from Strážovske vrchy, Slovakia.

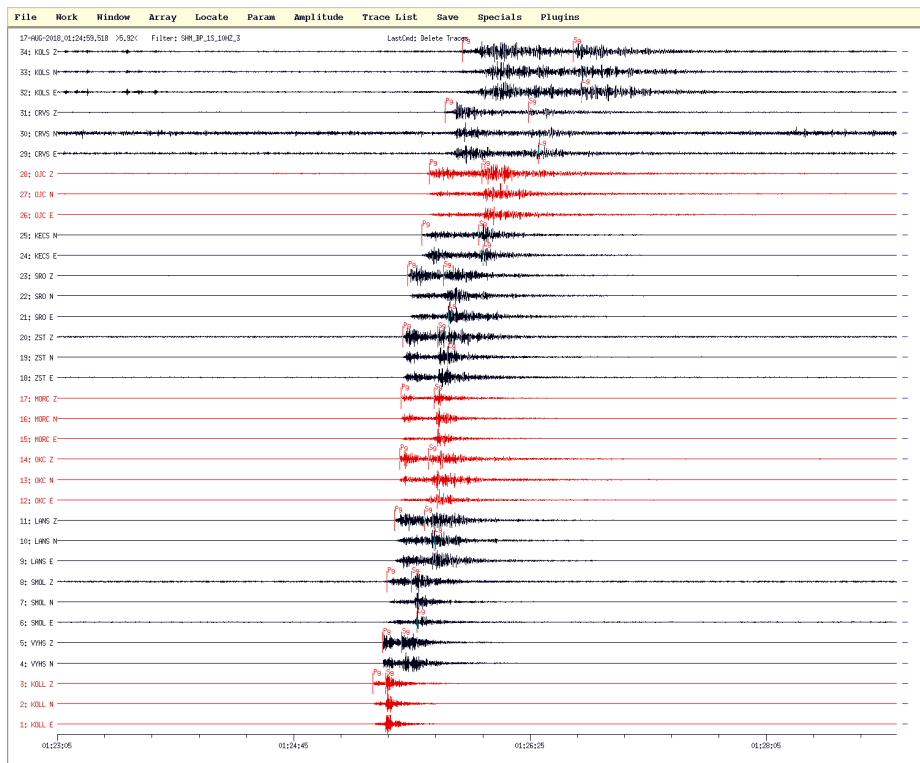


Fig. 3. An example of a manual local event interpretation using the Seismic Handler package. Displayed traces are from the Virtual Regional Seismic Network in the ESI SAS Bratislava for the August 17, 2018,  $M_L = 2.9$  local earthquake from Strážovske vrchy, Slovakia.

Besides seismometric data, the ESI SAS collects and analyses macroseismic data. In case of an earthquake with possible macroseismic effects on the territory of Slovakia, the ESI SAS issues public information and request for people to contact the institute if they observed macroseismic effects of the earthquake. Then macroseismic questionnaires are sent to people or people can

download them from the <http://www.seismology.sk> web page or directly fill in questionnaires on the web. If there is a possibility of exceeding intensity 6<sup>0</sup> EMS-98 in some localities, an on-site macroseismic survey is performed. Macroseismic intensity is then estimated for each locality using available macroseismic observations. The macroseismic intensity is estimated in degrees of a macroseismic scale EMS 98 (*Grünthal, ed., 1998*).

### Seismic activity on the territory of Slovakia in the period 2015–2018

The seismic activity on the territory of Slovakia for the period 2011–2018 is briefly characterized in Tab. 1 and illustrated in Fig. 4a,b.

Table 1. Seismic activity on the territory of Slovakia in the period 2015–2018.

Year	Microearthquakes	Macroseismically observed earthquakes (epicentre in SK)	Macroseismically observed earthquakes (epicentre outside SK)
2015	64	5	4
2016	86	1	1
2017	68	5	0
2018	80	4	1

Using data from the seismic stations of NNSS and LSSVS, 218 local earthquakes without macroseismic observations (microearthquakes) were localized with epicentre on the territory of Slovakia in the years 2015–2018. Seismic activity for the year 2018 is in the process of final reinterpretation and we can assume about 80 localized microearthquakes with epicenter on the territory of Slovakia. Microearthquakes occurred in all known Slovak seismic source zones.

During the period 2015–2018, 21 earthquakes were macroseismically observed on the territory of Slovakia. All macroseismically observed earthquakes were seismometrically localized. Epicentres of macroseismically observed earthquakes occurred in following parts of Slovakia: Záhorie (1 earthquake), Malé Karpaty source zone (1 earthquake), Komárno source zone (2 earthquakes), Strážovské vrchy (1 earthquake), Žilina area (3 earthquakes), Central Slovakia - app. Banská Bystrica-Horehronie area (5 earthquakes) and

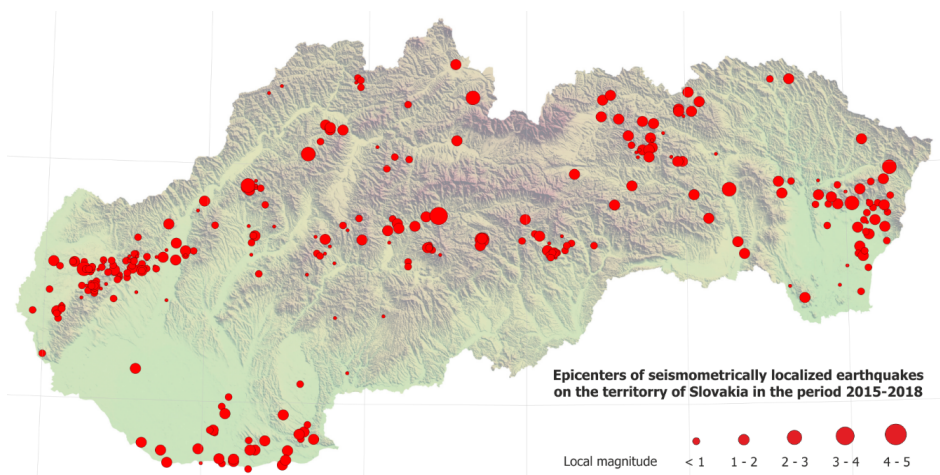


Fig. 4a. Epicenters of seismometrically localized earthquakes on the territory of Slovakia in 2015–2018. (Only preliminary results are shown here for year 2018.)

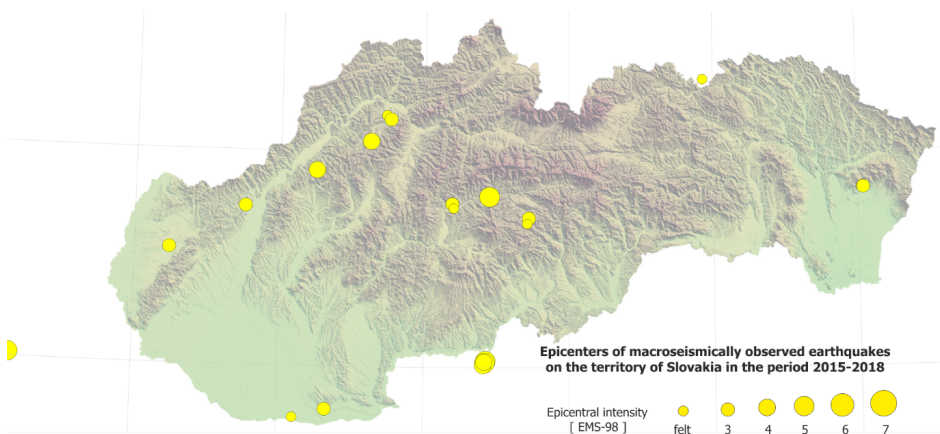


Fig. 4b. Epicenters of macroseismically observed earthquakes on the territory of Slovakia in 2015–2018.

Eastern Slovakia - Vihorlat (2 earthquakes). Except these earthquakes, several earthquakes with epicenters in neighboring countries were macroseismically observed on the territory of Slovakia too: Austria (1 earthquake), Poland (1 earthquake) and Hungary (4 earthquakes). As for macroseismically observed earthquakes point of view, the most active area in the period 2015–2018 was

Central Slovakia, app. area of Banská Bystrica-Horehronie, were 5 earthquakes with macroseismic observations occurred.

The highest reported macroseismic intensity in the period 2015–2018 was 5–6° EMS 98 for the earthquake with epicentre in Central Slovakia, the Horehronie region (3.11.2015). The ESI SAS has 556 macroseismic observations from 77 localities on the territory of Slovakia for this earthquake.

## 5. Integrated geophysical study of the continental lithosphere

### Determination of rock densities

The quantitative interpretation of gravity anomalies depends not only on the quality of methods for solution of direct and inverse gravimetric problems but significantly also on the knowledge of the rock densities. In general, the density modelling of the uppermost layer of the Earth's crust, down to a depth of about 5 km is based on current geological knowledge, borehole data, geophysical observations, which can be considered relatively reliable. For deeper parts of the crust and lithosphere it is necessary to apply other approaches. If we have information available about the velocities of the seismic waves in the crust and/or lithosphere then the best approach to defining the most real densities is to use the suitable formulae for transformation of the in situ seismic velocities to the in situ densities.

Therefore, in the paper of Šimonová and Bielik (2016) the seismic data obtained by the international project CELEBRATION 2000 were used for transformations of in situ P-wave velocities to in situ densities along all profiles running across the Western Carpathians and the Pannonian Basin: CEL01, CEL04, CEL05, CEL06, CEL09, CEL11 and CEL12. The calculation of rock densities in the crust and lower lithosphere was done by the transformation of seismic velocities to densities using the formulae of Sobolev-Babeyko (Sobolev and Babeyko, 1994), Christensen-Mooney (Christensen and Mooney, 1995) and in the lower lithosphere also by Lachenbruch-Morgan's formula (Lachenbruch and Morgan, 1990).

The density of the upper crust changes significantly in the vertical and horizontal directions, while the interval ranges of the calculated lower crust densities narrow down prominently. The lower lithosphere is the most homogeneous – the intervals of the calculated densities for this layer are

already very narrow. The average density of the upper crust ( $\rho = 2.60 \text{ g cm}^{-3}$ ) is the lowest in the Carpathian Foredeep region. On the contrary, the highest density of this layer ( $\rho = 2.77 \text{ g cm}^{-3}$ ) is located in the Bohemian Massif. The average densities  $\rho$  of the lower crust vary between  $2.90$  and  $2.98 \text{ g cm}^{-3}$ . The Palaeozoic Platform and the East European Craton have the highest density ( $\rho = 2.98 \text{ g cm}^{-3}$  and  $\rho = 2.97 \text{ g cm}^{-3}$ , respectively). The lower crust density is the lowest ( $\rho = 2.90 \text{ g cm}^{-3}$ ) in the Pannonian Basin. The range of calculated average densities  $\rho$  for the lower lithosphere is changed in the interval from  $3.35$  to  $3.40 \text{ g cm}^{-3}$ . The heaviest lower lithosphere can be observed in the East European Craton ( $\rho = 3.40 \text{ g cm}^{-3}$ ). The lower lithosphere of the Transdanubian Range and the Palaeozoic Platform is characterized by the lowest density  $\rho = 3.35 \text{ g cm}^{-3}$ .

### Study of the basin basement

The geology and hydrogeology of the Liptovská Kotlina Depression (Fig. 5) were studied by means of new geophysical methods (*Fendek, Grand, Daniel,*

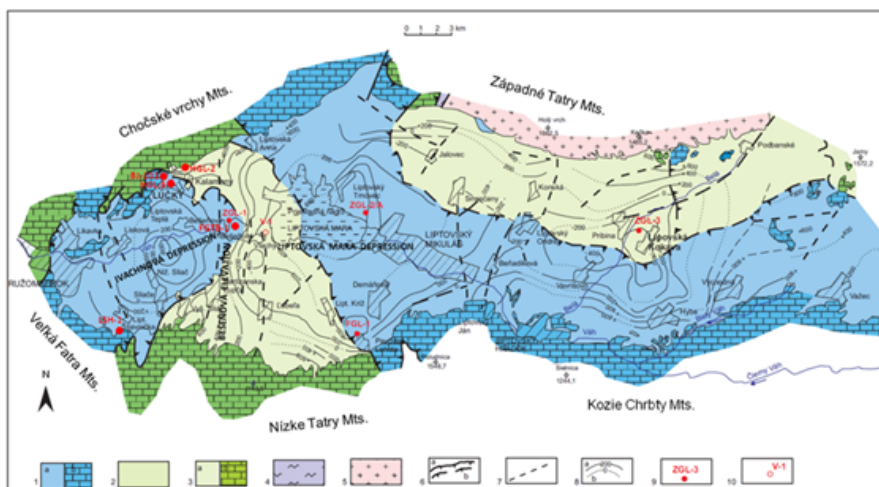


Fig. 5. Geological conditions and location of objects of interest in the Liptovská Kotlina Basin. Explanation: 1 – Choč Nappe (a – bedrock, b – on the surface), 2, 3a – Križna nappe (bedrock), 3b – Križna Nappe on the surface, 4 – Envelope Unit, 5 – Crystalline, 6 – overthrust line (a – proved, b – assumed), 7 – Faults (assumed), 8 – isolines of the Palaeogene bottom in m a.s.l. (a – proved, b – assumed), 9 – geothermal borehole, 10 – oil borehole.

*Blanárová, Kultán and Bielik, 2017*). Controlled source audio-frequency magnetotellurics enabled us to delineate the relief of the pre-Cainozoic basement in the western part of the Liptovská Kotlina Depression into two segments with different lithostratigraphic units. Our complex findings disprove the interconnection between the Bešeňová and Lúčky water bearing structures located in the study area. The geophysical surveys were carried out along the profile PF1 (Fig. 6).

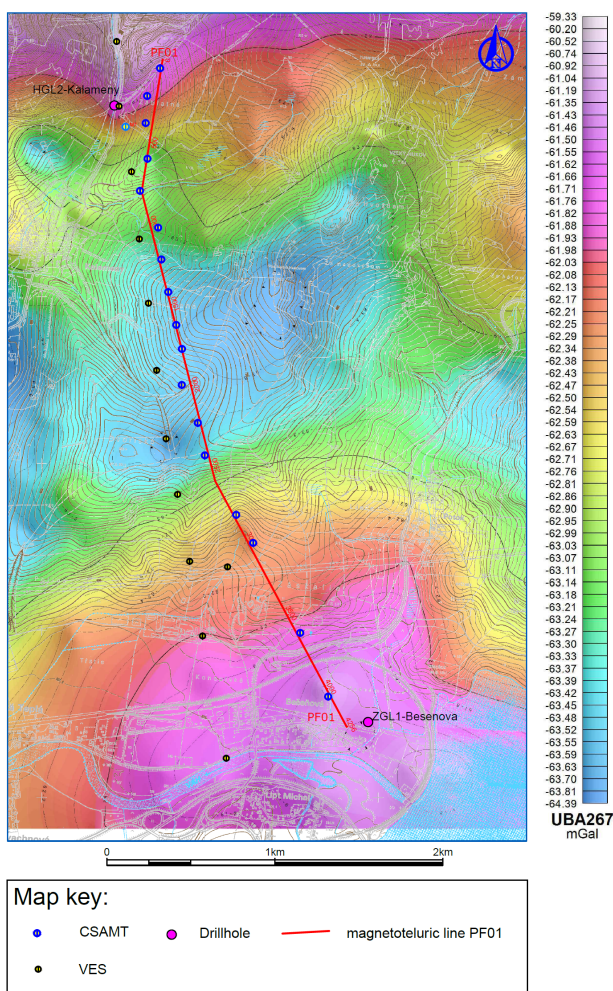


Fig. 6. Location of geophysical surveys imposed on Bouguer anomaly gravity map.

The geological interpretation of the obtained results, taking into account the other geophysical and geological constrains showed that the pre-Cainozoic basement has a tectonically disrupted, broken relief. The Bešeňová and Lúčky structures appear to be isolated by the Palaeogene sediments (sandstone, claystone) and in the deeper part also by marly carbonates and marlstones of the Jurassic age belonging to the Fatricum. It was confirmed that the structural connectivity of geothermal aquifers in the area between the Bešeňová and Lúčky–Kaňameny should not exist (Fig. 7). The assumption of different circulation depth was also confirmed by geothermometry and existing radiocarbon analyses applied on groundwater in both areas.+

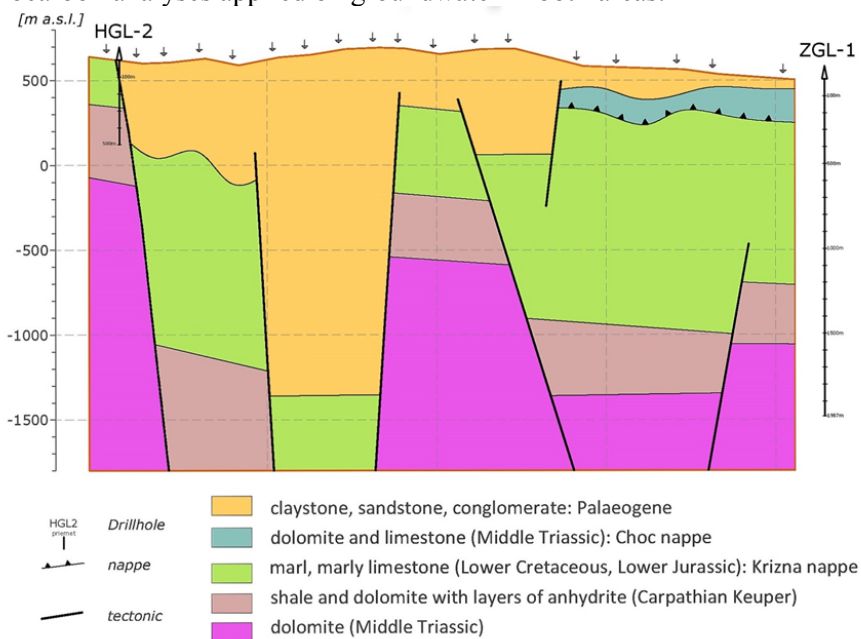


Fig. 7. Integrated geologic-geophysical interpretation – geological section.

### Seismic models and its geological implications

Brixová, Mojzeš, Pašiaková, Zubalová, Bartošová and Bielik (2016) present the results of velocity analysis performed in the Nesvačilka and Vranovice troughs. The troughs extend in the south-eastern part of the Bohemian Massif (the



Moravian Block). As both belong to the most promising areas of the Bohemian Massif in the search for and production of hydrocarbons, their geological and geophysical survey is very important. Therefore, one of the key points is to determine the accurate data on the depth of the significant geological and stratigraphic units, which form the Nesvačilka and the Vranovice troughs. For this purpose the velocity analysis and the application of synthetic seismograms have been defined and applied. The results indicate that the lithostratigraphic units of the studied region are characterized by a large velocity interval. Based on the data from well log measurements (check shots) and synthetic seismograms the following velocities of seismic waves were determined in single lithostratigraphic units: 2.4–3.3 km/s in sediments of Flysch nappes, 2.7–3.6 km/s in the Palaeogene sediments, 3.3–4.3 km/s in the Jurassic sediments (3.7–5.1 km/s in carbonates and 3.5–4.8 km/s in pelites and conglomerates), 4–5.4 km/s in the Carboniferous sediments, and 4.6–6.6 km/s in the Devonian carbonates. Moreover, the synthetic seismograms and check shot results point to significant velocity interfaces. We discovered that: (a) within the sediments of Flysch nappes velocities in Menilitic Formation are higher than in the Submenilitic and the Ždánice-Hustopeče formations, (b) interface sediment of the Flysch nappes and Palaeogene deposits is characterized by a decrease of velocity, and (c) big contrast of velocity reflects the boundary between the carbonates (the Devonian and the Jurassic) and their surrounding rocks. The velocity analysis helps significantly for mapping of the Outer Carpathian Flysch nappes (the Pouzdřany Unit and especially the Ždánice Unit), the Neogene deposits, the Palaeogene deposits and the Devonian carbonates. All the knowledge we obtained has been used in detailed mapping and assessment of potential and confirmed hydrocarbon deposits in the studied area.

### **Density and magnetic modelling**

The position of the Gemic Superunit within the Western Carpathians is unique due to the occurrence of the Lower Palaeozoic basement rocks together with the autochthonous Upper Palaeozoic cover. The Gemic granites play one of the most important roles in the framework of the tectonic evolution of this mountain range. They can be observed in several small intrusions outcropping in the western and south-eastern parts of the Gemic Superunit (Fig. 8). Moreover, these granites are particularly interesting in terms of their mineralogy, petrology and ages. The comprehensive geological and geophysical

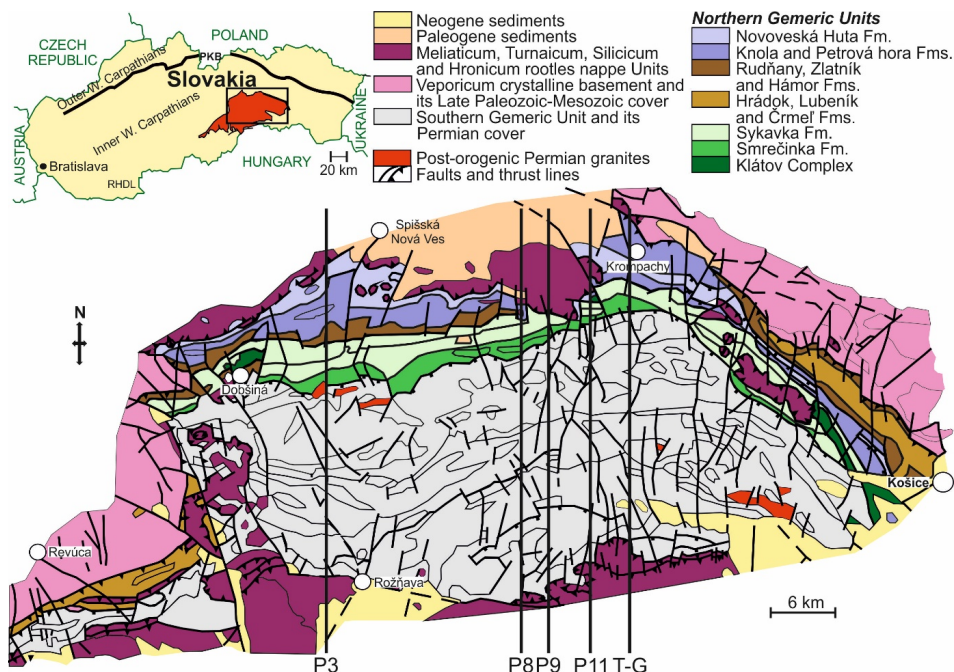


Fig. 8. Geological map of the Gemic Superunit – a segment of the studied region (modified after *Vozárová et al., 2013* and Geological Map of the Slovak Republic at scale 1:500,000; *Biely et al., 1996*). The course of the approximated Transect G and the interpretative profiles shown in Fig. 10.

research of the Gemic granites can help us to better understand structures and tectonic evolution of the Western Carpathians. Therefore, a new and original 3D density model of the Gemic granites was created by using the interactive geophysical program IGMAS (*Šefara, Bielik, Vozár, Katona, Szalaiová, Vozárová, Šimonová, Pánisová, Schmidt and Götze, 2017*). The results show clearly that the Gemic granites represent the most significant upper crustal anomalous low-density body in the structure of the Gemic Superunit (Figs. 9–10). Their average thickness varies in the range of 5–8 km. The upper boundary of the Gemic granites is much more rugged in comparison with the lower boundary. There are areas, where the granite body outcrops and/or is very close to the surface and places in which its upper boundary is deeper (on average 1 km in the north and 4–5 km in the south). While the depth of the lower boundary varies from 5–7 km in the north to 9–10 km in the south. The

northern boundary of the Gemeric granites along the tectonic contact with the Rakovec and Klátov Groups (North Gemeric Units) was interpreted as very steep (almost vertical). The results of the 3D modelling show that the whole structure of the Gemeric Unit, not only the Gemeric granite itself, has an Alpine north-vergent nappe structure. Also, the model suggests that the Silicicum–Turnaicum and Meliaticum nappe units have been overthrust onto the Golčatov Group.

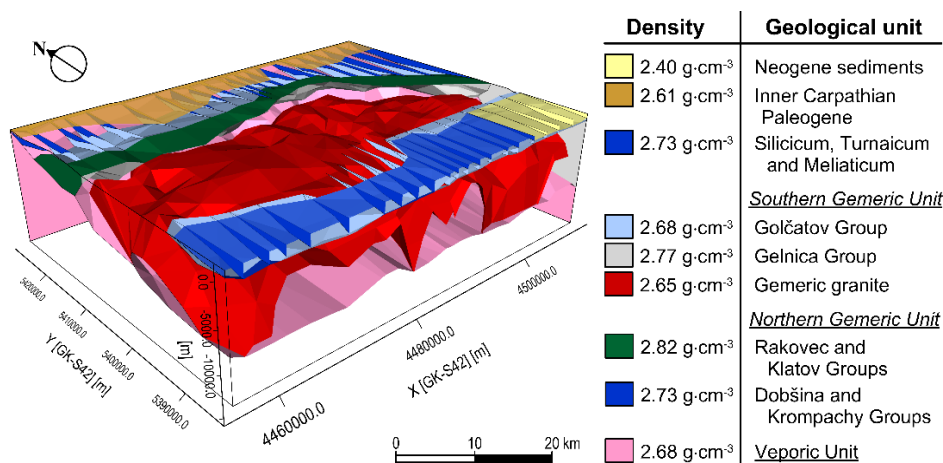


Fig. 9. The resultant 3D density model of the Gemeric granites showing their tectonic position in relation to the surrounding tectonic units.

Three-dimensional geophysical modelling (Pánisová, Balázs, Zalai, Bielik, Horváth, Harangi, Schmidt and Götze, 2018) of the early Late Miocene Pásztori volcano (ca. 11–10 Ma) and adjacent area in the Little Hungarian Plain Volcanic Field of the Danube Basin (Fig. 11) was carried out to get an insight into the most prominent intra-crustal structures here. We have used gridded gravity and magnetic data, interpreted seismic reflection sections and borehole data combined with re-evaluated geological constraints. Based on petrological analysis of core samples from available six exploration boreholes, the volcanic rocks consist of a series of alkaline trachytic and trachyandesitic volcanoclastic and effusive rocks. The measured magnetic susceptibilities of these samples are generally very low suggesting a deeper magnetic source. The age of the modelled Pásztori volcano, buried beneath a 2 km-thick Late Miocene-to-Quaternary sedimentary sequence, is  $10.4 \pm 0.3$  Ma belonging to the dominantly

normal C5 chron. Our model includes crustal domains with different effective induced magnetizations and densities (Figs. 12–14): uppermost 0.3–1.8 km thick layer of volcanoclastics underlain by a trachytic-trachyandesitic coherent and volcanoclastic rock units of a maximum 2 km thickness, with a top situated at minimal depth of 2.3 km, and a deeper magmatic pluton in a depth range of 5–15 km. The 3D model of the Danube Basin is consistent with observed high  $\Delta Z$  magnetic anomalies above the volcano, while the observed Bouguer gravity anomalies correlate better with the crystalline basement depth. Our analysis contributes to deeper understanding of the crustal architecture and the evolution of the basin accompanied by alkaline intraplate volcanism.

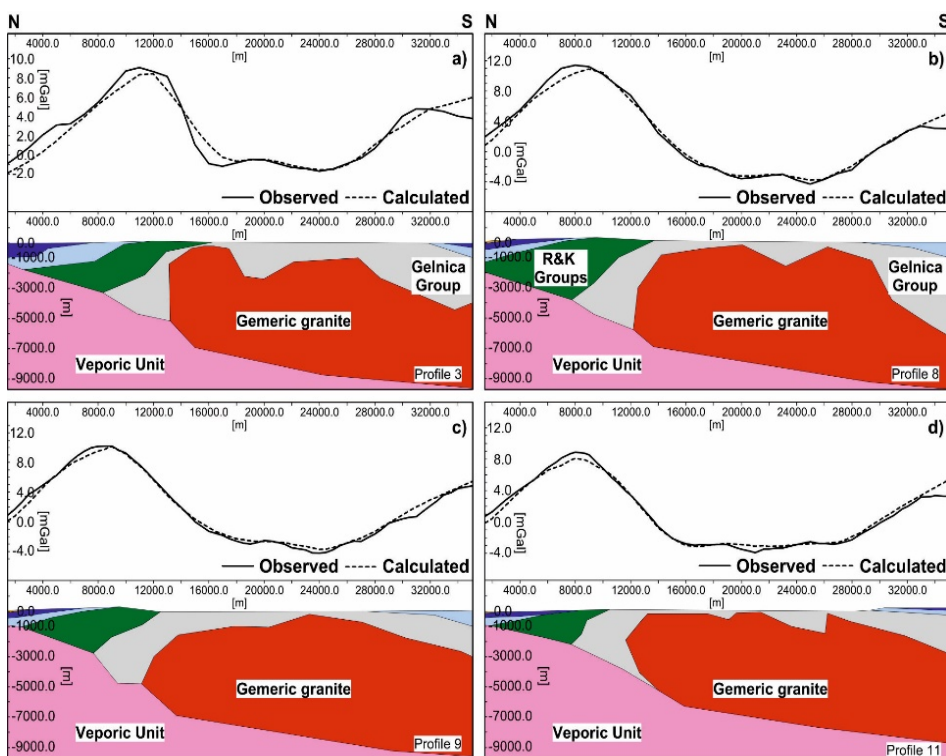


Fig. 10. The geometry and position of the Gemic granites along the selected four 2D cross-sections: a - profile 3; b - profile 8; c - profile 9; d - profile 11.

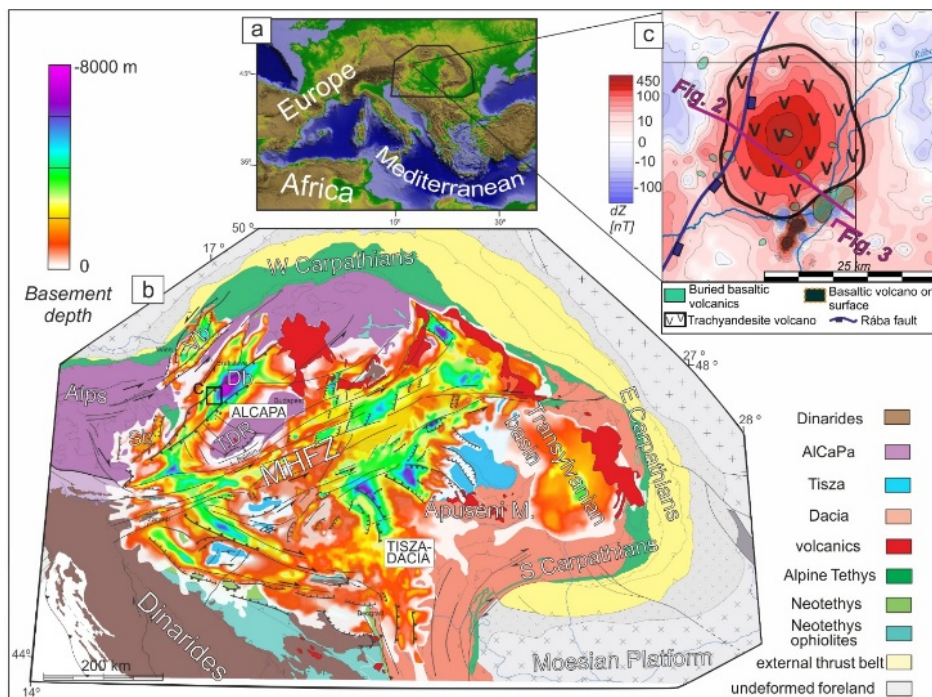


Fig. 11. a) Topography and location of the Pannonian Basin system of the Mediterranean region, b) simplified tectonic map of the Alps-Carpathians Dinarides region (modified after Schmid *et al.*, 2008) overlain by the Miocene–Quaternary sedimentary thickness (in meters) of the Vienna (Vb), Pannonian and Transylvanian basins. MHFZ Mid-Hungarian Fault Zone, Db Danube Basin, TDR Transdanubian Range, Sb Styrian Basin (modified after Balázs *et al.*, 2017), c) magnetic  $\Delta Z$  anomaly map (after Kiss and Gulyás, 2006) of the Danube Basin overlain by the location of surface and subsurface igneous bodies.

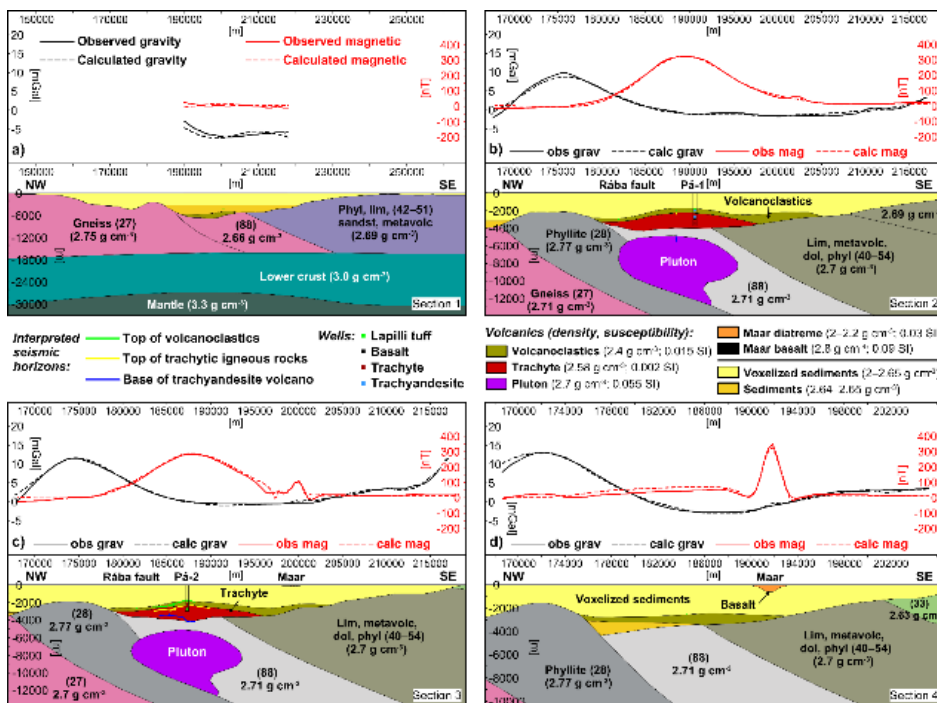


Fig. 12. Four selected cross sections of the final model in Section 1 (a), Section 2 (b), Section 3 (c), and Section 4 (d). Locations of particular sections (S1–S4) oriented in NW–SE direction are drawn by black lines in Fig. 11.

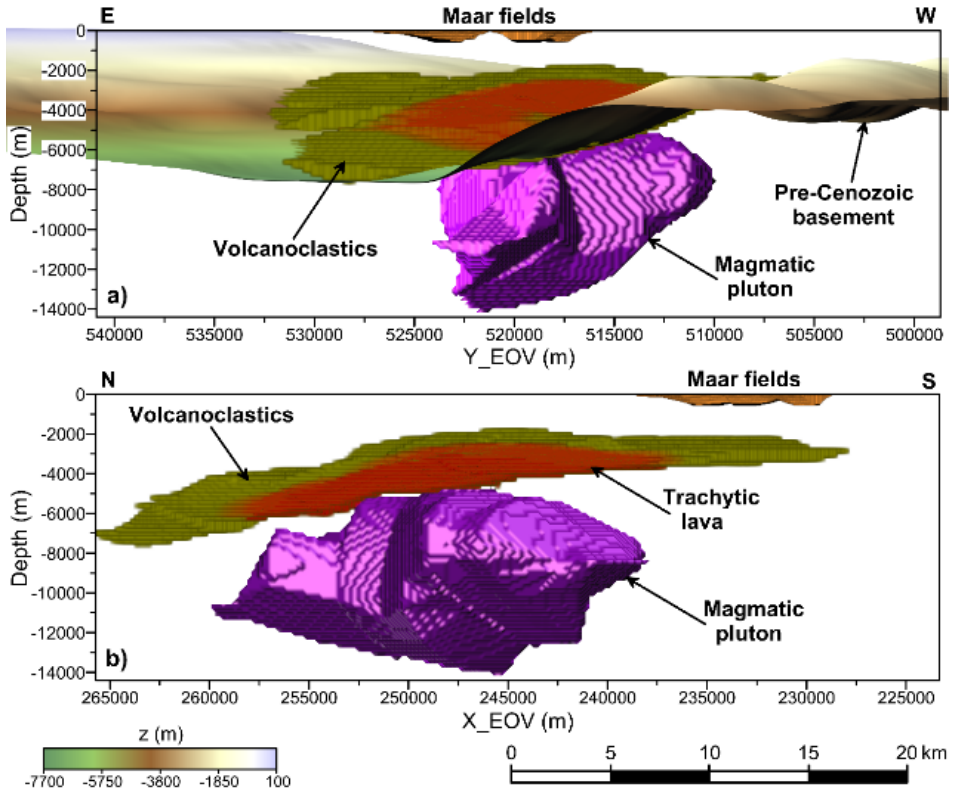


Fig. 13. 3D geophysical model of the Pásztori volcano: north view (a) and west view (b).

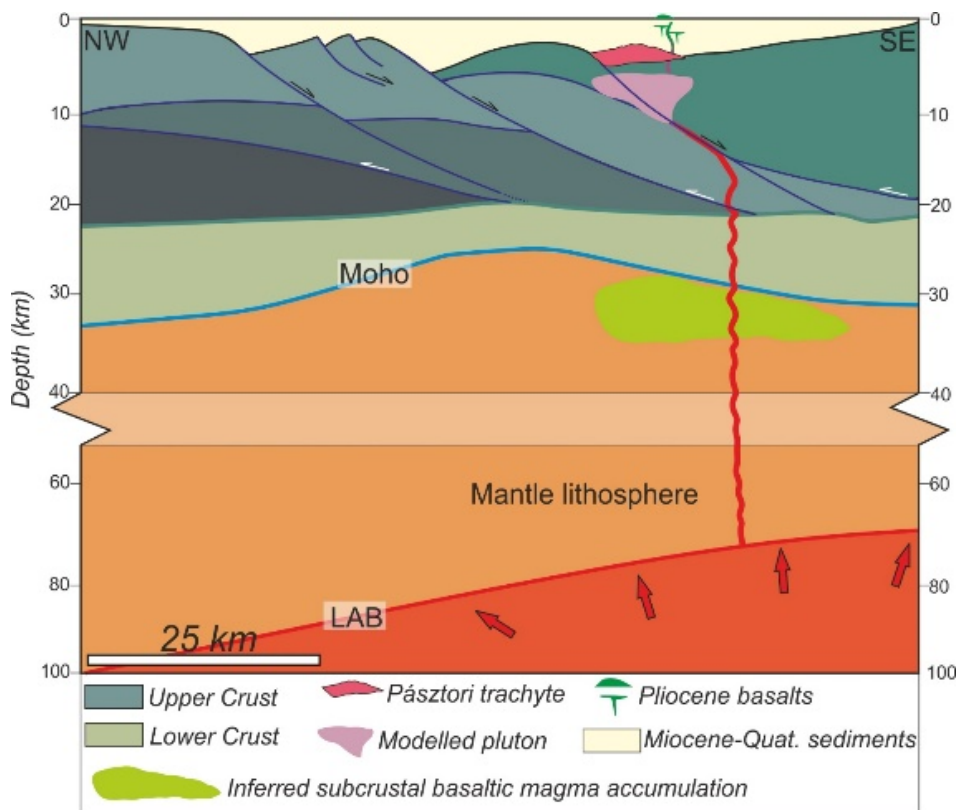


Fig. 14. Simplified sketch showing the asthenospheric sourced volcanism in the LHPVF. Note the Pliocene basalt volcanoes on the surface, stalled Pannonian basalt bodies within the Pannonian sedimentary succession, the early Late Miocene Pásztori volcano underlain by the modelled pluton and an inferred massive basaltic magma accumulation below the Moho. LAB lithosphere–asthenosphere boundary. Red arrows indicate inferred mantle convection (Horváth et al., 2015; Balázs et al., 2017).

### Temperature distribution and rheological properties of the lithosphere

The temperature model of the lithosphere along profile passing through the Red Sea region (Dérerová, Kohút, Radwan and Bielik, 2017) has been derived using 2D integrated geophysical modelling method. Using the extrapolation of failure criteria, lithology and calculated temperature distribution, we have constructed the rheological model of the lithosphere in the area. We have calculated the strength distribution in the lithosphere and constructed the strength envelopes



for both compressional and extensional regimes. The obtained results indicate that the strength steadily decreases from the Western desert through the Eastern desert towards the Red Sea where it reaches its minimum for both compressional and extensional regime. Maximum strength can be observed in the Western desert where the largest strength reaches values of about 250–300 MPa within the upper crust on the boundary between upper and lower crust. In the Eastern desert we observe slightly decreased strength with max values about 200–250 MPa within upper crust within 15 km with compression being dominant. These results suggest mostly rigid deformation in the region or Western and Eastern desert. In the Red Sea, the strength rapidly decreases to its minimum suggesting ductile processes as a result of higher temperatures.

The 2D integrated geophysical modelling approach (*Radwan, Dérerová, Bielik, Šimonová and Kohút, 2017*) has been also used to determine the temperature distribution in the lithosphere along the profile passing through Aswan. Based on the temperature model and the rheological parameters, we have calculated strength distribution in the lithosphere for the studied profile. The strength envelopes have been calculated for both compressional and extensional regimes. Our results indicate that the strength is constant along the whole length of the profile passing through the Nubia plain. The largest strength can be observed within the upper crust which allows us to assume rigid deformation in this part of the lithosphere, with compressional processes predominant. Towards the lower crust and upper mantle, strength values rapidly decrease for both regimes, suggesting ductile deformations in the lower part of the lithosphere.

### **Density modelling of the crust and lithosphere**

Density modelling was carried out by *Šamajová, Hók, Bielik and Pelech (2018)* along five profiles oriented across the expected deep contact between the Bohemian Massif and the Internal Western Carpathians in western Slovakia (Fig. 15).

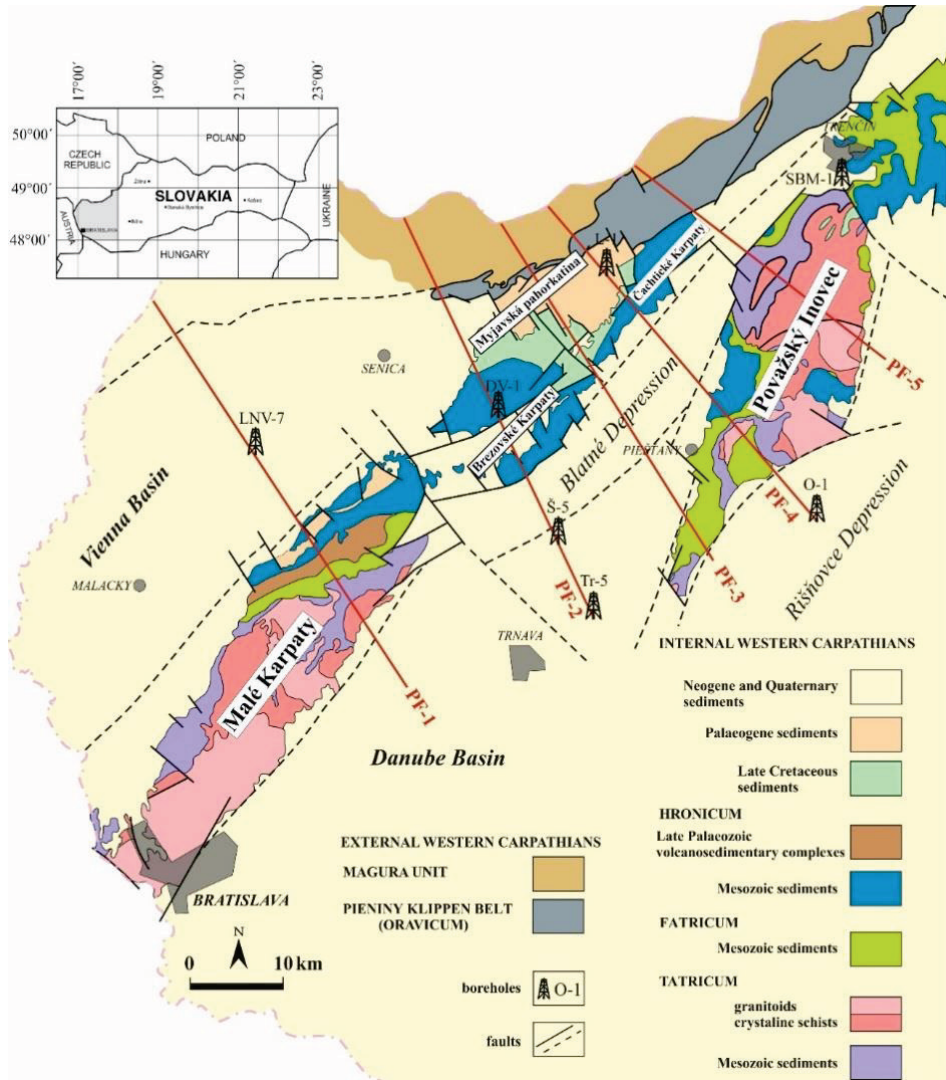


Fig. 15. Simplified tectonic map of the western part of Slovakia with position of gravimetric profiles and deep boreholes.

The density models reveal the continuation of the Bohemian Massif beneath the External and Internal Western Carpathians tectonic units (Fig. 16). The eastern margin of the Bohemian Massif is situated at depth south-east of the surface outcrops of the Pieniny Klippen Belt and changes its position in the surveyed area (Fig. 17).

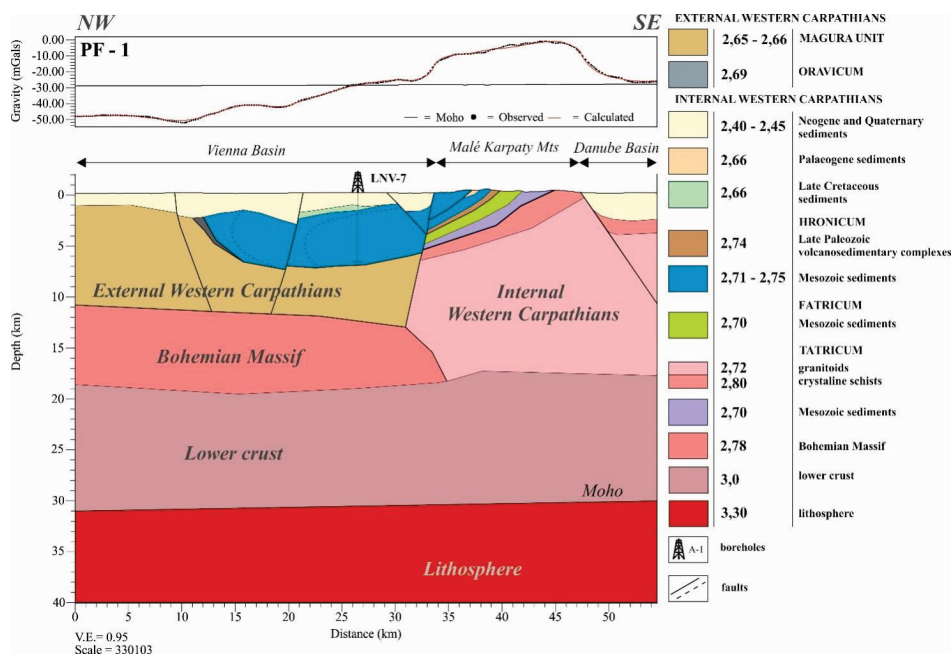


Fig. 16. Density model along the profile PF-1.

The contact of the Internal Western Carpathians with the Bohemian Massif and External Western Carpathians is subvertical. This sharp contact is manifested as the transension to extension zone towards the surface.

The main aim of the *Godová, Bielik and Šimonová's (2018)* paper is study is to compile 2D density model of the CELEBRATION 2000 profile CEL12, which is based on seismic refraction data. The profile CEL12 crosses the Outer Western Carpathians Flysch zone and is located in the southern part of Poland (Fig. 18). The general feature of the resultant density model (Fig. 19) shows significant changes in the crustal thickness. The Moho depth changes in the interval from 31 km to 43 km. The interpreted 43 km crustal thickness over a 60

km section of the profile results in the discovery of an area, which represents the thickest crust in the entire West Carpathians. This area is situated ~50 km northeast from the High Tatras in Poland.

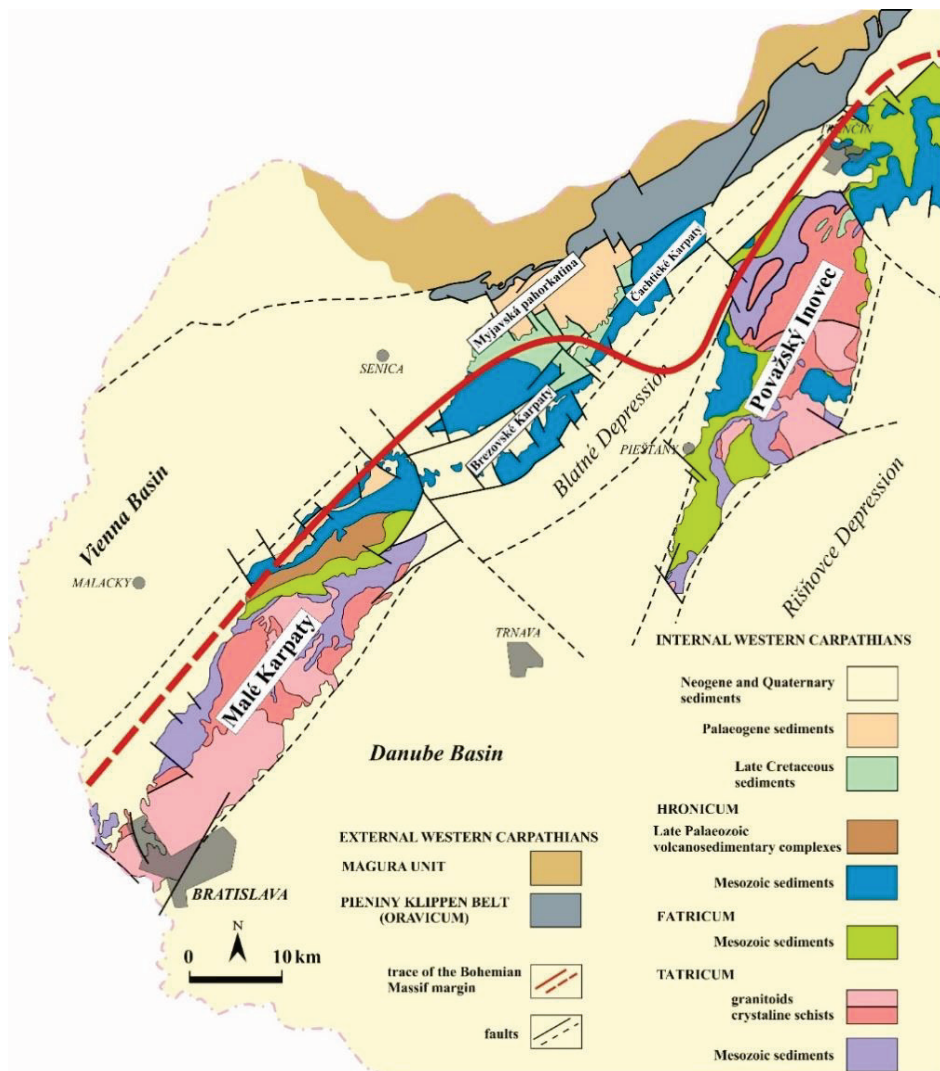


Fig. 17. Trace of the Bohemian Massif margin in a simplified tectonic map.

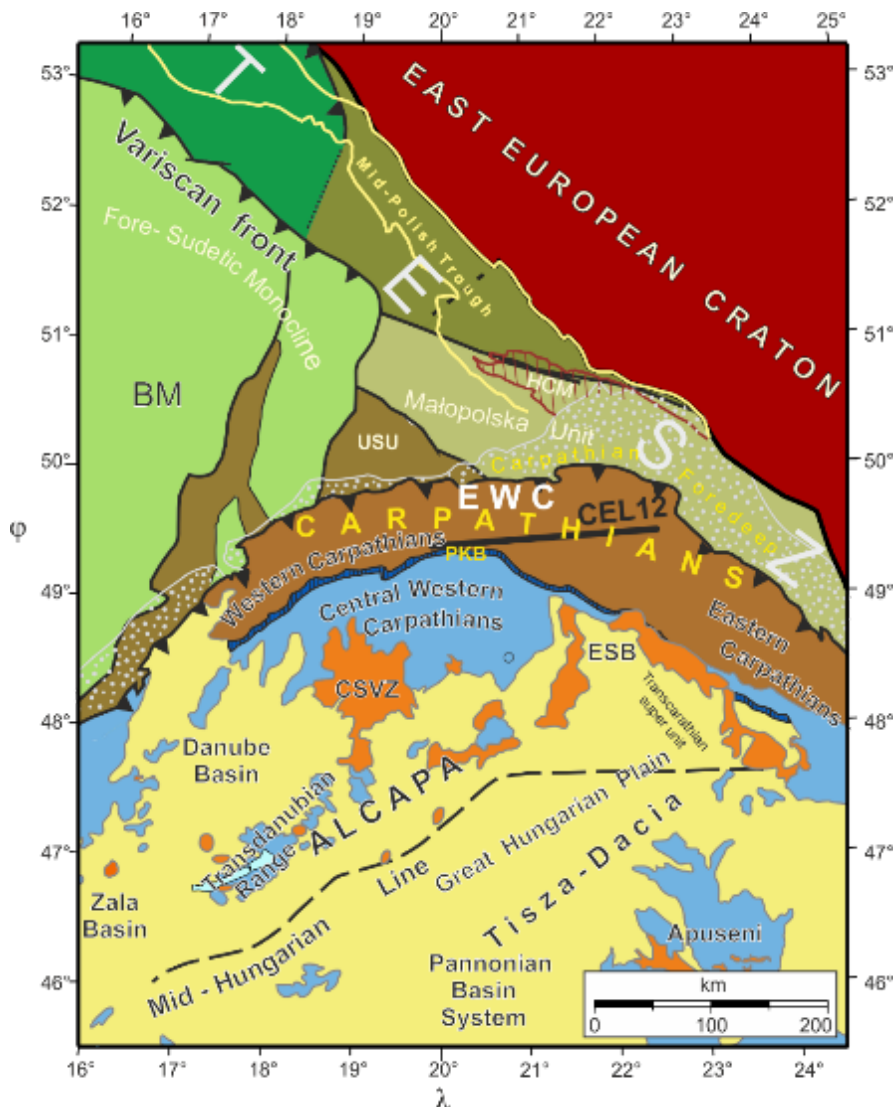


Fig. 18. Position of the CEL12 seismic profile on geological map of the Central Europe (modified after Janik *et al.*, 2011). EWC – External Western Carpathians; HCM - Holy Cross Mts.; BM – Bohemian Massif; USU - Upper Silesian Unit; CSVZ – Central Slovak Volcanic zone; ESB – East Slovakian Basin; PKB – Pieniny Klippen Belt; TESZ – Trans-European Suture Zone.

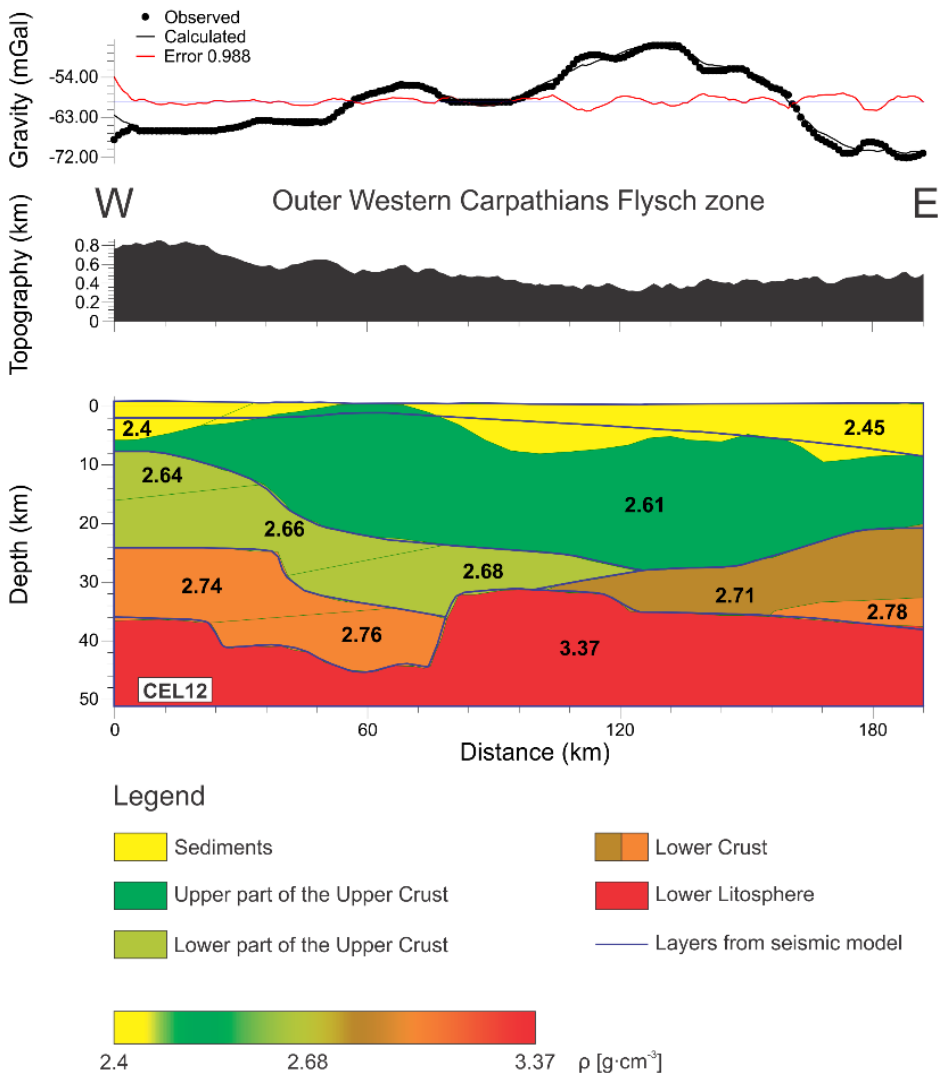


Fig. 19. 2-D density model of the profile CEL12. Blue lines show the seismic model used as a starting model.

The paper of Šimonová, Bielík and Dérerová (2015) presents a 2D density model along a transect from NW to SE China. The model was first constructed by the transformation of seismic velocity to density, revealed by previous deep seismic soundings (DSS) investigations in China. Then, the 2D density model was updated using the GM-SYS software by fitting the computed to the observed gravity data. Based on the density distribution of anomalous layers we divided the Chinese continental crust along the transect into three regions: north-western, central and south-eastern. The first one includes the Junggar Basin, Tianshan and Tarim Basin. The second part consists of the Qilian Orogen, the Qaidam Basin and the Songpan Ganzi Basin. The third region is represented by the Yangtze and the Cathaysia blocks. The low velocity body ( $v_p = 5.2 - 6.2$  km/s) at the junction of the North-western and Central parts at a depth between 21–31 km, which was discovered out by DSS, was also confirmed by our 2D density modelling.

### **Study of the Moho discontinuity**

The main aim of the paper Godová, Bielík and Šimonová (2018) is to determine 2-D density model of the CELEBRATION 2000 profile CEL12, which is based on seismic refraction data. The profile CEL12 crosses the Outer Western Carpathians Flysch zone and is located in the southern part of Poland. The general feature of the resultant density model shows significant changes in the crustal thickness. The Moho depth changes in the interval from 31 km to 43 km. The interpreted 43 km crustal thickness over a 60 km section of the profile results in the discovery of an area, which represents the thickest crust in the entire West Carpathians. This area is situated ~50 km north-east from the High Tatras in Poland.

Bielík, Makarenko, Csicsay, Legostaeva, Starostenko, Savchenko, Šimonová, Dérerová, Fojtíková, Pašteka and Vozár (2018) present a new digital Moho depth map of the Carpathian-Pannonian region (Fig. 20). The map was produced by compiling Moho discontinuity depth data, which were obtained by interpretation of seismic measurements taking into account the results of 2-D and 3-D integrated geophysical modelling. The resultant map is characterized by significant Moho-depth variations. The trends and features of the Moho in this region were correlated with tectonic units.

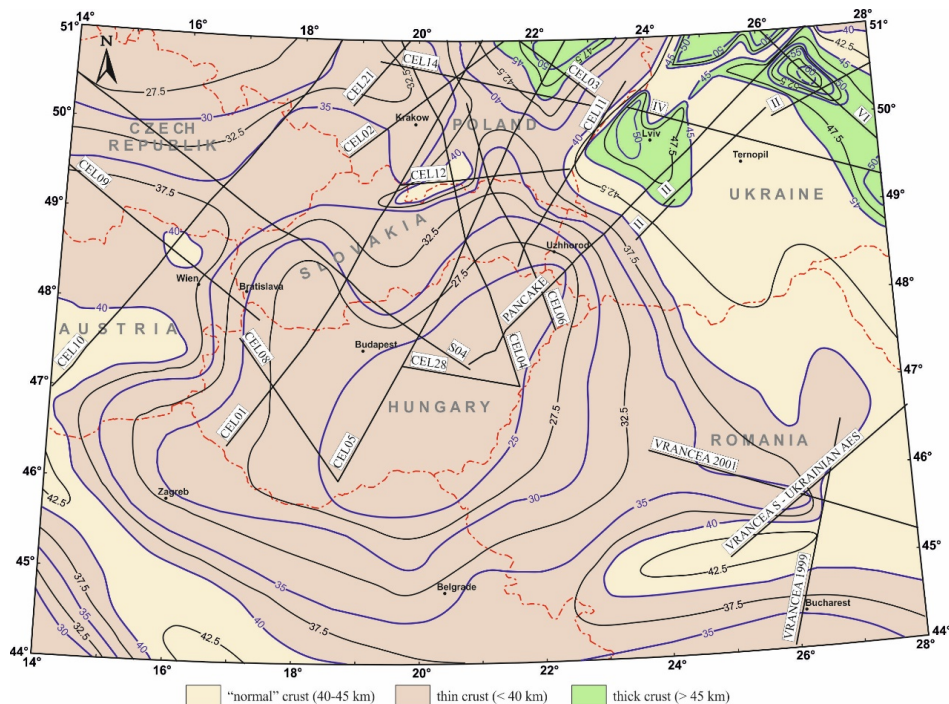


Fig. 20. The Moho depth map in the Carpathian-Pannonian region.

### Integrated geophysical modelling

Using 2D integrated geophysical modelling we recalculated lithospheric model along transect KP-X in the eastern part of the Western Carpathians (*Hlavňová, Bielik, Dérerová, Kohút and Pašiaková, 2015*). Our model takes into account the joint interpretation of the heat flow, free air anomalies, topography and geoid data. A more accurate model of lithospheric structure has been created, especially the lithosphere-asthenosphere boundary. Lithosphere thickness in the study region increases from the area of the Pannonian Basin where we modelled it at the depth of 80 km towards the oldest and coolest area of the European Platform where it reaches about 150 km. In the Pannonian Basin the modelled Moho depths reach about of 25 km and it decreases towards the Western Carpathians. The Western Carpathian's crustal thickness varies from about 30 km to 45 km. The largest crustal thickness (45 km) has been located beneath the Externides (Carpathian Foredeep) of the Western Carpathians. In the direction of the European platform a Moho depth gradually increases until



the end of the profile, where the crustal thickness reaches of about 42 km. Our modelling has confirmed the existence of an anomalous body with average density of  $2850 \text{ kg m}^{-3}$  seated mostly in the lower crust. Its uppermost boundary reaches a depth of about 12 km. The lower crust beneath the Western Carpathian Externalides is much thicker (20 km) in comparison beneath the Pannonian Basin, where it is only 8 km on average.

*Alasonati Tašárová, Fullea, Bielik and Sroda (2016)* have analysed the thermochemical structure of the mantle in Central Europe, a complex area with a highly heterogeneous lithospheric structure reflecting the interplay of contraction, strike slip, subduction, and extension tectonics (Fig. 21). Our modelling is based on an integrative 3-D approach (LitMod) that combines in a self-consistent manner concepts and data from thermodynamics, mineral physics, geochemistry, petrology, and solid Earth geophysics. This approach minimizes uncertainties of the estimates derived from modelling of various data sets separately. To further constrain our 3-D model we have made use of the vast geophysical and geological data (2-D and 3-D, shallow/crustal versus deep lithospheric experiments) based on experiments performed in Central Europe in the past decades. As case study of the result the profile CEL01 (Fig. 22a) is showing the fit to the observables and modelled layers; the solid black lines are calculated values and red dashed line are measured data. Green line in the elevation panel is calculated based on flexural isostasy assuming an effective elastic thickness of 25 km. The Fig. 22b shows density, temperature, and seismic velocity distribution in the lower lithosphere. Given the amount and the different nature/resolution of the available constraints, one of the most challenging tasks of this study was to consistently combine them, finding a trade-off between all local and regional data sets available in a way that (i) preserves as many structural details as possible and (ii) summarizes those data sets into a single robust regional model. The resulting P/T-dependent mantle densities are in LitMod 3-D calculated based on a given mineralogical composition. They therefore provide more reliable estimates compared to pure gravity models, which enhance modelling of the crustal structures. Our results (Fig. 23) clearly indicate presence of several lithospheric domains characterized by distinct features, Pannonian Basin being one of the most outstanding ones. It has the thinnest crust and lithosphere in the area modelled, characterized by relatively fertile composition.

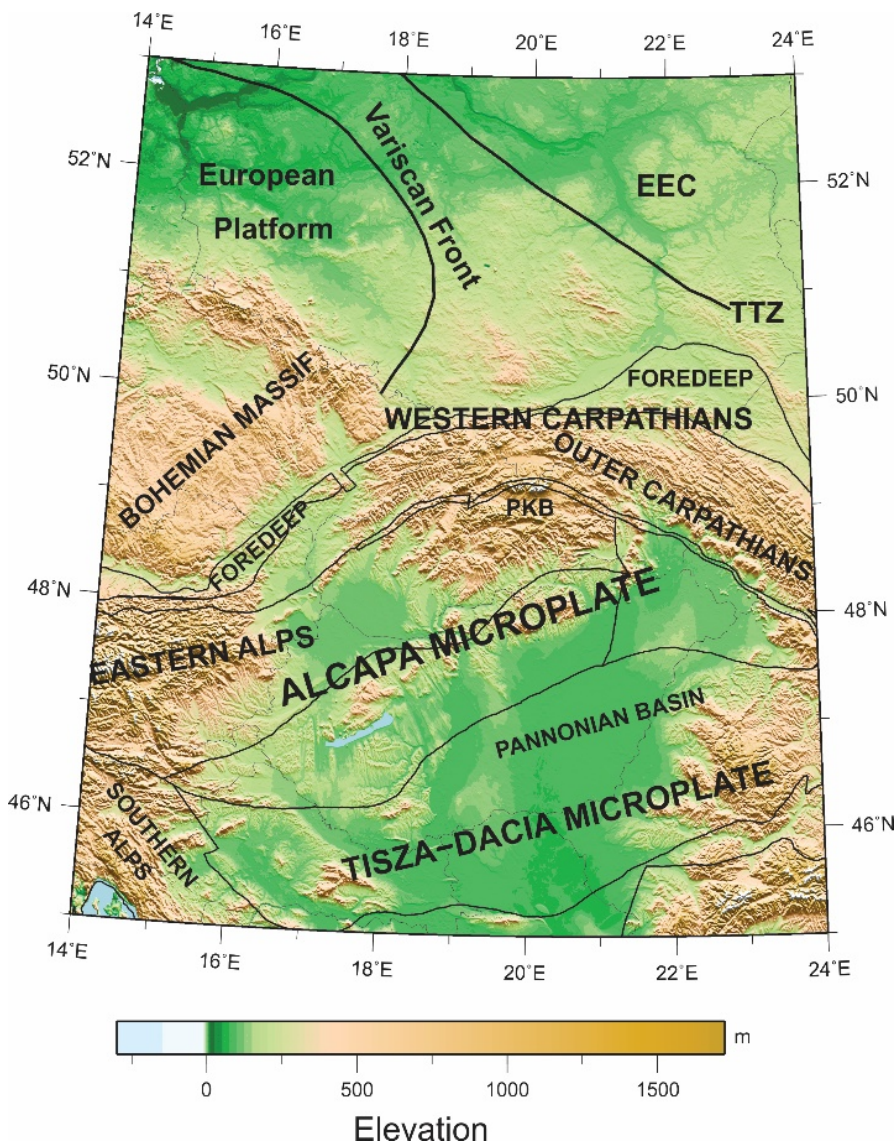
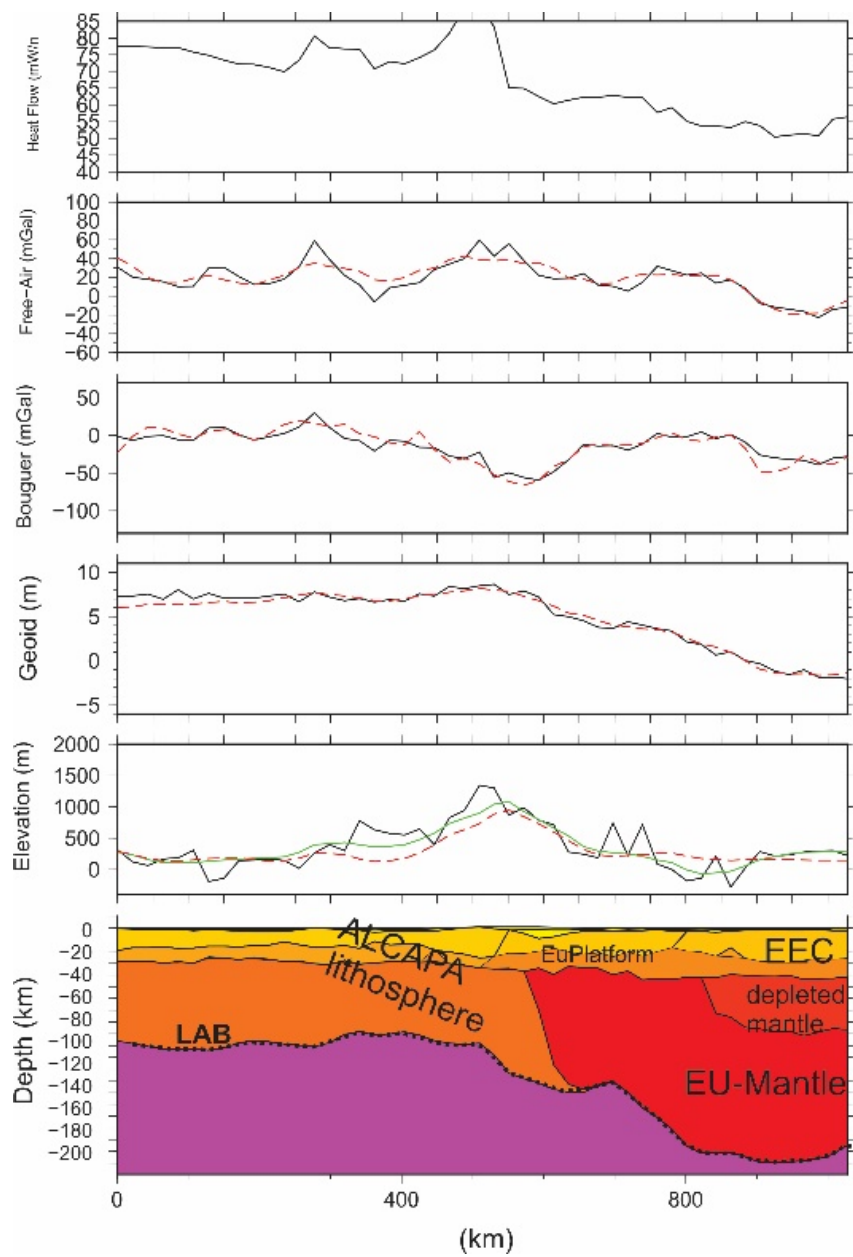


Fig. 21. Elevation, tectonic units and major plate boundaries. Here, only the north-eastern boundary of the Trans-European Suture zone (TESZ) is shown, which coincides with the Tornquist-Teisseyre zone (TTZ).



a)

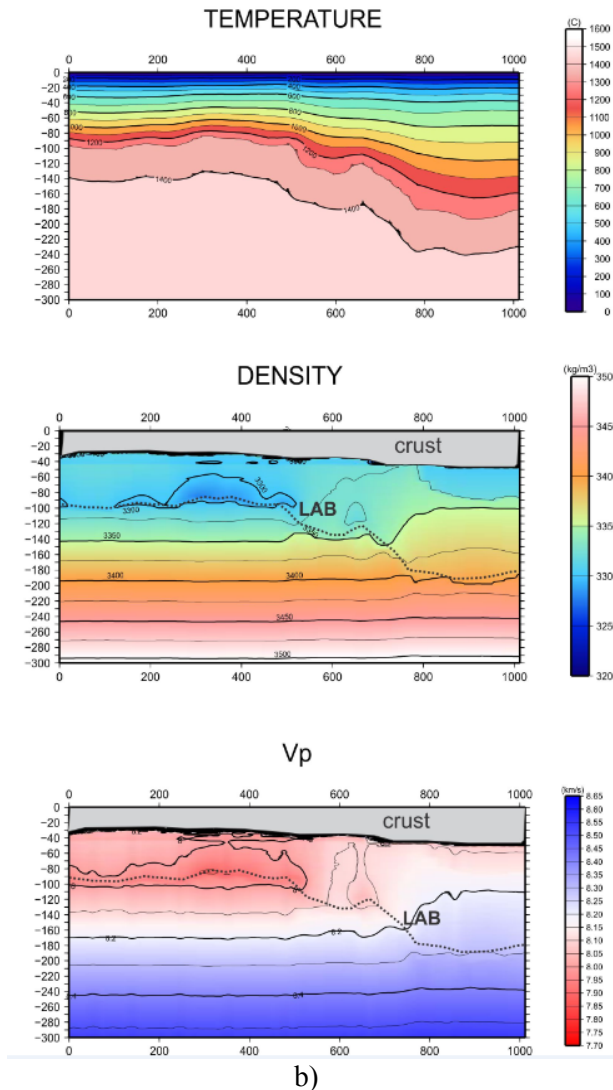


Fig. 22. (a) Upper panel: Profile CEL01 showing the fit to the observables and modelled layers; the solid black lines are calculated values and red dashed line are measured data. Green line in the elevation panel is calculated based on flex-ural isostasy assuming an effective elastic thickness of 25 km. lower panel: density, temperature, and seismic velocity distribution. (b) Distribution of temperature, density and seismic velocity in Lower Lithosphere and Asthenosphere.

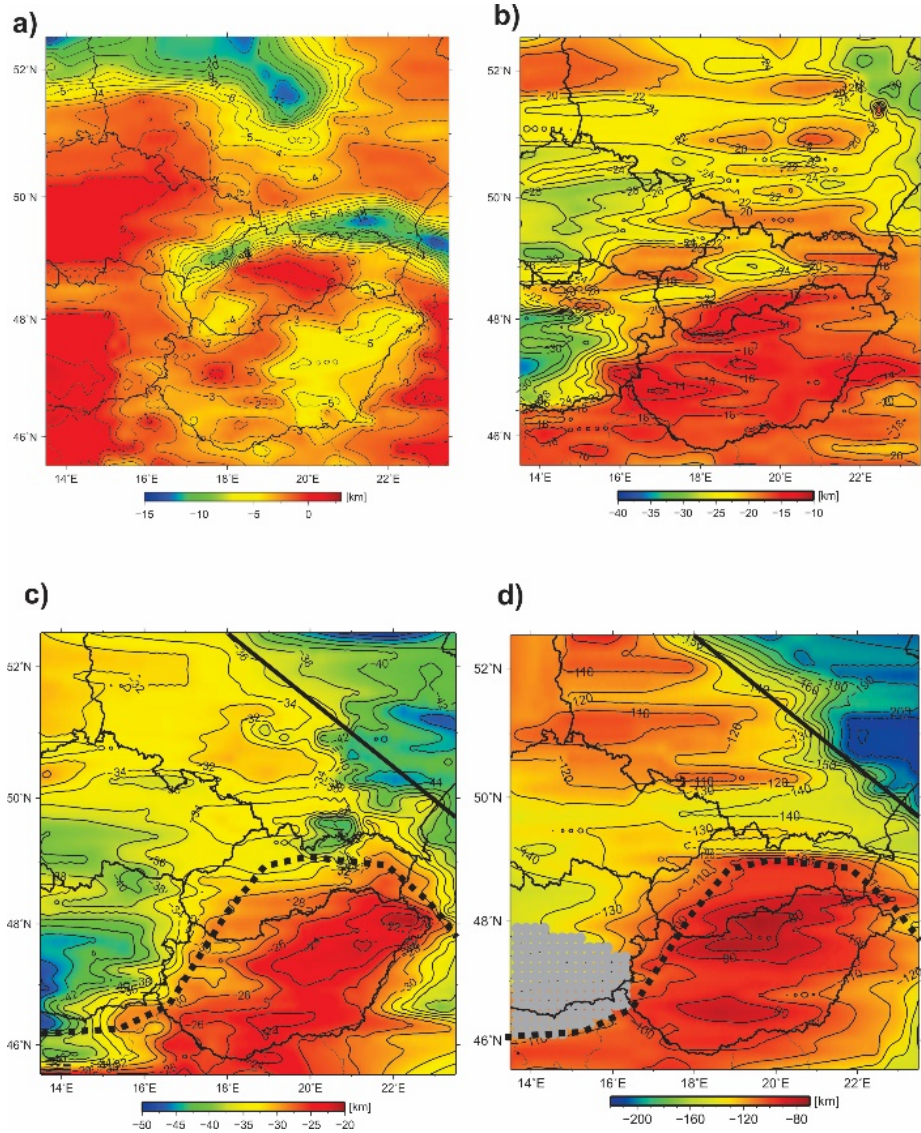


Fig. 23. Results of the modelling showing the depth to the (a) basement, (b) top of the lower crust, (c) Moho, and (d) LAB. The grey circles denote the area of the 360 km deep Alpien slab modelled. The black lines denote the three different mantle domains.

Due to uncertainty of single-method interpretation Šimonová, Zeyen and Bielik (2018) applied 2-D integrated lithospheric modelling along three CELEBRATION 2000 profiles CEL01, CEL04 and CEL05 (Fig. 24). Modelling of the lithospheric thermal structure is based on the joint interpretation of gravity, geoid, topography and surface heat flow data with temperature-dependent density. The models for each profile were constrained by seismic modelling results of the large-scale international project CELEBRATION 2000. The results indicate (Fig. 25, Table 2). large variations of the lithosphere thickness from the old and cold East European Craton (~200 km) and the Trans European suture zone via the Western Carpathian orogeny to the young and hot Pannonian Basin (~90 km). Important differences in the lithospheric thickness were also found along-strike of the Western Carpathian orogeny and the Trans-European Suture Zone. The western part of the Western Carpathians is characterized by weak thickening of the lithosphere (only about 145 km), while their eastern segment presents strong lithospheric thickening (~190 km). The Małopolska unit in southern Poland has a lithospheric thickness of about 130 km. Thickest lithosphere (220 km) is observed around the junction of the Carpathian Foredeep and the East-European Craton. The crustal thickness follows generally the course of the lithosphere-asthenosphere boundary. The results suggest different geodynamic evolution of the collision of the ALCAPA microplate with the European platform on the one hand and the East-European Craton on the other hand. It is suggested that the tectonic evolution of this very complex area consisting of different tectonic units has changed in time and space.

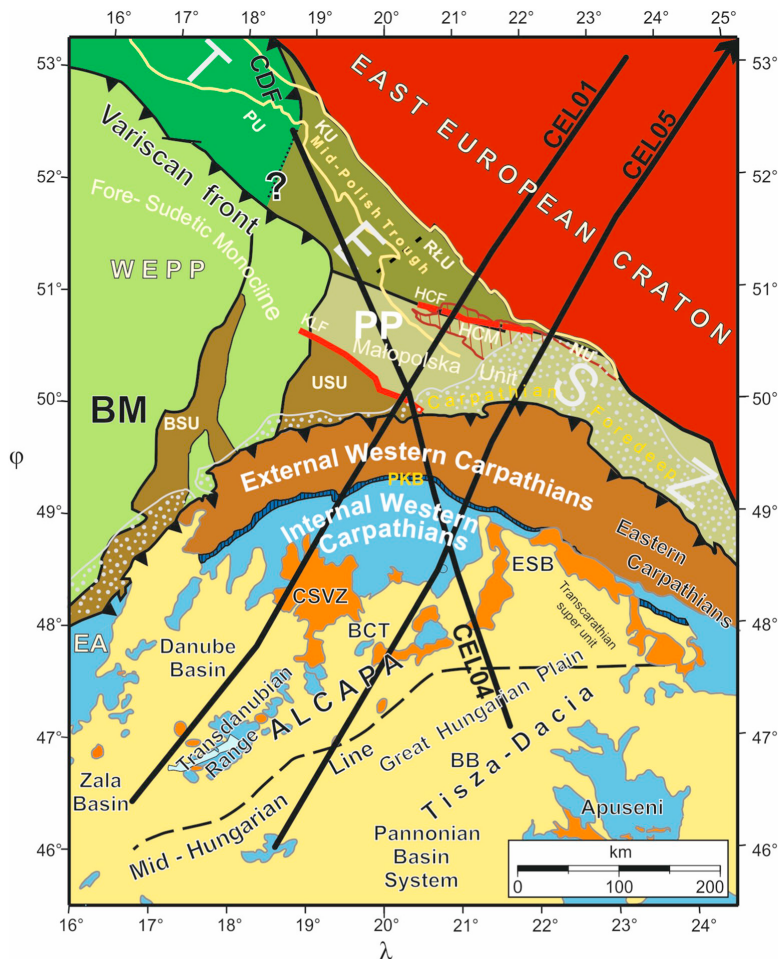


Fig. 24. Location of the CELEBRATION 2000 seismic profiles CEL01, CEL04 and CEL05 interpreted in the paper on the background of geological map of Central Europe modified from *Środa et al. (2006)* and *Janik et al. (2009, 2011)* with elements for Carpathian–Pannonian basin area after *Kovač (2000)*, Palaeozoic platform after *Dadlez et al. (2000)*, and for Mid-Hungarian Line after *Fodor et al. (1999)*. WEPP – West European Palaeozoic Platform; TESZ – Trans-European Suture Zone; CDF – Caledonian Front; PU – Pomeranian unit; KU – Kuiavian unit; MPT – Mid Polish trough; RLU – Radom-Łysogory unit; HCF – Holy Cross Fault; HCM – Holy Cross Mts.; NU – Narol unit; KLF – Krakow-Lubliniec Fault; USU – Upper Silesian unit; PKB – Pieniny Klippen Belt; ESB – East Slovakian Basin; CSVZ – Central Slovak Volcanic zone; BCT – Bukk Composite Terrane; BM – Bohemian Massif; BSU – Bruno–Silesian unit; BB – Bekes Basin; EA – Eastern Alps.

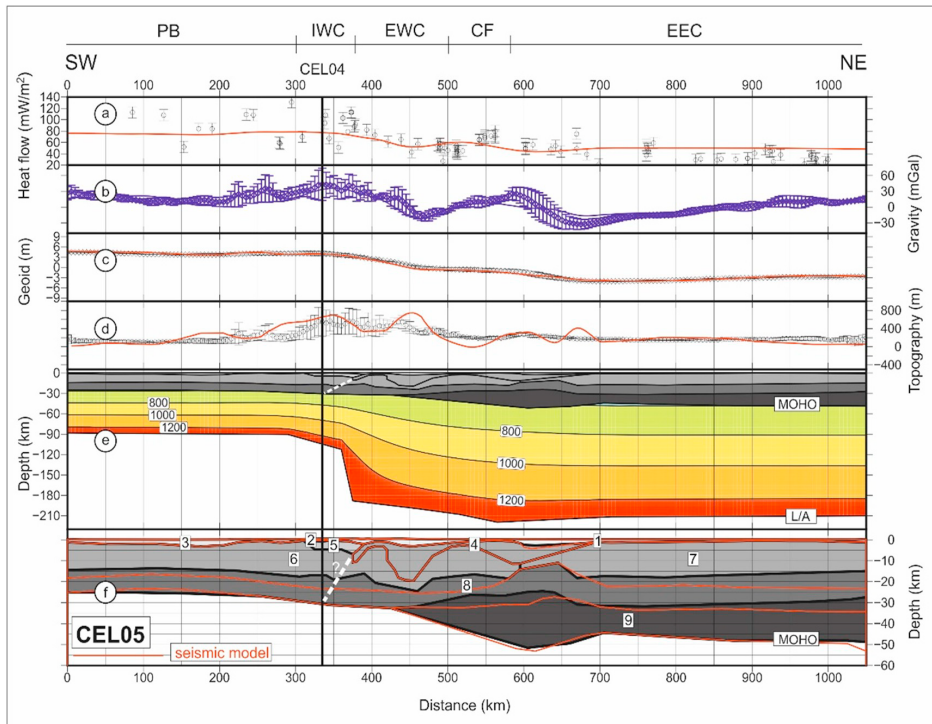


Fig. 25. Lithospheric model for profile CEL05. (a) Surface heat flow density, (b) free-air gravity anomaly, (c) geoid, (d) topography with dots corresponding to measured data with uncertainty bars and solid lines for calculated values; (e) lithospheric structure (vertical = horizontal scale), in the lithospheric mantle, isotherms are indicated every 200 °C; (f) blow-up of crustal structure, numbers refer to bodies in Table 1; red lines show the seismic model used as starting model. The white dashed line indicates the expected boundary between microplate ALCAPA and EEC or WEPP respectively (after Janik *et al.*, 2011). Keys: PB – Pannonian Basin, CSVZ – Central Slovak Volcanic zone, IWC – Internal Western Carpathians, EWC – External Western Carpathians, MU – Małopolska unit, MPT – Mid-Polish Trough, EEC – East European Craton.



Table 2. Densities and thermal properties of the different bodies used in profile CEL05.

CEL05					
Layer	Unit	No	Density [ $\text{kg m}^{-3}$ ]	HP [ $\mu\text{W m}^{-3}$ ]	TC [ $\text{W m}^{-1}\text{K}^{-1}$ ]
Upper Crust (Uppermost layers)	East European Craton Carpathian Foredeep External Western Carpathians	1	2500	0.5	2
	Internal Western Carpathians	2	2400	0.5	2
	Pannonian Basin	3	2500	0.5	2
Upper-Middle Crust	East European Craton - partly Carpathian Foredeep Outer Western Carpathians	4	2720	0.5	2
	Central Western Carpathians	5	2700	2	2.5
	Pannonian Basin Internal Western Carpathians External Western Carpathians Carpathian Foredeep	6	2720	2	2.5
	East European Craton	7	2720	1	2.5
Lower Crust	All	8	2970	1	2.5
	East European Craton Carpathian Foredeep External Western Carpathians - partly	9	3050	0.2	2
Lower Lithosphere	All	10	3200	0.02	3.4

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## Defended PhD Theses

- Institution: Faculty of Natural Sciences, Comenius University, KAEG, Bratislava, Slovak Republic  
Title: Evaluation of natural radioactivity of the rock environment in selected regions of Slovakia  
Student: Barbara Porubčanová  
Supervisor: Miroslav Bielik  
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## **International Research/grant projects**

COST-ES1401

### **Time Dependent Seismology (TIDES)**

since 2014

The Action aims at structuring the EU seismological community to enable development of data-intensive, time-dependent techniques for monitoring Earth active processes (e.g., earthquakes, volcanic eruptions, landslides, glacial earthquakes) as well as oil/gas reservoirs.

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### **E2VP II - EuroseisTest Verification and Validation Project II**

20011–2015

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AREVA, ENEL, EDF, France

### **SIGMA - Seismic Ground Motion Assessment**

20011–2015

Coordinator – Gloria Sanfaute

## **Web pages**

<http://www.seismology.sk>

<http://www.nuqake.eu>

<http://www.fyzikazeme.sk>





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