Geodesy and Geophysics in Slovakia
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Contents

Geodetic, gravimetric, and geodynamic research in Slovakia 2019–2022 (Report to IAG)

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1. Volcano Gravimetry research

Research in the area of volcano geodesy/gravimetry focused on methodological aspects of compiling and interpreting spatiotemporal (time-lapse) gravity changes. We have derived a new numerical prescription for computing the gravitational effect of surface deformation, referred to as the Deformation-Induced Topographic Effect (DITE). We have shown on several case studies the numerical difference between the accurately computed DITE and its commonly used approximations, as well the impact of this difference on the interpretation of temporal gravity changes. We have modified the Growth inversion approach to be applicable to sparse time-lapse gravity changes with poor signal to noise ration observed in volcanic areas, typically associated with volcanic unrest. We have applied the Growth method to inverting and interpreting gravity changes observed in several volcanic areas and compared the Growth solutions to previous interpretations to demonstrate the benefits and limitations of the Growth approach.

1.1 Gravitational effect of surface deformation

We have presented a comprehensive review of the origin, significance and implications of topographic effects in gravimetry across several earth science fields such as physical geodesy, geophysics and geodynamics (Vajda et al., 2020a), including the effect of the topographic surface deformation. In most gravimetric applications and their computational realizations, when topography is not the focus of the study, these effects need to be properly treated as corrections (reductions). First, we look at topographic effects in geodesy and focus on those that affect the determination of the geoid from terrestrial gravity data. We review the origin and role of both the direct and indirect, the primary and secondary topographic effects. Then, we review the Bouguer concept in geophysical applications. Finally, we take a look at the topographic effect induced by the deformation of the topographic surface and its importance in the interpretation of observed spatiotemporal gravity changes. We have investigated also the possibility of predicting the in-situ vertical gradient of gravity by adding to the normal gradient the modelled topographical component of the gradient (Vajda et al., 2020b).

We have improved the methodology of compiling and interpreting residual spatiotemporal gravity changes in volcanic areas by deriving an accurate expression for the deformation-induced topographic effect (DITE) used as a correction in residual gravity changes evaluation. This methodology may improve the gravimetric assessment of volcanic hazard associated with magma intrusions and migration (Vajda et al., 2019). We analyzed the DITE field, and its various approximations, respective to the surface deformation associated with the Etna volcano eruption of 24 December 2018 (Vajda et al., 2021b), and the DITE field respective to surface deformation associated with the 2017 destructive earthquake on the Ischia island, Italy (Berrino et al., 2021), as well as the DITE respective to surface deformation (inflation) associated with the 2013–2016 unrest at the Laguna del Maule volcanic field in the Southern Andes of Chile (Vajda et al., 2021a).

1.2 Growth inversion of spatiotemporal gravity changes

We have tailored the Growth approach originally developed to invert the complete Bouguer anomalies in structural studies to the inversion of sparse and noisy micro-gravity changes (Camacho et al., 2021) for the interpretation of subsurface spatiotemporal density changes.

We applied the Growth inversion method to re-interpreting the spatiotemporal gravity changes of three annual periods covering 2013–2016 associated with the unrest at the Laguna del Maule (Chile) accompanied by high surface inflation (Vajda et al., 2021a). We applied the Growth approach also to time-lapse gravity changes observed on the Ischia island over a period of several months covering the event of the destructive 2017 earthquake (Berrino et al., 2021). We revisited the volcanic unrest of 2004–2005 on Tenerife (Canary Islands) and reinterpreted the observed temporal gravity changes of this period. (Vajda et al., 2022).

1.3 Publications

Vajda Peter, I. Foroughi, P. Vaníček, R. Kingdon, M. Santos, M. Sheng, M. Goli (2020).

Topographic gravimetric effects in earth sciences: Review of origin, significance and implications. Earth-Science Reviews, https://doi.org/10.1016/j.earscirev.2020.103428
Vajda Peter, Antonio G. Camacho, José Fernández (2022). Benefits and limitations of the Growth inversion approach in volcano gravimetry demonstrated on the revisited Tenerife 2004–2005 unrest. Surveys in Geophysics (26 Sept. 2022), doi 10.1007/s10712-022-09738-9.
Vajda Peter, Pavol Zahorec, Dušan Bilčík, Juraj Papčo (2019). Deformation–induced topographic effects in interpretation of spatiotemporal gravity changes: Review of approaches and new insights. Surveys in Geophysics (2019) 40:1095–1127, https://doi.org/10.1007/s10712-019-09547-7
Camacho Antonio G., Peter Vajda, Craig A. Miller, José Fernández (2021) A free-geometry geodynamic modelling of surface gravity changes using Growth-dg software. Scientific Reports 11, 23442 (6 Dec 2021) doi 10.1038/s41598-021-02769-z.
Vajda Peter, P. Zahorec, C.A. Miller, H. Le Mével, J. Papčo, A.G. Camacho (2021a) Novel treatment of the deformation–induced topographic effect for interpretation of spatiotemporal gravity changes: Laguna del Maule (Chile). Journal of Volcanology and Geothermal Research 414, 107230 (June 2021) doi 10.1016/j.jvolgeores.2021.107230
Vajda Peter, P. Zahorec, J. Papčo, D. Carbone, F. Greco, M. Cantarero (2020b). Topographically predicted vertical gravity gradient field and its applicability in 3D and 4D microgravimetry: Etna (Italy) case study, Pure and Applied Geophysics, 177(7): 3315–3333, https://doi.org/10.1007/s00024-020-02435-x
Berrino Giovanna, Peter Vajda, P. Zahorec, A.G. Camacho, V. De Novellis, S. Carlino, J. Papčo, E. Bellucci Sessa, R. Czikhardt (2021). Interpretation of spatiotemporal gravity changes accompanying the earthquake of 21 August 2017 on Ischia (Italy) Contributions to Geophysics and Geodesy, 51(4): 345–371, doi: 10.31577/congeo.2021.51.4.3.
Vajda Peter, Pavol Zahorec, Juraj Papčo, Richard Czikhardt (2021b) Deformation-induced topographic effect due to shallow dyke: Etna December 2018 fissure eruption case study. Contributions to Geophysics and Geodesy, 51(2): 165–188, doi 10.31577/congeo.2021.51.2.4.

2. Establishment of new gravimetric tidal station in Hurbanovo

New station Hurbanovo located in Slovakia joined IGETS (International Geodynamics and Earth Tide Service, ISDC: IGETS Data Base (gfz-potsdam.de)) in 2021. The station is equipped with the relative spring gravimeter gPhoneX #108.
The Hurbanovo Gravimetric Observatory in southern Slovakia was established in 2019 as a part of the integrated station HUVO (GNSS permanent station and seismic station). HUVO is located on a ground floor in a small building in the vicinity of the Hurbanovo Geomagnetic Observatory, which was founded on September 30, 1900. Integration of InSAR transponder into current station architecture is also planned in 2022.

The Gravimetric Observatory equipped with the spring gravimeter gPhoneX #108 provides continuous time-varying gravity and atmospheric pressure data. The spring gravimeter gPhoneX #108 is installed on a concrete block isolated from the rest of the building grounding. The room containing gravimeter is thermally stabilized at around 22 ± 1°C using an air conditioning unit. An additional thermal polystyrene insulation is placed around the instrument further decreasing temperature variations on its surface.

The operation and maintenance of the HUVO gravimetric instrumentation is done mainly by the staff of the Slovak University of Technology (SUT). HUVO gravimetric observatory is also equipped with the accelerometer Raspberry Shake (4D) installed on the same concrete block as the spring gravimeter, operated by the staff of the Slovak Academy of Sciences.

Several other meteorological sensors are also present at the site in the close vicinity of the gPhoneX #108: the meteorological station MWS 9-5, a well equipped with the ground-water level sensor and a total number of 16 sensors measuring the soil moisture. These sensors provide information necessary for modelling the gravity response associated with the variation of local hydrological masses.

Concerning signal to noise ratio, the HUVO station can be characterized as moderately noisy. The Level 1 data from July 2020 are available via IGETS service.

Fig. 1: *View of the Hurbanovo Geomagnetic Observatory and new Gravimetric Observatory. The pillar with the relative gravimeter gPhoneX is located in the small building in the middle of the picture.*

Fig. 2: *Relative metal spring gravimeter gPhoneX #108 in Hurbanovo station.*

3. Publications sorted according to IAG Commissions

3.1 Reference Frames

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3. 2 Gravity Field

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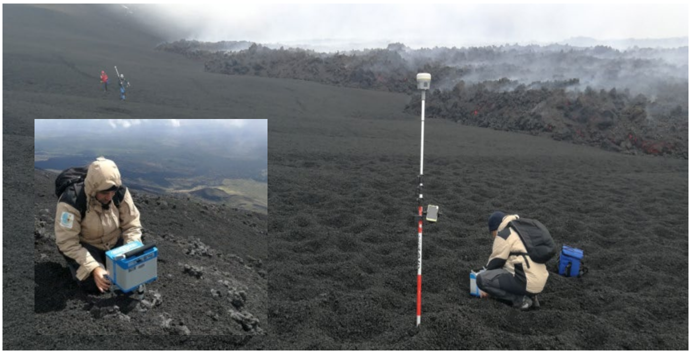
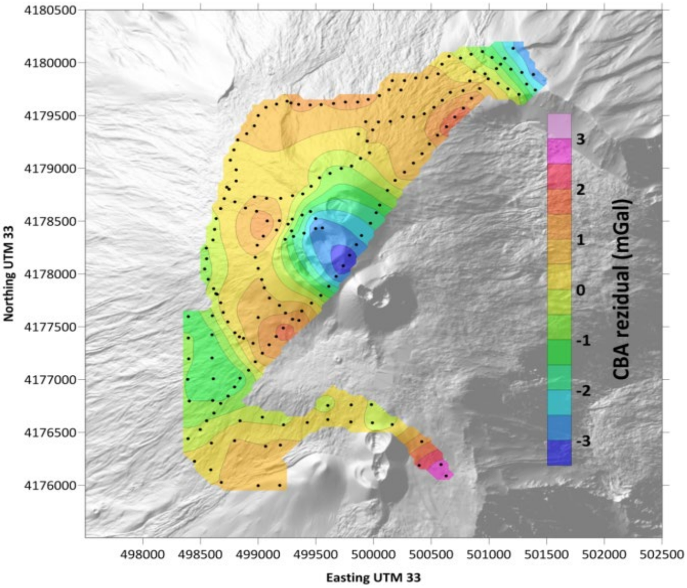
4. International Research/grant projects

03/2020–11/2021 (principal investigator: Peter Vajda, Earth Science Institute SAS)

Gravimetric investigation of the structure of the Etna summit craters system (acronym G-ET-SUMMIT)

Trans National Access project granted under EUROVOLC project that received funding from EU Horizon 2020 research and innovation actions under grant agreement No 731070




Northing UTM 33
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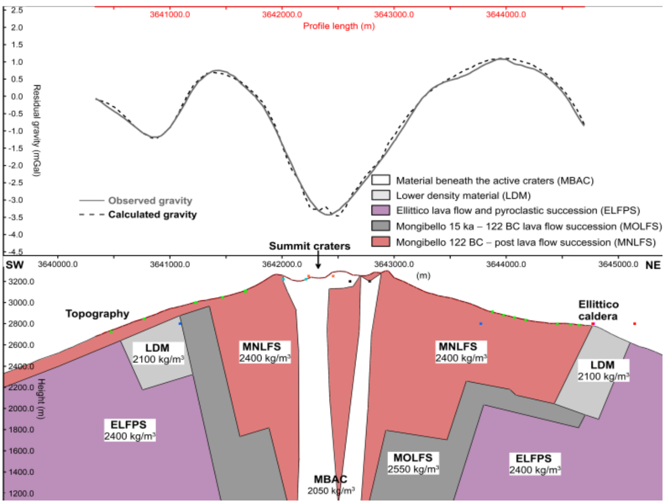
CBA rezidual (mGal)


Profile length (m)
Residual gravity (mGal)
Observed gravity
Calculated gravity
Material beneath the active craters (MBAC)
Lower density material (LDM)
Ellittico lava flow and pyroclastic succession (ELFPS)
Mongibello 15 ka – 122 BC lava flow succession (MOLFS)
Mongibello 122 BC – post lava flow succession (MNLFS)
Summit craters
SW
NE
Topography
Ellittico caldera
LDM 2100 kg/m³
MNLFS 2400 kg/m³
ELFPS 2400 kg/m³
MOLFS 2550 kg/m³
MBAC 2050 kg/m³
Height (m)

Geomagnetic and aeronomic studies in Slovakia in the period 2019–2022 (Report to IAGA)

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1. MHD dynamo theory and physics applicable to the processes in the Earth's core

Rotating magnetoconvection with anisotropic diffusivities

(Geophys. Astrophys. Fluid Dyn., Filippi, Brestenský, Šoltis, 2019; Astron. Nachrichten, Filippi, Brestenský, 2020)

The Geodynamo problems and the turbulent state of the Earth's outer core inspire development of rotating magnetoconvection models which can be used also in solution of astrophysical problems related mainly to Natural Dynamos and magnetic fields behaviour of cosmic bodies.

In our magnetoconvection models (Filippi, Brestenský & Šoltis 2019, and Filippi & Brestenský 2020) as well as in one in the earliest published paper

(Šoltis & Brestenský 2010), which henceforth are respectively assigned as FBS19, FB20 and SB10, we suppose that the basic state of the horizontal layer rotating about the vertical axis with a vertical gradient of basic temperature and permeated by the basic horizontal magnetic field is also determined by the background turbulence through the parameterized turbulent diffusive coefficients (viscosity, thermal and magnetic diffusivities). In some sense, increasing instabilities related to the instability of the basic state are affected by the basic turbulence accompanying the basic state, and it is shown that more complex diffusive coefficients, particularly anisotropic ones, may significantly influence the properties of resulting instabilities. So far we have studied almost all cases of combinations of anisotropy (a) and isotropy (i) of the diffusive coefficients, i.e. (viscosity, thermal diffusivity, magnetic diffusivity) = ($\nu\kappa\eta$) = (*iii, aii, iai, iia, aai, aia, iaa, aaa*), where e.g. *iia* has meaning that ν is isotropic, κ is isotropic and η is anisotropic. Firstly, in SB10 we studied the case (*aai*) with only isotropic η, in FBS19 the fully anisotropic case (*aaa*) and in FB20 were studied cases (*iia, iaa*) with anisotropic η and roughly the case (*iai*) with only κ anisotropic. Of course in all papers we compared the studied cases with fully isotropic case (*iii*), and in the cases of later papers the comparison was made with the cases of former papers.

As is usual in linear magnetoconvection models, we used the analysis in terms of normal modes to look for preferred modes. Following Roberts & Jones (2000) and noting the orientation of the convection rolls, we considered Stationary Cross rolls (SC) modes, Stationary Oblique rolls (SO) modes, and Stationary Parallel rolls (P) modes if the roll axes are cross (perpendicular), oblique, and parallel to the applied magnetic field, respectively. It was demonstrated (in SB10, FBS19 and FB20) how different anisotropies strongly influence the occurrence of the preference of such types of convection (SC, SO, and P modes).

In the two first papers, it was also shown how two different subcases of anisotropic diffusion, Stratification Anisotropy (SA) and Braginsky-Meytlis (BM) anisotropy, influence the convection in very different ways. In the SA case, there is horizontal isotropy, in the sense that the viscosity and thermal and magnetic diffusive coefficients along the *x* and *y* axes are identical to each other, but the ones in the vertical direction, the *z*-axis, are different ($\nu xx = \nu yy \neq \nu zz$, $\kappa xx = \kappa yy \neq \kappa zz$, $\eta xx = \eta yy \neq \eta zz$). In the models used first in SB10 and then extended in FBS19 and FB20, this SA case physically means that the density stratification is determined by the vertical direction of gravity and/or that the Archimedean buoyancy force has a dominant influence on the quality of anisotropy, as well as on the dynamics; furthermore, the axis of rotation also tends in the vertical direction in *z* in this situation. In BM, the diffusion along the *x*-axes is lower than the diffusion along the *y*- and *z*-axes (directions of basic magnetic field and rotation axis in the aforementioned studies), so the horizontal isotropy is broken ($\nu_{xx} < \nu_{yy} = \nu_{zz}$, $\kappa_{xx} < \kappa_{yy} = \kappa_{zz}$, $\eta_{xx} < \eta_{yy} = \eta_{zz}$). Thus, these BM cases physically occur if the rotation and the magnetic field have a dominant influence on the dynamics of turbulent eddies and thus on the quality of anisotropy. In SB10 anisotropic parameter $\alpha = \nu_{xx} / \nu_{zz} = \kappa_{xx} / \kappa_{zz} = \eta_{xx} / \eta_{zz}$ was introduced as a ratio of horizontal and vertical diffusivities and it is used in all our anisotropic studies. In SA anisotropy we distinguish Sa and So anisotropies for $\alpha < 1$ and $\alpha > 1$, respectively.

In the 2nd and 3rd papers FBS19 and FB20, we focused attention on stationary modes of convection; indeed, it was observed (see, e.g. Roberts & King 2013) that overstable modes are inefficient transporters of heat and are easily overwhelmed by the stationary modes that are excited at slightly larger *Ra*. We focused also on strong SA anisotropies deriving asymptotic formulas for anisotropic parameter $\alpha \ll 1$ and $\alpha \gg 1$. Further, in the 3rd paper we focused our attention only on SA anisotropies. In particular, in strong Sa anisotropy ($\alpha \ll 1$, strong SA anisotropy of atmospheric type) the change of preference between P/SO modes and SO/SC modes is at values of Ekman number, $E \ll 1$, closer to the Earth's outer core conditions.

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Convection, numerical approaches

(Geophys. Astrophys. Fluid Dyn., Rani, Rameshwar, Brestenský, 2019)

Numerical approach using commercial software, ANSYS Fluent, was used mainly in (Rani, Rameshwar & Brestenský 2019) to problems of convection, namely, Rayleigh–Bénard Convection (RBC), Magnetoconvection with no rotation (MC) and Rotating Magnetoconvection (RMC). It allowed to solve not only the linear problems of convective instabilities onset, but respecting non-linear terms in basic equations the highly developed convection was studied for huge Rayleigh number, *Ra*, too. Thus, our numerical simulations confirmed basic knowledge on RBC, MC and RMC (Chandrasekhar 1961) and even results of the experiments with liquid gallium (Aurnou & Olson 2001), too. The efficiency of heat transfer in convective fluid was also studied confirming its increase by *Ra*.

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Natural Dynamos

(Geophys. Astrophys. Fluid Dyn., Šimkanin, Kyselica, Brestenský, Guba, 2019)

Šimkanin, Kyselica, Brestenský & Guba (2019) were the Guest Editors of the Special Issue of Journal “Geophysical & Astrophysical Fluid Dynamics” related to contributions to the Conference on “Natural Dynamos” which was held in Valtice Castle in the Czech Republic in June 2017. The Conference was organized by Czech and Slovak institutions and was supported by IAGA – International Association of Geomagnetism and Aeronomy of IUGG. The topics of the conference covered hydromagnetic dynamos, magnetoconvection and various hydromagnetic processes, all of which occur in the Earth and planetary cores, in the Sun and other stars, in galaxies, in accretion discs and other astrophysical objects, as well as in laboratory hydromagnetic and dynamo experiments.

Convection in mushy layers
(*Daniel M. Anderson, Peter Guba, Andrew J. Wells, Mushy-layer convection, Physics Today 75(2), 34--39, 2022)*

The formation of sea ice in the polar oceans and the development of defects in metal casts may seem like two unrelated processes, but they have one important feature in common: the occurrence of a so-called mushy layer. Mushy layers host complex dynamics of fluid flow, thermal and chemical transport, phase transformations, nonlinear dynamics and pattern formation. The consequences can be significant, ranging from degradation of industrially cast turbine blades for aerospace and energy industries to global climate change (see Anderson & Guba 2020 for a review).

Mushy layers are multiphase porous mixtures of dendritic solids and solute-rich interstitial fluid, which arise during the solidification of multicomponent alloys. We present the results of mathematical modelling of the phase change and fluid flow in the mushy layers arising during the solidification of binary and ternary alloys. The mushy layer equations are derived by applying the general principles of continuum mechanics to control volumes containing representative samples of both phases. The model consistently describes the interactions between solidification and convection in mushy layers: fluid flow causes the advective transport of heat and solutes, which in turn affects the local solidification rate.

Convection in mushy layers can be localized and form narrow solid-free channels, or chimneys, which are oriented parallel to the growth direction. This process was directly observed in recent computer simulations of sea-ice evolution using an advanced numerical scheme based on the enthalpy method. In materials engineering, these channels are associated with structural defects in the resulting alloy (ingot).

2. Electromagnetic and integrated geophysical research

Crustal and lithospheric studies in Slovakia
(Geol. Q., Bezák, Vozár, Majcin, Klanica, Madarás, 2021; Geol. Carpath., Vozár, Bezák, Marko, 2021; Geophys. multiparametric modeling [...], Vozár, Bielik, Bezák, 2022)

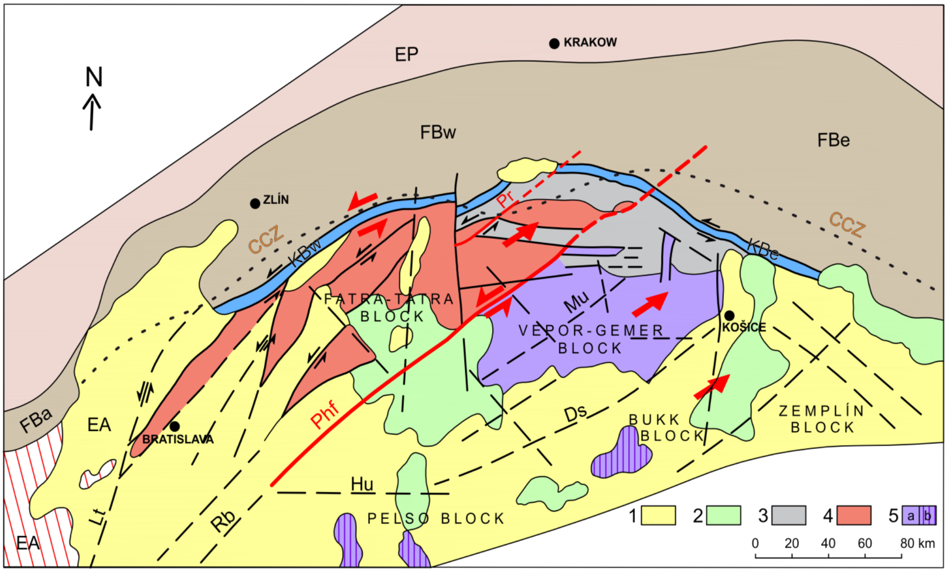

Fig. 1: *Scheme of division of the Inner Western Carpathians into two blocks with different kinematics during the Neoalpine tectonic development in the Cenozoic (Bezák et al., 2021).*

Most of the studies imaging crust and lithosphere were obtained within the project APVV-16-0482 (LITHORES) (Vozar et al., 2022). The modelling is based on magnetotellurics (MT) providing conductivity models of structures, which was combined with other geophysical methods. The research was conducted to image structures at the contact of the Outer and Inner Carpathians (Bezak et al., 2021). The conductivity profiles across the Klippen Belt (KB) from 2D and 3D MT modelling were used to compare the deeper structures of the KB in its western and eastern sections. In the western section the tectonics is dominated by the Flysch Belt (FB) overthrusts onto the KB. On the other hand in the eastern section the situation is opposite, where the KB is thrusted on the FB. By later processes, the southern part of KB is cut off by steep faults. The contrasting tectonic style of the western and eastern sections of KB reflects the different kinematics of the Inner Western Carpathians (IWC) and the European Platform (EP) collision in the western and eastern parts. While in the western part the transpression tectonics dominated, in the eastern part there were frontal thrusts on the EP. Only then the transpression movements along the BP begin. In the central Slovakia we modelled and interpreted MT data along the seismic profile 2T, which from north to south the 2T profile crosses all the basic tectonic units of the Outer and Inner Carpathians. The interpretation was combined with seismics, gravimetric and geothermal information on the section. Compared to the 2D model, the 3D MT model gives qualitatively new information about the physical properties of the crust along the profile and in its immediate vicinity. The new phenomena are highlighted in the 3D image, such as whole crustal conductivity zones at the boundary of physically contrasting blocks, namely the Carpathian conductivity zone (CCZ), the Pohorelá shear zone and the Zdychava fault zone. We see a significant difference especially in the case of the interpreted CCZ, which was not visible in the 2D section. On the contrary, in the sections through 3D model the CCZ is clearly visible and we assume that it reflects significant fault zones at the EP-IWC junction (Vozar et al., 2021).

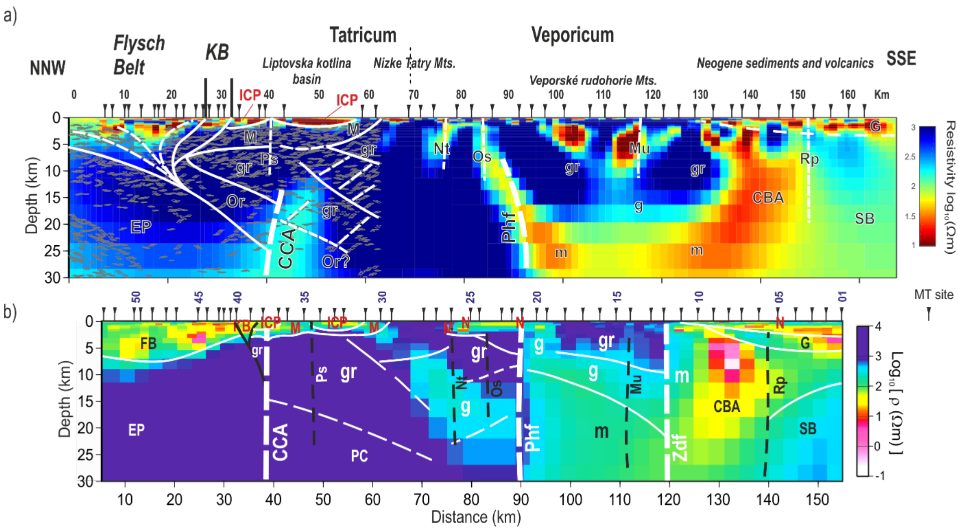

Fig. 2: *Comparison of (a) MT 3D model and (b) MT 2D model along 2T section and their geological interpretations (Bezák et al., 2020 a Vozár et al., 2021).*

Studies of faults

(Geophys. J. Int., Vozár, Jones, Campanya, Yeomans, Mullerm, Pasquali, 2020; Contrib. Geophys. Geod., Ondrašová, Vozár, Hók, Cipciar, Godová, Klanica, 2022)

The MT models revealed a conductive feature down to depths of 4 km and they were interpreted with existing seismic profiles in the area of the Blackrock–Newcastle Fault (BNF) zone in Ireland (Fig. 3). The first shallower zone is connected with shallow faults or folds probably filled with less saline waters. The second deeper conductive structures are oriented along the BNF and they are interpreted as geothermal-fluid-bearing rocks. Porosity and permeability estimations from the lithological borehole logs indicate the geothermal potential of the bedrock, to deliver warm water to the surface. The fluid permeability estimation, based on Archie's law for porous structures and synthetic studies of fractured zones, suggests a medium permeability, which is prospective for geothermal energy exploitation (Vozár et al., 2020).

The well-known seismoactive Dobrá Voda area in the Malé Karpaty Mts. was investigated by MT method. Magnetotellurics provides an image of the shallow conductive structures are associated with Neogene sediments of the Danube Basin, sedimentary fill of the Dobrá Voda Depression, and partial nappes of Hronicum, probably saturated with water. Less conductive structures are the Fatricum sediments and the lowest conductivity values belong to crystalline basement of the Tatricum tectonic unit. Whole structure of the Dobrá Voda seismoactive area along our magnetotelluric profile is disrupted by NE – SW oriented normal faults (Fig. 4). Based on the location of earthquake hypocentres, we can identify main seismoactive areas as crystalline complexes of Tatricum (Ondrašová et al., 2022).

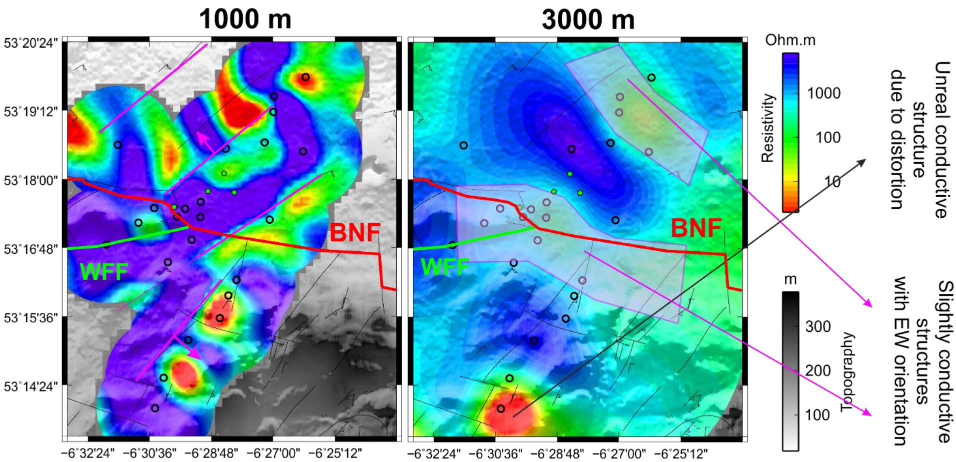

Fig. 3: *Horizontal sections at depth 1km and 3km with indicated main features in the model and its possible interpretation. The purple lines in 1km section highlight strong lateral boundaries which are correlated with surface traces of faults (WFF - Wheatfield Fault). The 3km section show deeper conductive structures, which are oriented along the BNF (purple semi-transparent areas). The high conductive structure in the south is interpreted as unreal structure (black arrow).*

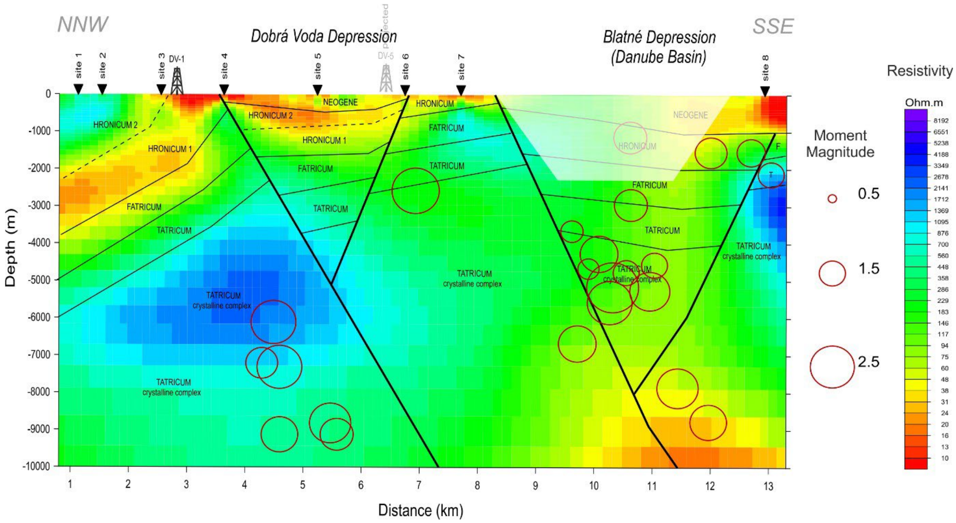

Fig. 4: *The final 2D model of the MT profile DVMT01with interpreted tectonic structures and positions of earthquake hypocentres. Shaded area indicates low resolution part of the model.*

Understanding 1D magnetotelluric apparent resistivity and phase
(J. Electromagn. Waves Appl., Marsenić, 2020)

In order to understand the measured electromagnetic response of the investigated geological substratum, in addition to practical experience, knowledge of the possible physical processes that contribute to it is also required. Both of these abilities participate in building-up the scientific intuition, which is necessary especially when information about the system is mediated or ambiguous. Some simplifying circumstances help to unravel a generally complex situation. The magnetotelluric method works with the model of a vertically incident plane-polarized electromagnetic wave, which means that the excitation electric and magnetic fields are horizontal. Considering this assumption, it appears that the real response in a three-dimensional situation (in an ideal case without perturbations) is composed of elementary responses in one- and two-dimensional situations. Therefore, it makes sense to deal with these cases in detail. Another important assumption of the magnetotelluric method is the diffusional nature of the propagation of source electromagnetic fields in the ground. The possibility of reflection, and therefore also scattering of the electromagnetic signal on the internal interfaces, is thus excluded (let us note that present magnetotellurics, despite its own assumption, takes these phenomena into account). The measured response of the subsoil is represented by its impedance, a complex quantity, from which the apparent resistivity and impedance phase are derived as more evident characteristics. All these quantities depend on the frequency (or period) of electromagnetic field variations. The inspiration for the presented study was the book by Simpson and Bahr (2005), which currently represents one of the collections of knowledge about the basics of magnetotellurics.

This study deals with a 1D model of a layered half-space. Based on physical considerations about the exponential attenuation of the electric field with depth, a relation for the apparent resistivity of the known system of resistive layers was derived. This attenuation is gradual and its rate depends on the conductivity of the layer into which the electromagnetic signal with a given frequency is able to penetrate, while the history of passing through the higher layers is recorded in amplitude and phase shift. Subsequently, the cause of the impedance phase change was investigated. It was found that the magnetic field does not penetrate into the medium from the surface, but is created by telluric currents inside the layer with the appropriate conductivity due to the penetrating electric field. Unlike the electric field, it does not have a history of overcoming higher layers, which is also reflected in its propagation constant. This fact is reflected in the phase shift between these two fields. Such a view of the behaviour of electromagnetic fields in the earth is very different from the previous ideas and is documented in the attached images.

Results for two different layer systems are presented in a logarithmic scale for frequency from the interval [0.0001, 10000] Hz. Both consist of three layers characterized by resistivity and thickness on a homogeneous resistive substratum. The resulting dependences of apparent resistivities and impedance phase are characterized by sharp changes at the border frequencies, which is a consequence of the sharp conductive interfaces between the layers. Apparent resistivities and impedance phases were also calculated by means of the traditionally used Wait's recursion formula. These curves are smooth, but show some spurious, unphysical oscillations before the real change arrives. For the purposes of this study, they are important for two reasons: to provide some basis for comparing the results obtained; and to serve instead of actual measured data to test the reliability of the later inversion.

On the left in Figs. 5 and 6, in addition to the calculated curves for the apparent resistivity, the intrinsic resistivities of the individual layers affected by the electromagnetic signal of the respective frequency are shown. It is obvious that the signals of the highest frequencies are not felt by the lower layers and with decreasing frequency they react to them gradually. Thus, the calculated apparent resistivity curve never exceeds the limit values from the interval of possible values determined by the layers' own resistivities. For very low frequencies it approaches to the intrinsic resistivity of the substratum. The derived formula represents a form of averaging the resistivities of the penetrated layers, taking into account their thicknesses, and meets all the criteria for a correctly defined apparent resistance established in the work of Basǫkur (1994). Impedance phases are shown on the right. Although local extremes of apparent resistivity indicate transitions between individual layers, an even better indicator is a change in the curvature of the impedance phase. Phase inflection points are a unique indicator of resistive interfaces. This is the factor that makes the impedance phase such an important diagnostic tool of the magnetotelluric method, as it provides valuable information for the inversion of the actual measured data in order to determine the composition of the geological bedrock.

Understanding of these behaviours may help in interpretation of real measured data. Based on our findings, a data inversion method was proposed. It is performed in two steps. First, the border values in terms of frequency - apparent resistivity pairs are identified based on the inflection points of the impedance phase. These values are then used to calculate layer thicknesses and resistivities in a straightforward manner using the derived relations.

References:

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System 1

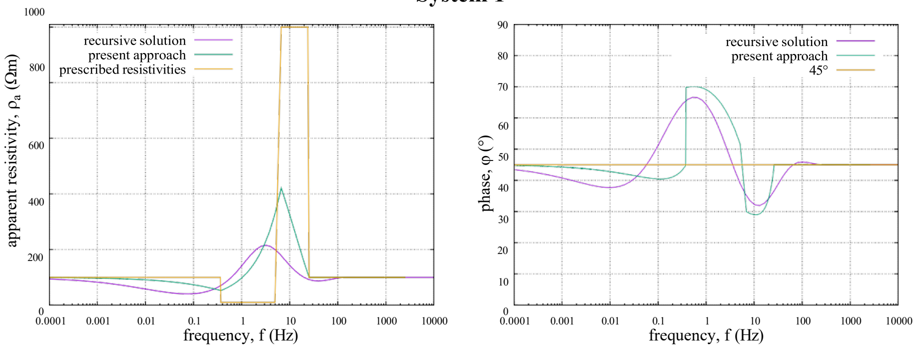

Figure 5. *Computed apparent resistivity and phase difference between electric and magnetic fields for Half-space 1. The dependences obtained as a result of this study show sharp changes that reflect sharp transitions in the physical conditions at the interfaces between the layers.*

System 2

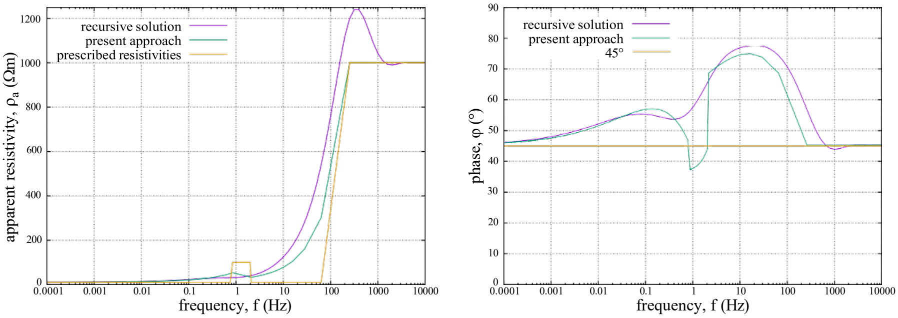

Figure 6. *Computed apparent resistivity and phase difference between electric and magnetic fields for Half-space 2. The dependences obtained as a result of this study show sharp changes that reflect sharp transitions in the physical conditions at the interfaces between the layers.*

3. Paleomagnetic studies

New paleomagnetic constraints for the large-scale displacement of the Hronic nappe system of the Central Western Carpathians

(J. Geodyn., Márton, Madzin, Plašienka, Grabowski, Bučová, Aubrecht, Putiš, 2020)

The aim of our paleomagnetic research is to obtain the appropriate amount of paleomagnetic data from the nappe units of the Late Cretaceous nappe stack of the Central Western Carpathians, Slovakia. Based on the paleomagnetic data we try to decipher the origin of Western Carpathian arc. Lately, a robust dataset of paleomagnetic results from the structurally highest thin-skinned Hronic nappe Unit of the Central Western Carpathians has been published. We carried out a systematic paleomagnetic study on 24 Permian and 20 Triassic geographically distributed localities. We documented the pre-tilting age of remanences for the majority of both the Permian and Triassic age groups. However, the latter was interpreted as remagnetized during the Cretaceous Normal Super-Chron due to nappe stacking between 90-80 Ma. The Permian group is exhibiting about 70°, the Triassic about 34° clockwise vertical axis rotations with respect to the present north. The obtained paleomagnetic directions are consistent throughout the entire studied area, therefore, there is no indication in our dataset for oroclinal bending of the Hronic Unit during or after the nappe emplacement.

Magnetic fabrics in the turbidite deposits of the Central Carpathian Paleogene Basin in relation to sedimentary and tectonic fabric elements
(Geol. Carpath., Madzin, Márton, Starek, Mikuš, 2021)

The magnetic fabric represents powerful tool for studying preferred orientation especially in weakly deformed rocks. We studied AMS (Anisotropy of magnetic susceptibility) and AARM (Anisotropy of anhysteretic remanent magnetization) in Oligocene turbidite deposits of the Central Carpathian Paleogene Basin (Western Carpathians, Slovakia). We compared magnetic fabrics in individual intervals of the Bouma sequence with sedimentary structures and tectonic brittle mesostructures (joints) in order to decide whether the magnetic fabric can be related to deposition from a paleoflow or to incipient weak tectonic deformation. In the Ta–Te intervals we observed a good correlation between maximum susceptibility axes and SW(W)–NE(E) oriented paleoflows. Within convoluted and slump folded sandstones the AMS fabric coincides with the orientation of soft-sediment deformation structures. These features suggest the sedimentary origin of the AMS fabric. The AARM (orientation of only ferromagnetic mineral phases) showed more complex fashion related mostly to conjugate joint system. Magnetic and microscopic analyses indicate that the AARM fabrics are connected to magnetite associated with subordinate ferrimagnetic iron sulphides. Both minerals occur in a sub-microscopic size and formed most likely during late diagenesis through the alteration of pyrite, possibly accompanied by burial clay transformation processes. The growth of the authigenic ferrimagnetic minerals was conditioned by combined effects of the sedimentary petrofabric, lithology and stress conditions during the inversion of the basin in the Early to Middle Miocene.

4. Ground-based observations of the geomagnetic field

The geomagnetic activity and study of historical records of the geomagnetic field
(J. Space Weather Space Clim., Valach, Hejda, Revallo, Bochníček, 2019; Ann. Geophys., Hejda, Valach, Revallo, 2021)

Besides the continuous routine monitoring of geomagnetic activity at the national geomagnetic observatory – Hurbanovo Geomagnetic Observatory of the Earth Science Institute of the Slovak Academy of Sciences (since 1998 a member of INTERMAGNET) – attention was also paid to the study of historical records and the interpretation of extreme geomagnetic events in the past.

The research was focused on those geomagnetic observations that began at the historic Clementinum observatory in Prague in 1839. The records of declination for the period 1839 to 1917 and horizontal intensity between 1839 and 1904 have been preserved in printed yearbooks until the present time. However, the data from the first years were not given in physical units but in divisions of the scale – as they were read from the scale of measuring device. The research of historical geomagnetic records in cooperation with the Institute of Geophysics, Academy of Sciences of the Czech Republic consisted of collection, processing and digitization of the data on geomagnetic declination and horizontal intensity for the entire period of operation of the Clementinum observatory.

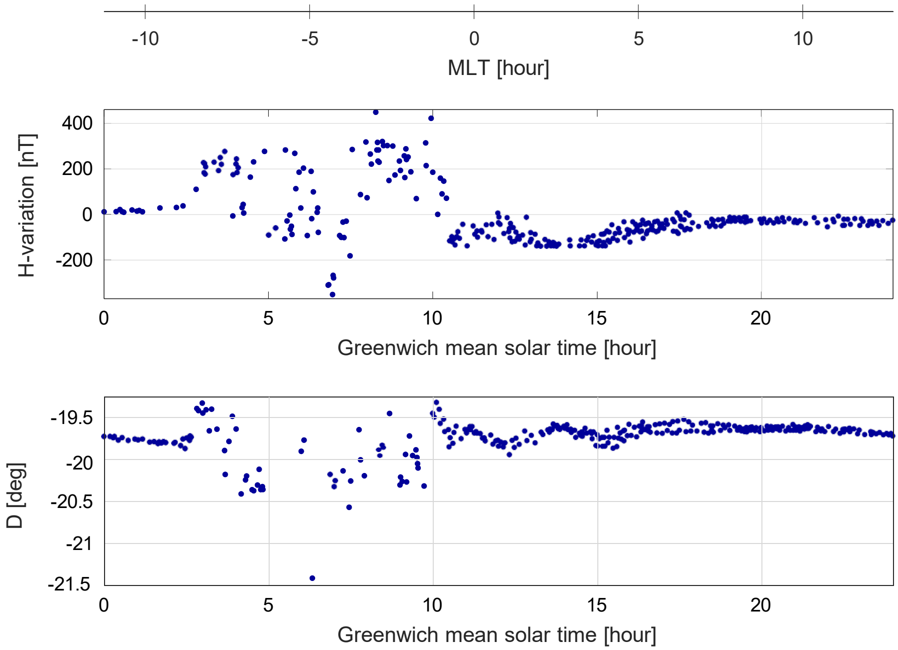

Figure 7. *The records of the horizontal intensity (horizontal component of the geomagnetic field) and magnetic declination from the observatory Greenwich during the extreme magnetic storm on 4 February 1872 (in Valach et al., 2019). At the top of the figure, MLT stands for magnetic local time.*

It turned out, that declination measurements could be converted to angular units in a relatively straightforward manner. On the other hand, more effort was needed to recalculate the data on horizontal intensity of the geomagnetic field. It should be noted that in the 19th century, a specific device known as a bifilar magnetometer was commonly used to monitor the changes of horizontal intensity, such as magnetic storms. It was a device based on a magnetized rod (or a large needle) suspended on two long thin threads (hence the name bifilar). However, the magnetization of the rod was strongly temperature dependent, which was the major shortcoming of the device. When converting the divisions of the scale to the horizontal intensity, it was necessary to determine the proper temperature corrections. During the first years of the operation of the observatory the temperature corrections were not performed. It is important to note that the completed and thoroughly corrected geomagnetic data from the early years of the Clementium observatory are of great scientific value. In turn, for a part of the later measurements, it was necessary to verify and sometimes recalculate the temperature correction coefficients determined at that time. Measurements using the Gaussian absolute method were also an essential part of the observation of the geomagnetic field intensity. The absolute measurements that were carried out in the first years also had to be carefully and critically evaluated. The final data in digital form expressed in the SI units were published in full *(Hejda et al., 2021)*.

The very first measurements in Prague (being started on 1 July 1839) were initially characterized by great unreliability, which is why the data of 1839 were not included in the digital database. Nonetheless, the first documented Prague observations of an intense magnetic storm, which began on 3 September 1839, were processed and made public in subsequent study. During the first hours of this event, there were two very sharp drops in the horizontal intensity (respectively at 01:39 and 04:59 of the magnetic local time; during the second of the drops, the horizontal intensity decreased by about 400 nT). A probable interpretation of these drops is that they were associated with substorms or some variations caused by electric currents related to the auroral oval. There is a report about the northern lights on 3 September 1839 which were seen in Ashurst in West Sussex, England, at a similar latitude as Prague, which indirectly supports the substorm hypothesis.

The role of the auroral-oval related electric currents was also investigated in the records of two other historical events that occurred on 17 November 1848 and 4 February 1872, respectively *(Valach et al., 2019)*. This time, the auroras were again observed in both cases at very low geomagnetic latitudes. The first of the events was also found in the records of the Clementinum observatory in Prague. Here, the decrease in horizontal intensity occurred around magnetic midnight, with the horizontal intensity dropping by more than 400 nT. It was a very sharp and short-lasting drop, followed by an equally sharp return to near-normal values. The record of the magnetic declination at that time had a distinct sinusoidal shape: first a deviation to the west and immediately after it a deviation to the east. From the variations of the magnetic declination and horizontal intensity, it was concluded that in this case, too, it was a disturbance caused by the substorm electrojet. The well-known event of 4 February 1872 is considered to be the strongest magnetic storm ever recorded, based on the extent of the accompanying aurora borealis; or this event is at least comparable to the famous Carrington storm of 2 September 1859. The records of declination and horizontal intensity (with variation of more than 500 nT) from the observatory Greenwich shown in Fig. 7 and the horizontal intensity record from the Colaba observatory (a drop deeper than 800 nT caused by the ring current) were interpreted.

According to the published interpretation in Fig. 8, the increase in horizontal intensity by more than 200 nT is attributed to the eastward electrojet, an inconspicuous decrease in horizontal intensity and declination by about 5 UT to a field aligned current, and a significant temporary decrease in horizontal intensity (by 350 nT compared to the quiet state) to the ring current (in time it agrees with the decrease in Colaba). The whole event ended with a sudden drop of about 500 nT in half an hour, when the eastern electrojet stopped affecting the measured horizontal intensity. It was assumed that Greenwich was then located a little north of the eastward electrojet.

The interpretations of all the three events mentioned above (3 September 1839, 17 November 1848, and 4 February 1872) suggest that the electric currents of the auroral oval and/or field aligned currents connected to the auroral oval may play a significant role in extreme geomagnetic variations occurring in the mid-latitudes.

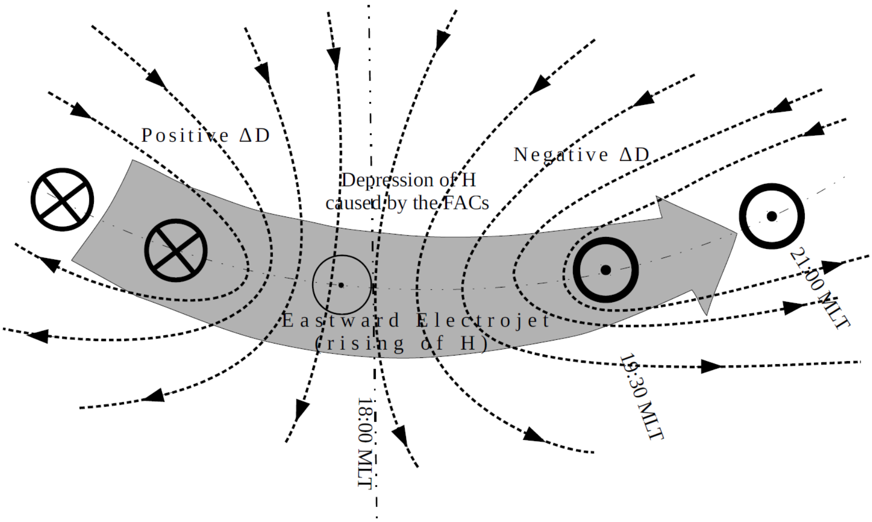

Figure 8. *The eastward electrojet that was located a bit equatorward from the Greenwich observatory at the time of the extreme geomagnetic disturbance on 4 February 1872 – according to the interpretation of Valach et al. (2019).*

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CZECH – SLOVAK Bilateral Project
Comparison of geophysical and geological structures of the Western Carpathian lithosphere with other orogenic areas in Europe (mainly Bohemian Massif and Norwegian Caledonides)
2020–2022
Coordinators – Radek Klanica and Vladimír Bezák

POLAND – SLOVAK Bilateral Project
Regional conductivity anomalies role in tectonic development of the Carpathians
2019–2022
Coordinators – Szymon Orzynski and Ján Vozár

ERA.MIN2 (ERA.NET, H2020) Multi-lateral Project
D-Rex - Deposit-to-Regional Scale Exploration
2019–2023
Coordinators – Maxim Smirnov and Ján Vozár

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

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Interactions of natural and anthropogenic drivers and hydrological processes on local and regional scales: review of main results of Slovak hydrology from 2019 to 2022 (Report to IAHS)

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1.Introduction

It is internationally recognized that the need to increase understanding of the impacts of changing natural and anthropogenic drivers on hydrological processes on local and regional scales is an essential prerequisite not only for the advance of the science of hydrology but a necessary precondition for addressing practical water resources management problems (Blöschl et al., 2019a; Blauhut et al., 2022; Dolejš et al., 2022). The abundance of spatial and temporal variability of climatic drivers and regional and local runoff generation controls in Slovakia (Lehotský et al., 2022; Lehotský and Boltižiar, 2022) results in various runoff regimes. That complicates the attempts to arrive at generalized descriptions of the genesis of particular types of regimes and events. The same applies to hydrological extremes, which generally exhibit specific patterns of regional and local hazards (Blöschl et al., 2019b), complicating thereby the design of generally applicable mitigation schemes (Lun et al., 2021; van Loon et al., 2022). In this respect, understanding the local, catchment and regional scale of hydrological processes became imperative in addressing science and practical water resources management questions. Specifying ecosystem services (Kaletová et al., 2019; Pastor et al., 2022) requires studying fundamental drivers that alter patterns and processes across spatial and temporal dimensions in catchments and streams (Allen et al., 2020). New data sources (such as remote sensing (Kuban et al., 2022), radar meteorology (Nechaj et al., 2019; Méri et al., 2021), Lidar measurements (Vorobyeva et al. (2019)) experiments on hillslopes, and tracer studies have offered unique opportunities to develop and compare different models of the same type (e.g., distributed) or different types of models (e.g., distributed vs lumped, process-based vs conceptual) on a local and regional basis. The confrontation of catchment experiments with results from catchment modelling has become popular in recent years in the region (Szolgay et al., 2020). This report continues the tradition of the Slovak National Reports to IUGG on behalf of the IAHS (Szolgay, 2003, 2007, 2011, 2015, 2019). It reviews the response of hydrologic research in Slovakia from 2019 to 2022 to these challenges. The main research focuses are referenced in the bibliography of selected research papers with a short description of the paper.

2. Soil-water-plant-atmosphere interactions on point and plot scales

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 has been partly focused on quantifying the water balance components in the unsaturated zone of soils in natural, agricultural and forested catchment ecosystems. Field research was conducted, and methodological aspects of modelling were tested and verified under lowland conditions 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 using monitoring and mathematical modelling 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 natural soils. Laboratory and field research on the shrinking and swelling processes in heavy soils was focused on the East Slovakian Lowland.

Botyanszká et al. (2022) investigated the effect of the microplastics in silty loam soil on selected soil properties and the growth of radishes. Still, the measured values of the soil characteristics have not shown significant changes. Czachor et al. (2020) investigated how sample geometry affects the water retention curve by simulation and experimental proof. A 3D virtual network was numerically constructed from particles of various sizes, and the drainage process was simulated. The resulting moisture retention curves suggested that the sample geometry affects the drainage. Dulovičová et al. (2022) assessed the hydraulic conductivities from 14 empirical formulas. They developed a simple method to estimate hydraulic conductivities for clayey sand sediments using sediment samples extracted from irrigation canals in Žitný Ostrov, Southern Slovakia. Gluba,etal., (20211) studied the effect of fine-size-fractionated sunflower husk biochar on water retention properties of sandy arable soil and explained the water retention effects as the interplay between the dose, the size of biochar particles, and the porous properties of biochar fractions. Gomboš et al. (2021) studied the winter water refill of the soil profile of heavy clay soils, lighter clay-loam-silty soils and the lightest loam soils from three localities of East Slovakian Lowland (ESL). The soil water storage, vertical scatter of soil profile moisture volume, temporal and spatial moisture regime changes and soil water availability for plant cover during the 2015 extreme drought period were analyzed.

Gomboš et al. (2022) presented results of theoretical approaches and experimental measurements of the settling rate of soil microparticles from laser diffraction measurements on soil samples taken in the East Slovakian Lowland. The results were compared with the results calculated by the Stokes equation. Hlaváčiková et al. (2019a) presented results of quantification of the number of macropores, their relative volume and the ratio of water infiltrating through the macropores for five study sites with stony soils located in a mountain catchment of northern Slovakia. Hlaváčiková et al. (2019b) investigated the effect of two types of biochars on the water retention of clay, loamy soil and silica sand. Despite the positive effect on soil water retention, a statistically significant increase in available water capacity was identified only in the loam soil.

Jančo et al. (2021) investigated the effect of mature spruce forests on canopy interception in subalpine conditions during three growing seasons. Throughfall and gross precipitation measurements were carried out at an elevation of 1,420 m a.s.l. in the Western Tatra Mountains and evaluated with respect to the interception process during the growing season from May to October 2018–2020. Kidron et al. (2022) reviewed mechanisms for biocrust-modulated runoff generation concerning mechanisms for runoff generation due to water repellency, pore-clogging, soil texture and structural features, including surface roughness. Oravcová and Vido (2022) aimed to evaluate the risk of drought from a meteorological point of view and the subsequent response in soil hydrology throughout the hydrological years 2015 and 2016 in beech forests in Central Slovakia. The drought lasted longer in deeper layers and retreated only after long-lasting rainfall. Sudden heavy rainfall has proven ineffective at moistening the entire soil profile, impacting only the upper few centimetres while the main root zone suffers from water shortage. Rončák et al. (2021) analyzed and statistically confirmed the relationship between the computed daily values of the effective precipitation index and the measured moisture content of the topsoil of a research site near Nitra, Slovakia. Sándor et al. (2021) considered the impact of climate, soil properties and grassland cover on soil water repellency. They showed an area of land is more likely to be water-repellent if it has a sandy soil texture and a high frequency of prolonged drought events. To study the separate and combined effects of soil texture, climate, and grassland cover type, four sites from different climatic and soil regions were selected in Italy, Hungary, UK and Slovakia.

Tall et al. (2019) studied the influence of soil texture on the course of volume changes of soil on 172 soil samples with different textures collected from 11 sites in the Eastern Slovak Lowland. These were used to measure dependencies between soil volume changes and soil moisture changes under laboratory conditions. Ten mathematical models were created to estimate the relationship between volume changes of soil and soil moisture content and texture. Tall et al. (2019) and Tall and Pavelková (2020) dealt with the development and comparison of individual soil water balance components in two different soil profiles from the Easter-Slovakian-Lowland using two lysimeters filled monolithically with sandy soil profile and silty-loam soil maintaining a constant groundwater level of 1 m below ground. The level was maintained in both soil profiles. Under the same meteorological conditions, all differences in the development of water balance components were caused only by the differences in soil profiles. The actual evapotranspiration and water flow at the bottom of the soil profiles were compared. Under the specific conditions of this experiment, it was shown that the silty-loam soil profile was more prone to drought than the sandy soil profile.

3. Catchment scale surface, subsurface and groundwater flow processes and mathematical modelling of runoff and water quality

With a particular interest in surface, subsurface and groundwater runoff, runoff components were estimated by experimental research, mathematical rainfall-runoff models, water balance studies, and runoff separation methods. Tracer techniques were used to study water movement in the soil and bedrock and the mean transit times in catchments. Modelling was used to estimate the relationship between surface waters and groundwater in the weathered zone of stony soils, where rapid runoff and the reaction of groundwater were studied. Remote sensing was used when describing the spatial distribution components of the hydrological cycle in mountainous catchments. The overall trends in the spatial and temporal distributions of snow density, height and water equivalent in several mountainous catchments were analysed. Snowmelt components hydrologic models used both energy-based and temperature-index approaches in general. The validation of snow models using satellite images was tested.

Cisty et al. (2021a) presented a study dealing with the similarity of catchments, which may be utilised in estimating river flows in catchments without flow measurements. A penalisation method of evaluating similarity was proposed, which helps to identify hydrological similarity, i.e., finding the most similar catchment to a given catchment in the rainfall-runoff process. Kaya et al. (2021) studied the capabilities of soft computing techniques for estimating daily evapotranspiration in Košice. Daily solar radiation, relative humidity, air temperature, and wind speed were the meteorological variables considered in different combinations of multilayer perceptron MLP, support vector regression, and multilinear regression models and are compared with each other and with the Hargreaves-Samani, Ritchie, and Turc empirical equations. Model results showed that the MLP model performed better than the other soft computing techniques. Kuban et al. (2022) investigated the effects of satellite soil moisture data on the parametrisation of topsoil and root zone soil moisture in a conceptual hydrological model in those catchments, which in the validation of the dual-layer conceptual semi-distributed model showed improvement in the runoff simulation efficiency compared to the single objective runoff calibration. The runoff simulation efficiency of three multi-objective calibration approaches was separately considered. Inferences about the specific location and the physiographic properties of the catchments where the inclusion of ASCAT data proved beneficial were made. Lukasová et al. (2019) and Lukasová et al. (2020) investigated the potential of phenological metrics from moderate resolution remotely sensed data to monitor the altitudinal variations in phenological phases of European beech and phenological response to drought. Phenological metrics were derived from the NDVI annual trajectories fitted with a double sigmoid logistic function. Ground observations of phenological phases from twelve beech stands along the altitudinal gradient were employed. The effect of altitude was evaluated through differences in local climatic conditions, especially temperature and precipitation, from the last 30 years in 12 study stands. The approach presented in this paper contributes to a more explicit understanding of satellite data-based beech phenology along the altitudinal gradient. It will be useful for determining the optimal distribution range of European beech under changing climate conditions in hydrological modelling.

Mačejná et al. (2021) hydro-bio-chemical balance of total mercury at former cinnabar mining locality. The most important fluxes of total mercury in two small forested catchment areas with different anthropogenic loads in the Kremnické vrchy Mountains. The study highlighted the importance of forest areas to the biogeochemical cycle of Hg and the influence of areas close to cinnabar mining, even inactive ones. Mezei et al. (2019) combined yearly

Landsat-derived bark beetle infestation spots from 2006 to 2014 and meteorological data to identify the susceptibility of forest stands to beetle infestation. Digital elevation model-derived potential radiation loads predicted beetle infestation, especially in the peak phase of the beetle epidemic. indicating that bark beetles prefer sites with higher insolation during outbreaks. Solar radiation, easily determined from the DEM, better identified beetle infestations than commonly used meteorological variables and can be used in hydrological models in beetle infestation prediction sub-models.

Sokáč and Velísková (2021) conducted laboratory experiments focused on pollution transport and dispersion phenomena in conditions of low flow (low water depth and velocities) in sewers with bed sediment and deposits. Such conditions occur very often in sewer pipes during dry weather flows. Results show that in the hydraulic conditions of a circular sewer pipe with the occurrence of sediment and deposits, the value of the longitudinal dispersion coefficient decreases almost linearly with the decrease of the flow rate (also with the Reynolds number) to a certain limit (inflexion point), blow which it starts to rise again. Tátošová et al. (2021) evaluated the extent of changes in land use in Nitra from 1954 to 2017. The growth of areas with minimal infiltration capacity in the Slovak University of Agriculture area was identified. The possibilities of using rainwater and its accumulation in the monitored area were discussed. Varga and Velísková (2021) assessed the time course of water and air temperature in the locality of the Turček reservoir during its operation from 2005–2019. The analysis confirmed that it is impossible to determine a significant trend despite the rise in annual air temperature during the study period.

Experimental research in snow hydrology has a long tradition in Slovakia. Systematic measurements resulted in a large database of field measurements which started in 1960 in the Low Tatra Mountains and were later extended to the West Tatra Mountains by the Institute of Hydrology of the Slovak Academy of Sciences (Holko et al., 2021). The snow regime of forested sites received particular attention (Bartík et al., 2019). The estimation of snow redistribution by the wind was also outlined, and the spatial and temporal variations of snow water equivalent and the water balance were also documented (Holko et al., 2021). The impact of the changing climate on the snow water using isotopic data, trend and attribution analyses were studied (Holko et al., 2020b). Snow accumulation and melt modelling were practically oriented recently (Holko et al., 2022). Ways were explored how to constrain the parameters of the snowmelt components of an HBV-type model and improve its performance (Sleziak et al., 2020). Studies focusing on the distribution of snow cover in the forests and ski slopes in Central Slovakia were also conducted, and implications for ecosystem services were defined (Mikloš et al., 2020a; Mikloš et al., 2020b).

4. Erosion, sediment transport, river morphology and hydroecology

Qualitative and quantitative investigations of the effect of river morphology on ichthyological fauna in both natural and regulated segments of selected rivers were conducted (e.g. 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, etc.). Factors affecting fish population density were also specified. In a natural stream segment, the number of species, the diversity of species and equitability indices were higher than in regulated ones. Several projects focused on studying river and floodplain processes (flow regime, development of river channels and floodplains, sediment transport) using numerical and physical models to analyse the impacts of human interventions on the river's environmental quality and the adjacent areas. Morphologically stable and environmentally sensitive river training measures were also sought to support creating a natural range of instream and bankside habitats for fisheries, flora and fauna and to protect the wetland ecosystems.

Cisty et al. (2021b) set out options for modelling suspended sediment concentrations for ungauged periods on the Danube River profile in Bratislava. Regression using least absolute selection and shrinkage operator, support vector regression and deep learning neural network were compared using various data sources. A significant increase in the precision of modelling suspended sediment concentrations over the standard rating curve method was achieved. Hlavčová et al. (2019) estimated the effectiveness of crop management on sediment transport on hilly agricultural land in the Myjava region. Field experiments with a rainfall simulator on experimental plots estimated surface runoff and the mass of sediments transported and were used to parameterise the SMODERP physically-based hydrological model. The hydrological modelling of the surface runoff on the selected slope profile quantified the protective effect of various soil covers on reducing surface runoff and sediment transport. Honek et al. (2020) estimated and compared sedimentation rates in small reservoirs by three empirical models (USLE, RUSLE and USPED) applied to two small catchments taking advantage of real measured and modelled sedimentation during 2012 and 2017. The study emphasised the importance of the R-factor value. The USPED model was recommended to estimate the modelling of the siltation rate in small reservoir maintenance projects.

Kaletová et al. (2019), Kaletova et al. (2021), and Pastor et al. (2022) considered the temporal flow variability of non-perennial rivers and the relevance of intermittent rivers in an agricultural landscape in assessing their ecosystem service provision for three different hydrological phases: flowing conditions, isolated pools, and dry streambeds. They also discussed the applicability of new indicators, including the temporal and spatial variability of flow regimes. Kidová et al. (2021) evaluated the impact of river training works on the braided-wandering Belá River in the Slovakian Carpathians. Decreasing geodiversity in managed river reaches, a rapid increase in flow velocity during an extreme flood in trained river reaches, and increasing erosive force in the channel zone was confirmed.

Lehotský et al. (2022) reconstructed the history of the Danube Plain (Podunajská rovina), the largest fluvial system in Slovakia. They showed that in the past, the territory of the Danube Plain has operated as a dynamic fluvial system (inland delta) with its anastomosing, migrating, meandering and braided river channel patterns and the development of several fluvial terraces, levees, abandoned channels and aeolian landforms. Okhravi et al. (2022) addressed the problem of flow resistance in lowland rivers impacted by distributed aquatic vegetation by hypothesising that a fixed value for the bed roughness coefficient in lowland rivers (mostly sand-bed rivers) is deemed practically questionable in 45 cross-sections in four lowland streams. They showed that bed forms and aquatic vegetation were significant sources of boundary resistance in lowland rivers. The study ended with two new flow resistance predictors, which connected the dimensionless unit discharge to flow resistance factors, Darcy-Weisbach (f) and Manning (n) coefficients.

Rodríguez-González et al. (2022) stressed the role of Riparian zones as the paragon of transitional ecosystems, providing critical habitat and ecosystem services that are especially threatened by global change. Following consultation with experts, they identified ten key challenges which must be addressed for riparian vegetation science and management improvement. Using a sediment cascade approach, Rusnák et al. (2020) studied channel and cut-bluff failure connectivity in the braided-wandering Belá River. A terrestrial laser scanning time series was generated by systematically monitoring the cut-bluff slope surface. Volume changes were estimated, and the conceptualisation model of coupling of cut-bluff slope based on spatial and temporal analyses of channel hydrology, a gravity-conditioned transformation of matter and detailed sediment budget calculations was developed. Rusnák et al. (2019) monitored a chute cutoff in the meander bend, the avulsion channel evolution and river morphology changes using UAV photogrammetry on the gravel bed of the Ondava River in Outer Western Carpathians after the 2010 flood events. The mechanism of evolution and post-cutoff avulsion channel adjustment using photogrammetry and field survey was described. Sokáč et al. (2019) presented new approaches to simulating 1D substance transport and tested them on tracer experiments in three small streams in Slovakia with dead zones. Evaluation of the proposed methods, based on different probability distributions, confirmed that they approximate the measured concentrations significantly better than those based upon the commonly used Gaussian distribution.

Štefunková et al. (2020) evaluated a methodology to assess the influence of hydraulic characteristics on habitat quality from the Riverine Habitat Simulation model, which represents the quality of the aquatic habitat by the weighted usable area using brown trout as the bioindicator. The influence of flow velocity and water depth as basic abiotic characteristics that determine the ratio of the suitability of the instream habitat on the objective evaluation of the habitat quality was targeted. Three methods for assessing the habitat quality were tested. Štefunková et al. (2021) evaluated the relationship between abiotic flow characteristics and habitat quality in mountain streams of Slovakia, which was assessed using the Instream Flow Incremental Methodology (IFIM), which uses bioindication. Brown trout was selected as a bioindicator because of its sensitivity to morphological changes, and its occurrence in sufficient reference reaches. Fifty-nine reference reaches of fifty-two mountain and piedmont streams in Slovakia were analysed. Valent et al. (2019) performed a joint sedimentation-flood retention assessment of a small water reservoir in Slovakia. They presented an analysis of changes in the retention capacity over eight years based on a detailed reservoir bathymetry conducted using an acoustic Doppler current profiler. The possibility of strengthening the reservoir's role in flood protection was also investigated.

Pekárová et al. (2020) analysed the long-term development of runoff and nitrates nitrogen concentrations in the Parná River at Horné Orešany water gauge station during the period 1991–2018. Discharges in the Parná River decreased slightly; nitrate concentrations markedly decreased in this river basin. The relation between discharge and nitrate concentration was used to derive exponential empirical relations for estimating the nitrate-nitrogen concentrations in the stream based on mean daily discharge. Siman and Velísková (2020) presented results of the comparison of yearly total nitrogen emissions and the contribution of different emission pathways on these emissions into surface streams for three river catchments in Slovakia territory with a contrasting proportion of agricultural land to the total area of the river catchment using the numerical MONERIS model. Results indicated that in river catchments with a higher proportion of agricultural land, higher contribution of nitrogen emission was carried out mainly via groundwater (especially in lowland) and agricultural erosion and drainage systems.

5. Groundwater

The quantitative aspects of groundwater formation and regimes were studied regionally. Research is also oriented towards the influence of human activities on the natural groundwater regime and surface-groundwater interactions.

Research on the impact of human activities on the recharging groundwater amounts and water quality under different hydrologic conditions was conducted. Numerical groundwater models were used to analyse, predict and control groundwater levels at several water structures in Slovakia. The conditions under which technical measures could improve groundwater regimes, even in extreme hydrologic conditions, were also sought. Abd-Elaty et al. (2019) contributed to groundwater protection techniques based on changing boundary conditions, installing a cut-off wall and using linings for polluted drains. They presented a possible way forward to treat contaminated stream networks. It was concluded that technical measures could improve the groundwater regime. Abd-Elaty et al. (2020) presented simulation-based solutions for reducing soil and groundwater contamination from fertilisers in arid and semi-arid regions by installing drainage networks, which can decrease the groundwater and soil contamination from nonpoint contamination. Baroková et al. (2020) assessed the impact of cut-off walls on the regime of groundwater levels during extreme hydrological conditions in the broader area for both steady and unsteady scenarios. Červeňanská et al. (2021) reconstructed in a case study concerning the May and June 2010 flood the groundwater level rise in the Žitný ostrov region and established the basis for the construction of flood hazard maps and flood risk management plans. Pekárová et al. (2022) aimed to analyse and model the groundwater temperature at the water table in different regions of Slovakia by a simple groundwater temperature model based on a one-dimensional differential Fourier heat conduction equation. It can estimate future groundwater temperature trends using regional air temperature projections for different greenhouse gas emission scenarios. Šoltész et al. (2020) presented a hydraulic assessment of groundwater flow in the area affected by the realisation of the hydraulic gate on a river branch. A 3D mathematical model was created to simulate groundwater flow by changing boundary conditions of surface water flows during flood periods.

6. Hydrological extremes

Recent extreme events in Europe have also stimulated public discussion on the issue of whether the frequency and severity of these have been increasing in Europe and Slovakia and if such changes could be attributed to anthropogenic influence. Large floods and droughts occurred in some regions of Central Europe also during the period covered by this report. That increased interest in the flood and drought formation in catchments from various areas of Slovakia. Statistical analysis was used to study past extreme events. Knowledge of the genesis of extreme precipitation and floods and data on rare events was needed to develop regional generalizations of the flood and drought regime. Several extreme events were individually investigated, and the formation of these 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. An assessment of the historical extremes floods in several rivers complemented characteristics of measured and historical extreme flows. The various risks associated with flooding and droughts were characterized.

Almikaeel et al. (2022b) used a machine to learn hydrological drought forecasting. The assessment of hydrological drought was carried out by indexing dry, normal, and wet hydrological situations. Artificial neural networks and support vector machine models were applied to predict the hydrological drought based on daily average discharges. Bačová Mitková et al. (2021) stressed the need to harmonize design flood assessment methods along long international rivers in the example of the Danube River. Using the Log-Pearson type III distribution, the regionalization of the Log-Pearson type III distribution skew parameter, they also analyzed the effect of the inclusion and exclusion of the historical extremes. Bartok et al. (2022b) applied a novel approach in using machine learning-based fog nowcasting for aviation. Various machine learning algorithms (support vector machine, decision trees, k-nearest neighbours) were adopted to predict fog with visibility below 300 m for a lead time of 30 min. Beyond the standard meteorological variables as predictors, the forecast models also used information on visibility obtained through remote camera observations. These were also applied by Bartok et al. (2022a) to assess visibility conditions.

Blöschl et al. (2019a) and Blöschl et al. (2020), with the participation of Slovak hydrologists, analyzed a comprehensive dataset of flood observations in Europe. They showed that the changing climate has increased river flood discharges in some regions of Europe but decreased in others. They also showed that the past three decades were among the most flood-rich periods in Europe in the past 500 years. The flood changes were broadly consistent with climate model projections for the next century, suggesting that climate-driven changes are already happening. This period differs from other past flood-rich periods in terms of its extent, air temperatures and flood seasonality. The results support calls for considering climate change in flood risk management. The same dataset was used by Lun et al. (2021) to provide a performance baseline for more local flood studies by assessing the estimation accuracy of regional multiple linear regression models for estimating flood moments in ungauged basins.

Čubanová et al. (2019), Šoltész et al. (2021), Mydla et al. (2021), Šoltész et al. (2022), and Čubanová et al. (2022) proposed several management solutions for mitigating flood and drought risk in smaller municipalities based on hydrological-hydraulic assessment. Markovič et al. (2021) investigated extreme heavy precipitation events in the Slovak Republic in the period 1951–2020 in terms of their spatial and temporal distribution. The goal was to create a dynamic-climatological analysis of atmospheric circulation patterns that can eventually lead to extreme multi-day precipitation events. Onderka and Pecho (2021) evaluated the sensitivity of total rainfall kinetic energy, 15-min peak intensities, and total event depth concerning pre-event atmospheric conditions in the northern part of the Pannonian Plain. The analyses revealed strong responsiveness of rainfall kinetic energy and 15-minute peak rainfall intensities to dew point temperature.

Solín and Rusnák (2020) presented a methodological approach to preliminary flood risk assessment conceptually based on the regional typing and integrated flood risk assessment. The basic spatial unit was defined as the municipality district. The flood risk potential index was determined as aggregating the flood hazard and flood consequences. Šurda et al. (2020) aimed to determine the monthly values of the meteorological drought indices of the Nitra region in 2014-2018 and to analyze their sensitivity based on comparing the determined droughts frequency. Vojtek et al. (2022a) and Vojtek et al. (2022b) mapped and assessed the riverine flood potential in municipalities of Slovakia using vector-based spatial multi-criteria analysis and geographic information systems. The flood potential index in municipalities was computed based on eight flood factors, and sensitivity analysis using the modelling approaches was proposed.

Raška et al. (2022) focused on the empirical evidence of the effects of nature-based solutions in flood risk mitigation across various fragmented settings, and their implementation faces a series of institutional barriers. A community expert perspective was used to identify barriers and their cascading and compound interactions. A comprehensive set of 17 barriers affecting the implementation of 12 groups in both urban and rural settings in five European regional environmental domains were identified, and avenues for further research, connecting hydrology and soil science, on the one hand, and land use planning, social geography and economics, on the other suggested. Solín (2019) and Solín and Sládeková Madajová (2019) identified regional types of flood hazards in mountainous regions resulting from the physiographic characteristics. It has been shown that the soil texture permeability and the forest cover are the basin attributes that influence the spatial variability of flood hazards. Based on their combination, several physical geographic classes were created. A framework of integrated flood risk assessment was taken into account.

Vojtek et al. (2019) reported a sensitivity analysis of flood inundation mapping in small and ungauged basins using the event-based approach for small and ungauged basins and a one-dimensional in terms of simulated flood area and volume to different combinations of input parameters. Hydrologic modelling results highlighted the great variety of design peak discharges, which strongly influence the modelled area and volume. Vojtek et al. (2021) identified areas with different levels of riverine flood potential in the Nitra River basin using multi-criteria evaluation, hierarchical analytical process, geographic information systems, and seven flood conditioning factors. Zeleňáková et al. (2019) presented a case study of flow modelling focusing on the open channel of the Slatvinec stream running through the north-east Slovakian village of Kružlov for identifying flood risk areas in the village. Cost analysis for evaluating flood damage to property supplemented the modelling.

7. Runoff fluctuations and anthropogenic impacts on hydrological processes

Time series of precipitation, air temperature and runoff were analysed in several studies to detect and attribute climate change signals using statistical methods. The long-term variability of extremes of Slovak rivers, as well as rivers in the temperate zone of the Northern Hemisphere, were also analysed. The analysis detected a time shift in the occurrence of runoff extremes in the regions studied. 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 the sensitive regions, such as agricultural land and wetlands, were studied, too. Intermittency was observed recently in several rivers, and the phenomenon started to be explored. Several RCM and 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 precipitation totals began. According to these scenarios, a significant increase in air temperature, small changes in long-term precipitation totals, and a remarkable rise in short-term precipitation extremes are expected in Slovakia in the warm half-years. On the other hand, more frequent and extended periods of drought may occur, mainly in the Slovak lowlands, because higher precipitation and a warmer climate in winter will significantly affect the winter runoff and snow regime on most of the territory of Slovakia. Therefore, the whole territory of Slovakia could become more vulnerable to drought in the summer and autumn.

Almikaeel et al. (2022a) investigated flow rate fluctuations in two different streams in Slovakia to investigate the low and peak flow periods and to identify the trends in monthly and annual mean flows for both rivers. Analysing daily mean discharge data from two different types of streams has required using a robust normalisation approach to verify the comparability between the chosen streams. Aziz et al. (2019) dealt with the effects of dams on the water resources in downstream countries, the example of the Grand Ethiopian Renaissance Dam, which included reducing surface water and groundwater levels and changing the crop patterns in the Nile Delta. Blaškovičová et al. (2022a) and Blaškovičová et al. (2022b) focused on the assessment of river drought in Slovakia. Low-flow characteristics and their changes in the 2001–2015 period compared with the 1961–2000 reference period were evaluated with two methods at selected representative water-gauging stations. The results show significant changes in the compared periods. Differences in individual regions of Slovakia were also described.

Csáki et al. (2020) described a multi-model climatic water balance prediction in the Zala River Basin using a modified Budyko framework. The research included validating models and predictions of the main components of the water balance (evapotranspiration and runoff) and using precipitation and temperature results of 12 regional climate model simulations. The mean annual evapotranspiration rate is expected to increase slightly during the 21st century, and for runoff, a substantial decrease can be anticipated. Danáčová et al. (2021) studied the occurrence of areal droughts from 2011 to 2020 in Slovakia based on the data from 164 water gauging stations. The mean monthly discharges were compared with the long-term mean monthly discharges for the baseline period 1961–2000. Trend detection analysis of the mean monthly discharges in 1961–2020 was conducted. The months of April, June, July, August and October were detected as the months with the highest occurrence of mean monthly discharges below 40% of the long–term mean monthly discharges for the reference period.

Halmová et al. (2022) evaluated changes in the hydrological balance of the Krupinica River for the entire 90-year period of observations and three 30-year subperiods. Changes in water resources in the river basin over the three mentioned time subperiods were analysed, and a simple regression relationship between runoff, precipitation and the air temperature was derived to estimate the future development of the annual runoff from the basin. Holko et al. (2020a) Analysed changes in the hydrological cycle of a pristine alpine mountain catchment by isotopic data, trend and attribution analyses. δ18O in precipitation has remained constantly higher since 2014, which might be related to greater evaporation in the region of origin of the air masses bringing precipitation to the studied part of Central Europe. The seasonality of δ18O became less pronounced since 2014. Linear regressions between the drivers and supposedly changed data series explained only about 31% to 36% of the variability.

Lukasová et al. (2021) dealt with regional and altitudinal aspects of summer heatwave intensification in the Western Carpathians for various elevations. The percentile threshold-based calculation of heatwaves was used, which, compared to those using absolute thresholds, allows for revealing the possible threats of climate warming extremes at the range of altitudes. The greatest intensification of heatwaves was evident, particularly in the last decade. Minďaš et al. (2020) evaluated the long-term changes in the chemical composition of precipitation in the mountain forests of Slovakia in a forty-one-year period (1987 to 2018). Two stations with long-term measurements of precipitation quality were selected, all basic chemical components were analysed, and changes in the individual components were statistically evaluated. The results showed significant declining trends for almost all components, which can significantly affect element cycles in mountain forest ecosystems.

Onderka et al. (2020) evaluated the efficiency and reliability of water harvesting systems in dependence on the local climate in Slovakia using 84 rainfall records from climatologically distinct regions. A considerable spatial and seasonal variability has been observed in the statistics of rainfall events. Inter-event times decrease with elevation, whereas event volume and annual incidence of rainfall events increase with elevation. The applicability of the derived rainfall statistics was illustrated by simulations for a typical residential house using the analytical probabilistic approach. Empirical relationships between tank size and site elevation have been developed to estimate tank sizes for un-gauged locations. The simulations show that rain barrels in the southern parts of Slovakia require larger storage capacities than those located in the mountainous regions. The presented annual and seasonal estimates of rainfall characteristics are published for the first time.

Škvareninová et al. (2022) stressed that the onset and duration of phenological events are key indicators of the ecological impact of climate change on vegetation. During 1987–2016, they analysed the occurrence and intensity of frosts during May. Results indicate that recent climate change caused the beginning of flowering to start significantly earlier; thus, the risk of late frost damage to flowers is highly probable, particularly at 160, 300 and 500 m a.s.l., where the flowering and frosts co-occur. Decreased risk of frost damage was found at 400 and 700 m a.s.l. Vido and Nalevanková (2020) stressed that the West Carpathian region forms a transitional zone for drought patterns, which are complicated because of the geomorphologically complicated landscape and analysed drought occurrence and trends indices at available climatological stations of the Slovak Hydrometeorological Institute (SHMI) in the upper Hron region within the 1984–2014 period. They found that drought incidence decreased with increasing altitude, and increasing air temperature increased the difference in drought trends between lowlands and mountains. Abrupt changes in the time series of drought indices, which could indicate some signals of changing atmospheric circulation patterns, were not revealed.

8. Conclusions

Changing climate, recent extreme events and the requirements of implementing the European Water Framework Directive have stimulated public and scientific discussion in Slovakia on improving observing, monitoring and modelling hydrological processes describing these (Szolgay et al., 2020). This report reviewed the response of hydrologic research in Slovakia to the challenges of global hydrologic research between 2019 and 2022. It follows previous reports from 1999, 2004, 2007, 2011 and 2015, and 2019. It summarizes the results and outcomes of the leading research programs in hydrology in Slovakia. The short review and the selected bibliography on hydrological research in Slovakia showed how research reflected the need to investigate the effects of changing natural drivers and new societal pressures on water resources and hydrological processes. In its reaction, Slovak hydrology contributed broadly to the comprehensive understanding of the impacts of the changing climate and altered landuse.

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Defended PhD Theses

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Optimization of flood protection in river basins
Student: Janík, Adam
Supervisor: Šoltész, Andrej
Year of defense: 2020

Institution: Slovak University of Agriculture in Nitra, Faculty of European Studies and Regional Development
Title: The Bioenergetic Potential of Crops as an Adaptation Strategy to Climate Change on Agricultural Land in the Slovak Republic
Student: Žilinský, Matej
Supervisor: Šiška, Bernard
Year of defense: 2020

Institution: Slovak University of Agriculture in Nitra, Faculty of European Studies and Regional Development
Title: The Potential of Greenhouse Gas and Ammonia Emissions Production in the Agriculturally Utilized Land and Model Evaluation of Possible Strategies to Mitigate Emissions in the Slovak Republic
Student: Tonhauzer, Kristína
Supervisor: Šiška, Bernard
Year of defense: 2020

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Optimalization of Filtration Process of Surface Water Treatment Plants to Ensure of Safe Drinking Water
Student: Kapusta, Ondrej
Supervisor: Barloková, Danka
Year of defense: 2019

Institution: Technical University in Zvolen, Faculty of Forestry
Title: Measuring the change of the forest land expectation value in the presence of the risk of fire and an ongoing climate change
Student: Korená Hillayová, Michaela
Supervisor: Holécy, Ján
Year of defense: 2020

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Runoff concentration and soil erosion modeling for the evaluation of nature near flood protection measures
Student: Nosko, Radovan
Supervisor: Szolgay, Ján
Year of defense: 2020

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Surface runoff and erosion modelling under climate change for erosion control
Student: Látková, Tamara
Supervisor: Szolgay, Ján
Year of defense: 2020

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Reverse logistics of waste management
Student: Trošanová, Mária
Supervisor: Škultétyová, Ivona
Year of defense: 2020

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Using multicriterial analysis for sustainability of water resources systems
Student: Dubcová, Mária
Supervisor: Škultétyová, Ivona
Year of defense: 2019

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Identification and removal of micropollutants from water
Student: Marton, Michal
Supervisor: Ilavský, Ján
Year of defense: 2022

Institution: Technical University in Zvolen, Faculty of Forestry
Title: Interception and selected hydric functions in climax spruce after the bark beetle infestation
Student: Jančo, Martin
Supervisor: Škvarenina, Jaroslav
Year of defense: 2020

Institution: Technical University in Zvolen, Faculty of Forestry
Title: Analysis of the impact of changes bio meteorological factors on selected species of game with regard to the fulfilment of ecosystem services
Student: Špiaková, Jana
Supervisor: Škvarenina, Jaroslav
Year of defense: 2019

Institution: Technical University in Zvolen, Faculty of Forestry
Title: Bioclimatic risk of drought in a forest landscape
Student: Oravcová, Zuzana
Supervisor: Vido, Jaroslav
Year of defense: 2022

Institution: Technical University in Zvolen, Faculty of Forestry
Title: Analysis of the Impact of Climatic Extremes on the Quality of Brown Hare Habitats in the Planar and Collin Type of Landscape
Student: Kvas, Andrej
Supervisor: Vido, Jaroslav
Year of defense: 2021

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Assessment of the impact of landscape management on soil ecosystem services
Student: Kudrnová, Lenka
Supervisor: Hlavčová, Kamila
Year of defense: 2022

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Detection of changes in hydrometeorological time series in Slovakia in the conditions of climate change
Student: Ďurigová, Mária
Supervisor: Hlavčová, Kamila
Year of defense: 2020

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Estimation of impact of land use change on design floods in river basins
Student: Labat, Marija Mihaela
Supervisor: Hlavčová, Kamila
Year of defense: 2022

Institution: Slovak University of Agriculture in Nitra, Faculty of Horticulture and Landscape Engineering
Title: Research of phosphorus movement in soil-water-sediment system
Student: Sedmáková, Miroslava
Supervisor: Jurík, Ľuboš
Year of defense: 2019

Institution: Slovak University of Agriculture in Nitra, Faculty of Horticulture and Landscape Engineering
Title: Use of GIS tools for registration and evaluation of water reservoirs in the nitra river basin for the needs of administration and technical safety supervision
Student: Gacko, Igor
Supervisor: Jurík, Ľuboš
Year of defense: 2020

Institution: Technical University of Košice, Faculty of Civil Engineering
Title: Using of information technologies in water management
Student: Fijko, Rastislav
Supervisor: Zeleňáková, Martina
Year of defense: 2019

Institution: Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics
Title: Influence of orography on supercells in Slovakia
Student: Šinger, Miroslav
Supervisor: Gera, Martin
Year of defense: 2021

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Contribution to the water management solution of irrigation reservoirs
Student: Soldánová, Veronika
Supervisor: Čistý, Milan
Year of defense: 2020

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Utilization of climatic databases in analysis and interpolation of suspended sediments on Danube river
Student: Cyprich, František
Supervisor: Čistý, Milan

Year of defense: 2021

Institution: Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics
Title: Impact of selected meteorological and climatic factors on the surface layer ozone deposition in the High Tatras forest environment
Student: Buchholcerová, Anna
Supervisor: Lapin, Milan
Year of defense: 2022

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Identification of the water balance changes in the Danube region subbasins
Student: Garaj, Marcel
Supervisor: Pekárová, Pavla
Year of defense: 2020

Institution: Slovak University of Agriculture in Nitra, Faculty of Horticulture and Landscape Engineering
Title: Research of transport processes in riverbeds of small watercourses
Student: Manina, Martin
Supervisor: Halaj, Peter
Year of defense: 2020

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Climate change impact on short-term rainfall in Slovakia
Student: Földes, Gabriel
Supervisor: Kohnová, Silvia
Year of defense: 2021

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Evaluation of the land use change impact on the intensity of erosion processes using the physically based EROSION-3D model
Student: Németová, Zuzana
Supervisor: Kohnová, Silvia
Year of defense: 2020

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Influence of catchment parameters on water quality indicators in selected profile of surface stream
Student: Siman, Cyril
Supervisor: Velísková, Yvetta
Year of defense: 2020

Institution: Slovak University of Agriculture in Nitra, Faculty of Horticulture and Landscape Engineering
Title: Research the impact of environment on water stress as a possible indicator of irrigation management
Student: Kišš, Vladimír
Supervisor: Bárek, Viliam
Year of defense: 2019

Institution: Slovak University of Agriculture in Nitra, Faculty of Horticulture and Landscape Engineering

Title: Research on Synergy Processes of Remote Sensing Methods and Dendrological Plant Changes for Irrigation Management
Student: Kováčová, Martina
Supervisor: Bárek, Viliam
Year of defense: 2022

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Quality Assessment of The Aquatic Habitat of The Stream Using a Bioindication
Student: Doláková, Gréta
Supervisor: Macura, Viliam
Year of defense: 2022

Institution: Slovak University of Technology in Bratislava, Faculty of Civil Engineering
Title: Interaction of water flow and invasive plants in riverbank vegetation
Student: Vaseková, Barbora
Supervisor: Macura, Viliam
Year of defense: 2020

Research/grant projects

Research in hydrology and related water sciences was supported by the European Regional Development Fund under several Operational Programs. These projects were acknowledged in the papers of the annotated review:

- Centre of excellence for the integrated river basin management in the changing environmental conditions, Project code 26220120062;
- Infrastructure completion of hydrological research stations, Project code 2621012009;
- Sustainable smart farming systems taking into account the future challenges, Project Code 313011W112;
- Scientific support of climate change adaptation in agriculture and mitigation of soil degradation Project Code 2014+ 313011W580.

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- SESAR Joint Undertaking under the European Union’s Horizon 2020 Research and Innovation Programme under the grant agreement No. 733121 Solution PJ04-02 Enhanced Collaborative Airport Performance Management;
- EU-FP7 RECARE Preventing and Remediating degradation of soils in Europe through Land Care project ID No. 603498.

The VEGA agency is the Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic and the Slovak Academy of Sciences. It provides research grants for basic research projects carried out at universities and scientific institutes of the Slovak Academy of Sciences. In the reviewed period the Agency supported 43

projects in hydrology and related water sciences, which were mentioned in this report:

- VEGA 1/0057/22, VEGA 1/0068/19, VEGA 1/0103/22, VEGA 1/0111/18, VEGA 1/0202/15, VEGA 1/0217/19, VEGA 1/0308/20, VEGA 1/0367/16, VEGA 1/0370/18, VEGA 1/0392/22, VEGA 1/0463/14, VEGA 1/0500/19, VEGA 1/0589/15, VEGA 1/0632/19, VEGA 1/0662/19, VEGA 1/0710/15, VEGA 1/0728/21, VEGA 1/0747/20, VEGA 1/0781/17, VEGA 1/0782/ 21, VEGA 1/0800/17, VEGA 1/0805/16, VEGA 1/0828/17, VEGA 1/0880/21, VEGA 1/0891/17, VEGA 1/0940/17, VEGA 2/0003/21, VEGA 2/0003/21, VEGA 2/0004/19, VEGA 2/0006/18, VEGA 2/0015/18, VEGA 2/0020/20, VEGA 2/0025/19, VEGA 2/0038/15, VEGA 2/0044/20, VEGA 2/0053/18, VEGA 2/0055/15, VEGA 2/0065/19, VEGA 2/0085/20, VEGA 2/0086/21, VEGA 2/0093/21, VEGA 2/0098/18, VEGA 2/0189/17.

The Cultural and Educational Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic (KEGA) manages grant system aimed at the financial support of applied research projects in the field of education, pedagogy and creative and performing arts financed by the Ministry of education, science, research and sports of the Slovak Republic in specified thematic areas for public universities. In the reviewed period the Agency supported 4 projects in hydrology and related water sciences, which were mentioned in this report:

- KEGA No. 011TUZ-4/2021, KEGA 015UKF-4/2019, KEGA 027SPU-4/2020, KEGA project 059TUKE-4/2019.

The Slovak Research and Development Agency, https://www.apvv.sk/, which was established in 2005, is a national grant agency established in order to support research and development in Slovakia by granting financial means from the State Budget. It promotes high-end fundamental and applied research and development of all science and technology fields including hydrology and related water sciences and relevant interdisciplinary and multidisciplinary research. In the reviewed period the Agency supported 32 projects, which were annotated in this report:

- APVV-10-0423, APVV-11- 0303, APVV-15- 0497, APVV-15-0054, APVV-15-0160, APVV-15-0425, APVV-15-0489, APVV-15-0497, APVV-16-0025, APVV-16-0253, APVV-16-0278, APVV-16-0306, APVV-17-0549, APVV-18-0185, APVV-18-0205, APVV-18-0347, APVV-18-0390, APVV-19-0183, APVV-19-0340, APVV-20-0374, APVV-19-0383, APVV-20-0023, APVV-18-0360, APVV-16-0278, APVV-15-0489, APVV-20-0571, APVV-17-0549, APVV-16-0278, APVV-15-0489, APVV-16-0278, APVV-19-0383, APVV-15-0663.

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Selected achievements in Meteorology and Atmospheric Sciences in Slovakia in 2019–2022 (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 for 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 publishd mostly in 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

The main activities in the field of atmospheric modelling in Slovakia (namely at the Slovak Hydrometeorological Institute, SHMU) are related to the research, development and operational exploitation of the numerical weather prediction (NWP) system ALADIN, within the cooperation framework of the ALADIN, ACCORD and RC LACE consortia. The challenging task of forecasting high impact weather events as non-frontal thunderstorms often accompanied with the flash floods, hail, strong wind, heat waves etc. is the driving force for this endeavour (Simon et al., 2021).

The main operational model used at SHMU has not changed since the last report. It is a so-called ALARO configuration of the ALADIN NWP system with 4.5 km horizontal resolution and 63 vertical levels with hydrostatic dynamics. Significant progress has been achieved in the preparation of the initial conditions for the model integration. The 3-dimensional variational data assimilation configuration (3D-Var) has been implemented and tested. Additional observation types with high temporal and spatial resolution have been explored, such as the aircraft Mode-S data (Čatlošová and Derková, 2020), Zenith total delay observations (Imrišek et al., 2020), Doppler weather radar measurements, high resolution radiosonde data etc. Downscaled ensemble background error covariance matrix has been prepared. New operational setup denoted BLENDVAR has been proposed that combines the currently used Blending by digital filter with 3D-Var. Such a method enables to profit from the large scale analysis provided by 4D-Var data assimilation of the driving model ARPEGE via blending, and improves the small scales phenomena description based on local 3D-Var assimilation. This setup has been thoroughly validated using selected weather events as well as in the long term parallel suites. BLENDVAR outperforms the current operational version in most of the upper air objective verification scores, while it was mostly neutral for the near surface ones. It will be implemented in operations in 2023.

The uncertainty of the severe weather events forecast is addressed using the probabilistic approach based on the ensemble prediction system (EPS). A-LAEF - a limited area EPS system based on ALARO configuration has been implemented at the ECMWF in 2020 (Belluš, 2020) . A-LAEF is a common operational system of Central European national weather services (RC LACE) and Turkey. SHMU is the principal A-LAEF developer and is also responsible for its operational implementation, monitoring and maintenance. A-LAEF ensemble consists of 16 members with 4.8 km horizontal resolution and 60 vertical levels. It is coupled to the ECMWF ensemble. The initial conditions uncertainties as well as model uncertainties are simulated (ALARO multiphysics and surface stochastic physics are utilized), aiming for reliable probabilistic forecasts of meso-synoptic scales up to three days. Within that time range it can outperform deterministic models that have a similar or even higher spatial resolution (Belluš et al., 2022). The A-LAEF potential to indicate high impact weather including heavy flash floods or wind storms have been proven in many case studies. At SHMU a brand new visualization of standard and derived probabilistic A-LAEF outputs have been developed, both in map and epsgrams forms.

The acquisition of the new High performance computer system @SHMU (Vivoda et al., 2021) enabled to start the numerical weather prediction experiments at the convection-permitting scales (1-2 km). Together with an increased horizontal resolution a special attention is paid to the correct representation of the physiography fields. The non-hydrostatic dynamics is being improved (Smoliková and Vivoda, 2023). Impacts of physical parametrizations, namely turbulence, are studied as well. The aim is to build an hourly rapid update cycle system based on 3D-Var for deterministic nowcasting and very short-range forecasting purposes.

In parallel with standard operational production, the NWP data are provided for other users including air quality or hydrological modeling, road weather forecasting and other specific purposes (Bistak et al, 2021). Moreover, new diagnostic parameters are being developed, e.g. maximum subgrid wind or the wet snow load (Somfalvi-Tóth and Simon, 2023), that provide an added value with respect to ordinary NWP products.

European survay of the use and preception of weather forecast (Sivle at al. 2022) indicates there might be benefits of increased collaboration and sharing of data between European NMHSs as well as in the contact in between the providers and the users of the weather forecast.

Belluš, M., F. Weidle, C. Wittmann, Y. Wang, S. Taşku, and M. Tudor, 2019: "Aire Limitée Adaptation dynamique Développement InterNational – Limited Area Ensemble Forecasting (ALADIN-LAEF)", Adv. Sci. Res., 16, 63–68, DOI:10.5194/asr-16-63-2019

Belluš, M., 2020: New high-resolution ensemble forecasting system A-LAEF (in Slovak with English abstract). Meteorological Journal of the Slovak Hydromet. Inst. 23, 75–86

Belluš, M., M. Tudor, X. Abellan, 2022: "The mesoscale ensemble prediction system A-LAEF", ECMWF Newsletter, Vol. 172, p27-34, DOI: 10.21957/xa927ug5k0

Bisták, A.; Hulínová, Z.; Neštiak, M.; Chamulová, B., 2021. "Simulation Modeling of Aerial Work Completed by Helicopters in the Construction Industry Focused on Weather Conditions", Sustainability, 13, 13671. https://doi.org/10.3390/su132413671

Čatlošová, K. and Derková, M., 2020: Exploitation of aircraft Mode-S data in AROME/SHMU numerical weather prediction model. Meteorological Journal of the Slovak Hydromet. Inst. 23 65-74

Dian, M., M. Derková, M. Petraš, 2022: "Algorithmic amelioration of the deficiencies in the screen level parameters forecast based on a dynamical downscaling approach". 2nd Accord newsletter, 91-95.

Imrišek, M., Derková, M. and J. Janák, 2020. "Estimation of GNSS tropospheric products and their meteorological exploitation in Slovakia", Contrib. Geophys. Geod., vol. 50, no. 1, pp. 83-111, May 2020

Simon, A., M. Belluš, K. Čatlošová, M. Derková, M. Dian, M. Imrišek, J. Kaňák, L. Méri, M. Neštiak and J. Vivoda, 2021: Numerical simulations of 7 June 2020 convective precipitation over Slovakia using deterministic, probabilistic and convection-permitting approaches. IDŐJÁRÁS, Vol. 125, No. 4, 571–607

Sivle, A.D., Agersten, S., Schmid, F., Simon, A. 2022. Use and perception of weather forecast information across Europe Meteorological Applications, 29 (2), art. no. e2053, https://www.scopus.com/inward/record.uri?eid=2-s2.0-85128790921&doi=10.1002%2fmet.2053&partnerID=40&md5=f19ebc84bdab97de0ab

5cb103fde0bc9
Vivoda, J., M. Belluš, M. Derková, 2021: "High performance computing and weather forecasting at SHMU". HPC Focus, p44-53, ISSN 2729-9090
Wang, Y., M. Belluš, F. Weidle, et al., 2019: "Impact of land surface stochastic physics in ALADIN-LAEF", Quarterly Journal of the Royal Meteorological Society, 1–19, DOI:10.1002/qj.3623
Wastl, C., M. Belluš, G. Szépszó, 2022: "EPS research and development in RC-LACE in 2021". 2nd Accord newsletter, 152-165.

2. Uper atmosphere monitoring, Air quality, environmental aspects

Complex monitoring of the atmospheric profile and air quality issues is done in the Slovak Hydrometeorological institute. This includes the aerological stations in Ganovce where continue aerological measurements in higher layers of the atmosphere as well as the measurements of global ozone and spectra in UV wave band of solar radiation. Total ozone and atmospheric aerosol optical depth measurements are based on the detection of ultraviolet solar radiation reaching the Earth's surface. The station is also functioning as national radiation centre and the content and aerosols characteristics are monitored here, as well. The station is also a part of aerosol network - Aerosol Robotic Network (AERONET).

National monitoring network of air quality is also run by the Slovak Hydrometeorological institute. This network was upgraded by 14 automatized stations with online data access in the areas not covered by monitoring so far. The network reached 52 stations, now. New methods of air quality monitoring were introduced into operative practice. This includes the introduction of RIO, CMAQ, IFDM/OSPM and CALCUF models to standard evaluation of air quality and some component are also prepared for air quality forecasting.

The research activities in this area also continued mostly in the frame of Slovak Hydrometeorological Institute. High resolution residential emission model was used for the air quality modelling (Krajčovičová et al. 2020). The method was implemented by the REM-2 model and the results for the whole Slovakia were compared with the emissions in 4 years period reported in the frame of CLRTAP. The results of the model for PM10, PM2,5, NOX a SO2 were close to reported data while modelled results of benzylaminopurine emissions were lower by 10 to 20 %. Further research was done in the field of identification of the areas with hazardous air quality regrading PM10 (Nemček et al., 2020). It was done by using geospatial analysis of the relief during the heating period. The results were compared with the outputs of 2 models CMAQ and RIO. General results showed the highest concentration of hazardous areas in Zilina region. This type of mapping can also sere for the distribution of air quality stations. Mean diurnal profiles of pollutants NO2, NO and O3 obtained from long-term measurements at stations of National air quality monitoring stations were presented by Štefánik and Šedivá (Štefánik D., Šedivá T., 2022). The impact of meteorological and chemical conditions factors on the mean diurnal concentration profile was analysed. Analyse showed that the different type of stations and their allocation can be clearly distinguished based on the diurnal profile of NO2. This analysis was also suggested for quality control of data from low-cost sensors. Air quality analyse influencing the human health was investigated in Mladý et al., 2022. The authors gave the estimation of 4300 premature deaths due to the air pollution by PM2.5 only in 2019. A part of ozone concentration and evaluation was done in different aspects mentioned in different sections. Ground-level ozone concentration in beech forests in the West Carpathian Mountains showed the influence of local conditions on the ozone concentration. It was shown, that the amount of ground-level ozone in beech forests depends not only on the pollution intensity but also on the other environmental factors. The maximum concentration of ozone was observed on the plot at the original beech stand (without management intervention) the minimum concentration was found immediately after the management intervention on the plot, where adult trees were removed.

Beňo J., Štefánik D., 2020: "Impact of Covid-19 protective measures on concentrations of pollutants in Slovakia – Analysis of the first month", Meteorological Journal of the Slovak Hydromet. Inst., 23 (1), 5-14

Janík, R., Kubov, M., Schieber, B., 2020: "The ground-level ozone concentration in beech (Fagus sylvatica L.) forests in the West Carpathian Mountains“, Environmental Monitoring and Assessment, 192 (4), 233, DOI: 10.1007/s10661-020-8176-7

Krajčovičová J., Matejovičová J., Nemček V., 2020: "High-Resolution residential emission model for use in the air quality modelling", Meteorological Journal of the Slovak Hydromet. Inst., 23 (1), 31-40

Mladý M., Pukančíková K., Mináriková V., Paveleková B., 2021: "Air and health in Slovakia within the years 2010 – 2020". Meteorological Journal of the Slovak Hydromet. Inst., 24 (2), 105-116

Nemček V., Krajčovičová J., Štefánik D., 2020: "Determination of the areas with the increased risk due to PM10 air pollution from local heating in Slovakia“, Meteorological Journal of the Slovak Hydromet. Inst., 23 (1), 47-52

Štefánik D., Šedivá T., 2022: "Mean daily concentration profiles of NO2, NO and O3 at national air quality monitoring network in 2010 - 2020", Meteorological Journal of the Slovak Hydromet. Inst., 25 (1), 41-56.

3. Climate, analyses of climatic variability, extreme weather events, solar energy

A good recognition of the long term observing work was reached in 2020. Climate analysis in the territory of Slovakia are based on the data series which firstly started in January 1872 in Hurbanovo. WMO has a mechanism to recognize centennial observing stations and Hurbanovo time series, after going through the process of quality evaluation, was accepted to the set of world centennial stations.

More than 700 stations of different status continued in monitoring the atmospheric phenomena. Climatological network of about 90 stations was completely automatized and provides the online data, manual observations continue at selected stations.

Digitalization and homogenization of the data series enabled swift production of the new WMO climatological “normals” for the period of 1991-2020 for more than 90 stations. This work included also the phenological characteristics.

Big part of the research activities in the field of climatology was done in two research projects dealing with drought and knowledge support for adaptation measures to climate change in agriculture. International project DriDanube concentrated on increasing adaptation capacity of Danube region on the impacts of climate variability by bringing new instruments. Strategy to improve drought emergency service, drought risk impact methodologies and drought watch component are the main outputs of the project. National project URANOS built the data and knowledge platform to support the decision strategy in adaptation of agriculture to the climate change impacts and to minimize the soil degradation.

Further research activities were scattered to many topics. Number of articles dealt with the temperature and precipitation changes in different aspects. Global analysis of the changes in the long-term averages of air temperature values and atmospheric precipitation totals which includes changes in monthly, seasonal, and annual values of average daily air temperature and daily total precipitation was based comparing the WMO normal periods from 1931 to 2020 (Faško et al., 2022). Works continued also on the projections of the temperatures for Slovakia based on the regional climate models (Melo et al., 2021). Comparison of the air humidity characteristics produced by KNMI and MPI climatic models done by Lapin and Damborska (Lapin, M., Damborská, I., 2021) with real data indicates much bigger changes than predicted by the respective scenarios. It looks more pessimistic scenarios could take place. Local temperature research was employed into the wider cooperation in European temperature records homogenization (O’neill et val., 2022), relation of extreme air temperatures and related synoptic conditions (Nikolova et al., 2022) and influence of Temperature Changes on Phytoplankton Community Structure (Klisarova et al., 2022).

Further evaluations of temperature were concentrated on more specific temperature parameters. Tropical nights and their course since 1945 were evaluated by Babin et al., 2021, heat risk assessment based on mobile phone data was suggested by Holec et al., 2021, surface temperature maps production in urban areas by combining 2 remote sensing data sources was investigated by Onačilová et al., 2022. Study of the surface temperature and urban island monitoring was done in the series of work of authors from University in Kosice (Hofierka et al., 2020, Hofierka et al., 2022).

Temperature influence on human comfort in mountain areas of north Carpathians with the regard to geographical factors and air circulation was evaluated by using the UTCI index (Blazejczyk et al. 2020 and Blazejczyk et al. 2021).

Different aspects of the evaluation of precipitation evolution were done by Onderka et al. It includes specific investigation of the erosivity of the rains (Onderka et al., 2019), how rainfall characteristics affect the sizing of rain barrels in Slovakia (Onderka et al., 2020), considering storage capacity of rain tanks optimized for the local climate in two metropolitan areas of Slovakia (Onderka et al., 2020). Declining number of days that can be classified as cyclonic situations was identified in the evaluation of precipitation annual totals of with respect to cyclonic situations in Slovakia (Mészároš et al., 2022). Methods of heavy rain evaluation were compared in Kupco et al., 2021.

Drought resonated in many climate oriented works. Drought occurrence in Slovakia was investigated by Slovak authors (Onderka et al., 2020), (Turňa et al., 2021), much wider regional context to which slovak authors contributed was done i regional drought evaluations (Jakubínský et al., 2019, Řehoř et al., 2021, Jaagus et al., 2022, Blahut et al., 2022). Methodological aspects of the drought index calculation were analysed in Slávková et al., 2022. Potential use of satellite products in drought monitoring in the scale of Slovakia was considered by Kaňák and Okon, (Kaňák, P., Okon, Ľ., 2022).

Mihálka et al. evaluated the use of solar energy for photovoltaic panels in real climatic conditions (Mihálka et al., 2020, Mihálka et al., 2022) possible detection of the hydrometeors in the atmosphere by using BTS signal using new method of frequency shift detection was suggested in Fabo et al., 2021, the influence of climate change on the modelling of stomatal conductance and ozone dosages was performed in Buchholcerová et al., 2022. Specific extreme events evaluating large hail occurrence in Slovakia indicated much higher frequency of this phenomena in the eastern part of Slovakia (Šinger and Dlhoš., 2019),

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4. Agrometeorology, Forest meteorology and Phenology

The development of agrometeorology and forest meteorology was oriented to the detection of the climate change impacts in order to form the information basis for the activities regarding adaptations and climate services. This effort was mainly concentrated on the changing local climate conditions and their impacts on the agricultural production and forest management but in many cases local experts were involved in wider international cooperation. Drought monitoring in all regions of Slovakia which forms the information basis for the agricultural management was enriched by continuous cooperation with a number of farmers and foresters who report on real vegetation conditions in the fields and in forests as well as on the expected impact on yields. Hydrological drought characteristics of both surface and underground water were added to drought monitoring system. The cooperation in adaptive methods with farmers including the environmental impacts of their production is essential. The search performed in different European countries in which Slovak experts cooperated showed different attitudes of farmers in North and Central and South European countries to adaptive methods already applied. Nevertheless, crop protection, crop insurance, and early warning/forecast systems were considered effective ways to reduce the economic losses from increased climate-related risks and extremes across all Europe (Zhao et al., 2022). Other search (Altobeli et al., 2019) showed the farmers willingness to pay for certification claiming for reduced environmental impact of food production that may guarantee an efficient use of water resources.

Phenological research continued in the description of changing climate parameters impact on different plant communities. Different research activities showed strong influence of changing climate - the effect of selected meteorological variables on full flowering of some forest herbs in the Western Carpathians (Kubov et al., 2022), summer drought impact on autumn phenological response of European beech (Lukasová et al., 2020) and the effect of climate change on spring frosts and flowering of Crataegus laevigata (Škvareninová et al., 2022). Validation of the use of satellite metrics from MODIS to detect spring phenology using ground based observations (Bucha et al., 2022) showed a good agreement between the medians of ground-and satellite-based leaf unfolding onset dates. However, the differences in the marginal percentiles, 5 and (%%, remained unexplained.

Big number of the works in forest meteorology aimed to answer questions about reduction in growth and production and health status of forest trees under climate change and subsequent higher frequency of drought and partial aridisation as indicators of plant stress and ecosystem disturbances, as primary mortality factors or by creating predisposition for the activation of other factors. The works were mostly done by the research teams at Faculty of Forestry at Technical University in Zvolen, Institute of Forest Ecology SAS and National Forest Centre. In the research of physiological processes in drought-stressed tree species, most experiments have been performed so far on young individuals with a limited generalisation to mature stands. A number of research activities focused on the tree species that are common parts of vegetation in our area and have different needs and level of sensitivity to drought and heat stress (Leštianska et al., 2020, Húdková et al., 2020, Condes et al., 2022) Despite the problems with the definition of stress, the works have an ambition to clarify the indication of the hazard rate of an individual and ecosystem with regard to changes of various physiological parameters. The findings contribute to a more accurate prediction of damage and disturbances of plants and ecosystems or to the development of preventive measures which is possible only thanks to the understanding of the mechanism of drought impact on individual key processes occurring in the system soil - plant - atmosphere. The modelling team of researchers proposed an original method of parametrisation of process models.

Specific aspects of the influences of climate parameters on metabolites and pests infestation were investigated in the works of Vanekova et al., 1019 and Mezei et al., 2020.

The works dealing with different impacts of harsh weather on the forests showed

that ongoing climate change has a significant impact on increasing the risk of forest fires. The indicated risk of fire occurrence under the assumption of a climatic change is substantially higher than in the case when this assumption is neglected (Hillayová et al., 2022). Wider influence of climate change on different morphodynamic processes in High Tatras valleys was studied by Hreško et al., 2022. Several processes that indicate changing climate conditions, especially in the context of their frequency and randomness of occurrence, were found and several manifestations of abrupt processes that can be considered a result of a changing climate have occurred.

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5. 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. As the project monitoring phase ended in 2019 it is operated and maintained by the SHMI out of the further project frame support. The system parts of the infrastructure were replaced by new components and the hydrological models were amended within SHMI activities. Data collection is already done aside of the project structure.

Significant part of the research was devoted to the runoff water cycle in mountain catchments under the climate change and also to the role of snow in these processes.

Changes in the runoff under the climate change and in changing natural environment studied in mountain catchment (Labat et all. 2019) showed that the changes in the land-use and also the change in the rainfall intensities, have a significant impact on the runoff increase counting 36-62%.

A joint effort of a number of experts resulted in a publication on the Thematic Issue of Snow Resources and the Hydrological Cycle published in the Journal of Hydrology and Hydromechanics the Journal of Institute of Hydrology SAS (Zappa et al, 2019). The collection delt with the role of snow in the hydrological cycle. It brought ten specific papers and a technical note. They presented innovative methods of snow characteristics measurements, research of the relationships between snow and runoff, on the monitoring and evaluation of environmental tracers in the snow-related part of the hydrological cycle. Further to that a number of specific aspects of snow were investigated.

A survey at the European level on which local experts cooperated gave a survey of snow monitoring methods and networks over Europe (Haberkorn, A. (Ed.), 20190).

An important parameter regarding the runoff and hydrological modelling in mountain areas, the snow water equivalent, and its measurement uncertainty by using different instruments, resp. was investigated with Slovak contribution in the study Lopez-Moreno, et al., 2019. Results confirmed that instrumental bias exceeded both the natural variability and the error induced by observers. The effect of the snow weighting on some aspects of hydrological models in different locations was investigated by Slezak et.al., 2019. Following research on the influence of snow melting on the water cycle in small mountain catchment indicated that hydrological cycle has become more dynamic since 2014. Nevertheless, though the snow cover characteristics and climatic conditions during the snow accumulation and melting period did not show pronounced changes, some changes in flow characteristics in the cold period of the year were indicated (Holko et al, 2020 and Holko et al, 2021). Differently wooded areas also influence isotopic composition of the rain reaching the ground. Throughfall in the alive forest was isotopically heavier than in dead forest and the open area rainfall (Holko et al, 2022). Changes in the runoff induced by the expected changes in the precipitation distribution over the year in future decades investigated in Hron river basin (Roncak et al., 2022) indicated their possible impact on the forest composition in this area and possibly also in other regions of Slovakia.

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RONČÁK, P., VITKOVÁ, J., ŠURDA, P., 2022: Impact of climate change on runoff and development of forest composition in the coming decades in a selected river basin in Slovakia. In Vodohospodářské technicko-ekonomické informace - Water management technical and economic information, 2022, vol. 64, no. 3, p. 25-30. ISSN 0322-8916

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Defended PhD Theses

Institution: Faculty of Forestry, Technical University in Zvolen,
Thesis title: Impacts of global climate change on the growth of spruce, fir and beech in the Carpathians on a gradient of altitude and latitude
Written by (author):Marčiš Peter, Ing., PhD.
Thesis supervisor: Bošeľa Michal, Ing., PhD.
Department: Department of Natural Environment (FF)
Year of defense: 2022

Institution: Faculty of Forestry, Technical University in Zvolen,
Thesis title: Bioclimatic risk of drought in forest landscapes
Written by (author):Ing. Zuzana Oravcová, PhD.
Department: Department of Natural Environment (FF)

Thesis supervisor: assoc.prof. Ing. Jaroslav Vido, PhD.
Year of defense: 2022

Institution: Faculty of Forestry, Technical University in Zvolen,
Thesis title: Analysis of the impact of climatic extremes on the quality of hare habitats in planar and collinear landscapes
Written by (author):Ing. Andrej Kvas, PhD..
Department: Department of Natural Environment (FF)
Thesis supervisor: assoc.prof. Ing. Jaroslav Vido, PhD.
Year of defense: 2021

Institution: Faculty of Mathematics, Physics and Informatics
Thesis title: The influence of selected meteorological and climatological factors on deposition of surface ozone in forest conditions in High Tatras
Written by (author):Ing. Anna Bucholcerová, PhD
Department: Department of Meteorology and Climatology
Thesis supervisor: RNDr. Pavel, ŠťastnýPhD.
Year of defense: 2022

Institution: Faculty of Mathematics, Physics and Informatics
Thesis title: Influence of orography on supercells in Slovakia
Written by (author):Mgr. Miroslav Šinger, PhD.
Department: Department of Meteorology and Climatology
Thesis supervisor: doc. RNDr. Martin Gera, PhD.
Year of defense: 2021

Institution: Faculty of Mathematics, Physics and Informatics
Thesis title: Optical properties of atmospheric aerosol in selected solar radiation spectrum
Written by (author):Mgr. Peter Hrabčák, PhD.
Department: Department of Meteorology and Climatology
Thesis supervisor: RNDr. Pavel, ŠťastnýPhD.
Year of defense: 2019

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. 2016-2021.

The main objective is to define CSF in the European context, which will require the identification of key silvicultural characteristics and the harmonisation of CSF in mountain areas to create a common knowledge at European level.

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

FRENCH – SLOVAK Bilateral Project Integrated geophysical modeling of the Carpatho-pannonian region assessment

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.rclace.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

SK participating Institutes: Slovak Hydrometeorological Institute

Seismological and integrated geophysical research in Slovakia 2019–2022 (Report to IASPEI)

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1. Numerical modelling of seismic motion and seismic wave propagation

A discrete representation of a heterogeneous viscoelastic medium for the finite-difference modelling of seismic wave propagation.
(*Jozef Kristek, Peter Moczo, Emmanuel Chaljub and Miriam Kristekova, Geophys. J. Int. 2019, 217, 2021–2034*)

The accuracy and efficiency of numerical simulations of seismic wave propagation and earthquake ground motion in realistic models strongly depend on discrete grid representation of the material heterogeneity and attenuation. We present a generalization of the orthorhombic representation of the elastic medium to the viscoelastic medium to make it possible to account for a realistic attenuation in a heterogeneous viscoelastic medium with material interfaces. An interface is represented by an averaged orthorhombic medium with rheology of the Generalized Maxwell body (GMB-EK, equivalent to the Generalized Zener body). The representation is important for 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. This 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 (i.e. representing reasonably averaged medium) grid moduli and densities. Accuracy of modelling thus very much depends on how the medium heterogeneity is represented/averaged. We numerically demonstrate accuracy of the developed orthorhombic representation. The orthorhombic representation neither changes the structure of calculating stress-tensor components nor increases the number of arithmetic operations compared to a smooth weakly heterogeneous viscoelastic medium. It is applicable to the velocity–stress, displacement–stress and displacement FD schemes on staggered, partly staggered, Lebedev and collocated grids. We also present an optimal procedure for a joint determination of the relaxation frequencies and anelastic coefficients.

A discrete representation of material heterogeneity for the finite-difference modelling of seismic wave propagation in a poroelastic medium.
(*Peter Moczo, David Gregor, Jozef Kristek, and Josep de la Puente, Geophys. J. Int. 2019, 216, 1072–1099*)

As recently demonstrated the most advanced finite-difference (FD) schemes are sufficiently efficient and accurate numerical-modelling tools for seismic wave propagation and earthquake ground motion especially in local surface sedimentary structures. The key advantages of the explicit FD schemes are a uniform grid, no matter what positions of material interfaces are in the grid, and one scheme for all interior points, no matter what their positions are with respect to the material interfaces. Efficiency and accuracy is determined by the grid dispersion and discrete representation of a material heterogeneity. After having developed discrete representations for the elastic and viscoelastic media, we present here a new discrete representation of material heterogeneity in the poroelastic medium. The representation is capable of subcell resolution and makes it possible to model an arbitrary shape and position of an interface in the grid. At the same time, the structure and thus the number of operations in the FD scheme are unchanged compared to the homogeneous or smoothly heterogeneous medium.

Subcell-resolution finite-difference modelling of seismic waves in Biot and JKD poroelastic media.

(*David Gregor, Peter Moczo, Jozef Kristek, Arnaud Mesgouez, Gaëlle Lefeuve-Mesgouez and Miriam Kristekova, Geophys. J. Int., 2021, 224, 760–794*)

We present a discrete representation of strongly heterogeneous poroelastic medium with the JKD-model of the frequency-dependent permeability and resistive friction, and the corresponding finite-difference (FD) scheme for numerical modelling of seismic wave propagation and earthquake ground motion in structurally complex media. The scheme is capable of subcell resolution, that is, allows for an arbitrary shape and position of an interface in the spatial grid. The medium can have either a zero resistive friction or non-zero constant resistive friction or JKD frequency-dependent resistive friction. The scheme has the same computational efficiency as the scheme for a smoothly and weakly heterogeneous medium (medium without material interfaces) because the number of operations for updating wavefield is the same. Several comparisons with a semi-analytical approach proves the efficiency and reliability of the subcell-resolution FD scheme. An illustrative example demonstrates differences between earthquake ground motion in the Biot's and JKD variants of the model of the surface sedimentary basin. The example indicates that it is desirable to perform an extensive parametric study in order to find out when it is necessary to apply relatively complicated and computationally more demanding JKD model and when much simpler Biot's model is sufficient.

Numerical wave propagation simulation.
(*Peter Moczo, Jozef Kristek, Alice-Agnes Gabriel, Emmanuel Chaljub, Jean-Paul Ampuero, Francisco J. Sánchez-Sesma, Martin Galis, David Gregor and Miriam Kristekova, The 6th IASPEI / IAEE International Symposium: Effects of Surface Geology on Seismic Motion August 2021*)

Numerical modelling of seismic wave propagation, earthquake ground motion, seismic ambient noise and earthquake rupture dynamics are all crucial tasks in any comprehensive investigation of seismological and diverse geophysical processes in the Earth's interior as well. The increased resolution power of recent measurements requires faithfully numerically simulated seismic wavefields in realistic models of the Earth that take into account its complex rheology and geometry. This is well reflected by outstanding recent advances in numerical modelling. Three complementary approaches of paramount importance are the finite-difference, spectral-element and discontinuous Galerkin methods. In order to gain basic insights both on wave propagation features and on rupture dynamics, the boundary element methods are useful companions.

Seismic waves in medium with poroelastic/elastic interfaces: a two-dimensional P-SV finite-difference modelling.
(*David Gregor, Peter Moczo, Jozef Kristek, Arnaud Mesgouez, Gaëlle Lefeuve-Mesgouez, Christina Morency, Julien Diaz and Miriam Kristekova, Geophys. J. Int., 2022, 228, 551–588*)

We present a new methodology of the finite-difference (FD) modelling of seismic wave propagation in a strongly heterogeneous medium composed of poroelastic (P) and (strictly)- elastic (E) parts. The medium can include P/P, P/E and E/E material interfaces of arbitrary shapes. The poroelastic part can be with (i) zero resistive friction, (ii) non-zero constant resistive friction or (iii) JKD model of the frequency-dependent permeability and resistive friction. Our FD scheme is capable of subcell resolution: a material interface can have an arbitrary position in the spatial grid. The scheme keeps computational efficiency of the scheme for a smoothly and weakly heterogeneous medium (medium without material interfaces). Numerical tests against independent analytical, semi-analytical and spectral-element methods prove the efficiency and accuracy of our FD modelling. In numerical examples, we indicate effect of the P/E interfaces for the poroelastic medium with a constant resistive friction and medium with the JKD model of the frequency-dependent permeability and resistive friction. We address the 2-D P-SV problem. The approach can be readily extended to the 3-D problem.

An Efficient ADER-DG Local Time Stepping Scheme for 3D HPC Simulation of Seismic Waves in Poroelastic Media.
(*Sebastian Wolf, Martin Galis, Carsten Uphoff, Alice-Agnes Gabriel, Peter Moczo, David Gregor, Michael Bader, J. Comp. Physics (2022) 455, 110886*)

Many applications from the fields of seismology and geoengineering require simulations of seismic waves in porous media. Biot's theory of poroelasticity describes the coupling between solid and fluid phases and introduces a stiff reactive source term (Darcy's Law) into the elastodynamic wave equations, thereby increasing computational cost of respective numerical solvers and motivating efficient methods utilising High-Performance Computing.

We present a novel realisation of the discontinuous Galerkin scheme with Arbitrary High-Order DERiva- tive time stepping (ADER-DG) that copes with stiff source terms. To integrate this source term with a reasonable time step size, we utilise an element-local space-time predictor, which needs to solve medium-sized linear systems – each with 1,000 to 10,000 unknowns – in each element update (i.e., billions of times). We present a novel block-wise back-substitution algorithm for solving these systems efficiently, thus enabling large-scale 3D simulations. In comparison to LU decomposition, we reduce the number of floating-point operations by a factor of up to 25, when using polynomials of degree 6. The block-wise back-substitution is mapped to a sequence of small matrix-matrix multiplications, for which code generators are available to generate highly optimised code.

We verify the new solver thoroughly against analytical and semi-analytical reference solutions in problems of increasing complexity. We demonstrate high-order convergence of the scheme for 3D problems. We verify the correct treatment of point sources and boundary conditions, including homogeneous and heterogeneous full space problems as well as problems with traction-free boundary conditions. In addition, we compare against a finite difference solution for a newly defined 3D layer over half-space problem containing an internal material interface and free surface. We find that extremely high accuracy is required to accurately resolve the slow, diffusive P-wave at a or near a free surface, while we also demonstrate that solid particle velocities are not affected by coarser resolutions. We demonstrate that by using a clustered local time stepping scheme, time to solution is reduced by a factor of 6 to 10 compared to global time stepping. We conclude our study with a scaling and performance analysis on the SuperMUC-NG supercomputer, demonstrating our implementation's high computational efficiency and its potential for extreme-scale simulations.

Material Interface in the Finite-Difference Modeling: A Fundamental View.

(*Peter Moczo, Jozef Kristek, Miriam Kristekova, Jaroslav Valovcan, Martin Galis and David Gregor, Bull. Seismol. Soc. Am., 2022, 113, 281–296*)

By analyzing the equations ofmotion and constitutive relations in the wavenumber domain, we gain important insight into attributes determining the accuracy of finite-difference (FD) schemes. We present heterogeneous formulations of the equations of motion and constitutive relations for four configurations of a wavefield in an elastic isotropic medium. We Fourier-transformthe entire equations to thewavenumber domain. Subsequently, we apply the band-limited inverse Fourier transform back to the space domain. We analyze consequences of spatial discretization and wavenumber band limitation. The heterogeneity of the medium and the Nyquist-wavenumber band limitation of the entire equations has important implications for an FD modeling: The grid representation of the heterogeneous medium must be limited by the Nyquist wavenumber. The wavenumber band limitation replaces spatial derivatives both in the homogeneous medium and across a material interface by continuous spatial convolutions. The latter means that the wavenumber band limitation removes discontinuities of the spatial derivatives of the particle velocity and stress at the material interface. This allows to apply proper FD operators across material interfaces. A wavenumber band-limited heterogeneous formulation of the equations of motion and constitutive relations is the general condition for a heterogeneous FD scheme.

2. Seismic hazard analysis of the Slovak territory

Final report from the seismological part of the task Computational determination of seismic hazard of critical infrastructure sites of EBO (nuclear power plant Jaslovské Bohunice) and EMO (nuclear power plant Mochovce).
(*Peter Moczo, Jozef Kristek, Róbert Kysel, Andrej Cipciar, Lucia Fojtíková, Miriam Kristeková, Martin Šugár, Kristián Csicsay, Bratislava 2022: Comenius University Bratislava – Earth Science Institute of Slovak Academy of Sciences - EQUIS spol. s r. o., 232 p. + 12 bound appendices.*)

A probabilistic seismic hazard analysis on bedrock (Vs,30 = 800 m/s) was performed for a grid of points covering the EBO polygon and the EMO polygon. A deaggregation of the probabilistic calculation for grid points of the EBO and EMO polygons for return periods of 475, 2 475 and 10 000 years was performed and alternative scenarios of controlling earthquakes were proposed. For the alternative earthquake scenarios, the seismic hazards at the locations of critical infrastructure objects were deterministically calculated and the results were normalized to the UHS spectrum obtained by the probabilistic calculation. These were then related relatively to the seismic hazard values at the plant site. The spatial variability of the local conditions of the EBO polygon and the EMO polygon was characterized using maps and tables of the values of the parameter Vs,30 and the depth at which the S-wave velocity reaches 800 m/s. Based on numerical modelling, amplification factors for all spectral ordinates in all locations of critical infrastructure objects have been calculated. The relative seismic hazard of the critical infrastructure object sites was determined with the inclusion of local effects in the EBO polygon and in the EMO polygon with respect to the seismic hazard values of the EBO and EMO nuclear power plant sites determined for bedrock.

3. Analysis of earthquakes and explosions

The Finite-interval Spectral Power method for detecting underground cavities using seismic ambient noise.

(*Miriam Kristekova, Jozef Kristek, Peter Moczo and Peter Labak, Geophys. J. Int., 2021, 224, 945–960*)

Undetected natural and man-made cavities pose a serious geotechnical hazard to human safety. It is therefore important to develop methods for identifying and locating underground cavities in urban development and civil construction. Another important type of cavity is the one generated by an underground nuclear explosion. Identification and location of such cavities is an important proof in case of suspicion of violating the Comprehensive Nuclear-Test-Ban Treaty (CTBT), an international treaty banning nuclear weapon test explosion or any other nuclear explosion which is yet to come into force. We present a new method for detecting and locating a horizontal position of cavity which uses the Finite-interval Spectral Power of seismic ambient noise. The method makes it possible to use single-station measurements at a set of potentially irregularly distributed points in the area on the Earth's free surface over a suspected cavity. Because the method gives better results for undistorted segments of noise records, we also present a method of automatic identification of such segments. We tested our method using records of noise from a site near the Felsőpetény, Hungary, which were collected for the CTBT Organization during a field test in the framework of developing on-site inspection capabilities. The method is ready for further tests in different cavity conditions and applications.

Seismic waves velocities inferred from the surface waves dispersion in the Malé Karpaty mountains, Slovakia.

(*Renata Lukešová, Lucia Fojtíková, Jiří Málek, Petr Kolínský, Acta Geodynamica et Geomaterialia, 2019, 16 (4), 451-464*)

The study area of Western Carpathians belongs to one of the most seismically active regions in Slovakia, where the available velocity models are not precise enough for accurate location and determination of focal mechanism. To improve the uppermost part of the currently used models, seismic surface wave data from two blasts in the quarry Rohožník, recorded at the MKnet local seismic network, were analyzed. Group velocity dispersion curves of Rayleigh and Love waves were determined by the frequency-time analysis. A mean group velocity dispersion curve for Love and Rayleigh waves for the central part of the MKnet network was settled and consequently joint inversion, for the period range 0.9 – 2.7 s, was performed to obtain a 1-D velocity model using the isometric method. The 11-layered model extends to depth of 2.5 km and indicate increase of the velocities from the surface down to the depths of 0.9 km. Then, velocities slightly decrease. The minimum of the low-velocity zone is at the depth of 1.8 km after which the velocities moderately increase to the velocity of the halfspace with vP = 5.35 km/s and vS = 2.96 km/s.

4. The monitoring of earthquakes

Improving Cross-Border Seismic Research: The Central and Eastern Europe Earthquake Research Network (CE3RN)
(*Wolfgang A. Lenhardt, Damiano Pesaresi, Mladen Živčić, Giovanni Costa, Tomislav Fiket, István Bondár, Llambro Duni, Petr Spacek, Liliya Dimitrova, Cristian Neagoe, Dmytro Malytskyy, Kristian Csicsay, László Tóth, Lucia Fojtikova, Seismological Research Letters, 2021, 92 (3): 1522–1530*)

The complex tectonic setup of eastern Europe—resulting in strong spatial variations of the local seismic hazard—caused relevant institutions of neighboring countries to form a research cooperation to ease seismological research cooperations across borders.

Here, we briefly introduce the original and new Central and Eastern Europe Earthquake Research Network (CE3RN) parties, with a synthesis of the common results achieved so far and an indication of possible future developments. Since the formal establishment of CE3RN, several common projects have been initiated, such as the SeismoSAT Project for the seismic data center connection over satellite and the Historical and Recent Earthquakes in Italy and Austria Project, both funded by the European Union INTERREG Italy–Austria Program.

The most recent 22 March 2020 earthquake near Zagreb, resulting in considerable damage in the capital of Croatia, demonstrated the importance of fast data exchange, thus facilitating reliable analysis of the earthquake. In addition, a recent breakdown of data lines in Austria demonstrated the usefulness of alternative data transmission via satellite.

Seismic activity on the territory of Slovakia in 2016
(*Róbert Kysel, Andrej Cipciar, Zuzana Chovanová, Kristian Csicsay, Lucia Fojtíková, Martin Gális, Miriam Kristeková, Contributions to Geophysics and*

Geodesy, 2019, 49, 1-10)

The National Network of Seismic Stations of Slovakia (NNSS) consists of eight short period and five broadband permanent seismic stations and a data centre located at the Earth Science Institute of the Slovak Academy of Sciences (ESI SAS). The NNSS recorded and detected 10888 seismic events from all epicentral distances in 2016. Totally 87 earthquakes originated in the territory of Slovakia in 2016. This paper provides basic information on the configuration of the NNSS, routine data processing, seismic activity on the territory of Slovakia in 2016 as well as macroseismic observations collected in 2016.

Seismic activity on the territory of Slovakia in 2017
(*Róbert Kysel, Andrej Cipciar, Zuzana Chovanová, Kristian Csicsay, Lucia Fojtíková, Jozef Kristek, Contributions to Geophysics and Geodesy, 2019, 49, 195-206*)

The National Network of Seismic Stations of Slovakia (NNSS) consists of eight short period and five broadband permanent seismic stations and a data centre located at the Earth Science Institute of the Slovak Academy of Sciences (ESI SAS). The NNSS recorded and detected 10719 seismic events from all epicentral distances in 2017. Totally 73 earthquakes originated in the territory of Slovakia in 2017. This paper provides basic information on the configuration of the NNSS, routine data processing, seismic activity on the territory of Slovakia in 2017 as well as macroseismic observations collected in 2017.

Seismic activity on the territory of Slovakia in 2018
(*Róbert Kysel, Andrej Cipciar, Kristian Csicsay, Lucia Fojtíková, Martin Šugár, Jozef Kristek, Contributions to Geophysics and Geodesy, 2019, 49, 511-523*)

The National Network of Seismic Stations of Slovakia (NNSS) consists of eight short period and five broadband permanent seismic stations and a data centre located at the Earth Science Institute of the Slovak Academy of Sciences (ESI SAS). The NNSS recorded and detected 11704 seismic events from all epicentral distances in 2018. Totally 86 earthquakes originated in the territory of Slovakia in 2018. This paper provides basic information on the configuration of the NNSS, routine data processing, seismic activity on the territory of Slovakia in 2018 as well as macroseismic observations collected in 2018.

Seismic activity on the territory of Slovakia in 2019
(*Róbert Kysel, Andrej Cipciar, Kristian Csicsay, Lucia Fojtíková, Martin Šugár, Jozef Kristek, Contributions to Geophysics and Geodesy, 2020, 50, 413-424*)

The National Network of Seismic Stations of Slovakia (NNSS) consists of eight short period and five broadband permanent seismic stations and a data centre located at the Earth Science Institute of the Slovak Academy of Sciences (ESI SAS). The NNSS recorded and detected 11,487 seismic events from all epicentral distances in 2019. Totally 91 earthquakes originated in the territory of Slovakia in 2019. This paper provides basic information on the configuration of the NNSS, routine data processing, seismic activity on the territory of Slovakia in 2019 as well as macroseismic observations collected in 2019.

Seismic activity on the territory of Slovakia in 2020
(*Róbert Kysel, Andrej Cipciar, Martin Šugár, Kristian Csicsay, Lucia Fojtíková, Peter Pažák, Contributions to Geophysics and Geodesy, 2021, 51, 373-389*)

The National Network of Seismic Stations of Slovakia (NNSS) consists of eight short period and six broadband permanent seismic stations and a data centre located at the Earth Science Institute of the Slovak Academy of Sciences (ESI SAS). The NNSS recorded and detected 11229 seismic events from all epicentral distances in 2020. Totally 96 earthquakes originated in the territory of Slovakia in 2020. This paper provides basic information on the configuration of the NNSS, routine data processing, seismic activity on the territory of Slovakia in 2020 as well as macroseismic observations collected in 2020.

Seismic activity on the territory of Slovakia in 2021
(*Róbert Kysel, Andrej Cipciar, Martin Šugár, Kristian Csicsay, Lucia Fojtíková, Peter Pažák, Contributions to Geophysics and Geodesy, 2022, 52, 565-578*)

The National Network of Seismic Stations of Slovakia (NNSS) consists of eight short period and six broadband permanent seismic stations and a data centre located at the Earth Science Institute of the Slovak Academy of Sciences (ESI SAS). The NNSS recorded and detected 10 656 seismic events from all epicentral distances in 2021. Totally 88 earthquakes originated in the territory of Slovakia in 2021. This paper provides basic information on the con guration of the NNSS, routine data processing, seismic activity on the territory of Slovakia in 2021 as well as macroseismic observations collected in 2021.

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 NSSS 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 intension to monitor in detail local seismic microactivity.

Five 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 by a yellow triangle in red square in the Fig. 1.

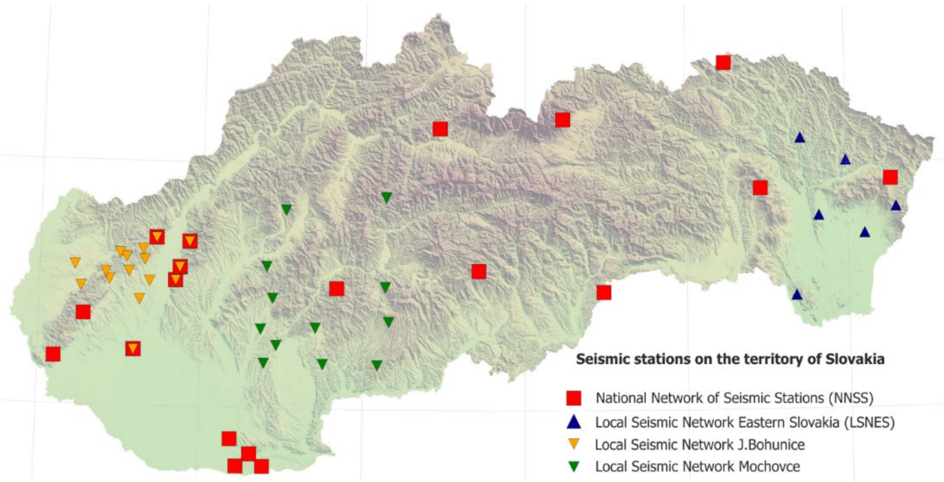

Fig. 1. *The seismic stations on the territory of Slovakia.*

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 & 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.

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. 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 & 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 that is in operation since 1996. Fig. 3 shows an example of the macroseismically felt local event interpretation for the January 28, 2021 with estimated ML=3.2 and epicentral intensity I0=3° EMS-98 from the Vtáčnik Mountains, Slovakia.

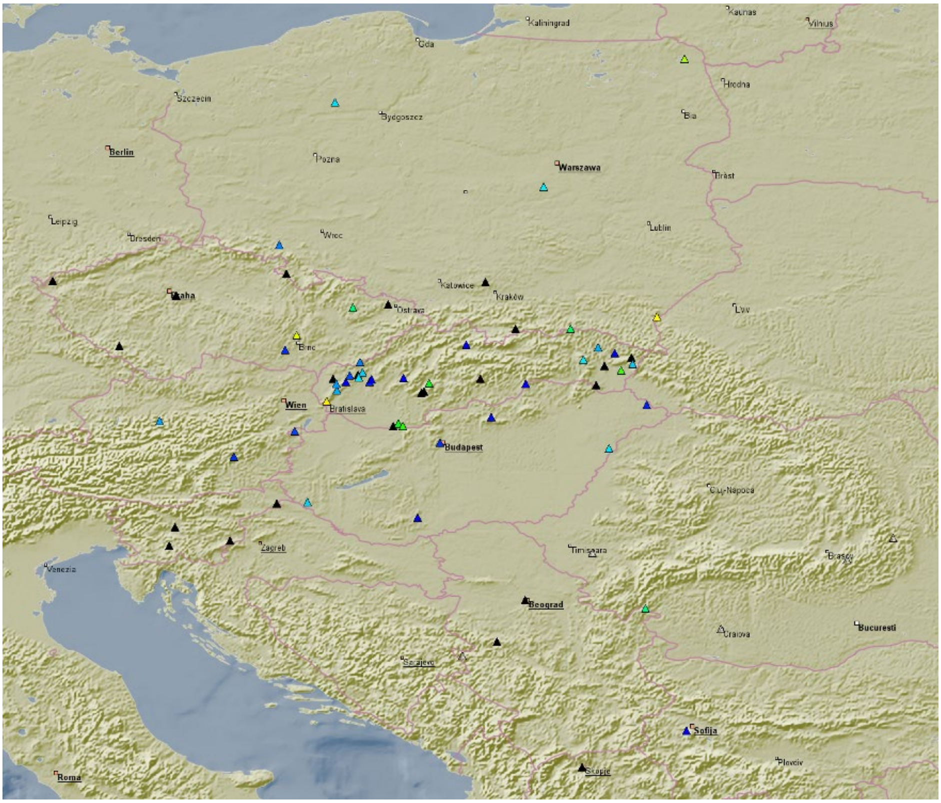

Fig. 2. *Virtual Regional Seismic Network in the ESI SAS, Bratislava.*

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 6^0 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).

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 January 28, 2021, M_L=3.2 local earthquake from the Vtáčnik Mts., Slovakia.*

Seismic activity on the territory of Slovakia in the period 2019-2022

The seismic activity on the territory of Slovakia for the period 2019-2022 is briefly characterized in Table 1 and illustrated in Fig. 4a, 4b. Using data from the seismic stations of NNSS and LSSVS, 336 local earthquakes without macroseismic observations (microearthquakes) were localized with epicentre on the territory of Slovakia in the years 2019-2022. Microearthquakes occurred in all known Slovak seismic source zones.

Table 1. *Seismic activity on the territory of Slovakia in the period 2019-2022.*

Year	Micro-earthquakes	Macroseismically observed earthquakes (epicentre in SK)	Macroseismically observed earthquakes (epicentre outside SK)
2019	87	4	0
2020	92	4	2
2021	84	4	3
2022	73	3	1

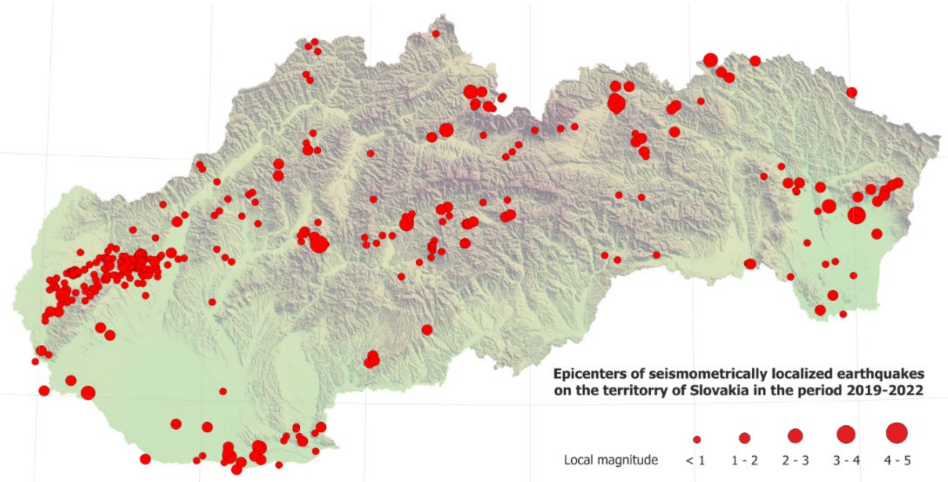

Fig. 4a. *Epicenters of seismometrically localized earthquakes on the territory of Slovakia in 2019-2022.*

During the period 2019-2022, 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 (2 earthquakes); Komárno source zone (2 earthquakes); Strážovské Mountains (1 earthquake); Orava region (1 earthquake); Central Slovakia: Horehronie area (3 earthquakes), Vtáčnik Mts. (1 earthquake), Veporské Mts. (1 earthquake);

Levočské Mts. (1 earthquake) and Eastern Slovakia - Vihorlat (3 earthquakes). Except these earthquakes, several earthquakes with epicentres in neighbouring countries were macroseismically observed on the territory of Slovakia too: Austria (2 earthquakes), Bosnia and Herzegovina (1 earthquake) and Croatia (3 earthquakes). As for macroseismically observed earthquakes point of view, the most active area was Central Slovakia - Horehronie and Eastern Slovakia - Vihorlat both with 3 earthquakes with macroseismic observations reported in the period 2019-2022.

The highest reported macroseismic intensity in the period 2019-2022 was 5-6° EMS 98 for the earthquake with epicentre in Eastern Slovakia, Vihorlat Mountains (23.4.2020). The ESI SAS has 544 macroseismic observations from 56 localities on the territory of Slovakia for this earthquake.

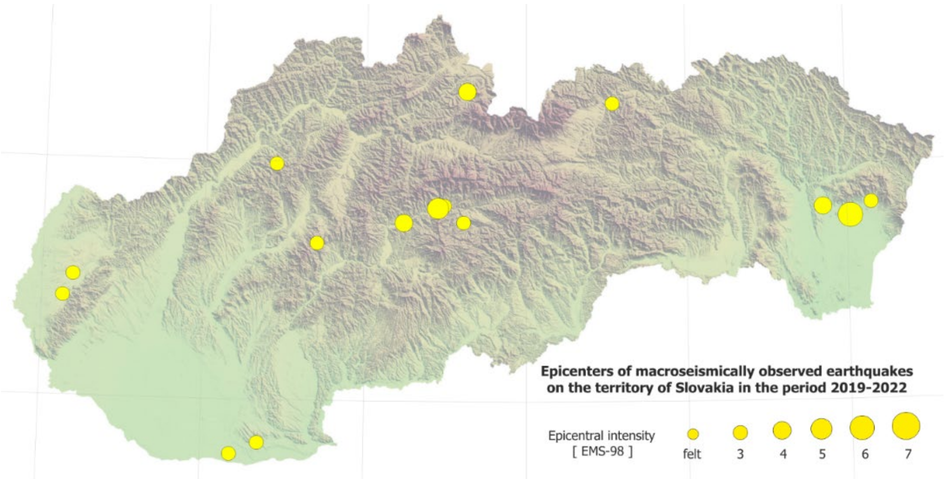

Fig. 4b. *Epicentres of macroseismically observed earthquakes on the territory of Slovakia in 2019-2022. Only the earthquakes with epicentre in Slovakia are shown in the map.*

5. Integrated geophysical study of the lithosphere

Study of the faults

Physical properties of Hradište border fault (Turiec Basin, Western Carpathians, Slovakia) inferred by multidisciplinary geophysical approach
(Geologica Carpathica, Kušnirák, Zeyen Bielik, Putiška, Mojzeš, Brixová, Pašteka, Dostál, Zahorec, Papčo, Hók, Bošanský and Krajňák, 2019)

The Hradište border fault zone (Fig. 5) has played an important role in the development of the tectonic contact of the Cenozoic sediments of the Turiec Basin with the Malá Fatra Mountains crystalline basement.

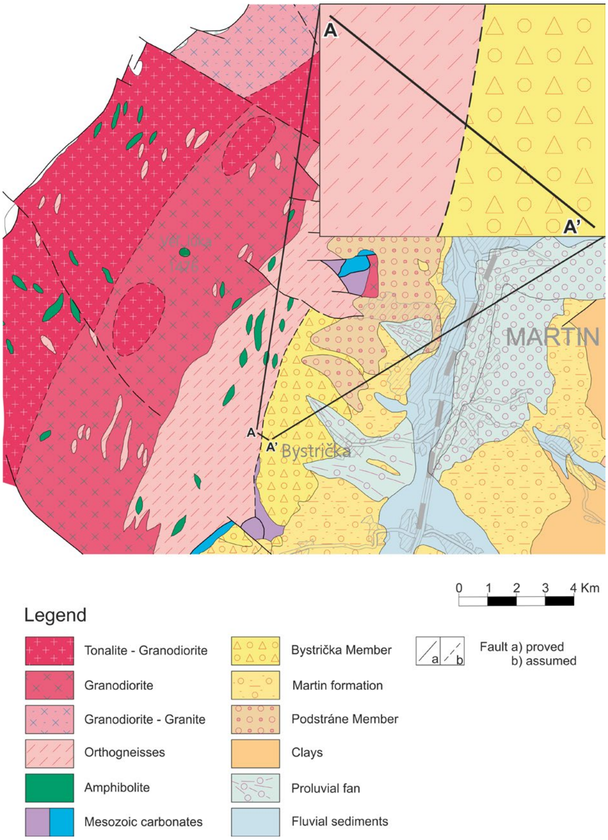

Fig. 5. *Location of the investigated Profile A-A´ on a detailed geological map (after Polák et al., 2008). Coordinates of the first and final points of the profile are A: N 49° 3'27.7"; E18°50'46.57" and A´: N 49° 3' 19.91"; E 18° 51' 4.12".*

Seismic, geoelectric, radiometric, gravimetric, magnetometric and ground penetrating radar measurements were used to determine the exact position and inclination of this fault zone down to a depth of up to 40 m. Detailed analysis of the geophysical measurements and their interpretations indicate that the Hradište border fault zone represents a sharp velocity, resistivity and density contrast located at 165 m from the origin of the profile. This zone is almost vertical and characterized by a decrease of the velocity from 3.0 km.s^{-1} to 2.2 km.s^{-1} (Fig. 6) and of electric resistivity from 500 to 150 Ω.m (Fig. 7) and by a maximum horizontal gravity (Fig. 8). Based on SP and radiometric measurements there is no clear indication of this fault zone at the stations around 165 m (Fig. 9). This vertical anomalous zone separates two different materials: the orthogneisses of the Tatric crystalline complex belonging to the Malá Fatra Mts. in the NW with high seismic velocities (3.0 km.s^{-1}), resistivity (500 Ω.m), density (2670 kg.m^{-3}), total gamma-ray activity (11 to 14 Ur) and low volume activity of radon (15 kBq.m^{-3} on average) in contrast to the sediments of the Bystrička Member of the Turiec Basin in the SE with low values of seismic velocity (< 2.5 km.s^{-1}), resistivity (< 200 Ω.m), density (2560 kg.m^{-3}), total gamma-ray activity (10 to 11 Ur) and higher volume activity of radon (25 kBq.m^{-3} on average). These two blocks are covered by a thin surface layer (with a thickness varying in an interval of 5 to 12 m), characterized by rather low seismic velocities 0.5–1.5 km.s^{-1}.

Our study serves as a case study for geophysical research of faults in different tectonic units of the Western Carpathians and other similar orogens.

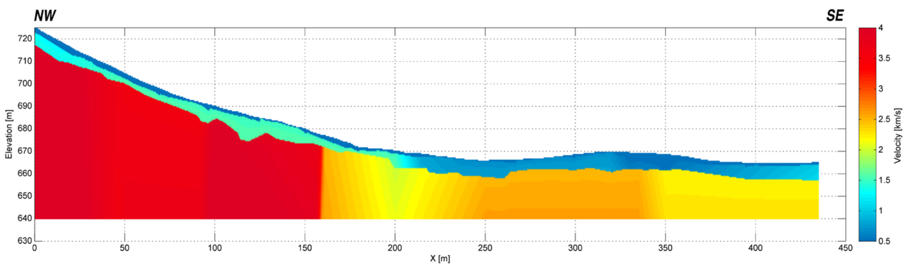

Fig.6. *P-wave velocity cross-section along the Profile A-A′ constructed from seismic tomography measurement.*

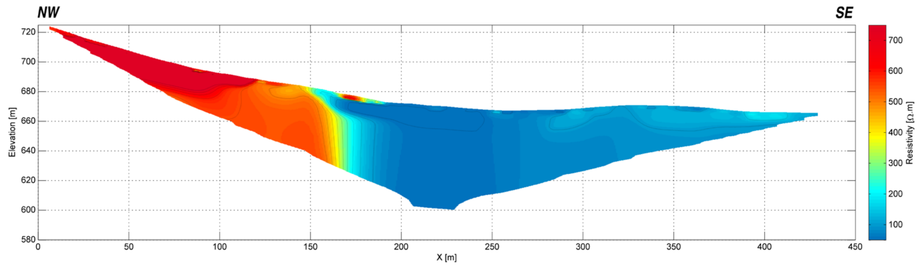

Fig. 7. *Resistivity cross-section along the Profile A-A′ constructed from electrical resistivity tomography measurement.*

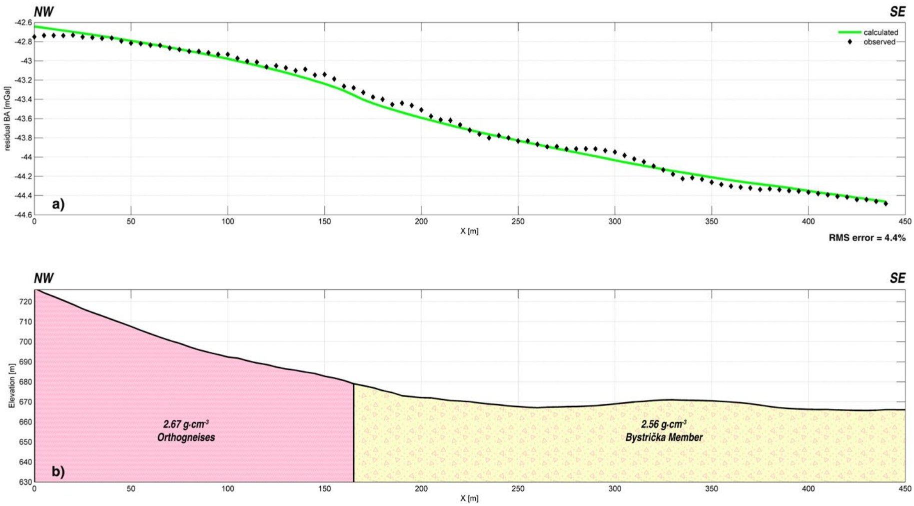

Fig. 8. *Density modelling results. (a) Observed (black diamonds) and calculated (green line) gravity anomalies related to the constructed density model (b).*

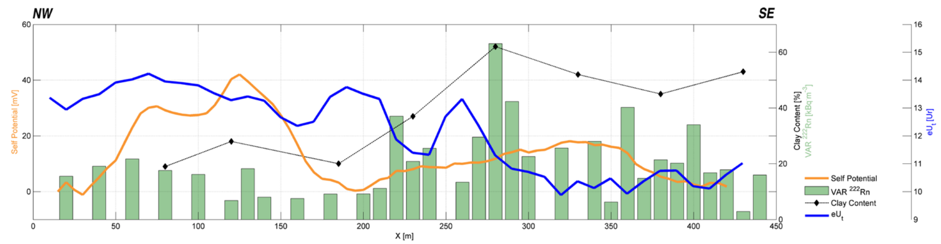

Fig. 9. Self-potential (orange line) and radiometric measurements – in the form of the volume activity of radon (green bars), the total gamma-ray activity eUt [Ur] curve (blue line) and grain analysis results (black line) along the Profile A-A′.

Study of the basin basement

The polyphase rifting and inversion of the Danube Basin revised
(Global and Planetary Change, Šujan, Rybár, Kováč, Bielik, Majcin, Minár, Plašienka, Nováková and Kotulová, 2021)

To track the evolution and formation of one of the major sub-basins of the Pannonian back-arc basin system, we re-evaluate pre-rift, syn-rift, post-rift, and inversion stages of the Danube Basin (Fig. 10). This synthesis builds upon a new compilation of (i) geophysical measurements, (ii) current data about the substratum of the basin, (iii) recent advances in stratigraphic architecture of the basin fill, (iv) subsidence history, (v) geomorphological evolution, and (vi) new biostratigraphic and geochronological data. The history of the basin begins with the pre-rift stage represented by the pre-Neogene basement, which belongs to an Eo-Alpine mountain range uplifted at the end of the Cretaceous. The core of the mountain range was formed by pre-Alpine high-grade metamorphic complexes, with a dome-like structure. The crystalline complexes were overlain by late Palaeozoic and Mesozoic cover and nappes, which were later eroded during the early Cenozoic. These pre-rift processes were triggered by (i) the late Cenozoic collision of the Alpine-Carpathian orogenic wedge with the European platform, (ii) the crustal extension resulting from the north-eastward lateral extrusion of the Alpine-Carpathian-Pannonian lithospheric microplate, and (iii) the subsequent updoming of the lithospheric mantle. This stage was followed by the polyphase rifting of the basin associated with extensive volcanic activity. This syn-rift stage consists of four phases. The first syn-rift phase dated to the early Badenian (~15.2–13.8 Ma), with subsidence documented in the Blatné and Želiezovce depressions, was characterized by accommodation rates up to ~900 $m\cdot Ma^{-1}$. The second syn-rift phase dated to the late Badenian (~13.8–12.6 Ma), exhibited accelerated subsidence with accommodation rates up to ~2300 $m\cdot Ma^{-1}$, and mainly affected the Blatné depression. The third and fourth syn-rift phases took place during the Sarmatian (~12.6–11.6 Ma) and early Pannonian (~11.6–9.5 Ma) and the accommodation rates reached ~900 m·Ma-1 and ~1000 $m\cdot Ma^{-1}$, respectively. They were documented in the Rišňovce, Komjatice and Gabčíkovo-Györ depressions, confirming the eastward subsidence migration, up to the external zone of the middle Miocene mantle upheaval. The late Miocene post-rift stage, commonly refered to as a thermal subsidence stage (~9.5–6.0 Ma), was associated with formation of a widespread planation surface called the "Mid- Mountain level" on the margins of the basin. The history of the Danube Basin terminates with the inversion stage which began after ~6.0 Ma and is still ongoing. It includes the continuous uplift of the basin margins and the subsidence of the central depocenters. The fluvial depositional systems did not behave steadily, because (i) lateral channel mobility and area of deposition increased progressively until ~4–3 Ma and caused onlaps on the base of the succession, followed by (ii) gradual confinement of the streams to the central part of the basin by uplifting basin margins, recorded by formation of river terrace staircases.

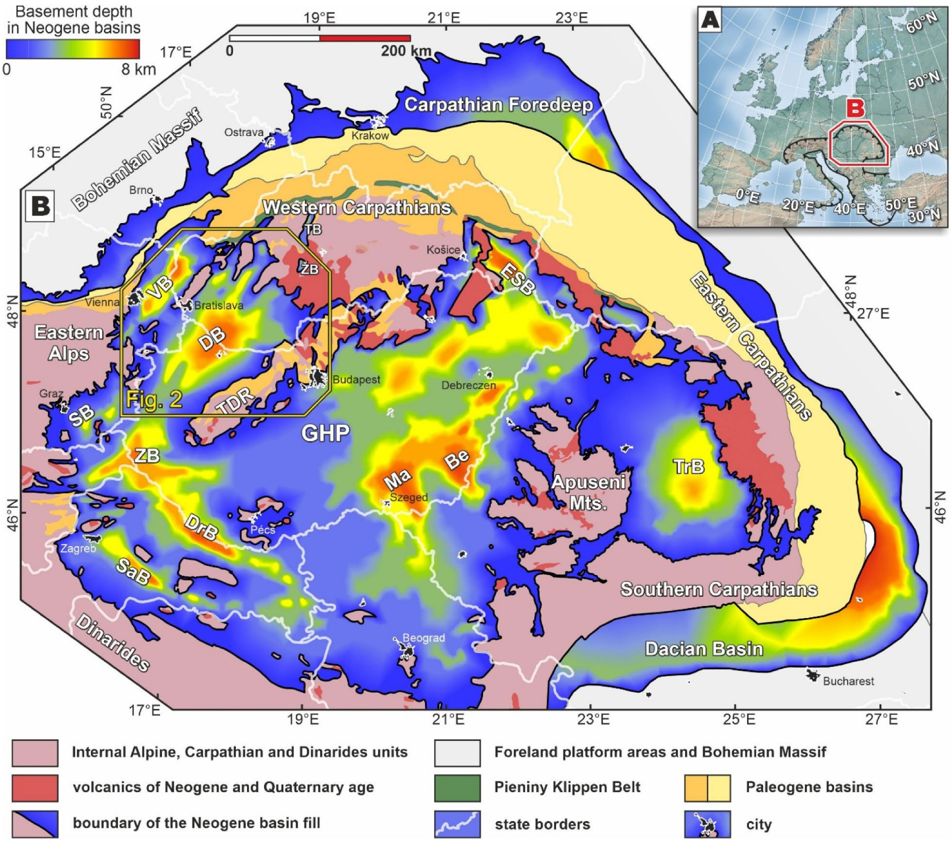

Fig. 10. *(A) Geographic location of the Pannonian Basin System; (B) Thickness map of Neogene sediments within the PBS and the position of the Danube Basin, based on Kilényi and Šefara (1989), Kováč (2000) and Horváth et al. (2006). Abbreviations: VB -Vienna Basin, DB – Danube Basin, TDR – Transdanubian Range, SB – Styrian Basin, ZB – Zala Basin, GHP – Great Hungarian Plain, DrB – Drava Basin, SaB – Sava Basin, Ma – Makó Trough, Be – Békes Basin, ESB – East Slovakian Basin, TrB – Transylvanian Basin, TB – Turiec Basin, ZB – Žiar Basin.*

Density modelling

Geophysical and geological interpretation of the Vienna Basin pre-Neogene basement (Slovak part of the Vienna Basin)
(Geologica Carpathica, Šamajová, Hók, Csibri, Bielik, Teťák, Brixová, Sliva and Šály, 2019)

We investigated the problem of geophysical and geological interpretation of the Vienna Basin pre-Neogene basement. The basin is situated at the contact of the Bohemian Massif, Western Carpathians, and Eastern Alps. Deep borehole data and an existing magnetotelluric profile were used in density modelling of the pre-Neogene basement in the Slovak part of the Vienna Basin. Density modelling was carried out along a profile oriented in a NW–SE direction (Fig. 11), across the expected contacts of the main geological structures. From bottom to top, four structural floors have been defined. Bohemian Massif crystalline basement with the autochthonous Mesozoic sedimentary cover sequence. The accretionary sedimentary wedge of the Flysch Belt above the Bohemian Massif rocks sequences. The Mesozoic sediments considered to be part of the Carpathian Klippen Belt together with Mesozoic cover nappes of Alpine and Carpathian provenance are thrust over the Flysch Belt creating the third structural floor. The Neogene sediments form the highest structural floor overlying tectonic contacts of the Flysch sediments and Klippen Belt as well as the Klippen Belt and the Alpine/Carpathians nappe structures.

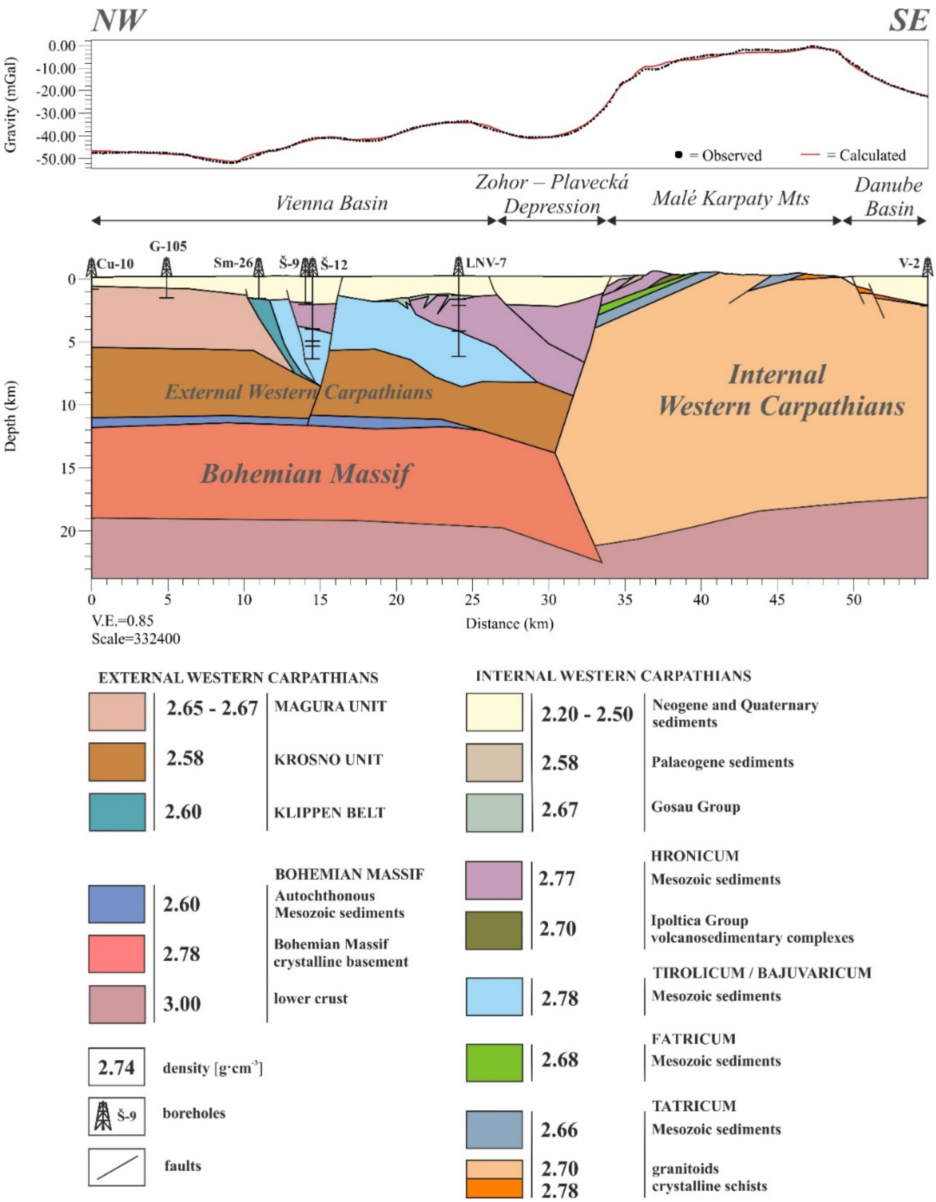

Fig. 11. *Geological interpretation of the gravimetric profile.*

Lithospheric density model along the CEL09 profile and its geological implications

(Geologica Carpathica, Godová, Bielik, Hrubcová, Šimonová, Dérerová and Pašteka, 2021)

The paper presents new 2D lithospheric density model along the seismic profile CEL09 crossing the Bohemian Massif, the Western Carpathians, and the Pannonian Basin (Fig. 12). The resultant model (Fig. 13) consists of five principal layers: sediments, upper crust, lower crust, lower lithosphere, and asthenosphere. The thicknesses of the Neogene sedimentary basins vary from 0 to ~5.5 km while the Palaeogene flysch sediments dip to a depth of ~6.5 km.

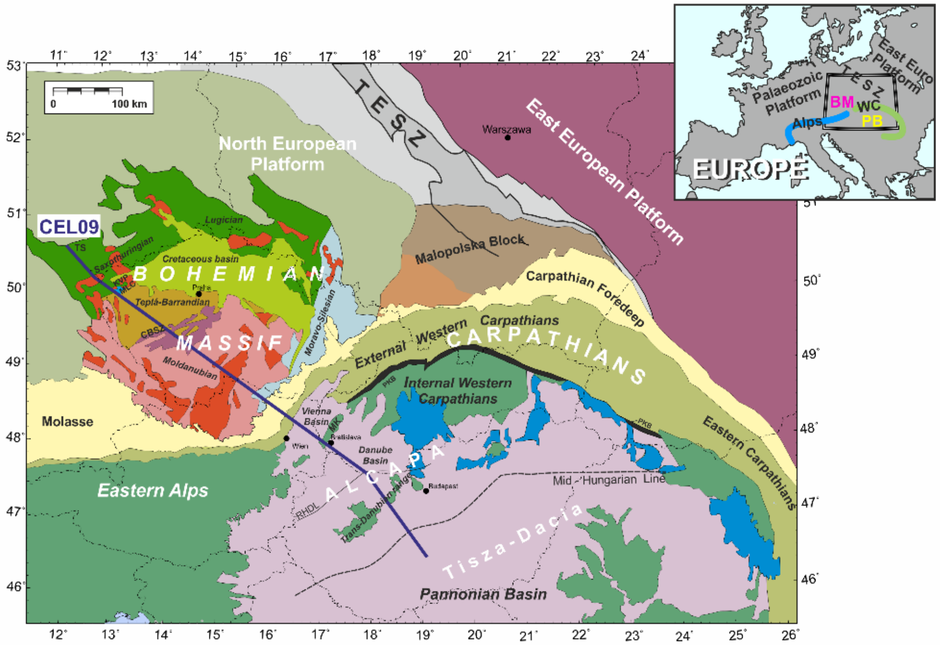

Fig. 12. *Simplified tectonic map of the Bohemian Massif, the Western Carpathians, the Pannonian Basin, and their surrounding tectonic units with the localization of the CELEBRATION 2000* ***refraction*** *seismic profile CEL09 (modified after Hrubcová et al., 2010; Hók et al., 2014; Grygar, 2016; Šujan et al., 2021). TS – Teuschnitz syncline, KVP – Karlovy Vary Pluton, MLC – Mariánské Lázně amphibolite Complex, CBSZ – Central Bohemian Shear Zone, MK – Malé Karpaty Mts, PKB – Pieniny Klippen Belt, RHDL – Rába-Hurbanovo-Diósjenö lineament, TESZ – Trans European Suture Zone.*

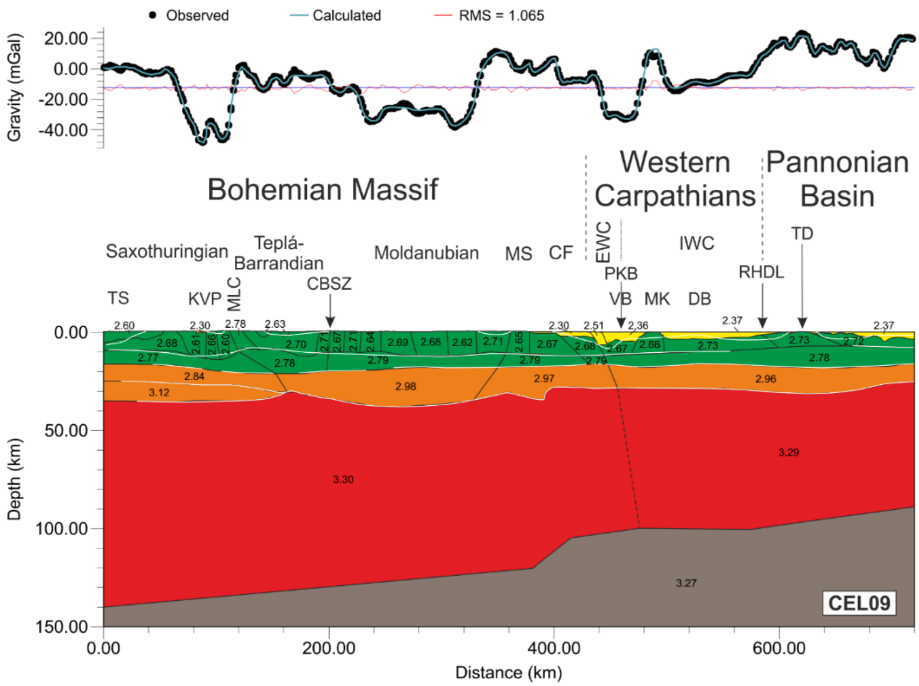

Fig. 13. *Optional 2D density lithospheric model of the CEL09 profile. Variant of the resultant 2D density model, where a density contrast of 0.01 g cm−3 between the Bohemian Massif and the Western Carpathian-Pannonian lower lithospheres was assumed. White dashed lines represent boundaries of the seismic model calculated by Hrubcová et al. (2015). For explanations, refer to Fig. 7.*

The most complex upper part of the upper crust in the Bohemian Massif is represented mainly by low-density granitoid plutons (~2.60-2.68 g cm−3), metamorphic rocks (~2.69-2.74 g cm−3) and high-density basic and ultrabasic bodies (~2.78-2.79 g cm−3). In the Western Carpathians, this layer is built by the crystalline Malé Karpaty Mts. (2.66-2.67 g cm−3), Trans-Danubian range (2.73-2.74 g cm−3), and the pre-Cainozoic basement of the sedimentary basins (2.67-2.74 g cm−3). The densities of the lower part of the upper crust range from 2.78 g cm−3 (in the Western Carpathian-Pannonian region) to 2.77-2.80 g cm−3 (in the Bohemian Massif). In the lower crust, four different sectors were modelled. In the Saxothuringian, they are divided into two layers, the upper layer (2.84-2.85 g cm−3) and the lower layer (3.12 g cm−3). The Moldanubian has the thickest lower crust (~20 km) with a density of 2.98 g cm−3; the lower crust in the Moravo-Silesian has a density of 2.97 g cm−3. The Western Carpathian-Pannonian region is represented by slightly lower densities of 2.94-2.96 g cm−3. The gravity modelling indicates that the Western Carpathians were overthrusted by ~30 km onto the Bohemian Massif resulting in a neo-transformation of the crust/mantle and related lithosphere after subduction.

Temperature distribution and rheological properties of the lithosphere

Calculation of temperature distribution and rheological properties of the lithosphere along transect IV in the Western Carpathian-Pannonian Basin region
*(*Contributions *to Geophysics and Geodesy, Dérerová, Bielik, Kohút and Godová 2019)* and
Rheological model of the lithosphere along prole VII in the Eastern Carpathians
(Contributions to Geophysics and Geodesy, Dérerová, Bielik, Kohút, Godová and Mojzeš 2021)

2D integrated modelling algorithm has been used to calculate the temperature distribution in the lithosphere along the transect IV and VII located in the Western Carpathian-Pannonian Basin area (Fig. 14). The Lithospheric models along profile IV and VII are shown in the Figures 15 and 16. Based on the determined temperature field and given rheological parameters of the rocks, it was possible to calculate the strength distribution for both compressional and extensional regimes, construct the strength envelopes for chosen columns of the main tectonic units of the model, and thus construct a simple rheological model of the lithosphere along transect IV and VII. The obtained results (Fig. 17) indicate decrease of the lithospheric strength from the European platform and the Western Carpathians towards the Pannonian Basin. The largest strength (valid for all tectonic units) can be observed within the upper crust with its maxima on the boundary between upper and lower crust, decreasing towards lower crust and disappearing in the lithospheric mantle, suggesting mostly rigid deformation occurring in the upper crust. A local increase in the values of strength can be observed in the eastern segment of the Western Carpathians where crustal thickening accompanies the lithospheric thickening (formation of the lithospheric root).

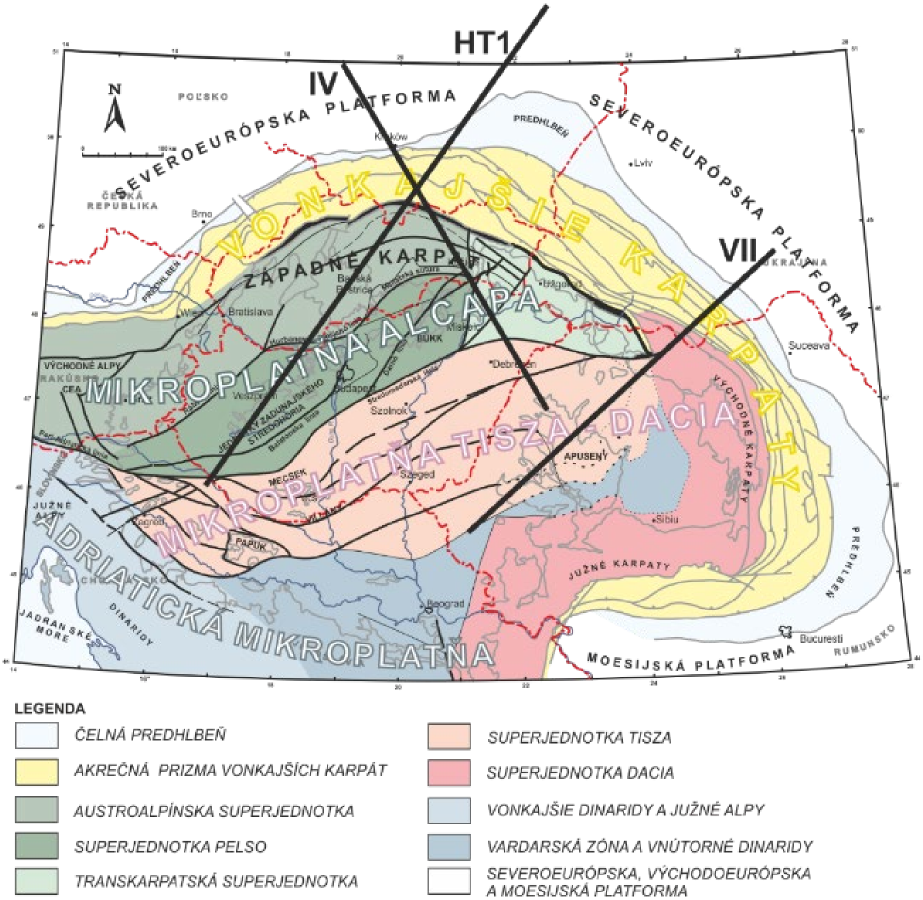

Fig. 14. *Location of transect IV and VII on the map of the Carpathian-Pannonian Basin region (modified after Zeyen et al. (2002) and Dérerová et al. 2019).*

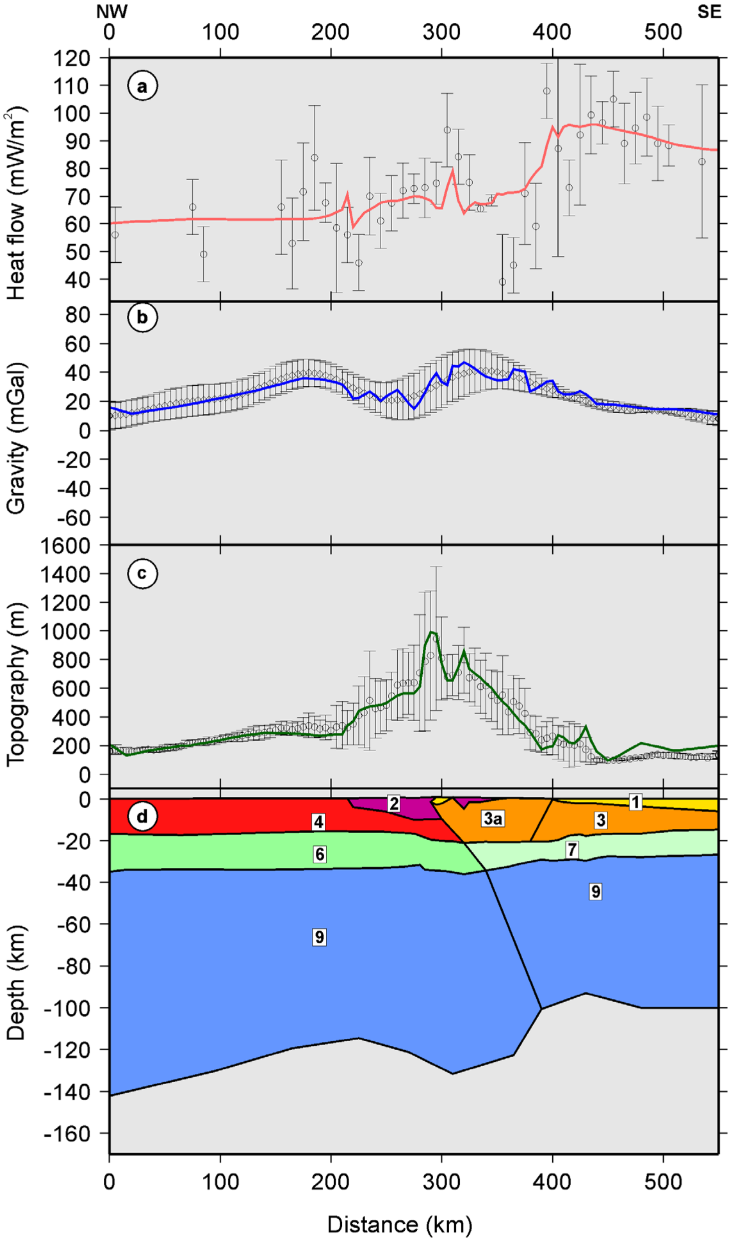

Fig. 15. *Lithospheric model along transect IV. (a) Surface heat flow, (b) free air gravity anomaly, (c) topography with dots corresponding to measured data with uncertainty bars and solid lines to calculated values. Numbers in (d) correspond to material number in Table 2 (Zeyen et al., 2002).*

Table 2. *Thermal and rheological parameters used for modelling along transect IV (after Carter and Tsenn (1987) and Goetze and Evans (1979)). HP: heat production (µWm-3), TC: thermal conductivity (Wm-1K-1), ρ: density at room temperature (kgm-3), Ap: power law pre-exponential constant, n: power law exponent, Ep: power law activation energy (kJmol-1).*

Nr.	Unit	HP	TC	Density	A_p	*n*	E_p
1	Neogene sediments	2.5 – 3.0	2.5	2400 – 2550	3.16E-26	3.30	186
2	Flysch and Volcanics	1.0 – 2.5	2.0 – 2.5	2550 – 2650	3.16E-26	3.30	186
3	Carpathian and Pannonian upper crust	3.0 – 3.5	3.0	2750	3.16E-26	3.30	186
3a	Inner Western Carpathian upper crust	2.0 - 2.5	3.0	2750	3.16E-26	3.30	186
4	European upper crust	0.5 – 2.0	2.5 – 3.0	2750 – 2800	3.16E-26	3.30	186
6	European lower crust	0.2	2.0	2960	6.31E-20	3.05	276
7	Carpathian and Pannonian lower crust	0.2	2.0	3000	6.31E-20	3.05	276
9	Lower (mantle) lithosphere	0.05	3.4	3325	7.94E-18	4.50	535

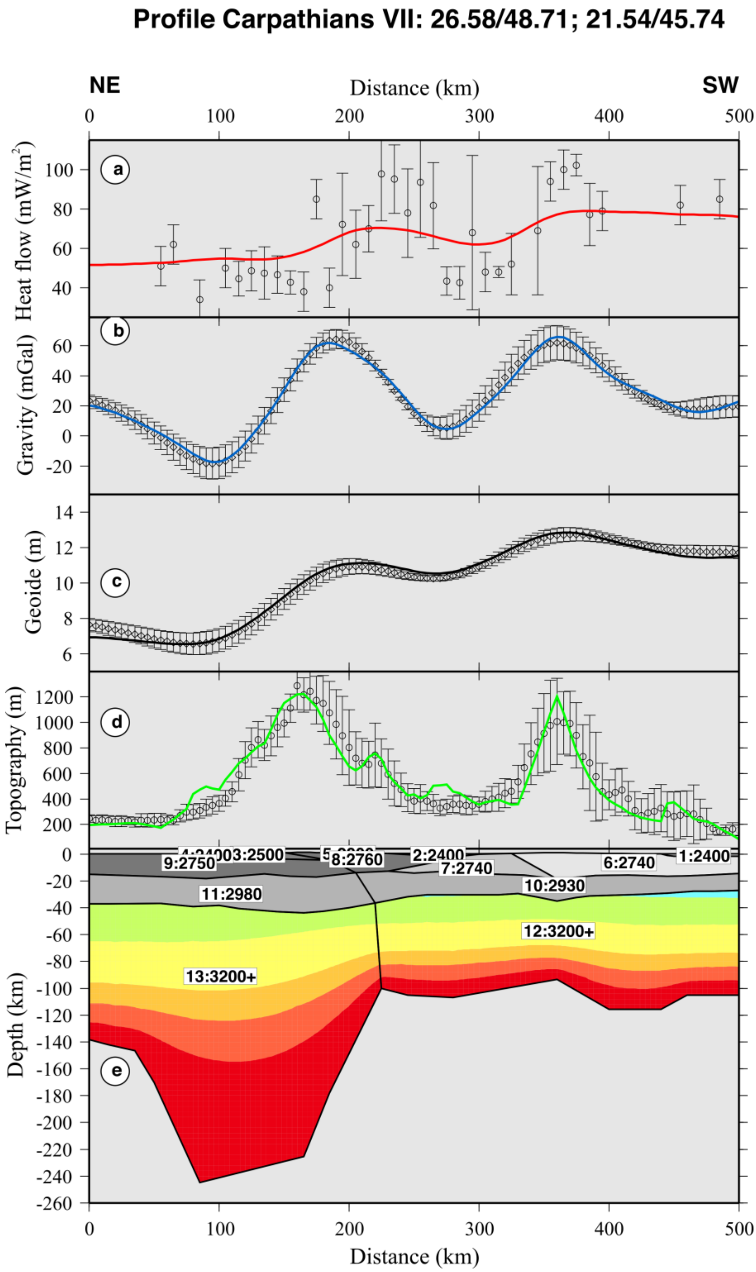

Fig. 16. *Lithospheric model along profile VII. (a) Surface heat flow, (b) free air gravity anomaly, (c) topography with dots corresponding to measured data with uncertainty bars and solid lines to calculated values. Numbers in (d) correspond to material number in Table 3 (Dérerová et al., 2006).*

Table 3. *Thermal and rheological parameters used for modelling along profile VII (after Carter and Tsenn (1987), Goetze and Evans (1979) and Lankreijer et al., (1999)). HP: heat production (µWm-3), TC: thermal conductivity (Wm-1K-1), ρ: density at room temperature (kgm-3), Ap: power law pre-exponential constant, n: power law exponent, Ep: power law activation energy (kJmol-1).*

Nr	Unit	HP	TC	Density	A_p	*n*	E_p
1	Neogene sediments	3.5	2.0	2400	3.16E-26	3.30	186.5
2	Neogene sediments	3.0	2.5	2400	3.16E-26	3.30	186.5
3	Flysch, foreland basin, sedimentary cover of European Platform	2.0	2	2500	3.16E-26	3.30	186.5
4	Flysch, foreland basin, sedimentary cover of European Platform	3.0	2	2400	3.16E-26	3.30	186.5
5	Volcanics	3.5	3	2800	3.16E-26	3.30	186.5
6	Carpathian and Pannonian upper crust	2.5	3.0	2740	3.16E-26	3.30	186.5
7	Carpathian and Pannonian upper crust	2	2.5	2740	3.16E-26	3.30	186.5
8	Carpathian and Pannonian upper crust	2.5	3.0	2760	3.16E-26	3.30	186.5
9	European platform upper crust	1.5	2.0	2750	3.16E-26	3.30	186.5
10	Carpathian and Pannonian mantle crust	2930	0.2	2.0	6.31E-20	3.05	276
11	European Platform lower crust	2980	0.2	2.0	6.31E-20	3.05	276
12	Carpathian and Pannonian mantle lithosphere	0.05	3.4	3200+	7.94E-18	4.50	535
13	European mantle lithosphere	0.05	3.4	3200+	7.94E-18	4.50	535

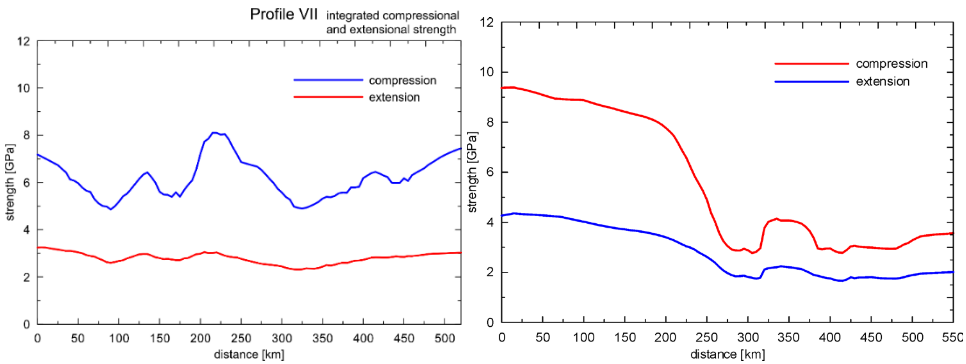

Fig. 17. *Vertically integrated compressional (blue line) and extensional (red line) strength calculated along profile VII (left) and IV (right)***.**

Integrated geophysical modelling

Continental lithospheric structure from the East European Craton to the Pannonian Basin based on integrated geophysical modelling

(*Tectonophysics, Šimonová, Zeyen and Bielik 2019***)**

Due to uncertainty of single-method interpretation we applied 2-D integrated lithospheric modelling along three CELEBRATION 2000 profiles CEL01, CEL04 and CEL05 (Fig. 18). 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 (Fig. 19) indicate 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. The 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

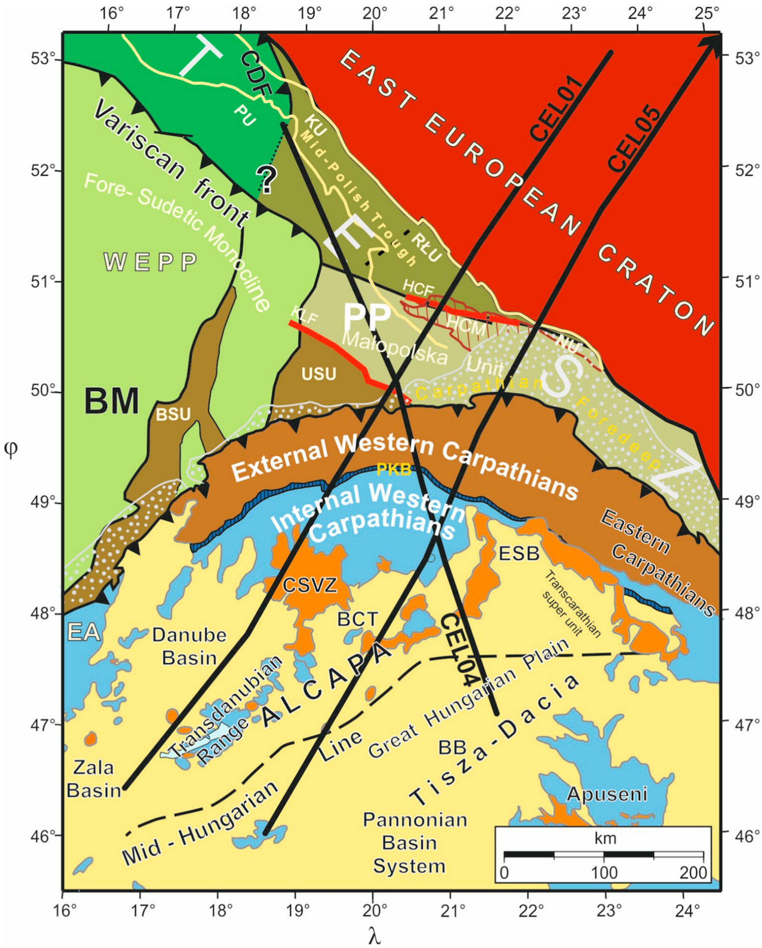

Fig. 18. *Location of the CELEBRATION 2000 seismic profiles CEL01, CEL04 and CEL05 interpreted in the paper on the background of geological map of Central Europe modified from Środa et al. (2006) and Janik et al. (2009, 2011) with elements for Carpathian–Pannonian basin area after Kováč (2000), Palaeozoic platform after Dadlez et al. (1994, 2000), Dadlez (2003), Belka et al. (2002) and Verniers et al. (2002), 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; RŁU – Radom-Łysogóry unit; HCF – Holy Cross Fault; HCM – Holy Cross Mts.; NU – Narol unit; KLF – Kraków-Lubliniec Fault; USU – Upper Silesian unit; PKB – Pieniny Klippen Belt; ESB – East Slovakian Basin; CSVZ – Central Slovak Volcanic zone; BCT – Bükk Composite Terrane; BM – Bohemian Massif; BSU – Bruno–Silesian unit; BB – Békés Basin; EA –Eastern Alps.*

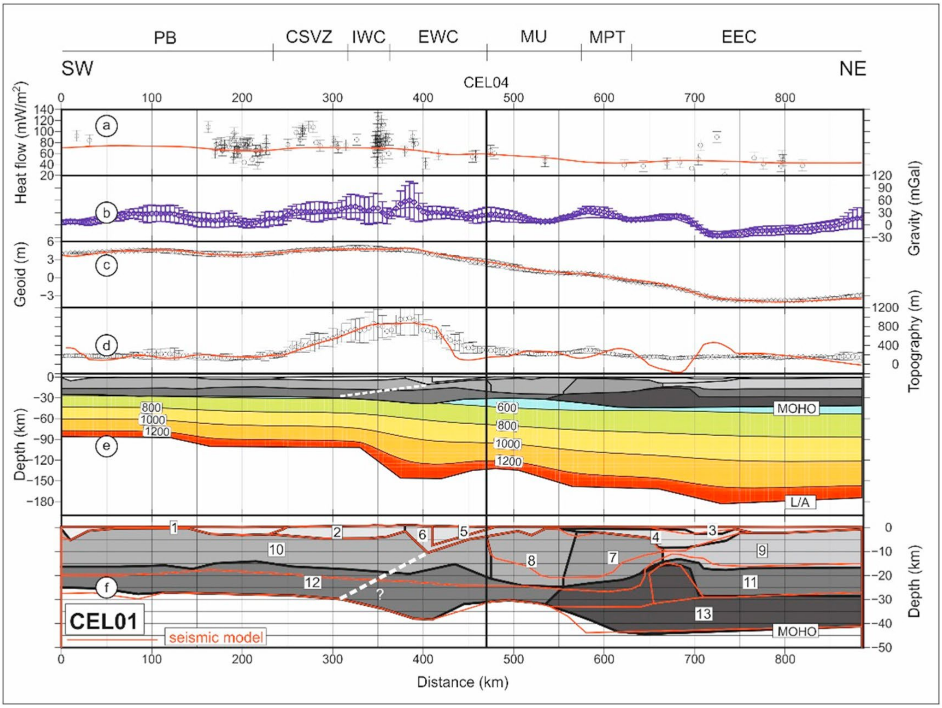

Fig. 19. *Lithospheric model for profile CEL01. (a) Surface heat flow density, (b) free-air gravity anomaly, (c) geoid, (d) topography with dots corresponding to measured data with uncertainty bars and solid lines for calculated values; (e) lithospheric structure (vertical=horizontal scale), in the lithospheric mantle, isotherms are indicated every 200 °C; (f) blow-up of crustal structure, numbers refer to bodies in Table 2; 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.*

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.

Lithospheric model along transect HT-1 across Western Carpathians and Pannonian Basin based on 2D integrated modelling
(*Contributions to Geophysics and Geodesy, Dérerová, Bielik, Kohút, Godová and Vozár, Bezák 2020***)**

The main goal of this paper was applied 2D integrated modelling approach to determine the lithospheric structure along transect HT-1 located in the Carpathian-Pannonian Basin–European platform region (Fig. 14). Our approach combines simultaneous interpretation of surface heat flow, topography, gravity, and geoid data. All available geophysical and geological data were used to create an initial model that has been afterwards modified by trial-and-error method until reasonable fit was obtained between input data and model predictions (Fig. 20). The focus of our study was the position and shape of the lithosphere-asthenosphere boundary (LAB). In the Pannonian Basin the modelled LAB is at depths of about 80-90 km and rapidly dips towards the Western Carpathians where its depth reaches values 145 to 150 km. Beneath the European platform the LAB depth is about 135-140 km. We can observe a slight lithospheric root under the Western Carpathians. This lithospheric thickening is interpreted as a small remnant of a subducted slab. This result is in a good agreement with the previous lithospheric models in the Carpathian-Pannonian Basin.

Table 4. *Densities and thermal properties of the different bodies used in our modelling along transect HT-1. No: Reference number in Figure 2, HP: heat production (µWm−3), TC: thermal conductivity (Wm−1K−1), ρ0: density at room temperature (kgm−3).*

No.	Unit	HP	TC	ρ_0
1	Pannonian Basin sediments	3.5	2.5	2500
3	Flysch sediments	1.0	2.0	2610
4	Pannonian upper crust	3.0	2.5	2750
5	Carpathian/European platform upper crust	2.0	2.5	2750
6	Lower crust	0.2	2.0	2950
7	Lower (mantle) lithosphere	0.05	3.4	3200

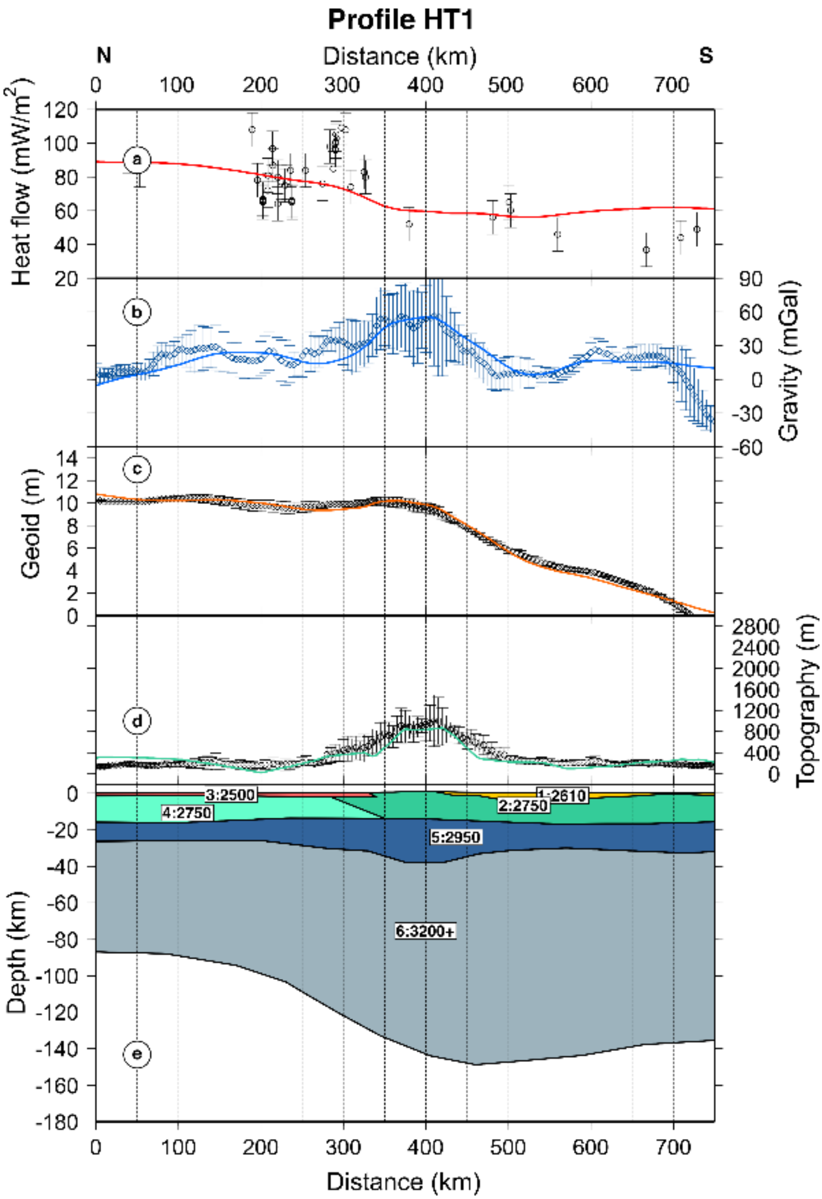

Fig. 20. *Lithospheric model along transect HT-1. (a) Surface heat flow, (b) free air gravity anomaly, (c) geoid, (d) topography with dots corresponding to measured data with uncertainty bars and solid lines to calculated values. Numbers in (e) correspond to material number in Table 4.*

A review of geophysical studies of the lithosphere in the Carpathian–Pannonian region

(*Geologica Carpathica, Bielik, Zeyen, Starostenko, Makarenko, Legostaeva, Savchenko, Dérerová, Grinč, Godová and Pánisová, 2022***)**

The paper deals with the most prominent features of the complete Bouguer anomalies (Fig. 21) and the lithospheric thickness in the Carpathian-Pannonian region. The stripped gravity map as well as the modelling of gravity data were used to re-evaluate the sources of the most important gravity anomalies. The Carpathian gravity low was divided into three sub-lows: the Western, Eastern and Southern Carpathian gravity lows. The Western Carpathian gravity low consists of the External and Internal Western Carpathian gravity lows, whose causes are different (Fig. 22). The source of the External Western Carpathian gravity low is the low-density sediments of the External Western Carpathians and the Foredeep, while Internal Western Carpathian gravity low is explained by the upper crustal deficit mass, which is formed by the rocks of the Tatricum and Veporicum. The main sources of the Eastern and Southern Carpathian gravity lows are crustal roots, whose gravity effect together with the gravity effect of surface sediments of the External Carpathians and the Foredeep form the observed gravity anomalies over both orogens. The Pannonian gravity high is caused by the expressive Moho elevation (24-26 km). Based on the calculated stripped gravity map several local gravity highs (>+50 mGal) were recognized. They correlate with the Danube Basin, the Transcarpathian Basin, the Békés Basin and the Makó trough. Their sources are high-density crustal bodies, whose apical parts reach depths of only 7 to 12 km (Fig. 23). Finally, the expressive different depths of the lithosphere-asthenosphere boundary in the Western and Eastern Carpathians were explained by the different Neo-Alpine development of both orogens. The mantle lithospheric root (~240 km) in the Eastern Carpathians is a result of a sinking of the upper part of the broken slab during the frontal continental collision. On the contrary, no thickening of the mantle lithosphere was observed in the junction zone of the Western Carpathians and the Bohemian Massif. The typical thickness of the continental lithosphere (~100 km) in this zone was explained by the oblique continental collision. The Pannonian Basin system is characterized by one of the thinnest continental crusts (~25 km) and lithospheres (~75 km) in the world.

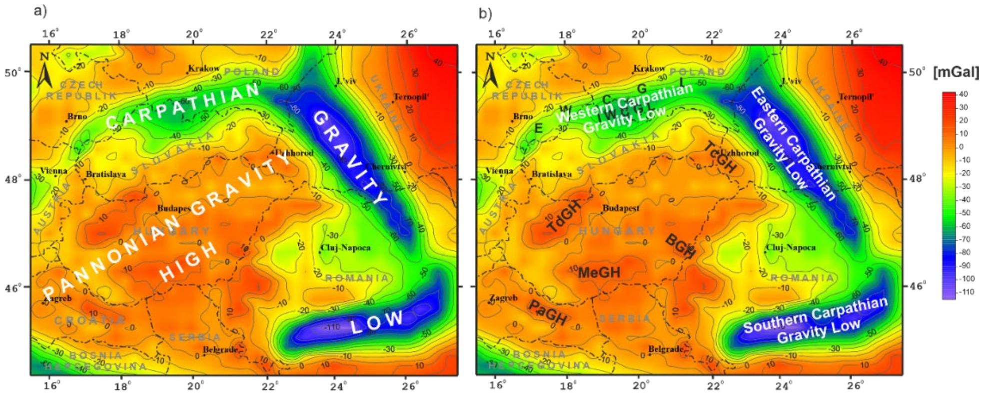

Fig. 21. *Complete Bouguer anomaly (CBA). Compilation based on gravity data published by Ibrmajer (1963), Švancara (2004), Bielik et al. (2006), Švancara et al. (2021). (a) The most prominent regional gravity anomalies of the CBA. (b) The most prominent local gravity anomalies of the CBA. Abbreviations: EWCGL = External Western Carpathian gravity low, IWCGL = Internal Western Carpathian gravity low, TcGH = Transcarpathian gravity high, TdGH = Transdanubian gravity high, PaGH = Papuk gravity high, MeGH = Mecsek gravity high, BGH = Békés gravity high.*

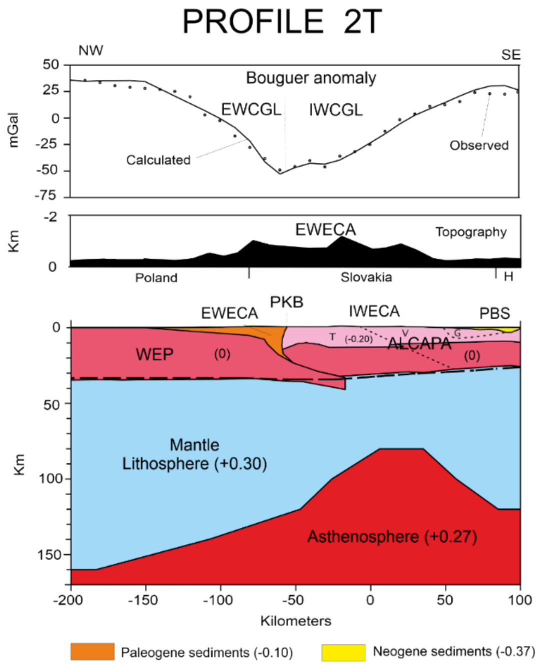

Fig. 22. *Density model along the seismic 2T profile. The density contrast values are in g cm-3. Abbreviations: WEP = Western European Platform, EWCGL = External Western Carpathian gravity low, IWCGL = Internal Western Carpathian gravity low, H = Hungary, EWECA = External Western Carpathians, IWECA = Internal Western Carpathians, PKB = Pieniny Klippen Belt, PBS = Pannonian Basin System.*

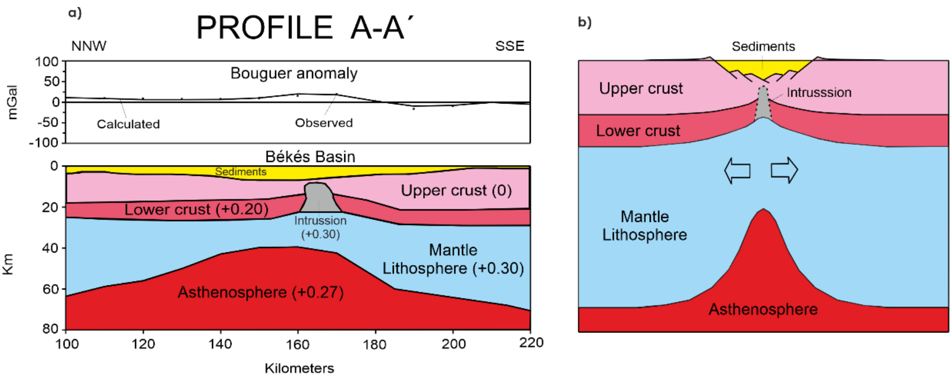

Fig. 23. *(a) Density model along the profile A-A´. The density contrast values are in g cm-3. (b) Scheme of a narrow rift model (sub-basin) of continental extensional tectonics for the Pannonian Basin System (modified after Bielik & Ádám 2006).*

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Defended PhD Theses

Institution: Faculty of Natural Sciences, Comenius University, KAEG, Bratislava, Slovak Republic
Title: Sensitivity study of the seismic hazard analysis of the locality of Jaslovské Bohunice
Student: Zuzana Chovanová
Supervisor: Jozef Kristek
Year of defense: 2019

Institution: Faculty of Natural Sciences, Comenius University, KAEG, Bratislava, Slovak Republic
Title: Interpretation of gravity anomalies along deep seismic refraction profiles running through the Western Carpathians
Student: Mgr. Barbora Šimonová
Supervisor: Miroslav Bielik
Year of defence: 2019

Institution: Faculty of Mathematics, Physics and Informatics, Comenius University Bratislava, Slovak Republic
Title: The finite-difference modelling of seismic wave propagation in the poroelastic medium – the 2D P-SV case
Student: Dávid Gregor
Supervisor: Peter Moczo
Year of defense: 2020

Institution: Faculty of Mathematics, Physics and Informatics, Comenius University Bratislava, Slovak Republic
Title: Identification of key factors of earthquake ground motion in surface sedimentary structures
Student: Svetlana Stripajová
Supervisor: Jozef Kristek
Year of defense: 2021

Institution: Faculty of Natural Sciences, Comenius University, KAEG, Bratislava, Slovak Republic
Title: Revision and analysis of the catalogue of earthquakes for the territory of Slovakia
Student: Martin Šugár
Supervisor: Jozef Kristek
Year of defense: 2022

International Research/grant projects

CTBTO Preparatory Commission
Numerical Modeling Sensitivity Study and Concept of Operation for Resonance Seismometry for CTBT OSI
2019
Investigators: Jozef Kristek, Miriam Kristekova, Peter Moczo

CTBTO Preparatory Commission
Services to Document the Technical Development of Seismic Geophysical Techniques for OSI – TASK 1 AND 2
2020-2021
Investigators: Jozef Kristek, Miriam Kristeková, Peter Moczo

CEA, France
Multidimensional numerical simulation of the propagation of seismic waves for the study of the site effects of the Cadarache and Marcoule centers
2022–2025
Principal Investigators: Jozef Kristek, Peter Moczo

Web pages

http://www.seismology.sk
http://www.nuqake.eu
http://www.fyzikazeme.sk

APPENDIX

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