Description of the main research directions investigated by the institute

Research in the IRSM covers two main research fields according to generally used classification - Natural Sciences and Engineering and Technology. Within the field of Natural Sciences the research is mainly focused on Earth and related environmental-and geosciences. Within the field of Engineering and Technology the research is mainly focused to Materials engineering, Material science and Nanotechnology. Someof the main results presented here belong also to the field of Medical and Health Sciences.

Several new, progressive research areas have been strongly developing in the IRSM since 2015, such as paleoseismology and thermochronology and application of new technologies in geoscience (TLS, multispectral UAV, continuous ERT, EME, etc.),

In the framework of Earth and related environmental sciences, the main research activities are focused on:

1. natural hazards: research of landslides and slope deformation (monitoring, hazard and risk assessment), monitoring and analyses of micro-movements (slips) on tectonic faults, paleoseismology and tectonic geomorphology, research on weathering of carbonate rocks and sandstones, seismological studies (seismic hazard analysis, moment tensor inversion and evaluation of possible precursors), monitoring and analyses of fluid-induced micro-seismicity, applied geophysics.
2. geochemistry: study of organic-rich matter, properties of waste materials as sorbents, properties of natural and synthetized materials, organic and inorganic pollutants in the environment, granitic rocks, tektites, tufa and uranium ore.

In the framework of Materials engineering, Material science and Nanotechnology, the main research areas are:

1. advanced composite materials: composite materials for tissue engineering andmedicine, heat-resistant composites,
2. special glasses: modelling of glass melting processes, batch to glass conversionand vitrification, special glasses for infrared radiation,
3. methods of processing of waste materials,
4. novel geopolymer materials: synthesis, properties and applications.

Research organization

The research in the IRSM is performed by 6 research departments (Department of Materials Structure and Properties, Department of Composites and Carbon Materials, Department of Geochemistry, Department of Seismotectonics, Department of Engineering Geology and Department of Neotectonics and Thermochronology), 2 jointresearch laboratories (Laboratory of Inorganic Materials, managed by IRSM and Faculty of Chemical Technology, University of Chemistry and Technology in Prague and Laboratory of sorption and porosimetric analysis managed by IRSM and Faculty of Science, Charles University in Prague) and in the scope of the World Centre of Excellence for Landslides Reduction (managed by IRSM and Faculty of Science, Charles University in Prague).

During the evaluation period, a several changes in the organizational structure of the IRSM were performed. In 2015, a new scientific department was formed - Dpt. of Neotectonics and Thermochronology. In 2017, the new heads were appointed in the Dpt. of Seismotectonics and Dpt. of Engineering Geology. In 2019 the new International Advisory Board was established.

Supporting research infrastructures

The IRSM maintains currently 4 research infrastructures in cooperation with the Institute of Geophysics CAS, and 4 more research infrastructures alone. In the scope of these research infrastructures, the IRSM performs regular monitoring in Europe (CR, Slovakia, Poland, Germany, Belgium, Italy, Austria, Slovenia, Bulgaria, Greece, Spain (Canary Isles), Switzerland, Norway (Svalbard) and Iceland. Within the frame of the global infrastructure network cooperating with the European networks, the monitoring is being performed in USA, Peru, Indonesia, Ethiopia and Kyrgyzstan.

Research activity and characterisation of the main scientific results

The research activities of the team are presented separately according to the above mentioned working groups.

1. Modelling of glass melting processes

1.1. The space without batch blanket (homogenization channel)

The continual glass melting is affected not only by the kinetics and sequencing of melting phenomena but also by the *route* of the melting process. The quantity *utilization of the space* has been introduced recently to quantify the space utilization for sand dissolution and bubble removal in the horizontal melting channel [1–2]. In the relevant calculation experiments, the space utilization was calculated using by analytical relations [3–4] and by mathematical modelling under boundary conditions simulating different types of melt flow [5–10]. The models of dissolution of sand particles and removal of bubbles were used to track their history in the melt. The impact of the batch blanket was ignored in this case in order to clarify the behaviour of the melt itself.

The results of detailed calculations have shown that the longitudinal melt circulations are the main obstacle of the high utilization of the melting space whereas the spiral flow can further increase the value [10]. The intensity of longitudinal circulations was determined by the energy distribution along the space and by the arrangement of heat sources. When the energy in the space is balanced, the uniform flow or helical flow (arising at intensive transversal circulations) sets in the space, showing highest space utilization and consequently, highest melting performance. The mass melting performance of the uniform flow under condition of balanced energy distribution in space heated by the Joule heat is given by the equation [7–9].

$$\dot{M}_{bal}[kg/s] = \frac{\dot{H}^L(k_1-\xi)}{H_M^T(1-k_1)}, \qquad (1)$$

where $\dot{H}^L$ means the overall heat losses through boundaries [W], k_1 is the fraction of energy delivered to the input region of the space, ξ is the fraction of heat losses in the input region, and H_M^T is the theoretical heat [J/kg]. The results showed a clear application potential [11–17].

The increasing values of $\dot{M}_{crit}$ at constant average temperature of glass and at k_1 values being between 0.45 and 0.9 are the consequence of growing values of the space utilization, the best values being achieved near the $\dot{M}_{bal}(k_1)$ curve. The principal factor of high space utilization is therefore in the balanced energy distribution; nevertheless, the arrangement of the central longitudinal barrier should be clearly preferred to others at lower values of k_1. The results show that the critical melting performance should be up to several times higher, compared with the case of uncontrolled melt flow which is so often in real industrial furnaces.

The specific melting performance of the channel being 6.5m long, 2m wide and with glass layer 1m high attained in optimum cases near the $\dot{M}_{bal}(k_1)$ curve more than 30 tons/(m^{3}day) for the float glass and average temperature of glass of 1420 °C. The principal quantity determining the melting performance of the channel became the fraction of overall energy delivered to the input region of the space, k_1. The treated melting channel for glass homogenization (removing sand particles and bubbles) can work as a part of two-space melting facility in which a batch conversion space is followed by the homogenization channel.

1.2. The glass melting furnace with the batch blanket on the melt level and with double-sided heating

Subsequently, two-region facility was designed and studied; the first region is determined for batch-to-glass conversion and the second region for final homogenization of the melt under condition of controlled melt flow (dissolution of sand particles and fining of bubbles). Thus, the studied facility has one space divided into region of batch conversion [18] and region of final homogenization, as presents Figure 2b:

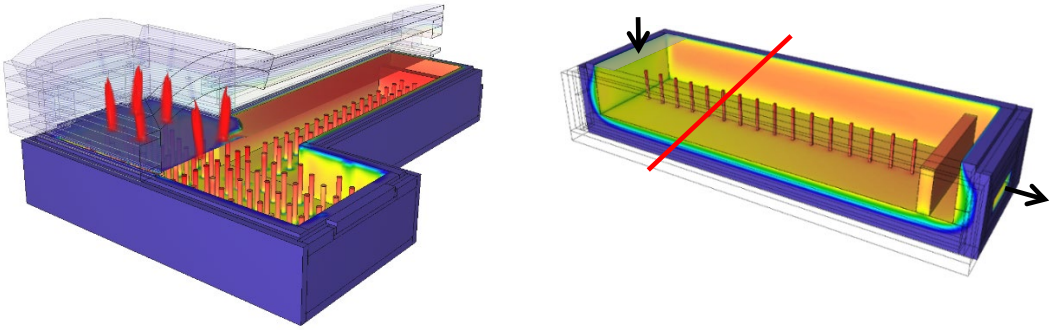

Figure 2: The view on the proposed melting spaces: homogenization module without batch (a), T-melter with batch blanket (b). The average temperature of glass is 1420 °C.

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2. Batch to glass conversion and vitrification

Ensuring high processing rates, a steady melter operation, and preventing operational issues and potential run offs related to the batch-to-glass conversion in a melter is of critical importance both for commercial and waste glass melting industry. A significant amount of work has been performed in recent years in our laboratory to gain fundamental understanding about the batch conversion during glass batch melting – both for commercial glass batches and for nuclear waste glass batches. This includes analysis of the conversion kinetics, heat flux into and within the batch, and understanding of foaming at the batch blanket bottom.

Our studies are performed to support the development of advanced batch conversion models. While the development of mathematical models of heat and mass transfer in glass-melting furnaces began in the 1970s and progressed rapidly with advances in sophisticated experimental/numerical techniques and increasing computational power, the batch melting models in use today do not adequately represent the complex chemical and physical phenomena occurring in the batch blanket and at the batch–melt and batch–gas interfaces. As a result, their ability to simulate batch conversion to glass (e.g., to estimate the batch melting rate, optimize the selection of raw materials, etc) is limited. Only with a realistic model of the batch blanket, mathematical models of glass-melting furnaces will be able to reliably estimate the melting rate, and thus determine the melter's productivity.

There is also a major practical importance of this work – glass making in Czech Republic has a long tradition. The know-how developed at Czech universities and/or companies continues to be recognized worldwide, especially in the field of design, optimization, and control of the melting process in glass melting furnaces. However, in order to defend, or even strengthen this position, it is essential to stay at the top of the field, not only by observing and replicating what is done elsewhere, but by testing new approaches and opening new research areas. Exactly this is the goal of our work.

While the peer-review process in never easy, we have been successful in publishing our research in the top journals in our field – see the list of more than 15 scientific publications in the references section. In the following sections, let us summarize our recent achievements.

2.1. Melting rate correlation equation

In [1-4], we describe the development and validation of a relationship between the rate of melting of a glass batch (per unit area of a melter) and the key process parameters, the so called "Melting rate correlation equation" (MRC):

$$j = \xi_0 \left(1 + \frac{u_B}{u_0}\right)^{\beta} \left(\frac{\eta_{MO}}{\eta_R}\right)^{-\alpha} (T_{MO} - T_B)\Delta H^{-1}$$

The MRC contains two types of parameters:

- *Melter processing data*: the melter operating temperature (T_{MO}) and the gas bubbling flux (u_B)
- *Batch and melt properties*: the conversion heat per mass of glass (ΔH), the batch blanket bottom (or interface) temperature (T_B), and the melt viscosity at T_{MO} (η_{MO}). These properties can be measured: ΔH by calorimetry, η_{MO} by viscometer (η_R, an arbitrary reference viscosity to make the viscosity term dimensionless, was selected to be 1 Pa·s), and T_B by batch expansion test or other method.

The coefficients ξ_0, α, β, and u_0 were determined by fitting the melting rate correlation to melting rate data measured in pilot-scale melters, obtaining good agreement between model estimated and measured values, see Fig. 4.

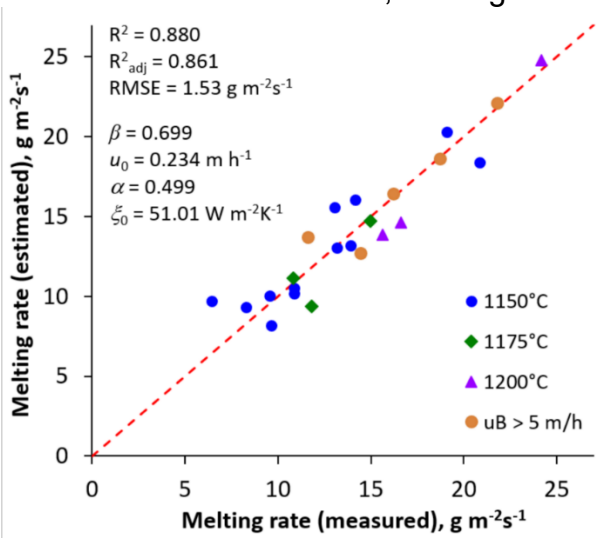

Fig. 4 Estimated versus measured melting rates. The legend shows melter operating temperature (T_{MO}) values and indicates experimental data for which bubbling rate (u_B) > 5 m h^{-1}, RMSE is the root mean square error of the estimated melting rates, and R^2 and R^2_{adj} are the coefficient of determination and its adjusted value, respectively.

The MRC can be used to test the influence of individual variables on melting. For the range of waste glass batches tested, the most influential variable was viscosity, closely followed by bubbling rate. The contributions of T_B and $(T_{MO} - T_B)$, i.e., the temperature difference across the thermal boundary layer, were also substantial. Clearly, the melting rate correlation provides a tool for a rapid assessment of glass production rate and can help limit the expensive and time consuming reduced-scale melter experiments to the most promising cases.

2.2. Analysis of batch melting process and batch properties

The ultimate goal of our batch melting studies is to develop an advanced cold cap model and incorporate it in the full CFD glass melter model [5] as its integral component. Under this task, we are performing studies to investigate the processes occurring during the batch melting, and analyze the batch thermal and mechanical properties to solve the heat and mass balance. This includes measurement methods such as in-situ X-Ray tomography [6], evolved gas analysis [7-9], or methods to evaluate the feed rheology and heat conductivity [11-12]. We were also testing the effect of batch composition on feed melting [13-14].

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3. Special glasses for infrared radiation

In the period of 2015-2019 the research was focused on two main groups of special glasses – to heavy metal oxide and oxy-halide glasses and to chalcogenide glasses. It consists of searching for new glass forming compositions and characterization of their physico-chemical properties. and searching for the relationship between glass composition, structure, conditions during its preparation and physical (particularly optical) properties. Homogeneous As_2S_3 films were prepared by spin coating from solutions of As_2S_3 diluted in n-propylamine and diethylamine and the obtained results are summarized in [1]. The thickness of the prepared layers varies between 200–1500 nm, refraction index depending on used solvent falls between 1.7 and 2.3.
On the investigation of optical properties with emphasis on photoluminescence and low-temperature photoluminescence spectroscopy the group cooperated with the team of dr. J. Zavadil at IPE (actually dr. Zavadil is employed at IRSM within the research project of P. Kostka and the team at IPE is led by dr. R. Yatskiv). One of the essential findings obtained in the period under review is related to this topic. Chalcogenide glasses doped with various RE ions were studied by low-temperature photoluminescence (PL) spectroscopy. Particularly interesting was the observation of

the broad host-glass PL with superimposed narrow absorption dips whose energy coincided with 4*f*-4*f* transitions of RE ions. The dips were observed previously but so far not properly interpreted. We were the first to show they correspond to 4*f*-4*f* up-transitions of RE, providing evidence of energy transfer between host-glass electronic system and RE ions [2].
The effects of caesium halides on the optical properties of Ge-Ga-S and Ge-In-S glasses were investigated in [3-4]. It was found that the fundamental absorption edge as well as the position of broad band luminescence of the host glass is shifted towards shorter wavelengths for CsI in contrast to CsCl and CsBr and that the addition of halides leads to narrowing of rare-earth related emission bands and to more pronounced fine structure due to crystal field splitting of involved electronic manifolds.
However, the laboratory primarily deals with heavy metal oxide and oxy-halide glasses. In this field the heavy metal oxide (HMO) glasses doped with rare-earth ions were investigated in cooperation with IPE. Various compositions of erbium doped zinc borate glasses were investigated by transmission and low-temperature photoluminescence spectroscopy. Low-temperature photoluminescence spectroscopy allowed us to deduce a schematic Stark levels splitting for the two lowest manifolds of Er^{3+} ions in this matrix [5].
Similar methodology supplemented by photoluminescence excitation spectroscopy was used also in the case of Er-doped lead-antimonite glasses modified by addition of ZnO and ZnS [6-7]. Among others we demonstrated that the broadening of rare-earth related emission bands takes place primarily in the high energy part and it can be correlated with electronic thermal energy ($kT \approx 208\ cm^{-1}$).
Lead tellurite oxy-chloride glasses modified by addition of different *d*-metals were the subject of two studies. The first one regarded these materials as large band-gap semiconductors [8] and was focused on optical transmission, band gap energy together with thermal stability. In the second work we investigated these glasses for optoelectronic applications in environments exposed to high-energy radiation and/or for radiation shielding. The glasses containing WO_3 and B_2O_3 appear as the most effective in gamma radiation shielding among the examined glass compositions [9].

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4. Novel geopolymers

In the area of geopolymer materials, the new types of composite materials using waste/unused materials (blast-furnace slags, ashes, fly ashes, etc.) were studied and their properties as setting time, mechanical strength, abrasive ability, leachability etc. was determined. A necessary step for using waste or unused materials is the characterization of the basic parameters as chemical and mineralogical composition, granulometry, leachibility, porosity, etc.

4.1. Waste material characterization

The heating of fluid fly ash (FFA), considered as waste, can lead to the formation of a stable system with newly formatted phases. The specific phase changes of the thermally treated FFA were described and the stable final phases, gehlenite and anorthite, were identified by XRD and FTIR analyses These findings could open a new way of FFA application in the preparation of products for heat and fire protection

because the thermal stability of these products means safety for the protected constructions and people (Perná et al., 2018).

The Kladno town deposit (Central Bohemian Region, Czech Republic) contains approx. 10–12 million tons of blast-furnace slag, a vestige of the massive iron production (1855–1975) and its possible reuse requires the deposit mapping and chemical and mineralogical characterization (Hanzlíček et al., 2017). This study identifies the changes in its composition occurring during the reaction of blast-furnace slag and alkalis which creates hard and insoluble final product with newly formed crystal phases and a certain share of amorphous participants (Perná et al., 2019).

Based on successful cooperation with Czech University of Live Sciences Prague the ashes from biomass combustion were monitored from the point of view of the possibility to use the releasable nutrients as alternative mineral fertilizer. It was found (Perná et al., 2016a) that high burning temperature considerably changes possibility of extraction of nutrient elements because of their major incorporation into the generally insoluble feldspars. However the results have confirmed small amount of nutrient elements which could be extracted and the experiments proved plant-available portions of Ca, Mg, and K in biomass ashes.

It was found that some ashes contain dangerous substances, e.g. polycyclic aromatic hydrocarbons (PAHs) which can be potent carcinogens, mutagens and teratogens. For these reasons 96 samples of fly and bottom ash derived from incineration of phytomass and dendromass was investigated. It was corroborated (Košnář et al., 2016) that the presence of polycyclic aromatic hydrocarbons is strongly influenced by the fuel type and the differences in boiler operating conditions, especially combustion temperature, and that the total PAHs present in ash increased with increased levels of unburned carbon. The main point is that the biomass incineration can be improved and these ashes could be used as an alternative mineral fertilizer and not landfilled as hazardous waste.

4.2. The waste-material utilization in geopolymers

The setting time of inorganic binders is decisive for their production, transport, storage, and workability. The possibility of influencing the setting time of a clay-slag geopolymer matrix was studied by a modification of the clay/slag ratio and by a change of the mixing method (separate and collective mixing). The results showed (Perná and Hanzlíček, 2016) that in comparison with a pure clay matrix, whose setting time was 12 h, the addition of blast-furnace slag significantly accelerates the solidification process. The setting time ranges from 120 min for clay/slag ratio 1:0.5 to 50 min for the clay/slag ratios 1:0.7. Depending on the proportions of additives, the setting and hardening of the geopolymer matrix could be accelerated, which is important for quick repairs, and on the other hand retarded if geopolymer mortar is transported at a long distance or if it is necessary to prolong the workability period.

Geopolymers are known as high strength and durable construction materials but have a brittle fracture. The geopolymer mortars reinforced with glass fibers (0, 2.5 and 5 wt %) were prepared and the effect of fibers on the mechanical properties and acid water resistance was investigated. The study showed that glass fiber reinforcement can change the fracture mechanism and chemical stability of geopolymer composites (Steinerová et al., 2017).

The interlayer formed between two different source materials is responsible for the adhesion and therefore stability of the final material. From this reason the interlayer created by a combination of two different waste materials was observed: (a) the Ca-K geopolymer binder (matrix) and (b) solidified fluid fly ash (aggregate). The results

showed the migration of ions (K^+ and Ca^{2+}) between a matrix and the aggregates which caused changes in color and a formation of an inseparable coating layer bounding both participants (Perná et al., 2017a).

After finding that some of the biomass ashes contain polycyclic aromatic hydrocarbons (PAHs) it was logical to look for ways how safely inhibit these ashes. The incompletely combusted straw ash containing high content of unburned carbon and PAHs (Košnář et al., 2016) has been used in metakaolin-based geopolymers with the purpose of studying the quality of its inhibition and its influence on the resulting properties (Perná et al., 2019). The results have shown a dependence of compressive strength on the ash content added and although the mineralogical composition of geopolymers solids with straw ash added was almost identical. FTIR analyses have confirmed the incorporation of straw-ash elements into the clay materials and the formation of geopolymer bonds by alkali activation. These results were verified by PAH's extraction and determination which have proved significant reduction in the amount of poly-aromatic hydrocarbons (PAHs) detected after solidification.

4.3. Know-how transfer from the laboratory to the industry

Technology transfer from the laboratory to the industrial level is an indispensable step in the process of putting new technology into practice. The laboratory developed Ca–K geopolymer matrix was used in company Best – Business, A.S. manufacturing grinding tools. The parameters of the industrially fabricated grinding wheel bonded by the Ca–K geopolymer were evaluated by the standard company quality testing procedures. The results proved that this geopolymer matrix could be used for the preparation of grinding tools whose properties are comparable with those based on a fired ceramic binding agent (Perná et al., 2016b).

Successful laboratory experiments on development of the specific geopolymer matrix for emergency were applied on an industrial scale and highly contaminated and damaged concrete floors in an industrial plant (approximately 80 m^2) were repaired in 8 hours during a night shutdown. This industrial-scale experiment confirmed laboratory results and long-term monitoring of the floor condition proved that a clay-slag geopolymer matrix filled with sand or pebbles can be used e.g. for a fast repair of heavily contaminated cement or concrete floors in industrial productions (Perná et al., 2017b).

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5. Processing of waste materials

In 2015–2019, the research activity of the group was targeted to processing of plastic waste mixtures, waste tires and biomass. Further, mineral processing of industrial raw material mixtures by magnetic separation was solved. The main scientific results achieved are as follows.

1) Thermal conversion of polyolefins/polystyrene ternary mixtures was described by advanced kinetics and mechanisms of fission reactions. On this basis, a promotion of fission of polyolefins by polystyrene (PS) radicals was newly clarified. Obtained findings were confirmed in laboratory and, mainly, commercial-scale experiments which showed that even small amounts of PS in the starting mixture (5 wt.%) effectively promote a thermal fission of waste polyolefins, while the high amounts of valuable liquid hydrocarbons are obtained. In this way, processing of waste polyolefins/polystyrene mixtures was effectively solved. Team's contribution to the publication was 95%; the third author, from another team, carried out part of FTIR analyses and her contribution was 5%. Publication: Straka P., Bičáková O., Šupová M. (2017), Thermal conversion of polyolefins/polystyrene ternary mixtures: Kinetics and pyrolysis on a laboratory and commercial scales, Journal of Analytical and Applied Pyrolysis 128, 196–207.

2) Co-processing method of waste tire with coal for smokeless fuel, maltenes and hydrogen-rich gas was developed. Slow co-pyrolysis of waste/coal mixtures, potentially applicable on a large scale, was applied. A low-sulfur, low-ash smokeless fuel was obtained, alternatively useful as a low-cost carbonaceous sorbent. Further, energetic gas with 60% of hydrogen and 20% of methane for further use was produced. Tar obtained can serve as a liquid fuel (LHV 36–41 MJ/kg), moreover, as a source of

maltenes for repairing of roads asphalt surfaces. Thus, waste tires can be successfully processed instead of landfilling, even in high amounts. Team's contribution to the publication was 100%. Publication: Bičáková O., Straka P. (2016), Co-pyrolysis of waste tire/coal mixtures for smokeless fuel, maltenes and hydrogen-rich gas production, Energy Conversion and Management 116, 203–213.

3) Oxygen-steam gasification of waste-tyre with lignite on a commercial scale was implemented and assessed. It was found that (a) the content of the waste-tyre particles in the mixture should not exceed 22 wt.%, then the utility properties of the resulting energetic gas are improved and in the IGCC will not cause any operational problems, (b) waste-tyre improves the lower heating value of the raw gas in comparison with that from the gasification of lignite alone, (c) co-gasification of waste-tyre is suitable for lower or medium gasifiers performance, because less unburned carbon and CO_2 are produced, (d) the addition of waste-tyre has no significant effect on the properties of resulting ash. Team's contribution to the publication was 100%. Publication: Straka P. (2015), The use of Lignite for the Thermal Treatment of Waste-Tyre on a Commercial Scale. In the book: Advances in Environmental Research. Editor: Justin A. Daniels, Nova Science Publishers, New York, 2015, pp.159–171.

4) Processing of poorly treatable biomass was performed and evaluated. Pyrolysis and combustion were applied. It was found, that pyrolysis of two types of biomass whose use and processing are problematic, orange peel and apricot stones, provided (a) gas with a lower heating value of 11–14 MJ/m^3, which can be, after improving, further used as the energetic gas; (b) bio-oils with a higher heating value of 30–32 MJ/kg that can be used as fuel oils; considering the large number of organic substances present in these oils, they can be alternatively utilized as a source of chemicals; (c) solid carbonaceous residue (yield of 27–29 wt.%) with a higher heating value of 33–35 MJ/kg which may be used as auxiliary fuel for common solid fuels. Tested biomasses were further combusted. Use of obtained ashes was examined with the result that they can be used for the preparation of fertilisers for agricultural lands, because of significant amounts of essential elements – phosphorus, potassium and magnesium as well as calcium and sulphur. Team's contribution to the publication was 100%. Publication: Straka P., Bičáková O. (2018), Laboratory pyrolysis and combustion of poorly treatable biowastes, Paliva 10, 122–137.

5) Thermal treatment of waste polyethylene terephthalate by co-pyrolysis with coal. It was found that the addition of PET to coal in coking blends have impacts on coke yield, its true density, volume contents of fissures and mean reflectance, volume and surface of pores, and the formation of aromatic structures. However, the properties of coke and gas did not change significantly until 20% of the coal had been replaced with waste PET bottles in the coal charge.
Publication: M. Havelcová, O. Bičáková, I. Sýkorová, Z. Weishauptová, A. Melegy, Characterization of products from pyrolysis of coal with the addition of polyethylene terephthalate, Fuel Processing Technology 154, 2016, 123–131.

6) Mineral processing of industrial raw materials mixtures by magnetic separation. The new methods of purification of raw materials using magnetic separation and magnetic filtration using neodymium magnets were developed and applied.
Publications:
1) Žežulka V., Straka P., 2015, the Czech patent No. 305590, 2015.

2) Žežulka V., Straka P. (2016), The Creation of a Strong Magnetic Field by Means of Large Magnetic Blocks from NdFeB in Opposing Linear Halbach Arrays, Journal of Magnetics 21(3), 364–373.
3) Žežulka V., Straka P. (2017), The Design of a Device for the Generation of a Strong Magnetic Field in an air Gap Using Permanent Magnets, Journal of Magnetics 22(2), 250–256.
4) Žežulka V., Straka P. (2018), Linear Halbach Structures: The Influence of Different Arrangement and Dimensions on the Resulting Magnetic Field, Journal of Magnetics 23(2), 229–237.
5) Straka P., Žežulka V. (2019), Linear structures of Nd-Fe-B magnets: Simulation, design and implementation in mineral processing – A review. Minerals Engineering 143, 2019, no.105900.

7) Research for practice

Two practical tasks were solved in order to obtain ethylene glycol for the production of antifreeze mixtures: Processing of waste PET plastic after melting with calcium hydroxide and Processing of waste PET in the form of flakes. The processing conditions of were determined, namely heating rate and a final temperature, which should be used to produce a key product. Further, the developed magnetic filter was sold to the Technical University of Košice, Faculty of Mining, Ecology, Process Control and Geotechnology, for solving of technological tasks and for teaching, too.

Research activity and characterisation of the main scientific results

In the period of 2015-2019, research of the team has focused on modern fibrous, particulate, and hybrid composite materials on the basis of natural or synthetic materials. These activities can generally be divided into two thematic groups: (*i*) composite materials for tissue engineering and medicine and (*ii*) research of preceramic polymers and their use in the development of ceramic foams, ceramic matrix composites and all-ceramic sandwiches. In this report the activities of the team have been divided into these two main research areas, while each comprises of a number of topics.

First research area: Composite materials for tissue engineering and medicine

- ***Topic 1: Collagen-calcium phosphate nanolayers with controlled elution of antibiotics***
- ***Topic 2: Collagen composite scaffolds for bone surgery***
- ***Topic 3: Collagen porous foams for wound healing***
- ***Topic 4: Calcium phosphate nanoparticles for the repair of bone defects***
- ***Topic 5: Evaluation of functional characteristics of nanofibrous materials***

Second research area: Research of preceramic polymers and their use in the development of ceramic foams, ceramic matrix composites and all-ceramic sandwiches

- ***Topic 6: Advanced ceramic foams from a pyrolysed polymer precursor***
- ***Topic 7: Ceramic sandwich materials***

All the topics mentioned above were all supported by the Czech Science Foundation, the Technology Agency of the Czech Republic or by the Czech Health Research Council, Ministry of Health of the Czech Republic.

Topic 1: Collagen-calcium phosphate nanolayers with controlled elution of antibiotics

Since September 2014, the team has been engaged in the development of a collagen coating for orthopaedic implants in the form of a nanofibrous layer, which exerts a strong local anti-infection effect with no indication of cytotoxic effects and, simultaneously, leads to an increase in the rate of osseointegration necessary for the suitable fixation of the implant (Fig. 1). It is expected that such a layer will be used particularly in the case of known prosthetic joint infections or as a preventative procedure regarding primary joint replacement in a potentially infected site. The layer will provide a bone/implant (titanium alloy) bioactive interface, which will enhance the physiological healing process, will be capable of filling bone defects, and will act as a powerful antibacterial agent. In this project, the team demonstrated the benefits and limitations of the single and combined application of antibiotics in collagen electrospun layers with differing amounts of hydroxyapatite. The study revealed that collagen electrospun layers that exhibit sufficient antimicrobial activity are not directly toxic for human cells. Moreover, it was demonstrated that collagen/hydroxyapatite layers directly electrospun on the surface of 3D printed titanium implants and impregnated with vancomycin have the potential to prevent infection while maintaining osseointegration. The antimicrobial activity of collagen/hydroxyapatite/vancomycin layers was found to be sufficient to prevent the development of bone infection *in vivo*

as proved by a rat femur implant-related infection model with the inoculation of a clinically-relevant Staphylococcus epidermidis strain. *In vivo* tests employing a pig model concluded that a collagen/hydroxyapatite/vancomycin coating is capable of effectively improving the rate of osseointegration. Both the antimicrobial and osteoinductive functions of electrospun collagen/hydroxyapatite/vancomycin layers help to reduce the revision rate and enhance the long-term success of bone implants.

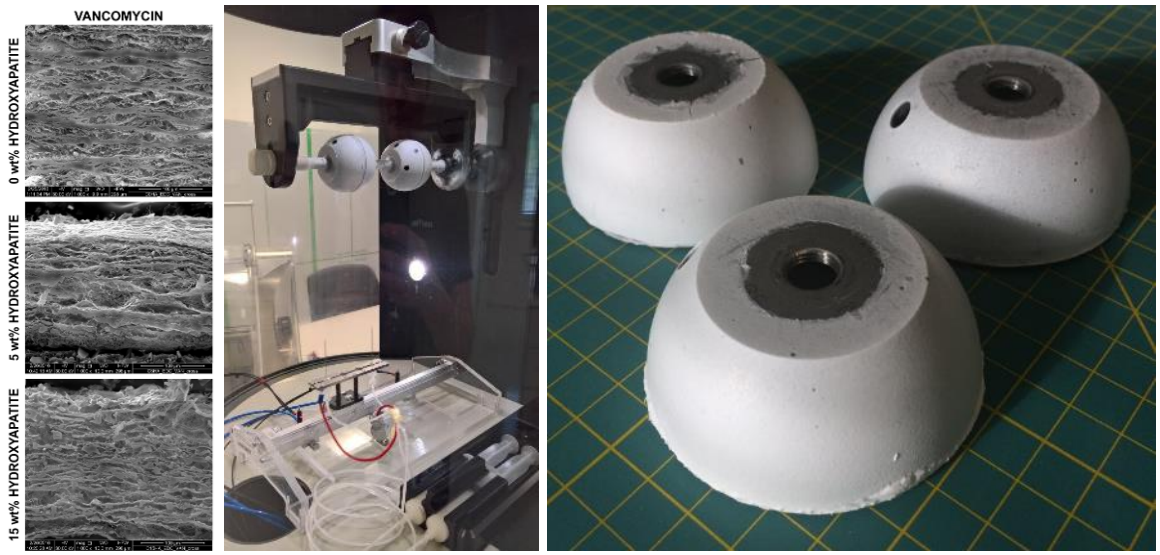


Fig. 1 Collagen nanofibrous layers with 0, 5 or 15 wt% of hydroxyapatite and antibiotics can be directly electrospun on the surface of implants (acetabular cup of total hip replacement).

In the frame of this project, the team collaborated with two Czech commercial companies and five research organizations or universities. The team member was a principal investigator of this project. The contribution of the team was over 50% (preparation of materials, comprehensive analyses, coordination of the project). Beside publications [1–4], 5 utility models (Industrial Property Office) [5–9] and functional samples, the main output was the developed technology for preparation of functional surface layers of implants for orthopaedics and dentistry. Presently (March 2020), the examining division of the European Patent Office intends to grant a European patent on the basis of our application "*A nanocomposite layer on the basis of collagen nanofibers, and a method of preparation thereof*"(No. EP 17 197 245.8 - 1109). The material composition as well as its preparation procedure have been also submitted for the granting of a Czech patent, Industrial Property Office of the Czech Republic, application number PV 2016-656).

Topic 2: Collagen composite scaffolds for bone surgery

Optimal bone replacement materials imitate the real bone composition and structure so as to allow for the functioning of repair mechanisms by providing a temporary porous scaffold that, in turn, provides mechanical support for cells up to the time that the tissue has regenerated and remodelled itself naturally. The application of collagen is problematic due to its poor mechanical properties, high swelling rate in aqueous environments, low structural stability and low level of resistivity to the enzymatic degradation of its untreated form. In the period of 2015-2018, the team has been engaged in the project dealing with the development and comprehensive pre-clinical testing of novel composite materials for bone surgery. In the frame of this project, the team demonstrated that the mechanical and structural properties of collagen can be

improved via chemical cross-linking and via the creation of composite materials in which the collagen matrix is reinforced by fibres or particles. It was further demonstrated that the selection of the optimum cross-linking system constitutes a key factor. It has been shown that while the improvement of the stability of collagen scaffolds following cross-linking is demonstrated via an improvement in the mechanical properties, such changes cannot be evaluated separately without the evaluation of other effects principally on the secondary structure of the collagen and the overall structural properties of the collagen scaffolds. Only the combination of mechanical and structural analyses is able to provide reliable information on the success rate of such modifications. Moreover, it was shown that changes in the mechanical, chemical and structural properties should be evaluated in the hydrated rather than the dry state of the collagen (Fig. 2). The hydrated state allows the collagen molecules to adopt conformations with maximal entropy, and the system exhibits a low level of dihedral energy. Such effects significantly influence the mechanical properties of the material in the environment for which it is designed. It was documented that with respect to the simulation of the body environment, the conditions must be considered very carefully. As with the evaluation of the structural parameters, it is crucial that the best method be selected for their characterisation.

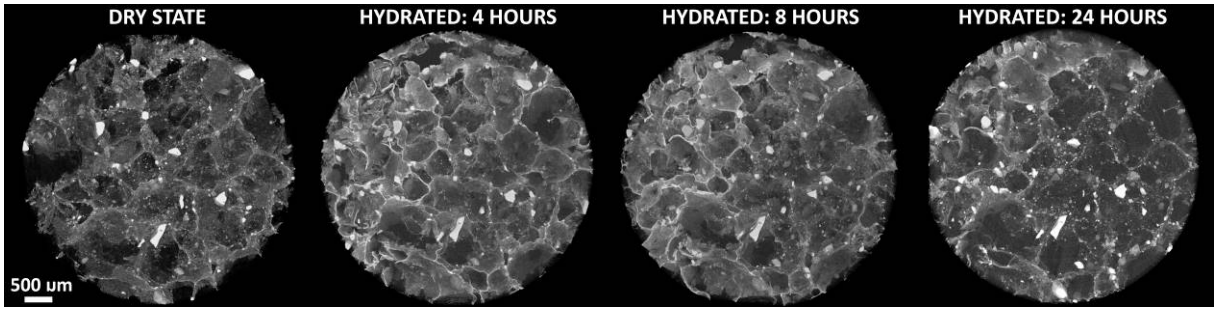


Fig. 2 An example of micro-CT images of collagen composite scaffold in the dry and hydrated states.

In the frame of this project, the team collaborated with three research organizations or universities. The team member was a principal investigator of this project. The contribution of the team was about 40% (preparation of implants, structural characterization and design of *in vivo* testing). Main outputs were publications in prestigious peer-reviewed journals [10–16] and two utility models (Industrial Property Office) [17,18] and functional samples.

Topic 3: Collagen porous foams for wound healing

The team addressed development of a novel collagen wound dressing foam prepared from freshwater fish (*Cyprinus carpio*) skin collagen. Surgical site infections may lead to a marked worsening in patient outcomes and represent a financial burden due to prolonged hospital stay. Local antibiotic treatment has been proven to provide an effective way in which to reduce wound infection at the surgical site. The aim of this project was the development and optimization of antibiotic delivery wound dressing based on freshwater fish skin collagen. Advantage of utilization of fish collagen remains in lower antigenicity than its mammalian counterparts, excellent biocompatibility, and promotion of direct cell adhesion and differentiation. A further advantage of fish collagen is that it does not bear the risk of the transmission of ruminant zoonosis thus rendering wound dressings made from fish collagen potentially safer than those based on other collagens. Three different construction of foams were developed and

analysed (Fig. 3). The first consisted from a simple homogeneous foam. The second developed type was sandwich foam with highly porous peripheral layers and rigid core with lower porosity. The third type represented a composite foam prepared as combination of collagen nanofibrous reinforcement embedded in porous collagen matrix. In the frame of this project, different antibiotics were applied in the inner structure of foams, namely gentamicin, vancomycin, rifampicin and nitrofurantoin. The resulting highly homogeneous products characterized by excellent structural and clinical properties proved effective in terms of the treatment of a surgical wound infection in a *in vivo* models. Antibiotics released was effective only locally without signs of systemic load. Such a antibiotics-containing foams provide a promising tool for the treatment and prevention of surgical site infection.

In the frame of this project, the team collaborated mainly with two research organizations. The contribution of the team was about 40% (collagen isolation, foams preparation, structural characterization). Besides publications [19–21], the main outputs were two utility models [22,23] (another one utility model application is under review), three functional samples and one national patent application (Industrial Property Office).

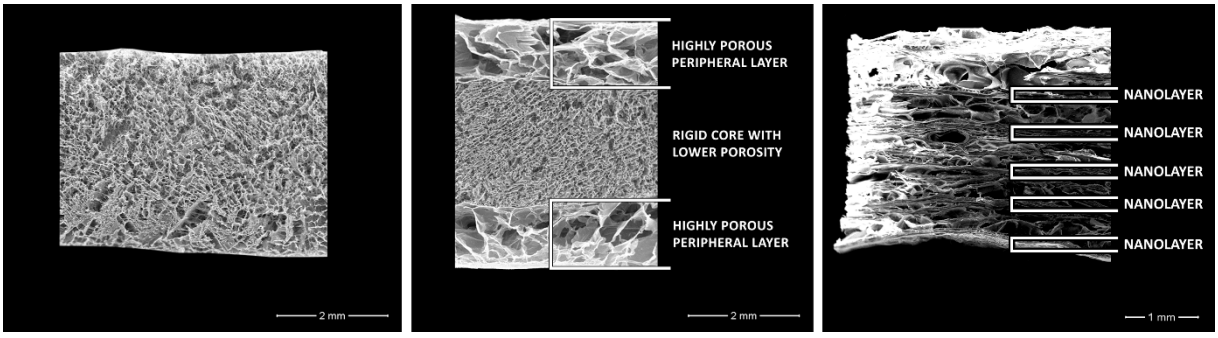


Fig. 3 Three different construction of foams (from left): a simple homogeneous foam, sandwich foam with highly porous peripheral layers and rigid core with lower porosity, and a composite foam prepared as combination of collagen nanofibrous reinforcement embedded in porous collagen matrix.

Topic 4: Calcium phosphate nanoparticles for the repair of bone defects

Calcium phosphates (CaP) have traditionally been used for the repair of bone defects due to their strong resemblance to the inorganic phase of the bone matrix. The wide variety of natural and synthetic CaP-based biomaterials available today are used extensively in dental and orthopaedic applications owing to their high levels of biocompatibility, osteoconductivity and osteoinductivity. Various calcium phosphate calcium phosphates were isolated and utilized by the team within the period of 2015-2019 in order to obtain a suitable filler for the studied biocomposites. Bioapatite isolated or prepared from biogenic sources exhibits enhanced resorbability and a much higher degree of bioactivity than micrometer-sized or synthetic calcium phosphates. One of the most important results achieved by the team was the comprehensive assessment of eight different CaP nanopowders (Fig. 4) both synthetic and isolated from natural bone material [24]. This work pointed out the often ignored interplay of various physio-chemical parameters influencing the cell behaviour. The team published or contributed to several other studies dealing with application of calcium phosphates. Beside a highly cited review written by M. Šupová (over 240 citations in March 2020, Web of Science) [25], the team members collaborated in investigation of the strength and structure

changes occurring during the biodegradation of highly porous sintered CaP scaffolds with a similar macrostructure but different phase compositions, in which the biodegradation activity of osteoclastic cells was simulated by an acidic environment *in vitro* [26]. The team also cooperated in the study aiming at improvement of the properties of CaPs via the addition of a thermosensitive, biodegradable, thixotropic copolymer [27].

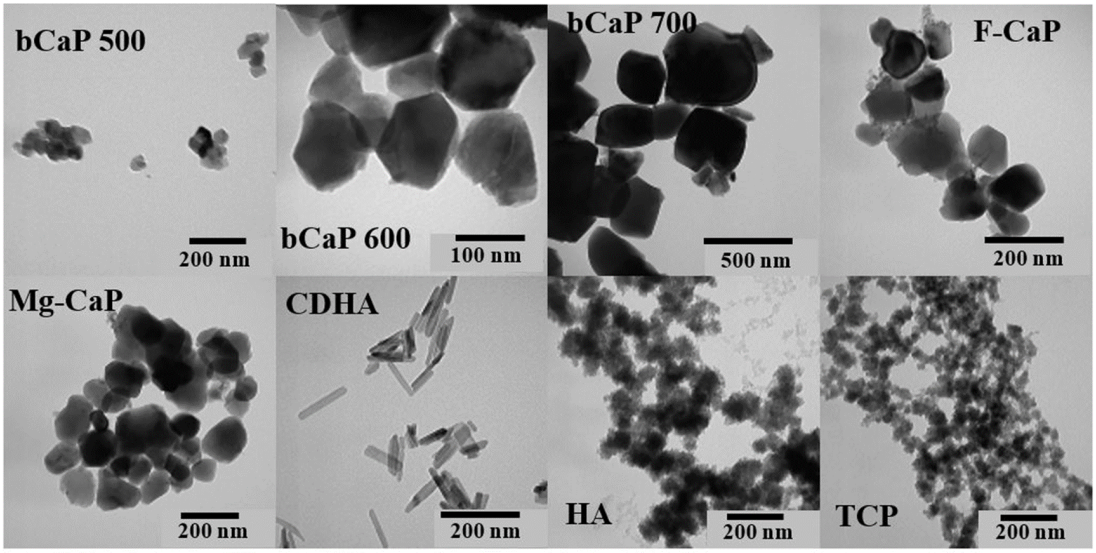


Fig. 4 TEM images of evaluated calcium phosphate nanoparticles, namely bovine bioapatite (bCaP) isolated from chemically and thermally treated bovine bone (calcined at 500, 600 or 700 °C), fluorinated calcium phosphate (F-CaP), Mg-Doped brushite (Mg-CaP), Ca-deficient hydroxyapatite (CDHA) and commercial nano powders (HA: hydroxyapatite, TCP: tri-calcium phosphate, both obtained from Berkeley Advanced Biomaterials, CA, U.S.A.)

Topic 5: Evaluation of functional characteristics of nanofibrous materials

In the period of 2015-2019 the team also continually participated in the evaluation of functional properties of various nanofibrous materials, namely fibrin-coated electrospun polylactide nanofibers in skin tissue engineering [28], protein nanocoatings on synthetic polymeric nanofibrous membranes designed as carriers for skin cells [29] and electrospun vascular grafts made from biodegradable polyesters [30,31]. These results were achieved mainly in the cooperation with the Institute of Physiology of the Czech Academy of Sciences and Technical University in Liberec. In each of these studies, a member or members of the team significantly collaborated, their overall contribution to each study was about 20%.

Topic 6: Advanced ceramic foams from a pyrolysed polymer precursor

At the beginning of the period of 2015-2019, the team was engaged in a detailed study of the pyrolysis transformation of polysiloxane thermosets into Si-O-C ceramics. The research was focused on simple basic polymethlylsiloxane and polymethyphenylsiloxane resins. The effects of the pyrolysis process on changes in the chemical structure of the material and on induced changes in mechanical properties at various degrees of this conversion in the range of 250 to 1000 °C have been reported in [32]. This conversion was also investigated in terms of gaseous pyrolysis products by GC-MS in [33]. The results of this research were used in the development of special construction materials in several cases below.

Long-term experience with pyrolysis processes and newly acquired knowledge in the field of pyrolysis of polysiloxanes were used in the development of advanced ceramic foams [34,35]. In cooperation with the Institute of Macromolecular Chemistry and the Institute of Physics of Materials of the Czech Academy of Sciences, several principally different methods of cross-linked polymer precursor preparation have been tested. First, standard foaming principles were tested by the expansion of simple low molecular weight hydrocarbon compounds. A general disadvantage of these methods is the achievement of an uneven porous structure mainly due to the gravitationally induced porosity distribution together with the effect of gaseous products released during the curing reaction of the thermoset precursor. The results of these experiments were published in [36]. Another foam preparation method tested was to use epoxy particles as pore-forming templates. This technology reduces these harmful effects. In addition, a structure with a very specific pore shape can be obtained by this method and, unlike other methods tested, a lower porosity of the resulting material with significantly improved mechanical properties can be achieved [37]. The most promising results in the preparation of ceramic foams were obtained by adding starch into the thermoset precursor prior its curing (for illustration please see Fig. 5). In this case, the foaming rate can be controlled by a suitable temperature regime for the curing of the polysiloxane precursor and the resulting porous structure is satisfactorily uniform. This technological process has been described in [38]. The effect of high temperature annealing on mechanical properties of Si-O-C ceramic foam is given in [39].

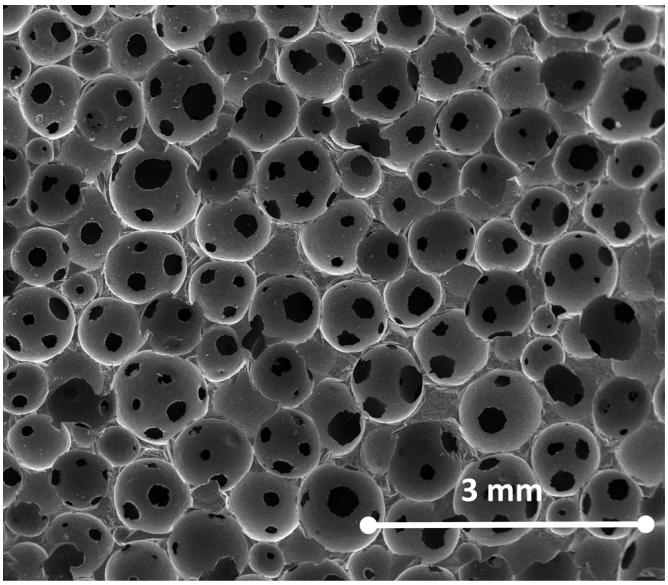


Fig. 5 SEM micrograph of the Si-O-C foam (polysiloxane precursor was modified by the addition of 12.5 wt% starch).

Topic 7: Ceramic sandwich materials

The experience of the team with the production of ceramic matrix composites and the knowledge gained in the field of ceramic foam preparation were utilized in the development of sandwich material, all components of which are made of ceramic. A ceramic fibre reinforced composite with a nanocrystalline mullite - corundum structure was used for the outer bearing layers of this sandwich (for illustration please see Fig. 6). The matrix of the bearing layers is formed of Si-O-C ceramics. The outer bearing layers were made separately by placing the fibres into a polysiloxane thermoset and its subsequent pyrolysis to 1000 °C. The core of the sandwich is formed of Si-O-C

ceramic foam which was prepared by foaming the polysiloxane precursor by the addition of starch and subsequently pyrolyzed to a temperature of 1000 °C. The outer bearing layers were adhered to the foam core with an inorganic silicate adhesive and subsequently the sandwich was annealed to 1000 °C to cure the adhesive. The technology of this sandwich is described in detail in [40]. This work also deals with dilatation properties of individual components and also dilatations occurring in adhesive during its curing.

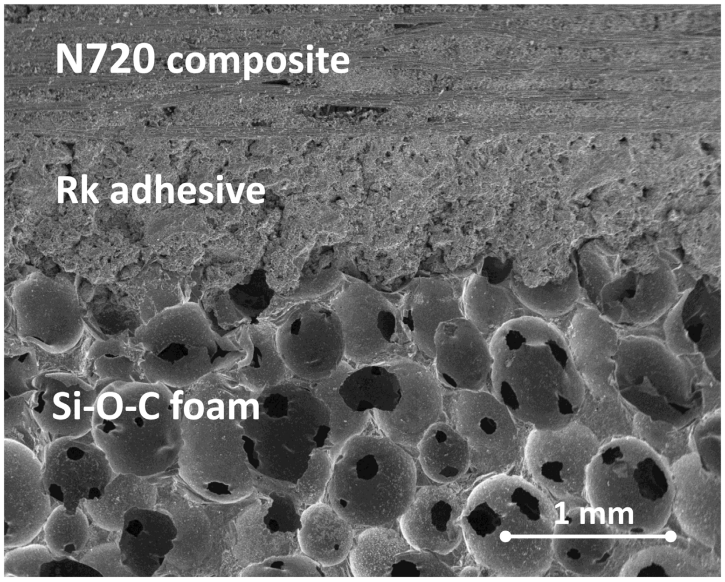


Fig. 6 Adhesive connection between the Si–O–C foam core and the CMC composite bearing layer of ceramic sandwich (SEM micrograph).

In the frame of Czech Science Foundation project the properties of partially pyrolyzed basalt fibre reinforced composites investigated. This material was developed by IRSM in cooperation with the Institute of Macromolecular Chemistry and the Institute of Physics of Materials of the Czech Academy of Sciences in 2009-2014. The results of thousands-hour exposure tests of these materials, especially with regard to their residual mechanical properties, were published in [41]. Furthermore, the effect of thermal exposure during partial pyrolysis on reinforcing basalt fibres was investigated. The publication [42] deals with the identification of crystalline phases formed in the amorphous matter in this technological step. Most attention is devoted to the formation of iron crystals, which at temperatures around 700 °C is a surprising phenomenon.

In the period of 2015-2019 the team also participated in further particular studies beside the main two above mentioned areas. These results originated mainly from the cooperation with other teams from the Institute [43–46] or previous cooperation [47,48].

Research activity and characterisation of the main scientific results

Activities of the team can be divided in five topics. These topics do not fully correspond to the focuses mentioned above, because all three teams intensively cooperate in order to provide a complex and interdisciplinary approach:

1. **Study of organic-rich matter**
2. **Properties of waste materials as sorbents**
3. **Properties of natural and synthetized materials**
4. **Organic and inorganic pollutants in the environment**
5. **Granitic rocks, tektites, tufa and uranium ore deposits**

TOPIC 1: Study of organic-rich matter

The laboratories are the only centre in the Czech Republic which systematically focuses on organic geochemical and petrographic analysis of fossil samples. This covers systematic description of carbonaceous materials for characterisation of the source organisms and palaeoenvironmental conditions, studies of transformation processes, such as degree of coalification, maturation, alteration and weathering, and condition for accumulation of organic matter in rocks and sediments. The studied organic-rich materials have included samples with various contents of organic carbon: fossil resins (up to 90 wt %), lignite, coal, and sedimentary rocks with 3 wt%.

Fossil resins - unique organic materials - were concern of studies due to their physicochemical features which have not been fully explore yet. Resin, called duxite, from the North Bohemian and Sokolov basins, collected from trunks stored in sandstones in situ or secondarily deposited were studied (*Havelcová et al., 2018*). Samples of studlovite - Eocene amber from Študlov (Southeast Moravia, Czech Republic) were investigated (*Havelcová et al., 2019*), and compared with valchovite (Boskovice Furrow, Czech Republic), and Baltic amber (Burg on Fehmarn, Germany) (*Havelcová et al., 2016*). Also, the first finding of amber from sediments of the Central Carpathian Paleogene Basin (Slovakia) was also documented and the matter was structurally described (*Kotulová et al., 2019*). The aim of the systematic fossil resins research is creation of a database containing analytical records of samples from around the world.

Changes in polymeric structure of fossil resins due to radiolytic and chemical alterations, occurring in the presence of local uranium mineralization, were studied in a sample of **uranium-rich** Cretaceous (Cenomanian) **amber** from Křižany (the North Bohemian Cretaceous uranium ore district) (*Havelcová et al., 2016*). The structural changes on a microscale around micropores and cracks filled with uranium were detected, chemical alteration of the organic matter close to the uranium minerals was

A **B** **C** **D**

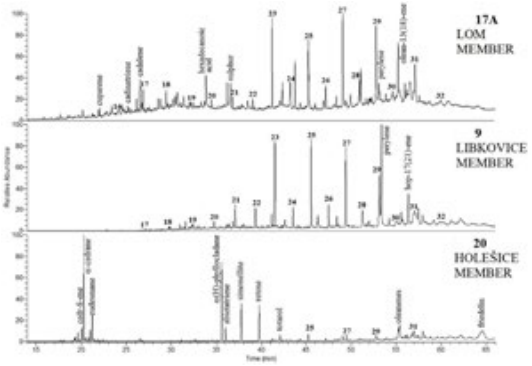
Examples of studied fossil resins: (A) studlovite at the exposure of the clay sandstone, (B) duxite, (C) valchovite and (D) radiolytic altered sample from Křižany.

determined, and also chemical composition of the bulk sample was documented. This result was an impulse for a project that received the support of the Czech Science Foundation, and started in 2019 (19-05360S “Radiolytic alteration of organic matter in uraniferous environment”).

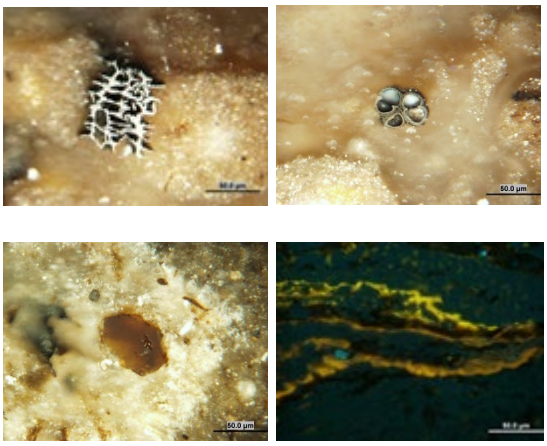
Terpenoids, relatively stable and main components of fossil resins, were studied not only in fossilised materials such as coalified woods or resins but also in recent conifers for better understanding of the conifer evolution. Differences in terpenoids production have been examined depending on seasons and on tree parts in which the terpenoids are produced using chromatographic and spectroscopic methods. The research is conducted on a long-term scale, estimated at least at 5 years, in order to obtain sufficiently robust data. This research is provided in cooperation with the Institute of Botany CAS.

Multidisciplinary approaches were used for characterization of **coal** deposits and selected seams including recognition of original vegetation, elucidation of sedimentary facies, the type of peatlands, aquatic conditions, occurrence of hydrocarbons and impact of climate change in the landscapes of the Middle Moscovian upper Radnice Member in the Pecinov and Lubná areas (Central Bohemian Basin) (*Opluštil et al., 2015*), the Early Pennsylvanian Prokop Coal (Upper Silesian Basin) (*Opluštil and Sýkorová, 2018*), Jurassic Mikulov Marls from the Czech Republic (*Geršlová et al., 2015*) and Maghara main coal seam in north central Sinai in Egypt (*Edress et al., 2018*). The petrographic and mineral composition of Namurian sediments in Němčičky Sub-basin (sandstones) in conjunction with seismic data helped to explain a potential source of hydrocarbons (*Opletal et al., 2019*). These works are components of continuous systematic and detailed petrographic and chemical studies dealing with geological samples from various areas around the world.

Similarly, **sedimentary matter** with organic components is the material of scientific interest. Changes in light reflectance of coal particles and definition of thermal history of sediments in Central and Western Bohemia were evidenced, and paleothermal and coalification history of Carboniferous and Permo - Carboniferous sedimentary basins was modelled (*Suchý et al., 2017; Suchý et al., 2019*). Lacustrine and prodeltaic clay sediments, and clayey coal from Holešice, Libkovice, Lom and Osek members (Most



Chromatographic analysis of organic extracts as typical records for samples from Holešice, Libkovice and Lom Members (Most Basin), with different biomarker distribution among samples documenting different condition of environment during sedimentation.



(A) Fusinite in the sediment from the Holešice Member, (B) funginite and (C) resinite in the sediment from the Libkovice Member, (D) cutinite in the sediment from the Lom Member.

Basin) were the topic of sedimentological study focusing on maceral composition and rank, chemical parameters and biomarkers for characterization and reconstruction of the original biological materials and basic conditions for their deposition (*Havelcová et al., 2015*). Macerals of liptinite of aqutic origin as are alginate, liptodetrinite and bituminite also dominated in the lacustrine Cypris Formation claystones in the Sokolov Basin whose geochemical history was also studied (*Kříbek et al., 2017*).

Special attention was paid to the study of the formation of different types of high reflective and highly structured **carbonaceous particles** corresponding to anthracite, semigraphite and graphite stage in relation to paleotemperature history of gold-bearing deposits of West Africa (*Kříbek et al., 2015*) and to the Lower Palaeozoic sediments of Barrandian Basin in Czech Republic (*Suchý et al., 2015*).

Further research was focused on accumulation and stabilization of **soil organic matter** supporting restoration of natural ecosystems. Litter decomposition represents a crucial process leading to organic matter formation and plays therefore an essential role in soil carbon sequestration. Soil macrofauna are important drivers for the formation of soil structure and play a key role in soil organic matter dynamics. To explore the question how litter and macrofauna feces respond to temperature and how respiration differs for litter with a different CN ratio and phenolic content, the decomposition rates of leaf litter and *Armadillidium vulgare* (Isopada) feces produced from the same litter were measured in response to three constant and one fluctuating temperatures in a 50-week laboratory experiment and in a field trial (*Špaldoňová and Frouz, 2019*).

TOPIC 2: Properties of waste materials as sorbents

Waste or scrap materials as power fly ash, biochars, sewage sludge or slag can be recycled and reused. The amount of waste is so reduced, and moreover, the prepared recycled materials can be used as sorbent for removing or reducing pollutants from the environment.

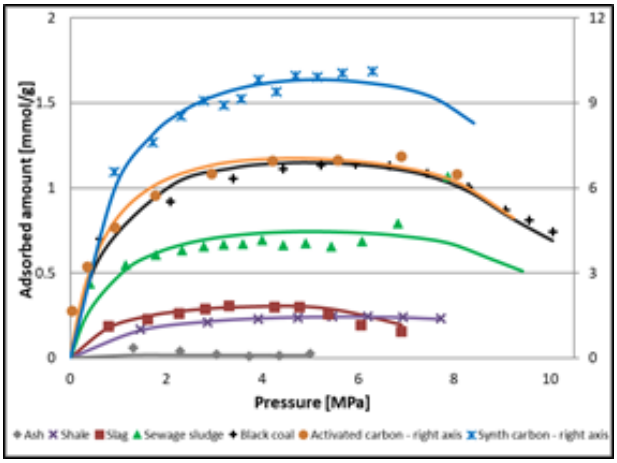
Ash, that have the 500-times lower adsorption capacity than activated carbon because of low porosity, can be used as medium for chemisorption onto its particle surface or for capture of the special pollutants. In addition, due to the ashes contain a large number of rare elements and methods for obtaining these elements have been developed. High content of titanium was identified in samples of fly ash and slag from combustion of coal from Sokolov basin (*Renkerová et al., 2019*). This work was realized in cooperation with University of Chemistry and Technology.

Biochars prepared from the biomass or from unprocessable residue after fruit processing (stones, shells) were thermally processed (in cooperation with another team of the institute) and tested to convert these materials to “low-cost” sorption materials with sufficient ability to remove pollutants from environment. The team performed specific analyses to determine the properties of the prepared materials and to define the sorption capacities of the selected environment gas pollutants. The first results of this study were presented (*Řimnáčová et al., 2018a; 2018b*).

Another promising material for removal and capture of pollutants seems to be carbonized **sewage sludge** prepared by pyrolysis of raw material by another team of the institute. The prepared carbonized sewage sludge was activated by air and water steam in order to improve its sorption properties, and then was subjected to complete textural analyses. The improved sorption properties in respect to CO_2 were experimentally observed by performing sorption experiments at different regimes as

pressures, temperatures, times etc. In some cases, water steam activation in combination with a higher activation temperature caused material degradation and consequently decrease in sorption ability (*Bičáková et al., 2019, Řimnáčová et al., 2019*).

Slag is the potential material for capture of gases with the possibility of the underground gas storage after adsorption process. As an inert material produced by thermal processes in power and heating plants has sufficient sorption abilities for a wide range of pollutants and can be used as eco-friendly sorption material. Chemically activated slag has better sorption properties, but the chemical process increases the price of the material and reduces the possibility of use directly in environment. The possible way to improve their sorption properties as activation by gases or water steam was explored.



The CO_2 sorption isotherms of studied materials fitted by Langmuir sorption model and measured by the high pressure apparatus. The figure documents wide range of sorption abilities for different materials.

Porous semi-coke with mesh thin-walled texture in a mixture of mineral grains predominantly based on aluminosilicates and silica. Ash with mineral fraction was one of tested material.

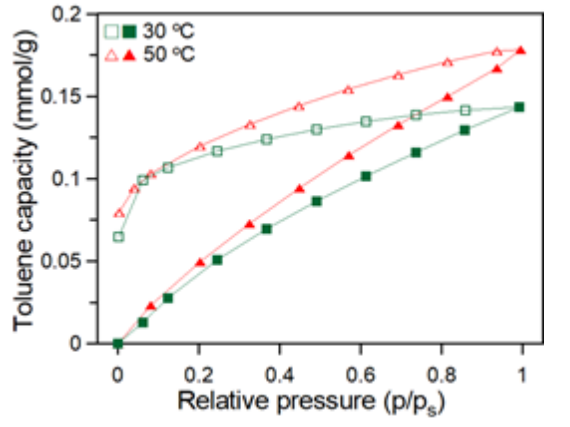
An interesting aspect was the cooperation with colleagues from the National Research Center in Egypt during a collaborative research project which was aimed at the ecological and economic use of **plastic waste** mixed with bituminous coal from Egyptian deposit Maghara for the production of coke for steel industry, and on which participated another team of the institute as well (*Havelcová et al., 2016*).

A project by Technology Agency TH02030105 “Racionalization of handling with exhausted activated carbon based adsorption materials” was being solved, in cooperation with the company Dekonta, a.s. The main goal of this project is construction of experimental equipment for regeneration and/or reactivation of activated carbon. Used activated carbon is by means of the legislation a waste material and has to be handled according to it. Regeneration/reactivation enables to repeatedly use this material for its initial purpose.

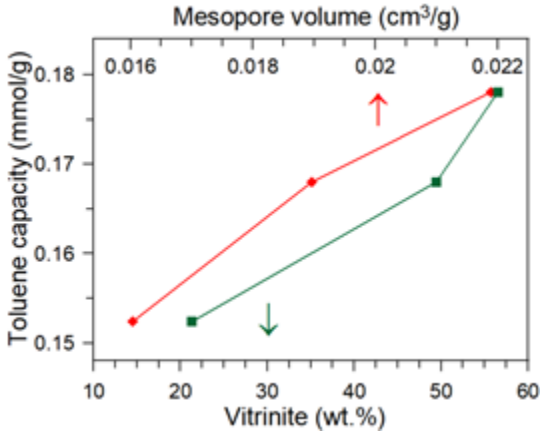
Based on the results from the tests conducted in the equipment, knowledge for offering complex services in the field of re-use of exhausted carbon-based adsorption materials from various applications, including technical evaluation of the particular sorbent will be obtained. The focus lies mainly on the activated carbon from water treatment. In contrary to air treatment applications, where usually low temperature regeneration is sufficient, activated carbon from water treatment requires higher temperatures. High temperature reactivation of activated carbon is not only cost consuming and technically demanding, it also requires careful setting of process parameters in order to achieve high reactivation efficiency and low burn off. Reactivation of activated carbon from waterworks is a highly actual topic, as all large water treatment plants are being fitted with activated carbon filters. The participation of the institute lies mainly in applying of methods for characterization of solid materials and subsequent evaluation of particular activated or reactivated carbons. In frame of this project, a utility model “Experimental equipment for activated carbon regeneration and/or reactivation tests”, and a patent Process for regeneration and/or reactivation of activated carbon in multiple hearth furnace and a multiple heart furnace for carrying out the process have been awarded.

TOPIC 3: Properties of natural and synthetized materials

The spontaneous self-heating of coal in mines results in emission of various hydrocarbons into the mine atmosphere, leading to dangerous endogenous fires. As toluene is one of the hydrocarbons produced during the self-heating of coal, the study was aimed to investigate the sorption characteristics of toluene vapour on bituminous coals from different mines in the Upper Silesian Basin in the Czech Republic. A detailed petrographic and textural analyses of the coals were performed and effect of the rank, maceral composition and porosity on the **toluene sorption** capacity at different temperatures and saturation pressure was evaluated. Toluene sorption capacity was revealed to be the highest in the coal with the highest mesopore volume and vitrinite content at the highest measured temperature. It was also found strong bonding of toluene molecules to the surfaces of the coal. The results of the research were presented at international conference and published in conference paper (*Vorokhta 2019a*).



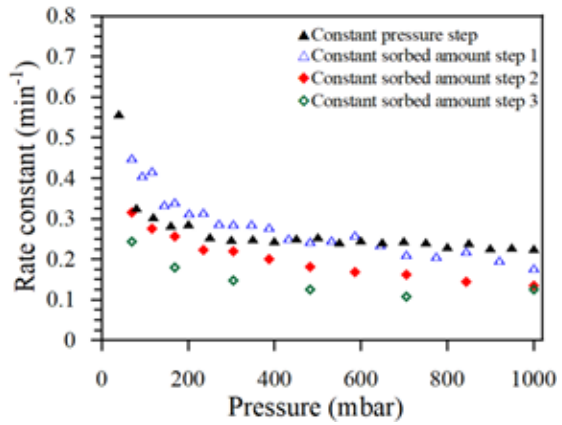
Toluene sorption isotherms obtained on coal sample at 30 °C and 50 °C.



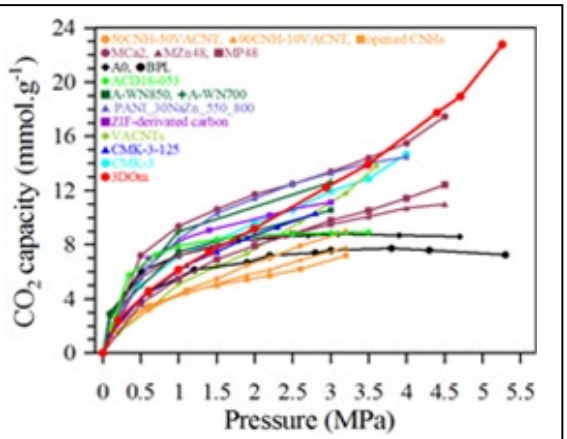
Dependence of the toluene capacity on mesopore volume and vitrinite content obtained on coal at 50 °C.

Further research was focused on development and synthesis of promising carbon adsorbents for CO_2 capture, which is a major greenhouse gas. Thus, the **highly micromesoporous ordered carbon materials** were synthesized and studied for their CO_2 capture ability over a wide range of pressures and temperatures. The prepared 3DOmm carbon materials were found to be the efficient adsorbents for CO_2, especially applicable as adsorbents in pre-combustion capture due to their very high adsorption performance, exceeding the adsorption capacity of many other carbon materials in the literature, including commercially (*Vorokhta et al. 2019a*). The characterization of prepared carbons was done in cooperation with J. Heyrovsky Institute of Physical Chemistry and Institute of Macromolecular Chemistry CAS. All sorption analyses, data processing and interpretations have been formulated and presented by our team at international conferences (*Vorokhta et al. 2019c, 2018a, 2018b, 2018c, 2017*) by the team of the institute.

The adsorption kinetics is a very important parameter for an adsorbent, which is influenced by various factors. Thus, the investigation how kinetics rate of CO_2 sorption is influenced by the character of experimental setup was performed. Accordingly, the dependence of CO_2 sorption as a function of pressure and sorbed amount on bituminous Czech coal and a specially synthesized polymer was studied. The results showed that the sorption rate is very dependent on the type of isotherm, pressure step and CO_2 sorbed amount during a single pressure step, as well as on the type of isotherm. This fact makes it necessary taking into account the choice of experimental setup when comparing kinetics results of different adsorbents. All analyses and data processing were performed by the team from the institute. The results were presented at international conference and published in conference paper *(Vorokhta et al. 2016).*



Rate constants of the CO2 sorption on coal sample as function of pressure. The sorbed amount at the step 1 was twice smaller than the sorbed amount at the step 2 and three times less than the sorbed amount at the step 3.



Comparison of the CO2 adsorption capacities of 3DOmm carbon with the adsorption capacities of different carbon materials measured at 25 °C.

Silicon oxycarbide glass, a material of considerable interest due to its good oxidation resistance and to its structural stability at elevated temperatures, was prepared by another team of the institute. But for the material characterisation, geochemical methods were used and resulted in joint articles. The role of the components in the temporary “micro-creep” behaviour of some polysiloxanes during their pyrolysis to SiOC was studied (*Havelcová et al., 2016; Černý et al., 2015*). Also,

nitrogen-containing polysilazanes, prepared by a new three-step procedure were characterised (*Strachota et al., 2015*). These works were results of cooperation with the Institute of Macromolecular Chemistry CAS.

During the evaluated period a project by Technology Agency TA04020432, "The System of Active Runoff Pollutants Capture as a Solution for the Implementation of the ČSN 759010 and TNV 759011 Standards" was solved in cooperation with the company Chemcomex Praha, a.s. and University of chemistry and technology. The aim of the project was to develop a technical solution for the active systems for **cleaning of rainwater** located in subsurface. Rainwater is responsible for the transport of wide range of input (polluting) materials into the environment. The experimental test polygon was developed, and the methodological and technical solutions replenished for capture contaminants before entry of rainwater into the groundwater.

Experimental gas sorption measurements were performed to study effect of **bituminous methane-bearing coal** properties from the Bohemian part of the Upper Silesian Basin on CO_2 and CH_4 high pressure sorption (*Weishauptová et al., 2015*). CO_2 sequestration with enhanced coal bed methane recovery is a topical issue in the early 21st century.

Sorption abilities of the **Silurian shales** from the Barrandian Basin as potential source of fossil energy and with possibility to store CO_2 were studied under conditions close to the conditions in situ. The composition, textural properties of the shales and CH_4 sorption capacity was studied in the first step. The positive correlation between the methane sorption and content of organic carbon was found (*Weishauptová et al., 2017*). Subsequently CO_2 sorption capacity was experimentally measured, and found out that micropore content and inorganic matter intensified the CO_2 sorption capacity. The comparison of the CH_4 and CO_2 adsorption capacities in dependence on the texture and composition were presented at a conference (*Římnáčová et al., 2017*).

The team participated in **inter-laboratory comparative study,** where the sorption of CH_4 and CO_2 on zeolite samples in the wide range of pressures was performed. To join this study by the team was possible due to the unique home-made manometric sorption apparatus for high pressure sorption measurements (1.5-20 MPa) and commercial gravimetric sorption analyser for low pressure sorption measurements (0-2 MPa) available. This research, involving nearly 30 laboratories, was headed by National Institute of Standards and Technology (USA).

TOPIC 4: Organic and inorganic pollutants in the environment

Environmental hazardous pollutants are a global problem. They are closely monitored and much efforts are given to remove or reduce pollutants in the environment. Studies of the composition of coal wastes and the definition of their impact on the environment were undertaken within the Czech Science Foundation project "A Model of Mobilisation and Geochemical Cycles of Potentially Hazardous Elements and Organic Compounds in Burned Coal Heaps", 2015-2017.

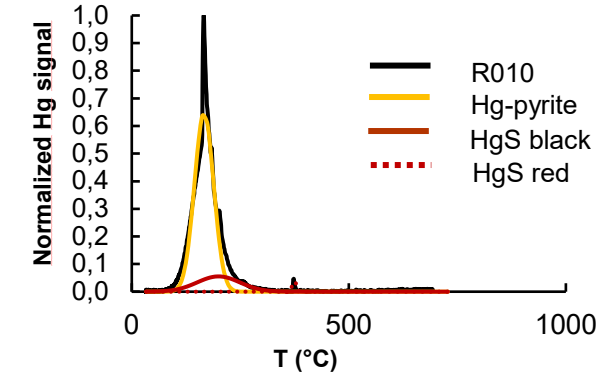
The **effects of uranium mineralization and self-burning processes** on organic and inorganic components of coal were studied at samples from waste pile of the former Novátor coal and uranium deposit at Bečkov (Intrasudetic Basin, Czech Republic) (*Sýkorová et al., 2016, Kříbek et al., 2017*). Uranium minerals caused local radioactive alterations in uranium-rich coal matrix, and in the waste heap burning zone, coal and claystone were transformed to coke particles and "clinkers" composed of variable mineral phases. The results revealed that the concentrations of many metals and metalloids are significantly higher in the burnt part of the dump than in the unburnt

section which can be explained by their mobilization and accumulation in the surface layer of the burnt part of the dump.

Another waste coal heap, close to the Eliška Mine (Intra-Sudetic Basin in the Žacléř coal district) burned intensely in the 1960s and 1980s, and even now, the heap surface still features active vents emanating warm air and water vapour. Burnt coal heap substrates were collected and studied to compare the organic petrography and geochemistry of unburnt coal with products of coal burning and to evaluate the time relationship between **burning processes** and the formation of coal-derived hydrocarbon condensates, cokes and associated argilites at the surface of the heap. Potentially harmful elements were present in the waste samples and determined using batch and percolation tests. The concentrations of Hg, Pb, and Cd in some leachates exceeded the limit values for inert wastes according to EU legislation. However, the concentration of other elements was low, probably due to prolonged washout of burnt materials by rainwater at a very low pH (*Sýkorová et al., 2018*).

The behaviour of trace elements in environment depends on their concentration and mode of occurrence. The **mobility potential and the distribution of elements** were studied in coal collected from the Lower Bench in the Holešice Member of the Most Coal Basin (*Vörös et al., 2018a*). The vast majority of studied elements leached in the oxidisable fraction. Studied trace elements were mostly associated with sulphides or/and organic matter and could be readily mobilized under oxidising conditions. Simultaneously, increased levels of some of the elements proved their natural occurrence from the weathered volcanic material which might have been transported due to the last volcanic activity.

Another piece of research regarded to the **mercury** assessment of a heavily polluted river in the same region where the Most Basin takes place. The mercury content and its speciation were studied at stream sediment samples of the Bílina River in order to evaluate the severity of this element to the environment. The vast of Hg content was strongly bound to sulphides with a minor occurrence of organic-associated Hg among samples, considered to be as a consequence of geochemical interaction of the element with the lignite, and chars originated from lignite and biomass combustion (*Vörös et al., 2018b*). It came to the conclusion that mercury might not pose a threat to the living organism unless it changed to organic-associated Hg in the form of the toxic methylmercury).



Thermodesorption profiles of Hg species indentified at river sediment sample R010.

Due to the lack of information about the natural **occurrence of elements** that influence stream sediments in the Bílina River, the intention was to study the natural contribution of As, Zn, Pb, Cr, Ni, V and Cu at samples of rock, sediment, coal to consider whether the increased levels of these elements were merely derived from anthropogenic sources as once assumed to be. Using the enrichment factor established on the basis of the regional geological background values proved that elevated levels of elements in stream sediments are not always the result of industrial contamination. Lastly, there was a finding that defunct tailings contain Neogene sediments which were subject to intense weathering on contact with precipitation, and

resulted in the higher values of the elements studied at the geogenic background (*Vöröš et al., 2019*).

Worldwide pressure on environmental protection also attaches increasing importance to ecological behaviour in the reduction of the volume of the fossil fuels combusted. Multidisciplinary research, in cooperation with other team of the institute, was used to describe a novel use of **geopolymer materials** for the incorporation of specific straw ash that contains carcinogenic polyaromatic hydrocarbons (*Perná et al., 2019*).

TOPIC 5: Granitic rocks, tektites, tufa, silicified wood, and uranium ore deposits

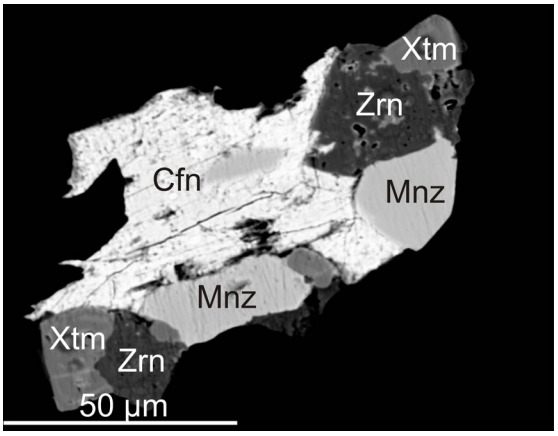
The study of granitic rocks covered geochemistry, petrology and mineralogy of selected Variscan granite suites of the Bohemian Massif, especially on Li-mica granites from the Krušné Hory Mountains and Slavkovský Les Mts (Krudum granite body), their hydrothermally altered varieties (greisens) and selected magmatic suites of the Moldanubian batholith (MB). The **granitoids** of the MB were studied by detailed geochemistry and divided into three main suites: melts of the Weinsberg granite suite generated by low-pressure partial melting of lower crust rock sequences, two mica granites of the Eisgarn suite having three main geochemical varieties (low-Th Deštná granites, the intermediate-Th Mrákotín/Číměř granites and the high-Th Lipnice/Steinberg granites) emplaced at shallow levels at relatively reducing fO2 conditions, and melts of the Freistadt granodiorites generated by low-pressure partial melting of lower crust sequences (*René, 2015a,c, 2016, 2017a,b; Verner et al., 2015*).The **Krudum granite body** revealed highly fractionated granitic rocks, with variable concentrations of monazite and zircon were found, while xenotime was only found in the high-F, high-P2O5 Li-mica granites and in the alkali-feldspar syenites of the Vysoký Kámen stock. Detailed microprobe analysis of monazites, xenotimes and zircons was performed (*René, 2018d*). The **Krásno–Horní Slavkov Sn-W ore district** showed mineralised topaz alkali-feldspar granite stocks evolved along the south-east margin of the Krudum granite body. The inner structure of the granite stocks (Hub and Schnöd) is remarkably stratified, comprising greisens, weakly greisenised topaz alkali-feldspar granites and layers of alkali-feldspar syenites. The greisens evolved in the apical part of the Hub stock are represented predominantly by Li-mica-topaz, and topaz-Li-mica greisens (*René 2018a*). The Nb-Ta-Ti-bearing oxide minerals (Nb-Ta-rich rutile, columbite-group minerals, and W-bearing ixiolite) were detailed studied by microprobe in high-F, high-P Li-mica granite from the **Geyersberg granite stock** from the Krušné Hory/Erzgebirge Mts. Batholith (*René 2018e; Szameitat et al., 2018; Tomasek et al., 2018*).

Australasian tektites (AAT) represent the largest group of tektites, and their strewn field covers one sixth of the Earth's surface. Yet, a parent crater for AAT has not been found so far. Based on geochemical and isotopic compositions, the study has seriously doubted the universally accepted hypothesis of a crater location in Indochina and suggested a location in deserts of NW China. The new hypothesis alters the current view of formation and transport of impact ejecta (*Mizera et al., 2016*; Mizera, J., 2019).

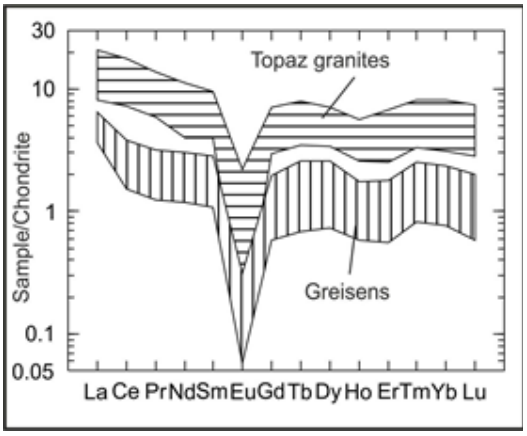
Integrated petrographic, mineralogical and geochemical analyses were performed in order to elucidate the origin and timing of deposition of carbonate deposits and the source of precipitating waters of Pleistocene **calcareous tufa deposits** (*Suchý et al., 2019*). Two generations of tufa were found representing the oldest known examples of tufa in the Bohemian Karst, probably escaping erosion due to their occurrence in an isolated subterranean cave.

Natural permineralisation of wood is a unique fossilisation process. A research was conducted in an interdisciplinary way for the understanding of **wood permineralisation** and contributing to broadening the knowledge on wood preservation. The Early Permian Mengkarang Formation of the western Jambi Province, Sumatra, preserves abundant evidence of a Permian forest, which grew at the foot of an active volcano, where pyroclastic flows often made way and destroyed the vegetation and where epiclastic reworked pyroclastics rapidly entombed the vegetation. A detailed study of three localities using multiple approaches was done (*Matysová et al., 2018*). The anatomy of silicified Agathoxylon-type wood of Late Palaeozoic age was studied. Wakefieldite, identified in silicified plant tissue for the first time, and supposed to be formed as a secondary mineral during post-depositional diagenesis (*Matysová et al., 2016*).

The study of mineralogy and geochemistry of **uranium ore deposits** was concentrated on detailed description of shear-zone hosted uranium deposits of the Bohemian Massif in the Rožná, Okrouhlá Radouň and the Zadní Chodov uranium deposits (*René and Dolníček, 2017; René 2017c, René 2018b,c*). The uranium mineralisation occurs in high-grade metamorphic rocks of the Moldanubian Zone (Rožná) and/or in granitic rocks of the Moldanubian batholith (Okrouhlá Radouň) and Bor pluton (Zadní Chodov) as complex uraninite–coffinite and uraninite–coffinite–brannerite assemblages. For analysed coffinites and brannerites, anomalous enrichment of Y (up to 3.4 wt % Y_2O_3) and Zr (up to 13.8 wt % ZrO_2) is significant. Brannerite from the Zadní Chodov uranium deposit is present in unaltered and altered grains with variable concentrations of U^{4+} (0–0.5 apfu), U^{6+} (0.06–0.49 apfu) and Ti (0.90–2.63 apfu) (*René and Dolníček 2017; René 2015b, 2017c, 2018c*).



Back-scattered electron image of complex intergrowths of coffinite (Cfn), zircon (Zrn), monazite (Mnz) and xenotime (Xtm) from high-F, high-P2O5 Li-mica granite, Hub stock, Slavkovský Les Mts.



Chondrite normalised REE patterns of weakly greisenised high-F, high-P2O5 Li-mica granites and quartz-Li-mica-topaz greisens, Hub stock, Slavkovský Les Mts. Normalising values according to Boynton (1984).

Research activity and characterisation of the main scientific results

SEISMIC MONITORING

Permanent or temporary seismological stations have been deployed on the territory of the Czech Republic (WEBnet and Czech Regional Seismic Network, both in cooperation with IG CAS), Slovakia (cooperation with Slovak Academy of Sciences), Fig.1, Iceland (cooperation with IG CAS and Icelandic Geological Survey ISOR), California (cooperation with USGS) and Ethiopia (cooperation with Czech Geological Survey, Charles University (CUNI) and Geological Survey of Ethiopia). The part of this monitoring concerning Europe belongs to the European Plate Observing System (EPOS) and CzechGeo projects. The collected data is used both for basic research as well as for monitoring seismic activity and the related seismic-hazard issues associated with important infrastructure (especially nuclear power plants Temelín, Dukovany and Jaslovské Bohunice).

The data from these networks is used for seismological and volcanological purposes and, in the future, they can also be used to ensure safety of geothermal power plants. Four seismic stations were deployed in Ethiopia as part of a development program of scientific infrastructure. Six-component seismographs of a new type (Rotaphones) were operated in California for more than two years to test their parameters.

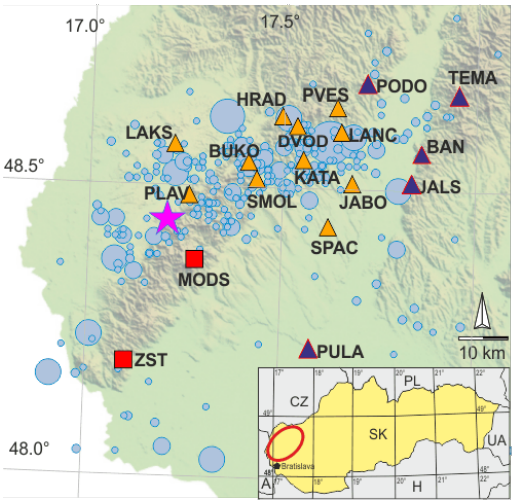


Fig. 1 The MKnet seismic network monitors seismic activity in the region of the Little Carpathians (Male Karpaty). The blue and gray circles symbolize earthquakes with magnitude ML > 3, 1 < ML < 3 and ML < 1, respectively. The historical 1906 earthquake of magnitude 5.7 is shown by big purple star. Stations JALS, BAN, PODO, PULA, TEMA are provided by IRSM CAS

Development of a six-component seismograph called ROTAPHONE

Rotaphone is a six-component short-period seismic sensor developed by the Department of Seismotectonics in cooperation with the Faculty of Mathematics and Physics, Charles University. This innovative device is capable of recording both the translational and rotational components of the ground motion induced both by natural and artificial events. It has been developed and tested since 2011. In the period 2015-2017, a pilot study was carried out in California. First, the instrument monitored induced seismic events at the geothermal power plant The Geysers. Then, an array of three Rotaphones was operated in Long Valley Caldera, monitoring volcanic seismicity.

This research was financed by GACR Project P210/15-02363S (2015-2017). In November 2019, another bilateral project between IRSM and USGS started, using

financing from the LTAUSA program. Under that new project, monitoring in Long Valley Caldera will be performed until 2022.

Rotaphones are now used for regular permanent measurement in the Czech Republic. Seven Rotaphones were installed around the town of Litoměřice where the Ringen geothermal project is being implemented, Fig.2. Another Rotaphone was installed in the Dukovany nuclear power plant. One of the advantages of Rotaphone is that it can reduce short-period seismic noise generated by the technology installed in the nuclear power plant.

Fig.2. Installation of Rotaphone station RICC inside the repository of nuclear waste in mine Richard near Litoměřice

SEISMIC AND VOLCANIC HAZARD

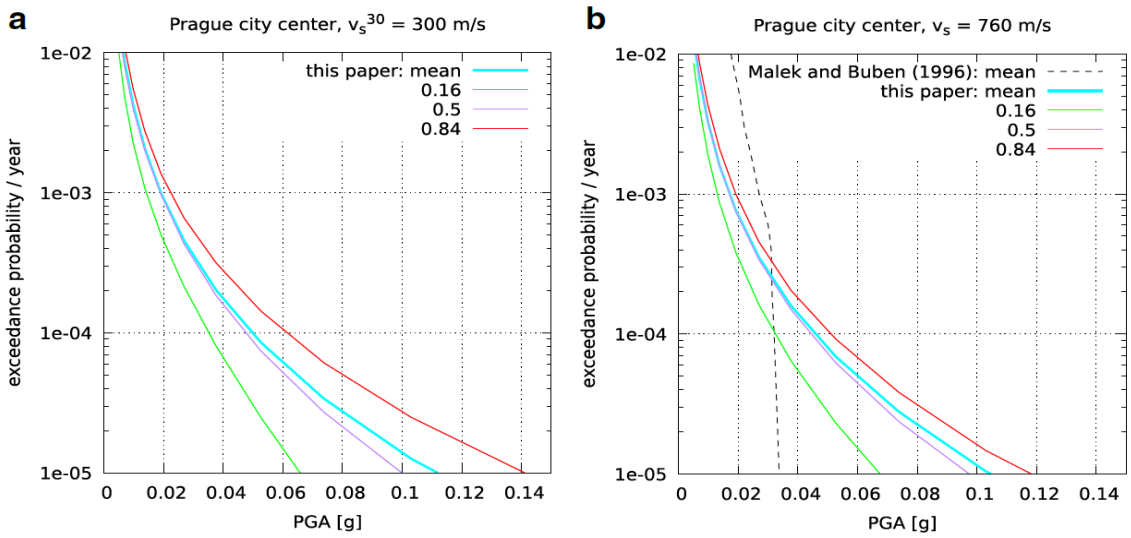
Attenuation is an important parameter for seismic hazard assessment. We used the 2018 seismic swarm to investigate attenuation in West Bohemia. We made a spatial and temporal analysis of Q in the region. We developed a differential Q measurement to investigate Q in the source area. We show that the average Q is higher than the values within the source area. The temporal analysis revealed an increasing strength of attenuation during the swarm. We associate it with an increasing CO_2 emanation during the swarm. This supports the role of fluids in the origin of the swarm (Wcislo et al., 2018).

The seismic activity in the Czech Republic is moderate. However, significant seismic hazard is connected with strong earthquakes in the Eastern Alps. In the paper by Málek et al. 2017, the decay of seismic amplitudes is found to be anomalously small in the North and Northwest direction, towards the Bohemian Massif. This anomaly was identified earlier from macroseismic observations, but it was proved here for the first time using instrumental measurements. The results will support the seismic hazard assessment of the Czech Republic.

Seismic hazard and ground motion are explored in the international project Sigma-2 (https://www.sigma-2.net). It is a research and development project and the members of the Department of Seismotectonics are involved in it. It is funded by a consortium of industrial companies: EDF (France), Pacific Gas & Electricity (USA), Swissnuclear (Switzerland), CEA (France), CEZ (Czech Republic), Orano (France) and CRIEPI (Japan). Its objective is to improve data and develop methods necessary to estimate SHA as well as possible by producing more site-specific hazard levels. Our team deals with topics in the scope of WP3-Ground Motion prediction.

Jiří Málek has drawn up several expert reports for CEZ a.s. concerning seismic safety of our nuclear power plants. These reports were used during missions of the International Atomic Energy Agency (IAEA) in the Czech Republic.

Moreover, our team has been involved in Strategy AV21, program Systems for Nuclear Power Industry, where we have developed new methods for determining seismic hazard of nuclear installations (Entler et al., 2017). One of these methods was used to compute the seismic hazard for Prague (Málek and Vackář, 2019), Fig.3.



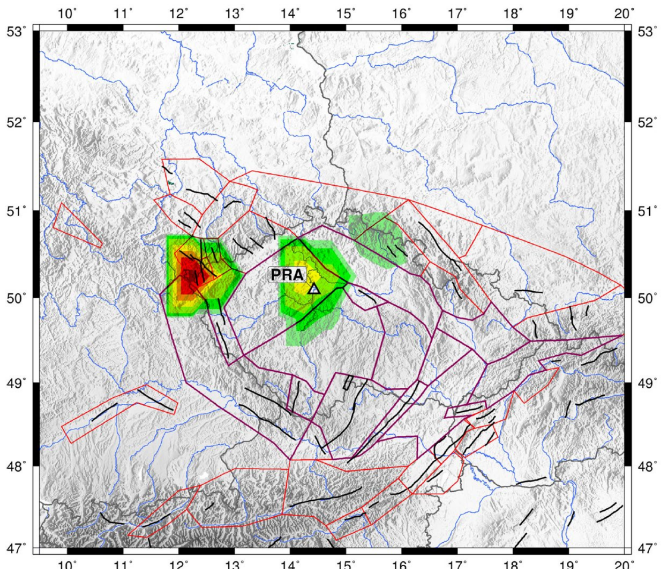


Fig.3. Seismic hazard curves for peak ground acceleration in Prague City
a) for sediment localities
b) for rock localities
c) Disaggregation of seismic hazard

Within the project Strategy AV21, the stability of precariously balanced rocks is employed in seismic hazard estimates as well. This research is primarily applied to computation of seismic hazard for nuclear power plants. We developed a methodology based on digital imaging of objects and compilation of numerical models satisfying the measured quantities (normal modes and seismic attenuations). The models are then used to estimate the PGA/PGV for the selected region. We started with "the Hus Pulpit" rocking stone located in the Central Bohemian Pluton (Zábranová et al., 2019). Different numerical models, where seismic displacements are considered as a direct

input at the rock base, can result in rock instabilities under a presence of an M=7 earthquake at a distance of about 150 km. We measured rocking stones and mushroom rocks also at other localities, for example near Bedřichov in North Bohemia and in the immediate vicinity of the Hronov-Poříčí fault zone.

Near-surface geophysical methods play an important part in seismic hazard assessment. These methods can be used to explain natural phenomena related to seismic and volcanic hazard. For instance, we investigated the inner structure of diatremes and volcanic cones. The goal was to find models or scenarios of how the magma reaches the surface and behaves in low pressure conditions close to the surface and inside scoria cones. Such model could be ultimately used to assess volcanic hazards. The inner structure of volcanic edifices was visualized by means of appropriate geophysical methods (most often the ERT, shallow seismics, gravity and magnetics). In close cooperation with paleomagnetic labs, the age of the different volcanic phases and the direction of the magma flow in outcropping dykes was determined. The results were interpreted in close cooperation with volcanologists and geologists.

The current research suggests that the flow of the magma is much more complex than previously thought. The model structures (e.g. the monogenetic Tertiary Zebín volcano; Petronis (2019)) shows a much longer timespan of the volcanic activity with several volcanic phases, a very complex plumbing system and even a possible deformation of the cone during the individual eruptions. The unexpected complexity of monogenetic volcanoes could be related to structural constraints. Although some monogenetic eruptions develop rapidly from mantle derived magma sources, others rise more slowly. Possibly, the channeling of magma into several conduits could be responsible for such complexity and longevity of such systems.

Detailed studies of the individual cones allow the complexity of the magma plumbing system to be unraveled, and provide insights into the conditions that exist in the lithosphere during continental rifting. In potentially active settings, this can allow eruption scenarios to be developed to prepare for the potential hazard.

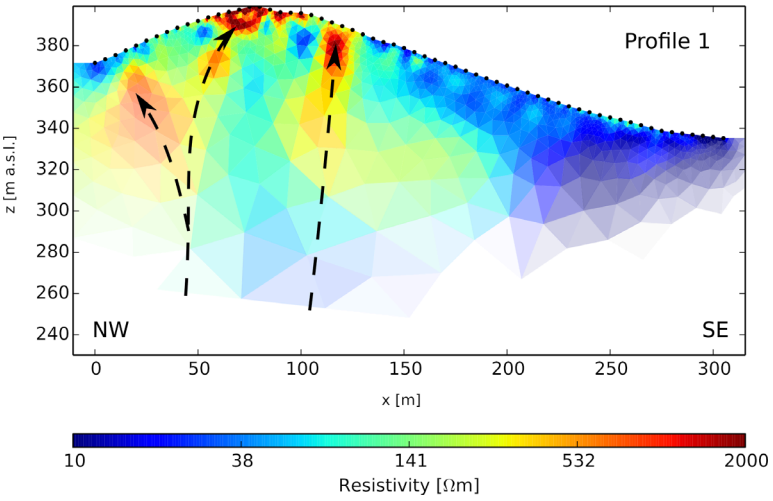


Fig. 4: Two-dimensional inverted resistivity (electrical resistivity tomography) image of the Zebín Volcano along profile 1. Low resistivity zones (up to approximately 100 Ωm, blue and bluish colors) represent clay-rich sediments, whereas the high resistivity areas (approximately 300 Ωm and more, red colors) represent coherent basic dikes. The possible magma feeder conduits/dikes are indicated by dashed arrows.

SURFACE WAVES

A significant part of the research of surface waves is inventing and validating new methodologies both in terms of computational aspects and with respect to practical considerations about the related field procedures (Dal Moro et al., 2016).

A new approach to the Rayleigh-wave analysis is formulated in Dal Moro et al. (2017). The particle motion (RPM) frequency curve has been introduced, which, for a given offset (i.e. source-receiver distance), quantitatively describes the actual prograde-retrograde particle motion as a function of the frequency. It has been shown that, in spite of the common belief, prograde motion was actually extremely common. The RPM curve has been used for the holistic analysis of Rayleigh-wave propagation.

The method of analyzing surface waves has been used for analyzing vibration data for the characterization of the eigen modes of buildings. In order to fully describe the actual behavior of a building, we implemented the GHM (Gaussian-filter Horizontal Motion) technique, which is able to define both the eigen frequencies and the type of motion (flexural or torsional) and the damping.

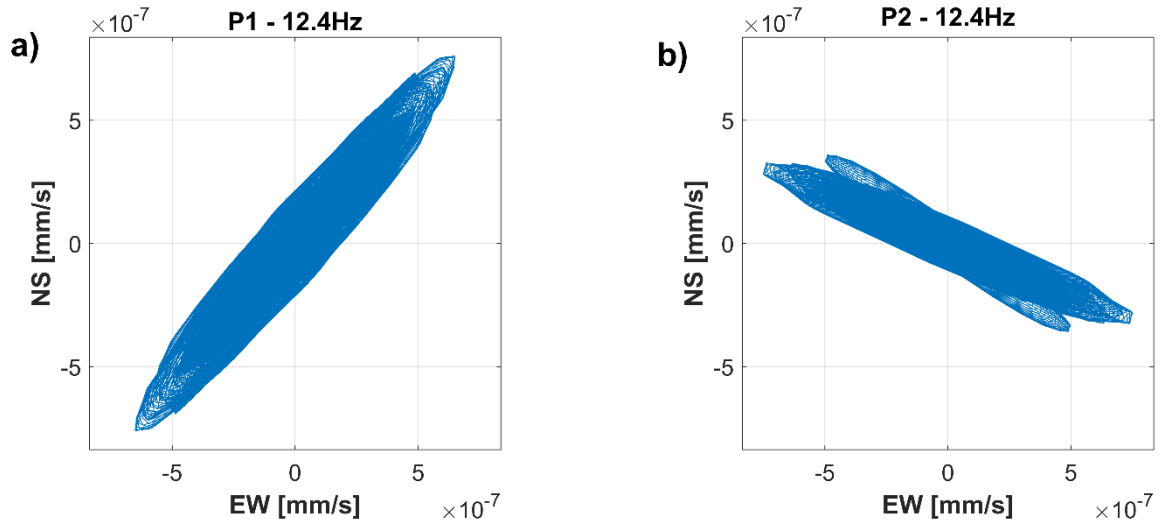


Fig.5. Characterization of the vibration modes of a building: identification of a torsional mode at 12.4 Hz for a three-story building by means of the GHM (Dal Moro et al., 2018)

A robust inversion procedure capable of providing a well-defined shear-wave velocity model in spite of the simple acquisition procedures has been presented in Dal Moro et al. (2019). The approach is based on a joint inversion of surface waves recorded by a single 3-component geophone Synthetic and field data has been considered to validate the presented methodology. To improve the readability, fundamentals on the joint inversion via Multi-Objective Evolutionary Algorithm (MOEA) and the Full Velocity Spectrum (FVS) have been recalled.

A site-specific S-wave structure beneath the Reykjanes Peninsula, southwest Iceland, was computed. The data come from the REAKJANET seismic network, operated in Iceland by IG and IRSM. The structure was derived from the Rayleigh phase velocity dispersion using a newly developed zero-crossing point method and a phase-plane method. At depths exceeding 20 km, the dispersion data require low S-wave velocities, indicating a noticeable low-velocity zone. It is a new methodology that can be used worldwide (Málek et al., 2019).

A surface wave analysis of data from different sources has been studied. Fourier transform-based modified multiple filtering techniques to evaluate velocity models of the medium have been studied. E.g. Lukešová et al. (2019) presented new 1-D velocity models of the Little Carpathians range in the Western Carpathians, Slovakia, determined from seismic surface wave data from quarry blasts.

Surface waves are a robust tool to analyze the structure of near-surface zones not only on Earth but even on the Moon. Seismic data from the Apollo 14 and 16 missions are jointly analyzed with the aim of determining reliable shear-wave velocity (VS) profiles of the uppermost lunar strata (Dal Moro, 2015). While data from the Active Seismic Experiment (ASE) allow the study of Rayleigh-wave dispersion by means of Multiple Filter Analysis (MFA), data acquired by the Passive Seismic Experiment (PSE) are used to determine the Horizontal-to-Vertical Spectral Ratio (HVSR). These two datasets have been jointly analyzed using state-of-the-art procedures in order to overcome the intrinsic limitations of both methodologies (when considered independently) and with the aim of determining a solution (i.e., the vertical VS profile) not affected by the non-uniqueness of the solution and not based on any a priori assumption. The obtained results are confirmed by a number of seismological studies on moonquakes and meteoroid impacts.

INDUCED SEISMOLOGY

A part of our team is focused on microseismicity and induced seismicity. The results of our work include case stories, mechanisms of the development of microearthquakes, statistical analysis of induced seismicity and methodological developments of attenuation measurements from microseismicity.

We have developed new sophisticated processing algorithms and new methods which allow us to process different datasets acquired from both surface and borehole monitoring arrays. We have studied characteristic differences between natural and induced seismicity and geomechanically interpreted our observations in order to better understand the relationship between fluid injection and reservoir response. Such modelling could ultimately increase the effectiveness of reservoir stimulations and injection programs; and help mitigate unexpected, potentially felt, hazardous induced seismicity. We have developed an entirely new algorithm for processing microseismic data from large and dense surface arrays (Staněk et al., 2015), processed data from hydraulic fracturing of shale in Oklahoma, USA, and interpreted the observed seismicity with a new geomechanical model of bedding plane slip (Staněk and Eisner, 2017).

We investigated seismic attenuation and the Vp/Vs ratio in the region of Agri-Valley where the inland oil field is located. We used microseismicity that is induced by wastewater injection back into the Apulian Platform formation. Our results reveal a Q and Vp/Vs ratio anomaly in the vicinity of the injection well. We found an unusually high (>1) Qp/Qs ratio in the vicinity of the injection well, which has been recently found more frequently in the partially saturated media (Wcislo et al., 2018).

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Research activity and characterisation of the main scientific results

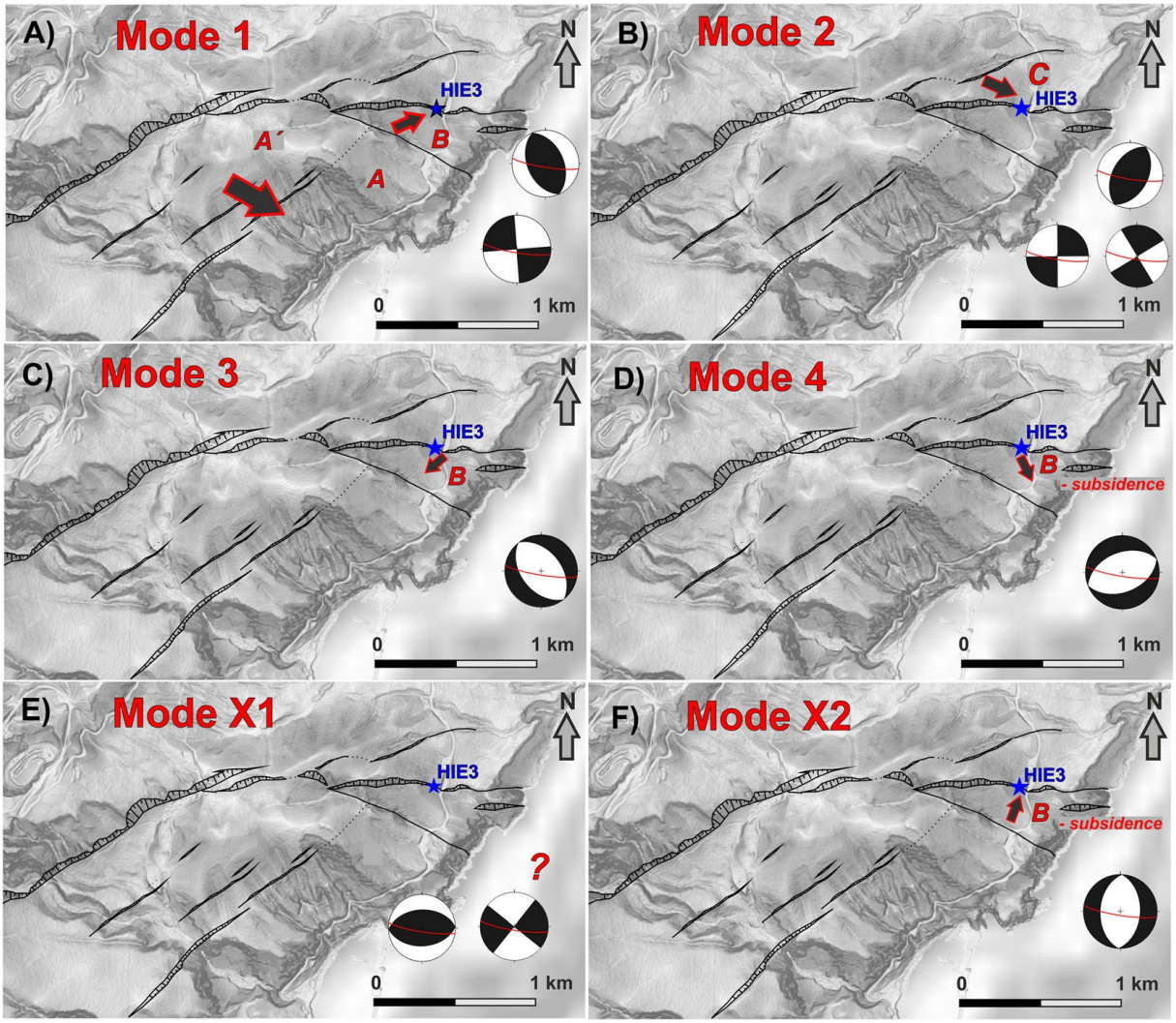
1. Slope processes research, monitoring and assessment

During the evaluated period, the researchers of the dpt. of engineering geology have been working on number of sites subject of long-term ongoing research as well as newly initiated studies, and reached very interesting conclusions.

One of the most intensively studied sites in last years was the volcanic island of El Hierro (Canary Is., Spain). This landslide has been monitored since 2013 and several different movement modes have been defined based on exogenous and endogenous impulses (Blahůt et al. 2018b). This research is being developed more in depth in order to analyse the past dynamics and future behaviour based on advanced data analysis.

Detailed field investigations of the megalandslide on the volcanic island included for the first time also very precise 3D movement monitoring using the in-house developed monitoring device (Klimeš et al., 2016b). The acquired information revealed the presence of sets of weakened planes representing the sliding surfaces. Their detailed monitoring revealed for the first time ongoing creep movements on these prehistorical sliding surfaces of landslide which has been considered as aborted, so far. This observation along with documented specific morphological attributes suggests a high susceptibility to future megalandslide movement acceleration at the site, which is very important information for its hazard assessment.

Furthermore, special focus has been paid on the research of volcanic flank collapses from oceanic islands. First comprehensive worldwide database has been compiled (Blahůt et al, 2018a, 2019) coupling information from available sources and bathymetric data. It has been showed that landslides from these collapses belong to the largest features on the Earth´s surface developed in single geological moment and are comparable with the largest landslides observed on Mars.

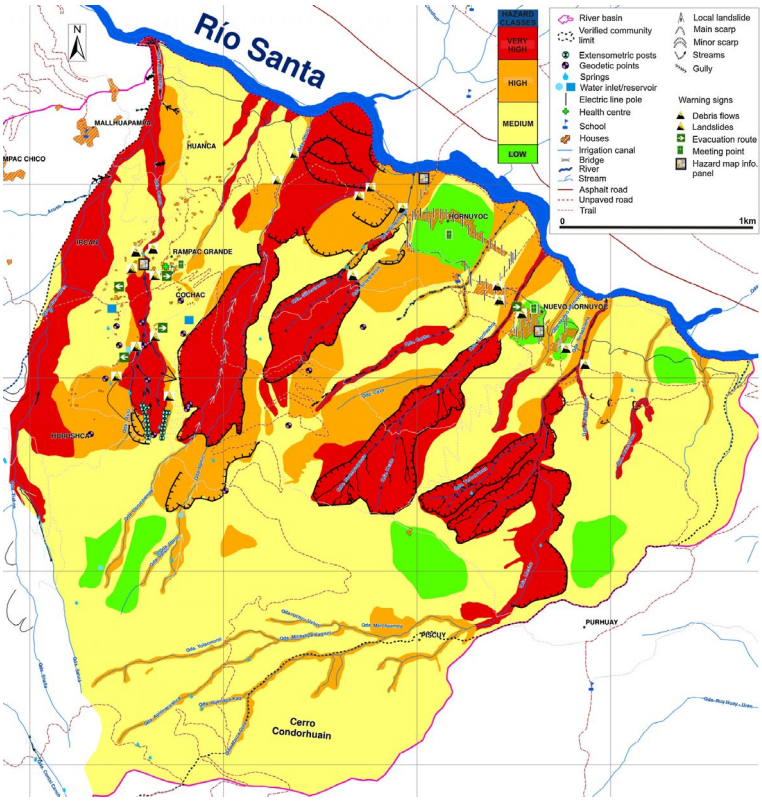


Interpretation of a giant landslide (El Hierro, Canary Islands, Spain) activity modes in response to specific stress states – endogenous and exogenous impulses (Blahůt et al. 2018b).

Another study area, where we started to work in the last evaluation period, is the Svalbard in the High Arctic. We observe effects of recent rather fast deglaciation, temperature changes or tectonics on rock environment ranging from shallow rock-slope conditions to faults response (Stemberk et al., 2015) and study pre-historical slope phenomena. We published a multidisciplinary study of a rock glacier deformed into unusual shape by a rock avalanche (Hartvich et al. 2017). This is the first study from the High Arctic that reveals the coupling of the periglacial and slope processes and describes the landform, developed as a result of activity of both. Additionally, the ERT profiles shed light on the internal extent and position of the ice core within the rock glacier. Current research focuses on describing the causes, timing and consequences of an exceptional rockfall/rock avalanche event.

One of the traditional study areas (since early 2000) of the team is in Peruvian Andes, where we worked on several slope deformations and potentially dangerous moraine-dammed lakes. Mathematical models based on detailed site characterization describe and quantify chain of processes initiated by landslide resulting to the outburst flood from the high-mountain glacial lake threatening regional capital city (Klimeš et al., 2016a). The results based on detailed local knowledge allowed preparation of reliable models assessing hazard for the studied site and significantly improved understanding

of this potentially very damaging process affected by global climate change. It was the first work evaluating in depth the hazards related to landslide occurrence on moraine slopes in Peru providing valuable information for local civil protection offices. Further extension to community protection represents ongoing research and involvement in risk reduction of specific rural community (Klimeš et al., 2019b) or regional landslide hazard assessments (Bueechi et al., 2019; Strozzi et al., 2018) applicable for the regional land development planning.



Landslide hazard zonation map prepared during joint project with Peruvian research institute Instituto Nacional de Investigación en Glaciares y Ecosistemas de Montaña and the local community, Peru (Klimeš et al., 2019b)

Our world-wide based expertise in the slope processes allowed preparation of an extensive review article (Pánek and Klimeš 2016), which summarizes for the first time results of large number of works describing development of deep-seated gravitational slope deformations during geological time scale as well as results of their engineering monitoring. Jointing of this information brings new, valuable insight to their hazard assessment. Conditions and triggers of possible reactivations of the deep-seated gravitational slope deformations are discussed as such events often result in catastrophic events threatening infrastructure and human lives. Article results are thus applicable in many regions world-wide.

2. Tectonics

Our research on the field of tectonics has also brought worthy results. The unique research focus specialty of the team is the monitoring of the slow, yet omnipresent aseismic creep along tectonic faults (creep). These movements, whose velocity varies from centimetres/year in highly active areas to less than 0,01 millimetres/year in less active regions, accommodate part of the tectonic stress and thus their understanding

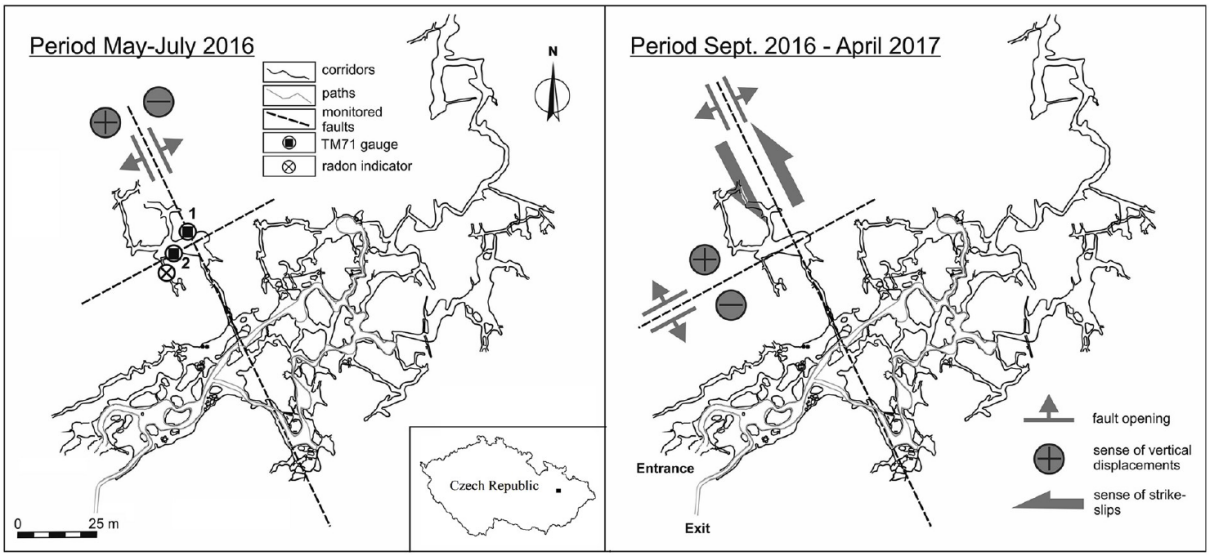
is one of the crucial conditions for development of forecasting of the earthquakes, as the ultimate goal of tectonic research. As our dedicated network for the fault monitoring TecNet covers many countries in Europe and world, also the range of our study sites is correspondingly wide. Such monitoring setting gives us an opportunity to search for possible continent-wide or even global patterns in the dynamics of the Earth´s crust. Recently, we have begun advancing towards an important achievement: calculation of current stress field and its changes, based on the direct measurements of behaviour of the tectonic faults.

One of the most important findings in the research and monitoring of the tectonic displacement is published in the paper by Stemberk et al. (2019), with a study area in central Italy. Using the 3-D monitoring of strain along active faults in the Central Apennines we have discovered that fault slip development is nonlinear and it is affected by remarkable transient periods of fault slip acceleration lasted up to several months. Stress analysis resulted to finding that the recorded accelerations were induced by the switching extensional and compressional stress/strain state correspond to the principal SW-NE stress and preceding major earthquakes in L'Aquila 2009 and Norcia 2016.

As part of assessment of our monitoring network results we have developed a novel mathematical approach for the present-day stress inversion from any single near-surface fault (Sokol et al., 2018). The stress tensor calculation is possible thanks to specific near-surface conditions. The orientation of the principal stresses and the shape parameter of the stress ellipsoid are the outputs of the method. Great advantage and potential application in earthquake engineering is the effective possibility of observation the near-surface stress variations in real time.

We conducted a systematic research on present-day kinematic behaviour of active faults in the Eastern Alps (Baroň et al., 2019), which was the first such a comprehensive insight into present-day fault activity in that area. Our high resolution direct 3D measurements revealed a variety of particular aseismic displacement events at subsidiary faults associated to major regional fault systems. The phases of higher fault activity usually coincided with periods of increased local seismicity. We identified specific countervailing displacements registered few days in advance to distinct local earthquakes, which were probably associated to elastic rebound. These countervailing events should be further studied as potential indicator of impending near earthquake within the rebound zone.

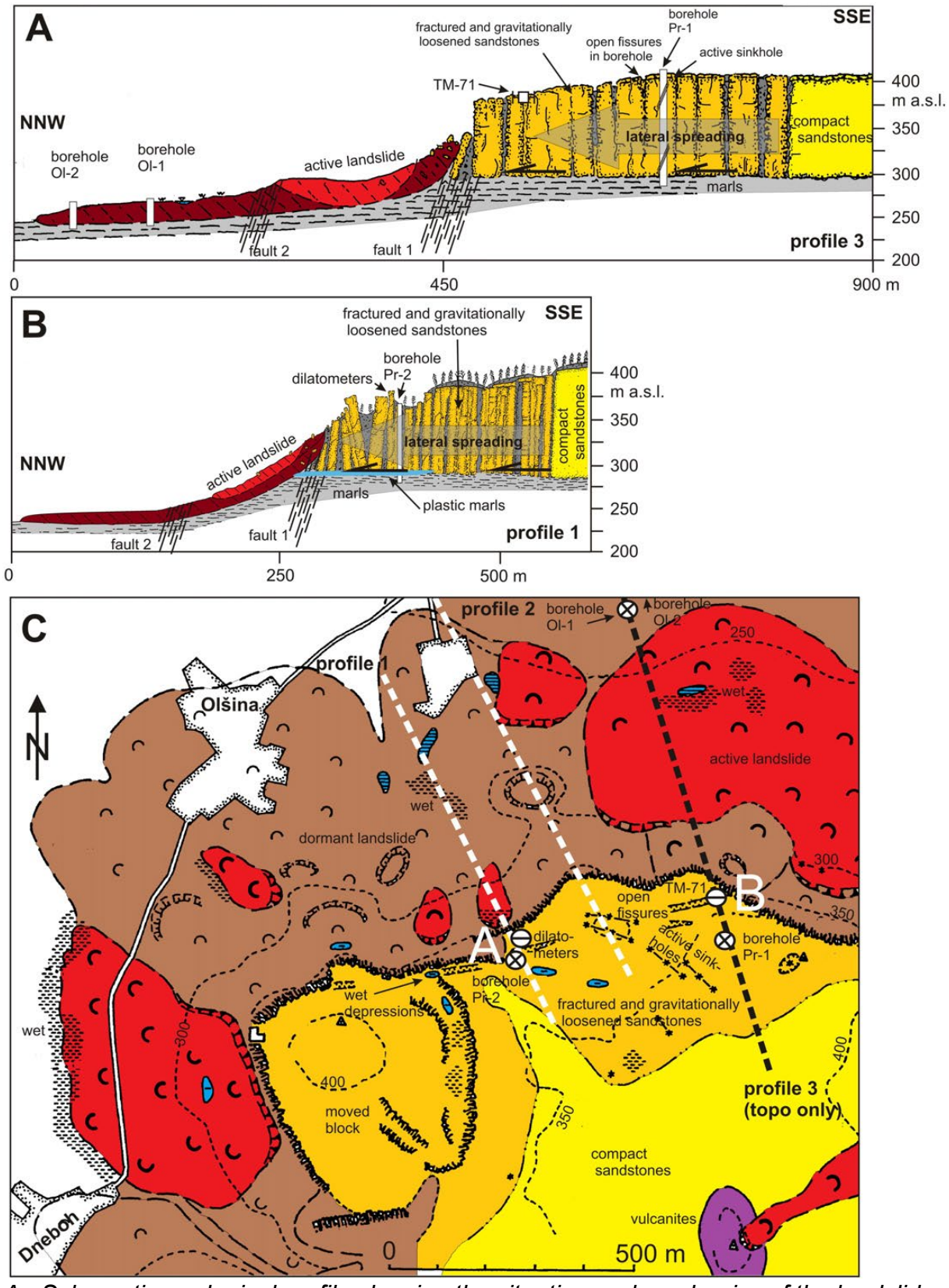
Our extensive research of tectonic movements in Slovakia, describing the present-day stress orientation and tectonic pulses registered in the caves of the Slovenský kras was published by Briestenský et al. (2018). The results of long-term neotectonic activity obtained from two underground study sites localized in the Slovenský kras Mts. (SE Slovakia) showed generally NE-SW oriented dilatation. Moreover, differing short-lasting trends were distinguished in 2011–2012 and 2013–2015. The using of fault monitoring results to compute orientation of stress-field was used for the first time here.



Situation of TM71 extensometric gauges, monitoring the selected faults, and radon monitoring observatory in the Mladeč Caves. Also, two significant periods inducing fault displacements across the observed faults are show (Ambrosino et al. 2019)

A research of the influence of tectonic background on the current relief-shaping processes in the Ethiopian Highlands was performed within the PhD thesis of Michal Kusák, and consequently published (Kusák et al. 2016, Kusák et al. 2017, Kusák & Krbcová, 2017; Kusák et al. 2019). Among the main conclusions was that the influence of tectonics on the valley network is low in the older deep and wide canyons and on the high plateau covered with Tertiary lava flows, whilst in the younger upper part of the canyons it is high. Orientation of lineaments, faults and river networks combined with features of erosion, cross-sectional and transversal valley profiles as well as stream order hierarchy reveal a change in the dominant stress fields and stages of topography development.

Aside from monitoring of the fault movements, we also observe other processes related to tectonic activity. Namely we studied Radon and CO_2 emanation routinely measured in our underground fault monitoring sites (caves, gallery mines). This promising research is performed to shed some light on the behaviour of the rock environment under changing stress field. We described investigation of the dynamic nature of radon flux and uses the results to predict cave radon concentration for successive iterations (Rowberry et al. 2018). Input data were recorded at Driny Cave in the Little Carpathians



A - Schematic geological profile showing the situation and mechanics of the landslides and DSGSD (modified after Rybář et al., 2006); B - Schematic geological profile 1 showing the situation and mechanics of the landslides and DSGSD (modified after Stemberk and Rybář, 2005); C - Map of geodynamic phenomena affecting the NW part of Mužský Hill Plateau (following Rybář et al., 2006). Adopted from Stemberk et al. (2017).

Mountains of western Slovakia. The first part of our numerical modelling procedure focuses on calculating cave air flow velocity while the second part isolates flux in a mass balance equation to simulate real time dependence among the variables. This numerical modelling has revealed that it is possible to relate radon flux anomalies to conspicuous slip anomalies on active tectonic faults.

In another case study, the anomalous Radon emanation periods were compared with earthquake occurrences in Europe. Coincidences between both phenomena were found, since all monitored caves reflect contemporaneous local tectonic changes. The results indicate that Radon continuous monitoring could assist a better understanding of Radon emissions, along active tectonic structures, during seismic events (Ambrosino et al. 2019).

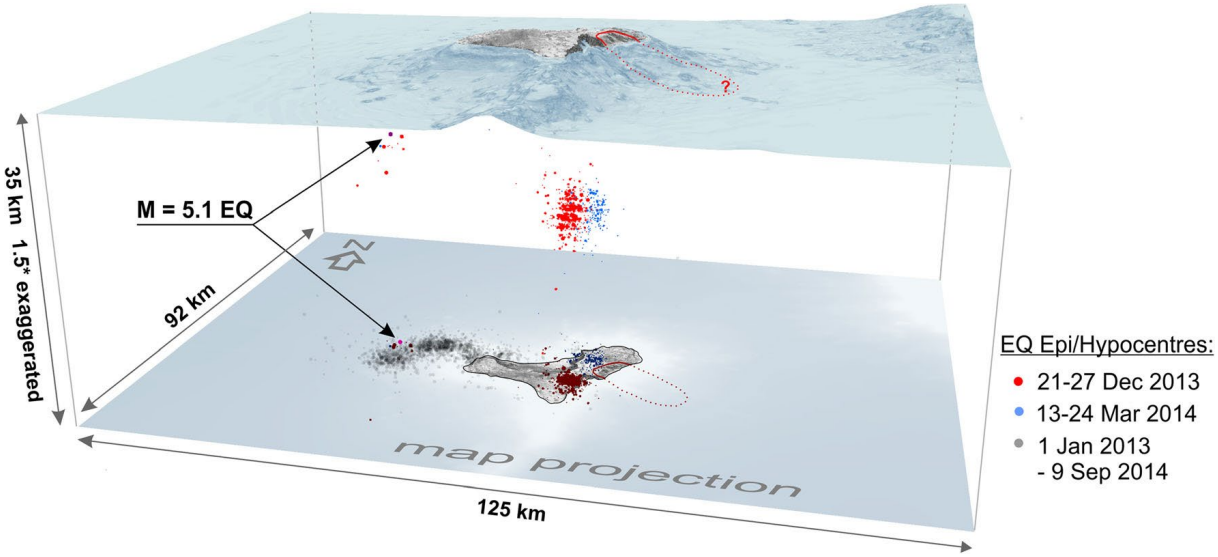
3 Slope tectonics

Interesting results brought joint research of our two major topics: slope processes and tectonics. This field of research is among the newly emerging ones with the growing attention illustrated by series of dedicated conferences on “Slope tectonics”, fostered by Prof. Jaboyedoff from the University of Lausanne in in collaboration also with members of our department.

We have tested a novel stress-state numerical approach by Sokol et al. (2018) for assessing the role of tectonic horizontal stresses in activating deep-seated gravitational slope deformations. The research was conducted at the active Obir Fault conjugated to the the seismogenic Periadriatic Line fault in the Eastern Alps, which is also a detachment plane of a deep-seated gravitational slope deformation (Baroň et al., 2019b). The research revealed, that the tectonic displacements opposing to the general fault kinematics could destabilize DSGSD at the micrometre level and the applied stress-tensor calculation is a reliable method that can reveal stress states almost in real-time.

Another research on this emerging field is the paper by Stemberk et al. (2017), on the tectonic strain influence on the development of deep-seated landslides (DSGSDs). It was discovered that aseismic transient stress/strain changes related to active tectonics represent an important and hitherto underappreciated geomorphological process accelerating the development of the DSGSDs in low seismic region as Bohemian Massif. Tectonically driven accelerations reach comparable amplitudes as accelerations recorded during extreme rainfalls generally supposed/considered as the main factor of slope deformation activation.

The slope tectonics is being further developed by ongoing research of DSGSDs at El Hierro (Canary Is.) and their relation to the tectonic and volcanic events, as well as several other sites in the Bohemian Massive, Carpathians and Alps.



Oblique view of El Hierro from the south-southeast showing epicentres and hypocentres associated with endogenous impulse I (red dots) and endogenous impulse II (blue dots). Seismic data were provided courtesy of the Instituto Geográfico Nacional (Blahůt et al. 2018b).

4 Rock weathering

Some of our studies deal with various aspects of rock weathering, mineral changes and their slope stability consequences. On this research we cooperate with internationally renowned teams. One of the main results describes a quantitative method for calculating a weathering index for carbonate rock samples based on a range of petrophysical models. In total, four models are proposed, each of which incorporates one or more of the processes involved in carbonate rock weathering (calcite dissolution, gravitational compaction, and the incorporation of inputs, Dubois et al. 2015). The selected weathering processes are defined for each model along with theoretical laws that describe the development of the rock properties.

Physical modelling with Střeleč locked sand from the Czech Republic was used to simulate weathering and decay of the UNESCO World Heritage site of Petra (Jordan). Sharp forms made of the locked sand subjected to water erosion decayed to rounded shapes strikingly similar to weathered tombs in Petra. The physical modelling results enabled visualization of the recession of monument surfaces in high spatial and temporal resolution and indicated that the recession rate of Petra monuments was far from constant both in space and time. Numerical modelling of stress fields confirmed the physical modelling results. This novel approach to investigate weathering clearly demonstrates that increased stress decreases the decay rate of Petra monuments. To properly delineate the endangered zones of monuments, the potential damage caused by weathering agents should be combined with stress modelling and verified by documentation of a real damage (Řihošek et al. 2016).

Rowberry et al. (2018) have described the processes responsible for the formation of an enclosed mass of altered rock at Červený Quarry near Prague. The results demonstrate that carbonate dissolution has not been accompanied by gravitational compaction or the incorporation of mineral inputs. Negligible calcite dissolution helps to explain the exceptional nature of the fossil preservation at the site while the dolomite dissolution accounts for the ease with which it is possible to extract the fossils.

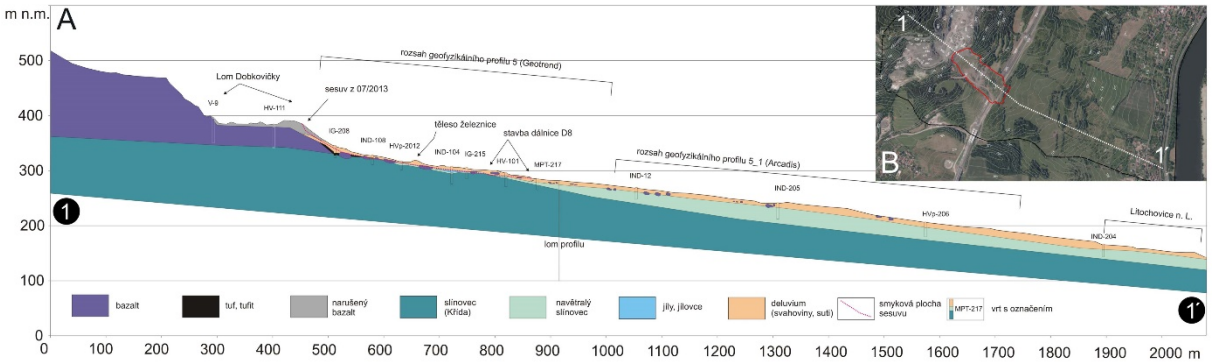
Finally, the combination of selected factors (erosion rate, moisture, salt content, suction, tensile strength, frost weathering, numerical modelling of stress) controlling the weathering and erosion of sandstone on the field scale suggested that overhangs in Central Europe (and elsewhere) might be the result of rapid frost weathering of nearly saturated sandstone during the Last Glacial because the sandstone landforms in temperate climates may potentially develop very rapidly if the pore space is nearly saturated with water, and will later remain relatively stable when the moisture content decreases (Bruthans et al. 2017).

5 Research for practice

Although the bulk of the work undertaken in the Department of Engineering Geology focuses on basic research, and publishing the results in scientific journals, we also maintain and further develop our strong collaboration with various partners from public institutions and private enterprises bridging often wide gap between the science and practice. Most often we work on the assessment of rockfalls and landslides in various environments assessing their hazard and designing mitigation measures for different purposes (e.g. communication infrastructure construction, protection of existing houses, hiking paths.

In this way, we are following the motto of the Strategy AV21 program: “Top Research in the Public Interest”, in which our Institute leads the Natural Hazards programme and we have already undertaken numerous applied research activities (see the Outreach activities chapter). Among our most notable projects within the research for practice range are several court expert witness reports that have been prepared for various courts or institutions. An analysis of causes of a devastating landslide that hit the construction of a D8 motorway in 2013 have been prepared for the Ministry of Transport of the Czech Republic. An analysis of landslide hazard along the planned roads and motorways has been done for the Road and Motorway Directorate of the Czech Republic. Member of the department is serving since 2018 as an independent expert in the Geotechnical Monitoring Board of the D8 motorway. Currently, the Institute figures as court-appointed expert institute in the case of D8 landslide.

For full list of our research for practice projects, see the attached table.

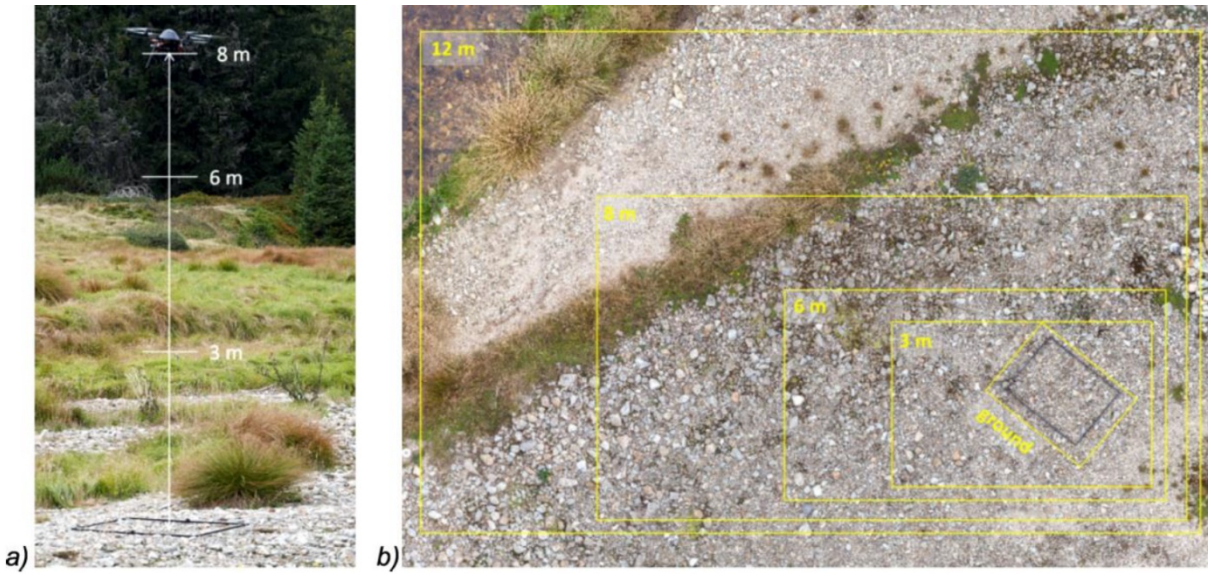


Longitudinal profile of the geotechnical model of the slope with D8 highway construction site affected by 2013 landslide (Stemberk, Mašín et al. 2016)

6 Instrument research and development

The department team is very active in the application, testing and also development of the cutting-edge technologies and methods. Since devices as TLS (terrestrial laser scanner or LiDAR), UAVs (unmanned aerial vehicles or drones) with various sensors, and similar new tool became available (and affordable), we have been experimenting with them, finding new applications in our various researches and improving the quality and usefulness of the gained results. We are continuously developing our own monitoring device since 1970ies, when the first optical-mechanical models were introduced. Recently its development is directed towards finer measurement resolution, automatic readings, data downloading and even their processing. Its improvements are accompanied with in-house production of new parts using 3D printing technology.

In 2016, we have performed one of the world´s first studies attempting to combine the ascending technology of UAVs with an equally innovative attitude to granulometry, which uses image analysis to measure grain size distribution in the coarse sediment accumulation. In conclusion, the paper proved potential of the UAV and optical granulometry combination and set some questions and directions of its further development and improvements (Langhammer et al 2017).



Determining the optimum flight altitude: (a) imaging the point bar at low-level flight altitudes; and (b) varying coverage at different levels of imaging altitudes (Langhammer et al. 2017).

In another study using the UAVs, we decided to offer a critical evaluation of the use of an inexpensive camera mounted on a recreational unmanned aerial vehicle as a tool for landslide research. The constructed 3D surface models were compared to those generated using a DSLR camera, Total Station and Terrestrial Laser Scanning. It was shown that the cheaper and more affordable UAV approach has considerable potential despite the fact that its performance was slightly inferior to the other methods as demonstrated in a case study of a small shallow landslide (Balek and Blahůt 2017).

A series of laboratory tests were performed to estimate precision and accuracy of SAA (Shape Accel Array) sensor, before it was installed on a landslide site in the České Středohoří. Laboratory testing of the sensor was realized with cooperation with Czech Technical University in Prague and it resulted into a so far unavailable set of standard deviations describing accuracy of the sensor in different orientations and

different types of installations including both internal and external accuracy characteristics (Urban et al. 2016, Balek et al. 2019)

An evaluation of the instrumental resolution of a mechanical-optical 3D extensometer TM-71 in light of its recent automatization was performed. The ultimate sensitivity of the automated instrument is determined on the basis of a generic least square differences fitting procedure while the instrumental resolution is defined on the basis of realistic, rather than optimal, scenarios. This assessment represents the first step towards a global numerical repository for processed data recorded by the automated extensometers (Rowberry et al. 2016).

We are also searching for new promising monitoring technologies applicable for our main research topics. Recently, we designed a contactless positioning system to monitor the kinematic behaviour of mechanical discontinuities such as faults and fractures in three dimensions (Rinaldi-Montes et al. 2017). The contactless positioning system has a range of potential applications in many areas of basic and applied research including geology, geotechnical engineering, and structural health monitoring.

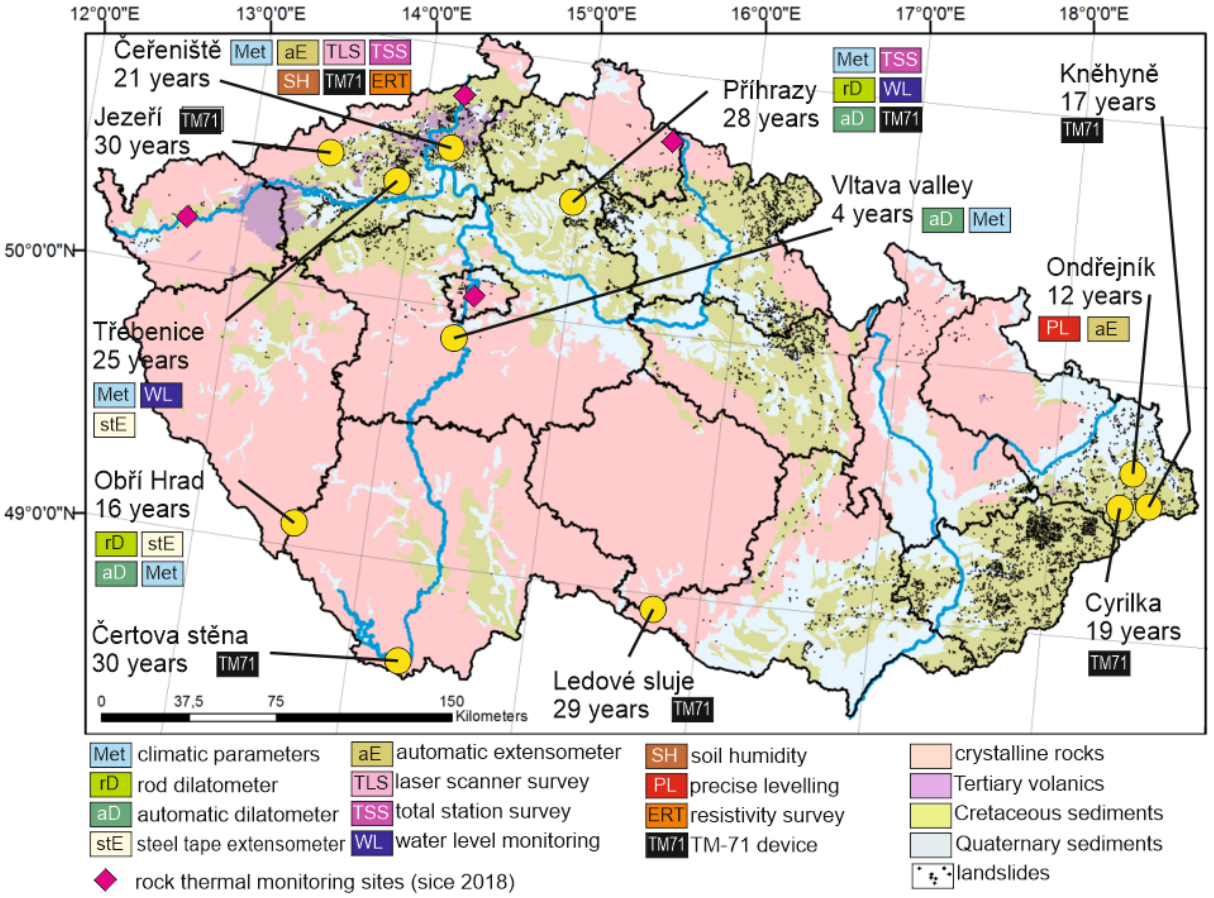
6 Networks

The department of engineering geology runs three networks, monitoring various geodynamic movements. The most extensive is the TecNet, observing the slow movements on tectonic faults using the TM-71 3D extensometers, then there is the geodynamic network GEONAS, dedicated to GNSS measurements at selected stabilised geodetic points, and finally SLOPENET, fast developing network monitoring the slope deformations using various direct movement observations and environmental monitoring sensors. Design of the TecNet and SLOPENET networks illustrates significant overlap of our research in slope and tectonic processes.

The systematic building of a network for monitoring of 3-D fault displacements using an optical-mechanical 3D extensometer TM-71 (patented by IRSM CAS) started in 2001. The main advantage of the device is the possibility to record movements on-site directly across a fault plane, and yielding very accurate results of 3D fault movements including possible rotation of the blocks. Measuring devices are placed across the faults preferentially in the underground (caves, galleries) to minimize the undesired influence of exogenous or anthropogenic processes. The TecNet currently consists of more than 150 gauges situated on tectonic faults within the Czech Republic, Slovakia, Slovenia, Poland, Germany, Austria, Switzerland, Italy, Greece, Bulgaria, Belgium, Peru and Norway (for sites´ position see http://www.tecnet.cz/). Measurements in the caves or galleries without power source are performed at one month frequency. At sites with available electricity source, the fully automated devices are mounted, with a direct connection to the internet or GSM where possible. The frequency of data readings depends on the site, ranging from one day to one hour. Data samples from selected sites are accessible on http://www.tecnet.cz/online monitoring. Data are processed in the IRSM and are freely accessible on request. We plan to upgrade gradually all the devices (where possible) to automatic version with the data transfer via internet or GSM.

The Geodynamic Network of the Academy of Sciences (GEONAS) is a network of permanent GNSS stations performing continuous observations of geodynamic movements on territory of the Czech Republic. GEONAS started to operate in 2001 with two stations (on Sněžka and Biskupská kupa). Nowadays, it consists of 18 permanent stations, three of them have been incorporated within EUREF Permanent

Network EPN. All stations operate with the 30 second sampling rate. The configuration was designed to cover various geological structures. The stations are equipped with old Ashtec Z-18 and Topcon GB1000 receivers capable of monitoring US NAVSTAR satellite signals of the GPS system as well as Russian GLONASS satellite signals. Some stations are equipped with new Topcon NET-G3A receivers capable to monitor signals of the newly-built EU Galileo system in the future. All stations are connected online to our operational centre where the recorded data are automatically checked. Data processing is performed using the Bernese software package.



Monitoring network Slopenet in the Czech Republic, showing the main sites and length of monitoring (modified after Klimeš et al 2017).

The network of long-term monitoring of the slope movements has been steadily growing since the beginnings of the 1970s. The most significant sites cover numerous slope deformations in different geological environments are included into SLOPENET network. The field data will be used for landslide hazard assessment, for design of mitigation measures, and for estimating the influence of global climate changes on the potential changes in landslide frequency of occurrence. The SLOPENET will use variety of sensors, specifically designed for landslide monitoring and observation of hydrometeorological conditions, which provide data applicable for designation of possible remedial measures and early warning. The key equipment includes a multiparametric column for 2D continuous landslide monitoring, which represents up-to-date technology combining piezometric and inclinometric readings with an application specifically designed for early warning purposes. Other sensors include wire extensometers and piezometers (Geocon), meteorological stations (Fiedler Inc.), suction sensors (UMS T8 Tensiometer) and ground water level gauges (MiniDiver

Schlumberger). Rock mass stability is being monitored with crack gauges (Geko Tag PZ-12-A-025) and temperature sensors (EMS Brno). Data processing will be automated under expert supervision. Data are processed in the IRSM and are freely accessible on request.

Research activity and characterisation of the main scientific results

In the period 2015-2019, research at the Department of Neotectonics and Thermochronology, which is focused on **Neotectonic and long-term landscape evolution**, could be divided into five research subtopics:

1) Neotectonics and paleoseismicity
2) Seismic hazard assessment
3) Thermochronology
4) Landscape evolution and morphostructural analysis of landforms
5) Dynamics and long-term evolution of slope deformation

Topic 1. Neotectonics and palaeoseismicity

Neotectonic activity and palaeoseismicity have been studied on morphologically pronounced tectonic structures in the Bohemian Massif, Carpathian Foreland, southern Iberian Peninsula, Trans-Mexican Volcanic Belt, South California, and Kashmir Himalaya, by using the multidisciplinary approaches of tectonic geomorphology, structural geology, applied geophysics, geochemistry, sedimentology, several dating methods, palaeoseismology and archeoseismology - young branches of the earth sciences first implemented in central Europe by our research team. Reconstruction of faulting history and seismicity helps to assess the tectonic hazard in the studied areas and several times the results have contributed to seismic hazard (re)assessment.

Several achievements in palaeoseismology and faulting history reconstruction have been fulfilled:

- The first comprehensive study on Late Quaternary tectonic activity in the Cheb basin using paleoseismic trenching and shallow geophysics revealed the kinematics of the fault and several large Plio-Quaternary and two Holocene Mw 6+ surface breaking earthquakes. The latest one appeared to be the largest historical (~1000 AD) event reported to date for the region, which has a great implication for seismic hazard assessment in the intraplate region (Štěpančíková et al. 2019, fig. 1). *The team members of the Neotectonics dpt. (Štěpančíková, Stemberk) did a substantial part of the research - initiated the study, organized and realized the field work, did mapping, paleoseismic and geomorphological analyses, wrote substantial part of the paper and made the conclusion. The member of the Seismotectonics dpt. (Nováková) did the analysis of fractured grains and wrote a part of the paper, the team member of Engineering dpt. (Hartvich) participated on the field work, did geophysical survey and wrote a part of the paper.* Several

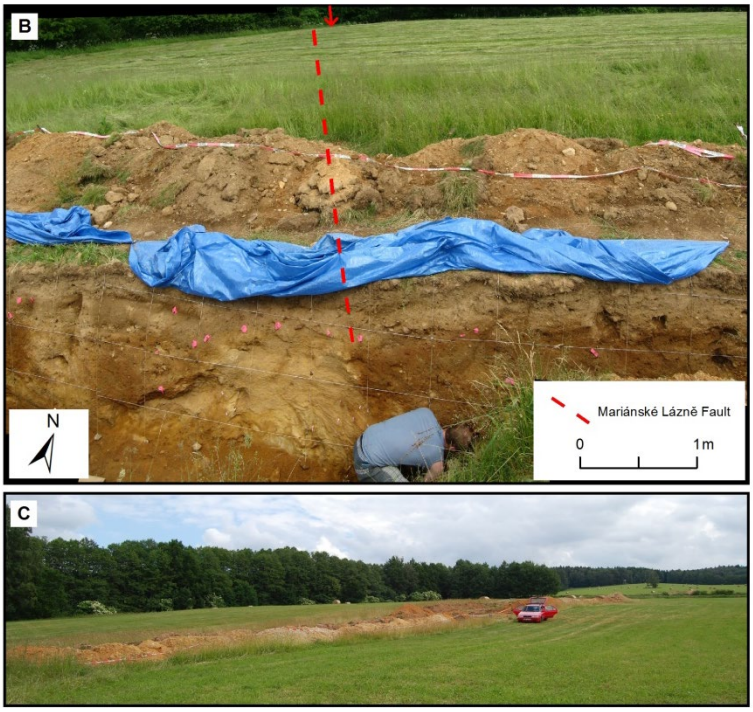


Fig. 1. Kopanina trenching site at Mariánské Lázně fault where Holocene faulting was proved.

geophysical methods also revealed the fault features and the structure of the basin to the depth (Blecha et al. 2018). *The team members (Tábořík, Štěpančíková) participated on planning the strategy, on field geophysical survey, data processing, interpretation and writing of related part of manuscript. J. Valenta (member of the team of Seismotectonics) participated on the field survey, data processing and writing of related part of manuscript.*

- Quaternary evolution of the Cheb basin and Mariánské lázně fault (MLF) was studied also from geomorphological record and neotectonic activity was proven based on fluvial terraces, changes in river network and morphometry features of the mountain front controlled by the MLF along its whole length (Štěpančíková et al. 2018, Balatka et al. 2019). *The team did the substantial part of the study Štěpančíková et al., analysed the digital elevation model and calculated the morphometric indices as well it as analysed the longitudinal river profiles crossing the MLF for the second study by Balatka, Štěpančíková contributed to data interpretation.*

- Quaternary tectonic activity, which is rarely studied in Czech Republic, was evaluated by comparison of landscape evolution of two lithologically and consequently morphologically different areas in the Sudetic Mountains by using unique combination of various classic geomorphological methods (e.g. longitudinal and cross-valley profiles analyses, mapping) with modern ones using the LiDAR DEM analysis and paleoseismic trenching. Late Pleistocene seismic activity and ice-loading related acceleration of the activity of the Sudetic Marginal Fault studied earlier by the team was also reviewed and presented (Štěpančíková, Stemberk jr). *Both authors are the team members.*

- Palaeoseismic records, the potential magnitude of faults, the recurrence period and slip behaviour in several different geological environments were determined. These not only related to plate boundaries (Carboneras fault in Iberian Peninsula) but also to such faults in the Trans-Mexican Volcanic Belt. The first study in Acambay graben (Ortuño et al., 2019) proved seismogenic characters of the faults and documented multiple large prehistoric earthquakes, some of them possibly volcanic-triggered. It also brings original explanation of complex behaviour and faults interplay showing clustered temporal distribution. Also strong ground shaking scenarios for central Mexico, where the population has grown substantially in the past few decades are suggested, which has a great implication for seismic hazard assessment. *The team member (Štěpančíková) did the field work and documented the trenches, analysed the data and did figures with interpretation for the paper.* Masana et al. 2018 presents the long-term collaborative study results of tectonic activity and seismicity of Carboneras fault in Iberian Peninsula on the African/European plate boundary. *The team member (Štěpančíková) participated on several trenching campaigns and data processing.*

- An innovative method of linking offset alluvial fans along the Elsinore fault back to their sources through analysis of clast assemblages and provenance was used within the system of San Andreas fault. U-Th dating of pedogenic carbonate in the fans confirms the utility of the technique in arid regions and helped to calculate a late Quaternary slip rate and earthquake frequency suggested for the Elsinore fault in the Coyote Mts, having great implication for seismic hazard assessment (Rockwell et al. 2019). *The team member (Štěpančíková) did a substantial part of the field work, mapping and data collection, analysed the data on the clast assemblages, participated on the manuscript. Later also T. Rockwell, the first author, became a team member, but most of this study was done by him before.* Another study on the continuation of the Elsinore fault in Baja California as a Laguna Salada fault showed its fault Kinematics and Rupture Patterns (Rockwell et al. 2015). *The team member Štěpančíková participated on the field work and data collection.*

- First comprehensive study on paleostress in northern Bohemian Massif showed several stress field phases since Late Cretaceous, which were distinguished based

on detailed field structural measurements on Lusatian fault (Coubal et al. 2015). *The team member Štěpančíková participated on manuscript part related to Plio-Quaternary activity (5%). Although the first author, who did the substantial part of data collection, analysis, manuscript writing) used only affiliation to Geological institute, he was already a member our team. The second author, Jiří Málek who did the paleostress calculation is a member of the team Seismotectonics*. Brittle deformation analysis also deciphered Alpine tectonic activity of the Železné hory Fault (Coubal et al. 2019).*The team members (Coubal, Stemberk) did substantial part of the study – field data collection, data analysis, stress calculation, morphology analysis, writing manuscript.*

- Revised review on neotectonic activity of the western Carpathain foreland (Nysa - Upper Morava Basin) was presented by Špaček et al. 2015, where *a team member (Štěpančíková) contributed to manuscript by information and data from Sudetic part of the area*. The deformations exposed by trenching across the faults and using shallow geophysics were firstly discussed and compared in detail to similar features which however could have been controlled by gravity (Špaček et al. 2017). *The member of Seismotectonics team, Valenta, did geophysical survey, while our team members (Táborík, Štěpančíková) contributed to manuscript by geophysical data processing and field data interpretation.* Seismic activity in the Carpathian foreland was proven for the first time also based on fractured speleothems (Bábek et al. 2015). *The team member Štěpančíková participated on data collection in the caves, the member of the team of engineering geology collected the data in the field and field mapping.*

- One of the rare studies conducted in the Kashmir basin to see how earthquakes have affected the ancient buildings of Kashmir clearly deciphered the damage imparted to the ancient twin temples of Pattan in

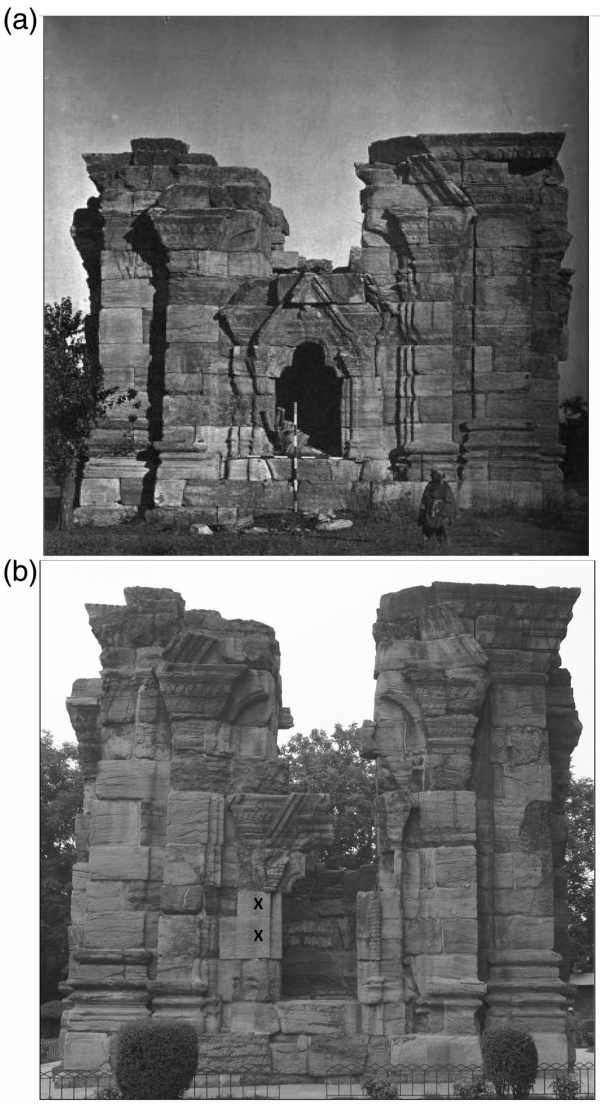


Fig. 2. a) Pre-1885 Kashmir earthquake picture (Cole, 1869) and (b) a recent photograph of the western face of the Sankargaureshwara temple. The stone blocks marked X have been added to support the remaining part of the trefoil arch after the 1950s.

Kashmir. Thus, this study is not only important from the archeo-seismological point of view but also for seismic hazard evaluation of the Kashmir basin (Sana et al. 2018). *Hamid Sana (the team member) did substantial part of the study, he initiated the study, wrote the manuscript and participated in the field trip (50%).* We also did a historical seismicity study in Střelín, Poland focussing on the moderate magnitude 1895 Poland earthquake. The work was focussed on the macroseismic intensity re-evaluation of the 11 June 1895 central Silesia earthquake, Southwestern Poland (Sana et al. 2018, fig. 2).

- Monitoring of present-day micro-movements on tectonic faults using extensometers TM-71 has been carried out on several places. The fault slips, recorded in Central Apennines (Stemberk J. et al. 2019), correspond to the minimum and maximum principal stress with a SW-NE orientation. We discovered that the switching of stress/strain state is coinciding with periods of major seismic events in this region (e.g. L'Aquila 2009 and Norcia 2016 strong earthquakes). *The team members Stemberk J. jr. and Coubal M. used the classical structural geological approach and applied it newly on the fault slip data derived from monitoring and calculated the stress field parameters.* The data from monitoring carried out in Rychlebské hory Mts in the Bohemian Massif showed the slow non-seismic transient fault slips in scale of 0.01-0.1 mm/year and accelerations, which were induced by switching two compressional stress/strain states – WNW-ESE to NW-SE compression corresponding to the stress field of the Western European stress domain and to NNE-SSW corresponding to the stress field of the NW part of the Carpathian stress domain. The extensional state, oriented NW-SE, corresponding to gravitational spreading due to the Rychlebské hory Mts. uplift, was recognised (Stemberk, J. jr. et al., 2019). *The team did the substantial part of the study, used the classical structure geological approach and applied it newly on the fault slip data to derive the stress field parameters. Moreover, the team determined and recognized the potentially activated faults by the current stress fields within the broader region.*

- To determine the relief evolution of the Rychlebské hory Mts. (and also other mountains within the Bohemian Massif) we measured the striae on slickensides in dated volcanic rocks near Lądek Zdrój). The datasets were separated to homogenous subsets and analysed using classical structure geological method to define the stress field parameters. Six different paleostress field regimes from the Late Miocene to Quaternary were distinguished. The results show switching of tectonic phases with dominant compression, transtension or extension. The timing of the derived regimes is determined more accurately based on dated volcanic rocks and is in good accordance with the data reported from different regions in Central Europe, In addition, one event or shorter events interrupting the main Plio-Quaternary extensional regime and one differently oriented Plio-Quaternary extension regime were discovered. The possible behaviour of the Marginal Sudetic fault and Biala fault were specified based on the parameters of recognized stress

fields since Late Miocene to Quaternary. *The team did the whole study Stemberk, J. jr. et al., 2020 (under review).*

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Topic 2. Seismic hazard assessment and Geotechnical Earthquake Engineering

The work related to seismic hazard and geotechnical earthquake engineering was focussed on the Kashmir basin of the NW Himalaya and on precariously balanced rocks studies as indicators of maximum possible experienced seismic wave acceleration in the studied areas.

- Sana (2019) presents a comprehensive seismicity based seismic hazard model for the Kashmir basin of the NW Himalaya. This was the first probabilistic seismic hazard assessment proposed for the region. The results show a very high seismic hazard for the Kashmir basin. The seismic hazard curves for four major cities of the Kashmir basin have also been evaluated. From this study it is evident that overall Kashmir basin shows a very high seismic hazard, with southeastern part showing relatively higher hazard as compared to northwestern part. Among the major

benchmark towns all show high predicted PGA, Anantnag shows the highest (0.65*g*). The present study thus advocates a significantly higher seismic hazard as compared to the BIS In: IS 1893–2002 (Part 1): Indian standard criteria for earthquake resistant design of structures, Part 1—general provisions and buildings, (2002). The design response spectra for four major cities of the Kashmir basin have also been presented.

- Another significant study that was carried out in the seismic hazard front was the site response analysis of the Kashmir basin using a geotechnical earthquake engineering approach (Sana et al. 2019). Due to non-availability of the strong motion data records, synthetic ground motions at the bedrock level were generated at each borehole location by the stochastic finite fault method. The soil type-specific relationships between SPT N value and shear wave velocity were used to generate shear wave velocity profiles at each borehole site, which were later interpolated to map the shear wave velocity pattern in the Kashmir valley. The analyses revealed that site classes C and D of the NEHRP classification are dominant in the valley. The results show that the local site conditions play an important role in the transmission of ground motion from the bedrock to the surface in the Kashmir valley, suggesting that it is imperative to consider the site effect in the seismic hazard assessment of the Kashmir valley. A detailed analysis of four important localities of Kashmir valley, namely, Anantnag, Baramulla, Kupwara and Srinagar, was also performed. The main methodology was proposed, analysis and paper writing was done by Sana (60%).

- Finally, the seismic microzonation of the Kashmir valley's main city, Srinagar was done (Sana, 2018). The objective was achieved by using probabilistic and geotechnical hazard representing the primary seismic hazard, secondary seismic hazard and site conditions are used as input themes. The themes considered for the holistic integrated hazard quantification are the peak ground acceleration at engineering bedrock, shear wave velocity distribution representing site conditions, liquefaction potential index, site amplification ratio and predominant frequency distribution. All these themes have been assigned appropriate weights and their features. These weighted themes are then integrated in the GIS environment to generate seismic microzonation map of the Srinagar city. This map is expressed in terms of the Seismic Hazard Index (SHI) and is accordingly grouped into two classes: very high and severe. The results demonstrate that Srinagar city is susceptible to very high seismic hazard, especially when predicted peak ground acceleration is of the order of 0.605–0.63 *g* at the bedrock.

- The stability of precariously balanced rocks is implied in seismic hazard assessment (Zábranová et al. 2019). We studied and trained the methodology on the Hus Pulpit PBR near Sedlčany. *The team members Stemberk J. and Coubal M. prepared and created the 3D model closed to reality by size and shape using the photogrammetry for further processing by colleagues from Dpt. of Seismotectonics. They measured,*

modelled and determined the eigenoscilations of the PBR. The result shows the rock instabilities under a presence of an M = 7 earthquake at a distance of about 150 km. The study is published as Zábranová et al., 2019.

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Topic 3: Thermochronology

The U-Th/He thermochronological laboratory was built during 2015 and 2016. It carried out thermochronological dating of low-temperature geological processes for purposes of studies within the institute as well as in cooperation with several international institutions. Whilst establishing and calibrating the laboratory for the first two years (2016-2018) considerable effort was made to ensure the international competitiveness and accuracy of our results by cross calibration with the laboratories at the University of Göttingen as well as conference publication of several internationally accepted dating standard results. Since then our laboratory has dated samples from more than 10 countries and established permanent collaborative relationships with numerous universities and institutes, such as the Universities of Göttingen (De), Warsaw (Pl), Padua (It), Bratislava (Sk) and Salzburg (At). In our own research, helium dating method was used in combination with structural analyses and morphotectonic research to study the interaction of erosion, tectonic, and climatic processes which formed the relief of Bohemian Massif and to reconstruct its geodynamic evolution in relation to interaction with Alpine-Carpathian Orogeny. Highlights of our research and findings to date are listed below. In addition we have several collaborative and in-house projects ongoing, including samples from Svalbard, Kashmir and varied smaller locations across the Czech Republic.

- Examination of the Cenozoic exhumation history of the Eger Rift flanks, as part of a wider interdisciplinary bilateral cooperation project with Germany. We showed an asymmetric pattern of uplift and formation along the Eger Rift as well as proving once and for all the timing of rift formation to be around 24Ma, which was previously debated (Tomasek et al.). This sheds new light on the formation of the Eger Rift, and is further the basis of ongoing structural and geophysical research by the other

authors. *The team members collected and processed the samples for this project (Szameitat, Kolesárová, Rahmonov), we conducted the thermochronological dating in our laboratory and the thermal modelling (Szameitat) to examine the exhumation histories. M. René, who is a member of the team of Geochemistry, did the petrological analysis.*

- The first complex structural study on the Šumava Mts investigated the morphotectonic evolution and inherited Variscan fault systems of the region (Kalinová et al.). A combination of structural analysis, paleostress analysis (team member: M. Coubal), fission track dating, apatite helium dating and thermal modelling (both: A. Szameitat) showed tectonic zonation and changes thereof during and after the Variscan orogeny, and how these are still represented in different structural and exhumational zones today. *The team participated on the thermochronological dating and modelling (Szameitat), paleostress calculations (Coubal) and data interpretation (Stepancikova, Coubal, Szameitat) of this study, which was cooperation with the Charles University and the Geological Institute of the CAS.*

- Through continued work on the PhD project results of Dr. Szameitat, she demonstrates that the uplift of the Canadian Rocky Mountains and Columbia Mountains is much younger than previously assumed, and that at least 3 uplift phases have been present in the past 50Ma, where previous studies presumed only one. We also showed that the elevation of these mountains has reached up to 3km higher than today in the past 50 Ma. These findings have important implications not only for local geologists, but also for climate models of the northern hemisphere, as previously unknown elevation of N-S striking mountain ranges poses a significant barrier for air masses travelling across the globe. (Szameitat et al.). *A. Szameitat was the principal investigator for this project, which began at the University of Leicester, but continued through re-evaluation and expansion of the thermal modelling while in Prague. The publication is finished will be submitted in the coming weeks.*

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Topic 4: Landscape evolution and morphostructural analysis of landforms

This topic incorporates various studies focused on landscape evolution or further morphostructural analyses of landforms. These studies reflect (i) interdisciplinary focus of the team and (ii) a need of the expert opinion of the individual team members.

- The paper Uxa et al. (2019) brings a comment on 'Geophysical approach to the study of a periglacial blockfield in a mountain area by Stan et al. (2017)' discussing some specific issues of the geophysical interpretations and introducing a new hypothesis correcting previous interpretations of the periglacial landforms evolution. Paper brings an expert opinion on the most probable evolutionary scenario. *The team member Tábořík contributed with his expert opinion on the design of geophysical surveying and namely on the further interpretations of the results. During whole process of writing the paper, close co-operation of all co-authors was necessary as well as a multidisciplinary approach (evaluating various aspects of periglacial evolution).*

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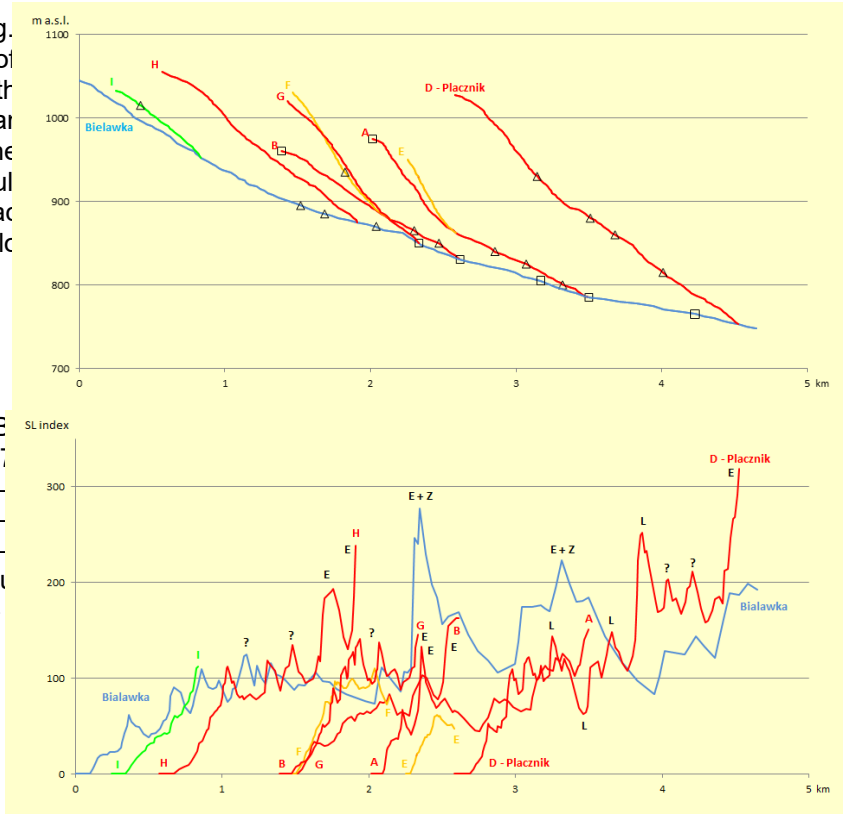

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- In the paper of Petronis et al. (2018) the authors team analysed the Zebín Volcano tuff cone (Czech Republic) that offers the opportunity to understand emplacement processes responsible for magma transport through a pyroclastic cone and magmatic processes involved in its development. A widespread complex of geochronological and geophysical methods was used. *The team member Tábořík was involved as the geophysical survey team member. He contributed with the geophysical fieldworks and further data interpretations.*

- A valley evolution analysis of the Biala Lądecka drainage network during late Cenozoic was elaborated in the study by Stemberk jr. et al. (2016) (Fig. 3). An investigation of the Biala Lądecka river basin geomorphology was performed in order to assess how Plio-Quaternary tectonic activity at the Bělský fault and near Sudetic Marginal Fault might have contributed to the river's asymmetry. A spatial distribution of landforms as well as stream network parameters (e.g. SL index) were studied and further elaborated. A distribution of the Biala Lądecka paleoriver sediments was investigated by means of geophysical measurements. The results suggest a Plio-Quaternary tectonic activity for the Bělský fault. *The paper and the related research was fully performed by the Dpt. Neotectonic team.*

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Topic 5: Dynamics and long-term evolution of slope deformation

The topic focuses on a dynamics and long-term evolution of slope deformations. The presented results are closely aimed at the mountain ridge disintegration and related slope processes. Within all studies, we investigated manifestations of the deep-seated gravitational slope deformations (DSGSDs), such as counter-scarp, crevice type caves and other landforms. We also accented the importance of the structure geological predispositions, controlling tectonic features and related kinematics on the faults. Furthermore, we widely used geophysical surveying within all studies and, in two cases, we also assessed methodological aspects of such surveys.

- The paper by Březný et al. (2018) analysed the structural conditions of the deep-seated mountain ridge disintegration and described how these structural forms may affect the development of the slopes. The study accents the recently emerged concept of "slope tectonics" suggesting that mass movement processes can produce structures similar in morphological expression to that of extensional, strike-slip and compressional tectonic deformations. *The team member Tábořík*

contributed (within the long term co-operation with University of Ostrava) with the electrical resistivity tomography and ground penetrating radar measurements as well as with its processing and data interpretation. He also wrote relevant parts of the paper.

- The study Chalupa et al. (2018) (Fig. 4) describes the flysch nappe outliers as a structural setting vulnerable to the development of deep-seated gravitational slope deformations (DSGSDs). With the aim of detecting the main controlling factors of the DSGSDs, a multi-approach investigation combining surface and underground studies has been performed. Data integration indicate that structural conditions, including lithological boundaries, tectonic disruption and local folding to be the main controlling factors of the DSGSDs evolution. *The team of IRSM (Tábořík, Klimeš, Hartvich) participated on fieldworks (mapping, geophysical surveying), data processing and interpretation as well as writing the relevant parts of the paper. The team member gnificantly contributed to the interpretation of the data and discussion on the results.*

- A structural analysis and a new general tectonic plan of the Cyrilka Cave (the longest crevice-type cave in Czechia), with detailed geometry and analysis of the kinematics of the relaxed rock massif, were reported by Lenart et al. (2018). Along with DEM imaging and the detailed cave survey, 2D and 3D ERT measurements completed an image of the main predispositions and revealed the internal structure of the slope deformation, including the discoveries of unknown crevices above the existing headscarp, which indicate the retrograde evolution of the landslide. Based on radiocarbon dating of the stalactite core, the minimum age of the cave is up to 19,900 ± 280 cal BP, which is the oldest age detected in the area of the Outer Flysch Carpathians so far. *Team member Petr Tábořík, significantly contributed to the research by designing, performing and processing of the ERT survey as well as by interpretations of the obtained data and 3D models. He also wrote particular parts of the paper and took part of the discussion.*

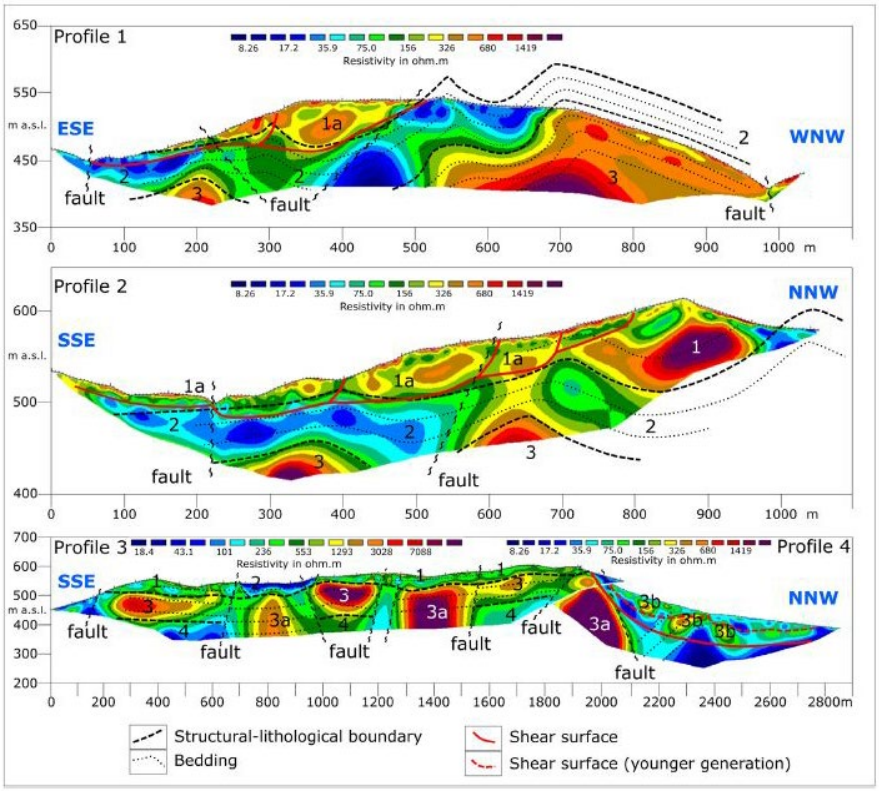

Fig. 4. ERT profiles. Profiles 1) and 2): 1 upper coarse-grained thick-bedded sandstone flysch (Palkovice Formation), 1a gravitationally disrupted 1, 2 fine-grained thin-bedded claystone flysch (Palkovice Formation). Profiles 3) and 4): 1 sandstone colluvium (Palkovice Formation), 2 tectonically affected claystone (Palkovice Formation), 3 tectonically separated sandstone blocks (Baška formation), 3a sagged 3, 3b gravitationally disrupted 3, 4 claystone flysch (Sub-Silesian unit).

- A geophysical anatomy of counter-slope scarps, the typical manifestation of the relaxed zones of rock massifs, was introduced by Tábořík et al. (2017). Based on a multidisciplinary geophysical survey, integrated interpretations of the measured geophysical data provided a new insight into massif disintegration and the geomorphic origin of the landforms related to the deep-seated landslides. The combined results of multidisciplinary geophysical surveying confirmed an importance of employing more than one geophysical technique and introduced a novel approach to interpretation of measured data. *The team member Petr Tábořík, as the main author, initiated the geophysical research of the disintegrated part of the rock massif and was responsible for organizing of the whole research. He was attended in whole parts of the research including field work, data processing (partly) and data interpretations, namely the final integrated interpretations of the various geophysical result. He is also responsible for the concept of the whole paper and, as the main author, for majority of the text (writing and supervision).*

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Research for practice

The team also contributed to the research for practice through several agreements with companies, e.g. Czech Power Company, (ČEZ a.s). For this company, in cooperation with Dr. P. Špaček (MU Brno) and Dr. I. Prachař (Energoprůzkum Prague Ltd.), we have been constructing *Active fault database* (https://faults.ipe.muni.cz/doku.php?id=start) within Sigma 2 project. The database can contribute to hazard assessments in areas selected for large civil engineering projects such as nuclear power plants, the construction of reservoirs, and the disposal of radioactive waste. A part of the team has also been contributing to the practical research activities of the Dpt. Enginering Geology, namely in the research of the slope deformations and applications of the geophysical surveying for purposes of the expertise (Insurance companies, Courts, Ministry of Transport of the Czech Rep.), etc.). Thermochronological lab was also collaborating with Merebit, ltd on development of a prototype of magnetic separator for mineral separation purpose, which was built for our lab and tested here.