# Description of the main research directions investigated by the institute

In the following we outline 11 research themes spanned by the Institute.

## 1. Seismic source and wave propagation

The study of seismic sources and wave propagation has a strong tradition at our Institute both in terms of basic research and in applications of practical seismology. Studies frequently draw on extensive datasets of natural earthquakes, such as those provided by the WEBNET seismological network in West Bohemia, or they employ theoretical and modelling approaches. A specific type of seismicity known as earthquake swarms has been studied both in intraplate regions (e.g., West Bohemia) and in plate-boundary settings. In addition to studying natural earthquakes, general processes of seismic wave propagation have been investigated experimentally via induced seismicity and in laboratory settings. A recent new direction has been the study of seismic ambient vibrations; these are being analysed for non-conventional characterization of unstable rock slopes that are potentially vulnerable to catastrophic landsliding.

## 2. Global active tectonics

Studying local seismicity in active tectonic settings can yield a direct understanding of ongoing deformation processes and the internal workings of the plate tectonic ‘engine’. Our work in seismotectonics builds upon the foundational studies of Jiří Vaněk and colleagues, who conducted pioneering early tests of the plate tectonics hypothesis by investigating deep structures and tectonic processes at plate subduction zones. In addition to seismicity in major tectonic zones, our research also embraces specific seismic signals related to volcanic activity.

## 3. Volcanic and magmatic processes

Research on volcanic and magmatic processes has focused on understanding the eruptive dynamics of volcanic systems, their evolution in time, the generation of magmas, and the relationship between magmatic systems and lithospheric tectonics/crustal evolution. The study of fundamental volcano-magmatic processes is complex and occurs over multiple scales and depths, necessitating a broad group of research methods (e.g., geophysical analysis, numerical & analogue modelling, field & laboratory observations) to provide an integrated picture of the processes controlling magma generation through eruption. Four main research directions have been: (i) magma propagation and reservoir dynamics, (ii) tectonic controls on magmatic processes, (iii) eruption dynamics, and (iv) planetary volcanism.

## 4. Earth's magnetic field and the geodynamo

Earth's magnetic field is one of the most variable geophysical fields and provides us with effective protection against cosmic rays, high-energy charged particles from the solar wind and solar flares. The geomagnetic field is also, of course, a useful navigational tool used by humans and non-human animals. Our research addresses different aspects of the geomagnetic field, including numerical modelling of the geodynamo, experimental approaches that employ solidification of an aqueous solution mimicking processes on the inner-outer core boundary, and reconstructions of space-weather relevant to historical records of geomagnetic storms.

**5. Structure of the European lithosphere**

The crustal and mantle architecture of the Bohemian Massif, the surrounding younger orogens (the Alps and Carpathians), and the East European Platform have been a long-standing research focus at the Institute. Given that present-day levels of seismicity and surface deformation across most of central and eastern Europe are generally below geodetic detection limits, we exploit induced seismic signals or those from far-field earthquakes to image the structure of the lithosphere.

**6. Sedimentary basins as archives of tectonics and climate**

Sedimentary basins reflect the interplay of lithosphere dynamics responsible for basin formation and surface processes that govern the rates of sediment production and transport leading to basin filling. Basin analysis is a typically multi-disciplinary field that combines geophysical and geological approaches to yield an understanding of the structural evolution of the lithosphere together with hydrogeology, thermal regimes, and natural resources. Sedimentary strata provide the benchmark source of information on changes in climate and oceanographic conditions over much of Earth's history. Such information is used to drive Earth System models aimed to better understand climate scenarios of the past and future. For example, time-series derived from geophysical wireline logs combined with geochemical data provide new insights into the astronomically driven climate variations under ancient greenhouse regimes and related dynamics of the global carbon cycle.

**7. Surface processes and dynamics**

The study of the processes and dynamics occurring at or near the surface of the Earth (and other planets) has undergone recent expansion at the Institute. This research deals with quantifying the fluxes of mass and energy that accompany lithosphere-atmosphere-biosphere interactions. Studies fall within five general topics: (i) climate in the sedimentary record, including absolute dating methods applied to fluvial, aeolian, and lacustrine sediments (see 6); (ii) climate reconstructed from geothermal records of deep boreholes (see 10); (iii) cryosphere forms and processes, especially periglacial landscapes; (iv) soils and environmental magnetism (see 11); and (v) geohazards, such as catastrophic floods and landslides.

**8. Structure and deformation of ancient orogens**

Orogens typically reflect crustal thickening caused by collision of tectonic plates, and are associated with processes of rock metamorphosis, melting, and transfer of heat and mass in the lithosphere. The geological structure of central Europe, exemplified by the Bohemian Massif, reflects the history of a large Palaeozoic orogen that is frequently compared to present-day Himalaya. Both recently active and ancient orogens form a large part of the continental lithosphere and are important targets for study using field structural mapping combined with petrological, geochronological and geophysical methods.

**Microscale rock fabrics: clues to deformation history and the physical properties of rocks**

Rock microstructures usually represent a complex combination of distinct features (or subfabrics) of diverse origins, orientations and strengths. Using a broad range of methods, our researchers correlate the natural (micro)structural record in rock with its manifestation in physical fields and connect those observations with other rock properties. A particular focus is with the application and development of techniques for evaluating magnetic fabrics—the anisotropy of magnetic susceptibility, which is generated by alignment of magnetic minerals. This field provides opportunities for collaboration with the Institute's specialists in geomagnetism. A related theme involves the quantification of porosity parameters, which is relevant to the permeability of rocks and their storage capacity. This is fundamental for evaluating rock suitability for geothermal energy production, for the oil and gas industry, and for the safety of deep nuclear waste repositories.

## 10. Geothermics

Geothermal research at the Institute builds on the legacy of the pioneering studies of heat flow by Vladimír Čermák and colleagues in the 1960s. The original focus on terrestrial heat flow measurements and predictions of crustal temperatures has now broadened to include additional aspects, such as reconstructions of atmospheric temperature histories from temperature logs of deep boreholes, processes of air-ground-bedrock temperature coupling, numerical simulations of permafrost and gas hydrates dynamics, as well as applications to geothermal energy production.

## 11. Environmental magnetism

Studies in environmental magnetism have focused on understanding the link between magnetic and geochemical properties of Andosols (iron-rich soils developed on volcanic rocks) and their interpretation. Long-lasting international collaborations have examined the magnetic signature of atmospheric dust from a variety of emission sources, the remediation of soils polluted by industry, discrimination of lithogenic and anthropogenic contributions to soil iron-oxides, and soil erosion.

## Research activity and characterisation of the main scientific results

### ***Monitoring earthquake activity on local scale***

This field of research has gradually developed since the late 80s around J. Horálek; in 2015-2019, the group consisted of J. Doubravová, M. Bachura, H. Jakoubková-Čermáková, Z. Procházková, A. Boušková, and J. Klicpera. Its research focus is the investigation of triggering mechanisms and driving forces of earthquake swarms using up-to-date methods of on-line local seismicity observations with preliminary quasi-real-time event location and magnitude estimation, and automatic data processing with machine learning techniques.

The main dataset used by the group comes from the Institute's local seismic network WEBNET that was instrumental in the long-standing research into the West Bohemia/Vogtland earthquake swarms. These form a main focal zone that is about 10km long and strikes N-S, with focal depths of 6-13 km. On a finer scale, it consists of a number of differently oriented fault segments that hosted the individual swarm sequences, a segmentation that was confirmed by source mechanism analyses. Some fault segments are very likely capable of higher loading, effecting mainshock-aftershock sequences rather than swarms. One of the major subjects of future investigation is whether such exceptional events could significantly increase seismic risk in West Bohemia. Analyses of the West Bohemian earthquake swarms in terms of their magnitude-frequency and inter-event time distributions as well as their spatial and temporal development and seismic moment release are presented in Čermáková and Horálek (2015), Jakoubková et al. (2017) and Bachura et al. (2020).

Moreover, the role of pressurized crustal fluids in generating local earthquake swarm initiation was investigated. The presence of non-shear sources in these swarms was verified by applying a more robust shear-tensile crack model for an earthquake mechanism (Šílený and Horálek 2016). The fluid-intrusion-driven pore pressure evolution during the ML 4.4 mainshock-aftershock sequence in 2014 was simulated numerically (Hainzl et al. 2016).

A last research avenue is the detection of local earthquakes by artificial neural networks, machine learning algorithms that are inspired by the architecture of the human brain. In collaboration with J. Wiszniowski from the Institute of Geophysics, PAN, in Warsaw, a novel neural network architecture named Single Layer Recurrent Neural Network (SLRNN) was developed by J. Doubravová (Doubravová et al. 2016). Its detection performance, which had been trained with seismograms from West Bohemia/Vogtland, was tested on data from the Institute's local seismic network on Reykjanes peninsula, SW Iceland, which demonstrated a very good generalization ability of the SLRNN network. This implies it can be used for event detection using any local seismic network without necessitating new training, provided that events' frequency contents are comparable (Doubravová and Horálek 2019).

### ***Lithospheric studies***

Headed by J. Plomerová, this group consists of 3 seismologists (JP, L. Vecsey, and H. Žlebčíková-Munzarová), a geologist (V. Babuška) and 3 specialists in data processing

(J. Kvapil, H. Kampfová Exnerová, and J. Chyba), and cooperates closely with an engineer-specialist (P. Jedlička) for seismic instrument deployments. The group studies the structure and development of the continental lithosphere in various tectonic environments (cratons, Variscan structures, Alpine orogeny etc.) and uses a range of methods (P-wave polarization diagrams, S-wave splitting, receiver functions, isotropic and anisotropic tomography) that are combined with data sets from neighboring fields, such as geology, tectonics, geodesy and potential fields.

High-resolution tomographic P- and S-wave velocity models from the passive experiment BOHEMA (Plomerová et al., G3, 2016) were instrumental in disproving the concept of a 'baby-plume' beneath the Bohemian Massif. The obtained 3D models showed no evidence of a plume signature.

A tomographic upper mantle model around the Trans-European Suture Zone was derived by inverting more than 12,000 P-arrival times from nearly 300 stations of the PASSEQ experiment (Chyba et al, PEPI, 2017). Results suggest that the Phanerozoic part of Europe over-thrusts the Precambrian East European Craton, in line with previous results of the group.

Building on a large range of datasets acquired over the past two decades, which were carefully processed and validated (a guideline on the procedure was published in Vecsey et al., 2017, Geosci. Instrum. Method. Data Syst.), an anisotropic mechanical model of the entire Bohemian Massif lithosphere was derived and interpreted (Babuška and Plomerová, Gondw. Res., 2017). Its major constituent is an asymmetric block of the Teplá-Barrandian unit between the Saxothuringian and Moldanubian units.

The group further participated in deploying the EASI transect, running N-S across contact between European and Adriatic plate beneath the Eastern Alps. The crustal model derived from the application of a suite of seismological tools (receiver functions, tomographic imaging) (Hetenyi et al., Tectonophysics 2018) confirmed the previously obtained concept of northward subduction of the Adria.

A novel code for coupled anisotropic and isotropic teleseismic P-wave tomography was developed (Munzarová et al., GJI, 2018a) and applied to data from the passive seismic experiment LAPNET in northern Fennoscandia (Munzarová et al., GJI, 2018b). The domain-like anisotropic structure of the mantle lithosphere was attributed to preserved fossil fabrics of the Archean microplates accreted during Precambrian orogenies.

Combining findings from seismology, petrology and geochemistry, the observation of tilted symmetry axes in tectonically different mantle lithospheric domains throughout Europe (Babuška and Plomerová, Solid Earth Sciences, 2020) was explained by successive subductions of ancient oceanic plates and their accretion enlarging primordial continent cores.

***<u>Site effects on seismic wavefields</u>***

A small but promising group has been forming since 2017 around the J. E. Purkyně fellow of the CAS, J. Burjánek, with senior seismologist I. Opršal, PhD student M. Labuta and close international co-operations. The group focusses on topographic site effects, assessment of local seismic site effects, characterization of local velocity structures by passive seismic methods, 3D numerical simulations of ground motions, seismic studies and monitoring of unstable slopes, earthquake triggered landslides. The group was involved in processing a systematic collection of ambient vibration measurements at 25 unstable rock slopes in Switzerland (Kleinbrod et al., Eng. Geology, 2019). A simple classification scheme was proposed according to their dynamic behaviour. A simple, effective model for fractured rock mass applicable to seismic wave propagation problems was introduced by Burjánek et al. (JGR, 2019). An attempt to monitor unstable slopes by means of ambient vibrations is presented in Burjánek et al. (GJI, 2018) with the aim to identify changes in the resonant frequency caused by internal damage preceding failure. A method for fracture network imaging on rock slope instabilities using resonance-mode analysis was introduced by Häusler et al. (GRL, 2019). The method detects hidden fractures that cannot be observed by geological field mapping.

***<u>Seismic event mechanisms</u>***

An important research topic within the Seismology Team is the inversion for earthquake moment tensors and their use in inverting for the stress field. Two groups of researchers work in this field: Senior seismologist V. Vavryčuk, supported by post-doc seismologist P. Adamová and PhD student J. Doubravová, mostly investigates moment tensor decomposition and stress field retrieval applied to seismic data collected in Western Bohemia and elsewhere. Senior seismologist J. Šílený and his collaborators P. Kolář and Z. Jechumtálová focus more on the moment tensor inversion itself, evaluating in detail the uncertainties of the retrieved mechanisms.

The paper of Vavryčuk (J. Seismol., 2015a) presents new compact formulae that have since been widely applied, as well as a novel view on shear vs. non-shear diagrams, which are an indispensable tool for interpreting moment tensor decomposition results. In Vavryčuk (BSSA, 2015b), the tool of composite fault-plane solutions is extended by inverting jointly for the full moment tensor instead of the double-couple. Such an approach adds information on the non-shear part of the composite mechanism, which yields insight on the mode of fracturing. This is particularly important when treating seismic events that likely feature mixed modes of fracturing: volcanic earthquakes, events accompanying migration of fluids, events induced by industrial activities. Vavryčuk (Geophysics, 2015c) developed a method to invert seismic wavefields for parameters of homogeneous viscoelastic anisotropy. Attenuation anisotropy – unlike velocity anisotropy - has been treated rarely up to now, although it is usually more pronounced than velocity anisotropy in most rocks. Vavryčuk et al. (SRL, 2017) applied principal component decomposition to retrieve the P-wave radiation pattern of events from the 2014 earthquake swarm in West Bohemia/Vogtland, and determined their full moment tensors. Thanks to semiautomatic processing, the method is fast and thus allows the analysis of large datasets of thousands of events. V. Vavryčuk also participated in the analysis of 984 microearthquakes from The Geysers geothermal field (Yu et al., GRL, 2019). Obtained results indicate that shear rupture radiates energy preferentially in lower frequencies than tensile fracture, which hints at a source model with a main shear fracture and smaller tensile cracks adjacent to it.

The group of J. Šílený targets seismic events induced by man-made activity: mining tremors, events due to hydro-fracturing in exploration contexts etc. Jechumtálová et al., PAGEOPH, 2016) developed a model of a seismic source in order to discern between tectonic and induced events at an underground gas storage in Central Bohemia. Occurrence of induced events correlated well with the pressurization of the reservoir. Šílený (Moment Tensor Solutions – A Useful Tool for Seismotectonics, Ed. S. D'Amico, Springer, 2018) published an overview of the shear-tensile crack seismic source model, together with case studies demonstrating its dominance over the traditional full moment tensor in ill-constrained inversions. Researchers of the group participated in laboratory studies of uniaxial loading of rock samples at the lab facilities of the CAS Institute of Geology by seismological interpretation of acoustic emission (AE) events. A reliable distinction between tension and shear-type AE events may be crucial for recognizing approaching rock failure (Petružálek et al., JGR, 2018a). Fracturing of highly anisotropic rock samples during loading mostly follows the foliation direction, which is likely typical for anisotropic rocks with low porosity (Petružálek et al., RMRE, 2018b).

***Crustal studies***

Researchers of the Team also investigate the structure of the crust and the Moho topography mainly in West Bohemia, where they benefit from the high-quality data gathered by the group of J. Horálek as well as the mechanisms of swarm earthquakes collected by the group around V. Vavryčuk. They revealed shallow crustal inhomogeneities in West Bohemia and below the KTB drill site in Germany (Hrubcová et al., JGR, 2016). In another study, they found seismological evidence for fault weakening due to erosion by crustal fluids. This could be an alternative process that initiates earthquake swarms in geothermal areas, next to the traditional concept of magmatic or hydrothermal fluid intrusion into highly fractured rock environments (Vavryčuk and Hrubcová, JGR, 2017). A similar study benefiting from the analysis of local seismicity and from the reinterpretation of a reflection seismic profile identified significant lateral variations of the high-velocity lower crust and related them to the distribution and chemical composition of mantle-derived fluids (Hrubcová et al., Tectonics, 2017). Hrubcová and Środa (Tectonophysics, 2015) analyzed wide-angle reflection profiles and deep refraction data, and identified anomalous upper-mantle Pn phases. Their origin was attributed to local Moho structure along the whole Western Carpathian arc. Close lateral proximity to the contact between the stable European Plate in the north and the Alpine-Carpathian-Pannonian microplate in the south suggests a relation to the formation of the Carpathian orogeny.

***Ray theory***

A substantial portion of research of the group was done by I. Pšenčík, a world-renowned specialist in ray theory. Recently, he focused on perturbation methods for studying wave propagation in 3D layered, inhomogeneous isotropic or anisotropic, elastic or anelastic structures.

During the evaluated period, research has been performed in four directions:

Using weak-anisotropy approximation (anisotropy is considered to be a perturbation of background isotropy), IP developed formulae that are applicable to weak-to-moderate anisotropy of arbitrary symmetry and orientation, and provide sufficient accuracy not only for small but any offsets (Pšenčík and Farra, Geophysics, 2017). In the traveltime inversion experiments, the inversion scheme was successfully applied to laboratory rock samples as well as to VSP (vertical seismic profiling) data (Pšenčík et al., GJI, 2018). The inversion scheme is applicable to weak-to-moderate anisotropy of any symmetry and orientation. The perturbation theory was used for the calculation of wave propagation in weakly attenuating isotropic or anisotropic media (Pšenčík et al., SW3D Consortium Report, 2019). An algorithm for the calculation of Green's functions in inhomogeneous anisotropic media was proposed based on the summation of Gaussian beams (Červený and Pšenčík, GJI, 2017). The approach removes some limitations of the standard ray theory, as it works properly in caustic regions and does not require time consuming two-point ray tracing.

## Research activity and characterisation of the main scientific results

***Seismicity at convergent plate margins***

In studying currently active tectonic settings, local seismicity can be the primary tool for understanding the ongoing deformation processes and the internal workings of the plate tectonic "engine". At our Institute, work on seismotectonics follows up on earlier efforts of our late colleague Jiří Vaněk and his co-workers, who had, since the early years of the plate tectonics hypothesis, concentrated on revealing deep structure and tectonic processes at subduction zones analysing available seismological datasets – hypocentral parameters and focal mechanisms. Apart from seismicity related to major tectonic zones worldwide, our research focused also on specific seismic signals related to volcanic activity.

The Seismotectonics group currently consists of Christian Sippl, Aleš Špičák, and Václav Kuna (joined in 2020). They focus on analyzing global seismicity datasets – hypocentral parameters and focal mechanisms – to reveal deep structure and tectonic processes at major tectonic zones worldwide, in particular on subduction zones. Another field of their interest is seismicity related to volcanic processes.

Earthquake swarms occurring above subducting slabs in the Andaman Sea area and the Ryukyu subduction zone were investigated for their seismicity patterns in space and time by Špičák and Vaněk (2016). This work significantly contributed to understanding the process of magma ascent beneath seamounts following shortly distant strong earthquakes, including the 2004 M 9.1 Sumatra–Andaman mega-earthquake. The analysis took advantage of the commonly available EHB earthquake catalogue and interpreted the occurrence and properties of seismic swarms, namely migration of events, as a consequence of magma unrest induced by static and/or dynamic stress changes following the distant mega-earthquakes.

By analyzing shallow earthquake swarms in southern Ryukyu area, Špičák and Vaněk (2017) continued in efforts to take advantage of detailed analysis of space-time distribution of individual events of earthquake swarms beneath the seafloor at convergent plate margins to indicate current activity of the magma plumbing system. Valuable is a concordance of regional (JMA) and global (EHB) earthquake catalogues. The repeated occurrence of earthquake swarms probably reflects fluid and/or magma migration in the plumbing system of the volcanic arc of southern Ryukyu.

In Northern Chile, in-depth studies of earthquakes occurring along the plate interface showed that aftershock productivity, i.e. the amount of aftershocks created by a given main shock, is indicative of the local distribution of coupling between the plates (Hainzl et al., 2019). An analysis of aftershocks of the 2014 Iquique earthquake (M8.1) revealed that aftershocks and aseismic slip occurring in the years after the main shock anti-correlate, i.e. they occur at the same time but occupy different regions of the plate interface (Soto et al., 2019). Looking at deeper earthquakes that occur within the downgoing slab at depths of 50-150 km, Sippl et al. (2019) found that the Nazca slab in this area shows an earthquake distribution that is distinct from other subduction zones. Combining information from earthquake locations, moment tensors and statistical seismology, they derived a conceptual model of how delayed phase transformations in the Nazca slab may create the retrieved seismological signature.

***Volcanic and Magmatic Processes***

Research on volcanic and magmatic processes has focused on understanding the eruptive dynamics of volcanic systems, the generation of magmas, and the relationship between magmatic systems and lithospheric tectonics/crustal evolution. The study of fundamental volcano-magmatic processes is complex and occurs over multiple scales and depths necessitating a broad group of research methods (geophysical analysis, numerical and analogue modelling, field and laboratory observations) to provide an integrated picture of the processes controlling magma generation through eruption. Research into seismological aspects of active volcanism is described above; this section focuses on analogue modelling and structural studies of magma flow and emplacement, potential field exploration of Quaternary volcanoes, and planetary volcanism, conducted by members of the Tectonic Modelling and Gravity and Geodesy groups.

Using analogue modelling, study of the relationship between magma pressures, thickness of magma (content of crystals in melt), deformation pattern on the surface, cohesion of host rocks and detailed internal flow pattern of magma using the AMS (Anisotropy of Magnetic Susceptibility) investigated dike propagation and growth. Experiments using AMS (anisotropy of magnetic susceptibility) fabrics in plaster of Paris with magnetite grains were designed in cooperation with Janine Kavanagh from University of Liverpool and conducted by her PhD. student Simon Martin, in collaboration with P. Závada (Martin et al., submitted).

Structural studies of magmatic plutons are integral part of decades-long efforts to understand magmatic systems and exchange of matter and heat in the lithosphere.

In a case study focusing on strain partitioning and magma flow in a small, concentrically expanded Castle Crags pluton (Klamath Mts., California, USA), Machek et al. (2019) proposed that the flow of dense crystal mush was accommodated by self-organized slip of the crystals and that the changes in granitic textures throughout the pluton reflect variations in magma conpaction, melt segregation, cumulate formation, and sub-solidus overprint, all caused by the intrusion of trondhjemite magma in the core of the pluton.

Studies of potential fields by the Gravity-Geodesy group were used to determine the eruption dynamics and reveal the unknown vent locations of the Cheb Basin, and to monitor the eruptive state and behaviour of the Nisyros Island in Greece. The existence of previously unknown twin maars in the Ztracený Rybník natural reserve was revealed using both gravity and magnetic methods (Flechsig et al., 2015; Mrlina et al., 2019). Interestingly, the two maars have similar gravity responses but strikingly different magnetic responses. This disparity in magnetic signature is the topic of ongoing research to understand both the cause of the difference and the implications for eruptive history. Recently an additional concealed vent has been identified ~3km to the West of the twin maars across the German border.

Studying volcanism of other planetary bodies provides a window into planetary evolution which can then provide information on past processes that shaped the modern Earth, or a perspective into the future evolution of the planet. On Mars, the identification of supposed scoria cones (kilometre-sized volcanoes formed by an accumulation of volcanic rocks), had previously not considered the lower gravity and atmospheric pressures would alter the formation processes. As shown by Brož et al. (2015) applying a numerical modelling study, on Earth scoria cones largely grow by gravity driven surface flows (rock avalanches) of material from near the vent location, whereas on Mars the lower gravity and atmospheric pressure allows for growth of these systems primarily by ballistic distribution of the ejected volcanic debris. The alternate ballistic formation model has subsequently been applied to similar geomorphic landforms on Mercury (Brož et al., 2018). Brož et al. (2017) studied an extensive field of pitted cones within the largest known system of canyons within the Solar system, Valles Marineris on Mars and concluded that morphologies of these features indicate igneous volcanism rather than mud volcanism. Spectral data revealed an opaline-silica unit indicative of hydrothermal processes. Dating by chronology model ages reveals relatively young Amazonian ages. These findings suggest that the late-stage evolution of Valles Marineris was associated with volcanism.

On the other hand, the volcanic landscape of the Chryse Planitia region of Mars is inferred to result from sedimentary (mud) rather than igneous volcanism, based on work by Brož et al. (2019). As water is unstable under the assumed Martian atmospheric conditions the mechanism of flow is enigmatic. In 2019, analogue experiments in a low-pressure chamber at the Open University in Milton Keynes, UK, were conducted by an international team led by P. Brož to investigate how these mud flows are able to propagate. As published in Nature Geoscience in 2020, the water-dominated mud used in the experiments was found to form an icy-muddy crust (given the lower atmospheric temperatures expected) allowing the mud flows to propagate in a similar fashion to pahoehoe lava flows (Brož et al., 2020). Thus, it is essential to consider the different environmental conditions when interpreting the processes responsible for production of similar landforms on different planetary bodies.

*Structure and deformation analysis of ancient orogens*

Orogens – regional to continental- scale mountain ranges – reflect mainly consolidation of continents during convergence and collision of tectonic plates, which are associated with rock metamorphosis, melting and transfer of heat and mass in the lithosphere. For instance, the geological structure of Central Europe, exemplified by the Bohemian Massif, reflects the history of a large Palaeozoic orogen, frequently compared to the recent Himalayan mountain range. Both recently active mountain belts and ancient orogens forming a large part of continental lithosphere are important targets for study using field structural mapping combined with petrological, geochronological and geophysical methods, and aided by analogue and numerical modelling techniques. Analysis of ancient orogenic processes is one of main themes of the Tectonic Modelling group (Prokop Závada, Zuzana Kratinová, Matěj Machek, Vladimír Kusbach, Martin Staněk, Petr Brož, Ondřej Krýza, Michael Warsitzka, Sadegh Adineh and associated technician Jiří Semerád). This group carries out most of the research in the Institute's analogue modelling lab.

Soejono et al., (2017, 2020) demonstrated that the basement rocks of the Bohemian Massif record widespread granite magmatism related to extension and rifting in Proterozoic to Early Paleozoic. Physical properties and geochemical evidence for the relamination of the crust in Bohemian massif was studied for example in the aureoles of mantle peridotites surrounded by granulites (Kusbach et al., 2015). Another study revealed that melt flux in the subducted continental crust is focused along shear zones parallel to the subduction-related deformation fabric (Závada et al., 2018). As the melt percolates along the shear zones, the melt weakening promotes decoupling from the underlying slab, folding and exhumation of the partially molten rocks to lower crustal levels. Exhumation is again enhanced by melt weakening, because melt redistributes along the fold planes and fold axial cleavage (Závada et al., 2017). Krýza et al. (2019) addressed the dynamics of folding on a crustal scale and the role of melt in development of associated metamorphic core complexes, using a series of shortening experiments with originally horizontal layers of heated paraffin wax superposed by sand. These models required a novel approach of strain quantification from a series of images using post-processing subroutines, where the local material fluxes were traced using a set of strain-based parameters (e.g. volumetric component of the strain tensor).

***<u>Micro-scale rock fabrics: clues to deformation history and physical properties or rock materials</u>***

Rock microstructures usually represent a complex combination of distinct features (or subfabrics) of diverse origins, orientations and strengths. Using a broad range of methods, our researchers focus on correlating the natural (micro)structural record in the rock with its manifestation in physical fields, and on connecting these observations with other rock properties. In particular, their research focuses on application and development of tech-niques for evaluation of magnetic fabrics –the anisotropy of magnetic susceptibility (AMS), which is generated by alignment of magnetic minerals in rocks. This field provides opportunities for collaboration with the Institute's specialists in geomagnetism. Another research area is related to quantification of porosity parameters, which is fundamental for calculations of the permeability of rocks and evaluation of their storage capacity, both of importance for evaluation of rock suitability for energy production from deep geothermal wells, for oil and gas industry or for safety of deep repositories of spent nuclear fuel (see below in Applied Research).

Závada et al. (2015) explained the role of solid second phases on the long-term mechanical properties of rock salt. Particles of solid second phases represent mostly the disaggregated siliciclastic interlayers of the original layered evaporite sequence. These particles render the rock salt weaker than pure salt, because dissolution rates of halite is much larger on grain boundaries of halite and silicate minerals in contrast to boundaries between halite grains.

Using analogue modelling coupled with analysis of AMS, Kusbach et al. (2019, Scientific Reports) brought new insights into the time and space relationships between finite strain microstructure and AMS fabric by providing new comparative data from field examples of shear zones and associated analogue models.

***Sedimentary basins as archives of tectonic and climatic processes***

Infills of sedimentary basins reflect the interplay of lithosphere dynamics responsible for basin formation with processes on the Earth's surface that control the weathering, transport and sedimentation which ultimately fill the basins. Basin analysis is a typically multi-disciplinary field combining geophysical and geological approaches, with outcomes for structural evolution of the lithosphere as well as hydrogeology, thermal regime, and natural resources. To basic research, sedimentary strata in basins provide unique information on changes in climate and oceanographic conditions in the deep geological past, which inform efforts in climate and Earth System modelling. For instance, study of time-series derived from geophysical wireline logs combined with geochemical data, including carbon isotopes, provide new insights into the astronomically driven climate variations in ancient greenhouse climatic regimes and related dynamics of the global carbon cycle. In the Sedimentary Basins group, multi-disciplinary studies of past climatic and oceanographic changes have been an integral part of the Institute's research during the past two decades; David Uličný, Jiří Laurin and Lenka Špičáková have focused mainly on records of palaeoenvironmental changes in greenhouse climates, in extensive interdisciplinary collaboration with a number of Czech and international colleagues. Michael Warsitzka, arrived in 2018 and has further developed his previous research focused on salt tectonics in sedimentary basins. He is involved mainly in structural modelling as member of Tectonic modelling group.

Research on sea-level changes, paleoclimate dynamics, and global carbon cycle of the mid-Cretaceous thermal maximum has received much attention in our research and in 2015 several papers were published from the multi-disciplinary project utilizing the core Bch-1 drilled in the previous period. Laurin et al. (2015) interpreted long-term modulation of obliquity of the Earth's axis as a significan control on the greenhouse carbon budget. Data and numerical models presented in this paper represent one of pioneering efforts to unravel the temporal structure of carbon-isotope anomalies during the peak greenhouse climate (c. 80-100 million years ago), and present robust numerical arguments for the astronomical origin of carbon-cycle perturbations. The article was selected as one of the journal's top cited papers published in the 2015-2016 timeframe. Other outcomes from this project include Olde et al., 2015a,b, and Jarvis et al. (2015).

Another line of research, led by J. Laurin in collaboration with a number of colleagues worldwide, focused on phasing of astronomical signals in sedimentary datasets. Building on extensive analysis of datasets containing evidence of astronomically-driven climate changes, Laurin et al. (2016) presented a new method to identify astronomical cycles based on phase relationships in the signal provided by sedimentary time-series. They found that interference patterns accompanying frequency modulation (FM) of short eccentricity provide a robust basis for identifying the phase of long eccentricity forcing in stratigraphic data. Apart from paleoclimatic implications, the FM approach provides a quantitative technique for testing and calibrating theoretical astronomical solutions, and for refining chronologies for the deep geological past. The authors demonstrated the concept on records of the Cretaceous and Eocene greenhouse climate regimes. A further development in this line of research, by Laurin et al. (2017), focused on identifying phase distortion in time-series data as a specific signature of the global carbon cycle reacting to orbitally-driven disturbances.

The mid-Cretaceous Turonian stage is widely recognized as one of key intervals in the Phanerozoic for understanding links between sea-level change, greenhouse climate, oceanographic conditions, and the carbon cycle; a 3-year project led by D. Uličný focused on comparing sedimentary archives, within sequence-stratigraphic framework, from Central Europe (the Bohemian Cretaceous Basin) and North America (foreland basins of the Western Interior Seaway). The project involved collaboration with B. Sageman and M. Jones, Northwestern Univ., Evanston, Illinois. With the project finalized in 2019, one of the first outcomes in the paper by Laurin et al. (2019) that links marine and terrestrial processes during the global Cretaceous climate event OAE2 (~95 million years ago). It is the first paper to document a causal link of orbitally paced insolation to perturbations in the carbon cycle, changes in the atmospheric carbon dioxide, and fluctuations in sea level during this major climate event.

In the field of salt tectonics in sedimentary basins, Warsitzka et al. (2019) published a review-type paper on the evolutionary history of the salt diapirs in the Central European Basin System is presented in geological overview maps. The timing of the initiation and of the main phase of growth of each salt structure is determined and related to phases of tectonic activity. This paper is a significant contribution for understanding the basin history and can be regarded as guideline for future research dealing with salt tectonics in this basin system.

***Geothermics***

The group of Geothermics was established as a formal department of the IG in the 1960s; it started the geothermal research in Czechoslovakia at that time, and brought this branch of geophysics in our country to the top European level. The original focus on the terrestrial heat flow determinations and predictions of crustal temperatures in service for geosciences has broadened since that time to include, for instance, topics such as reconstructions of the ground surface temperature history from the temperature logs of deep boreholes, the air-ground-bedrock temperature coupling, numerical simulations of permafrost and gas hydrates dynamics, and of the applied research like utilization of geothermal energy. The researczh staff of the group currently includeds J. Šafanda (head), P. Dědeček, T. Uxa, and V. Čermák (emeritus).

Reconstructions of ground surface palaeotemperature from deep boreholes are presented in papers by J. Šafanda and V. Čermák and colleagues. A signal of postglacial warming was extracted from a 2.36 km deep borehole in Alberta, Canada, by Majorowicz and Šafanda (2015). Expanding on this work, Majorowicz and Šafanda (2018) analysed temperature logs from 94 boreholes across central Canada, showing spatially heterogeneous trends that range from 3°C of warming to 1°C of cooling over the past two to three centuries. Šafanda (2018) addressed the thermal overprinting effect of the last glacial cycle when reconstructing palaeotemperature over the last millennium. In an important rectification, the paper demonstrates that the previous method of Beltrami et al. (Geophys. Res. Lett., 44, 355–364, 2017) leads to erroneous results.

Ongoing work is aimed at better understanding the interdependence of temperature measured in the air, on different ground surfaces, and in bedrock. Čermák et al. (2017) reported the results of a decade of monitoring four surface types on the premises of the Institute of Geophysics, Prague. Building on this, Čermák & Bodri (2018) incorporated rainfall records using the 'Granger causality test' and the results highlight the importance of timescale in the analysis. The significance of changes in substrate diffusivity over time was addressed by Majorowicz et al. (2015) who examine the influence on the surrounding permafrost of thermokarst lakes formed in northern Canada at 10–6 ka. Numerical modelling indicates that talik formation (i.e., melted permafrost in its entire thickness) is a function of average annual basal temperature and rock type, with complete melting restricted to clay-rich rocks with < 40% porosity.

Papers by T. Uxa and colleagues deal with periglacial forms generated by freeze-thaw processes in non-glaciated alpine and polar environments. Uxa & Mida (2017) linked the spatial distribution of periglacial forms studied in Czech and Slovak localities to cooler conditions, including the former more extensive presence of permafrost. Today, patterned ground exhibits marginal activity associated with seasonal freezing and, according to Uxa et al. (2019), the persistence of permafrost in the Sudetes Mts is highly improbable.

Uxa et al. (2017) examined the relationship of sorted circles and polygons to altitude in northern Billefjorden, central Svalbard, finding smaller diameters and shallower sorting depths due to a thinner active layer at higher elevations, reflecting temperature. Given that thermal regime and the thickness of the active layer respond rapidly to climate variations, they are important measures of cryosphere change in polar environments. Interestingly, a decade (2006–2016) of monitoring at James Ross Island, Antarctic Peninsula, by Hrbáček & Uxa (2020) reveal no statistically significant change in air and ground temperature over the monitoring period. Following up, Uxa et al. (2020) propose a new modeling approach to derive palaeo-temperature from thaw depth in past permafrost regions.

***Applied research***

The Geothermics group has been involved in the research infrastructure RINGEN (Research INfrastructure for Geothermal ENergy), focused on the research of geothermal energy utilization. The infrastructure involves 2 km deep experimental borehole in the city of Litoměřice with a monitoring network that includes both ground seismometers and dilatometres, underground stations at the depth of 200 to 1500 m and a temperature monitoring down to 1600 m by an optical cable (distributed temperature sensing system) technique. Research describing the geothermal potential of the Litoměřice site and surroundings, in relation to regional geological situation at the edge of the Eger Graben was published by Šafanda et al. (2020, Geothermics).

A significant part of activities of the Gravity and Geodesy group (1FTE researcher, J. Mrlina, 0.4 FTE M. Seidl, and technical staff) is related to observations of ground motion, including Earth tides, and assessment of potential slope instability. Contract-based monitoring of slopes of the Krušné Hory Mts. One of three tiltmeter observatories is devoted to contract-based monitoring of slopes of the Krušné Hory Mts. above an open-cast coal mine. The results show correlation with landslide activity with certain precursory potential. In addition to reports for the customer, the findings were published by Mrlina et al. (2016).

Important opportunity for practical applications is provided by research on porosity characteristics. Studying the geometry of the rock void space and its relation to the rock physical properties, Staněk and Géraud (2019) focused on granite microporosity changes due to fracturing and alteration. Using mercury intrusion porosimetry, polarized and fluorescent light microscopy and microprobe chemical analyses of granite samples, they developed a simple practical approach to estimation of the relation between granite structure, as potentially assessed from visual examination, and its physical properties including porosity and permeability. Hence, it has potential of direct application in currently demanded projects of geothermal heat production or deep repositories of radioactive waste.

In 2016, the Sedimentary Basins group finalized its involvement in a project by the Czech Geological Survey "Reassessment of groundwater reserves in the Czech Republic", which has since resulted in co-authorships of structural cross-sections of the Bohemian Cretaceous Basin, in a series of regional monographs covering individual hydrogeological regions (book series "Rebilance zásob podzemních vod", in Czech, published since 2019 by the Czech Geological Survey).

## Research activity and characterisation of the main scientific results

### ***Rock and environmental magnetism***

In this field of research, our experienced team members (E. Petrovsky, A. Kapicka, H. Grison, J. Kadlec) and a young soil expert S. Stejskalova published several novel results in the period concerned. Their research has been often carried out in cooperation with other teams from abroad (e.g., USA, India, Bulgaria, Greece, Poland).

Kadlec (2015) led large team of co-authors who addressed geological record of Pleistocene to Holocene climate change in fluvial, aeolian, and lacustrine sediments. J. Kadlec also contributed to number of other papers (Jamrichova et al., 2017; Kletetschka et al., 2018) in highly ranking journals, as well as two chapters, dealing with historical landscape development, in a book entitled *Landscapes and Landforms of the Czech Republic*, published by Springer.

Three papers by Grison et al. (2015, 2016, 2017) reported on magnetic and geochemical properties of Andosols in relation to pedogenesis factors. These were the first comprehensive reports on magnetic properties of Andosols, unique soils rich in iron oxides.

Petrovsky et al. (2018) reported on novel application of magnetic measurements of soils, namely magnetic mapping of the spatial extent and vertical migration of wood ash used as soil fertilizer in forest plantation.

The following are papers that resulted from domestic and international cooperations of this group. Paper by Szuszkiewicz et al. (2015) presents complex magnetic characterization of atmospheric dust rich in iron oxides with the aim to distinguish dust from a wide range of sources of air pollution (power industry, cement, coke, ceramic industries and biomass combustion). The paper is published in top journal dealing with applied geophysics and has high citation rate (25 in total). Paper by Aidona et al. (2016) delt with combined magnetic and geochemical analyses of soils with the aim to discriminate between different sources of magnetic enhancement. Paper by Jordanova et al. (2017) explored the potential of magnetic methods in assessing the soil restoration in the vicinity of a metallurgical plant. Floodplain sediments were investigated using magnetic and geochemical methods with the aim to determine the background values in a cooperative paper by Famera et al. (2018). Another process of great importance for soil scientists, soil degradation, was addressed by Jaksik et al. (2015, 2016). In these studies, magnetic susceptibility of soil was used as auxiliary parameter reflecting soil degradation.

### ***Geodynamo modelling (and related Earth's core processes)***

Research of this group focused mainly on rotating convection in spherical stratified shells. In addition, the group started new research, focusing on phase-change problems by numerical and laboratory analogue modelling of solidification of binary mixtures. This research is motivated by challenges associated with the dynamics of the solidifying systems found in geophysics and geology, in particular the growth of the inner/outer core boundary and the solidification of magma chambers, and is performed in cooperation with colleagues from Slovakia.

In the paper by Simkanin et al. (2018), thermochemical convection and hydromagnetic dynamos in a spherical shell using the so-called codensity formulation with different buoyancy sources was investigated: the secular cooling from the mantle, the buoyancy sources due to the solidification at the inner core boundary and a combination of these. The main finding of the study was that for Prandtl numbers lower than Ekman numbers, inertial convection was preferred and the character of the convection and of the generated magnetic fields were independent of the type of the buoyancy source.

Solidification of a binary melt lying on a cooled, moving substrate was investigated in a series of papers by Kyselica and Guba (2016), Kyselica and Simkanin (2018) and Kyselica et al. (2018). The solutions of mathematical models described the effects of a flow, forced by the moving substrate, on the growth of a partially solidified region, entrapped between the solid and liquid phases. This is completely new field of research, which is of interest to geophysicists and physicists.

***<u>Space weather and relation between geomagnetic activity and climate</u>***

Our team members J. Bochnicek and P. Hejda belong to internationally recognized experts in the field of studies of space weather, its geoeffectiveness, forecasting and solar forcing of the atmosphere. They are completed by a young PhD student H. Hanzlikova (Davidkovova). This research is in many cases carried out in close cooperation with colleagues from Slovakia. Unfortunately, V. Bucha retired and J. Bochnicek passed away and this research field is at present declining. However, H. Hanzlikova, with her experience in analysing and processing large datasets, has potential to carry on and establish herself as recognized expert.

The paper by Bochnicek et al. (2019) investigates the effect of strong geomagnetic disturbances on the lower atmosphere geopotential heights changes over the winter North Atlantic on the day-to-date time scale, represented by the daily index of North Atlantic Oscillation (NAO), during the second half of 20th century. The daily NAO average values in 3-days intervals before and after the disturbances onset are compared. The NAO response to geomagnetic disturbances shows a change in its behaviour around the year 1970, having reached its highest values between 1951 and 1969. The graphs of NAO differences are completed by maps of geopotential height differences.

Long-term relationship between geomagnetic activity and NAO is the subject of paper by Bucha (2019). The main results can be summed up as follows: Geomagnetic signal affects variability of the stratospheric polar vortex. Intensity and position of polar vortex influences sign of NAO and invasions of arctic air. Geomagnetic storms accelerate downward penetration of pressure anomalies. Positive NAO index prevails at times of long-term enhanced geomagnetic activity.

The recent terrestrial and satellite observations provide a rich data pool for the space weather studies. However, this time series are available only for several last decades. It is therefore interesting to employ historical data. The paper by Valach et al. (2019) analyses two intense magnetic storms recorded by observatory Prague-Clementinum in 1848 and Greenwich in 1872. The latter has been marked as an extraordinary event by several author, data for the former were acquired by our research team from printed yearbooks. Both these events possessed swift and extensive variation of the horizontal component of the geomagnetic field and were accompanied by auroras sighted at very low magnetic latitudes. They exemplify phenomena that are common in high magnetic latitudes, but which may occasionally happen also at mid-latitudes.

***Magnetotelluric and geoelectric studies***

Our team members J. Pek and V. Cerv are recognized leaders in the international magnetotelluric community, focusing on inversion methods and modelling. Their approaches and inverse-modelling code are widely used by the magnetotelluric community. However, they have both recently retired (at the end of 2019). On the other hand, young researcher R. Klanica defended his PhD thesis and upgraded to post-doc stage. Moreover, the group was significantly bolstered by arrival of Graham Hill from New Zealand, a top expert in magnetotelluric studies in polar and volcanic regions. Hill was awarded the prestigious Lumina Quaeruntur fellowship of the Czech Academy, shortly after arrival. He is PI joint with Maxim Smirnov (Lulea University, Sweden) and Jochen Kamm (GTK, Finland)of the D-Rex project focused on magnetotelluric investigation of mineral resources, funded (2020-2023) by ERC through ERA-MIN 2 program. This dynamic group will continue to attract PhD students and post-docs, mostly from abroad.

During the period in concern (2015-2019), several papers were published by these group members, most of them being result of international cooperations with colleagues from Slovakia, Germany, Ukraine and Bulgaria.

The work by Cerv et al. (2018) is a methodical paper analysing various strategies in the inverse thin-sheet method for modelling electrical conductivity in the Earth, based on the stochastic Monte Carlo Markov Chain simulation. The paper focuses on different sampling techniques and analyses their convergence. The method serves as a useful tool for modelling large areas hosting quasi-3D conductivity structures using long-period electromagnetic induction data from large-scale deep sounding arrays. The results are presented on a case study from the transition zone between the Bohemian Massif and the West Carpathians. The presented electrical conductivity model fits well the recorded geomagnetic induction data features and provides a reliable geological interpretation of the studied area.

Paper by Munoz et al. (2018) present results from regional magnetotelluric profile across seismically active zone in Western Bohemia. Profile is crossing Eger rift – the only known intra continental area in Europe, where an active lithospheric processes can be observed. Acquired data show local geological structures, but most striking discovered feature is deep reaching conductive channel extending from the surface into the lower crust, which can be spatially correlated with hypocentres of local seismic events.

In the paper by Klanica et al. (2018) results from regional magnetotelluric profile dealing with the eastern margin of Bohemian Massif are presented. Acquired data show deep structure of European significant border between the large-scale geological units the Bohemian Massif and Western Carpathians. The results agree with near-surface geology units and significantly extend our knowledge of the deep structures, especially regarding the Brunovistulian basement in the area.

Paper by Majcin et al. (2018) uses results from both existing and newly acquired magnetotelluric profile data in Northern Slovakia passing through the Outer Carpathian Flysch Belt, Klippen Belt and the Inner Western Carpathians Paleogene. The magnetotelluric data interpretation verified hypothesis about inclination of Flysh belt structures and shows more about thicknesses of local geology structures and their tectonic relations.

The contribution by Kovacikova et al. (2019) focused on the electrical conductivity distribution beneath the Ukrainian Eastern Carpathians and the link of electrically anomalous features to the tectonic structure of the region. The paper joins the results of 2D inverse modelling along a dense network of profiles and quasi-3D inversion based on a thin-sheet approach. In the Ukrainian territory, the main feature of the region, the Carpathian conductivity anomaly, is laterally widening and reaching the Outer Carpathians front. This may be related to processes at the intersection of the Carpathian Arc with transversal faults due to recent tectonic activation as well as to the effect of the approaching Trans-European Suture superimposed by the Eastern Carpathians. The relation of the position of the conductors to the heat flow models and to location of the earthquakes sources indicates possible geological mechanisms, such as saline pore fluids, thin films of grain boundary graphite, or partial melting, connected with recent activation zones.

In a paper by Srebrov et al. (2018) electrical conductivity distribution within the earth's crust in Bulgaria was investigated. The presented geoelectric models reveal anomalous zones delineating prominent tectonic boundaries in the Bulgarian territory, fault zones and thrust belts separating individual units of the Balcanides, as well as ancient deep-seated lineaments intersecting the territory. Geoelectric anomalies are most likely associated with highly mineralized fluids migrating along fault zones and more generally indicate active tectonic processes in the region, manifested by hydrothermal activity, seismic events and strike slip along the faults and controlled by continuing subduction in the Eastern Mediterranean, back-arc extension, relative motions of individual blocks of the system and melting in depth.

Review paper by Hill (2019) focused on the use of geophysical electromagnetic methods in polar regions. The main focus of the paper is identifying the unique challenges of working in polar environs and describing approaches to overcome these unique problems that arise. That is: non-plane-wave source fields, high contact resistance, and unique local noise sources (e.g. blizstatic). Case studies presented illustrate the breadth of fundamental outstanding solid-earth problems that can be addressed in the polar regions with global applicability

***<u>Geomagnetic field observations and analyses</u>***

The group consists of senior research worker P. Hejda engaged in general problems of geomagnetic data analysis, and experts M. Vlk and T. Bayer, who are working at the observatory, take care of the observatory service and data processing and prepare daily forecasts of geomagnetic activity which is sent to Czech TV. Budkov Geomagnetic Observatory is included in the global INTERMAGNET Network of digital geomagnetic observatories that meet high standards of data quality and deliver the data in nearly real-time to Geomagnetic Information Nodes. The observatory in agreement with the recommendations of INTERMAGNET produces one-second data, which are automatically transmitted to the INTERMAGNET web service every 10 minutes. The observatory team takes also an active part in the European initiative MagNetE and carries out bi-annual repeat station measurements. A close cooperation on development and testing of magnetic observatory instruments was established with the Department of Measurements, Faculty of Electrical Engineering, Czech Technical University.

The paper by Janosek et al. (2016) reports on the development of a low-noise, high stability observatory magnetometer with race-track sensors. As opposed to the standard instruments, novel race-track fluxgate sensors with planar oval core cut by state-of-the art picosecond UV-laser was used. The paper by Janosek et al. (2018) deals with the problem of improving the performance of variometer stations lacking temperature stabilization. It is shown that a carefully designed full-field instruments can provide vectorial and scalar data accurate to a few nT, if the raw data were postprocessed by compensating for gain temperature coefficient obtained by a precise calibration and long-term scalar measurements.

Specific methodology of data processing and determination of the Overhauser magnetometer uncertainty is described in paper by Ulvr et al. (2015). This activity was initiated by the Czech Metrology Institute. Interactive computer method (IM) for producing K indices of geomagnetic activity is a compromise between traditional hand-scaling method used since 1932 and computer methods introduced in 1990’s. The IM make use of computer data processing, however, the final selection of solar quiet curve is in hands of the operator. Tests of IM carried out on data of Budkov and Hurbanovo observatories indicated that for K>5 the tested method follows the traditional hand-scaling method better than the widely used computer methods FMI and AS (Valach et al., 2019).

P. Hejda participated in the ad-hoc international team established for compilation of the HISTMAG database that combines historical, archaeomagnetic and volcanic data (Arneitz et al., 2017).

Research results of this group are of importance to the geomagnetic observatory community due to their technical and methodological novelty and originality.

Most of the above papers were published in top-ranking peer-reviewed journals focusing on geophysics, tectonophysics, soil and environmental sciences, or applied physics. Despite their short lifetime many of them are highly cited, with more than 20 citations to date and a rate up to 5 citations per year.