# Characteristics of main research directions investigated at the institute and the achievements 2010−2014

| Institute | Institute of Geophysical of the CAS, v. v. i. |
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The Institute of Geophysics of the Czech Academy of Sciences conducts fundamental research in physics of the solid Earth and its immediate space environment, with the mission to increase the level of general scientific knowledge as well as to contribute to practical application of the results of scientific research. The period 2010-2014 which is subject of the present evaluation can be characterized by increased international cooperation, including observational activities abroad.
The research is organized in four departments that are identical with the scientific teams in the present evaluation.

**Department of Geomagnetism** takes up the long tradition of geomagnetic observations and research in the Czech Republic. According to the recommendation given by the Evaluation Committee in 2010, the Geoelectric Department was incorporated into the Department of Geomagnetism. Observations of geomagnetic field and its secular variation belong to permanent activities of the department. Space weather studies were partly devoted to the forecast of geomagnetic activity – with direct input into the daily forecast sent to Czech TV, partly in studies of the impact of solar/geomagnetic activity on weather and climate. Characteristics of the crustal conductivity obtained by magneto-telluric studies were used for complex studies of geological structure. Modelling of the dynamics of the Earth core and geodynamo studied the structure of the convection in dependence on various physical parameters. The quickest developing discipline is the environmental magnetism. The main results include papers dealing with magnetic examination of soil, atmosphere and snow pollution, and modelling the transport of atmospherically deposited particles in soils.

**Department of Geothermics** was established in the 60s, 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 has broadened since that time to several other topics, relevant for the study of climate change or exploitation of geothermal energy. Currently, the main attention is paid to the reconstruction of the long-term ground surface temperature changes from the present-day temperature-depth profiles in deep boreholes. In this field, the team participated in the method development, contributed to its acceptance by climatologists and studies related topics like the air-ground-bedrock coupling and mechanism of the heat transfer in this border interval.

**Department of Tectonics and Geodynamics** was established in 2004 and has grown as a group of researchers with a broad geoscience background, involved in studies of the principal geodynamic processes within the solid Earth and on its surface, their modelling, and in comparisons to dynamics of other planetary bodies. The staff members are geophysicists and geologists who typically employ multi-disciplinary approaches, from field work and laboratory analysis through numerical and analogue modelling to analysis of global geophysical data. The multi-disciplinarity is a defining feature of the department which has been successful in attracting prospective graduates interested in opening new directions of research (among department members are two awardees of the ASCR Otto Wichterle Award and one of the L´Oréal Award For Women in Science). Currently, the researchers of the department

concentrate on several topics that combine high scientific and societal relevance, in particular a number of aspects of volcanic and magmatic processes on Earth and Mars, sedimentary archives of past climate changes and modelling of greenhouse carbon cycle. Research of various aspects of rock physical properties, deformation and microstructure finds use in a broad range of tasks, from studies of dynamics of continental collision processes to applied research relevant to radioactive waste storage or hydrocarbon industry. Tilt and gravity / microgravity measurements bring results relevant to geological hazard monitoring and mitigation, civil engineering, or archaeology. All researchers of the department combine their scientific efforts with rich educational and outreach activities.

**Department of Seismology** is one of the traditional sections of the Institute, continuing the legacy of the State Institute of Geophysics founded in 1920, on the personnel line the founders of seismological research in Czech countries Professors V. Láska and A. Zátopek. Later on, in 60ties and following decades, among the staff there was V. Kárník, a world renowned seismologist and co-author of the MSK macroseismic scale. Nowadays, the Department of Seismology is a team of scientists working on several topics within seismology itself and on its frontiers with geology (investigation of the crust and continental lithosphere), physics and chemistry (geodynamical processes in West Bohemia), and mathematics (theory of seismic wave propagation and modeling of the fracturing). From a different point of view, the team deals both with fundamental science and applied research: the theorists and modellers within the Department provide useful tools for applied seismology (algorithms and computer codes for seismic prospect, methods for seismic assessment of extent and permeability of oil, gas and geothermal reservoirs). Researchers of the Department are active also in education, mostly by supervising PhD students here and abroad as well, and in outreach, especially on the occasion of occurrence of large earthquakes in the world and during increased seismic activity in West Bohemia.

The research activities of the Institute can be grouped into following main directions (with a lot of overlaps):

### Structure of the lithosphere and interactions with the upper mantle

Department of Seismology has been contributing to the theme by developing a new method for mapping thickness of European lithosphere and for studying its fabric (e.g. Vecsey et al., 2014), enabling to infer development of the continental lithosphere in the past and its relation to the sub-lithospheric upper mantle. The advanced model of the LAB (e.g. Plomerová and Babuška, 2010) is step-by step refined by incorporating new data allowing us to create homogeneous and integral view on the first-order discontinuity in the Earth mantle from the point of view of plate tectonics. 3D self-consistent models of anisotropic structure with inclined symmetry axes delimit individual, often sharply bounded, domains (e.g. Babuška and Plomerová, 2013), which led to weakening the idea of a simple Earth cooling, even prior the modern plate tectonics, as we know it nowadays, started. By developing a new code of anisotropic tomography, at present tested on synthetic data (Munzarová et al., EGU2015-5429), the team enriches family of standard isotropic tomography codes (Karousova et al., 2013) with the new tool of realistic modelling the Earth structure based on data of new generation coming from temporary dense seismic networks.

The team members of Department of Tectonics and Geodynamics constrained the rheological properties of different magmatic rocks or rock salts and their

deformation/emplacement history and dynamics (Kratinová et al., 2010; 2012; Žák, Kratinová et al. 2011; Machek et al., 2014; Závada et al., 2012; 2015). The team pioneers analogue modelling technique using the AMS (anisotropy of magnetic susceptibility) to understand magmatic flow patterns in natural plutons or lavas. Similarly, in rocks recording the crust-mantle mechanical interaction and evolution of the orogenic belts, we described the complex rheological properties of sub-continental mantle during its ascent in a hot collisional orogeny. We identified relamination as process responsible for formation of orogenic core zones in the Bohemian Massif (Kusbach et al., 2012, Kusbach et al., 2015).

The magnetotelluric group cooperated closely with colleagues from Slovakia and provided magnetotelluric model for the study of a complex geological structure of the Alpine nappe system, remnants of older Hercynian units and Neogene block tectonics in Western Slovakia (Bezák et al., 2014). New and more precise identification of the crustal structural elements of the Western Carpathians became possible. Magnetotelluric models were combined with previous seismic and gravimetric results and jointly interpreted in the final integrated geological model. The magnetotelluric models exhibit strong correlation with the geological structures of the crust in this part of the Western Carpathians.

**Earthquake and volcanic processes**

Dominant effort in the topic goes into investigation of focal processes of swarm earthquakes with an emphasis on the seismicity in the geodynamical active zone in West Bohemia/Vogtland. Advanced localization providing tiny details of the active fault surface is performed (Vavryčuk et al. 2013), source processes are investigated from the viewpoints both of the mechanisms (Vavryčuk 2011abc, Horálek & Šílený 2013) and of the source parameters enabling to hypothesize about the scaling laws (Michálek & Fischer 2013). Technical questions of detection of events and automation of the processing are solved (Bachura & Fischer 2014). Interpretation assuming the role of fluids in the seismic regime of the zone is attempted to be evidenced (Fischer et al. 2014, Hainzl et al. 2012). The goal of the effort is to understand the reasons of swarm earthquake energy release contrary the common scheme main shock – aftershocks. Recently, the scope of the swarm seismicity monitoring has been extended to the Reykjannes active area in S. Iceland.

A specific seismicity pattern has been observed beneath submarine portions of several volcanic arcs at convergent plate margins (Banda Arc, Nicobar-Andaman Arc, southern Ryukyu Arc). We have formulated several arguments that allow us to interpret such a seismicity pattern as a magma-driven process: (i) clustering of medium-size earthquakes (M>4) in space and time in shallow earthquake swarms beneath the volcanic arcs; (ii) a gap in earthquake occurrence in the Wadati-Benioff zone of the subducting slab beneath the swarms; (iii) lateral migration of earthquakes during the swarms; (iv) correlation of epicentral zones of the swarms with distinct seamounts and submarine ridges (Špičák et al., 2013a, 2013b).

Integrated methods of structural analysis of rocks and analogue and numerical modelling of cooling of magma revealed that the Devils Tower, famous volcanic mountain in Wyoming, USA, represents remnant of a low extrusive lava dome (coulée of lava) emplaced into the maars of phreatomagmatic volcanoes. Publicity of this work in North America (e.g. Scientific American) confirms that the new hypothesis was positively accepted by broader scientific community (Závada et al. 2011, 2015).

Composition of the recently discovered Mýtina Maar, West Bohemia was determined by detailed gravity, magnetic and resistivity measurements as a part of the multidisciplinary research on recent dynamics of this area of spas, mineral waters and repeated occurrence of fluid-driven earthquake swarms. (Flechsig, Mrlina et al. IJES 2015a, Nickschick, Mrlina et al. IJES 2015b).

Several sites of ancient explosive volcanism represented by scoria cones were recognised on Mars by detailed inspection of high-resolution imagery data, as well as other rare volcanic landforms - the lava domes associated with more evolved or crystal-rich magmas at breached volcanic cones or tuff rings (Brož and Hauber 2012, 2013, Brož et al. 2014, Brož et al. EPSL 2015).

**Theoretical modelling**

In seismology, by theoretical modelling both the topic of seismic wave generation, in a more general viewpoint the fracturing of geological medium, and the topic of seismic wave propagation are treated. The two disciplines proceed independently to much extent, also being dealt by different people. In the former, issues concerning seismic moment tensor as a force-equivalent of the fracturing have been tackled: its ambiguity or uniqueness on a material interface (Vavryčuk 2013), its decomposition (Vavryčuk 2015, doi 10.1007/s10950-014-9463-y), inversion (Vavryčuk & Kim 2014, Kuhn & Vavryčuk 2013, Davi & Vavryčuk 2012, Vavryčuk & Kuhn 2012, Jechumtálová et al. 2014) and resolution (Stierle et al. 2014ab, Šílený et al. 2014). Concerning the latter, traditionally especially ray methodology topics are investigated in detail. In particular, rays in anisotropic media (Červený & Pšenčík 2011, Červený et al. 2012, Pšenčík et al. 2012, Farra & Pšenčík 2013, 2014, Vavryčuk 2012). In addition, inversion of anisotropy constants has been designed (Vavryčuk 2013).

The simulations of thermal state and its dynamics within the Earth crust involve a broad scope of problems like (i) the permafrost and gas hydrate formation and decay under the long-term changes of surface conditions (temperature, ice sheets, sea transgression) (Majorowicz et al.,Climate of the Past, 2012), (ii) the talik (thermokarst lakes in permafrost areas) formation and its effect on the underlying permafrost and methane hydrate (J. Majorowicz, J.Šafanda and K. Osadetz: Gas hydrates stability and the dynamics of taliks in the Mackenzie Delta, Canada. Proceedings of the 7th International Conference on Gas Hydrates (ICGH 2011), Edinburgh, Scotland, United Kingdom, July 17-21, 2011. Paper number 684), (iii) the hypothetic rapid methane hydrate release during Permian (the "clathrate gun" hypothesis) (Majorowicz et al., Earth and Planetary Science Letters, 2014), (iv) the thermal effects of the phonolite magma emplacement into maar-diatreme structures (Závada et al., 2011) or of the lamprophyre dyke intrusion into the host rock salt (Machek et al.,2014).

In the field of numerical modelling of geodynamo, several papers were published dealing with rotating convection in non-uniformly stratified spherical shells in dependence of Prandtl, Ekman and Rayleigh numbers (Šimkanin et al., 2010) and hydromagnetic dynamos at various values of Prandtl and magnetic Prandtl numbers (Šimkanin and Hejda, 2011, 2013).

In the field of magnetotelluric studies, Červ et al. (2010) applied Bayesian stochastic method to the magnetotelluric directional analysis and impedance tensor decomposition, which are basic tools to validate a local/regional composite electrical model of the underlying structure.

## Past and present environmental changes

The Department of Geothermics contributes to the climate research by reconstructions of past long-term ground surface temperature changes from present-day measurements of temperature-depth profiles in boreholes. Čermák et al. (The Polish Climate in the European Context: An Historical Overview, 2010) summarized the results on the climate change research in the Czech Republic based on geothermal data. They discussed different aspects of the borehole climate method including their experimental data on the air-ground-bedrock temperature tracking, dependence of the ground temperature on a type of the surface, effects of the snow cover and the freezing/melting of the soil moisture. A summary of the results on the ground surface temperature history of the last 500 years in Poland based on the borehole temperature logs was published by Šafanda and Majorowicz (The Polish Climate in the European Context: An Historical Overview, 2010). The reconstruction of the last ice age/Holocene transition and the glacial conditions at the Hunt well site in Alberta, Canada were published by Majorowicz and Šafanda (Majorowicz, J., Šafanda, J., 2014. Effect of postglacial warming seen in high precision temperature log deep into the granites in NE Alberta, Int J Earth Sci (Geol Rundsch) doi:10.1007/s00531-014-1075-9, online).

Very active group of rock and environmental magnetism belongs to internationally leading groups in this field of research. The main results in the period concerned include papers dealing with magnetic examination of soil, atmosphere and snow pollution, and modelling the transport of atmospherically deposited particles in soils. The research is often carried out in cooperation with other teams from abroad (e.g., Bulgaria, Poland, Finland). E. Petrovský contributed significantly to first comprehensive report on magnetic properties of snow polluted by traffic (Bucko et al., 2011). Paper by Petrovský et al. (2013) provides first multidisciplinary proof of magnetite present in atmospheric particulate matter collected at sites with different level of air pollution. Grison et al. (2011) reported on detailed magnetic characteristics of strongly magnetic soils developed on non-magnetic rock basement in Bulgaria. Finally, our team members performed or significantly contributed to experimental and numerical modelling of vertical migration of atmospherically deposited magnetic particles in different media similar to soils (Kapička et al., 2011, Kodešová et al., 2011).

In the field of outer Earth environment, Geomagnetism team members are traditionally involved in space weather studies, in particular in assessing its geoeffectivness, forecasting and solar forcing of the atmosphere. We contributed significantly to paper by Valach et al. (2011), dealing with solar energetic particle (SEP) modelling, which gained great interest in the community, specifically in connection with the safety of crews and the protection of technological systems of spacecrafts. Papers by Valach et al. (2014) and Revallo et al. (2014) suggest improved methods of forecasting the geomagnetic activity. The above studies are done in close cooperation with colleagues from Slovakia. Finally, Bochníček et al. (2012) investigated the relationship between high long-lasting solar/geomagnetic activity and geopotential height (GPH) changes in the northern winter (December-March) lower atmosphere of years 1950-2002.

Results of a scientific drilling project in the Bohemian Cretaceous Basin, led by members of the sedimentology group of the Department of Tectonics and Geodynamics between 2010-2014, brought significant progress to the understanding of links between the global carbon cycle, orbitally-driven climate cyclicity, and sea-level change. The data obtained provided a new high-resolution reference section for correlations of mid-Cretaceous chemostratigraphic data between basins in Europe and

other continents (Uličný et al. 2014), as well as a basis for subsequent analysis of astronomical cyclicity in the sedimentary record and numerical modelling of the carbon budget. A new hypothesis of million-year scale variations in the Late Cretaceous greenhouse climate, controlled by amplitude modulation of axial obliquity was presented (Laurin et al. 2014, 2015).

**Applied research**

The Institute has participated on the project “Review of groundwater reserves of the Czech Republic”, led by the Czech Geological Survey, since 2011. The project is part of efforts of the Czech government to attain a sustainable balance between groundwater exploitation and recharge. The main output of our work is a series of cross-sections and contour maps showing, in much greater detail than before, the syn- and post-depositional geometries of principal aquifer and aquiclude units of the basin fill and their structural context.

The Institute has contributed to the government-funded survey of sites suitable for nuclear waste repositories by combined microstructural and petrophysical studies of granites from the Melechov pluton, Czech Republic – a test site for the nuclear waste repository (e.g. Staněk et al. 2013).

The long-term continuous ground tilt observations in the area of open-pit lignite mines in North Bohemia have served monitoring of the stability of the hazardous steep slopes of the mountain range situated just above the mines. The tidal observatory Jezeří of the Institute has been supported by the mining company as a part of the mine safety monitoring system.

Microgravity surveying was successfully applied to confirm the existence of a hidden phonolite body at the base of a coal mine suitable as a resource of construction stone. The method has been approved as a technique suitable for monitoring of gas or CO2 storage/injection/extraction processes.

Several directions of research performed in the Department of Seismology provide valuable outputs immediately applicable (and applied) in industry. The ray theory is a basic tool to tackle the tasks met by applied seismology, like tracing seismic rays in a 3-D medium with discontinuities. Additional troubles are anisotropy and attenuation, both of them investigated from the viewpoint of the theory resulting in design of algorithms suitable for coding (Červený et al. 2012, Pšenčík et al. 2012, Farra & Pšenčík 2013, 2014, Vavryčuk 2010, Vavryčuk 2012). The study of the earthquake mechanism has a potential to be applied for determination of the mode of rupturing of the rock mass, which is the parameter of a prime concern during hydrofracturing of oil, gas and geothermal wells for the assessment of the permeability of the reservoirs. A reliable control of the resolution of the retrieved fault orientation and especially the shear vs. non-shear contents is the goal of the studies of ill-posed inversions taking into account a poor geometry of the monitoring, noisy data, inexact location and a rough velocity/attenuation model (Kuhn & Vavryčuk 2013, Jechumtálová et al. 2014, Šílený et al. 2014).

The Department of Geothermics participates in geothermal energy exploitation studies. Members of the team contributed to the geothermal assessment of the deep aquifers of the northwestern part of the Bohemian Cretaceous basin in the Czech Republic (Jiráková et al., 2011) and to the temperature forecast at the target depth of 5 km of the planned geothermal project in Czechia (J.Šafanda, V.Čermák, P.Dědeček and M.Krešl: Uncertainties of temperature forecast at 5 km based on a 2 km deep pilot

borehole – a case study from the Czech Republic. Abstract ID 2646, IUGG General Assembly 2011, Melbourne).

Enlarged abstracts of most important and interesting results of the Institute were published in the Report 2010 – 2011 and Report 2012 – 2014. They are available at http://ig.cas.cz/en/about-us/annual-reports

# Research Report of the team in the period 2010–2014

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| Institute | Institute of Geophysical of the CAS, v. v. i. |

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| Scientific team | Department of Geomagnetism |

Department of Geomagnetism is one of the traditional departments of the Institute. In 2014, former Department of Geoelectricity joined the Department, thus extending the scope of research carried out by our team. The research is very diverse, from space weather through magnetotelluric studies to environmental rock magnetism. It combines observatory activities (Geomagnetic Observatory Budkov), field work, experimental laboratory measurements, numerical modelling and data analyses. Most of the research is carried out in collaboration with experts from abroad. The team is composed of several highly experienced and internationally recognized experts and completed by younger promising colleagues. The main results of the team can be divided into 5 categories:

## 2.1. Rock and environmental magnetism

In this field of research, our experienced team members (E. Petrovský, A. Kapička, H. Grison) are completed by a young soil expert Š. Stejskalová (Dlouhá), who recently got her PhD degree. The main results in the period concerned include papers dealing with magnetic examination of soil, atmosphere and snow pollution, and modelling the transport of atmospherically deposited particles in soils. The research is often carried out in cooperation with other teams from abroad (e.g., Bulgaria, Poland, Finland).

In the paper by Bucko et al. (2011), we reported on magnetic properties of snow collected along two roads in Finland. The data proved the presence of magnetite produced by traffic, reflecting different traffic intensity. The paper contributes significantly to extension of environmental magnetism to substances other than soils, sediments or tree leaves. This is the first comprehensive published report on magnetic properties of snow polluted by traffic. The paper is result of long-term activities of E. Petrovský in Helsinki, who provided the general design of the study, contributed to data interpretation, and remotely co-supervised PhD student (M. Bucko). The paper is published in top ranking environmental journal and has high citation rate (21 in total).
In the paper by Grison et al. (2011), detailed magnetic characteristics of strongly magnetic soils, developed on non-magnetic rock basement in Bulgaria, is provided. It is usually assumed that high magnetic susceptibility of soils is mostly due to either lithology rich in ferrimagnetic iron oxides, atmospheric deposition of anthropogenic iron oxides, or strong pedogenic production of iron oxides. In this specific case, none of these assumptions is evident and possible mechanisms are discussed. This research was carried out in cooperation with Bulgarian colleague N. Jordanova, who took part in the field trip and sampling and contributed to data interpretation.
Paper by Petrovský et al. (2013) provides first multidisciplinary prove of magnetite present in atmospheric particulate matter collected at sites with different level of air pollution. This finding is important for the interpretation of magnetic properties of atmospheric dust, which may be dominated by the presence of trace amount of

magnetite. The research was carried out in cooperation of 4 Czech institutions, including National Institute of Public Health. Our team members designed the experiment, carried out magnetic measurements and interpreted the data.
Finally, papers by Kapička et al. (2011) and Kodešová et al. (2011) deal with experimental and numerical modelling of vertical migration of atmospherically deposited magnetic particles in different media similar to soils. Results reported in these papers clearly show under certain circumstances distinct maximum in magnetic susceptibility is observed in depth of some few cm. The results are of importance for proper interpretation of magnetic susceptibility values measured on the soil surface and interpreted in terms of atmospherically deposited particles rich in ferrimagnetic iron oxides. Our team members designed the experiment, carried out magnetic measurements and contributed to data processing, interpretation and publishing.

### 2.2. Geodynamo modelling

Our two team members (J. Šimkanin, P. Hejda) were recently joined by a young PostDoc J. Kyselica, who defended his PhD in 2014 in Bratislava, Slovakia. Research of this group focused mainly on rotating convection in spherical stratified shells.

Šimkanin et al. (2010) investigated a rotating convection in non-uniformly stratified spherical shells in dependence of Prandtl, Ekman and Rayleigh numbers. They showed a strong dependence of results on the Prandtl and Ekman numbers but a weak dependence on the density stratification. This study became a motivation for a systematic parameter study of hydromagnetic dynamos at various values of Prandtl and magnetic Prandtl numbers. Šimkanin and Hejda (2011, 2013) analysed hydromagnetic dynamos in dependence on the Ekman and magnetic Prandtl numbers at low Prandtl numbers (in dependence of different coupling of viscous, themal and magnetic diffusive processes). In all the investigated cases, the generated magnetic fields were dipolar and neither transition to hemispherical dynamos nor weaker magnetic fields (which are less dipole dominated) were observed, although the inertia became important. The magnetic field became weak in the polar regions (was ‘‘convected out of polar regions’’) only for low Prandtl numbers and in case of important inertia. However, whether the magnetic field got weak in the polar regions (was ‘‘convected out of polar regions’’), or not, depended also on the magnetic Prandtl number. The magnetic Prandtl number had to exceed a minimum value in order to sustain dynamo action. If the magnetic diffusion is small (large magnetic Prandtl numbers) then this phenomenon does not exist but if it is large (small magnetic Prandtl numbers) it exists because the strong magnetic diffusion significantly weakens the magnetic field inside the tangent cylinder. The magnetic diffusion and inertia seem to act in the same direction as to weaken the magnetic field inside the tangent cylinder. At low Ekman number (small viscosity) the convection is small-scale and columnar, while the magnetic field remains large-scale. Scales of the flow and magnetic field are separated, which enables hydromagnetic dynamos to maintain the magnetic field at low values of the magnetic Prandtl number. At low Ekman number the inertia is negligible and the so-called MAC balance dominates by contrast to the case of high values of the Ekman number, when the so-called VAC balance may be preferred. When the magnetic field did not get weak in the polar regions we observed strong polar magnetic upwellings and weaker equatorial upwellings. Thus, an occurence of polar magnetic upwellings is coupled with a regenaration of magnetic fields inside the tangent cylinder and then with an intensity of magnetic fields in the polar regions.

Paper by Hejda and Reshetnyak (2010) deals with nonlinearity in geodynamo. Using a rotating flat layer heated from below as an example, effects leading to stabilization of an exponentially growing magnetic field in magnetostrophic convection in transition from the kinematic dynamo to the full non-linear dynamo are considered. Estimates of the energy redistribution over the spectrum and helicity quenching by the magnetic field are presented. These regimes are similar to those in planetary dynamo simulations.
In paper by Anufriev and Hejda (2010), Boussinesq approximation in geodynamo modelling is compared with the incompressible approach. The Boussinesq approximation simplifies the mathematics by neglecting the compressibility of the liquid in the Earth's core. However, this approach also neglects adiabatic cooling in the heat transport equation. The latter introduces significant error and makes the Boussinesq approximation nonadequate, especially at the onset of the convection. This paper showed that adiabatic cooling does not vanish in the incompressible limit used by the Boussinesq approximation and a new incompressible approach was proposed, which neglects the direct influence of compressibility, but takes into consideration its indirect cooling effects. There is not only adiabatic cooling, but also Archimedean cooling (heating) connected with Archimedean work. Using the adiabatic cooling as a natural inhomogeneity in the heat equation resulted in the estimation of amplitudes of the superadiabatic temperature, flow velocity, and magnetic field, which are in good agreement with those given by the simulation of Glatzmaier and Roberts (An anelastic evolutionary geodynamo simulation driven by compositional and thermal convection. Physica D, 1996, 97, 81-94). The last two papers represent result of cooperation with top experts from Russia and Bulgaria, respectively. P. Hejda significantly contributed to the design of the numerical experiment, data interpretation and publication.

### 2.3. Space weather

Our team members J. Bochníček 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. Hanzlíková (Davídkovová). This research is in many cases carried out in close cooperation with colleagues from Slovakia.

The paper by Valach et al. (2011) deals with solar energetic particle (SEP) modelling, which gained great interest in the community, specifically in connection with the safety of crews and the protection of technological systems of spacecraft situated outside the effective shielding by the Earth’s magnetic field. Two models for the prediction of SEP events are presented in this paper. The models are based on a linear filter and on a special type of dynamic artificial neural network known as the layer-recurrent neural network. In this work, the following parameters are used as the input: the X-ray flare class for flares originating close to the centre of the solar disk; observed type II or IV radio bursts; and the position angle, width, and linear speed of observed full or partial halo CMEs. The models are designed to provide forecasts of proton fluxes with energies exceeding 10 MeV at the L1 libration point.
The paper by Valach et al. (2014) deals with the relation of the southern orientation of the north-south component Bz of the interplanetary magnetic field to geomagnetic activity (GA). Subsequently, a method is suggested to forecast potentially dangerous high GA. It is shown that on a day with very high GA, hourly averages of Bz with a negative sign occur at least 16 times in typical cases. Since it is very difficult to estimate

the orientation of Bz in the immediate vicinity of the Earth one day or even a few days in advance, a neural-network model of forecasting is suggested, which assumes the worse of the possibilities to forecast the danger of high GA – the dominant southern orientation of the interplanetary magnetic field. The proposed model provides forecasts of potentially dangerous high geomagnetic activity when the interplanetary CME (ICME), the originator of geomagnetic storms, should hit the Earth under the most unfavourable configuration of cosmic magnetic fields.

In the paper by Revallo et al. (2014), model to forecast 1-hour lead Dst index is proposed. The approach is based on artificial neural networks (ANN) combined with an analytical model of the solar wind-magnetosphere interaction. In this study, a more comprehensive model compared to the previously used ones is proposed on the basis of the ANNs. The model is driven by input time histories of the discontinuity in magnetic field (Bt), which are provided by the analytical model. At the output of such revised model, the Dst index is obtained and compared with the real data records. In this way the model weights determined by the neural networks are used. The model was tested with real data from solar cycle 23. The ANN approach provided better results than a simple method based on exponentially decaying weights. Moreover, it is shown that the proposed ANN model could be used to predict Dst 1 h ahead.

The paper by Bochníček et al. (2012) investigated the relationship between high long-lasting solar/geomagnetic activity and geopotential height (GPH) changes in the northern winter (December-March) lower atmosphere of years 1950-2002. The analysis carried out using composite maps showed that the intervals (60-day in this case) distinguished itself by high mean values of solar/geomagnetic activity are associated with the occurrence of significant GPH anomalies. The analysis further showed the change of GPH anomaly values during the winter period and the different character of investigated relationship before and after the year 1970. The comparison of composite maps compiled from intervals with high mean solar activity values with those compiled from intervals with high mean geomagnetic activity values showed that geomagnetic activity affects the atmospheric circulation substantially more, than solar activity does. In the above 4 papers, our team members contributed to the design of the study, data analyses and interpretation and revisions of the manuscripts.

The paper by Saiz et al. (2012) presents the results of wide international cooperation in the frame of the COST Action ES0803 “Developing Space Weather Products and Services in Europe”. P. Hejda was responsible for Section 3 dealing with the response of the terrestrial environment to solar activity. In spite of the great effort made during the last years in a development of physics-based numerical models of processes from Sun to the Earth’s magnetosphere, their prediction ability is still low in comparison with models based on statistical methods. The paper summarizes the results of forecasting schemes that use artificial neural networks. The role of solar parameters, such as X-ray solar flares, Type II and/or Type IV radio emission and solar energetic particles enhancements, are discussed. Regarding the solar wind-magnetosphere-ionosphere interaction topic, the geomagnetic responses at high and low latitudes are considered separately. At low latitudes, new insights into temporal evolution of the ring current are presented in both main and recovery phases of the storm. At high latitudes, the PCC index appears as an achievement in modelling the coupling between the upper atmosphere and the solar wind, with a great potential for forecasting purposes. The scientific results in the framework of the COST Action ES0803 cover the topics from the short-term solar-activity evolution, i.e., space weather, to the long-term evolution of relevant solar/heliospheric/magnetospheric parameters, i.e., space climate. It is shown that on the timescales of 22- and 88-year cycles the trend of solar, heliospheric

and geomagnetic parameters shows the solar origin of the widely discussed increase in geomagnetic activity in the last century.

### 2.4. Magnetotelluric studies

Our team members J. Pek and V. Červ belong to recognized experts in the international magnetotelluric community, focusing on inversion methods and modelling. Their approaches and models are used by many experts in interpreting the magnetotelluric data. A young master student has recently joined the group.

In the paper by Červ et al. (2010), Bayesian stochastic method is applied to the magnetotelluric directional analysis and impedance tensor decomposition, which are basic tools to validate a local/regional composite electrical model of the underlying structure. It is assumed that the experimental impedance estimates are contamined with Gaussian noise and the likelihood of a particular composite model with respect to the observed data is defined. Two numerical methods are applied: the Markov chain Monte Carlo procedure based on the Gibbs sampler, and a single-component adaptive Metropolis algorithm. From the posterior samples, the estimates and uncertainties of the individual decomposition parameters are characterized. It is concluded that the stochastic scheme performs reliably for a variety of models, including the multi-site and multi-frequency case with up to several hundreds of parameters. Though the Monte Carlo samplers are computationally very intensive, the adaptive Metropolis algorithm increases the speed of the simulations for large-scale problems. This study was performed by our team members, with a significant contribution of the French partner to model set-up and interpretation.
A recent paper by Bezák et al. (2014) studied a complex geological structure of the Alpine nappe system, remnants of older Hercynian units and Neogene block tectonics in Western Slovakia using magnetotelluric data. In this way, new and more precise identification of the crustal structural elements of the Western Carpathians became possible. A NW-SE magnetotelluric profile, 150 km long, with 30 broad-band and 3 long-period magnetotelluric sites, was deployed, crossing the major regional tectonic elements. Magnetotelluric models were combined with previous seismic and gravimetric results and jointly interpreted in the final integrated geological model. The magnetotelluric models exhibit strong correlation with the geological structures of the crust in this part of the Western Carpathians. The significant resemblance in geoelectrical and crustal geological structures are highlighted in shallow resistive structures of the covering formations represented by mainly Tertiary sediments and volcanics. Also in the deeper parts of the crust alternating highly resistive and conductive structures are interpreted, which reflect the original building Hercynian crust, with superposition of granitoids or granitised complexes and lower metamorphosed complexes. Another important typical feature in the architecture of the Western Carpathians is the existence of young Neogene steep fault zones manifested by conductive zones throughout the whole crust. The most significant fault zones separate individual blocks of the Western Carpathians and the Western Carpathians itself from the European Platform. Our team member J. Pek joined the team of Slovak colleagues, provided the model and contributed to the data analyses and interpretation.

## 2.5. Geomagnetic field observations and analyses

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 team was empowered by two young colleagues graduated at the Faculty of Electrical Engineering, Czech Technical University. M. Vlk submitted PhD thesis “A novel method of noise reduction in the low-frequency parametric amplifier” in 2014. (The thesis was successfully defended in February 2015). Diploma thesis of P. Kubašta was devoted to the implementation of SW for derivation of quasi-definitive base-lines. The observatory followed-up new demands and recommendations of INTERMAGNET and started production of one-second data. The manual transmission of daily files via e-mail was replaced by an automatic transmission to the INTERMAGNET web service every 10 minutes.

The observatory team takes also an active part in the European initiative on coordination of repeat station measurements MagNetE. Paper by Hejda et al. (2012) describes recent stage of the magnetic surveying activities in the Czech Republic, which started in the fifties by setting up a basic network of the first order. It consists of 199 points. Complete measurements of three components, D, H, and Z, were carried out in 1976-78 and 1994-96. Since 1970 six selected points have been revisited approximately every two years. The repeat station measurements, together with the data from neighbouring observatories, were now used to reduce the data from the last magnetic survey to the epoch 2010.5 and new magnetic charts were drawn. The accuracy of the results and their comparison with IGRF model is also discussed. This research is fully comparable to and consistent with similar studies in European countries.

The oldest geomagnetic observatory data have been recently recognized as an important source of information for Space Weather studies. For example, series of workshop devoted to the long-term reconstruction of solar and solar wind parameters, supported by International Space Science Institute, was organized between 2012 and 2014. As the Observatory at Prague-Klementinum collected uninterrupted series of magnetic observation from 1839 to 1917, we were asked to digitize and process these data. The task was started at the end of 2013 and first outputs will be presented in 2015.

# Research Report of the team in the period 2010–2014

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| Institute | Institute of Geophysical of the CAS, v. v. i. |

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| Scientific team | Department of Geothermics |

Our team is identical with the Department of Geothermics that was established in the 60s, started the geothermal research in Czechoslovakia at that time, and brought this branch of geophysics in our country to the top European level. We have been trying to continue this legacy. The team consists of three senior researchers (Čermák, Krešl, Šafanda), three PhD students (Dědeček, Freyerová, Pechačová) and one technician (Kincler). The original focus on the terrestrial heat flow determinations has broadened since that time to several other topics that are reflected in this overview of our activities in the last five years.

### 2.1. Geothermal research of the impact structure Chicxulub

In the beginning of the evaluated period, Čermák et al. (International Journal of Earth Sciences, 2010) published the last paper of a series of papers analyzing and interpreting temperature data obtained during nearly one decade long geothermal research of the impact structure Chicxulub on the Yucatan Peninsula, Mexico. As part of the International Continental Scientific Drilling Program (ICDP), the 1.5-km-deep borehole Yaxcopoil was drilled from December 2001 through February 2002 within the meteor impact structure. The research included the repeated temperature logging of the hole by the geothermal group of the Institute of Geophysics in Prague and the Geophysical Institute, University of Karlsruhe, Germany. On the Czech side, the research was supported by two consecutive grants of the Czech Science Foundation. The repeated temperature logging of the borehole Yaxcopoil showed temporal temperature changes occurring a long time after the well drilling. They were interpreted as a thermal manifestation of a slow downward flow of a heavy drilling mud within the karstic environment of the borehole. The paper describes, among others, the results of 18-day temperature monitoring that revealed three completely different patterns of the free convection within depth interval of 20 m, below, above and within the head of the mud flow, conditioned by different values of the vertical temperature gradient. Also, two novel methods were employed for detection of stable, but weak tidal components in long noisy temperature records from different depths in the borehole, namely the Recurrence Quantification Interval analysis and the Histograms Cumulation method.

### 2.2. Simulations of permafrost and gas hydrates dynamics

This problem is studied within a long-term cooperation between Canadian colleagues and our department. The studies profited from expertise of J.Majorowicz as one of the leading persons in the geothermal research of permafrost and gas hydrate in Canada and from the software for numerical simulations of thermal behaviour of these formations written by J.Šafanda.

The studies address the problem of permafrost and gas hydrate formation and decay under the long-term changes of surface conditions (temperature, ice sheets, sea

transgression). The methodology is based on numerical solution of the heat conduction equation in a layered medium. The developed numerical code takes into account latent heat effects of the phase changes (interstitial ice/water, gas-water/hydrate), pressure and salinity dependence of the melting points, temperature and phase dependence of thermal conductivity, and represents one of the most universal present tools for simulations of permafrost and gas hydrate dynamics.
Results of simulations of the gas hydrate and permafrost stability in the Beaufort-Mackenzie Basin, Canada, were published by Majorowicz et al. (Climate of the Past, 2012)

The software was also used to simulate effects of talik formation (thermokarst lakes in permafrost areas) on the underlying permafrost and methane hydrate. The preliminary results were presented at the 7th International Conference on Gas Hydrates (J. Majorowicz, J.Šafanda and K. Osadetz: Gas hydrates stability and the dynamics of taliks in the Mackenzie Delta, Canada. Proceedings of the 7th International Conference on Gas Hydrates (ICGH 2011), Edinburgh, Scotland, United Kingdom, July 17-21, 2011. Paper number 684). The full paper was submitted one month ago and is under review.

Another application of the permafrost and gas hydrate stability simulations is described in Majorowicz et al. (Earth and Planetary Science Letters, 2014). Here we explored the hypothetic rapid methane hydrate release during Permian. The "clathrate gun" hypothesis has been invoked as a cause for the rapid global warming and associated negative carbon isotope excursion observed during the Latest Permian Extinction (LPE). We modeled the stability of gas hydrates through a warming Middle to Late Permian world, considering alternative settings for methane reservoirs. Model results show that terrestrial hydrates would rapidly destabilize over similar to 400 ky after deglaciation for moderate heat flow (40 mW/m(2)), and more rapidly for higher heat flow values.

### 2.3. Reconstructions of the ground surface temperature history

Reconstructions of the long-term ground surface temperature changes from present-day measurements of temperature-depth profiles in boreholes were established as one of the independent and physically justified ways to obtain information about the past climate on the scale of hundreds to thousands of years in the 80s and 90s. A doyen of our team, V.Čermák, can be considered as one of the pioneers of the method. We participated in the method development and contributed to its acceptance by climatologists.

Results of the long-term cooperation of our team with D.Rajver from Slovenian Geological Survey in Ljubljana were published by Dědeček et al.(2012). The paper discusses problems encountered in reconstructing the past ground temperature changes from temperature logs of deep boreholes, namely interference of the regional temperature signal connected with a changing climate and the local ground surface temperature signal caused by anthropogenic structures in the immediate vicinity of the borehole. Especially, the paper deals with influence of new buildings whose basements heat the ground and generate a spurious climatic signal in the borehole.

Another paper (Čermák et al., The Polish Climate in the European Context: An Historical Overview, 2010) summarizes the results on the climate change research in the Czech Republic based on geothermal data. Different aspects of the borehole climate method are discussed including our experimental data on the air-ground-bedrock temperature tracking, dependence of the ground temperature on a type of the surface, effects of the snow cover and the freezing/melting of the soil moisture.

A summary of the results on the ground surface temperature history of the last 500 years in Poland based on the borehole temperature logs was published by Šafanda and Majorowicz (The Polish Climate in the European Context: An Historical Overview, 2010). A majority of the logs used in the reconstructions were measured by our team in cooperation with the Polish Geological Institute. The results were compared with the longest homogenised surface air temperature series in Poland observed at the Warsaw meteorological station, where the observations started in 1779.

The reconstruction of the last ice age/Holocene transition and the glacial conditions at the Hunt well site in Alberta, Canada were published by Majorowicz and Šafanda (Majorowicz, J., Šafanda, J., 2014. Effect of postglacial warming seen in high precision temperature log deep into the granites in NE Alberta, Int J Earth Sci (Geol Rundsch) doi:10.1007/s00531-014-1075-9, online). The estimation of the last ice age temperatures from the borehole data represents the ultimate time limit of the geothermal method and requires boreholes deeper than 1.5 – 2 km. The signal of climate warming at the end of the last ice age found in the temperature log of the Hunt well, a 2.36 km deep borehole, provided a magnitude and a time scenario of the warming. Whereas the ground temperature of the coldest period of the last ice age (20 ka ago) reached -2°C to -3°C at the borehole site, its value during the climatic optimum 4-6 ka ago was as high as +8°C to +9°C. The mean temperature of the whole glacial cycle (ice age + interglacial) was estimated at 0°C.

Different aspects of the ground surface temperature history reconstruction in Canada by the borehole climate method were published by Majorowicz et al. (Journal of Geophysics and Engineering, 2012; International Journal of Earth Sciences, 2014). The first paper compares the observed temporal changes of the subsurface temperature obtained by repeated logging of boreholes with the synthetic once based on air temperature series. The second paper quantifies and discusses the possible influence of the changing solar activity on the ground surface temperature variations in the several last centuries.

### 2.4. The air-ground-bedrock temperature coupling

The current core activity of our team concerns the research of the air-ground-bedrock temperature coupling. This problem is related to the method of reconstructing the ground surface temperatures from borehole temperatures. Climatic interpretation of the ground surface temperature histories in terms of the surface air temperature histories is based on the assumption that the ground surface temperature variations track the surface air temperature variations on decadal to centennial and longer time scales. To test the validity of this assumption, experimental studies at site-specific locations are necessary. The observatories monitor air, ground and possibly bedrock temperature time series combined with other meteorological variables that are observed either at the location or at a near-by meteorological station over multiyear time intervals.

Our team has been running such an observatory in Prague-Spořilov since the year 1994. Similar observatories were established within a joint Czech-Slovenian-Portuguese project in Malence, Slovenia (in the year 2003) and Caravelinha near Evora, Portugal (2005).

The results from the observatory in Prague-Spořilov registered within the period 1994 – 2011 were summarized by Čermák et al. (2014). The paper by Dědeček et al. (2013) used the temperature - time series obtained by six year air- and subsurface temperature monitoring in Malence, Slovenia, to study the heat transfer in the uppermost 10 m. It was found that heat is transferred mostly by conduction. Its convective component is much smaller and it is in a quantitative agreement with the thermal effect of the rain water infiltration to the groundwater level.

**2.5. Expertise in experimental and theoretical estimations of the thermal state and processes of the Earth crust in service for geosciences**

Our team possesses a broad range of instruments for the borehole temperature logging and for estimation of thermophysical parameters of rocks and other materials. Beside it, an extended software package for calculations and simulations of thermal state and its dynamics of the Earth crust and rocks is available. It enables us to cooperate with other teams both in basic geothermal research and in the studies, where information on thermal state is required.

For instance, we participated in geothermal research of the Outokumpu deep drill hole in Finland (Kukkonen et al., 2011), where we carried out one of the precise temperature loggings including several hour monitoring at a given depth that provided information on the extent and character of the free convection within the borehole. Our contribution to the paper concerned especially the effect of the intra-hole convection.

Our PhD student P.Dědeček contributed by his expertise to several studies carried out by other teams, both within the Institute of Geophysics and outside it. Namely, he participated in geothermal assessment of the deep aquifers of the northwestern part of the Bohemian Cretaceous basin in the Czech Republic (Jiráková et al., 2011), helped in finding the mechanism of temperature fluctuations underneath the ice in Diamond Lake, Hennepin County, Minnesota (Kletetschka et al., 2013), simulated thermal regime and its dynamics during emplacement of phonolite magma into maar-diatreme structures (Závada et al., 2011) or during intrusion of lamprophyre dyke in the host rock salt (Machek et al.,2014).

# Research Report of the team in the period 2010–2014

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| Institute | Institute of Geophysical of the CAS, v. v. i. |

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| Scientific team | Department of Tectonics and Geodynamics |

**CHARACTERISTICS OF THE RESEARCH TEAM (DEPARTMENT OF TECTONICS AND GEODYNAMICS).** The department was established in 2004 and has grown as a group of researchers with a broad geoscience background, involved in studies of the principal geodynamic processes within the solid Earth and on its surface, their modelling, and comparisons to dynamics of other planetary bodies. The staff are geophysicists and geologists who typically employ multi-disciplinary approaches, from field work and laboratory analysis through numerical and analogue modelling to analysis of global geophysical data. The multi-disciplinarity is a defining feature of the department which has been successful in attracting prospective graduates interested in opening new directions of research (among department members are two awardees of the ASCR Otto Wichterle Award and one of the L´Oréal Award For Women in Science). Currently, the researchers of the department concentrate on several topics that combine high scientific and societal relevance, in particular a number of aspects of volcanic and magmatic processes on Earth and Mars, sedimentary archives of past climate changes and modelling of greenhouse carbon cycle. Research of various aspects of rock physical properties, deformation and microstructure finds use in a broad range of tasks, from studies of dynamics of continental collision processes to applied research relevant to radioactive waste storage or hydrocarbon industry. Tilt and gravity / microgravity measurements bring results relevant to geological hazard monitoring and mitigation, civil engineering, or archaeology. All researchers of the department combine their scientific efforts with rich educational and outreach activities. Scientific results of the Department, mostly in the form of papers in IF journals, have been produced by all department members, including young age categories. Part-time employment of four Department members over the age of 65 has been gradually reduced.

## (1) MAGMATIC / VOLCANIC PROCESSES AND STRUCTURES

**Submarine volcanism at convergent plate margins.** We contributed to better understanding of magma behaviour beneath the Earth's surface and to delimitation of domains of current submarine magma unrest by a detailed analysis of teleseismic earthquake occurrence. Large portions of volcanic arcs at convergent plate margins are submarine, hidden to direct observations. Their volcanic and magmatic activity as well as the eruptive history are thus poorly documented and understood. A specific seismicity pattern has been observed beneath submarine portions of several volcanic arcs at convergent plate margins (Banda Arc, Nicobar-Andaman Arc, southern Ryukyu Arc). We have formulated several arguments that allow us to interpret such a seismicity pattern as a magma-driven process: (i) clustering of medium-size earthquakes ($M>4$) in space and time in shallow earthquake swarms beneath the volcanic arcs; (ii) a gap in earthquake occurrence in the Wadati-Benoff zone of the subducting slab beneath the swarms; (iii) lateral migration of earthquakes during the

swarms; (iv) correlation of epicentral zones of the swarms with distinct seamounts and submarine ridges. Utilisation of teleseismically recorded and rapidly processed data (USGS/NEIC, Global CMT Project) enables to observe magmatic activity in almost real time (Špičák et al. 2013a, 2013b). These contributions were produced exclusively by the staff of the department.

**Intraplate volcanism.** Integrated methods of structural analysis of rocks and analogue and numerical modelling of cooling of magma provided a novel method that enabled reconstruction of two similar phonolite volcanic necks, Bořeň in NW Czech Republic and Devils Tower in Wyoming (USA). While field research revealed association of these volcanic features with phreatomagmatic processes, 25 analogue models were constructed to understand what physical parameters controlled final shapes of magma bodies emplaced into the maar-diatreme structures. Numerical models of cooling were created for selected shapes of the analogue models for comparison of their thermal structure with the shape of the columns on the phonolite volcanic necks. This integrated method finally revealed that both Bořeň and the world-famous Devils Tower represent remnants of extrusive lava domes or coulées emplaced into the maars of phreatomagmatic volcanoes. A report on this work in the Scientific American confirms that it was positively accepted by a larger scientific community (Závada et al. 2011, 2015). P. Závada is the leading author who formulated the hypothesis, did fieldwork, processed samples, created analogue models and compiled the manuscript.

Composition of the Mýtina Maar formerly discovered near the Quaternary volcano of Železná hůrka/Eisenbuehl, West Bohemia, was determined by detailed gravity, magnetic and resistivity measurements as a part of the multidisciplinary research on recent dynamics of this area of spas, mineral waters and repeated occurrence of earthquake swarms. The measurements also detected a tectonic fault connecting the two volcanic structures, determined the extent of volcanic eruption products (tuff, tephra) and correlated successfully a distinct gravity low with several sites of high CO2 emissions detected by the German colleagues (Flechsig, Mrlina et al. IJES 2015a, Nickschick, Mrlina et al. IJES 2015b). J. Mrlina performed the gravity measurements and their interpretation and took part in the manuscripts preparation.

**Planetary volcanism.** A concentrated interest in small-scale volcanic features on Mars provided several novel results. By detailed inspection of high-resolution imagery data, several sites of ancient explosive volcanism represented by scoria cones were recognised (Brož and Hauber 2012). Comparing shapes of terrestrial scoria cones with their possible Martian analogs and using a numerical model, it was found that the shape of the more voluminous Martian cones is controlled solely by ballistic accumulation of the ejected particles, while on Earth, these cones are reshaped by debris avalanching (Brož et al. 2014). Further survey of the Martian morphology revealed other rare volcanic landforms, the lava domes associated with breached volcanic cones (Brož et al. EPSL 2015) or tuff rings (Brož and Hauber, 2013). The leading author and team member of both these publications, P. Brož, found and described the respective features on Martian imagery data, provided the ideas to explain their morphology and assembled the manuscripts.

**Magma and/or salt flow processes in deforming crust.** Magmatism represents an important geological process that drives heat/mass transfer in the crust, controls crustal rheology and regional deformation, and thus significantly contributes to crustal growth and differentiation. Crucial information about the deformation mechanism of magma can be potentially inferred from fabric patterns preserved in plutons. We contribute to scientific debate on principal mechanisms of magma construction in the

crust through multidisciplinary studies comprising the detailed microstructural analysis, the rock magnetic methods and field/geochemical analysis (Kratinová et al., 2010). Similarly to magmas, salt rocks are materials of great geological importance due to their role in a variety of tectonic processes, in hydrocarbon trapping phenomena and their use as a disposal and storage medium. In cooperation with the IDL (Lisbon), we were able to separate para- and ferromagnetic signals in a magmatic dyke and attributed the respective subfabrics to distinct events during the dyke emplacement (Foum Zguid dyke, Southern Morocco; Loulé diapir, Portugal) (Silva et al. 2014; Machek et al. 2014). In cooperation with the ULP Strasbourg, we explained the significance of composite fabrics and fabric overprints in granite as a tool to understand succession of large-scale orogenic deformation episodes (Kratinová et al. 2012). The flow kinematics in shallow level plumbing systems from dykes to subsurface magmatic chambers/plutons was defined and explained by several studies (e.g. Žák, Kratinová et al. 2011). The team members (Kratinová, Machek) provided the datasets for the above mentioned studies, the analysis of magnetic properties of rock samples and greatly contributed in the preparation of these articles. Rheology of the rock salt and salt flow dynamics was characterized in both source layer and surficial extrusive portions of salt diapiric systems in Germany (Zechstein sequence, Neuhof salt mine) and Iran. Datasets acquired using state-of-the-art techniques at a collaborating institute, RWTH in Aachen, revealed significant contribution of grain-boundary diffusive processes and transgranular microcracking in the subsurface source layer. In contrast, for rock salt extrusions, it was found that rock salt flow is strongly accelerated by periodic input of annual rainfall and enhanced by presence of second-phase impurities (Závada et al., 2012; Závada et al., 2015). P. Závada (team member) was the leading author of both these publications, provided the samples and their processing, prepared datasets and wrote up the manuscripts.

## (2) UPPER MANTLE – CRUST INTERACTIONS

Complexes of lower continental crust and upper mantle rocks are crucial to understand processes of the crust-mantle interaction and evolution of the orogenic core zones. We focused mainly on deformation record in peridotites (microstructural analysis - qualitative and quantitative), interaction of rocks in lower crustal complexes (ultramafic rocks, amphibolites, granulites), dating and modelling.

**Ductile deformation of ultramafic rocks in crustal conditions:** We deciphered rheological evolution of sub-continental mantle in a hot collisional orogeny. The petrology and structural data result in a model of burial of peridotite below thickened crustal root, its exhumation and folding: 1) progressive mylonitization during decreasing temperature during emplacement of the peridotite into the lower crust and its ascent within a vertical granulite channel; 2) folding of the peridotite during indentation of weak vertically anisotropic crust by adjacent continental promontory. The degree of mechanical coupling between folded peridotite and granulite in mid-crustal levels was estimated using comparison of studied microstructures with experimental data (Kusbach et al. 2012). V. Kusbach (leading author and team member) compiled and processed all datasets and calculations and wrote the manuscript in frame of his PhD Thesis.

**From subducted slab through mantle wedge to internal orogenic domain.** Recent observations from large hot orogens indicate possible significant material transfers – relamination, responsible for formation of complex orogenic lithological profile. Based on our geochemical and geochronological data we consider relamination of felsic lower crust as a viable hypothesis accounting for the Variscan

evolution of the eastern part of the Bohemian Massif. In particular it explains the observed juxtaposition of the lower plate felsic crust (now HP–HT granulites) and mantle peridotite fragments. It is likely that this process is important in modern orogens, as indicated by chemistry and P–T conditions of HP granulitic and mantle peridotite enclaves in the Tibetan Plateau (Kusbach et al., 2015). In the latter work, V. Kusbach provided the datasets and their processing and compiled the manuscript with K. Schulmann, the major idea contributes to the relamination hypothesis in Bohemain Massif defined by the coauthors (V.Janoušek, K.Schulmann).

## (3) SEA-LEVEL AND CLIMATE CYCLES IN PAST GREENHOUSE PERIODS

Sedimentary archives of the Cretaceous period, particularly the mid-Cretaceous supergreenhouse interval, contain a record of past global climatic and oceanographic changes that can help to improve our understanding of the processes governing globally warmer climate regimes – an important task in view of the much-discussed anthropogenic global changes facing humankind in the future. Research of palaeoclimatic and palaeoceanographic dynamics requires a multi-disciplinary approach, using high-resolution, multi-proxy datasets. Much of our work in 2010-2015 has focused on sedimentary archives of the Bohemian Cretaceous Basin, which deserves to be called a „natural laboratory“ due to a rare combination of high-quality exposures and abundant subsurface data. Long-term research into the sedimentology and sequence stratigraphy of this basin has helped to establish, in the best-preserved and drilled parts of the basin fill, a three-dimensional picture of extent and geometries of its key depositional systems. This stratigraphic framework has been used already in several studies started before 2010, including numerical modelling of tide-driven, epeiric seaway circulation using the Imperial College Ocean Model (ICOM); this work, based on a PhD thesis chapter (Mitchell et al., 2010) was initiated by D. Uličný from our Department, and co-supervised by him in collaboration with G. Hampson and other colleagues from Imperial College, London (UK). Another numerical modelling study, led from our side, addressed the record of short-term sea-level falls in shallow-water hemipelagic strata, demonstrating a non-linear response of siliciclastic accumulation to sea-level changes (Laurin & Vodrážka 2010).

**High-resolution carbon-isotope and sea-level records of the Turonian stage.** New research core Bch-1 (Běchary), north-east Bohemia, Czech Republic, was drilled in 2010 as part of a project aimed at obtaining a high-resolution, multi-proxy stratigraphic record of the Turonian stage and led by members of our department in collaboration with the Czech Geological Survey and two British universities. The Turonian interval recorded the mid-Cretaceous thermal maximum linked to culmination of greenhouse climate, but also a long-term sea-level low in the Middle Turonian, and a range of short-term sea-level changes. Therefore, the Turonian is one of key intervals in the Phanerozoic within which to study the links between sea-level change, greenhouse climate, oceanographic conditions, and the carbon cycle. The drilling recovered a thick (> 400 m) succession of offshore strata of latest Cenomanian through middle Coniacian age. Primary data generated during the course of the project include a set of geophysical well logs, carbon stable-isotope data in a 50 cm resolution, quantitative palynological data, major and minor elemental proxies, TOC and carbonate contents, thin-section – based petrology, magnetic susceptibility, core photographs used for image analysis, macrofossil record, calcareous nannofossils, and standard macroscopic description of lithofacies. The results of the project brought significant progress to the understanding of the links between the global carbon cycle, orbitally-driven climate cyclicity, and sea-level

change, and provided a new high-resolution reference section for correlations of chemostratigraphic data between basins in Europe and other continents (Uličný et al. 2014). D. Uličný was the PI of a research project which included the drilling of the Bch-1 core and its multi-disciplinary analysis. He initiated the project, invited the international collaborators and coordinated work in individual disciplines. His main contribution was in well-log analysis, sedimentology, C-isotope stratigraphy and sea-level change interpretation. Another department member, J. Laurin, focused on quantitative analysis of time-series data and collaborated on tasks led by D. Uličný.
**Astrochronological time scale of the Turonian and orbital controls on a greenhouse-time carbon budget.** Additional C-isotope profiles acquired during the course of the above project and correlated to Bch-1, combined with spectral analysis of geophysical well logs, resulted in construction of a new, astrochronologically tuned time scale for the Upper Turonian substage. Building further on the above results, a new hypothesis of million-year scale variations in the Late Cretaceous greenhouse climate, controlled by amplitude modulation of axial obliquity was presented , supported by data from Bohemia as well as other localities worldwide, and by numerical modelling of variations in the Late Cretaceous carbon budget (Laurin et al. 2014, 2015). Department member J. Laurin conducted the time-series analysis of geophysical well log data, tied to C-isotope stratigraphy and biostratigraphy, created the astrochronological time scale and conducted isotope mass-balance modelling. D. Uličný (same department) was the PI of a project within which the research was developed and initiated the C-isotope analysis of archive sample material. Other collaborators have provided macrofossil data, archive samples, and supplementary palynological data.

## (4) APPLIED RESEARCH

Part of the project **"Review of groundwater reserves of the Czech Republic",** led by the Czech Geological Survey, 2010-2015 - genetic stratigraphic framework for use in hydrogeology practice.
In July 2010, the Czech Geological Survey initiated a project funded mainly from the European Regional Development Fund aimed to re-assess groundwater resources within approximately one-third of the territory of the Czech Republic. The project is part of efforts of the Czech government to attain a sustainable balance between groundwater exploitation and recharge. The Bohemian Cretaceous Basin holds significant reserves of groundwater and represents the largest geological unit studied within the framework of the reassessment project. A group of 3 researchers and two technicians from our Department has been involved, since 2011, in a review of genetic stratigraphy of the Bohemian Cretaceous Basin in all areas under hydrogeological assessment. The main output of our work is series of cross-sections and contour maps showing, in much greater detail than before, the syn- and post-depositional geometries of principal aquifer and aquiclude units of the basin fill and their structural context. These outputs form part of input data for hydrogeological modelling conducted by other groups within the project.
**Microstructural and petrophysical analyses**
A combined microstructural and petrophysical study of granite from the Melechov pluton, Czech Republic – a test site for the nuclear waste repository, has shown that the orientation of magmatic minerals together with their structural and mechanical anisotropies predefine the orientation of cracks that formed during post-solidus fracturing due to stress field changes caused by cooling and uplift of the pluton. Since the crack network represents the principal structure conditioning fluid mobility

in granitic rocks, this study contributed to our understanding of the impact of magmatic structure on the formation of cracks and consequently on the conduit/barrier function of granite which is a major concern in many actual applications related to energy production such as underground waste storage or production of heat and electricity from geothermal sources. The study has been a part of a government-funded survey of sites suitable for nuclear waste repositories (Staněk et al. 2013). M. Staněk collected and interpreted the datasets and prepared the manuscript. The paper constitutes a major output of his PhD thesis. His supervisors are the second and third co-authors.

**Tilt and gravity measurements.** The long-term continuous tilt observations in the area of open-pit lignite mines in North Bohemia served for the monitoring of the stability of the hazardous steep slopes of the mountain range situated just above the mines. The respective tidal observatory (Jezeří) is supported by the mining company as a part of the mine safety monitoring system. Equipment and data processing procedures have been developed in this and other two tidal observatories of the Institute in Central and West Bohemia. Microgravity surveying was applied for industrial purposes to confirm the existence of a hidden phonolite body at the base of a coal mine suitable as a resource of construction stone. Procedures for the gravity monitoring of gas/water contact movement in reservoirs as result of waterflooding, steam injection or other similar EOR/IOR techniques (enhanced/improved oil recovery) were developed. The results apply also to potential monitoring of gas or CO2 storage/injection/extraction processes. We developed a simple technique for approximate estimate of the feasibility of gravity monitoring of the above processes.

# Research Report of the team in the period 2010–2014

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| Scientific team | Department of Seismology |

Several groups have been working within the Department of Seismology during the period 2010-2014 on various topics. The research is mostly continuous, guided by leading ideas which are tested, verified, justified, corrected and adapted to new facts and knowledge, but the topics themselves are not changed abruptly apart from few cases. Similarly, the personnel involved in the research within individual groups is mostly stable. Of course, some people are active in several groups and contribute to more research topics according to their expertise (in the following lists they are assigned to the groups of their prevalent activity only). The groups are the following: (1) Structure and anisotropy of continental lithosphere (J. Plomerová, V. Babuška, L. Vecsey, H. Munzarová, H. Kampfová, J. Chyba, H. Karousová till 2013), (2) Geodynamic activity of West Bohemia/Vogtland – earthquake swarms (J. Horálek, T. Fischer, A. Bouškova, H. Čermáková, J. Doubravová), (3) Theory of seismic wave propagation in complex media (I. Pšenčík), (4) Theoretical modeling of fracturing the rock massif (V. Vavryčuk, J. Šílený, Z. Jechumtálová, P. Kolář, P. Adamová), and (5) Earth's crust structure and properties based on processing data from both active and passive seismic experiments (B. Růžek, P. Hrubcová). Within three of them (1, 2, 4) there is a good deal of young colleagues, partly undergraduate and PhD students, who are naturally incorporated into the research work – it is well seen in the author lists of the papers published. Apart from the fundamental research, several people deal with applications into industry: IP is the member of the SW3D consortium www.sw3d.cz, JS, PK and PA are enrolled into the effort of the Litoměřice municipality to exploit geothermal energy on the site www.prvnigeotermalni.cz, JS, PH and ZJ process routine contracts on macroseismic intensity determination demanded by insurance companies, and assessment of seismic load for civil engineering sector, people from seismic service and the WEBNET network provide alerts of increased seismic activity for commercial sector, see the Form 3-9. Research activity of the Department includes massive observation, which demands for construction and maintenance of research infrastructures – seismic networks (CRSN, WEBNET, MOBNET), and the data collection and exchange. The former implies database creation and maintenance, and concerns preferentially records from the WEBNET and MOBNET networks, the latter is the job of the seismic service.

## 2.1 Structure and anisotropy of continental lithosphere

The group is formed by 6 researchers, guided by experienced senior scientists (JP, VB). One middle career (LV) and three young researchers (HM and HK, PhD students, JCh, under-graduated student), form more than half of the group. Modeling the lithosphere thickness and large-scale fabric of the mantle lithosphere from anisotropic parameters of teleseismic body waves recorded by dense networks of temporary and permanent seismic stations, retrieving velocity structure of the upper mantle by seismic tomography and detailed model of the crust are main scientific objectives. They

inverted jointly shear-wave splitting parameters and P residual spheres based on data from several European regions ranging from the Apennines through the Variscan belt of central Europe to the Baltic Shield. Developing a unique code of anisotropic seismic tomography, which is tested on synthetic data, at present, broaden the tools for the scope. By studying the changes in orientation of the large-scale anisotropy, caused by systematic preferred orientation of olivine, they identified boundaries of large domains of mantle lithosphere. Individual domains, several hundred kilometers in lateral dimensions, are characterized by a consistent orientation of anisotropy approximated by hexagonal or orthorhombic symmetry with generally inclined symmetry axes. The domains are separated by mapped tectonic boundaries (sutures), which cut the entire lithosphere. The observations of consistent anisotropy within individual blocks of the mantle lithosphere reflect fossil olivine preferred orientation, most probably formed prior to the assembly of micro-plates that created the modern European landmass. The findings of the team support a plate-tectonic view, acting in early stage of the Earth evolution and represent the continental lithosphere as a mosaic of rigid blocks of the mantle lithosphere with complicated but relatively sharp contact zones. These contacts are blurred by the easily deformed overlying crust terranes.

In particular, research was focused on the deep structure of the Bohemian Massif and there especially on the Eger (Ohře) Rift, on the deep structure of the Phanerozoic and Proterozoic lithosphere around the central part of the Trans-European Suture Zone and Proterozoic-Archean contact in Fennoscandia (Sweden/Finland). Most of the investigations have been carried out within international passive seismic experiments (e.g., TOR-TESZ, SVEKALAPKO, BOHEMA, RETREAT, PASSEQ, LAPNET) and in cooperation with groups from numerous institutions, e.g., Institute de Physique du Globe (Strasbourg), Istituto Nazionale di Geofisica e Vulcanologia (Roma, Florence), Yale University (New Haven), Rudgers University (New York), University of Oulu and University of Uppsala. Members of the group take care about field work, data archiving, station documentation and data exchange.

From the outputs of the group, especially important are the following:

<u>Mantle lithosphere transition from the East European Craton to the Variscan Bohemian Massif imaged by shear-wave splitting</u>
Shear-wave splitting study (Vecsey et al., 2014) from data of the PASSEQ experiment (2006–2008), focuses on the upper mantle structure around the Trans-European Suture Zone (TESZ). Variable components of the splitting are associated with fabrics of the mantle lithosphere. No abrupt change in anisotropic structure can be related to the Teisseyre–Tornquist Zone (TTZ), marking the edge of the Precambrian province on the surface. Instead, regional variations of anisotropic structure were found along the TESZ/TTZ.

<u>Upper-mantle fabrics beneath the Northern Apennines revealed by seismic anisotropy</u>
Upper mantle structure beneath the Northern Apennines, based on body-wave data collected during the RETREAT experiment (2003–2006), is imaged (Munzarová et al., 2013). By joint analysis of anisotropic parameters evaluated from independent data sets, regions with different fabrics are identified. The lithosphere thickness of the Tyrrhenian and Adriatic plates are estimated at ~50 km and ~80 km, respectively, the latter being subducted down to no more than ~200 km with indications of inherited frozen-in anisotropic fabric.

Upper-mantle structure beneath the southern Bohemian Massif and its surroundings imaged by high-resolution tomography

Based on data from passive experiment BOHEMA II and BOHEMA III (2005-2006) and a part of the ALPASS array, the study introduces a new velocity model of the upper mantle down to 300 km retrieved by teleseismic tomography beneath the north-eastern and southern part of the Bohemian Massif (BM) and its surroundings. The most distinct low-velocity perturbations concentrate along the Eger Rift down to ~200 km and the extensive high-velocity heterogeneity is located south of the BM and is associated with the eastern Alpine root (Karousová et al., 2012; 2013)..

Boundaries of mantle–lithosphere domains in the Bohemian Massif as extinct exhumation channels for high-pressure rocks

Five domains (microplates) have been recognized by seismic anisotropy in the mantle lithosphere of the Bohemian Massif, each of them bearing a consistent fossil olivine fabric formed before their Variscan assembly (Babuška and Plomerová, 2013). The process consisted of at least three oceanic subductions, each followed by an underthrusting of the continental lithosphere. The findings support the bivergent subduction model of tectonic development of the central part of the BM.

Mapping seismic anisotropy of the lithospheric mantle beneath the northern and eastern Bohemian Massif (central Europe)

3D body-wave anisotropic parameters are evaluated from earthquakes recorded during passive seismic experiment BOHEMA II (2004–2005), which allowed scan in detail the upper mantle structure of the northern and eastern parts of the Bohemain Massif. The study shows an underthrusting of the Brunovistulian micro-plate beneath the eastern rim of the BM and indicates that its northern and southern fragments might have originally belonged to Baltica and to Gondwana, respectively (Plomerová et al., 2012; Geissler, Plomerová et al., 2012).

Effects of seismic anisotropy on P-velocity tomography of the Baltic Shield

Possible effects of neglecting seismic anisotropy on isotropic P-velocity tomographic images of the upper mantle beneath the Baltic shield are investigated. Differences in inversions from SV- and SH-waves are distinct down to depths of ~200 km and are associated with anisotropy of the lithospheric mantle (Eken, Plomerová et al., 2012). General features of tomography calculated from original and anisotropy-corrected data are similar, but large-scale anisotropy can contaminate the isotropic images in some parts of models.

Long memory of mantle lithosphere fabric — European LAB constrained from seismic anisotropy

Updated model of the European lithosphere–asthenosphere boundary (LAB) is presented along with results of mapping of large-scale domains of mantle lithosphere, characterized by uniform fossil fabrics (Plomerová and Babuška, 2010). Exploiting the long memory of the fabric of the deep continental lithosphere, the LAB is defined as a boundary between a fossil anisotropy in the lithospheric mantle and an underlying anisotropy related to present-day flow in the asthenosphere.

Mantle lithosphere control of crustal tectonics and magmatism of the western Ohře (Eger) Rift

Research on relationship between tectonics of the mantle and upper crust in western Bohemian Massif is summarized (Babuška and Plomerová, 2010). The rejuvenated Variscan junction of three mantle domains plays important role in the crustal architecture (Babuška et al., 2010). The crust above the mantle junction is characterized by earthquake swarms and mofettes emitting gases of mantle origin. Offsets of boundaries of the crustal units from their mantle counterparts indicate a detachment of the rigid upper crust from the mantle lithosphere.

Domains of Archean mantle lithosphere deciphered by seismic anisotropy – inferences from the LAPNET array in northern Fennoscandia

The study analyses P-wave travel-time deviations evaluated from recordings of the LAPNET array and shows examples of lateral variations of shear-wave splitting to demonstrate variability of fabrics of the Archean mantle lithosphere (Plomerová et al., 2011). Also the Archean mantle lithosphere consists of domains with consistent fabrics reflecting fossil anisotropic structures. 3-D self-consistent anisotropic models with inclined symmetry axes accommodate two independent sets of body-wave anisotropic observations.

## 2.2 Geodynamic activity of West Bohemia/Vogtland: earthquake swarms

The region of West Bohemia (Czech Republic) and Vogtland (Germany) is well known by periodical reoccurrence of intraplate earthquake swarms, with magnitudes ML< 5. The strongest earthquakes occurred during the 1908 swarm (ML~5.0), 1985/86 swarm (ML=4.6), 2008 (ML=3.8) and 2011 (ML=3.7) swarms. Since early 90's the region is permanently being monitored by the WEBNET network jointly operated by the Institute of Geophysics and the Institute of Rock Structure and Mechanics of the AS CR in Prague (currently 13 permanent and 10 temporary stations with sampling rate of 250 Hz). The records are routinely processed for phase identification, hypocentre locating, magnitude determination. Afterwards, the wealth of data is appreciated in value in studies investigating event migration, source parameters, scaling relations, mechanisms, event clustering, stress field determination, updating velocity models of the zone. Recently the range of research dealing with seismic energy release in terms of earthquake swarms has been broaden by extending the monitoring to South Iceland, namely the Reykjannes zone, where both tectonic and volcanic earthquake swarms occur. The idea is to learn on the nature of swarm energy release by comparing these two areas, geographically distant and tectonically different but similar in the manifestation of seismic activity. Since 2014, a network of 10 stations from the mobile pool MOBNET is monitoring the activity of the Reykjannes zone, in addition to the stations deployed by Icelandic research institutions.

The group engaged in the topic currently involves two experienced senior scientists (JH and TF), one person for data interpretation (AB), and two PhD students (HC and JD). This topic is undoubtedly that one which attracts also researchers from other groups largely as well as from abroad. It is well seen on the list of results related to West Bohemia area and seismicity – a good deal of authors is out from the WB group. The reason is exceptional quality of the WB data, thanks to advanced instrumentation and a well done monitoring. Among the results of the investigation of West Bohemia/Vogtland earthquake swarms and studies exploiting the data for related research, following items are especially worth of being listed:

Intra-continental earthquake swarms in West-Bohemia and Vogtland: A review

The wealth of data gathered in the target zone related to both seismic activity and gas emanation allows a joint interpretation and a synthesis of the insights into the processes involved. The observations suggest that earthquake swarms activate a complex fault system and display long-term migration that differs from the occurrence of CO2 escapes. The activity of individual swarms is consistent with models involving high-pressure fluids; the isotopic signature of the rising gas proves its origin at depths below the hypocentres. The earthquake swarms and degassing of CO2 of magmatic origin represent common result of the geodynamic activity of the area. Nevertheless, current knowledge does not preclude processes other than fluid-induced failure in triggering swarm seismicity (Fischer et al. 2014).

Moho depth determination from waveforms of microearthquakes in the West Bohemia/Vogtland swarm area

The study approaches the task to estimate the Moho depth in the target area non-traditionally. Common approach is represented by kinematic processing of arrival times picked in the records, while the current study suggests the preprocessing in a sophisticated way applying operations with waveforms: sorting according to the mechanism, cross-correlation, stacking. As a result, a more credible estimate of the Moho depth is obtained, indicating a possible splitting of the interface, which agrees with previous interpretations (Hrubcová et al. 2013).

Three-dimensional seismic velocity model of the West Bohemia/Vogtland seismoactive region

Seismic tomography was performed in the earthquake swarm area in West Bohemia, resulting in a smooth 3-D velocity model constructed independently for P and S waves. The added value of the tomographic study is conversion of the velocity fields into bulk modulus and Poisson ratio and their correlation to tectonics. The bulk modulus well coincides with the geological structure of the zone, the Poisson ratio acquires anomalously low values in seismically active zones Nový Kostel and Lazy (Růžek & Horálek 2013).

Mechanisms of the 2000 earthquake swarm

Detailed study concentrated on the issue of double-couple (DC) vs. non-DC mechanism. The question arose after processing of 1997 swarm, where significant portion of non-DC was detected at a part of the events. Now the particular attention was paid to assessing effects which might cause appearance of a spurious non-DC component of the mechanism: accuracy of location and velocity modelling, considering possible accidental errors in picking the amplitudes etc. Taking into account all these effects, the conclusion is that the earthquakes of the 2000 swarm are pure shear-slips (Horálek & Šílený 2013).

Source parameters of the West Bohemia/Vogtland swarm earthquakes

The question of a self-similarity of earthquake rupture scaling, which is a subject of ongoing debates, was investigated in the target zone by inspecting source parameters of 56 events from 2000 and 2008 swarms ranging local magnitudes from 0.8 to 3.3. A growth of stress drop with seismic moment seems to indicate a violation of the self-similarity, supported also by a wide span of the apparent stress (Michálek & Fischer 2013).

The 2008 West Bohemia earthquake swarm in the light of the WEBNET network

A detailed and exemplary analysis of the West Bohemia swarm in 2008 – the 3rd strongest activity within last 100 years – was performed which includes localization of the earthquakes, migration of the foci during the swarm activity and assessment of the cumulative seismic moment (Fischer et al. 2010). Considering the swarms since 1908, a maximum earthquake capacity of the principal swarm zone Nový Kostel was estimated: it can be equivalently related to a single earthquake exceeding local magnitude 5.

High-resolution fault image from accurate locations and focal mechanisms of the 2008 swarm earthquakes in West Bohemia, Czech Republic

High-quality data recorded during the West Bohemia earthquake swarm 2008 allowed sophisticated processing which yields a deeper insight into the structure of the active zone (Vavryčuk et al. 2013). The study combines precise locations with focal mechanisms of 400+ events and reveals a fine structure of the focal zone. The foci clearly map the geometry of active fault and display its segmentation with varying orientations. The most active parts acquire the optimum angle to tectonic stress, yielding shear mechanisms.

Principal earthquakes: Theory and observations from the 2008 West Bohemia swarm

The study introduces the concept put in the title as events which are related to faults, being most susceptible to slipping in terms of the Mohr-Coulomb friction law due to their optimum orientation within existing tectonic stress. The practical importance consists of the fact that mechanisms of earthquakes occurring in the zone of interest are generally close to those of principal earthquakes. It is demonstrated on W.Bohemia swarm in 2008 – the predicted faults correspond well to the tectonics (Vavryčuk 2011).

Seismicity-based estimation of the driving fluid pressure in the case of swarm activity in Western Bohemia

A modification of the Wadati methods was developed, which allows for determination of the Vp/Vs ratios in the focal zones of earthquakes with the use of arrival time double-differences (Hainzl, Fischer et al. 2012). Its application to the earthquake swarms of 1997, 2000 a 2008 has shown that the velocity ratios decreased down to 1.4 during short periods during each of these swarms. This anomalous behaviour can be explained by the presence of gaseous phase in the fault zone of the earthquake swarms.

Detection capability of seismic network based on noise analysis and magnitude of completeness

Two approaches for evaluation of the detection capability of seismic networks were compared using the data of the WEBNET seismic network. Statistical analysis has shown that seismic stations differ significantly in terms of the stationary character of the seismic noise, which does not necessary correlate with the absolute noise level. The Gutenberg-Richter distribution was further used for determining the magnitude of completeness of individual stations. The results show that the station sensitivity is mostly affected by the non-stationary character of the noise, rather than by its absolute level (Fischer & Bachura 2014).

**2.3 Theory of seismic wave propagation in complex media**

The topic of the investigation is seismic wave propagation in 3D laterally inhomogeneous, isotropic or anisotropic, perfectly elastic or inelastic media with curved interfaces. The basic tools for the study are high-frequency asymptotic methods such as the ray method or its various modifications and generalizations (Gaussian beam summation method, coupling ray theory, etc.). Currently there is a single senior researcher (IP) within the team, whose dominant activity is grounded in the topic. The other theorist of the Department, the senior scientist VV, has been engaged in the topic only marginally during the period assessed, and his main activity belonged to the topic of Theoretical modeling of fracturing, see next section. IP holds a close cooperation with Prof. V. Červený from Charles University, and is involved in tuition of young researchers from abroad.

The following items from the list of results are worth emphasizing, especially:

Two-point paraxial traveltimes in an inhomogeneous anisotropic medium

Computation of two-point traveltimes is a frequent task in exploration seismology. One possibility is to seek two-point rays, which is a time-consuming procedure, and to evaluate the two-point traveltime along them. An alternative approximate procedure was proposed and tested, which allows fast and sufficiently accurate calculation of two-point paraxial traveltimes in a paraxial vicinity of a ray, along which results of the dynamic ray tracing are known (Červený et al. 2012).

Boundary attenuation angles for inhomogeneous plane waves in anisotropic dissipative media

In this study, it was shown that the specification of the boundary attenuation angle of inhomogeneous plane waves as a free parameter, which is a common practice, may lead to non-physical results. An alternative procedure was proposed, which removes the problems (Červený & Pšenčík 2011).

Seismic ray theory

An excellent overview of the current state of the art in the seismic ray theory was published in Encyclopedia of Solid Earth Geophysics (Červený & Pšenčík 2011).

First-order coupling ray theory for S waves propagating in inhomogeneous, weakly anisotropic media

Proposed technique removes problems with failure of the standard ray theory for anisotropic media when the two S waves propagate with nearly the same phase velocity and mutually interfere (are coupled). This occurs in weakly anisotropic media and also in vicinities of the so-called S-wave singularities in any anisotropic media. The technique was tested on a variety of models (Pšenčík et al. 2012), for which standard ray theory fails. The technique yields results, which fit with high accuracy with results of independent method based on finite differences (FD). While FD requires several hours of CPU, the proposed first-order coupling ray theory needs just a minute or two. The technique will certainly find applications in exploration seismics.

Moveout formulae for weakly anisotropic media

Using the weak-anisotropy approach, in which anisotropy is considered as a perturbation of isotropy, was used for an alternative derivation of moveout formulae (formulae describing behaviour of the square of traveltime of a reflected wave as a

function of the squared offset). The formulae have a simple and transparent structure and offer accuracy comparable or higher than procedures commonly used in oil industry (Farra and Pšenčík, 2013a, b, 2014).

### 2.4 Theoretical modeling of fracturing the rock massif

The mechanism – a hypothetic force system equivalent to the intrinsic physical process – reports on the mode of fracturing in the focus of a seismic event. Vast majority of natural earthquakes corresponds to a shear-slip along a fault plane, which mechanism is a double couple (DC) in an isotropic medium. A more general process is indicated by a complex mechanism described by a complete moment tensor. Therefore, retrieval of moment tensors is a tool for approaching the physics of the process acting in the focus of a seismic event. In a case of a deficient observation, e.g., a single well monitoring of seismicity due to hydrofracturing of oil/gas wells, a simpler source model consisting of a shear and tensile component, has been designed and tested.

The group includes three experienced senior scientists (VV, JS and PK), one middle-career researcher (ZJ), and one recently graduated PhD (PA). Concerning the productivity, the group benefitted largely from the EC project AIM (Advanced Industrial Microseismic monitoring) performed during 2009-2012. Three postdocs - F. Bouchaala (France), R. Davi (Italy) and C. Alexandrakis (Canada) worked in the IG within the frame of the AIM project mostly on topics 2.3 and 2.4. Unfortunately, after the EC project expiry they quitted the Institute due to the low level of standard wages.

The following items from the list of results are worth of mentioning particularly:

<u>Tensile earthquakes: Theory, modeling and inversion</u>

The study by Vavryčuk (2011) extends the traditional model of an earthquake focus as a pure shear slip along a fault by considering an off-plane slip component. In this concept it is a follow-up of papers by Dufumier and Rivera (1997) and Vavryčuk (2001), but considers it much wider: it introduces a complete theory of the upgraded model, compares with the traditional one, generalizes nodal lines of the fault-plane solution into non-orthogonal source lines, and presents many useful formulas extending those well-known from the traditional seismic moment tensor analysis and decomposition. The outcome is a useful model which is simpler than moment tensor but retain volume changes. As such, it is supposed to be highly beneficial in application into induced seismicity, e.g., to events due to hydrofracturing of oil/gas wells. Finally, a method of inversion into the new source model is suggested and demonstrated on West Bohemia swarm earthquakes.

<u>Moment tensor inversion of waveforms: a two-step time-frequency approach</u>

By combining spectral and time domain approaches, a method is designed which in two steps inverts for the moment tensor and the source time function (Vavryčuk & Kühn 2012). In this way, it allows consider a realistic, complex time function, still keeping the moment tensor inversion linear. It is important from both methodological and practical point of view, as it represents an alternative to laborious procedures either linear but processing high-rank matrices (Sipkin, 1982) or nonlinear (e.g., Langston et al., 1982).

Iterative joint inversion for stress and fault orientations from focal mechanisms

The study reviews existing methods of inversion for stress from earthquake mechanisms. The principle trouble is a necessity to identify the fault from the two nodal planes. A failure makes the stress retrieval inaccurate. Here a new approach of simultaneous inversion for stress and the fault orientation is suggested which applies the fault instability criterion. The novel method works much better than the previous approaches concerning mainly the stress shape ratio (Vavryčuk 2014). Matlab code is provided freely upon request.

Seismic network calibration for retrieving accurate moment tensors

The study significantly extends the common practice in inverting for moment tensor by including the optimization for the station amplification (Davi & Vavryčuk 2012). The powerful option is enabled by a group processing of seismic events and allows treat the data, where some of the station amplifications are uncertain. In this way, it considers jointly effects of sensor amplification, gain of the acquisition system and station site effects. It is able to detect also polarity reversals and incorrect sensor orientation.

Source mechanisms of micro-earthquakes induced in a fluid injection experiment at the HDR site Soultz-sous-Forêts (Alsace) in 2003 and their temporal and spatial variations

Microearthquakes induced by hydrofracturing of industrial wells are important tools to assess the success of the related operations. In particular, the mechanism providing information on the mode of fracturing of the rock mass can answer the question on originating tensile fractures and, thus, enhancing the permeability of the reservoir. The processing was done for the Soultz geothermal site and indicated that the events were mostly shear, i.e. the injection operation was not a complete success (Horálek et al. 2010).

Small scale earthquake mechanisms induced by fluid injection at the enhanced geothermal system reservoir Soultz (Alsace) in 2003 using alternative source models

Two alternative models of a seismic source mechanism are treated: traditional moment tensor (MT) and shear-tensile crack (STC). They differ in the complexity: the STC is simpler but still capable to describe volume changes, which is extremely important in analyzing events induced by industrial activities. Both models are examined in the task of inversion, and the extent of biasing the mechanism by noise, monitoring configuration, hypocenter mislocation and velocity mismodeling are analyzed in detail (Šílený et al. 2014).

Non-double-couple earthquake mechanism as an artifact of the point-source approach applied to a finite-extent focus

The study examines the topic by using second order moments (SDM), a tool known in theory for decades but rarely applied (Adamová & Šílený 2010). The idea is that frequently there are finite-source effects in the data (e.g., directivity) which bias the estimate of the mechanism. An iterative procedure is designed which comprises of evaluating the contribution of SDM and removing them from the data, which are more relevant to the point-source approximation then, on which the earthquake mechanism determination is based. In a companion study, the approach is demonstrated on five moderate to strong earthquakes, to which large non-DC contents were assigned in regional MT catalogues.

**2.5 Earth's crust structure and properties based on processing active and passive seismic experiments**

The group consists of one experienced senior scientist (BR) and one middle-career researcher (PH).The research target of the group is the Earth's crust and uppermost mantle, research methods are applied on data from both active and passive experiments. The areas under study were Bohemian Massif, Western Carpathians and Pannonian Basin, and West Bohemia/Vogtland seismoactive region.

Joint inversion of teleseismic P waveforms and surface-wave group velocities from ambient seismic noise in the Bohemian Massif

In the study nearly 400 teleseismic earthquakes recorded at 54 broad-band stations located on the territory of Czech Rep. and nearby were processed jointly by cross-correlating long-term recordings of seismic noise and inverting the receiver functions (Růžek et al. 2012). Resulting 1-D velocity models compare well with local geology: complex crustal models are typical for stations located close to boundaries of major tectonic units.

From the Variscan to the Alpine Orogeny: crustal structure of the Bohemian Massif and the Western Carpathians in the light of the SUDETES 2003 seismic data

The interpretation of seismic refraction data from the SUDETES 2003 experiment in the Bohemian Massif and the Western Carpathians results in the seismic P-wave velocity model of the crust and the upper mantle (Hrubcová et al. 2010). For the interpretation, the tomographic inversion routine is used complemented by forward modelling with the ray tracing algorithm. Resulting 2-D models reveal differences in individual tectonic units as well as the complex structure at their contact.

For the outputs related to West Bohemia zone see above.

**Research tools**

Except the topic 2.3, research of all the groups within the team of the Department of Seismology is based largely on high-quality data which are recorded by permanent and temporary networks operated and processed mostly by ourselves. The group 2.1 builds on their data dominantly, and the group 2.2 exclusively. The group 2.4 uses in its research the data by group 2.2 to much extent. Therefore, high-quality and efficient tools for the data collection, i.e. seismic monitoring, are instrumental for the activity of the whole team. These tools are seismic networks listed below. The CRSN partly provides data for group 2.1 but prevailingly serves for the global seismology data collection. The dominant tool of group 2.1 is the MOBNET pool. The WEBNET network is a genuine tool of the group 2.2.

Czech Regional Seismic Network (CSRN)

Seismological observations of the Institute of Geophysics have a long tradition and form the fundamental of its research. The Institute of Geophysics operated 8 stations of the CRSN in the period 2010-2014. Digital data are transferred continuously from all stations to the IG by Internet. Software packages Antelope and SeisComP are used for automated data acquisition and international exchange with global data centers and a number of European national data centers and observatories. Virtual network of the IG consists at present of about 65 real-time seismological stations in central and southern Europe thanks to broad international cooperation of the IG established in the frame of EC projects Meredian (2000-2005) and Neries (2006-2010).

Seismological Data Center of the IG provides the following services:

- Automated near-real time data acquisition of continuous broadband and short-period seismic data by Antelope and SeedLink software packages.
- Global data exchange of both seismic phase readings and digital records with major international data centers (ISC, NEIC, IRIS, ORFEUS, EMSC) and a number of neighbouring national centers,
- Daily processing of digital seismograms by analysis program Seismic Handler.
- Archiving of digital continuous records on large raid systems.
- Compiling and publishing seismological catalogues and bulletins on the web, collection and evaluation of macroseismic reports about earthquakes felt on the territory of the Czech Republic.
- Recent automated locations of the CRSN and live seismograms of selected stations are displayed on the web pages of the IG.
- Informing the public through the media and web pages about strong and devastating earthquakes in Europe and worldwide.

<u>WEBNET seismic network</u>

West Bohemia/Vogtland earthquake swarm region belongs to the most closely monitored seismogenic areas in Europe. The principal tool is the WEBNET network, jointly operated by the Institute of Geophysics (IG) and the Institute of Rock Structure and Mechanics (IRSM) of the ASCR. WEBNET monitors local seismicity in a broader area of West Bohemia and Vogtland, the stations cover an area of about 1000 km2. WEBNET consists of 13 stations being networked via internet and 10 stations operated in an autonomous mode with continuous recording.

Seismometers are installed on concrete pillars in 3 to 5 m deep vaults. Networked stations are equipped with passive seismometers SM-3 (11 stations) and broadband seismometers Guralp CMG-40-T (2 stations), and with Janus-Trident or Taurus data-acquisition systems (DAS) by Nanometrics. The autonomous stations are equipped with short-period sensors Le-3D Lennartz and DAS Gaia of domestic provenience from the MOBNET station pool. All the WEBNET stations produce seismograms proportional to the ground velocity in the frequency band of 0.5-80 Hz for the telemetered stations, and 1.0-80 Hz for the autonomous stations. The sampling rate of all the stations is 250 Hz. The parameters of the seismographs (sensor and DAS) and a level of seismic noise guarantee high-quality recording of local events with magnitudes – $0.5 < ML < 5$ at the networked stations, and of about $-0.5 < ML < 3.6$ at the autonomous stations.

Data from the networked stations are transmitted via Internet to the data centre IG in Prague, data from the autonomous stations are downloaded every two months or as needed. The WEBNET database (catalogs, bulletins and seismograms) includes of about 80000 local events which have been recorded since 1992. Further networks providing relevant, high quality data have been working in NE Bavaria and SE Saxony. In 2015 the WEBNET stations will be upgraded to a large extent: outdated SM-3 sensors will be replaced by broadband force-balance sensors Guralp CMG-3ESPC, autonomous stations will be equipped with force-balance Guralp CMG-40-T sensors and with DAS Centaur by Nanometrics. After that WEBNET will consist of 23 broadband stations having a homogeneous frequency response of 0.03 to 80 Hz, the dynamic range of more than 120 dB and sampling rate of 250 Hz.

MOBNET network: pool of mobile seismic stations

The Institute of Geophysics owns a set of mobile seismic stations MOBNET, deployed flexibly on the basis of immediate need in different research projects. This set consists of 32 short-period Le3D sensors, 15 broad-band (VBB) STS2 and 6 CMG (Guralp) seismometers, and 55 GAIA acquisition systems (DAS). The DAS GAIA recording instrumentation is fully compatible with other standard third-generation seismic instrumentation and equipment, as regards built-in software and output data formats. Processing of seismic data is then easy and the data comply with all required standards. Stations of the pool participated in several passive experiments. Ten BB stations finished three year operation in the Northern Apennines in October 2006 within the project RETREAT 2002-2007. The pool of stations were further installed within the project PASSEQ (2006-2008), which focused on the upper mantle structure beneath an elongated array running from Bavaria, through western part of the Bohemian Massif (Eger Rift) and Poland to Lithuania. The stations were also included in experiment BOHEMA II (2004-2005), III (2005-2006) and BOHEMA IV( 20013-20014) covering different parts of the Bohemian Massif, EgerRift (2007-2011) and in experiment POLENET/LAPNET (2007-2009) carried out in northern Finland. At present twenty MOBNET GAIA stations equipped with broad-band seismometers are deployed in the field in the frame of the large scale international passive seismological experiment AlpArray-EASI, one of complementary projects of the AlpArray experiment, whose backbone array is going to be realized this year. Ten short-period stations (Le3D sensors with DAS GAIA) are installed in the West Bohemia seismoactive region as a part of the WEBNET network, further 15 GAIA instruments presently operate as the acquisition systems of the REYKJANET network, monitoring seismic activity of South Iceland.

Rotational seismometry

Thanks to the novelty of the field of rotational seismology, instruments recording seismic rotational motion are not standardly on sale by commercial manufacturers. Therefore they are developed by seismologists on the way. Within the long-term activity of the group engaged in this (J. Kozák, P. Jedlička, J. Buben), two new fluid-ring seismometers and a capacity sensor of rotational motion were developed and tested in ore mines in Lubin, Poland, and in a local quarry simultaneously with the instrument Rotaphone by the group from Charles University and Institute of Rock Structure and Mechanics ASCR. The two models of rotational instruments are patented in Czech Republic (Jedlička et al. 2012).