THE CZECH ACADEMY OF SCIENCES

INSTITUTE OF GEOPHYSICS

REPORT 2015 — 2020

Institute of Geophysics of the Czech Academy of Sciences

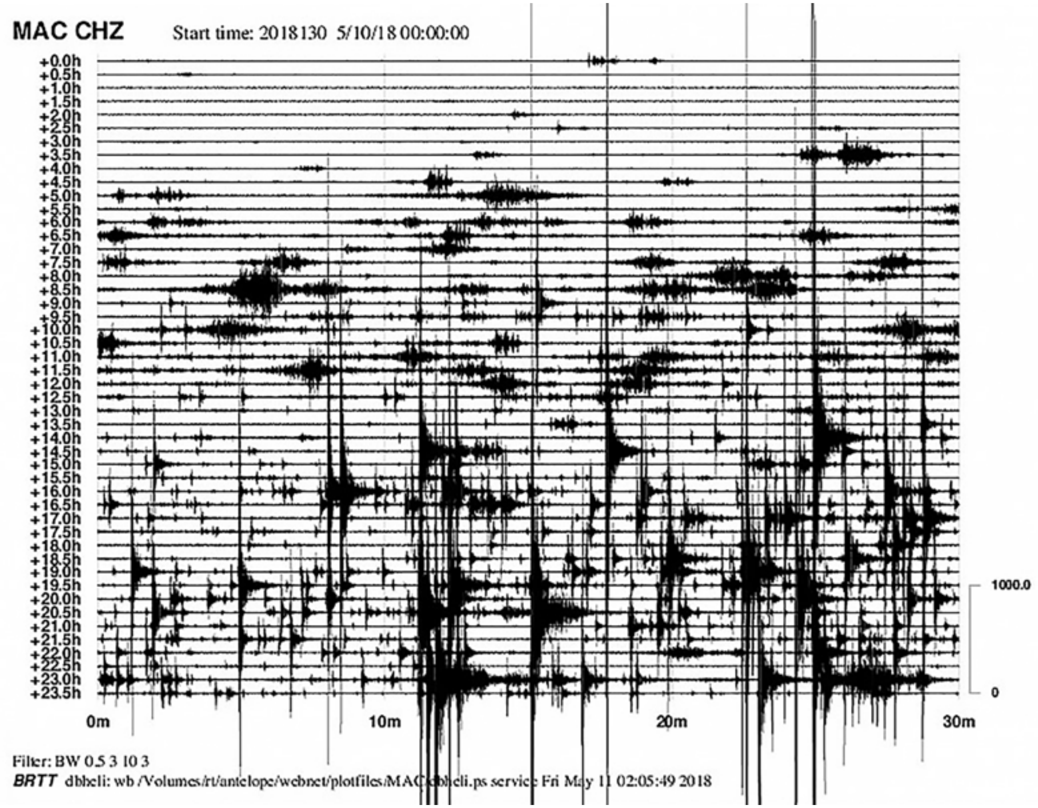
The Institute of Geophysics is a public research institution whose mission is to conduct fundamental and applied research in the Earth sciences, to disseminate the outcomes of this research to the national and international scientific community, to maintain a network of Earth observation facilities, and to engage in education at all levels together with informing the public on scientific issues of high societal importance.

Our research embraces a broad range of field-based, modelling and theoretical approaches to investigating the structure and dynamics of our planet. We study the Earth's crust, lithosphere and sub-lithosphere structure, geodynamics, magnetism, seismology, volcanism, magmatism and rock-forming processes, solar-terrestrial interactions, and surface processes on Earth (and other planets) including climate, tectonics and the biophysical environment. Earth observation is inherent to the activities of the Institute. We conduct continuous observations of Earth's physical fields (geomagnetic, seismological, geodynamic and geothermal) at facilities in the Czech Repubic together with short- and long-term observational networks abroad. The Institute is involved in data exchange and collaboration with international services and data centres, and in this regard the Institute fulfils the role of a national geophysical service.

The Institute employs over 70 researchers, post-docs, and technicians currently organized in four research departments: department of seismology, geomagnetism, geodynamics, and geothermics. The research activities are supported by about 30 staff members of the operating division (IT centre, library, administrative and maintenance services).

One of the goals of the management of the Institute in the immediate future is to transform its structure to a more flexible grouping of topic-oriented teams reflecting current research and social challenges. The Institute has recently succeeded in hiring several post-docs and early career scientists internationally. These individuals brought interesting topics new to the Institute and have already succeeded in obtaining prestigious domestic as well as European funding for their proposals. These well-funded projects will soon increase the number of talented post-docs and PhD students and help to further increase the international portion of our research staff.

Our researchers deliver courses and supervise research students at universities in the Czech Republic and abroad while also contributing to the international community via participation in scientific governance and by serving on the editorial boards of leading peer-reviewed journals. The Institute's own peer-reviewed journal, *Studia Geophysica et Geodaetica*, was founded in 1956 and is now distributed by Springer.



Seismogram obtained by our seismic station at Chlum u Svaté Máří in West Bohemia shows the earthquake swarm of May, 2018.
See related text in section "Seismic source and wave propagation studies"

Among the domestic partners of the institute, the most intense cooperation has been held with the the Department of Geophysics of the Faculty of Mathematics and Physics of the Charles University, geological section of the Faculty of Sciences of the Charles University, and the Czech Geological Survey. Occasional partners are the Institute of Geology of the Czech Academy of Sciences (CAS), the Institute of Rock Structure and Mechanics of the CAS, the Institute of Physics of the Earth of the Masaryk University, Brno, and the Department of Geology of the Faculty of Sciences of the Palacký University, Olomouc.

Our commitment to serve the people of the Czech Republic, to whom we are responsible as a public research institution, is manifested in numerous outreach activities, regular media appearances, and lectures and exhibitions aimed at elevating public awareness of our Earth and the importance of science in a civil society together with the role of the Czech Academy of Sciences.

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(until April 2017: RNDr. Pavel Hejda, CSc.)

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(five-year term beginning January 2017)

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Czech geophysics 100

The Institute of Geophysics of the Czech Academy of Sciences (Czechoslovak Academy of Sciences before 1993) has existed in its current form of a research institution since 1953 when the Czechoslovak Academy of Sciences was established. But the Institute did not start from nothing in 1953. Its establishment followed up on gradual evolution since December 29, 1920 when the (State) Institute of Geophysics at the Charles University was founded by the Ministry of Education of the Czechoslovak Republic. The Institute was rather virtual at that moment – without any property and with a single employee, Professor Václav Láska (1862 – 1943), the appointed director of the Institute with an uneasy task to establish a real institution dealing with geophysical observations and research.

The outstanding and inspiring personality of **Václav Láska**, early development of geophysics in Central Europe as well as the history and evolution of institutions dealing with geophysics in our country from 1920 to 1980 were meticulously described by **Alois Zátopek** (1907 – 1985), the first professor of geophysics in Czechoslovakia, in a commemorative paper "Sixty Years since the Foundation of the (State) Institute of Geophysics at the Charles University in Prague" published in 1981 (Studia Geophysica et Geodaetica, vol. 25, p. 296-312). The history of the (State) Institute of Geophysics documents a fact that is well known among the local geophysical community: the State Institute of Geophysics was a predecessor of all current publicly funded geophysical institutions in the country: the Department of Geophysics at the Faculty of Mathematics and Physics of the Charles University, the division of Applied Geophysics at the Geology Section of the Faculty of Science of the Charles University, and the Institute of Geophysics of the Czech Academy of Sciences.

Whereas the gradual growth of geophysical community, its leading personalities and newly born geophysical institutions are commemorated in many short summaries of history of geophysics in Czechoslovakia/Czech Republic (see, e. g., http://geo.mff.cuni.cz/historie.htm), less is known about the efforts by Professor Láska to establish an institution of a broader focus than just geophysics. He intended to begin with building a joint Observatory for Astronomy, Geophysics and Meteorology in the northern part of Prague, but "… this progressive plan failed for economic reasons just as the subsequent project for a joint Institute of Astronomy, Geophysics, Geodesy and Meteorology, the building up of which was planned on the Barrandov hills in the SW-part of Prague…" (Zátopek, 1981). Probably equally interesting is the fact that (almost?) no effort has been made by now to establish an institution merging the disciplines of geophysics and other Earth Sciences – a trend visible in the second half of the 20th century in many countries in Europe and beyond. For comparison: the American Geophysical Union currently covers all Earth, Ocean, Environmental, and Space sciences, and its annual assemblies attract thousands of researchers from all these branches, whereas in Czechia the term "geophysics" is understood mainly in a rather narrow sense by a sizeable part of local geoscience community.

Let's use the opportunity of the 100th anniversary of institutionalized geophysical observations and research in our country to help include geophysics in truly interdisciplinary research pursuing questions of critical importance to the Earth Sciences and the world society, including geological hazards, climate change and sustainable interaction of humans with their environment.

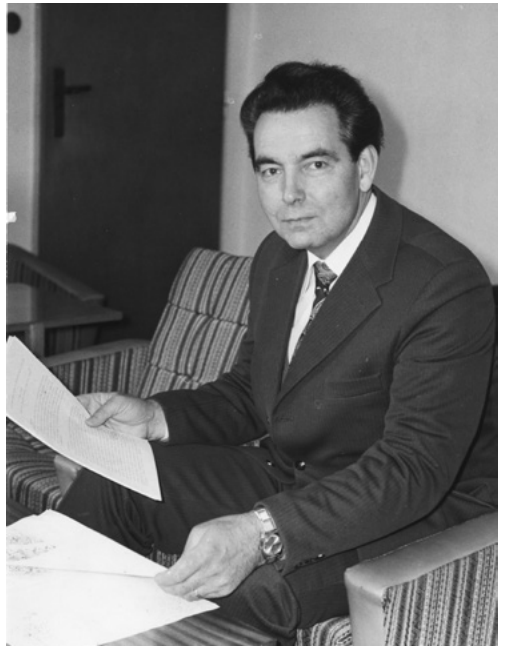
Participants of the 3rd General Assembly of the International Union of Geodesy and Geophysics (IUGG) held in Prague on September 3 – 10, 1927. 160 attendees from 30 countries participated at the Assembly. The Union was established in 1919.

Highlights of our Institute's history: people and ideas

The following paragraphs commemorate mainly the time period between establishment of the direct predecessor of the current Institute, the Geophysical Institute of the Czechoslovak Academy of Sciences in 1953, and the fundamental political changes in Central Europe in 1989. This era was characterised, on the one hand, by enthusiasm of founders of a new institute, and, on the other hand, by limited possibilities of researchers of the institute to keep international contacts, by lack of funds to obtain contemporary instrumentation and equipment, and by many other inconveniences of the Communist era. Fortunately, researchers of the Institute were allowed to organise international conferences and workshops in the facilities of the Academy of Sciences devoted to topics dealt with at the Institute – seismic wave propagation, lithospheric studies, earthquake risk and hazard, palaeo- and rock magnetism, heat flow and geothermal issues. These well-organised meetings attracted a broad international community that included leading personalities in geophysics from both the "West" and the "East" – Bruce Bolt, Viktor Kostrov, Keiti Aki, Anatolyi Levshin, Max Wyss, Slawomir Gibowics, Ota Kulhánek, Roman Teisseyre, Heinrich Soffel, Micke McElhinny, David Dunlop, E. Robert Engdahl, Alexander Guterch, Robert C. Liebermann, N. V. Kondorskaya, Paul G. Silver, J. V. Riznitchenko, Chris Chapman, Brian L. Kennet, and many others. Such meetings helped to maintain key personal contacts across the Iron Curtain.

Several researchers of the Institute considerably influenced diverse fields of geophysics. **Vít Kárník** (1926 – 1994), together with W. Sponheuer and S. Medvedev, developed a widely used macroseismic scale MSK and compiled a catalogue of European earthquakes (Kárník, V., 1968, 1971). **Axel Plešinger** (*1933) designed and activated the first very-broad-band measuring system in the world at the seismic observatory KHC (Kašperské Hory) in south Bohemia, in 1972. The system, capable of recording all frequencies of surface movements, became one of fundaments of modern seismometry. **Jiří Vaněk** (1927 – 2018) substantially contributed to a method of reliable determination of earthquake magnitude (Christoskov et al., 1982) and, together with V. Hanuš, to understanding the relations between seismic and magmatic/volcanic processes in subduction zones at convergent plate margins. **Vladimír Čermák** (*1937; director of the Institute of Geophysics 1990 – 1998) took part in international efforts to provide the regional heat flow pattern, a useful tool for studying crustal and lithospheric structure and evolution (Čermák and Rybach, 1979). In 2015, he hosted the 26. IUGG General Assembly in Prague. **Vladislav Babuška** (*1937) contributed to recognition of the importance of anisotropy of physical properties of rocks in interpreting measurements of any physical field, with emphasis on seismic observations (Babuška and Cara, 1991). **Miloš Pick** (1923 – 2007; director of the Institute of Geophysics 1960 – 1969) developed numerous theoretical methods at the intersection of geodesy and gravimetry and a procedure embodying topographic corrections to gravity survey data processing. **Zdeněk Pros** (1929 – 2008) developed a method for a 3D determination of ultrasonic-wave velocities in rock

Axel Plešinger (left) beside the sensors of the Kašperské Hory (KHC) seismological observatory, together with groundskeeper and technician B. Bartizal (mid-1970s; Archive of the Department of Seismology, Institute of Geophysics)



↑ (left) Ludvík Waniek, seismology, president of the European Seismological Comission 1990 – 1994, accompanied by his wife and (right) Jiří Vaněk, seismology

↗ Václav Bucha, geomagnetism, director of the Institute of Geophysics 1969 – 1990, vice-president, IAGA (1983-1987)

→ Vladimír Čermák, geothermics, director of the Institute of Geophysics in 1990-1998 (photo from the Liblice Castle Meeting on geothermal activity, 1982)

samples and constructed a unique laboratory apparatus for detection of anisotropy of seismic wave velocities in rocks under hydrostatic pressures corresponding to mid-crustal environment. The other laboratory established within the Institute, dealing with modelling of seismic waves and sources, mostly in artificial materials, benefited greatly from the experience and skill of its founder, **Ludvík Waniek** (1930 – 1996; president of the European Seismological Comission, ESC, 1990 – 1994). Using a unique optical set-up, ingenious experiments elucidating elastic wave propagation through complex media simulating lithosphere and crustal structures were performed in this lab at a time when tools of mathematical modelling were not available yet. He hosted the General Assembly of the ESC in Prague in 1992. **Václav Bucha** (*1927; director of the Institute of Geophysics 1969 – 1990) contributed to the development of palaeomagnetism, published first results on archaeomagnetic dating and palaeointensity determinations in former Czechoslovakia, and later dealt with relationships between geomagnetic and solar activity and climate changes. Between 1983 and 1987 he acted as the Vice-President of the International Association for Geomagnetism and Aeronomy (IAGA) and hosted the Scientific Assembly of IAGA in Prague in 1985.

In the 1960s, the Ionosphere Department was established at the Institute. The most spectacular achievement of researchers and technicians of that department was the construction and launch of the Magion 1 satellite in the framework of the Interkosmos programme in 1978. In early 1990s, the department moved to our partner Institute of Atmospheric Physics where the strong heritage of the Magion spacecraft series is being followed by a lively space research program (for more information see https://okf.ufa.cas.cz/en/).

The Institute of Geophysics played a decisive role in establishing international journal Studia Geophysica et Geodaetica (http://ig.cas.cz/en/studia-geophysica-et-geodaetica) in 1956. From the very beginning, the institute has coordinated the editorial process of the journal and technical production.

In addition to the standard outputs of scientific work and observatory operation, researchers of the institute participated in editing and publishing three monographs on local and regional geological structure and geodynamic processes that were of importance to the Central European geoscience community: *Geodynamic investigations in Czechoslovakia* (ed. J. Vaněk, Veda, Bratislava, 1979) *Geophysical synthesis in Czechoslovakia* (ed. A. Zátopek, Veda, Bratislava, 1981), and *Crustal structure of the Bohemian Massif and the Western Carpathians* (ed. V. Bucha, M. Blížkovský, Academia, Praha, 1994).

A more or less stable governmental support of research after 1989 made it possible to gradually upgrade the equipment of permanent geophysical observatories to European standards. A dense local network of seismic stations in the west Bohemian seismically active area belongs to the best-instrumented networks in Europe. A pool of mobile seismic instruments enabling participation in large international lithospheric experiments includes about 60 broad-band units. The geomagnetic observatory Budkov has been rebuilt to a modern facility that belongs to the global network of geomagnetic observatories INTERMAGNET.

From the present to the future

Scientific perspectives of any institution depend directly on the people who define key research topics, assemble and lead research teams, build laboratory facilities, and attract new generation of research students. For our Institute it is vital to provide home to scientific talent represented by Czech as well as international researchers. In 2018, a successful recruitment effort attracted over 120 international applications and resulted in hiring four excellent researchers. Another round of recruitment is under way at the time of writing this report.

The following pages highlight only a few of a number of colleagues from younger and middle generation who have in various ways significantly enriched the research and outreach that our institute provides to the society. They helped develop and internationalize our teams, brought significant research funding, or were recognized by awards from the scientific community.

Transportation of seismic stations by helicopter (Switzerland, Aletsch Glacier).

LISTENING TO LANDSLIDES

Jan Burjánek obtained his PhD from the Faculty of Mathematics and Physics of the Charles University in 2008. His next career step took him to the ETH in Zurich where he spent 8 years – first as a post-doc and later as a lecturer and senior researcher at the Swiss Seismological Service. In 2016, he joined our institute as a recipient of the **Purkyně Fellowship** of the Czech Academy of Sciences which was aimed at supporting his research and establishment of a research team focused mainly on earthquake hazards due to strong ground motions and earthquake triggered landslides.

Jan and his colleagues investigate local amplification of seismic waves caused by unconsolidated sediments and weathered rocks measuring the ambient vibrations of the ground. Computer simulations of ground motions in deep sedimentary basins and fractured rocks help them to explain the observed effects and to constrain three-dimensional geological models. They introduced, for example, a non-conventional method for characterization of unstable rock slopes based on their ambient vibrations.

Caldera of the Katmai volcano, Alaska. (Credit: USGS, J. Fierstein)

APPLYING ELECTROMAGNETISM TO STUDY ACTIVE MAGMA CHAMBERS

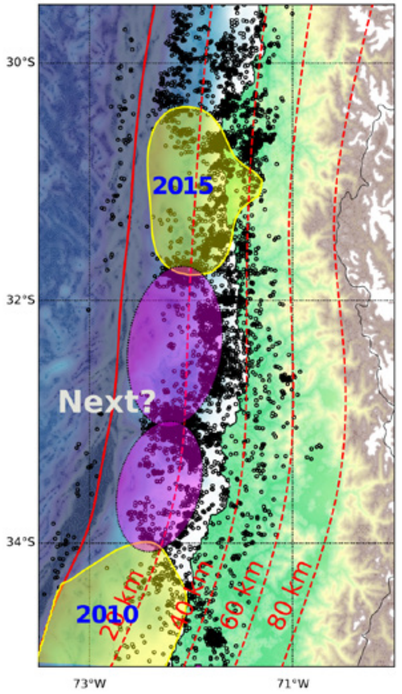
Graham Hill is an internationally acclaimed expert in electromagnetic research of the Earth's interior. Graham's research focuses on the relationship of electrical resistivity and physico-chemical properties of rocks by applying and developing the magnetotelluric method, in particular on understanding the role of geo-fluids (e.g. magma and magma-related solutions) in global tectonism, magmatic and geothermal systems, and ore deposits.

Graham's volcanic research has focused on important regions in North America, New Zealand, and Antarctica. He has published in leading journals including Nature, Nature Geoscience, and Nature Communications. At the Institute of Geophysics since 2018, Graham has been involved in building an interdisciplinary, and international, team to continue the research into active magmatic processes and both ancient and modern tectonics. One research direction will focus on the magmatic system of the Katmai volcanic group in Alaska, the site of the largest volcanic eruption of the 20th century. Funding for this research comes from the **Lumina Quaeruntur** premium, recently introduced by the Czech Academy of Sciences to promote excellent research in the Academy. Further supported research directions include, for example, an investigation of the construction of the Fennoscandian and Greenland Cratons to investigate deep Archean tectonic processes of craton evolution and concentration of metals at economic levels. The project is supported by the **ERAMIN2** program of the European Research Council.

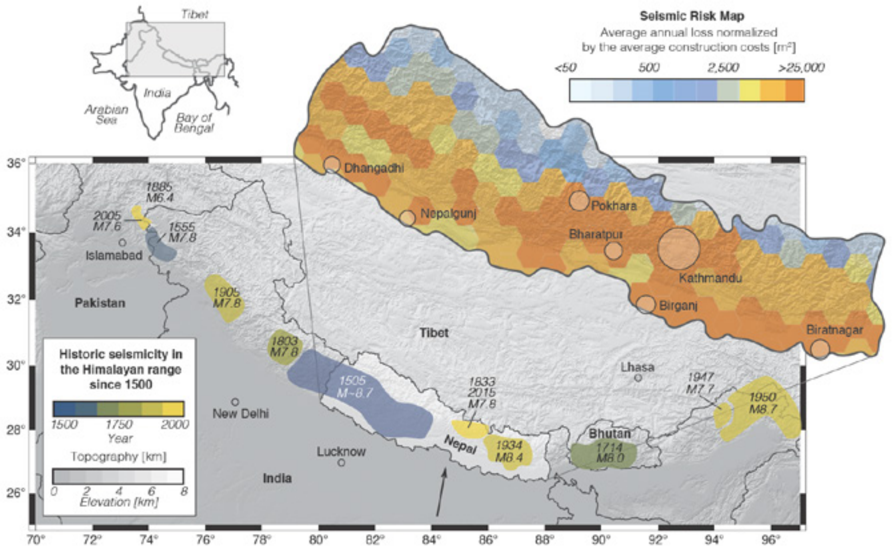
LOOKING AT SMALL EARTHQUAKES TO UNDERSTAND THE BIG ONES

Christian Sippl has joined the Department of Geodynamics in April 2019. A seismologist by training, he is interested in the dynamics of convergent plate margins, most recently in subduction zone settings. His PhD project, conducted at *Freie Universität Berlin* and *GFZ Potsdam*, was focused on the seismicity and structure of the Pamir Hindu-Kush region, a rare example of a fully continental subduction zone. Christian's post-doctoral research included fellowships at the Australian National University (Canberra) and the GFZ Potsdam.

At our Institute, Christian's focus on seismicity of active subduction zones helps to continue the tradition of plate-tectonic research carried out here since the mid-1970s by Jiří Vaněk, his associates and students. Much of Christian's future work, until 2025, will be centered around the **ERC Starting Grant** awarded in 2020 to his project MILESTONE („Microseismicity Illuminates Subduction Zone Processes"). The goals of this project are to help answer the following two questions: 1) What defines the loci and sizes of large subduction zone earthquakes?, and 2) How do earthquakes inside the downgoing plate function, and what can they tell us about active processes at these depths? Christian's team is going to focus on analyzing background microseismicity in four different subduction zones. Thousands of small earthquakes, identified and located with automated approaches, provide important information on the geometry, kinematics and dynamics of the subduction system. They can also help to define highly coupled patches on the plate interface, which are likely loci of future large, destructive earthquakes.



Map of earthquake epicentres (black dots) on the plate interface beneath Central Chile. The bold red line shows the boundary between the upper and lower (subducting) lithospheric plates. Yellow ellipses show the extent of past earthquakes. It can be seen that the epicenters of small earthquakes surround the rupture areas of large events which are characterized by a lack of microseismicity. Microearthquake epicenters outline two additional elliptical areas (magenta ellipses) that may correspond to the rupture areas of future large earthquakes. Dashed red lines show the depth of the subducting Nazca Plate.



Map of seismic risk and the impact of past major earthquakes in the Nepal region.

CHASING EARTHQUAKES, FROM OCEAN FLOOR TO THE HIMALAYAS

Václav Kuna had the first research experience with our Institute during his undergraduate study; supervised by Aleš Špičák, he devoted his MSc. thesis to the seismic expression of submarine volcanism, based on global seismic datasets. His PhD research, at the Oregon State University (Corvallis, USA) concentrated mainly on the seismicity of the Blanco Transform Fault, a 350-km-long oceanic fault in the northeast Pacific Ocean. Based on analysis of an extensive dataset from ocean-bottom seismometers, Václav formulated a new, detailed model of the mode of slip at oceanic transform faults. A summary of these findings were published in *Nature Geoscience* (Kuna et al., 2019, Nat. Geosci. 12, 138-142).

During his PhD work in Oregon, Václav took part in quick-response seismic research targeted towards monitoring aftershock seismicity in the Himalayan Range, following the devastating M7.8 Gorkha earthquake in April, 2015 that claimed about 9000 human lives. Field deployment in Nepal became an important formative experience for him. For further development of his professional career, Václav decided to use his skills and experience to develop directly applicable tools and methods beneficial to people in seismically endangered regions worldwide. Having started his post-doctoral employment at the Institute in 2020, Václav works on a project to develop and test an earthquake early warning (EEW) system, that is, a system that detects early stages of an earthquake, issues alerts, and provides critical time for users to seek cover or exit a building before the shaking arrives. The project aims to test a novel EEW solution that is enabled by recent development of *Internet of Things* (IoT) and cloud-computing. In 2021-2022, a real-time earthquake monitoring network is planned to be deployed (Covid-19 measures permitting) in a densely populated region in central Nepal, with the ultimate goal of assessing the feasibility of EEW in the region.

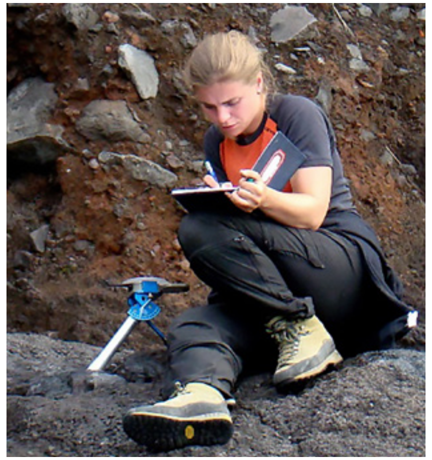
Women in our research

In Earth Sciences, the proportion of women researchers had notoriously been lower than in many other areas of science. In part, this had been due to historical ties of geology and geophysics with mining and exploration industries, and also due to physical and safety challenges of field work in many parts of the world. Although the situation has improved in the past two decades, still today the bulk of job applications we receive in response to our recruitment calls from geoscientists worldwide remains dominated by male applicants. In view of these historical and cultural biases that to some extent persist in various branches of geoscience, we appreciate the energy and enthusiasm of women involved in research at our institute and devoted to reconciling scientific work with responsibilities and workload of motherhood. Among the current 50 researchers employed in our institute, currently 17 are women; several of them, in the younger generation, are either on maternity leave or employed part-time. The five researchers highlighted below represent only a small part of the group of female scientists, exemplifying all stages of scientific careers. In the future, our institute will continue and further improve its friendly approach to female researchers, which will eventually result in their greater representation at all levels of leadership.

Jaroslava Plomerová belongs to outstanding scientific figures of the institute, having gained international recognition since the 1970s with the achievements by herself and her group in seismic research of the structure of the lithosphere. Her scientific interests include, among others, seismic anisotropy, structure and development of continental lithosphere and the relief of lithosphere-asthenosphere boundary, studied mainly using teleseismic methods. She has participated in many international collaborative projects (EUROPROBE-TOR, SVEKALAPKO, BARRANDE, BOHEMA I-III, LAPNET, PASSEQ, RETREAT, ALPARRAY). In addition to her own scientific work, Jarka has served in a number of governing bodies in research management – for instance, as member od executive committee of the ISC (International Seismological Centre), or as the secretary of the Czech National Committee of the International Lithosphere Programme of IASPEI (International Association of Seismology and Physics of the Earth's Interior). Since 2009, she has been a topical editor of the journal Solid Earth. Already in 1989, she received the medal of the Czechoslovak Academy of Sciences.

The scientific contribution of research carried out by her group, including V. Babuška and L. Vecsey, was

From left to right
Jaroslava Plomerová
Zuzaa Roxerová
Hana Grison
Helena Žlebčíková
Jana Doubravová



recognized by the **Award of the Czech Academy of Sciences** in 2010.

Zuzana Roxerová (born **Kratinová**) joined the Department of Geodynamics of our Institute in 2007, when she contributed to building an analogue-modelling laboratory. Zuzana's professional background includes classical field-based structural geology as well as a broad range of analytical methods, petrology, and physical modelling of geological processes. One of her primary research interests is the study of processes of magma flow and its record in finite rock and AMS (anisotropy of magnetic susceptibility) fabric. In 2012, Zuzana was among the laureates of the **L'Oréal/UNESCO Award For Women in Science.** Eight years later, as a mother of three, Zuzana keeps being involved in active research on a part-time basis.

Hana Grison (born **Fialová**) joined our institute in 2001 and in 2005 received her PhD with the thesis "*Magnetic Discrimination between Lithogenic and Athropogenic Minerals in Soils*". Her main areas of interest fall into the field of environmental magnetism, with main emphasis on magnetic and geochemical properties of soils, but including also topics such as atmospheric dust. Some of her research activities bring together archaeology, geophysics and soil science, with the overall goal of maximizing interpretation of proxy data for archaeological purposes. In addition to geomagnetic methods, she applies a range of other methods involving, for example, non-magnetic experimental methods: leaching and extraction methods; pedochemical analyses; optical microscopy; scanning electron microscopy; X-ray diffraction; Mossbauer spectroscopy; etc. Currently she leads the project under the COST (European Cooperation in Science and Technology) action scheme and SAGA (The Soil Science & Archaeo-Geophysics Alliance).

Helena Žlebčíková (born **Munzarová**) has worked at Department of Seismology since 2007. She is interested particularly in applying seismological tools to study the structure of the Earth's upper mantle, with a specific focus on anisotropy of seismic-wave velocities. Currently, she collaborates with J. Plomerová on development and application of a code for travel-time tomography that involves anisotropic propagation of seismic waves in the upper mantle. Helena has participated in several funded projects aimed at research of the lithosphere in various tectonic provinces of Europe, e.g., in the Alps and their surroundings, where experiment AlpArray is being operated. She spent six months at ETH Zürich as a research assistant in 2013. In 2019, she defended her PhD thesis, "*Anisotropic tomography of the European upper mantle*", at the Faculty of Mathematics and Physics, Charles University. Following maternity leave, she continues her research work on a part-time basis.

Jana Doubravová joined the Department of Seismology in 2010 and has focused particularly on monitoring seismic swarms. Her work is devoted mainly to primary processing of the measured data using automatic algorithms. Jana participated on the programme for interactive manual processing of data from seismic networks and keeps improving it and broadening its functionality. In addition, she participates on the maintenance of seismic networks WEBNET and REYKJANET. She is involved in scientific outreach activities, namely in the topics of West Bohemian seismic swarms, and maintains the seismic exhibit in Skalná. In 2020, she successfully defended her PhD thesis „ *Automatic and semi-automatic processing of seismograms from local networks WEBNET and REYKJANET*“, at the Faculty of Mathematics and Physics, Charles University.

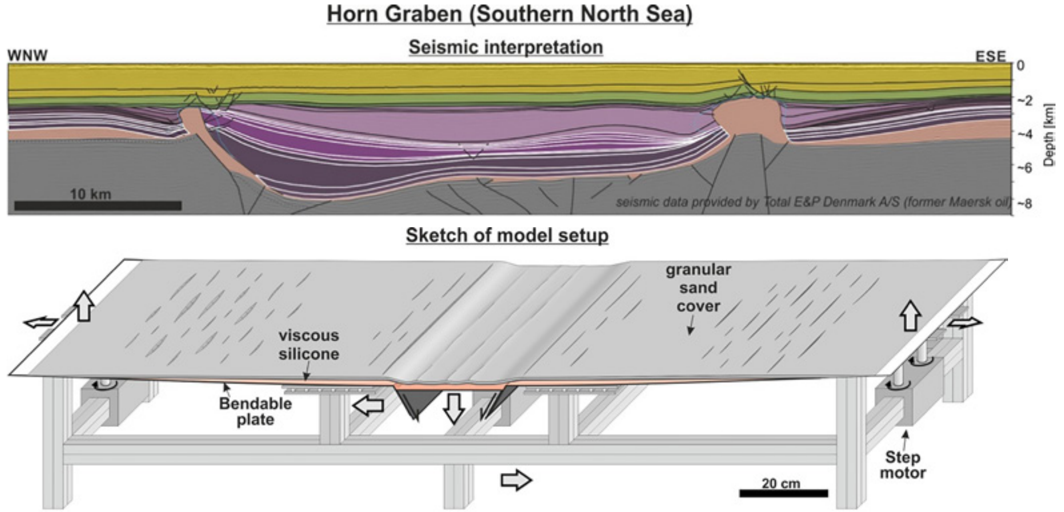
Professional awards to our young researchers

In 2018 and 2019, two of our young researchers were among the laureates of the Otto Wichterle award, named after a prominent Czech chemist who became the first president of the Czechoslovak Academy of Sciences after our country returned to democracy at the end of 1989. This award carries a financial premium of 330 thousand CZK and supports outstanding young researchers in developing and stabilizing their careers.

PLANETARY VOLCANISM, FROM CONES TO MUDFLOWS

For **Petr Brož** (*1984), volcanism across the Solar System has been the focus of research since his Master's thesis. During his PhD study at the Faculty of Science of the Charles University in Prague, he completed internships at the DLR (Germany) and at the Open University (United Kingdom). Petr's research has mostly been based on the analysis of remote sensing data from morphological and morphometric point of view, focusing on relatively small, kilometre-sized cones formed by explosive volcanic activity caused by magma degassing and water/magma interactions on the surface of Mars. More recently the scope of his work has expanded to include analogue modelling to help explain the possible origin of some lava-like features on the surface of Mars and to elucidate problems in identifying surface products of mud volcanism versus magmatic volcanoes (Brož et al., 2020a,b; Nature Geoscience; Earth and Planetary Science Letters). Petr has been awarded the prize of the foundation Nadání Josefa, Marie a Zdenky Hlávkových for talented students

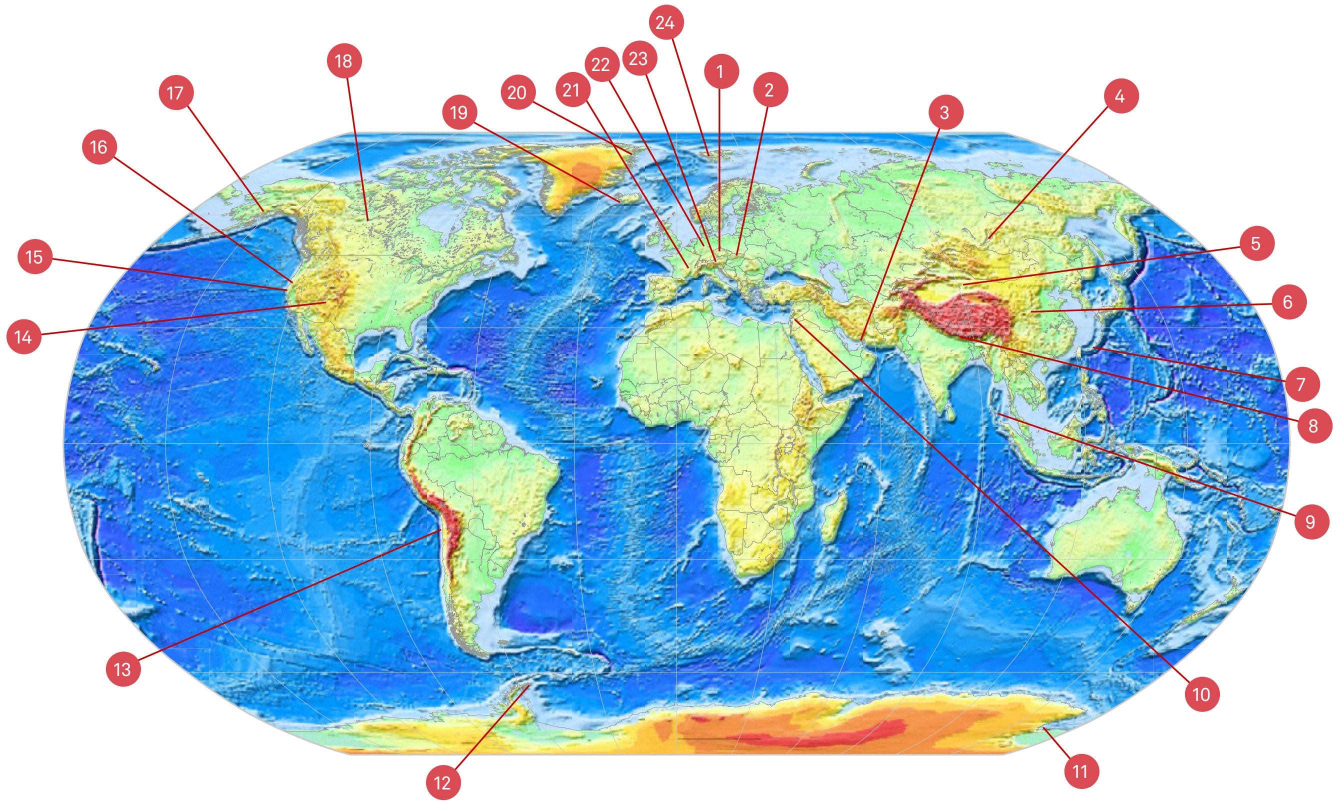
and young researchers (2017) and the Otto Wichterle Award of the CAS (2018). An important part of his activities lies in public outreach and education. Apart from popular science articles, lectures and videos, he has also engaged in development of teaching aids – for instance, an innovative "barrel organ" model of plate tectonics, designed jointly with Matěj Machek, which was awarded the prize SCIAP 2016.



SEDIMENTARY LAYERS IN MOTION

Michael Warsitzka (*1984) joined our institute in 2018, after finishing his PhD study at the Fridrich-Schiller – Universität in Jena, Germany. His prior experience includes also the Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences, and a stay at the University of Texas in Austin, USA. His research interests involve mainly the study of deformation of sedimentary basin fills by means of physical („analogue") modelling. This methodology is based on construction of scaled models of geological structures using a range of materials to simulate, in laboratory conditions, the behaviour of the real Earth's materials in deformation. In addition to their importance for basic research, Michael's analogue models have potential application in hydrocarbon exploration, radioactive waste storage, or hydrogeology. For 2019-20, Michael was granted a postdoctoral fellowship support by the CAS, and in 2019 he received the Otto Wichterle Award of the CAS.

Through his career so far, Michael worked on datasets from various parts of the world, including the South Atlantic Kwanza Basin, the North Sea, and the North German basin. Michael's current work includes, in collaboration with researchers and students from the Charles University, a new project funded by the Czech Science Foundation (GAČR) devoted to study and modelling of salt diapirism in the Zagros Mountains.



RESEARCH HIGHLIGHTS

The following pages are devoted to short communications summarizing the principal results achieved in various lines of research at the Institute between the years 2015 and 2020.

The topics studied and methods applied span a very broad range; our researchers are commonly involved in multi-disciplinary teams and collaborate with colleagues from many institutions worldwide. Therefore the organization of the text does not follow the traditional administrative structure of the Institute's departments, which will soon be replaced by a more flexible research team structure.

The global focus of research undertaken at the Institute of Geophysics in 2015-2020 is illustrated by the world map above.

World map constructed using the GMT software: Wessel, P. and Smith, W.H.F. (1998): New, improved version of the Generic Mapping Tools released. EOS Trans., AGU, 79, 579.

REGIONS OF OUR RESEARCH WORLDWIDE BETWEEN 2015 AND 2020

(1) the Bohemian Massif: West Bohemian seismicity; seismic imaging and Palaeozoic orogenic history of European lithosphere; Cenozoic volcanism; Cretaceous climate archives; Quaternary climate changes
(2) geophysical imaging of Western Carpathians
(3) salt structures in the Zagros foldbelt
(4) Baikal lake-level fluctuations
(5) geohazards, eastern margin of the Tibetan Plateau
(6) geohazards, Minjiang River, Sichuan
(7) seismicity and magmatism of southern Ryukyu Arc
(8) developing an Earthquake Early Warning system for Nepal
(9) seismicity and magmatism of Andaman Sea region
(10) palaeo-wetlands in Jordan
(11) imaging the magma chamber of Mt. Erebus volcano
(12) thermal regime of the active ground layer, James Ross Island
(13) seismicity of the Chilean megathrust
(14) Cretaceous greenhouse climate archives, SW USA
(15) induced seismicity at a geothermal reservoir, California
(16) Cenozoic magmatism, Klamath Mountains
(17) magma chambers of the Katmai volcanic system
(18) effects of postglacial warming in borehole temperature logs, N Canada
(19) REYKJANET seismic network, study of swarm seismicity in SW Iceland
(20) fjord-plateau formation, NE Greenland
(21) magnetic properties of soils, France (Massif Central)
(22) salt deformation in the North German Basin
(23) the Alps: re-dating oldest Alpine glaciation; participation in ALP Array seismic imaging; seismic signatures of Alpine slopes
(24) patterned grounds in Svalbard

Volcanic eruptions such as the Autumn 2017 eruption of the Agung volcano, Bali, Indonesia, underline the need for geoscientists to address topics that apart from scientific importance also have a significant impact on society. Seismicity patterns in the region that includes Agung and other highly active volcanoes, and their ties to plate-tectonic processes in SE Asia, belong to such topics and have long been studied by our researchers. The 2017 Agung eruption that caused evacuation of thousands of locals and tourists, and major disruption in air travel in SE Asia, was also commented by geophysicists of the Institute at its Czech web page (see https://www.ig.cas.cz/?s=agung). Photo provided by Petra Šimková.

Active plate-tectonic processes revealed by seismicity

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

Seismicity swarms occurring above subducting slabs in the Andaman Sea area and the Ryukyu subduction zone were investigated for their seismicity patterns in space and time (Špičák and Vaněk, 2016, 2017). The swarm earthquakes are shallow (1–60 km), in the body-wave magnitude range up to 5.8. In both areas, epicentral zones of the swarm earthquakes often coincide with distinct elevations at the seafloor – seamounts and seamount ranges. The upper plane of the Wadati-Benioff zone of the subducting slab reaches a depth of about 100 km beneath the zones of earthquake swarm occurrence, which is an average depth of a slab beneath volcanoes in general. The repeated occurrence of relatively strong, teleseismically recorded earthquake swarms thus probably reflects fluid and/or magma migration in the plumbing system of the volcanic arc. In addition, the Andaman Sea region repeatedly became a site of shallow swarms that followed distant mega-earthquakes (the December 26, 2004 Sumatra–Andaman MW 9.1 earthquake, the strong April 11, 2012 Indian Ocean MW 8.6 and 8.2 earthquake doublet west of Northern Sumatra) by days to weeks. Earthquakes of the most extensive January 2005 swarm migrated laterally at a rate of about 0.25 km per hour during the swarm evolution. It was concluded that the swarms likely accompany and trace the emplacement and migration of magma in the crust and mantle wedge above the downgoing oceanic lithosphere.

In Northern Chile, in-depth studies of earthquakes occurring along the plate interface showed that aftershock productivity, i.e. the amount of aftershocks created by a given main shock, is indicative of the local distribution of coupling between the plates (Hainzl et al., 2019). An analysis of af-

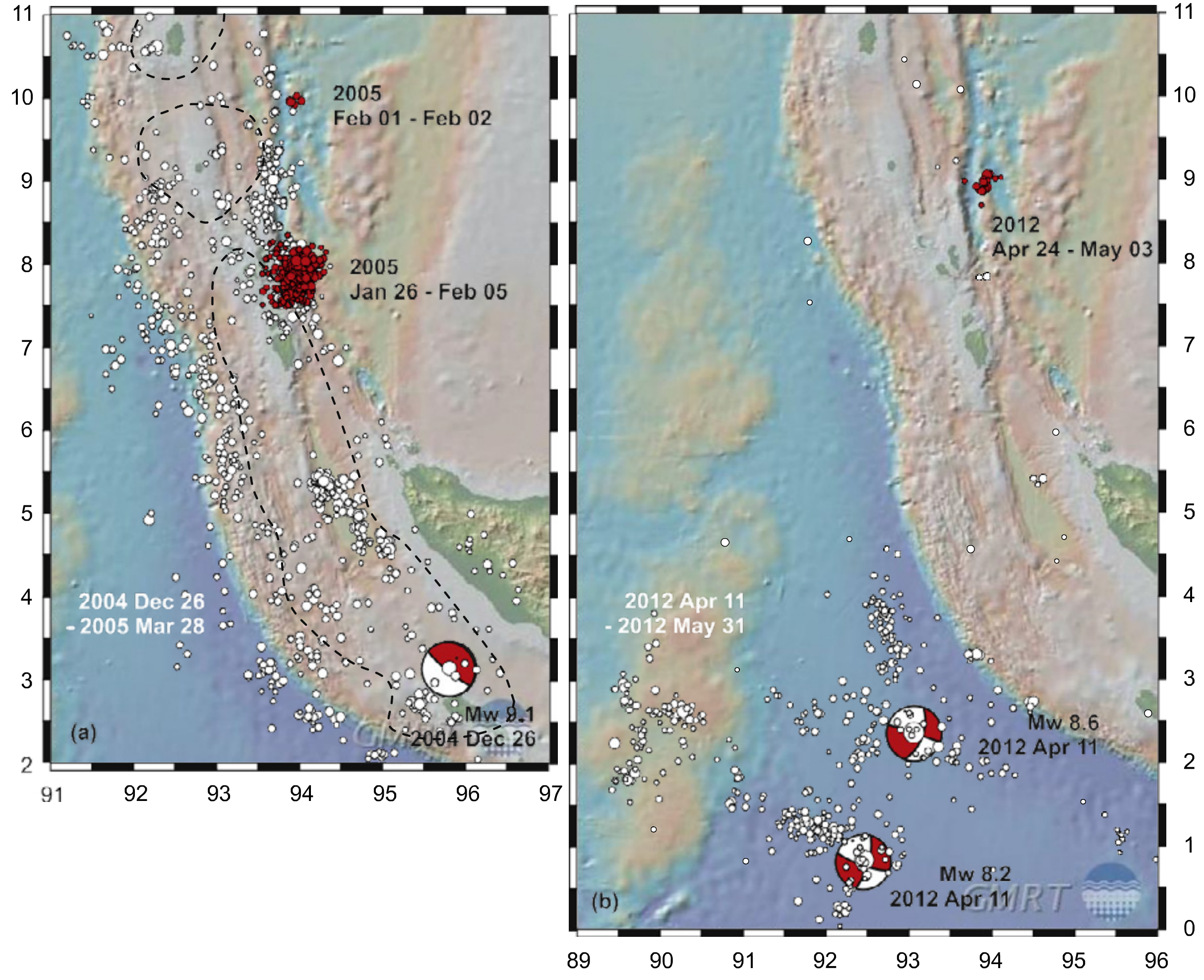


Fig. (a) Epicentral map (white circles) of the MW 9.1 December 26, 2004 Sumatra–Andaman earthquake and its aftershocks by March 28, 2005. Rupture areas of the Mw 9.1 event are circumscribed by dashed lines. Red circles denote the January 26 – February 05, 2005, and the February 01–02, 2005 swarm earthquakes. (b) Epicentral map (white circles) of the MW 8.6 + 8.2 April 11, 2012 Indian Ocean earthquake doublet and the aftershocks by May 31, 2012. Red circles denote the April 24–25, 2012 earthquake swarm. After Špičák and Vaněk (2016).

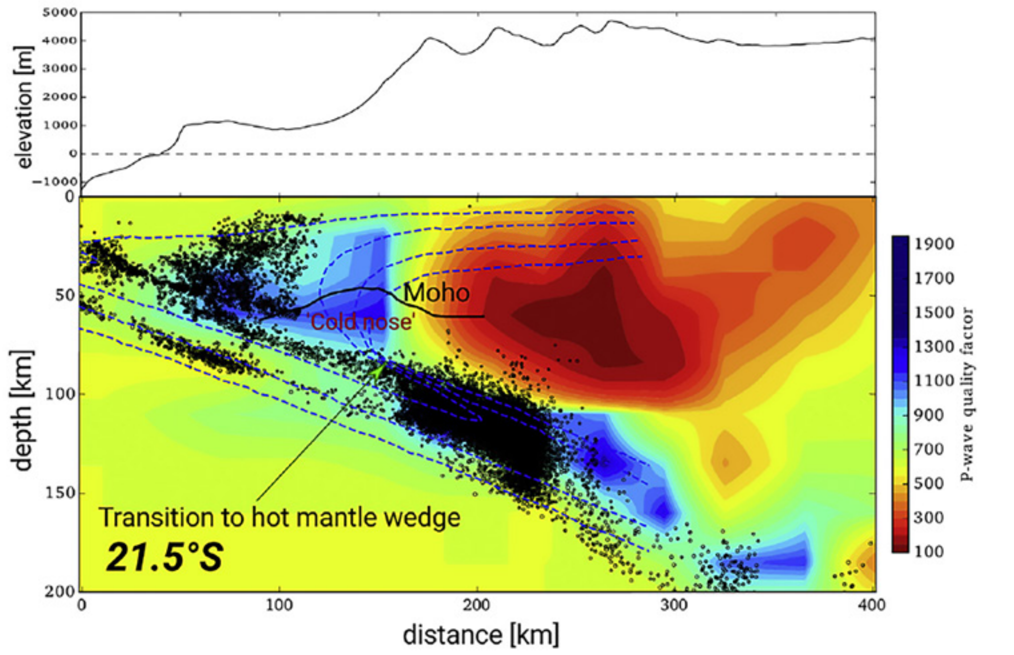


Figure 3: East-west cross section through the North Chile subduction zone at 21.5 degrees south. Slab seismicity (black dots) becomes most intense where temperatures in the overlying mantle wedge, indicated by attenuation values (blue – cooler; red – hotter), increase. Modified from Sippl et al. (2019).

tershocks of the 2014 Iquique earthquake (M8.1) revealed that aftershocks and aseismic slip occurring in the years after the main shock anti-correlate, i.e. they occur at the same time but occupy different regions of the plate interface (Soto et al., 2019). Looking at deeper earthquakes that occur within the downgoing slab at depths of 50-150 km, Sippl et al. (2019) found that the Nazca slab in this area shows an earthquake distribution that is distinct from other subduction zones (see Figure 3). Combining information from earthquake locations, moment tensors and statistical seismology, they derived a conceptual model of how delayed phase transformations in the Nazca slab may create the retrieved seismological signature.

Through collaboration with Marco Bohnhoff at GFZ Potsdam, GFU researchers are also involved in ongoing work along the North Anatolian Fault, a major active strike-slip system in Turkey. Examining signals from locally recorded microearthquakes along a fault segment east of Istanbul, a peculiar arrival type associated with a steep fault zone acting as a wave guide was identified (Najdahmadi et al., 2018). Obtained stress field properties for the Sea of Marmara, to the southwest of Istanbul, show that a future M7 earthquake in the area could feature either strike-slip or normal faulting (Wollin et al., 2019).

Structure of the European lithosphere

The Institute of Geophysics has long been focusing its research on the crustal and mantle architecture of the Bohemian Massif, the surrounding younger mountain ranges (the Alps, Carpathians) as well as the markedly older East European Platform. As most parts of Central and Eastern Europe feature only local and small-scale present-day tectonic activity, local seismicity rates or geodetically measured displacements are too low to be used in most areas. Therefore, we exploit signals from controlled sources or of distant origin (earthquakes) to image the structure of the lithosphere.

CRUSTAL STRUCTURE AND THE CRUST-MANTLE BOUNDARY

To image the shallow and deeper crustal structure, our researchers investigate electric and electromagnetic properties of crustal rocks (e.g. Červ et al., 2019; Kováčiková et al., 2019; Bezak et al., 2020). Larger-scale differences in electrical conductivity, for instance, can hint at differences in lithology, whereas more local anomalies can be due to fluid processes. For example, Klanica et al. (2018) used magnetotelluric data from a 140 km E-W profile across the eastern margin of the Bohemian Massif to retrieve the conductivity signature of lithologies corresponding to three different orogenic cycles in Central Europe. Bulk crustal structure can also be constrained with seismic background vibrations, as done by Růžek et al. (2016) who characterized the different crustal units of the Bohemian Massif by their shear-wave velocity profiles.

The geometry and character of the crust-mantle boundary (Moho) gives valuable clues to the tectonic evolution of a region. Re-processing of deep seismic reflection profile '9HR' helped to revise the crustal structure and the Moho in the western Eger Rift (Mullick et al., 2015). Complemented by results from refraction profiles and local seismicity, the reflection profiles reveal significant lateral variations of the lower crust which point to a local-scale magmatic emplacement and differentiate timing and setting of two tectonic episodes in this geodynamically active area (Hrubcová et al., 2017). Interpretation of several refraction and wide-angle seismic profiles in the Western Carpathians reveal systematic structure anomalies of the Moho discontinuity along the Carpathian arc (Hrubcová and Środa, 2015). Together with the Pieniny Klippen Belt at the surface these Moho anomalies represent the whole-crustal contact between the stable European Plate and the ALCAPA (Alpine–Carpathian–Pannonian) microplate related to tectonic formation of the Carpathian orogen (Figure 1).

The Institue is a member of the core group of the AlpArray programme, a large, multidisciplinary international initiative (http://www.alparray.ethz.ch/en/home), whose primary mapping tool – the AlpArray Seismic Network (Hetényi et al. 2018a) – consisted of over 600 seismic stations. Within over 2 years, the array collected ~15 TB of raw data, which will be enlarged by data from several regional complementary passive experiments. Beyond seismological targets, answers to questions from geology, gravimetry, geodynamics, petrology and geodynamic modelling contribute to the integrated mapping of the lithosphere. As a part of our involvement in the AlpArray Seismic network, a passive N-S traverse of ~540 km length (AlpArray-EASI complementary experiment), extending from north of the Eger Rift all the way to the Adriatic Sea, was investigated with the use

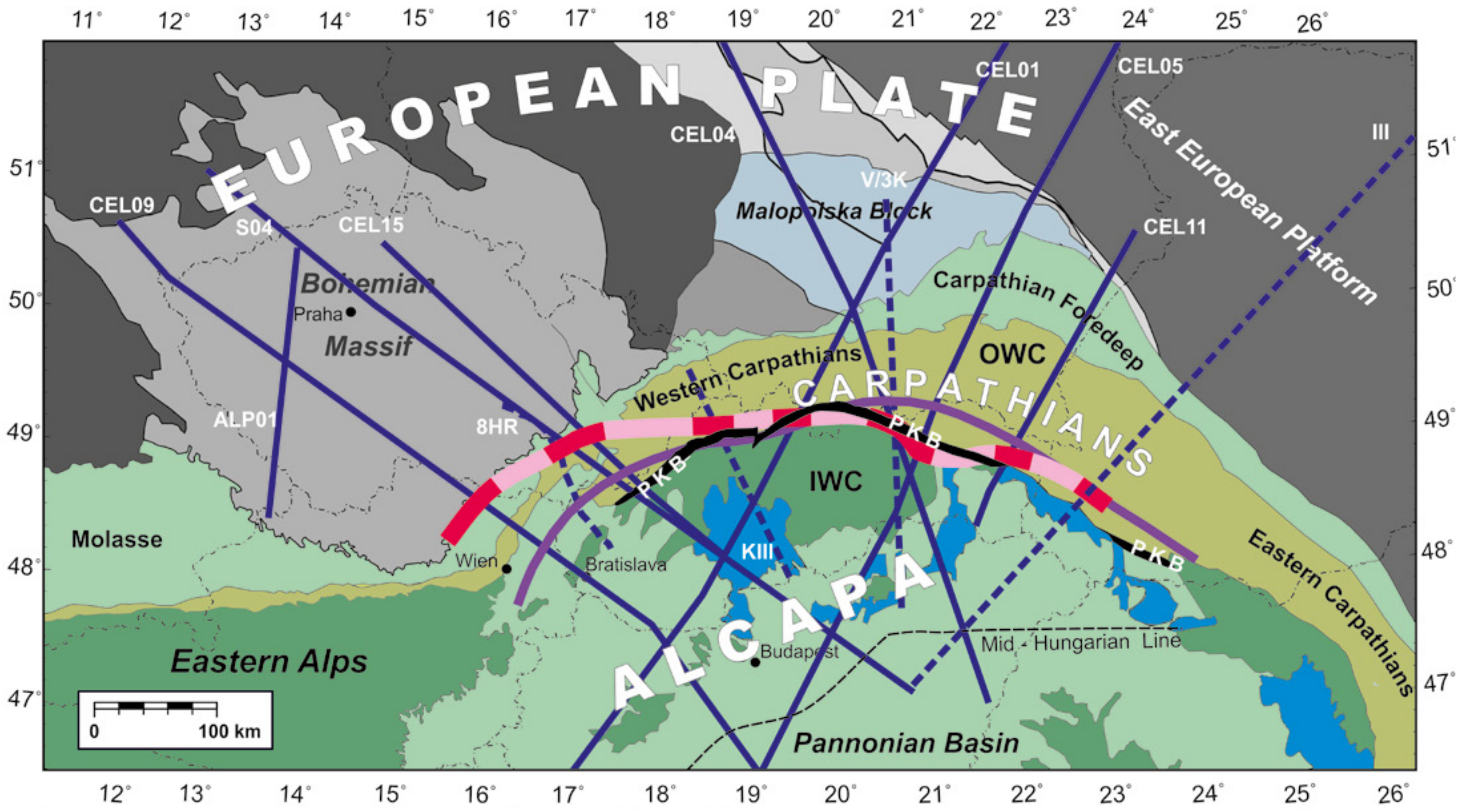


Figure 1: Simplified tectonic map with projected anomalies in Moho discontinuity interpreted at refraction and wide-angle reflection profiles (red/pink line) and Carpathian conductivity anomaly (magenta line). Note their proximity with the Pieniny Klippen Belt (black line denoted PKB) along the Western Carpathian arc (Hrubcová and Środa, 2015).

of converted waves (Hetényi et al., 2018b). The obtained high-resolution images of the crust show that the European and the Adriatic Moho dip steeply towards the Alpine orogen, the latter penetrating deeper in accord with the earlier tomography results of the upper mantle down to 300 km (Figure 2).

ARCHITECTURE OF THE MANTLE LITHOSPHERE

Signals from distant earthquakes allow us to resolve mainly the mantle part of the lithosphere. Teleseismic traveltime tomography exploits deviations in propagation of P and S phases from distant earthquakes recorded at networks of seismic stations located in the respective study areas. With this approach, Plomerová et al. (2016) showed there is no narrow, subvertical low-velocity anomaly beneath the Bohemian Massif, a feature that would be expected according to the previously suggested 'baby-plume' concept for the European Cenozoic Rift. Chyba et al. (2017) used a large dataset from stations across the Trans-European Suture Zone (TESZ) and the East European craton to model the contact of the Phanerozoic and Precambrian mantle lithospheres in north-eastern and central Europe. Similarly to our previous anisotropy studies, the tomography images an overthrusting of the Phanerozoic over the Precambrian mantle lithosphere in north-eastern and Central Europe.

Seismic anisotropy, i.e., variations of seismic wave speeds in dependence to the direction of wave propagation, is an observable well-suited to the in-depth investigation of upper mantle structure and past tectonic processes. Olivine, the most abundant anisotropic mineral in the Earth's mantle, aligns under pressure with the fast axis pointing in the direction of flow when mantle material is moving and deformed. A widely used tool for assessing strain and orientations of anisotropy is so-called shear-wave splitting, i.e., the birefringence of fast and slow shear-waves in anisotropic materials. The seismology group at the Institute develops and applies a wide range of methods to retrieve anisotropy in 3D, combining a generalized method of shear-wave splitting with the directional analysis of body wave residuals and a novel coupled inversion approach for body wave-speeds and anisotropy (Munzarová et al., 2018a,b).

Anisotropy constraints for the mantle lithosphere, down to the estimated lithosphere-asthenosphere boundary, allow us to delimit individual domains within plates. Babuška and Plomerová (2017) model the lithosphere domains of the Bohemian Massif and document that the rigid mantle lithosphere of the colliding microplates acted as the major stress guide during its amalgamation. Correlating domain boundaries in the mantle lithosphere with crustal blocks shows often a lateral offset between the two (see Figure 2). The prevailingly tilted fast symmetry axes found in the mantle lithosphere are explained as the consequence of a subduction origin of the individual lithosphere domains (Babuška and Plomerová, 2020). Anisotropy in the oceanic mantle lithosphere was "frozen-in" soon after the creation of the plate at the mid-oceanic ridge. The symmetry axes then became tilted during oceanic plate subduction. Subsequent plate fragmentation, followed by rifting and re-assemblage of the different micro-plates created the picture of juxtaposed domains with differently oriented and tilted anisotropy axes seen today.

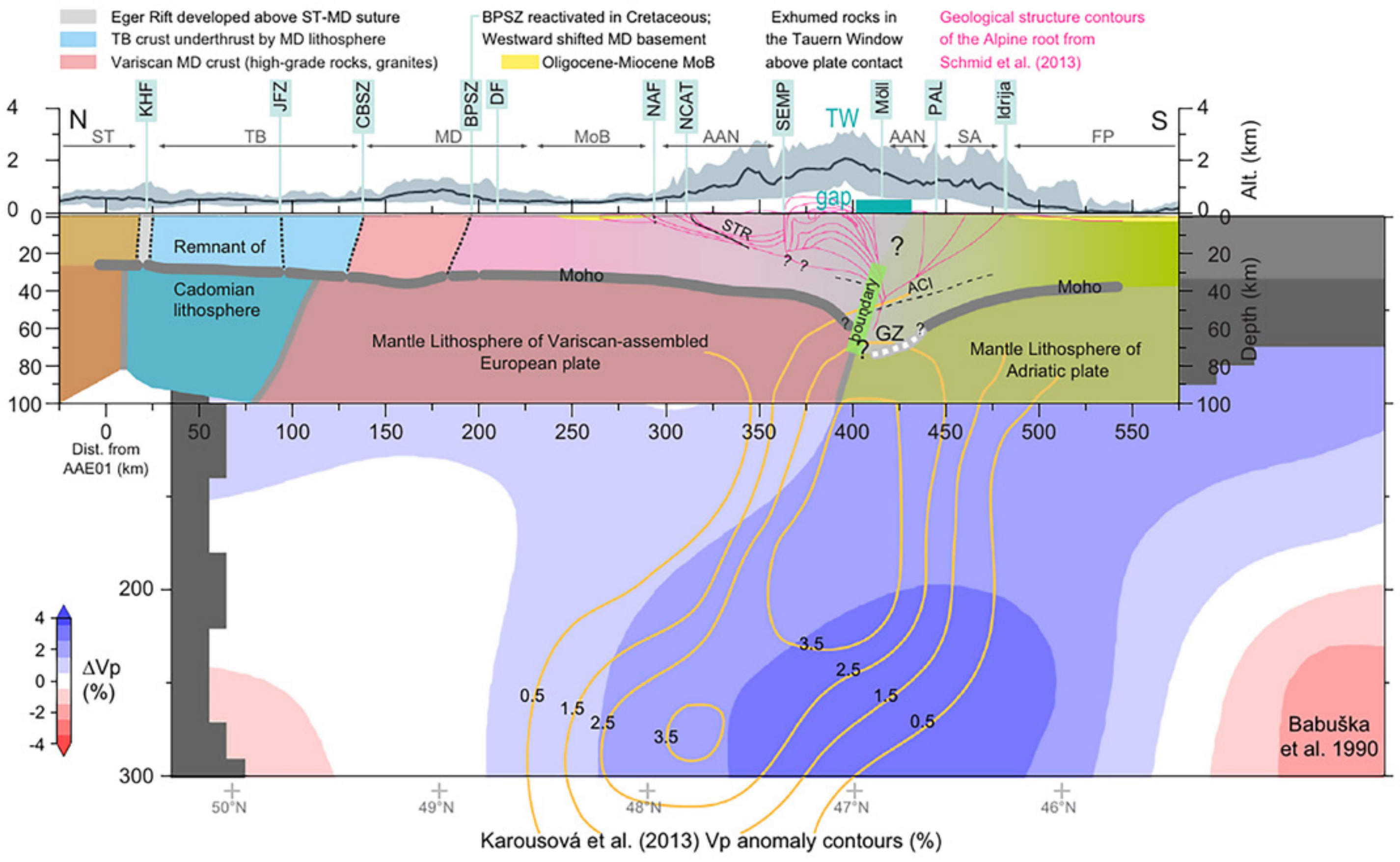


Figure 2: Summary of the current knowledge about crustal units, Moho geometry and mantle lithosphere structure along the AlpArray-EASI transect (Hetenyi et al., 2018b), extending from N of the Eger Rift (left end of the plot) to the Adriatic Sea (right end of the plot). The sub-vertical green band is the proposed plate boundary at middle and lower crustal depths. GZ – gradient zone, with white-dotted line as bottom. The colour-plotted P-wave upper mantle tomography (with 1.5° resolution) is redrawn from Babuška et al. (Tectonophysics, 1990); contours of Vp based on P-wave tomography by Karousová (Geophys. J. Int., 2013), with 40 km resolution, are shown for comparison.

Seismic source and wave propagation studies

The seismic source, as well as propagation of seismic waves, have been traditionally strong lines of research at our institute. These topics have a firm basis in basic research but also a significant range of applications in practical seismology. Many studies are based on extensive natural earthquake datasets, such as those provided by the WEBNET seismological network in West Bohemia, or they employ theoretical and model-based approaches.

WEST BOHEMIA/VOGTLAND SEISMOACTIVE REGION

The West Bohemia/Vogtland earthquake-swarm region, one of the most seismically active areas in Central Europe, has been a subject of ongoing research at our Institute for many years. Long-term seismic monitoring and systematic analysis is a key factor to understand this natural phenomenon. The research of this local phenomenon finds broad applications in geophysical modelling, especially in the field of fluid driven induced seismicity. Moreover, the research in this direction has a social relevance because of possible occurrence of a strong damaging earthquake in this region.

Intraplate earthquake swarms occur in the region quite irregularly (typical recurrence of 5-20 years). These intense bursts of seismic activity (Figure 1) present a challenging seismological problem in which the correct identification of single events in continuous seismogram traces is crucial for meaningful interpretations. Since manual identification of the events is time consuming, machine learning approaches have been developed and applied (Doubravová et al., 2016; 2019). The analysis of West Bohemia recent seismicity resulted in discovery of mainshock-aftershock activity in 2014 (Jakoubková et al., 2018). This can be explained by a stress anomaly at a tectonic fault step (Vavryčuk and Adamová, 2018) or by fluid intrusions (Hainzl et al., 2016). The Earth fluids (e.g., water and carbon dioxide) play a significant role in the observed seismic activity. For example, Fischer et al. (2017) detected a significant carbon dioxide release following one of the stronger events, Vavryčuk and Hrubcová (2017) presented seismic evidences of the fault erosion by fluids, and Bachura and Fischer (2016) introduced a seismic method for indirect monitoring of fluid presence in the focal area. High-quality datasets and event catalogues allowed for introduction of new methods for the seismic moment tensor inversion (Vavryčuk et al., 2017; Vavryčuk and Adamová, 2020), suitable for automatic processing large sets of earthquakes. The applicability of the new methods was demonstrated by inverting more than 400 micro earthquakes that occurred during the 2014 swarm. This allowed for identification of reverse faulting mechanisms anomalous for the region (Figure 2). The earthquake swarms source locations also served to illuminate the prominent crustal discontinuities and to determine their depth (Hrubcová et al., 2016). All of these studies would not have been possible without the seismic network WEBNET operated by the Institute.

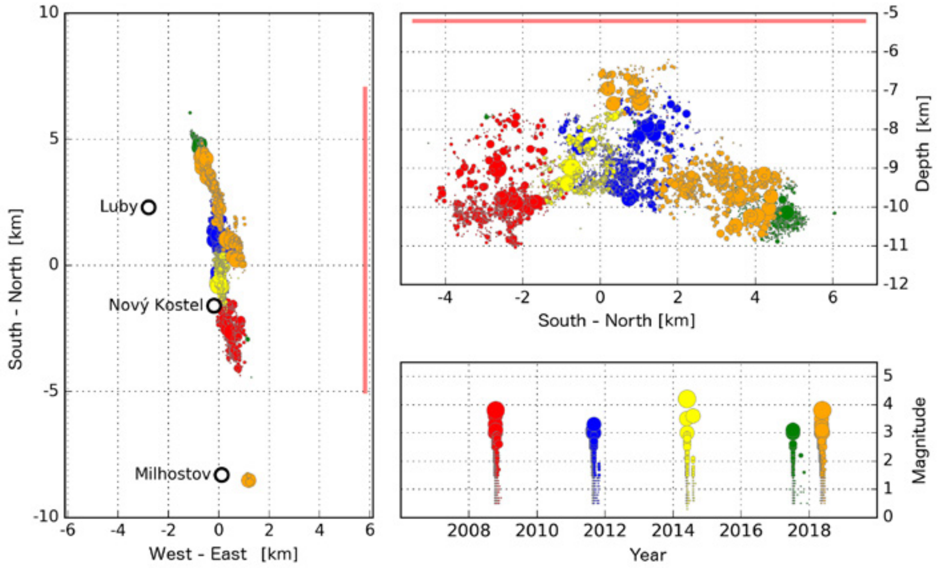


Figure 1: Recent bursts of seismic activity in Western Bohemia. Colors represent different swarms. Map-view shows the distribution of epicenters (left), while the vertical cross section shows the hypocenter distribution along the fault (top right). The mainshocks of the 2014 swarm can be recognized from the distribution of the earthquake magnitudes in time (bottom right).

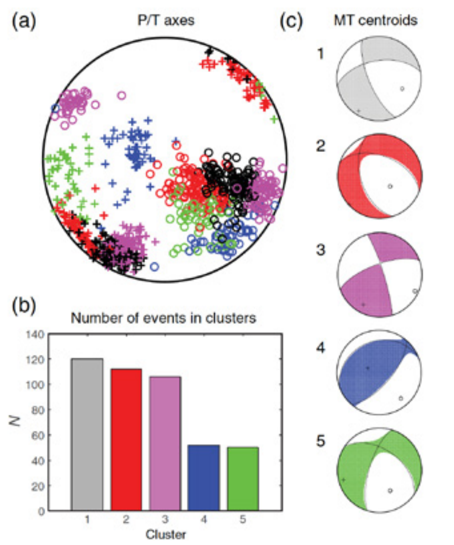


Figure 2: Classification of the 440 reliably determined moment tensors into five clusters by objective cluster analysis. (a) The focal sphere with P/T axes. (b) the number of events in individual clusters. (c) Corresponding focal mechanisms. The color coding follows the individual clusters. (from Vavryčuk et al., 2017).

RAY THEORY AND SEISMIC ANISOTROPY

Theoretical studies of seismic wave propagation at the Institute have focused on solving current problems in the field of anisotropic viscoelastic structures. Seismic anisotropy studies have evolved over the years from a largely theoretical field to a key component in building robust structural models from seismic data. The theoretical developments in asymptotic high-frequency methods find practical use in exploration geophysics (e.g., oil industry) or in laboratory rock sample characterization.

Seismic ray reflection moveout equation describes the arrival time of a reflected wave from a subsurface interface along a seismic profile. It is used to detect strong subsurface reflectors in active seismic experiments. A number of moveout equations have

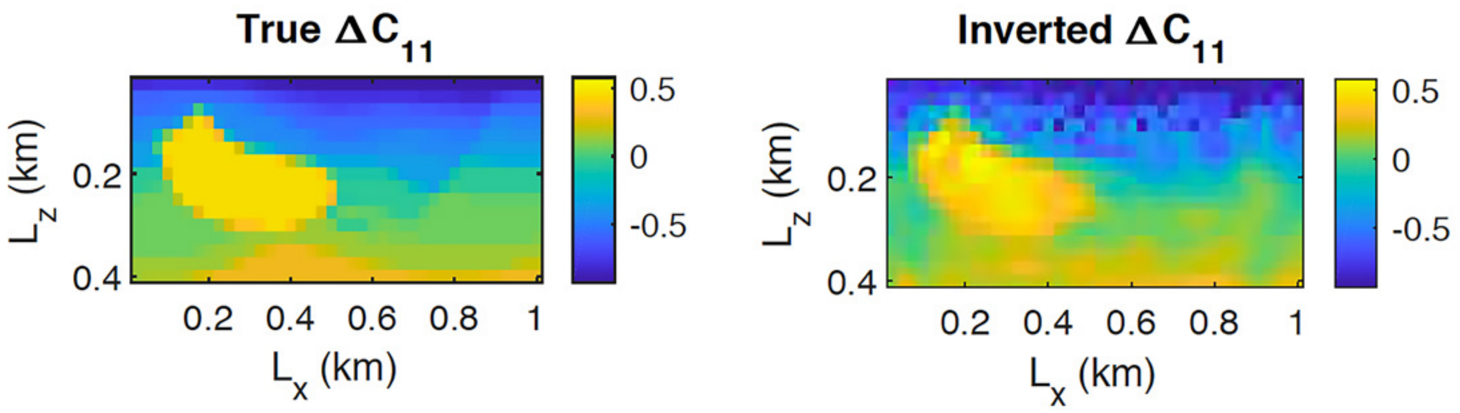


Figure 3: The true transversely isotropic Hess model (left) is laterally inhomogeneous and includes a high-velocity salt body as well as several faults. Result of anisotropic elastic full waveform inversion (right) replicates well the anisotropic characteristic except for the fault boundary. Modified after Jakobsen et al. (2020).

been introduced for various combinations of anisotropy types, wave polarizations and typical subsurface layering (Farra and Pšenčík, 2016, 2017, 2018, 2019; Pšenčík and Farra, 2017). For example, Farra and Pšenčík (2019) derived reflection moveout approximation for a P-SV wave in a moderately anisotropic homogeneous vertical transverse isotropic layer. Červený and Pšenčík (2017) derived elastodynamic Green's function for inhomogeneous layered anisotropic structures using Gaussian beams, which represent a computationally less demanding option compared to standard two-point ray tracing. Full waveform inversion scheme for estimation of anisotropic parameters was introduced by Jakobsen et al. (2020). A synthetic test of this method replicated well the image of the reference media (Figure 3). Seismic wave propagation in viscoelastic anisotropic media was studied by Vavryčuk (2015), who developed and numerically tested a method for determining parameters of homogeneous viscoelastic anisotropic samples. The method was extended and successfully applied to dataset recorded during ultrasound laboratory experiments on serpentinite rock sample from Northern Italy (Vavryčuk et al., 2017).

SEISMIC SOURCES IN NATURE AND IN LABORATORY

Understanding the origins of earthquakes represents one of the fundamental questions in seismology. The research of tectonic earthquakes has been based on rather uncontrolled experiments. Reliable seismic-event prediction considering magnitude, space, and time is not possible as yet. In contrast, seismic events generated in laboratory by deformation of rock samples are fully controlled experiments. There is also a certain level of control in case of induced or triggered earthquakes, for example in cases of waste water disposal in deep wells or production of geothermal energy. The researchers at our Institute take advantage of the induced and laboratory earthquakes in order to uncover general processes in earthquake foci by means of seismic waves. In particular, they mainly utilize their unique expertise in moment tensor inversions.

Analysis of hundreds of induced micro earthquakes from The Geysers geothermal reservoir in California was performed. It revealed that the retrieved moment tensors depend on the frequency band of the inverted waveforms (Yu et al., 2019). The shear-rupture mode source radiates energy preferentially in a lower frequency band, while tensile rupture does so in a higher frequency band. This might be related to the strong thermoelastic effects in the vicinity of injection points that promote opening of small cracks adjacent to the main fractures. Stress-field inversion from the retrieved moment tensors was also performed and its sensitivity to pore-pressure changes was investigated (Martínez-Garzón et al., 2016). The retrieved stress ratio was found useful for monitoring pore pressure changes at seismogenic depth. Significant spatial variations of faulting regime were also observed, which correlated with stress change due to fluid injection or regional tectonics (Yu et al., 2018), see Figure 4.

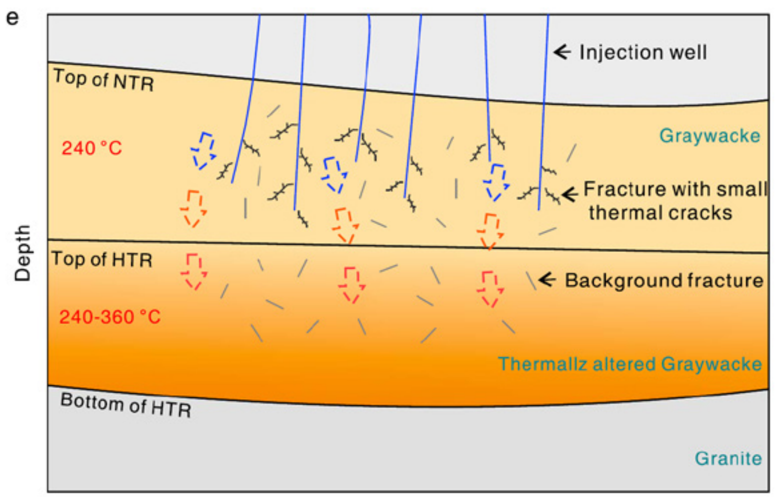


Figure 4: Schematic diagram illustrating the distribution and the mechanisms of events in the Geysers geothermal reservoir with a significant increase of volumetric changes during rupturing. Modified after Yu et al. (2019)

Moment tensors were estimated and analyzed also for seismic events (usually called acoustic emissions) recorded during a set of laboratory rock deformation experiments. It is a demanding procedure requiring careful calibration of the sensors and accurate knowledge of the velocity model which is changing due to opening or closure of microcracks in the sample during loading. Sensitivity of the rock deformation experiments to attenuation and anisotropy was studied by Stierle et al. (2016). They showed that moment tensors retrieved for anisotropic rock samples are affected by seismic anisotropy and deviate from the true orientation of faulting. Nevertheless, these can be utilized to provide information on the attenuation parameters of the rock sample. A shear-tensile model was implemented for acoustic emission events in a Westerly Granite rock sample and proved to be useful for recognizing the threshold of unstable microcracking, and indicative for determining the failure plain orientation (Petružálek et al., 2018). While the Westerly Granite is mostly isotropic, Petružálek et al. (2019) performed deformation experi-

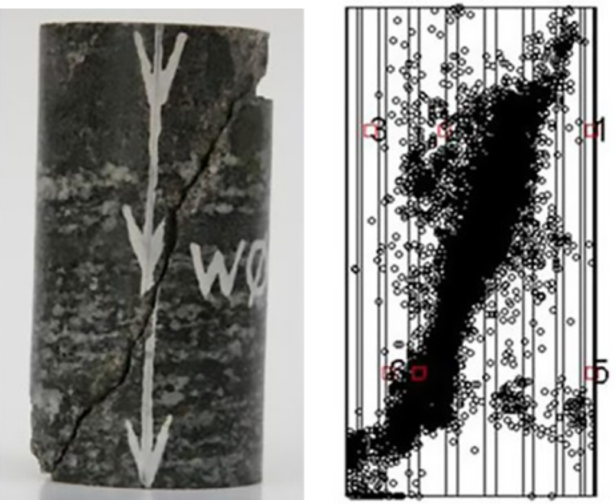


Figure 5: Macroscopic plain fracture of the migmatite specimen (left). Corresponding hypocenter locations of the acoustic emission events (right). Modified after Petružálek et al. (2019).

ments on anisotropic migmatite rock sample. An example of macroscopic plain failure of loaded specimen is shown in Figure 5 together with located hypocentres of acoustic emission events. The orientations of local stresses were retrieved from the moment tensor solutions and compared with the foliation and failure plain orientations. The provided detailed description of the rupture processes can be generalized for other types of metamorphic anisotropic rocks with a plane-parallel structure.

AMBIENT VIBRATIONS OF UNSTABLE ROCK SLOPES

Although it is natural and straightforward to study seismic response and structure of the Earth directly from the earthquake recordings, these are not always available (or just in a limited number). Therefore, a significant number of current seismological studies rely on the use of ambient vibrations. Seismic ambient vibrations are tiny persistent tremors of the ground not felt by humans but measurable by sensitive seismometers. The research at our Institute has focused on the use of ambient vibrations for non-conventional characterization of unstable rock slopes (i.e, sites capable to generate catastrophic landslides). Risk mitigation of potentially catastrophic landslides requires a thorough understanding of the mechanisms driving the slope movements and ambient vibration surveys might represent a cheaper alternative to methods like drilling or active seismics.

A systematic collection of ambient vibration measurements at 25 unstable rock slopes in Switzerland was presented in Kleinbrod et al. (2019). The sites had diverse geological properties, activity level, failure mechanism, fracturing and volumes. A simple classification scheme was proposed according to their dynamic behaviour. While for some of the slopes the seismic wavefield is controlled by horizontally propagating surface waves in the highly fractured and weathered material, the ground motions are dominated by the eigenvibrations of the rock mass for the rest of the sites. A simple, effective model for fractured rock mass applicable to seismic wave propagation problems was introduced by Burjánek et al. (2019). The proposed rock mass model was applied and tested for an unstable slope in southwest Switzerland, reproducing well the observed seismic response in a broad frequency range (Figure 6). An attempt to monitor unstable slope by means of ambient vibrations is presented in Burjánek et al. (2018). The goal was to identify changes in the resonant frequency caused by internal damage that may precede subsequent failure. The resonant frequencies exhibit seasonal trends related to temperature changes and sensitivity to freezing periods. These effects are attributed to thermal expansion driving microcrack closure and add up to ice formation increasing fracture and bulk rock stiffness. A method for fracture network imaging on rock slope instabilities using resonance-mode analysis is introduced by Häusler et al. (2019). The method potentially detects hidden fractures that cannot be observed by geological field mapping.

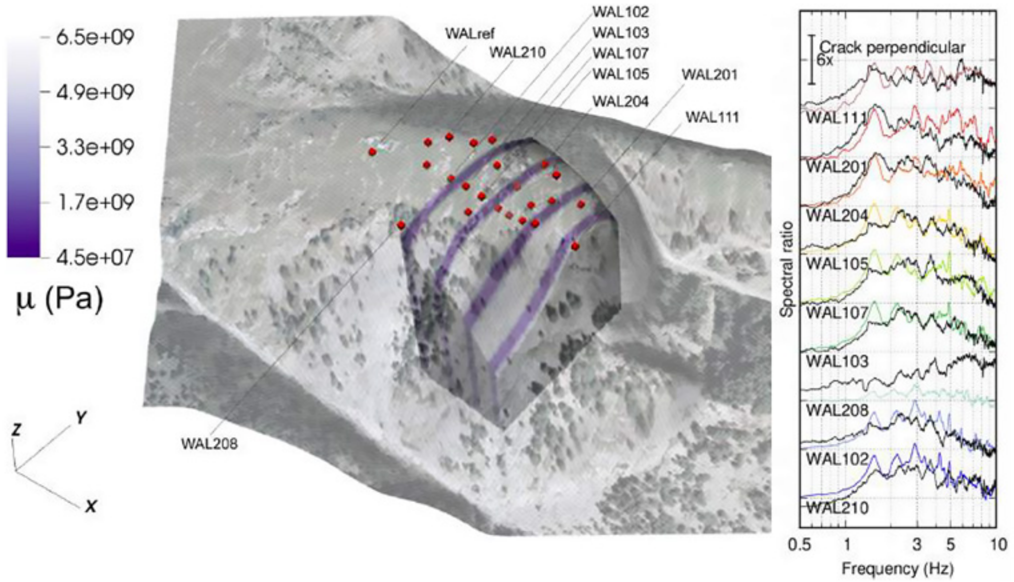


Figure 6: A 3-D snapshot of fractured rock mass (left). The shear modulus is shown in color, with dark magenta identifying the cracks. Red cubes indicate positions of the seismic stations. The comparison of the observed (black) and simulated (color) frequency dependent response shows good agreement (right). Modified after Burjánek et al. (2019).

Structure and deformation analysis of ancient orogens

Orogens – continental-scale mountain ranges – reflect consolidation of continents during collision of tectonic plates, which are associated with rock metamorphosis, melting and transfer of heat and mass in the lithosphere. For instance, the geological structure of Central Europe, exemplified by the Bohemian Massif, reflects the history of a large Palaeozoic orogen, frequently compared to the recent Himalayan mountain range. Both recently active mountain belts and ancient orogens forming a large part of continental lithosphere are important targets for study using field structural mapping combined with petrological, geochronological and geophysical methods.

The basement rocks of the Bohemian Massif record widespread granite magmatism related to extension and rifting in Proterozoic to Early Paleozoic (Soejono et al., 2017, 2020). After this rifting period, Bohemian Massif was finally consolidated by subsequent amalgamation of continental blocks in Variscan orogeny that culminated 340 million years ago. During collision of the blocks, continental subduction and heating of the crust, the rocks started to melt and became mechanically weak and buoyant. Some of this material returned upwards along the mantle-slab interface and then spread laterally along the bottom of the upper plate in a process called relamination. Physical properties and geochemical evidence for the relamination of the crust in Bohemian massif was studied for example in the aureoles of mantle peridotites surrounded by granulites (Kusbach et al., 2015). Another study revealed that melt flux in the subducted continental crust is focused along shear zones parallel to the subduction-related deformation fabric (Závada et al., 2018). As the melt percolates along the shear zones, the melt weakening migrates decoupling from the underlying slab, folding and exhumation of the partially molten rocks to lower crustal levels. Exhumation is again enhanced by melt weakening, because melt redistributes along the fold planes and fold axial cleavage (Závada et al., 2017).

A complementary and powerful method that helps understanding the complex geological evolution of orogens is *analogue modelling*. Construction of analogue models is motivated by the fact that the evidence about geological processes from rock outcrops is limited as the exposure in map view represents frequently the only section and a single timeframe of their complex evolution. The challenging task during design and construction of these models is identification of the key material parameters and structure of the system that govern the general physical behavior of the model reflecting the prototype. New models, constructed in our laboratory of tectonic modeling, employ, for instance, rheologically thermally dependent materials (e.g. paraffin wax for partially molten rocks) and quantification of deformation using the digital image correlation or particle image velocimetry (Krýza et al., 2019).

HISTORY OF CONTINENTAL CRUST OF THE BOHEMIAN MASSIF BEFORE THE VARISCAN OROGENY

The study of geochemical characteristics and zircon U–Pb ages of pre-Variscan meta-igneous complexes in the Bohemian Massif were interpreted to record a complete orogenic cycle from the Ediacaran–earliest Cambrian convergence and subduction to the Late Cambrian–Early Ordovician divergence and formation of the passive margin (Fig. 1). Two-stage geodynamic model was proposed as most plausible for the documented widespread crustal anatexis: (1) post-orogenic thermal and gravitational relaxation of a thickened continental margin (Fig. 1b); (2) followed by lithospheric thinning and asthenospheric mantle upwelling assisted by far-field forces of a distant subduction zone (Fig. 1c) (Soejono et al., 2017, 2020).

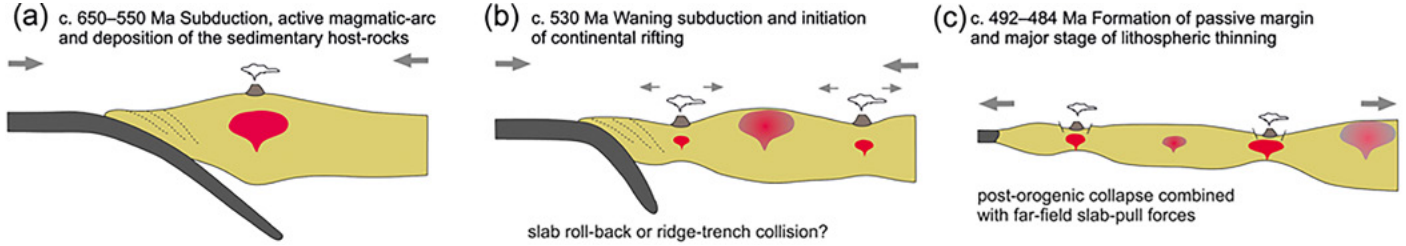


Fig. 1. Schematic diagrams illustrating the geodynamic evolution of the Gondwana periphery from the Neoproterozoic to the Early Paleozoic

CONTINENTAL CRUST RECYCLING THROUGH RELAMINATION AND DIAPIRIC EXHUMATION

The tectonic relamination model was proposed as the most suitable to explain the juxtaposition of contrasting crustal and mantle rocks in the Náměšť Granulite Massif in Bohemian Massif (Fig. 2). This hypothesis is based on several geochemical and petrological arguments. The possible scenario starts with the Late Devonian subduction of the Silurian–Devonian passive margin of the Saxothuringian continent beneath an Andean-type active margin. The final juxtaposition of mantle peridotites and lower crustal granulites was triggered by the influx of relaminated felsic material. The exhumation of Náměšť Granulite Massif was then driven by diapiric folding (Kusbach et al., 2015).

Závada et al. (2018) focused on high pressure and partially molten subducted crustal sequence in the Eger

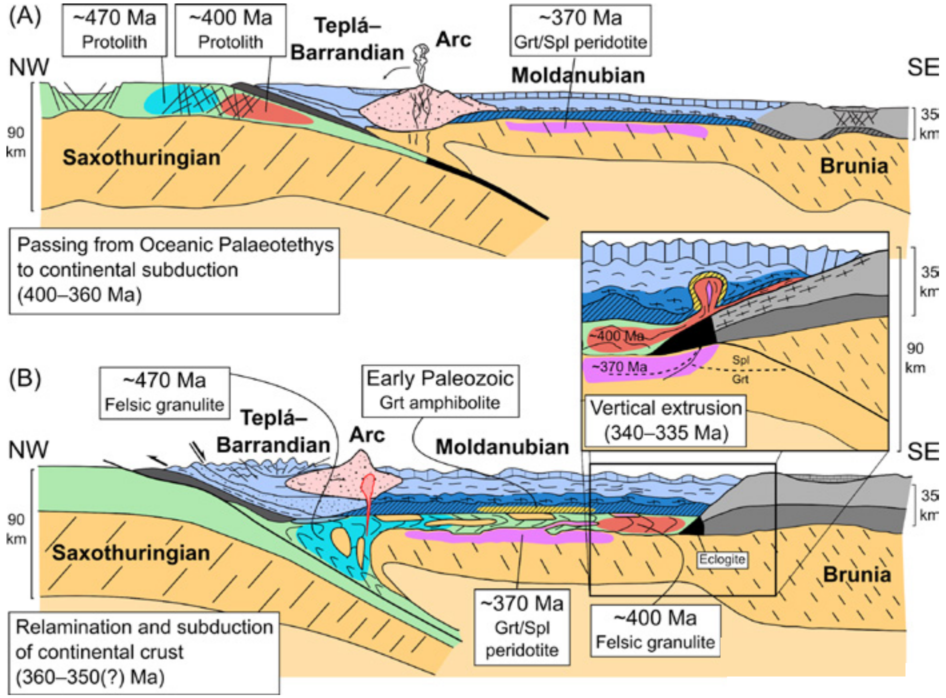


Fig. 2. Tentative geodynamic model for the origin of the Náměšť granulite–mantle peridotite association by deep crustal subduction and relamination. (a) Subduction stage; oceanic subduction leads to deep underplating of the Saxothuringian metaigneous crustal material under the arc region. (b) Relamination stage; part of the deeply underplated allochthonous Saxothuringian crust is injected at about the base of the continental crust (to be ultimately converted to felsic high-pressure granulites). (after Lexa *et al.* 2011)

crystalline complex in North Bohemia and identified physical processes that precede and accompany exhumation of the ultra-high pressure part of the subducted crust to shallow crustal levels (Fig. 3). Textures and compositional variations of these rocks reflect on the reactive porous melt flow along shear zones that modified the deformed metagranites into an anatectic layered sequence of migmatite and residual granofels and granulite. This sequence was then decoupled above the underlying subducting slab and folded and exhumed to shallow crustal levels.

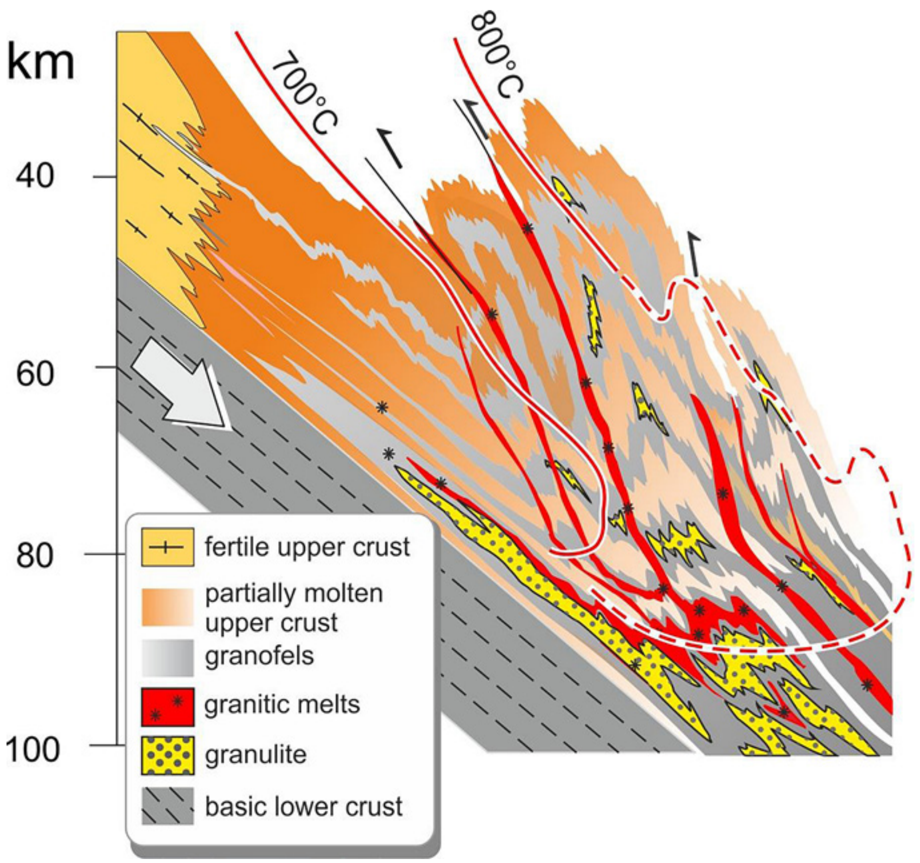


Fig. 3. Schematic geodynamic profile of the continental subduction and exhumation of the crust in the section of Eger crystalline complex in north Bohemia. Localized melt flux (red) along grey colored shear zones promoted rheological weakening and decoupling of the partially molten sequence to shallow crustal levels. The kinematics of exhumation is indicated by convoluted isotherms, folded layers and new shear zones that form parallel to the fold planes of exhumed domains.

ADVANCED TECHNIQUE OF STRAIN QUANTIFICATION IN ANALOGUE MODELS OF OROGENS

Accretionary orogens are frequently associated with episodes of partial melting and development of metamorphic core complexes in the aftermath of rollback driven crustal thinning, slab break-off and mantle upwelling or relamination of the subducted crust. The relamination scenario, for example, produces a mechanically stratified crust, where a partially molten felsic layer is sandwiched between the brittle upper crust and strong lithospheric mantle. To address the dynamics of folding on a crustal scale and the role of melt in development of associated metamorphic core complexes, we produced a series of shortening experiments with originally horizontal layers of heated paraffin wax superposed by sand (Fig. 4, 5). These models required a special approach of strain quantification from a series of images using post-processing subroutines, where the local material fluxes were traced using a set of strain-based parameters (e.g. volumetric component of the strain tensor).

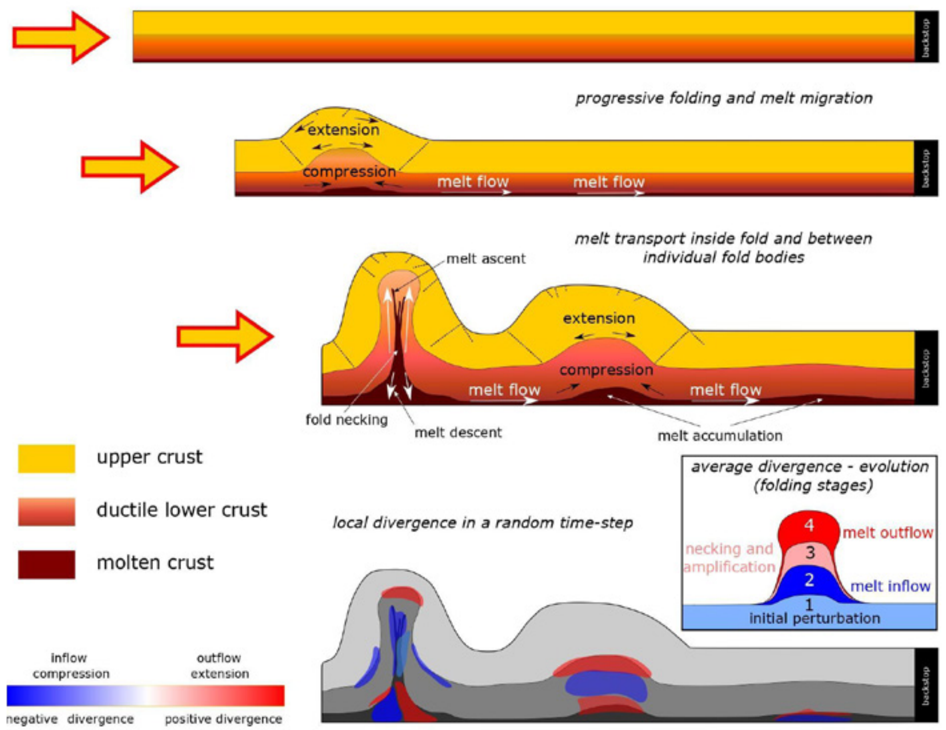


Fig. 4. Structure of the model, progressive development of the folded sequence and schematic diagram indicating the relative mass balance in different subdomains of the model, reflected by the divergence of the velocity field calculated from image samples using the particle image velocimetry (PIV) method. Negative (blue) values of the divergence correspond to the melt inflow-accumulation while the positive (red) values correspond to melt outflow and with zones of extension.

The calculations focused on melt flow between the source layer at the bottom of the model and progressively developing folds. The mass transfer analysis revealed a polyphase fold evolution where the initial perturbation at the upper-lower crust interface quickly amplifies as the melt accumulates in the triangular zone below the future fold. While the early amplification leads to decompression driving the melt into the hinge zone area (between the limbs), the fold lock-up stage and continued attenuation of the vertical limbs is associated with melt expulsion from the fold interlimb domain back into the source layer, where it can be transferred laterally to the foreland (Krýza et al., 2019).

Since the effect of melt migration on crustal strength and deformation is a significant parameter controlling dynamics of orogens, tracing the material fluxes on small scale may help us evaluate dynamics of crustal structures on scale of entire orogens.

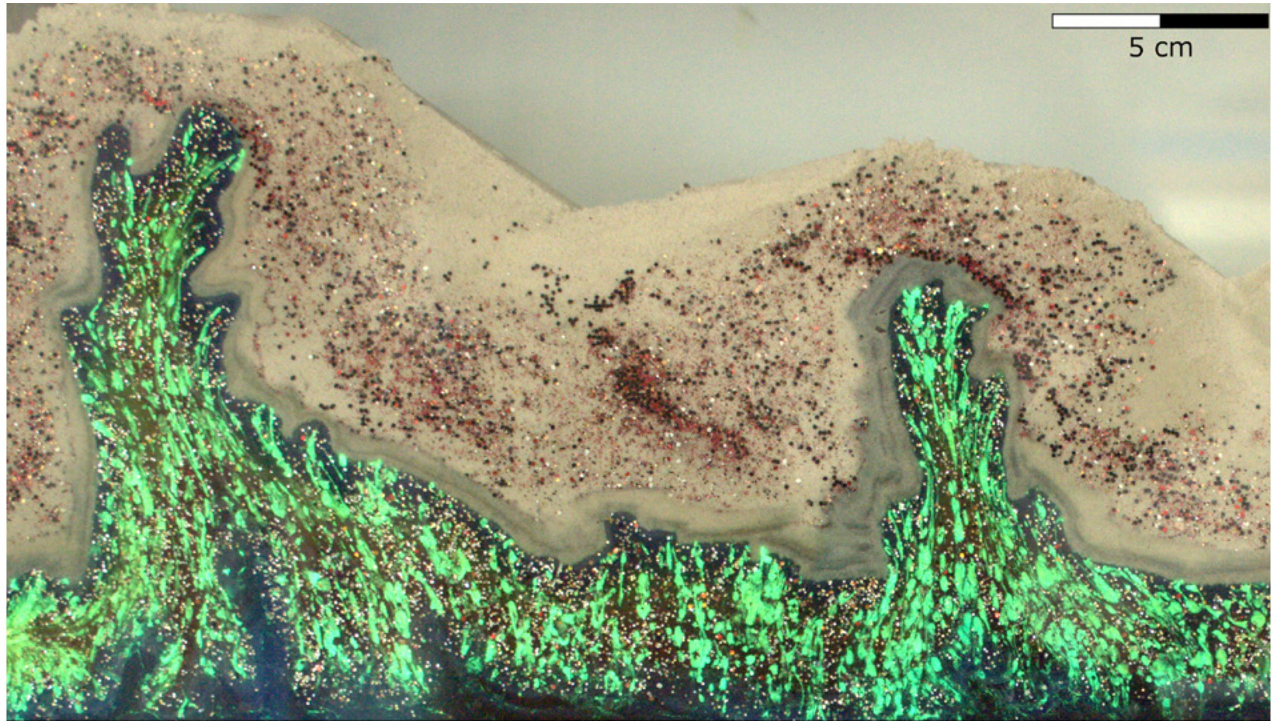


Fig. 5. Image of the detachment folding analogue model captured in a dark room during long light exposure, modified by increasing brightness and contrast. Note that the glowing pattern of greenish particles is induced by fluorescent color admixed to wax shavings superposed on the frontal side of the bottom paraffin wax layer. Upper layer is sand which represents the brittle upper crust. The bottom paraffin wax is molten at the base (dark zones). The coloured particles support the PIV accuracy, while the fluorescent wax, visualizes the deformation pattern in the ductile layers.

Micro-scale rock fabrics: clues to deformation history and physical properties or rock materials

A strong line of research at the Institute is focused on analysis and modelling of rock microstructure. Using a broad range of methods, the natural (micro)structural record in the rock is correlated with its manifestation in physical fields and these observations are connected with other properties of rocks.

QUANTITATIVE MICROSTRUCTURAL ANALYSIS APPLIED FOR INTERPRETATION OF ANISOTROPY OF MAGNETIC PROPERTIES OF ROCKS.

Our researchers have long focused on developing techniques for evaluation of magnetic fabrics – the anisotropy of magnetic susceptibility (AMS), which is generated by alignment of magnetic minerals in rocks. The formation of AMS fabric itself is an intensely discussed topic because it is widely used as a precise and quick technique to infer the internal rock structure. Rock microstructures frequently represent a complex combination of distinct features (or subfabrics) of diverse origins, orientations and strengths. Therefore, it is not only important to evaluate the contributions of the main susceptibility carriers to the anisotropy, but also identify the processes responsible for AMS development and eventual superpositions of subsequently forming subfabrics. The rock magnetic fabric analysis was studied in regard to geological processes in a range of settings, comprising the flow of rock salt, ductile flow of dacite lava, serpentinization of mantle peridotite, localized shear in marble and submagmatic flow in granite.

Superposition of submagmatic and subsolidus deformation fabrics related to folding was identified by Závada et al. (2017) in folded granite sills of a Variscan orogenic wedge (Fig.1). The composite nature of the fabrics was constrained by detailed study of AMS clustering patterns and microstructural analysis from two perpendicular sections. In another case study focusing on strain partitioning and magma flow in a small concentrically expanded Castle Crags pluton (California, USA), Machek et al., (2019) proposed that the flow of dense crystal mush was accommodated by self-organized slip of the crystals and that the changes in granitic textures throughout the pluton reflect variations in magma compaction, melt segregation, cumulate formation and subsolidus overprint, all caused by the intrusion of trondhjemite magma in the core of the pluton (Fig. 2).

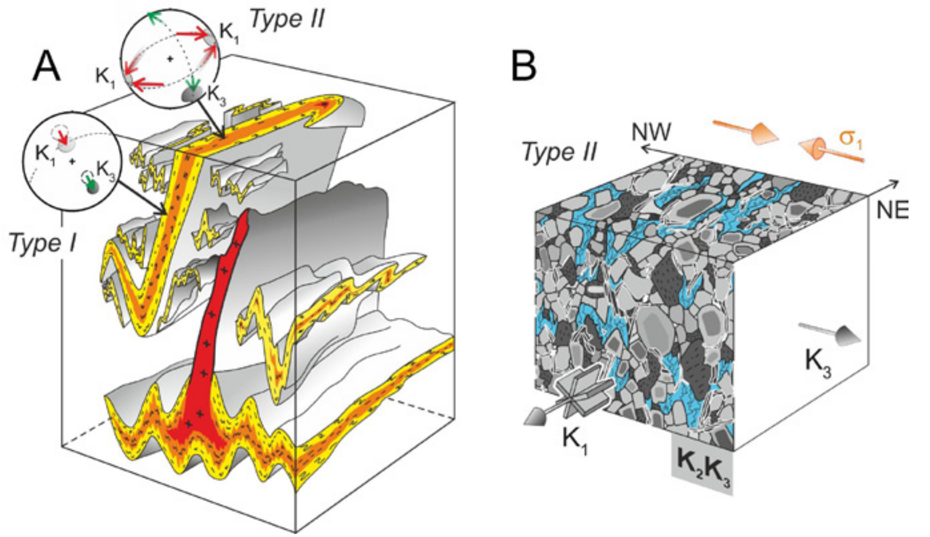


Fig. 1. Schematic block diagram (A) with a simplified sketch of folded sill array in the Orlica–Śnieżnik dome (Czech Republic) and related diagrams of AMS fabrics in the margin (Type I) and interior of the sills (Type II). While the linear, early submagmatic fabric is preserved in the margins of sills (Type I fabrics, clusters of K_1 and K_3 directions), internal parts of these same bodies shows an overprint of the early submagmatic fabric by fold axial cleavage related to horizontal compression and folding (Type II fabrics, cluster of K_3 and girdle of K_1 directions). Microstructure of Type II fabrics is also illustrated by microfolds of quartz aggregates (blue) in the K_2K_3 section (B).

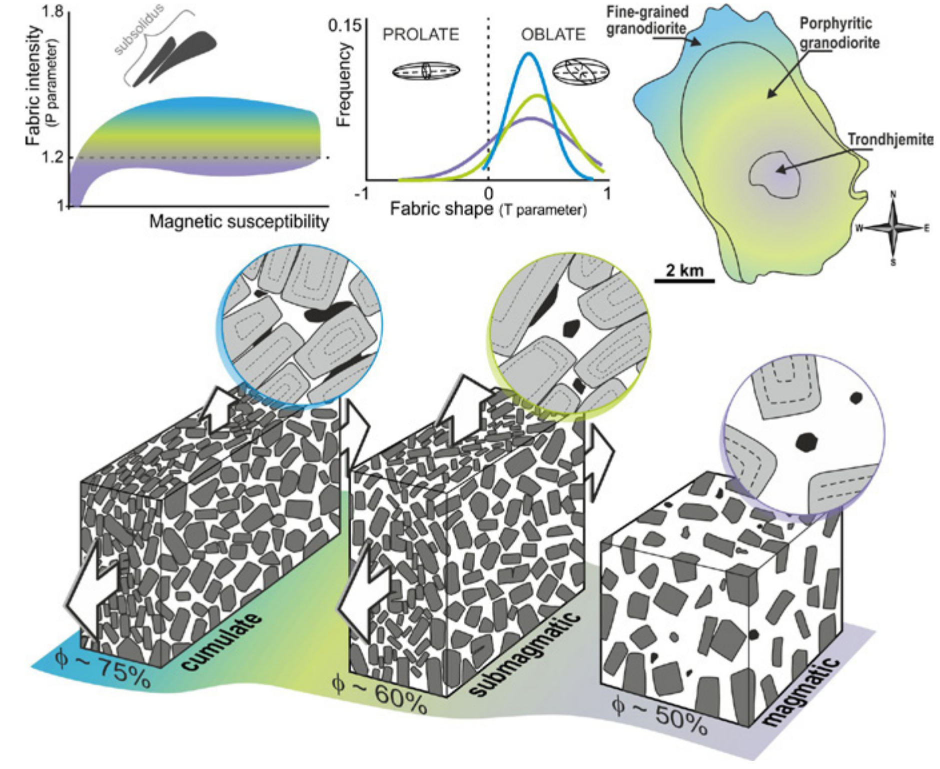


Fig. 2. Diagrams summarizing the magnetic fabric strength and shape measured throughout the Castle Crags pluton (Klamath Mts., California, USA), where the dominantly magmatic fabrics in the pluton's centre changes to submagmatic on the margins. Exceptionally strong anisotropy of magnetic fabrics on the margins of the pluton is induced by indentation and plastic shearing of magnetite crystals between the densely packed plagioclase porphyroclasts.

One of the strategies that allows understanding of the shear development in rocks and the corresponding development of AMS is analogue modeling using plaster of Paris (e.g. Kratinová et al., 2006). Firstly, this material is convenient as it displays strain-rate dependent rheology (thixotropic material), which is a more realistic proxy for the natural rocks (compared e.g. to Newtonian silicon putties). Secondly, using the anisotropy of magnetic susceptibility (AMS) in analogue modelling provides a great opportunity to record and study flow and deformation inside the model itself and in different time steps. The aim of this current work is to bring new insights into the time and space relationships between finite strain microstructure and AMS fabric by providing new comparative data from field examples of shear zones (Kusbach et al., 2019) and associated analogue models (Fig. 3, 4).

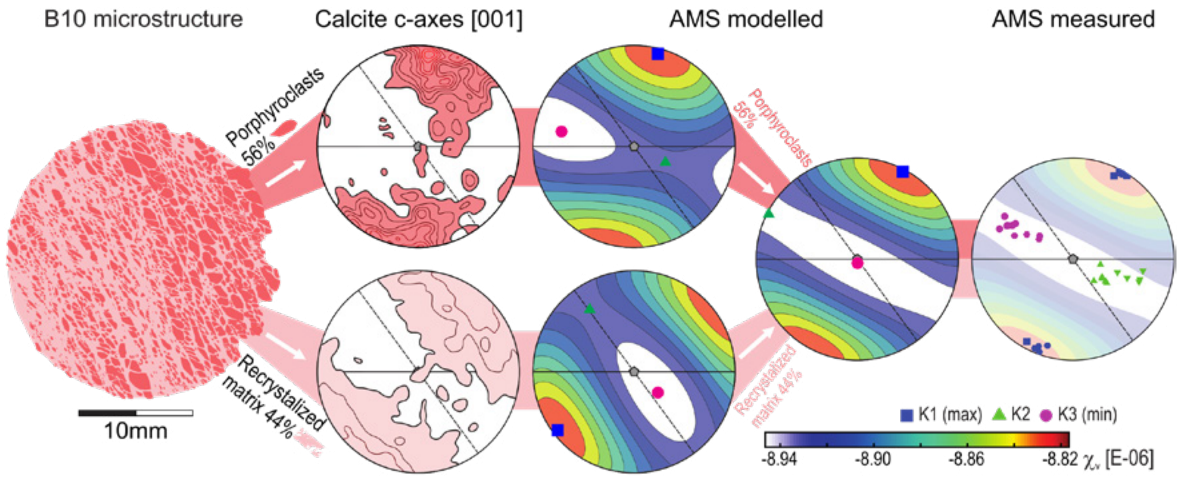


Fig. 3. A small-scale shear zone in marble (Ossa-Morena Zone, Portugal) showed that the localization of deformation at conditions of dislocation creep leads to the contemporaneous evolution of two microstructural subfabrics, one generated by recrystallized fine-grained matrix and the porphyroclasts (Kusbach et al., 2019). Associated numerical simulation illustrates how the combined AMS signal of these two fabric components changes in magnitude, shape and orientation with respect to the proportion of these subfabrics on the course of progressive dynamic recrystallization.

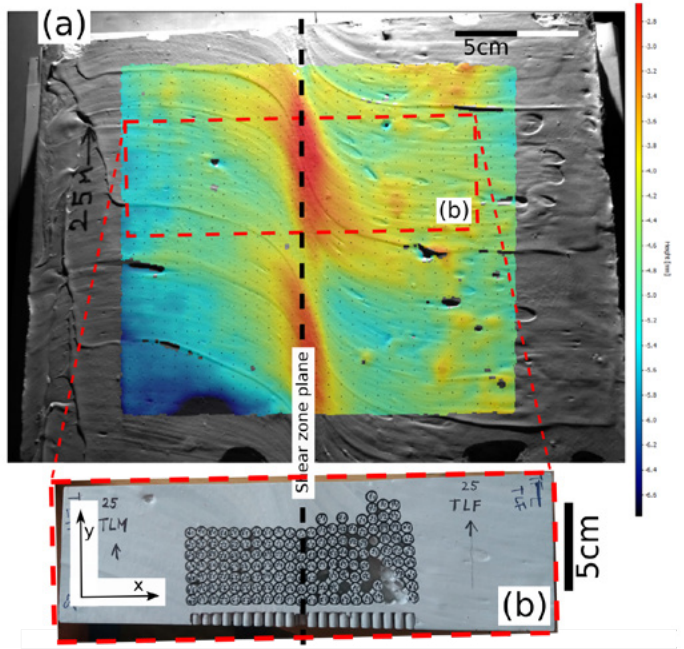


Fig. 4. (a) Plan view of the analogue model of shear zone with superimposed layer visualising surface topography. (b) Extracted part of experiment symmetric with respect to shear zone plane showing the drilled samples.

GEOMETRY OF THE ROCK VOID SPACE AND ITS RELATION TO THE ROCK PHYSICAL PROPERTIES

Most rocks comprise detectable volume of void space made of pores and cracks naturally filled by fluids. The total volume of the void space and the size, shape and orientation of its elements result from the rock deformation history and in turn have a crucial impact on the rock physical properties. Quantification of porosity parameters is fundamental for calculations of the permeability of rocks and evaluation of their storage capacity. Such parameters are important for evaluation of rock suitability for energy production from deep geothermal wells, for oil and gas industry or for safety of deep repositories of spent nuclear fuel. Our analyses provided both for research and industrial purposes help geoscientists to model the structure of the Earth's crust and to predict the development of rock permeability with depth.

The study by Staněk and Géraud (2019) focused on granite microporosity changes due to fracturing and alteration. Several alteration facies of fractured Lipnice granite have been studied in detail on borehole samples by means of mercury intrusion porosimetry, polarized and fluorescent light microscopy and microprobe chemical analyses. Using a simple model the authors have calculated permeability from the measured porosities and throat size distributions. The difference in permeability between the fresh granite and the most fractured and altered granite is 5 orders of magnitude. Our observations suggest that the porosity, the size of connec-

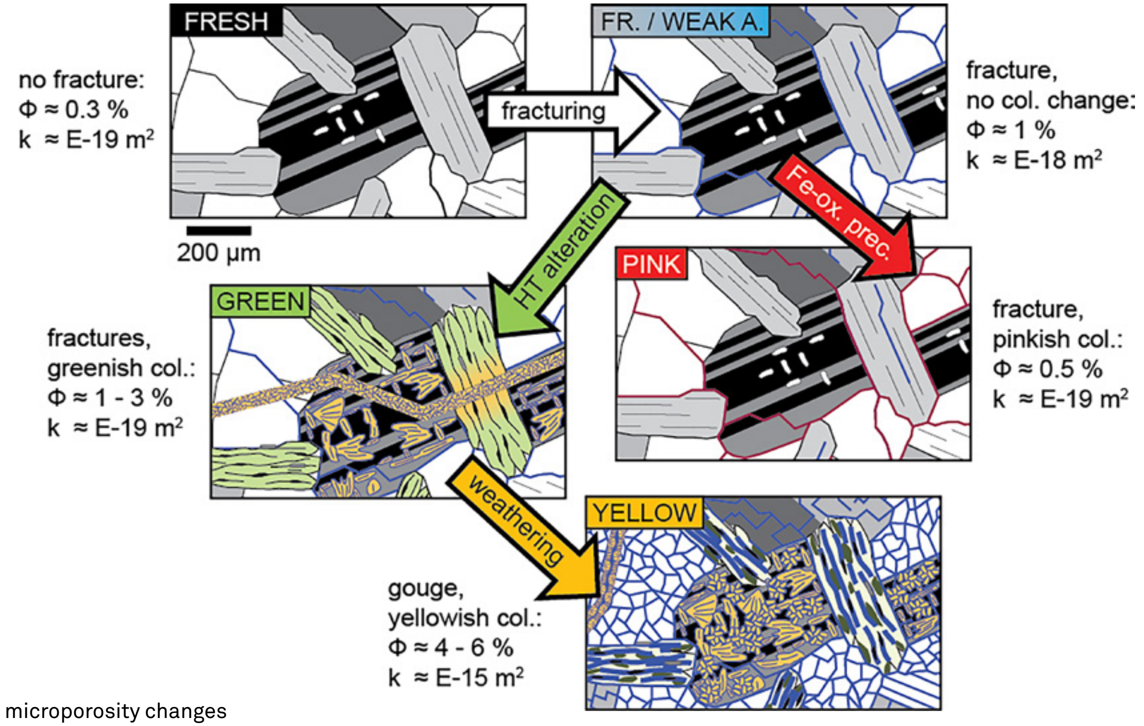


Fig. 5. Sketch of the granite microporosity changes due to fracturing and different kinds of alteration. Basic macroscopic features and the related values of porosity (Φ) and permeability (k) are given for each of the facies.

tions and the proportion of crack porosity increase with fracture density, while precipitation of iron-rich infills as well as of fine-grained secondary phyllosilicates acts in the opposite way (Fig. 5). This study also shows the possibility to use standard mercury intrusion porosimetry with advanced experimental settings and data treatment to distinguish important differences in void space geometry within a span of a few percent of porosity.

Earth surface dynamics

The study of processes and dynamics that occur at or near Earth's surface has undergone recent expansion at IG. This research embraces a variety of investigations examining and quantifying the physics of mass flux in the upper part of the lithosphere, plus the atmosphere, hydrosphere, and biosphere domains in which a vast complex of physical and chemical processes take place. These studies fall within five general themes: (1) Climate in the sedimentary record; (2) Climate reconstructed from deep boreholes; (3) Cryosphere forms and processes; (4) Soil magnetism; and (5) Geohazards.

CLIMATE IN THE SEDIMENTARY RECORD

Landscape responses to late Quaternary climate change, as recorded in sedimentary archives of Central Europe, are presented in papers by J. Kadlec (deceased, Nov. 2020) and colleagues. Kadlec et al. (2015) documents the effects of late Pleistocene to Holocene climate change on fluvial, lacustrine, and aeolian deposits in the Moravia River valley (Fig. 1). Combining a geophysical approach with sedimentology and two dating methods (^{14}C and OSL: optically stimulated luminescence), the authors argue that climate drove fluvial adjustments between braided, meandering, and anastomosing planform. Valley aggradation around the Last Glacial Maximum (21–19 ka) marked by lacustrine sand sheets and source-bordering dunes was followed by river incision at 13 ka linked to a high discharge regime that removed much of the valley fill. Another study involving J. Kadlec examines the Younger Dryas (YD) stadial (~12.85–11.65 ka) recognised across the Northern Hemisphere, though its cause remains hotly debated. Support for the bolide impact hypothesis is presented by Kletetschka et al. (2018) based on a lacustrine sequence they examined in the Šumava Mts, South Bohemia, which contains the well-dated Laacher See tephra marker (12.82 ka) together with a layer of magnetic microspheres marking the onset of YD cooling. This finding is consistent with one or more cosmic airburst events that potentially triggered YD cooling.

Climate based studies of shorelines formed by lakes and palaeo-wetlands over the last glacial cycle are documented in papers by J. D. Jansen and colleagues. The cause of water-level fluctuations in Lake Baikal, Siberia, has been disputed since the late 19th century mainly on the basis of its palaeoshorelines. Arzhannikov et al. (2020) identify eight palaeoshoreline terraces that indicate lake highstands up to 122 m above the present-day water level during Marine Isotope Stage 3. By accounting for the evolution of Baikal's outlet over time, the authors show that lake levels have followed swings in glacial-interglacial climate and not the result of tectonism alone.

Former lakes and wetlands can provide valuable insights to the late Pleistocene environments encountered by the first humans exiting Africa. Using OSL dating on the palaeo-wetland sediments in the 'Arabah valley of southern Jordan, Al-Saqarat et al. (2020) show that a small wetland oasis existed ~125 to 70 ka in response to a wetter climate coupled with a landslide dam. A minimum age of 74 ± 7 ka for two Levallois stone flakes suggests that the oasis was visited by humans during the critical 130–90 ka time-window of human migration out of Africa.

CLIMATE RECONSTRUCTED FROM DEEP BOREHOLES

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

Ongoing work is aimed at better understanding the interdependence of temperature measured in the air, on different ground surfaces, and in bedrock. Čermák et al. (2017) reports the results of a decade of monitoring four surface types on the premises of

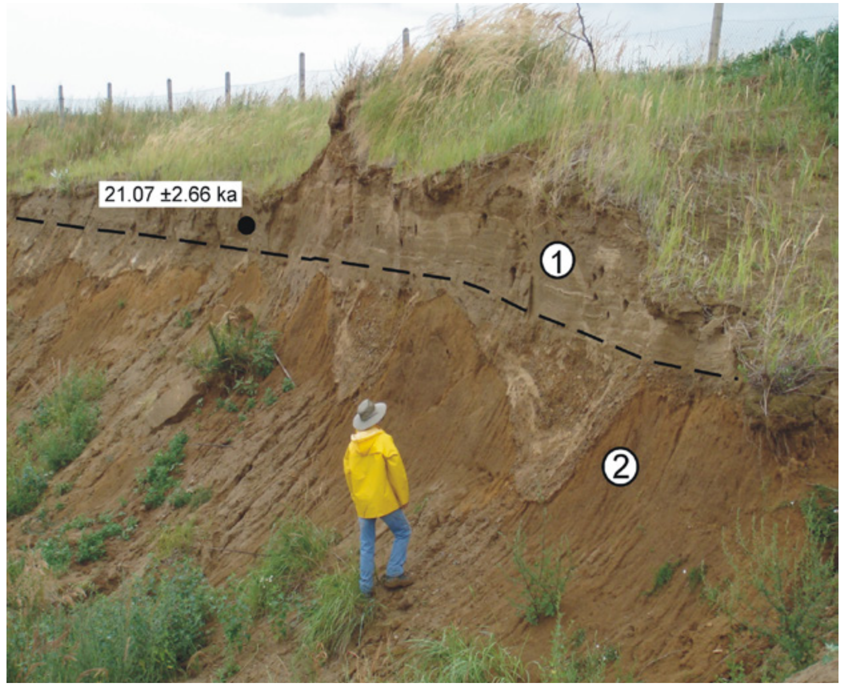


Fig. 1. A sedimentary exposure at Boršice gravel quarry on the Lower Moravia River. The cryogenically deformed upper unit (1) of crinkly laminated silty sand of probable lacustrine origin is dated to around the Last Glacial Maximum and overlies an alluvial fan sequence (2) of sandy gravel with clasts up to cobble size (Photo: J. Kadlec).

the Institute of Geophysics, Prague. Building on this, Čermák & Bodri (2018) incorporate rainfall records using the 'Granger causality test' and the results highlight the importance of timescale in the analysis. The significance of changes in substrate diffusivity over time is addressed by Majorowicz et al. (2015) who examine the influence on the surrounding permafrost of thermokarst lakes formed in northern Canada at 10–6 ka. Numerical modelling indicates that formation of taliks (i.e., melted permafrost in its entire thickness)

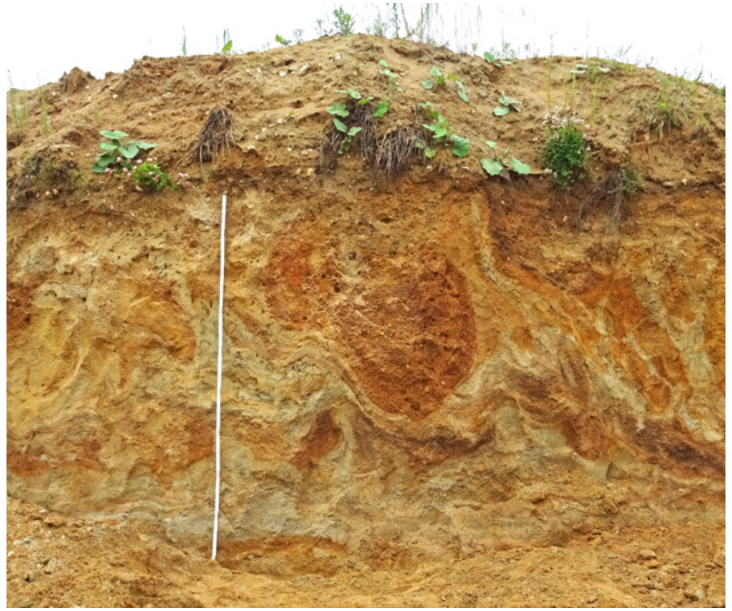


Fig. 2. Field example of cryoturbated horizons portraying a former active layer developed over permafrost in a sand-gravel pit near Nebanice, Cheb Basin (Photos: T. Uxa). Uxa et al. (2020) propose a new inversion-based modeling approach to derive palaeo-temperature from former active-layer (thaw depth) observations from a range of periglacial forms where permafrost has played an active formative role, such as cryoturbation, solifluction lobes, frost wedges, or authochthonous blockfields. The authors employ a variation of the heat equation known as the Stefan equation to describe how thawing propagates through a uniform thickness of permafrost. The model offers great potential for extracting palaeoclimate information from a vast array of polar and mountain environments.

is a function of average annual basal temperature and rock type, with complete melting restricted to clay-rich rocks with < 40% porosity.

CRYOSPHERE FORMS & PROCESSES

Periglacial forms described in papers by T. Uxa and colleagues are generated by freeze-thaw processes in non-glaciated alpine and polar environments. Central to their work is the comprehensive mapping in the High Sudetes Mts (Czechia-Poland) (Křížek et al., 2019) and in the Western and High Tatra Mts (Slovakia-Poland) (Uxa & Mida, 2017). The authors link the spatial distribution of periglacial forms to cooler conditions, including the former more extensive presence of permafrost. Today, patterned ground exhibits marginal activity associated with seasonal freezing and, according to Uxa et al. (2019), the persistence of permafrost in the Sudetes Mts is highly improbable.

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

The glacial history of Greenland and the European Alps are addressed in papers by J. D. Jansen and colleagues. Skov et al. (2020) constrain the last million years of glacial erosion at Dove Bugt, northeast Greenland, using a Monte Carlo inversion framework with measurements of cosmogenic ^{10}Be and ^{26}Al in bedrock and ice-transported boulders. Cosmogenic nuclide memory (i.e., the residence time of samples within the upper 2 m) is shown to be >600 kyr on the highest plateaus and <100 kyr at low elevations. Limited erosion on the highest plateaus since 1.0–0.6 Ma indicates a minimum age for fjord-plateau formation in northeast Greenland.

The outwash deposits of the northern Alpine Foreland inspired Penck and Brückner's (1909) classical glacial scheme, but the age of the oldest (Günz) glaciations have remained elusive. Knudsen et al. (2020) devise a new cosmogenic nuclide burial-dating model to constrain the age of the *Höhere Deckenschotter* outwash terraces to 1.0–0.9 Ma, suggesting the onset of major glaciation in the Alps coincided with the lengthening of glacial cycles from 40 to 100 kyr known as the Middle Pleistocene Transition. These findings corroborate a 1970s hypothesis proposed by the renowned Czech climatologist, G. J. Kukla.

SOIL MAGNETISM

The detection of minute concentrations of iron-bearing ferrimagnetic minerals in soils provides a powerful addition to conventional geochemistry for studying the genesis and evolution of soils and for identifying anthropogenic disturbances. Significant environmental questions are pursued via the rock-magnetic approach in papers by H. Grison, E. Petrovský, A. Kapička and colleagues.

Magnetic susceptibility, which is governed by the presence of Fe-oxides, can be used as an index of increased pedogenesis when measured in a vertical soil profile as shown by Grison et al. (2017), and can be employed to detect pollutants accumulated in topsoils (Szuszkiewicz et al., 2015; Aidona et al., 2016) and floodplain sediments (Faměra et al., 2018), to gauge soil degradation (Jakšík et al., 2015, 2016) or for detecting wood ash added to fertilise forest soils (Petrovský et al., 2018). In two papers, Grison et al. (2015, 2016) investigated the relationship between the magnetic and chemical properties of highly magnetic andosols developed on basalts in the Massif Central, France. Fe-bearing minerals present here were interpreted in terms of the age of parent material, climate and soil thickness.

The three main factors in concentrating magnetic soil particles is found to be precipitation, substrate age (age of basalts), and soil thickness. In particular, a persistently humid climate is conducive to concentrating magnetic soil particles at 15–20 cm depths. The findings open the way for further studies of the mechanisms involved in soil production and soil mixing with chronometric methods such as optically stimulated luminescence and cosmogenic nuclides.

GEOHAZARDS

Earthquakes and seismogenic landsliding are major natural hazards; river-blocking landslides can release catastrophic floods that claim thousands of human lives. J.D. Jansen and colleagues document such hazards in studies focused upon the seismically-active eastern margin of the Tibetan Plateau.

Fieldwork in the Massif Central, France, with Hana Grison in action conducting in situ measurements of the vertical distribution of magnetic susceptibility using an SM 400 kappameter (Photo: H. Grison). Grison et al. (2016) examine the chemical and magnetic attributes of soils (andosols) developed on volcanic rocks in the French Massif Central, with the aim of identifying a magnetic signature of pedogenic development.

The gigantic 250 m-high Diexi palaeolandslide (area in the foreground, incised by the Minjiang River) in Sichuan, China, spans 10.5 km^2 and holds an estimated volume of 1.1 km^3. Note the deeply incising knickzone (left) on the Minjiang River. This river-damming paleolandslide is one of examples treated in Fan et al. (2020a).

Fan et al. (2020a) present a comprehensive review of the literature pertaining to the formation and impact of river-blocking landslide dams, including an extensive set of global examples. Given that high-magnitude geohazards rarely occur in isolation, a deeper understanding can be gained by analysing multi-hazard chains, as shown by Fan et al. (2020b) who use numerical simulations to examine the dynamics of two large landslides and the floods they triggered in 2018 on the Jinsha River, China.

Deep-time sedimentary record of Earth's climate changes

Sedimentary basin fills provide archives of processes on the Earth's surface, including the history of climate and ocean dynamics, and their interactions with tectonic-driven lithosphere processes as well as with the evolution of biota. Multi-disciplinary studies of past climatic and oceanographic changes have been an integral part of the Institute's research during the past two decades and have focused mainly on archives of palaeoenvironmental changes in greenhouse climates.

HIGH-RESOLUTION RECORD OF GLOBAL CARBON CYCLE DURING PEAK GREENHOUSE

The mid-Cretaceous thermal maximum represents an interval of extreme greenhouse climate attributed to high partial pressure of atmospheric carbon dioxide (pCO2 800-1500 parts per million by volume, p.p.m.v.) and other greenhouse gases. The peak warmth was probably reached in the Turonian (c.94 to c. 89.7 Ma). This stage included a global long-term sea-level maximum near the Cenomanian-Turonian boundary (c. 94 Ma) as well as long-term sea-level lows in the Middle and Upper Turonian. 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, and has been of interest to palaeoclimatologists worldwide.

Work on the 400 m-deep research core Bch-1 in Běchary, Czech Republic, drilled in 2010 as part of a Czech Science Foundation project led by D. Uličný, was summarized and supplemented by new data by Jarvis et al. (2015, The Depositional Record, https://doi.org/10.1002/dep2.6). The Bch-1 dataset yielded so far the highest-resolution carbon stable-isotope curve for the middle and upper Turonian, and has been correlated to other high-resolution δ^{13}C data available worldwide (Fig. 1). The main focus of this paper was on the dual record of stable carbon isotopes from both the organic matter and carbonate, which may hold clues to fluctuations in pCO2 levels in the Turonian peak greenhouse. A link has been suggested between episodes of sea-level fall and lowered pCO2, potentially indicative of a role of small-scale glaciations and associated cooling events during the mi-Cretaceous.

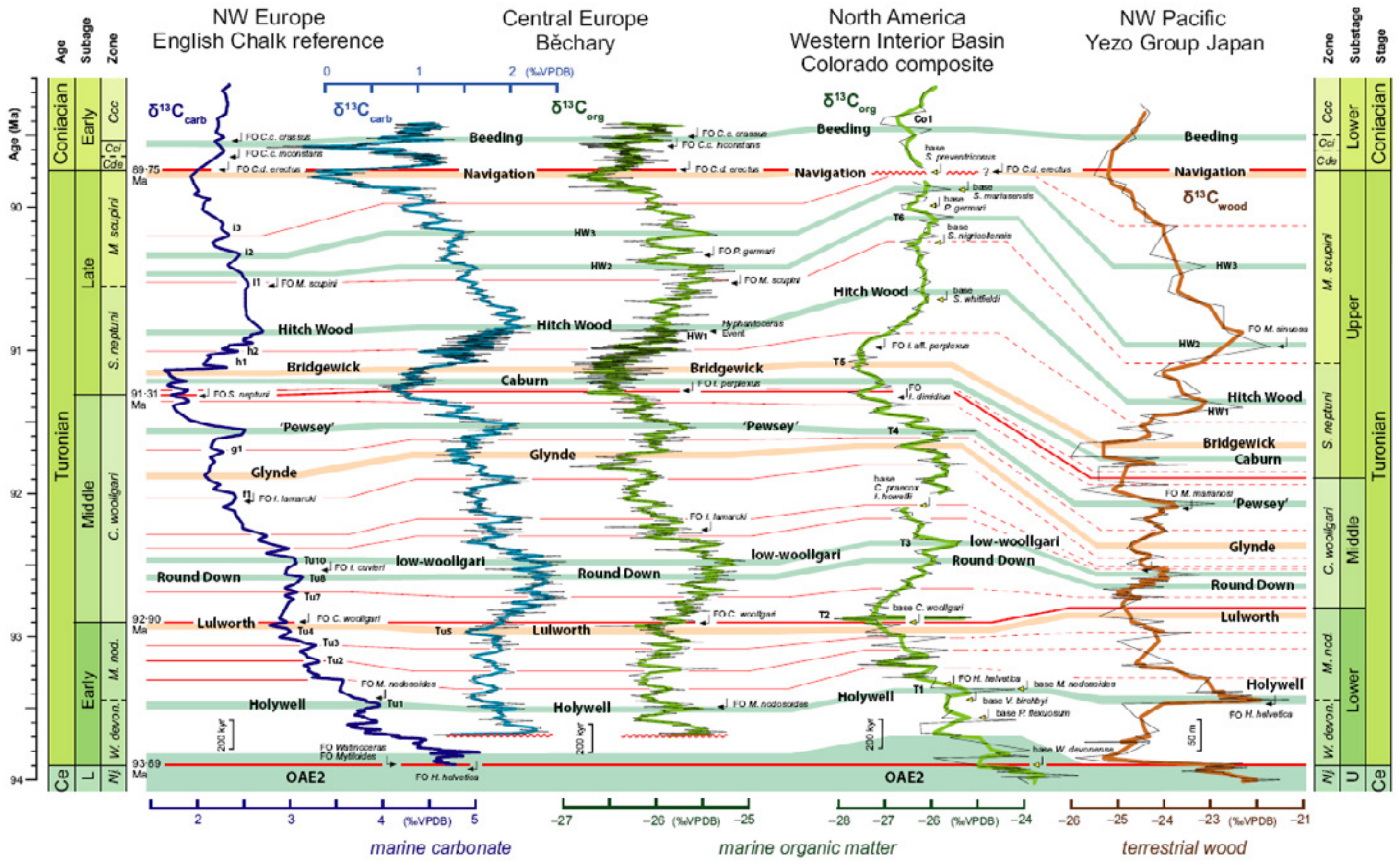
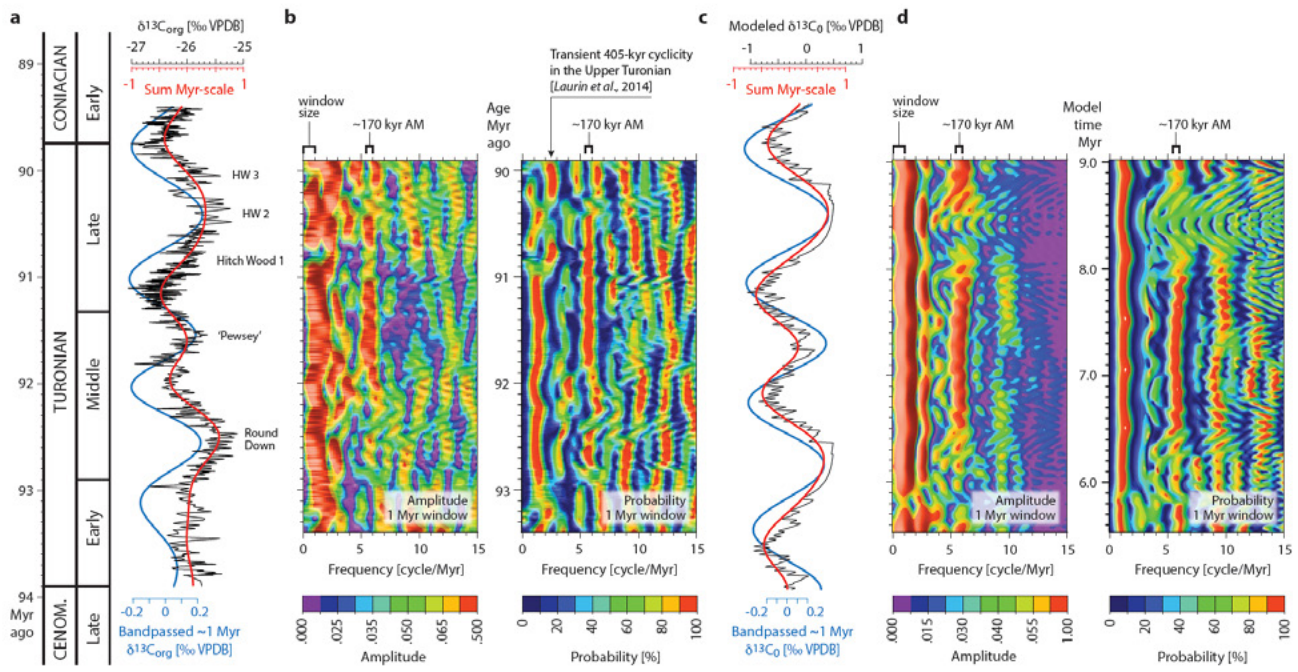


Fig. 1. Correlation of age-calibrated Turonian $\delta^{13}C_{carb}$ profiles for Europe (English Chalk reference curve and Běchary), with bulk marine $\delta^{13}C_{org}$ curves from Europe (Běchary) and North America (US Western Interior Basin composite), and the terrestrial wood record ($\delta^{13}C_{wood}$) from the NW Pacific (Yezo Group, Japan), from Jarvis et al., 2015, Dep. Record.

MILLION-YEAR – SCALE CHANGES IN GREENHOUSE CARBON CYCLE

Spectral analysis and carbon mass-balance modelling carried out by Laurin et al. (2015), using data from Bch-1 as well as from other European C-isotope time-series, found that the million-year scale variations in the Late Cretaceous carbon budget was controlled by amplitude modulation of Earth's axial obliquity. The nonlinear transfer of variance in d^{13}C from the much shorter pri-

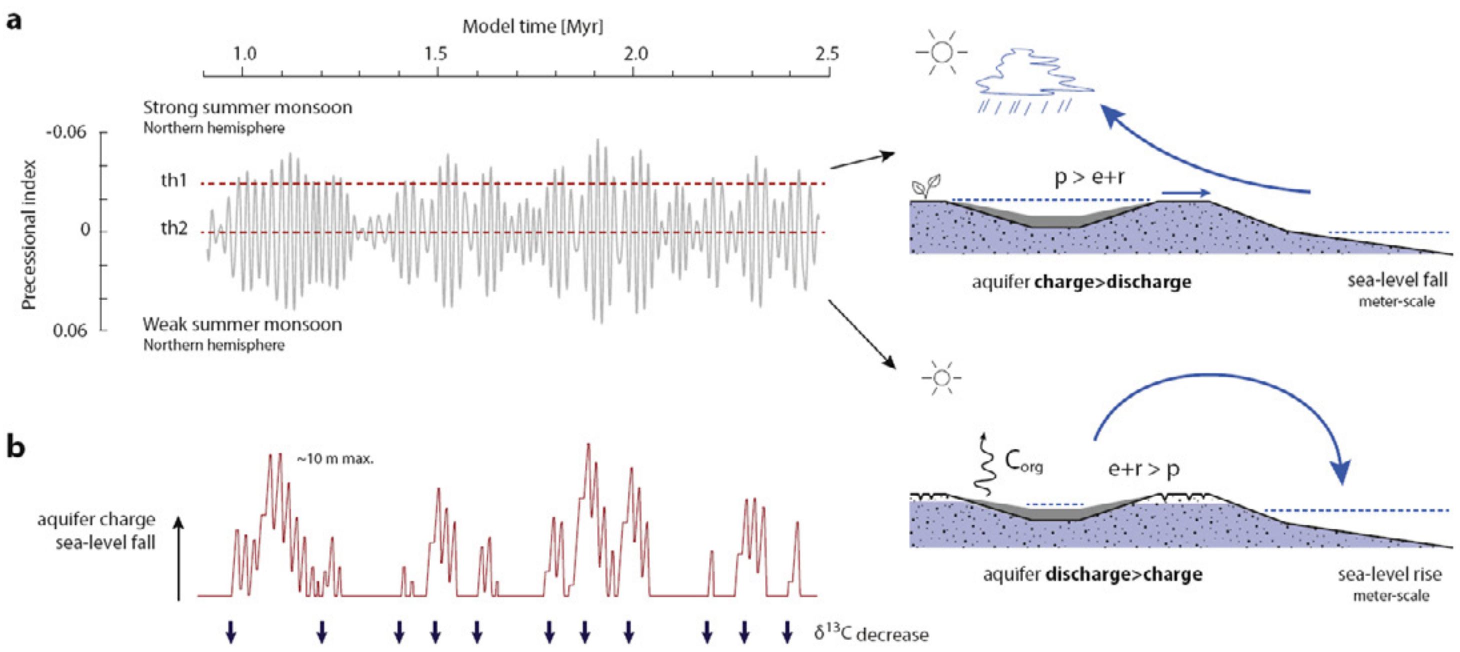


Data – model comparison of the C-isotope cyclicity of the Turonian stage. (a) Age-calibrated $\delta^{13}C_{org}$, Bch-1 borehole. Major C-isotope events indicated (HW2 and HW3 refer to Hitch Wood 2 and Hitch Wood 3 of Uličný et al., 2014, 3-Paleo). Bandpassed ~1 Myr signal (Gaussian filter 0.9 ± 0.3 cycle/Myr) in blue and a sum of Myr-scale components (piecewise linear filter 0.7 ± 0.7 cycle/Myr) in red. (b) Evolutive Harmonic analysis (EHA) spectral estimate for the calibrated Bch-1 curve. Note that the 405 kyr eccentricity signature interpreted earlier (Laurin et al., 2014, EPSL) forms only a transient feature in the study interval. (c) Modelled C-isotope record simulated with obliquity-driven, quasi-stable reservoir model (THM-OBL-La04; "0" model time = 100 Myr ago in Laskar et al. (2004). Bandpassed signals as in (a). (d) EHA spectral estimate for the simulated $\delta^{13}C_0$. Note the concentration of power at the ~170 kyr wavelength and its similarity with transient ~170 kyr signature in the calibrated Bch-1. Longer AM wavelengths are biased due to the size of the EHA window (1 Myr).

mary obliquity signal to longer amplitude-modulation periods was explained by recycling of carbon on astronomical time scales by episodic formation and decay of terrestrial reservoirs of organic matter and/or methane (e.g., terrestrial peat, soil and lakes, permafrost) in middle to high latitudes.

A NEW LOOK ON THE LARGEST OCEANIC ANOXIC EVENT – FROM THE LAND

Focusing on the late Cenomanian to earliest Turonian Oceanic Anoxic Event (OAE)2, Laurin et al. (2019) studied terrestrial and marginal-marine records in southwestern Utah which preserve information on changing volume and carbon-isotope composition of the atmospheric CO_2 inventory. This geological time interval



was an episode of organic-carbon sequestration from the ocean-atmosphere reservoir, accompanied by enhanced marine productivity, lack of oxygen in ocean bottom waters, and organic-carbon burial, fueled by nutrient fluxes from submarine volcanism and/or terrestrial sources. The study found that approx. 100-kyr period excursions in $\delta^{13}C_{org}$ characterize the initial phase of OAE2. These excursions originate from a combination of $\delta^{13}C$ changes in the atmospheric reservoir and physiological response of higher plants to changing *p*CO2. These excursions are absent or muted in the open-marine record due to preservational bias and/or differences in isotopic fractionation between terrestrial plants and marine plankton. Another finding is that negative excursions in the terrestrial-sourced δ^{13}Corg are coordinated with accelerations in sea-level rise,

Fig. 3. Conceptual model of the hypothesized relationships between insolation-controlled aquifer charge/discharge, meter-scale sea-level change and carbon storage in the monsoonal belt. (a) Precessional forcing; th1 and th2 are thresholds for aquifer charge and discharge, respectively. (b) Fluctuations in net aquifer charge controlled by the precessional index. Black arrows denote the first aphelial (i.e., dry) summers following the maximum lake level at the eccentricity scale; these intervals are considered to have the highest potential for rapid subaerial degradation of organic carbon from the terrestrial reservoir. The release of 13C-depleted carbon can be facilitated by increased wildfire frequency. This scenario produces negative δ13C excursions penecontemporaneous with the maximum rate of net water transfer to the ocean.

while medium-term intervals of ^{13}C enrichment overlap with regressions and evidence for relative sea-level fall. These relationships can be explained by changes in aquifer charge accompanied by biomass burial/degradation in the monsoonal belt.

Volcanic and magmatic processes

Research on volcanic and magmatic processes has focused on understanding the eruptive dynamics of volcanic systems, the generation of magmas, and the relationship between magmatic systems and crustal evolution. The study of fundamental volcano-magmatic processes is complex and occurs over multiple scales and depths necessitating a broad group of research methods (geophysical analysis, numerical and analogue modelling, field and laboratory observations) to provide an integrated picture of the processes controlling magma generation through eruption. Main research areas in 2015-2020 have been (1) magma propagation and reservoir dynamics, (2) tectonic controls on magmatic processes, (3) eruption dynamics, and (4) planetary volcanism.

MAGMA PROPAGATION AND RESERVOIR DYNAMICS

Research efforts into the migration of magma have largely focussed on seismic and geodetic monitoring of unrest prior to and during eruptive events. However, the accumulation and migration of eruptible magma volumes in shallow crustal magmatic systems often occurs without significant geophysical signals observed with the traditional monitoring approaches. In order to unravel the processes which control shallow crustal magma movement, researchers have been conducting analogue experiments of magmatic systems.

In our analogue modelling laboratory, studies of the relationship between magma pressures, thickness of magma (content of crystals in melt), deformation pattern on the surface, cohesion of host rocks and detailed internal flow pattern of magma using the AMS (Anisotropy of Magnetic Susceptibility) are being used to investigate dike propagation and growth. These experiments were designed in cooperation with Janine Kavanagh from University of Liverpool and conducted by her PhD student Simon Martin, in collaboration with Prokop Závada. During the experiments, plaster of Paris as a magma analogue was injected into a large flour-filled rectangular container (Figure 1). Experiments were stopped once the plaster erupted on the surface of the box. The solidified intrusions revealed development of three radial dykes that spread from the injection point, growth of central cup-shaped reservoir and vertical rise of a feeding conduit that brought the analogue magma to the surface. The observed fabrics, preserved by the orientation of the magnetite particles, indicate that the intrusion progressed by localized shear at the flow margins and progressive breakouts from the stagnated tips. These results have important implications for understanding the processes controlling magma migration in both active and fossil volcanic fields.

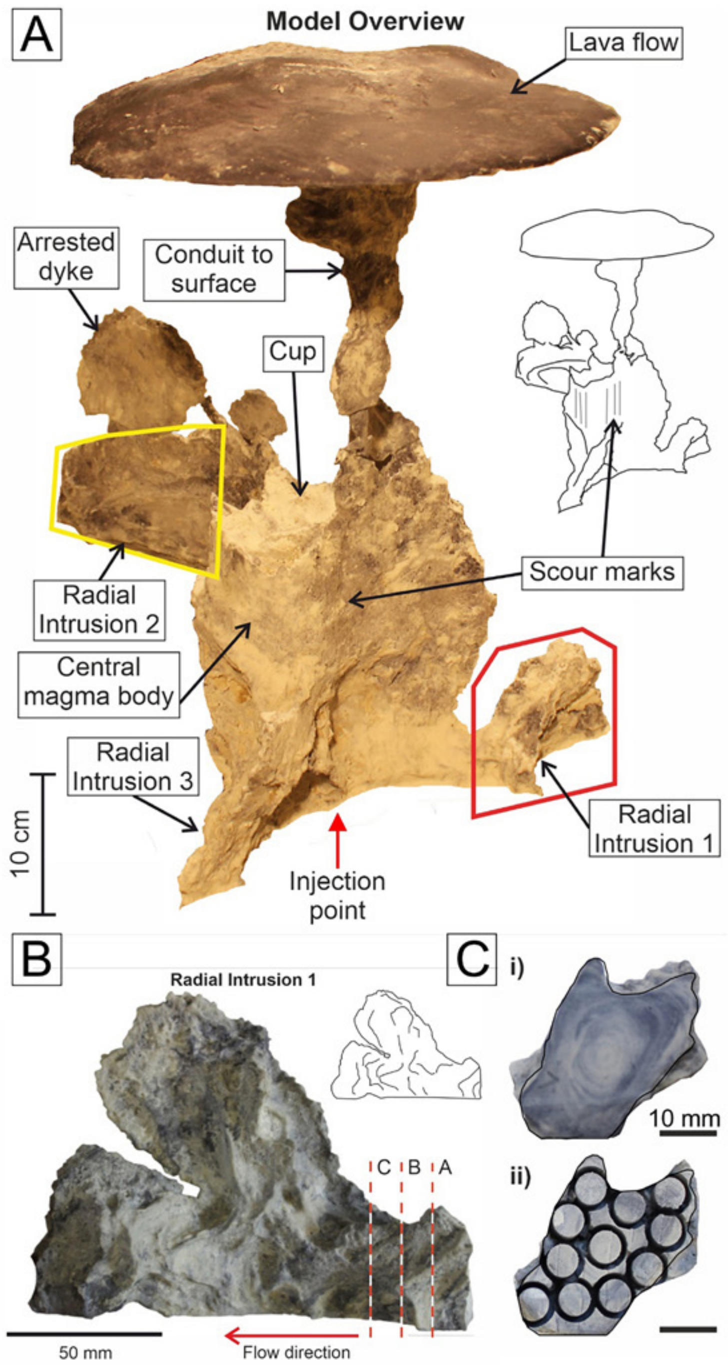


Fig. 1: Morphology of solidified plaster model of a volcanic plumbing system (a), detail of one of the radial dykes and location of transverse sections (b) that were studied in detail for internal flow patterns from coloured plaster (c,i) and sampling for AMS (c,ii) that reflects the 3D shape and intensity of the magnetic fabrics from dispersed fine-grained magnetite particles. Martin, S., Kavanagh, J., Závada, P. (submitted to *Earth and Planetary Science Letters*): Identifying the origin and evolution of magnetic fabrics in magma intrusions using laboratory modelling.

TECTONIC CONTROLS ON MAGMATIC PROCESSES

Understanding magmatic processes within a tectonic context and the role of inherited crustal structure on magmatic system geometry and eruptive behaviour is currently a major focus in this field of research. Incorporating the regional tectonic controls on magmatic processes requires geophysical investigation on a larger scale. Two ongoing projects are the investigation of the Mount Erebus, Antarctica, phonolite magmatic system, and the Katmai group, Alaska, USA.

Mount Erebus (Figure 2) on Ross Island denotes the southern end of the Terror Rift, and is the world's southernmost active volcano. The Mount Erebus lava lake and recent erupted lava flows have an unusual phonolite composition rich in sodium and potassium. Gas emissions from the lava lake are unusually rich in CO_2 compared to subduction volcanoes. Phonolite magmatic systems, with their ultra-alkalic and silica under-saturated compositions, unique plumbing and liquid lines of descent, and diverse volatile influences are important probes into upper mantle source regions. Phonolites are typically associated with zones of major crustal extension like the West Antarctic and East African rifts or hotspot environments, but can occur in other settings and are capable of producing violent eruptions. A phonolitic eruption of Vesuvius destroyed Pompeii in 79 AD. The Tambora eruption in Indonesia caused nearly 80, 000 deaths and significantly affected global climate. A large 3D magnetotelluric study has been carried out (Hill, 2020) to test current models for the Erebus magmatic system and place it in a regional tectonic framework as a step towards understanding the origin and mechanics of these ultra-alkalic systems globally.

The origin of andesite, the most common volcanic rock found in subduction zones, has been a subject of intense debate. Recent petrological research offers two models of andesite formation mixing with viscous crustal rhyolitic magma, and liquid crystal segregation of basaltic magmas originating at mantle depths. In the mixing model andesite volcanoes preferentially form at the edges of rhyolite reservoirs, where basaltic magmas rise from depth and mix with the rhyolite melt, avoiding the density trap posed by the less dense rhyolite, while in crystal fractionation of andesite formation individual andesite magmatic systems will be independent at crustal depths. Magma reservoirs are electrically conductive compared to their surroundings and may be delineated by magnetotellurics. We are testing the models of andesite generation by constructing 3D magnetotelluric models of the magmatic system of the Katmai Group in Alaska where active andesitic and rhyolitic systems occur in close proximity. This work is supported by Lumina Quaeruntur fellowship of the Czech Academy of Sciences to G. Hill.

ERUPTION DYNAMICS

Detection of a geophysical signature associated with a geologic event, such as a volcanic eruption, is key to understanding the underlying physical processes and making an accurate hazard assessment. Magma reservoirs are the main repositories for eruptible magma, and understanding them requires the ability to detect and interpret changes in the magmatic system from surface measurements. Traditionally, monitoring for these changes has been done with seismic and geodetic approaches, both of which require dynamic 'active' changes within the magmatic system. Seismic monitoring relies on the number and location of earthquakes, to indicate magma migrating within the magmatic system. In contrast, geodetic efforts rely on identifying ground inflation events which have traditionally been interpreted to represent recharge of magma from a deep parental source into shallower crustal reservoirs. Neither of these techniques is sensitive to the petrology or temperature of the magma, however. Thus additional monitoring techniques, such as magnetotellurics, able to detect 'static' phase changes in the evolving magma and the thermal structure of the magma reservoir are also needed.

In the Tongariro volcanic centre, New Zealand, pre- and post-eruption magnetotelluric measurements were used to determine the variation in sub-surface electrical properties resulting from changes in the magma reservoir associated with the 2012 eruptive cycle. The observed electrical property changes are related to the physical eruption properties (e.g. eruptive volume, style, and composition), revealing the state of the magmatic system both prior to and following the eruption. Knowing both the pre- and post-eruption state of the magmatic system and the surface eruptive properties enables reconstruction of the subsurface eruption mechanism. Successful identification of pre- and post-eruptive states of the volcano is evidence for

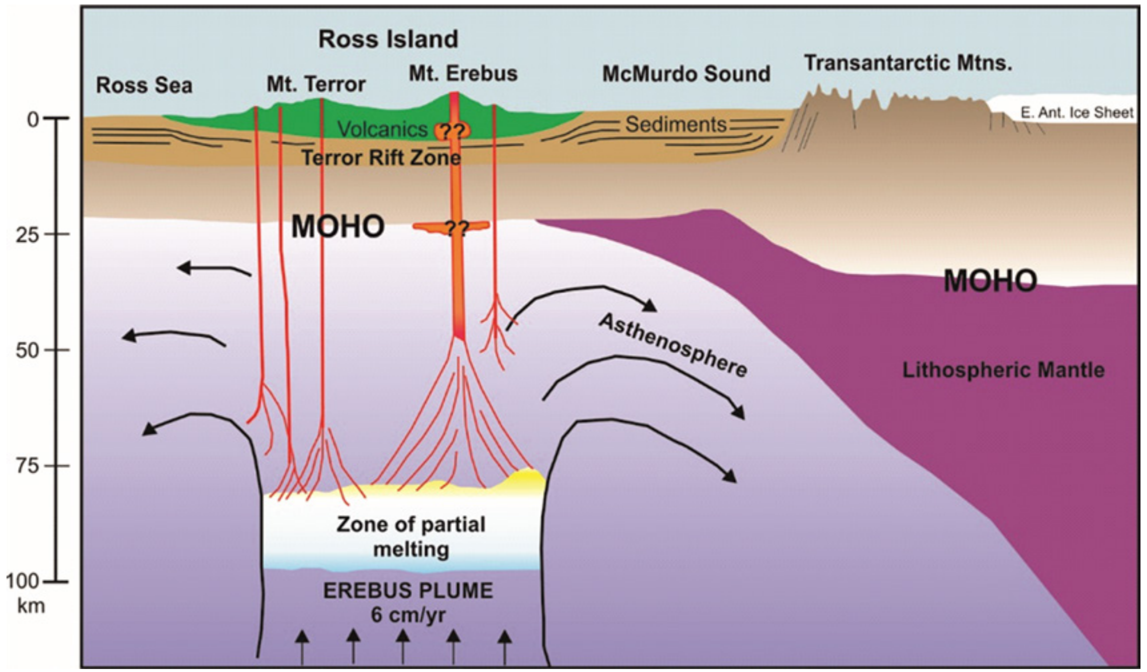


Figure 2: Schematic model for generation of phonolite melt based largely on petrological and geochemical studies. Ongoing magnetotelluric will update the model by imaging directly the plumbing system and ascent paths in the upper mantle and crust modified from Kyle et al. (1992).

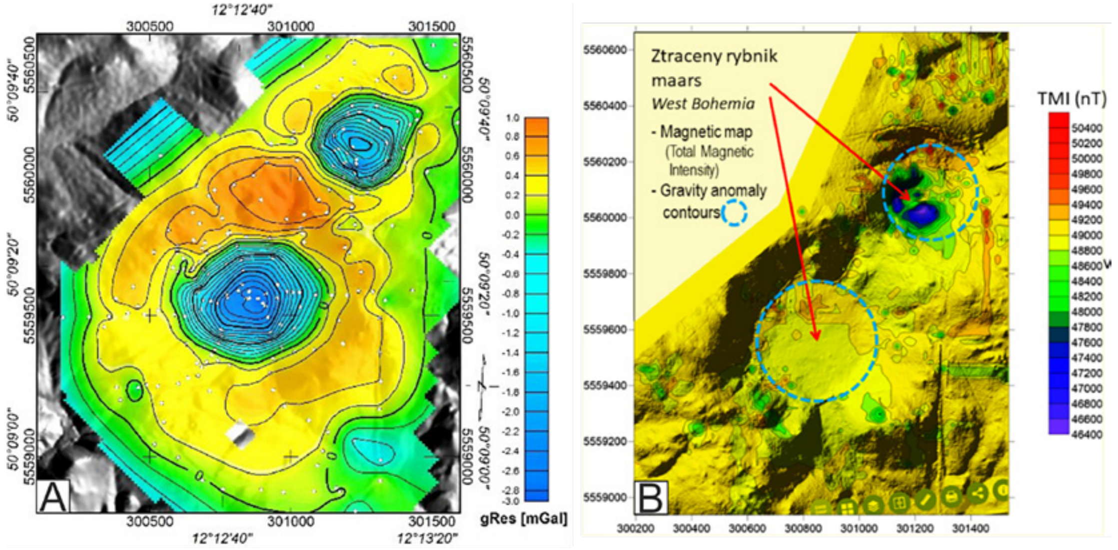


Figure 3: Gravity (A) and magnetic (B) maps of the Ztraceny rybnik twin maars, western Bohemia. Potential field results have been effective in identifying maar vent structures. .

the usefulness of continuous magnetotelluric monitoring of volcanoes to identify variations within magmatic systems that may be indicative of imminent eruption (Hill et al., 2020).

Studies of potential fields are being used to determine the eruption dynamics and reveal the unknown vent locations of the Cheb Basin, and to monitor the eruptive state and behaviour of Nisyros Island in Greece. The existence of twin maars in the Ztraceny Rybnik natural reserve (Figure 3) were revealed using both gravity and magnetic results (Mrlina et al., 2019, in Pánek & Hradecký eds., Landscapes and Landforms of the Czech Republic, Springer). Interestingly, the two maars have similar gravity responses but strikingly different magnetic responses. This disparity in magnetic signature is the topic of ongoing research to understand both the cause of the difference and the implications for eruptive history. Recently an additional concealed vent has been identified ~3km to the West of the twin maars across the German border, further characterisation of this feature using both potential field and geoelectrical methods is ongoing.

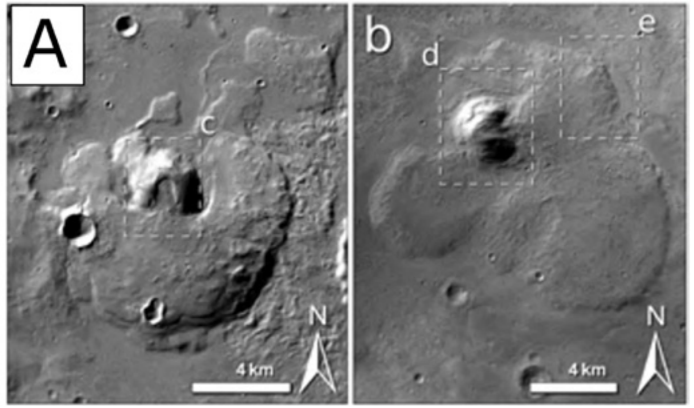
PLANETARY VOLCANISM

Formation of planets and moons resulted in capture of tremendous amounts of heat internally, and volcanic activity can be broadly considered the primary mechanism for releasing this stored heat. Smaller planetary bodies like our Moon or Mars cool more quickly than larger bodies like Earth. Studying volcanism of other planetary bodies provides a window into different stages of this cooling cycle and planetary evolution. This knowledge provides important information on past processes that shaped the modern Earth or provide a perspective into the future evolution of the planet.

On Mars, the identification of supposed scoria cones (kilometre-sized volcanoes formed by an accumulation of volcanic rocks) had previously not considered the lower gravity and atmospheric pressures would alter the formation processes (Figure 4). On Earth, scoria cones largely grow by gravity driven surface flows (rock avalanches) of material from near the vent location, however, on Mars the lower gravity and atmospheric pressure allow for growth of these systems primarily by ballistic distribution of the ejected volcanic debris (Brož et al., 2015). The alternate ballistic formation model has since been applied to similar geomorphic landforms on Mercury.

The volcanic landscape of the Chryse Planitia region of Mars is inferred to result from sedimentary (mud) rather than igneous volcanism. As water is unstable under the assumed Martian atmospheric conditions, the mechanism of flow is enigmatic. Analogue experiments in a low-pressure chamber (Figure 4) at the Open University in Milton Keynes, UK, were conducted to investigate how these mud flows are able to propagate. The water-dominated mud used in the experiments was found to form an icy-muddy crust (given the lower atmospheric temperatures expected) allowing the mud flows to propagate in a similar fashion to pahoehoe lava flows (Brož et al., 2020). Thus, it is essential to consider the different environmental conditions when interpreting the processes responsible for production of similar landforms on different planetary bodies.

Further experimental work to simulate more realistically mud volcano eruption and extrusion of flows will be conducted in the Milton Keynes low pressure chamber. These experiments will allow determination of temporal volumetric changes of chosen regions of the model using photogrammetry and velocimetry methods (Krýza et al., 2019), in order to reveal the mechanism of deposition and accumulation of material from a flow.



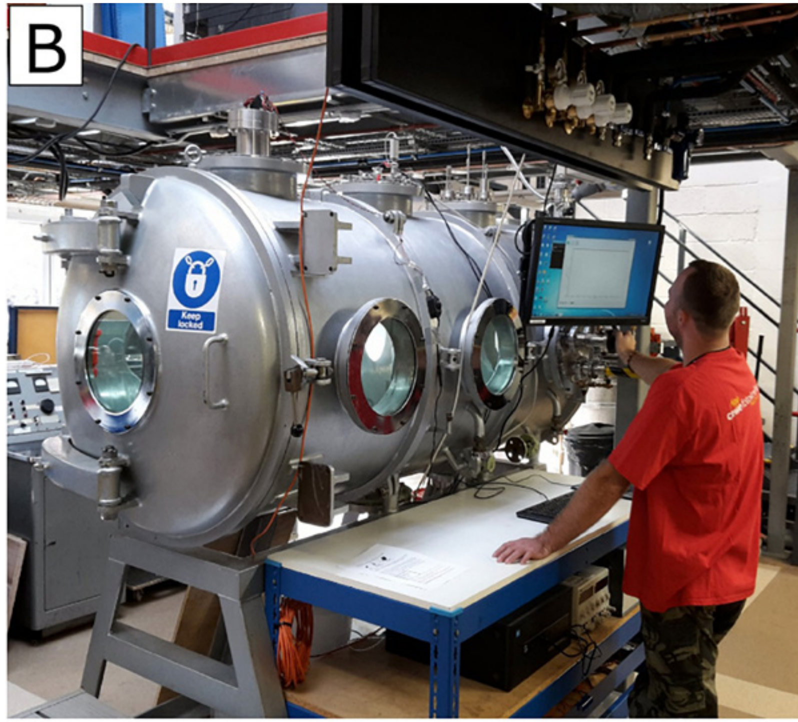


Fig. 4: Morphometry and physical modelling of the Martian volcanic features. (A) An example of two kilometre-sized cones with associated flows in Terra Sirenum region which are most likely results of igneous volcanism. Both cones are breached and central area from which the material came to the surface can be seen. Based on CTX images, NASA. (B) Large Mars Vacuum Chamber in the Hypervelocity Impact Facility (Open University in Milton Keynes).

Earth’s magnetic field and geodynamo

The Earth’s magnetic field is one of the most variable geophysical fields and provides us with effective protection against high-energy, electrically charged particles from the solar wind, solar flares and is a useful tool for navigation, not only for us, humans, but also for animals. Our research addresses various aspects of geomagnetic field, from numerical modelling of geodynamo using a range of boundary conditions, through solidification of aqeous salt solution mimicking the processes on the inner/outer core boundary, to reconstruction of space-weather relevant historical records of geomagnetic storms.

THE EARTH’S CORE AS A FACTORY FOR THE GEOMAGNETIC FIELD: NUMERICAL MODELLING

The Earth’s magnetic field is created by convective motions of an electrically conductive melt in the Earth’s outer core and penetrates the surface of the Earth. These processes of the field generation are collectively called the *geodynamo*. On the Earth’s surface, a large-scale, dipole-dominated field is observed. However, we have no direct information about the magnetic field in the Earth’s core. For this reason, the magnetohydrodynamic processes in the Earth’s core are modelled numerically.

Numerical modelling of geodynamo has made enormous progress during the recent years thanks to the development of computer technology. Numerical models construct a magnetic field that is close to the observed geomagnetic field; we are also able to reproduce its temporal changes, whether short-term or long-term ones (so-called secular variations). However, we cannot use parameters typical of the Earth’s core in our models. The real parameter values cannot be used for computational reasons – so far there is no supercomputer in the world that could solve a geodynamo model with such values. However, researchers are gradually approaching them; an example of this being numerical modelling of geodynamo by the Institute's researchers (Šimkanin & Kyselica, 2017). Here the lowest possible values of viscosity and magnetic diffusion were used, that were computationally possible at the time of this study. Figure 1 shows the dipole-dominated magnetic field (similar to the observed one), small-scale velocity structures typical of convection in the Earth’s core, and thermal plumes arising at the Earth’s inner/outer core boundary and propagating into the outer core. Recently, numerical modelling of turbulence in the Earth’s core has been completed as a step towards more realistic modeling of the geodynamo.

Current work, led by Ján Šimkanin and Juraj Kyselica, addresses the difference between dynamos driven by the secular cooling through the mantle and those driven by the buoyancy generated at the inner/outer core boundary. In addition to this, a series of numerical simulations of the geodynamo with varying inner-core size has been initiated. The goal will be to describe the

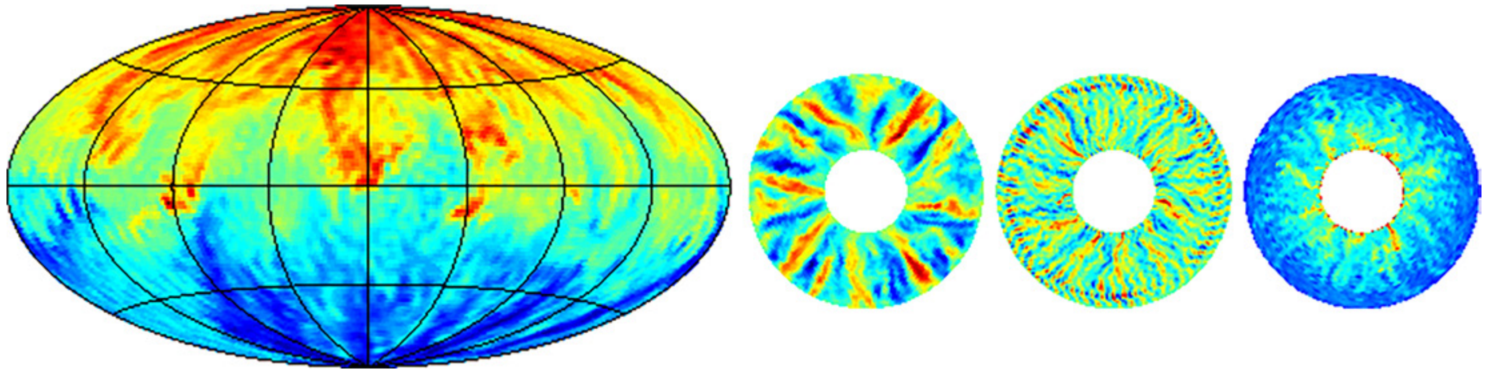


Figure 1: Spatial distribution (Hammer projection) of radial magnetic field component, and equatorial sections of the radial components of the magnetic field, the velocity field, and the temperature (from left to right). Red (blue) colours indicate positive (negative) values (Šimkanin J. & Kyselica J. 2017).

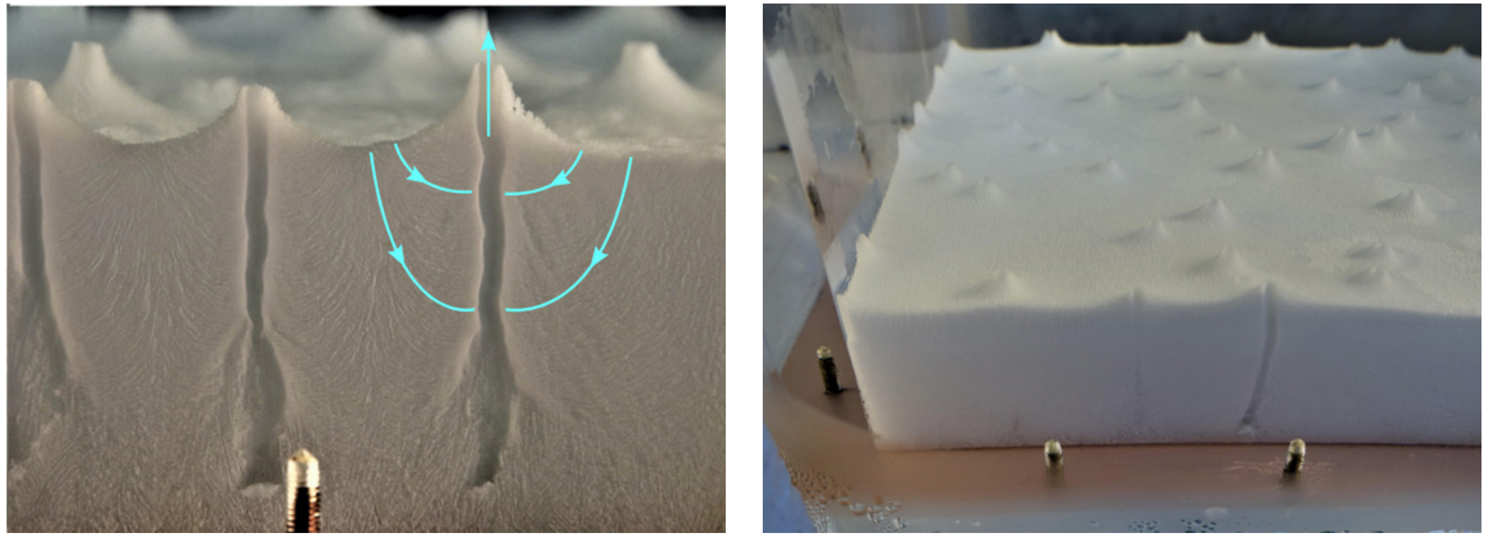


Figure 2: (Left) Convective chimneys growing in a mushy layer during solidification of a cooled aqueous ammonium chloride solution (experiments: J. Kyselica and J. Šimkanin, work in progress). The width of each channel is approximately 2mm. Note that the local structure of the mushy layer between the chimneys reflects the downward flow of heavier liquid towards the chimneys (the flow direction is indicated by arrows). Similar chimneys are expected to form at the inner/outer core boundary as the lighter elements are rejected during solidification. (Right) Top view of the system of chimneys growing from a convecting mushy layer.

effect of the varying inner-core size on the structure of the geomagnetic field, as well as to assess the possibility of geomagnetic field reversals.

SOLIDIFICATION AS A SOURCE FOR GEODYNAMO: MATHEMATICAL MODELLING AND EXPERIMENTS

Another line of research carried out by J. Šimkanin, J. Kyselica and their collaborators, focuses on the processes that serve as an energy source for the outer core convection, namely the solidification of the inner core. As the inner core gradually solidifies, the release of lighter components at the inner/outer core boundary leads to compositional convection in the liquid outer core. Thorough understanding of the solidification processes is therefore crucial for obtaining a full picture of the core's dynamics.

Only indirect information about the structure of the inner/outer core boundary is available, mainly from the analysis of the seismic waves, however, we can learn a lot from the solidification of metal alloys or aqueous salt solutions. It is a known fact that during solidification of multicomponent mixtures a partially solidified regions of mixed solid and liquid phases, so-called mushy layers, form. Recently results of mathematical modelling of mushy-layer dynamics over moving substrate have been published (Kyselica & Guba 2016; Kyselica, Guba & Hurban 2018 and Kyselica & Šimkanin 2018), as well as work on non-equilibrium solidification of supercooled systems (Kyselica, Guba & Chudjak 2020). To date, most of the mushy-layer studies have been focused on solidification under laboratory conditions – mainly in the context of magma-chamber or sea-ice solidification. However, the conditions at the inner/outer core boundary are specific since the solidification of the inner core is not due to cooling but due to high pressures. Development of a thermodynamically consistent model of a mushy layer under the inner-core conditions is an open task that our group is currently working on.

In 2020, an apparatus was constructed for physical experiments with solidifying aqueous salt solutions, frequently used as laboratory analogues of metal alloys. A typical pattern is shown in Fig. 2. As the solution is cooled from bottom, branched crystals grow, forming a mushy layer. The residual liquid is lighter and therefore tends to rise. The upward flow eventually leads to the formation of so-called chimneys, with plumes rising from them.

Experiments are under way to understand the dependence of the mushy-layer evolution on the input parameters such as the initial concentration, driving temperature difference and the initial liquid height. Besides this, future work of our group will be focused on the experiments with three-component solutions (water and two salts). The complex behaviour of such solutions during solidification may be similar to that of multicomponent mixtures found in the Earth's interior. Theoretical and experimental work on the theory of mushy layers is carried out in collaboration with colleagues from the Faculty of Mathematics, Physics and Informatics, Comenius University in Bratislava, Slovakia.

GEOMAGNETIC DISTURBANCES AND RELATIONSHIP OF SPACE WEATHER TO METEOROLOGICAL PROCESSES

The association between geomagnetic disturbances and pressure changes in the troposphere is the subject of so-called space weather. For decades this topic has been studied at the current Department of Geomagnetism by Pavel Hejda and Josef Bochníček (deceased 2020). As shown by Valach et al. (2019), data of historical magnetic observatories established in the first half of 19th century provide valuable information for the study of space weather events. Two intense magnetic storms from 17 November 1848 and 4 February 1872 were analysed in collaboration with colleagues from the Earth Science Institute of the Slovak Academy of Sciences. The storm of 4 February 1872 was recorded by observatory in Greenwich. The event has been marked as extraordinary by several authors. On the other hand, the storm of 17 November 1848 has received little attention in the space-weather community. The relevant data from observatory in Prague-Clementinum were only recently digitized and recalculated to physical units. Both these events possessed extensive variations of the horizontal (*H*) component of the magnetic field and were accompanied by auroras sighted at very low magnetic latitudes. It implies that the auroral oval on the northern hemisphere was vastly extended southward. The variation of the magnetic declination indicates that during these events the auroral oval was situated at magnetic latitudes lower than those of the observatories. The storms occurred at different magnetic local time and might thus represent mid-latitude events related to different parts of the auroral oval. The *H*-variation recorded at Clementinum in 1848 is interpreted to be a substorm due to the ionospheric substorm electrojet. The Greenwich event registered in 1872 then seems to be a combination of the ring-current storm with a positive variation of the *H*-component caused by the eastward electrojet. Both events show that phenomena common

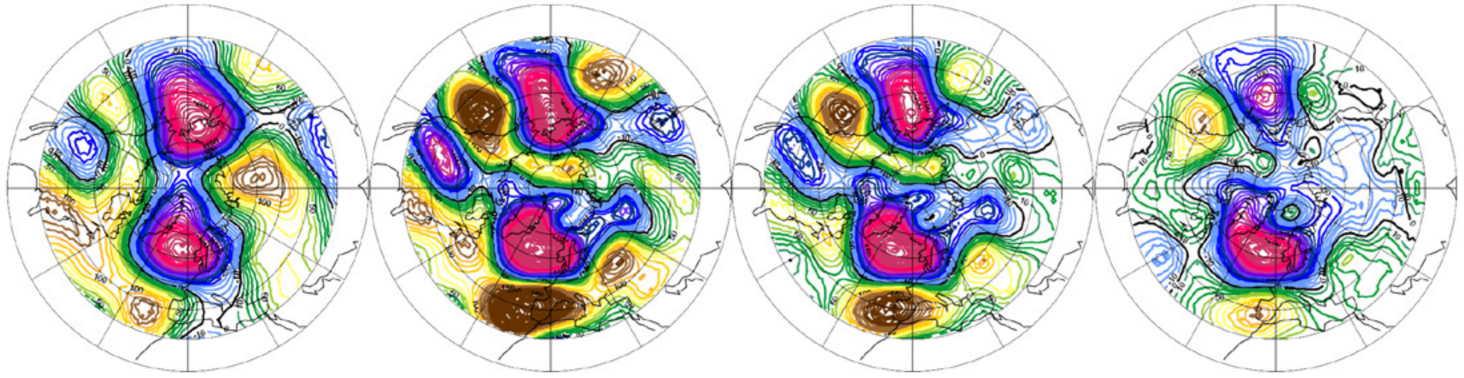


Figure 3: Differences between the average geopotential heights (GPH) 3 days before and 3 days after the onset of geomagnetic disturbances (characterized by index Ap>80) over the winter Northern Hemisphere in 1951-1969. From left to right: GPH levels of 100, 300, 500 and 850 mb. Yellow-green-brown colours depict positive changes (increasing atmospheric pressure), blue-red colours reflect negative changes (decreasing atmospheric pressure). Response of the North Atlantic Oscillation to geomagnetic disturbances is maximum in this period (usually 2-5 days following the onset of geomagnetic disturbance).

in high magnetic latitudes can occasionally happen also at the mid-latitudes.

The day-to-day effects of the strong geomagnetic disturbances on geopotential heights in the winter lower atmosphere were described in many papers at the beginning of the 1970s. Investigations led by our late colleague **Josef Bochníček** (Bochníček et al., 2019), showed that 2 – 5 days after the onset of geomagnetic disturbances, the rate of occurrences of large troughs substantially increased. These works focused on the North-East Pacific, while the North Atlantic was until now omitted. Our aim was therefore to investigate the possible effect of strong geomagnetic disturbances on the lower atmosphere geopotential height changes over the winter North Atlantic on the day-to-day time scale, represented by the daily index of the North Atlantic Oscillation (NAO). The investigation focused on winter periods (December – March) of 1951 – 2003. The NAO response to geomagnetic disturbance, as registered on the day-to-day time scale, also shows a change in its behaviour around the year 1970. This response reaches its highest values in the years 1951 – 1969, usually 2 – 5 days following the onset of geomagnetic disturbances (Fig. 3). Intensity of the response depends on the disturbance intensity (the largest differences were associated with extremely strong disturbances).

Field measurements in the area of Devils Tower volcanic structure in Wyoming, USA. Based on field observations and modelling, Závada et al. (2015) interpret the phonolite monolith as a remnant of a lava body filling a maar/diatreme volcano.

Research student supervision

Every year, a number of PhD and MSc – level projects is supervised by the researchers of the Institute of Geophysics, and commonly also funded by research grants to the Institute. Most of our PhD students, and also some MSc-level students, were part-time employees of the institute during the course of their graduate work. Below, we present a selection of student research projects, running or completed between 2015 and 2020, to illustrate the diversity of research topics dealt with by our PhD students. Names of supervisors and co-supervisors from the Institute are given in bold letters.

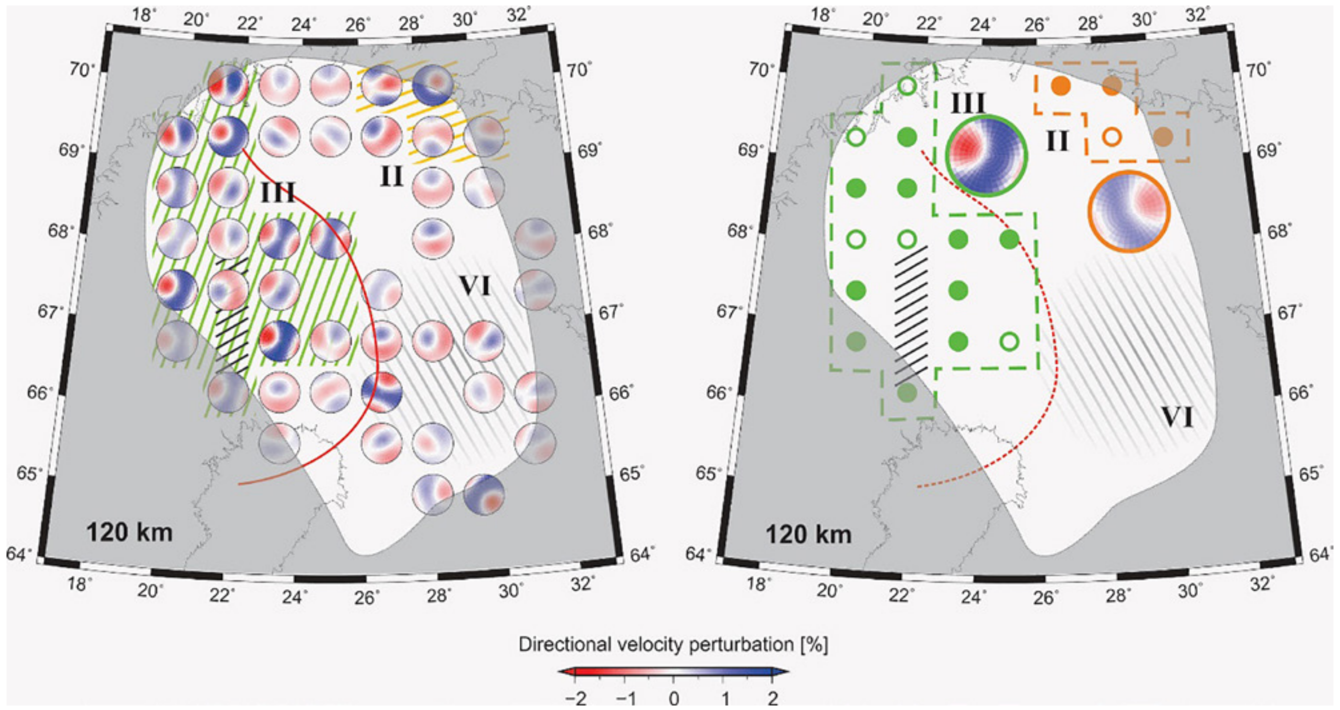
PHD-LEVEL PROJECTS

ANISOTROPIC TOMOGRAPHY OF THE EUROPEAN UPPER MANTLE

Student: **Helena Žlebčíková**, Charles University, Faculty of Mathematics and Physics, Department of Geophysics
Supervisor: **Jaroslava Plomerová**
Co-Supervisors: **Vladislav Babuška, Luděk Vecsey**
2011-2019

The PhD thesis presents the development, testing and application of a novel code, called AniTomo, for coupled anisotropic-isotropic travel-time tomography of the upper mantle. The code allows inversion of relative travel-time residuals of teleseismic P waves simultaneously for 3D distribution of P-wave isotropic-velocity perturbations and anisotropy of the upper mantle. For the first application of the novel code, we opted for data from international passive seismic experiment LAPNET (2007 – 2009) deployed in a tectonically stable region of northern Fennoscandia. The resulting tomographic model shows that the strongest anisotropy and the largest isotropic-velocity perturbations concentrate at the mantle-lithospheric depths while in the deeper parts their amplitudes decrease significantly. Regions of laterally and vertically consistent anisotropy can be delimited in the mantle-lithospheric part of the model. These regions are compatible with domains inferred from joint interpretation of P – and S-wave path-integrated anisotropy. We associate the domain-like anisotropy with fossil fabrics of blocks of the Archean mantle lithosphere, preserved probably from the time of the lithosphere origin.

The research was supported particularly by grant no. 210/12/2381 of the Grant Agency of the Czech Republic, by grant no. 111-10/253101 of the Grant Agency of Charles University, by grant no. M100121201 of the Czech Academy of Sciences, by SCIEX Scholarship Fund, by research infrastructure CzechGeo/EPOS LM2015079 funded by the Ministry of Education, Youth and Sports, and by project CzechGeo/EPOS-Sci, no. CZ.02.1.01/0.0/0.0/16_013/0001800, financed from the Operational Programme Research, Development and Education within ERDF.

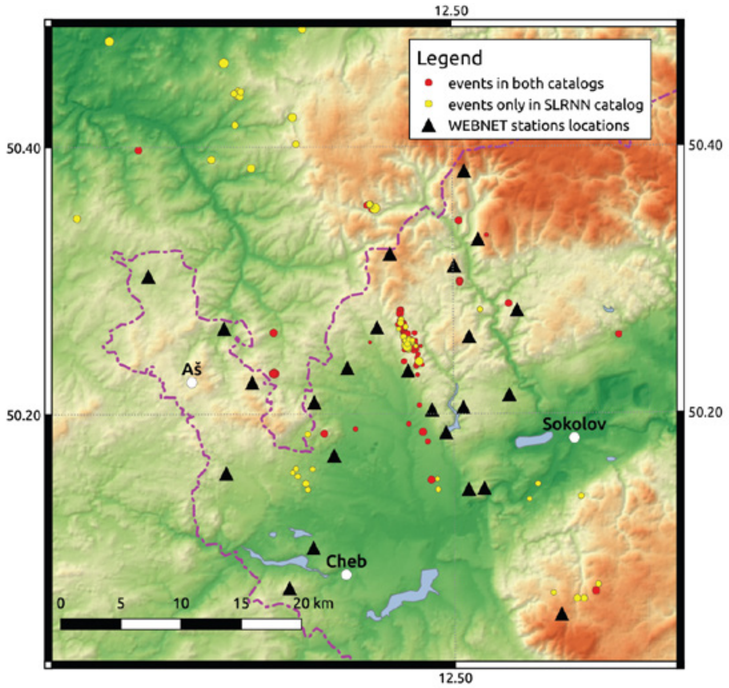


Anisotropic component of P-wave velocities at a selected depth of 120 km of the tomographic model. On the left, we present the anisotropic velocities averaged from the set of individual solutions at each grid node. The anisotropic models are shown only for those nodes, for which at least 8 individual solutions exhibit strength of anisotropy larger than 1 %. Nodes with a similar anisotropic pattern are marked as Regions I-V. A large region with no anisotropy at depth of 120 km is marked as Region VI. The black hatched area locates a zone of weaker anisotropy and velocity perturbations within Region III. The typical anisotropic patterns for Regions I-V are shown on the right. Full circles mark nodes, in which the anisotropic pattern matches the typical pattern, while the empty circles mark nodes with only a tendency to the typical pattern. Red curve contours the region with relatively low-velocity perturbations dominating the model. Part of the model with RDE < 0.5 is shaded.

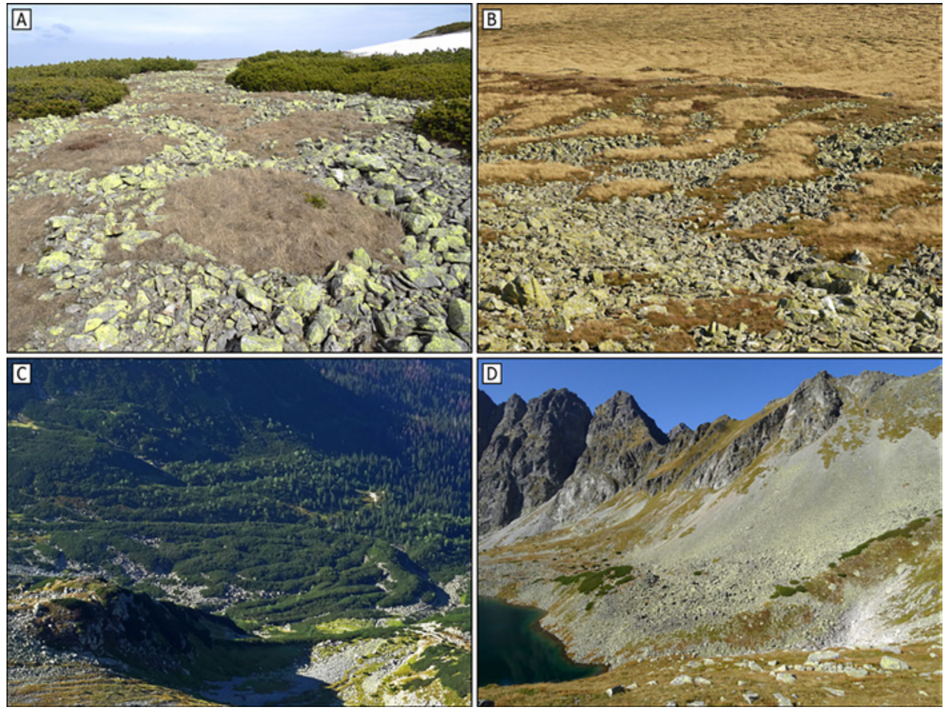
AUTOMATIC AND SEMI-AUTOMATIC PROCESSING OF SEISMOGRAMS FROM LOCAL NETWORKS WEBNET AND REYKJANET

Student: **Jana Doubravová**, Charles University, Faculty of Mathematics and Physics, Department of Geophysics
Supervisor: **Josef Horálek**
2012-2020

Well-performed pre-processing of seismic data leads to much more effective use of man-power as well as computational power in subsequent processing and interpretation of observed data. The main result of the presented thesis is a detector of seismic events based on the use of artificial neural networks, namely a newly defined architecture of the Single Layer Recurrent Neural Network (SLRNN). The neural network of this type enabled to use the detector trained on seismograms of West Bohemian local seismic network WEBNET to seismicity recorded on Reykjanes Peninsula (Iceland) by the REYKJANET local seismic network. A considerable reduction of amount of input data owing to reliable event detection is a key for both effective manual and sophisticated automatic primary processing leading to high quality scientific investigations. Furthermore, an interactive software SeismonWB used for routine manual seismic data processing is presented, because the automatic processing especially for utilization of artificial neural network using supervised learning is closely connected to the manual processing.



Improvement of local catalog of earthquakes based on SLRNN detector for West Bohemia/Vogtland.



(A) Sorted polygons and (B) sorted stripes in the High Sudetes Mts. and (C) debris–talus and (D) talus rock glaciers in the Western and High Tatra Mts.

PAST AND PRESENT PERMAFROST AND ACTIVE-LAYER PHENOMENA AS INDICATORS OF LATE QUATERNARY ENVIRONMENTAL CHANGES

Student: **Tomáš Uxa**, Charles University, Faculty of Science, Department of Physical Geography and Geoecology / employed at the Institute of Geophysics
Supervisor: Marek Křížek (Charles University)
2015-2020

The PhD thesis provides comprehensive data on the typology, distribution, and morphology of the most common and largely relict permafrost features in the High Sudetes Mts. and the Western and High Tatra Mts. (Fig 1). These features are closely related to increased severity of climates and/or sparser vegetation at higher elevations and, as such, they attest to the environmental conditions, which prevailed there towards the end of the Last Glacial Period to the early Holocene when the landforms presumably originated. Similar elevation trends are also documented for active permafrost features in the Svalbard archipelago. Nonetheless, these may also have been forming throughout the Holocene, and, as such, they are not in equilibrium with present-day climate conditions (also considering the excessively thick active layer caused by recent climate warming, which has occurred in most permafrost regions in the Northern Hemisphere). However, not all present-day permafrost regions are currently experiencing its degradation as active layer has been cooling and thinning in the Antarctic Peninsula in recent years.

STRUCTURAL, PETROLOGICAL, AND GEOCHRONOLOGICAL ANALYSIS OF SALT DIAPIRS AND THEIR CAPROCKS (CARBONATE BLOCKS): IMPLICATIONS FOR GROWTH DYNAMICS OF SALT DIAPIRS IN IRAN

Student: **Sadegh Adineh**, Charles University, Faculty of Science, Institute of Petrology and Structural Geology
Supervisor: **Prokop Závada**; co-supervisor at Charles University: Jiří Bruthans
started 2018

The Zagros fold and thrust belt (ZFTB) in southeastern Iran offers unique surface exposures of salt diapirs that can be directly studied in the field and by remote sensing methods over multiple scales. These structures reveal mobilized salt together with its overlying solid residuum (caprock) and halokinetic sequences that reflect reactivation of several km-high, columnar salt diapirs by compressional tectonic regimes. The thesis is part of an extended research project between the Institute of Geophysics, Charles University, and Ludwig Maximilian University of Munich. The principal aim of this study is the increased understanding of the mechanical and geochemical characteristics of caprock and the influence of the caprock properties on the diapiric extrusions and sedimentary layers adjacent to the salt diapirs. The research is partly supported by grants No. 20-18647J of the Grant Agency of the Czech Republic and No. 1542120 of the Grant Agency of Charles University.

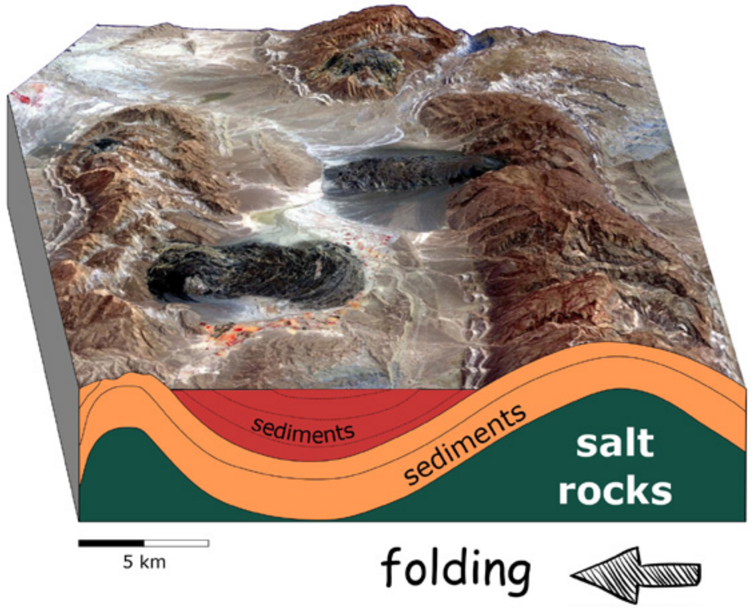


Illustration of the major structural elements (Zagros Simply Folded Belt and Salt diapirs, southern Iran). Satellite imagery by NASA; outcropping salt diapirs are visible as darkish irregular patches.

TRANSIENT TEMPERATURE FIELD OF THE SHALLOW SUBSURFACE AND ITS SOURCES

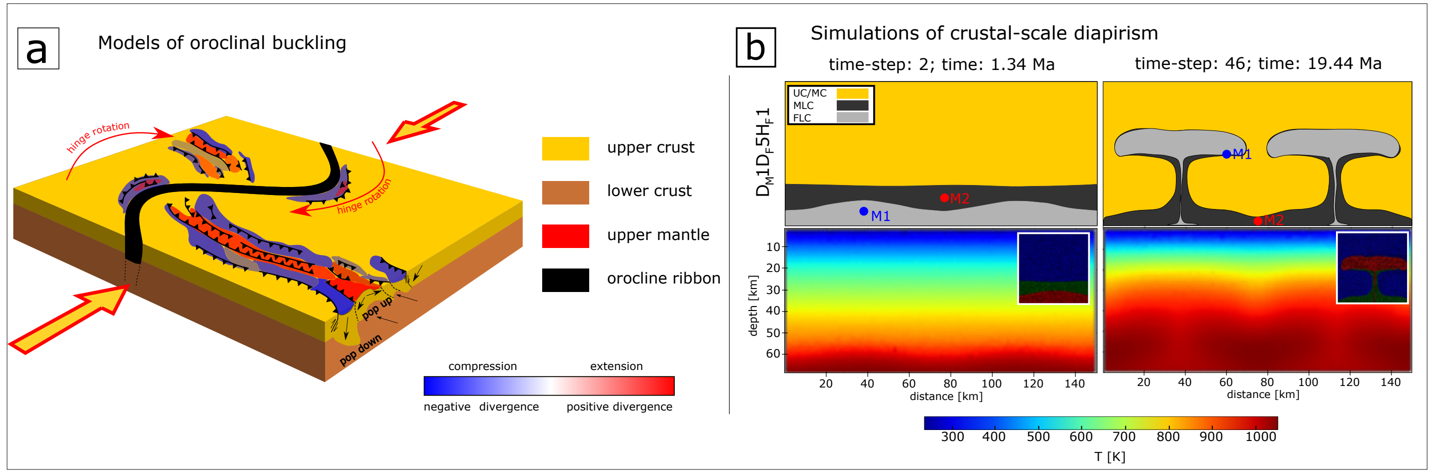
Student: **Petr Dědeček**
Charles University, Prague, Faculty of Science, Institute of Hydrogeology, Engineering Geology and Applied Geophysics
Supervisor: **Jan Šafanda**
2010 – 2019

Long-term air and ground temperature series and repeated temperature logs from several boreholes in Czech Republic, Slovenia and Portugal were processed to distinguish and describe possible sources of transient signals in subsurface temperature field. Two methods for estimation of the soil and bedrock thermal diffusivity from long-term temperature records are presented and compared. Results proved that on the annual time scale the convective heat transfer did not contribute significantly to the temperature-time variations monitored in the uppermost 10-m depth zone and that the influence of moisture changes on subsurface temperature field noticeably appears only in upper 5 cm of soil. Using 3D numerical modelling adirect human impact on the subsurface temperature warming was proved and contributions of individual anthropogenic structures to this change were evaluated. It made it possible to split the transient component of the present-day temperature depth profiles into the climatic and anthropogenic signals.

ANALOGUE AND NUMERICAL SIMULATIONS OF THE GEODYNAMICAL SYSTEMS – INSIGHTS FROM THE MODELS OF THE EARTH COLLISION TECTONICS AND MARTIAN MUDFLOWS

Student: **Ondřej Krýza**
Charles University, Faculty of Science, Institute of Petrology and Structural Geology
Supervision: Ondrej Lexa, **Prokop Závada**
2013-2020

The thesis presents the results of multiple geodynamical modelling projects including development and evolution of the large-scale oroclines, crustal-scale detachment folds, crustal-scale diapirism (based on Rayleigh-Taylor (R-T) instability evolution) and mudflows under the Martian atmospheric conditions. The oroclinal buckling analogue models revealed complex, polyphase crustal and mantle deformation which is associated with the mechanical coupling between individual lithospheric layers and results e.g. in a formation of the large pop-down / pop-up belts converging to the orocline ribbon inflection from surrounding regions. The analogue models of detachment folding in the lower crust show the effect of the melt migration between the MOHO and individual folds in the sequence and how this transfer affects dynamics of folding – resulting in the four stage evolution: 1. initial perturbation; 2. melt inflow and amplification; 3. Necking, locking and melt outflow; 4. vertical extrusion of the fold. These models are followed by investigation of the R-T instability propagation in dependence on the density contrast, thickness ratio, radiogenic heating and geometry of the lower crust layers (Fig. 1c). The



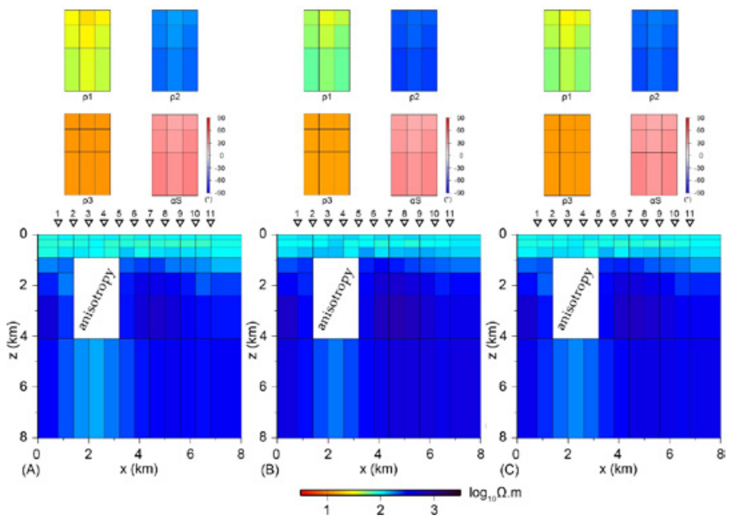
Examples of the models that describe individual geodynamical systems: (a) mapping of the extension/compression zones of the pop system in the formed orocline; (b) Numerical model of crustal-scale diapirism (material composition above; thermal evolution below).

physical models of the Martian mudflows revealed that the mud situated on the cold Martian surface behaves as the Pahoehoe lava type while on the warm surface propagates by flow-levitation transport. The research was supported by multiple sources of funding: GAČR: 19-27682X; GAČR: 17-17540S, 16-17457S; UNCE/SCI/006; EPN2020-RI: 654208

STOCHASTIC SIMULATIONS AND MODELLING IN THE MAGNETOTELLURIC METHOD

Student: **Radek Klanica,** Charles University, Faculty of Science, Institute of Hydrogeology, Engineering Geology and Applied Geophysics
Supervisor: **Josef Pek**
2016 – 2019

The thesis presents results from magnetotelluric stochastic inversion algorithm in a 1D/2D case with anisotropy, which was developed during the study. Stochastic methods are based on the exploration of the model parameter space, and they pick models according to their probability, which makes them effective for the solution of high-dimensional problems. Since the model parameter space is explored by a large number of models, the results are presented by a full probabilistic description of the parameters and not in a form of a single model. The stochastic inversion developed uses a sampling method DREAM, which belongs to adaptive Monte Carlo – Markov Chain algorithms. It runs multiple chains in parallel and combines a multi-try sampling with sampling from an archive of past states. New stochastic inversion was tested on both synthetic and field data. It gives satisfactory results in 1D case, as well as for synthetic 2D isotropic problems. The algorithm achieves worse results in 2D real isotropic examples only in case of large number of parameters (> 500). In case of 2D anisotropic problems, both synthetic and practical, the algorithm reaches better results than the classical non-probabilistic procedures. This approach benefits from offering full probability maps of the solution space, and thus from estimates of the uncertainties of the solutions.



Solution of synthetic anisotropic model using DREAM algorithm with prior information on smoothness. Into an isotropic model (300 Ω.m), an anisotropic block was added with three different resistivities (ρ1=3 Ω.m/ρ2=300 Ω.m/ρ3=3 Ω.m) along X-Y-Z axis; the block was inclined at angle αS=30°. Small triangles show individual simulated MT stations. (A) min. and (B) max. values for 90% credibility interval, (C) model from solution mean. The anisotropic block is well resolved by the method used, with only small variations between models plotted from min. and max. values within 90% credibility interval, thus obtained solution is stable. Resulting resistivities and angle are close to original model, proving that inversion procedure is functional and effective.

OTHER PHD THESES, 2015-2020:

Inversion of traveltimes of P-waves reflected in layers of arbitrary anisotropy
Student: **Han Xiao**, Geo-Exploration Science and Technology, Jilin University, China
(running; supervisor: **Ivan Pšenčík**)

SH plane-wave reflection/transmission coefficients in isotropic, weakly attenuating media
Student: **Milosz Wcislo**, Charles University, Faculty of Mathematics and Physics
(running; supervisor: **Ivan Pšenčík**)

Earthquake swarms in diverse tectonic environments: West Bohemia and Southwest Iceland
Student: **Hana Jakoubková**, Charles University, Faculty of Mathematics and Physics
Defended 2018; Supervisor: **Josef Horálek**

The Structure of the West Bohemian Earthquake Swarm Source Zone
Student: **Martin Bachura**, Charles University, Faculty of Science
Defended 2017; Supervisor: **Tomáš Fischer**

Small-scale volcanoes on Mars: image analysis, numerical modeling and comparison with terrestrial analogs
Student: **Petr Brož**, IG CAS / Charles University, Faculty of Science
Defended 2015; Supervision: David Dolejš, **Prokop Závada**

MSC. – LEVEL THESES

Magnetotelluric sounding of the Earth's crust in a region with strong industrial electromagnetic noise.
Student: **Radek Klanica** (Faculty of Science, Charles University, Prague)
(defended 2015; supervisor: **Josef Pek**)

Numerical simulation of a solidifying binary system
Student: **Simona Konečná**, Faculty of Mathematics, Physics and Informatics, Comenius University in Bratislava, Slovakia
(defended 2017; supervisor: **Juraj Kyselica**)

Stefan problem with kinetic undercooling
Student: **Miroslava Vidová**, Faculty of Mathematics, Physics and Informatics, Comenius University in Bratislava, Slovakia
(defended 2018; supervisor: **Juraj Kyselica**)

Microgravity exploration and modelling of geological structures
Student: **Roman Beránek**, (Faculty of Science, Charles University, Prague)
(defended 2020; supervisor: Vratislav Blecha, co-supervisor: **Jan Mrlina**)

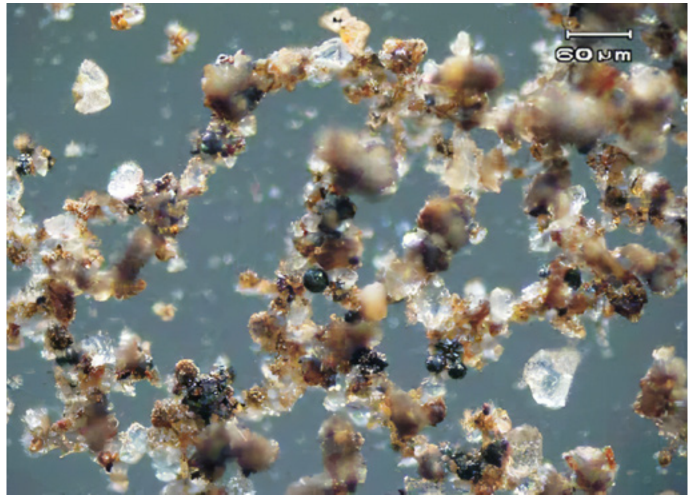
University – level courses

Specialized as well as fundamental courses are taught by researchers from the Institute of Geophysics at a number of universities in the Czech Republic and abroad.. The list below shows courses taught in 2015-20, fully or partly, by instructors whose main employer was the Institute of Geophysics. The names of instructors from the Institute are indicated by bold letters.

PETROPHYSICS

Faculty of Science, Charles University, Prague
Course Code: MG452P15
MSc programme, 3 hrs. /week, spring semester
Lecturer: **Eduard Petrovský**

Rock as a physical environment. Mass property of rocks: density, porosity, permeability. Magnetic properties of rocks: anisotropy of magnetic susceptibility, paleomagnetic and archaeomagnetic research, magnetostratigraphy. Electrical properties of rocks: resistivity, permitivity, electrochemic activity, special electric properties. Radioactive properties of rocks. Thermal properties of rocks. Mechanical (engineering) proper – ties of rocks. Inelastic and elastic constans of minerals and properties of rocks.



Petrophysics:
Magnetic extract of topsoil sample from the Ostrava region (N Moravia), with dark spherical magnetite of industrial origin.

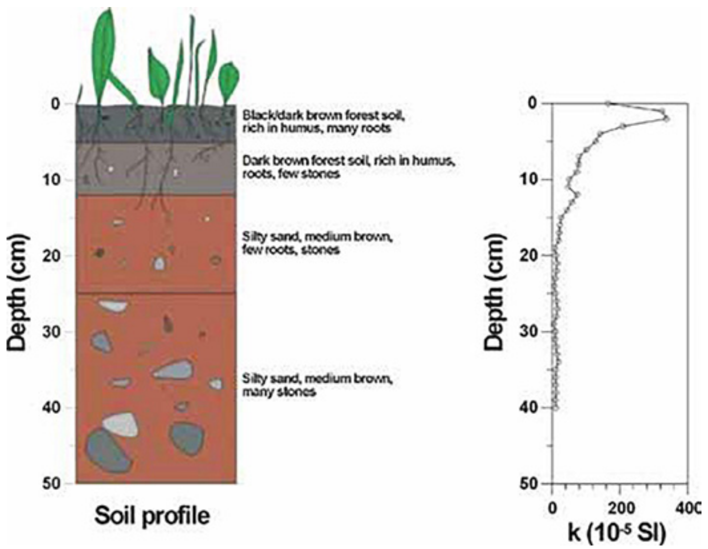
PETROPHYSICS

Faculty of Science, Palacký University, Olomouc
Course Code: KGE/PETF
MSc programme, 20 hrs., spring semester
Lecturer: **Eduard Petrovský**

MAGNETOMINERALOGY

Faculty of Science, Charles University, Prague
Course Code: MG452P68
MSc programme, 2 hrs. /week, autumn semester
Lecturers: **Eduard Petrovský**

The course is aimed at a general introduction into magnetic minerals as carriers of record of environmental changes. Magnetic record in geomaterials (environmental magnetism) reflects changes in geological histor of the Earth (paleomagnetism), past climatic changes (magnetic paleoclimatology) as well as environmen – tal impact of recent and present human activities, such as industrial pollution. Students will acquire basic knowledge of identification and characterization of magnetic minerals using magnetic methods and will learn to use this knowledge in environmental applications.

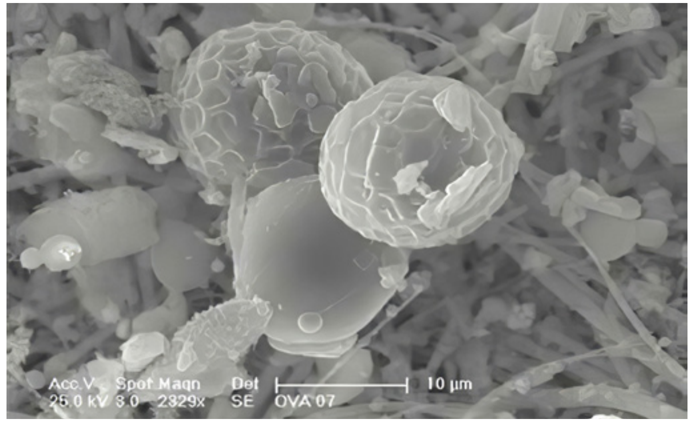


Magnetomineralogy:
Typical vertical distribution of magnetic susceptibility in a soil profile, dominated by atmospheric deposition of dust particles.

Analogous or closely related courses are also run at other universities under the following titles:

ENVIRONMENTAL MAGNETISM

Faculty of Science, Helsinki University, Helsinki, Finland
Course Code: GEOM_S2032
MSc programme, 20 hrs., spring semester,
each even year Lecturer: **Eduard Petrovský**



Environmental Magnetism:
Spherules of industrial origin rich in magnetite (FeOFe2O3) as part of flight ash.

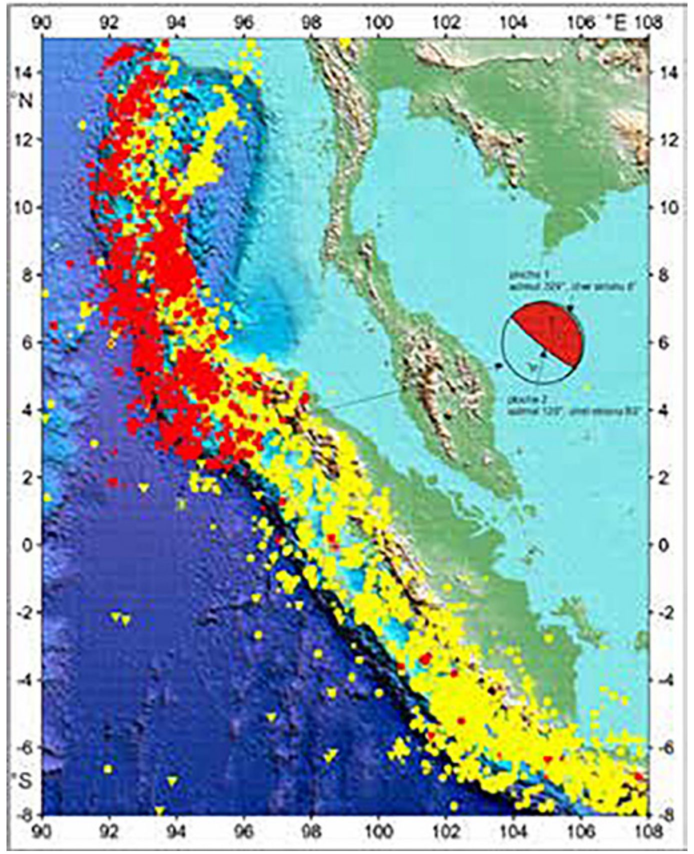
FAULT TECTONICS AND SEISMIC ACTIVITY

Faculty of Science, Charles University, Prague Course Code: MG440P40
MSc programme, 2 hrs. /week, winter semester Lecturer: **Aleš Špičák**

The course concentrates on the causes of earthquake occurrence (tectonic stress concentration, brittle and inhomogeneous environment, movements of rock masses), explains earthquake distribution in the lithosphere and the phenomenon of deep earthquakes. Classifications of seismic events and seismic waves are discussed. Phenomena and processes accompanying tectonic stress concentration are analyzed from the viewpoint of earthquake prediction. The course gives a detailed view on the most seismically active regions on Earth, e.g. SE Asia, Andean South America, Central America, Tonga-Kermadec, East African Rift, Gulf of California, the Mediterranean, etc. Students analyse professional papers on related topics published recently in major scientific journals (e.g., EOS, Science, Nature).

SEISMOTECTONICS

Faculty of Science, Palacký University, Olomouc
Course Code: KGE/SEIT
Lecturer: **Aleš Špičák**



Fault tectonics and seismic activity:
Map of epicentres (EHB data) of earthquakes in the Sumatra, Andaman and Nicobar Islands re – gion. Yellow symbols – events from 1964 to Dec. 26, 2004; red symbols – from Dec. 26, 2004, to March 15, 2005. The GCMT focal mechanism of the main shock of Mw 9.1 is shown.

GEOTECTONICS

Faculty of Science, Charles University, Prague,
Course Code: MG440P15
BSc programme, 2 hrs. /week, winter semester
Lecturer: Petr Jeřábek (Charles University),
with guest instructors from
the Institute of Geophysics: **Aleš Špičák**, **David Uličný**

The course provides the basic review of the inner composition of the Earth, in particular its crust and mantle and the physical processes behind the plate tectonics. An introductory part is devoted to a review of main geophysical methods. The main part of the course is focused on the plate boundaries, their tectono-metamorphic evolution, relationships to magmatism and sedimentary basin evolution.

Geotectonics:
The Basin and Range province of SW USA belongs to major continental domains of extensional tectonics

GEOLOGY OF SEDIMENTARY BASINS

Faculty of Science, Charles University, Prague, Course Code: MG421P38
primarily MSc level, but also available to BSc students; 2 hrs. /week, winter semester
Lecturer: **David Uličný**

The course is focused on the tectono-stratigraphic evolution of sedimentary basins and on the sedimentary record of lithosphere evolution on time scales of basins as well as plate-tectonic cycles. Lectures are combined with exercises (including basics of geological interpretation of seismic reflection data) and reading seminars to provide the students with both theoretical and practical knowledge of the classical concepts as well as current issues in sedimentary basin research. Case studies for seminars and exercises are

Geology of Sedimentary Basins:
Soft-sediment deformation in Miocene deltaic sediments interpreted as evidence for syndepositional seismic activity in the Most Basin, Czech Republic

SEDIMENTARY GEOLOGY

Faculty of Science, Charles University, Prague, Course Code: MG421P14
Lecturer: **David Uličný**

PHYSICS FOR GEOPHYSICISTS

Faculty of Science, Charles University, Prague, Course Code: MG452P71
The lecture consists of three parts: Mechanics, Electricity and Magnetism, Thermodynamics.
Each part is lectured one semester in MSc and PhD programmes.
Lecturer: **Josef Horálek**

INTERPRETATION OF GEOELECTRIC MEASUREMENTS

Faculty of Science, Charles University, Prague, Course Code : MG452P64
Theory of the electromagnetic field – part of lecture shared with T. Fischer
Lecturer: **Josef Horálek**

GEOTHERMAL PROSPECTING

Faculty of Science, Charles University, Prague, Course Code: MG452P47
Lecturer: **Petr Dědeček**

CAUSES AND CONSEQUENCES OF CLIMATIC PHENOMENA IN THE QUATERNARY

Faculty of Science, Charles University, Prague, Course Code: MG421P15
Lecturer: **Jaroslav Kadlec**

GEOLOGY OF THE QUATERNARY

Faculty of Science, Charles University, Prague, Course Code: MG421P18B
Lecturer: **Jaroslav Kadlec**

CLIMATIC CHANGES IN THE EARTH'S HISTORY

Faculty of Science, Charles University, Prague Course Code: MG421P4
MSc level, 2 hrs./week, winter semester
Lecturer: **Jiří Laurin**

This course describes in detail the key components of Earth's climate system and explains how these com – ponents evolved through the geological history, from the Precambrian to the Quaternary. Main focus is on the mechanisms of climate change at the time scales of thousands to millions of years. The origin of the three prominent climatic modes – greenhouse, icehouse and snowball – is discussed in detail. Certain methods of paleoclimate research, such as numerical modeling and time-series analysis, are demonstrated using both synthetic and real geological data.

Climatic changes in the Earth's history:
The sedimentary record of permanent and ephemeral lakes provides important information on the past climate. Shortwave infrared through red wavelength image of Lake Carnegie, Australia, courtesy NASA, Visible Earth (http://visibleearth.nasa.gov/).

INVITED SHORT COURSES

The Institute of Geophysics organized short courses attended by audience from a number of academic institutions and companies.

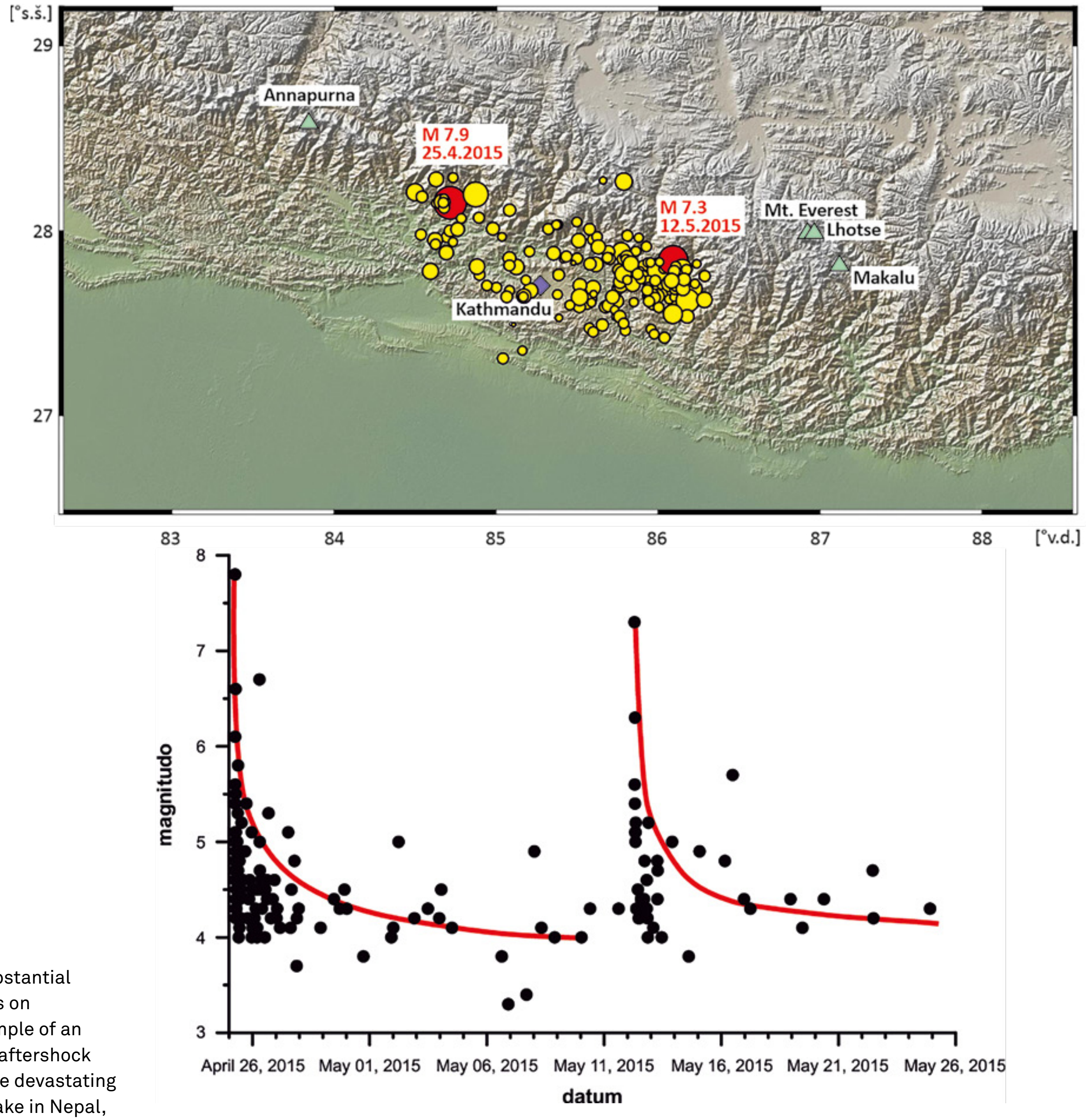
GEOLOGICAL INTERPRETATION OF SEISMIC REFLECTION DATA

Instructor: **Kateřina Schöpfer** (Univ. Vienna, Austria)
12. – 15.3. 2017

APPLICATIONS OF THE DISTINCT ELEMENT METHOD (DEM) IN STRUCTURAL GEOLOGY AND GEOMECHANICS

Instructor: **Martin Schöpfer** (Univ. Vienna, Austria)
18.10.2018

The short course by dr. K. Schöpfer on geological interpretation of seismic reflection data was attended by participants from several universities and geoscience institutions.



Case studies are a substantial component of lectures on seismotectonics: example of an unusual decay of the aftershock sequence following the devastating Gorkha M 7.8 earthquake in Nepal, April 25, 2015.

Conferences and other professional events

XXVI GENERAL ASSEMBLY OF THE INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS, PRAGUE, 2015

“Earth and Environmental Sciences for Future Generations” was the theme for the XXVI General Assembly of the International Union of Geodesy and Geophysics (IUGG, www.iugg.org), the most important and largest event organized by our Institute in 2015. The IUGG is the primary international body of our research interest, consisting of eight scientific associations. Its general assemblies are organized every 4 years and Prague has become the only city to host an assembly twice – in 1927 and 2015. The 2015 event was attended by 4231 participants from 87 countries worldwide. The scientific program was complex and multi-levelled, reflecting the complexity of the Union as a whole. Nine Union lectures were given by top experts representing all scientific associations, including Yuan T. Lee, a Taiwanese chemist and a Professor Emeritus at the University of California, Berkeley, Nobel Prize laureate in chemistry 1986. Eleven Union symposia were identified as being of wide interest to all, with oral presentations by invitation only. Joint inter-association symposia were put forward by two or more associations. Association symposia and workshops, as well as open panel discussions were of more specialised interest to individual associations. In total, 198 symposia and workshops were organized and more than 5400 contributions were presented.

In addition to the XXVI IUGG Assembly, researchers of our Institute organized several topical meetings of international significance. The first workshop **ACTIVE AND PASSIVE SEISMICS IN LATERALLY INHOMOGENEOUS MEDIA (APSLIM)**, which was held in the Loučeň Castle on June 8-12, 2015, followed the tradition of the SWLIM (*Seismic Waves in Laterally Inhomogeneous Media*) workshops held since 1978 roughly every 5 years. These meetings were known as unique places where scientists from both East and West met and exchanged ideas. The 2015 meeting was attended by 37 participants from 11 countries worldwide.

THE 2ND CONFERENCE ON NATURAL DYNAMOS was held on June 25 – July 1, 2017 in Valtice. It was dedicated to hydromagnetic dynamos, magnetoconvection and various hydro-magnetic processes acting in the Earth’s core, planetary cores, in the Sun and other stars, in galaxies, accretion discs and other astrophysical objects, and also to laboratory hydromagnetic and dynamo experiments. The conference was co-organised by our Institute, the Earth Science Institute of Slovak Academy of Sciences, Bratislava, and the Department of Astronomy, Physics of the Earth and Meteorology of the Faculty of Mathematics and Physics, Comenius University, Bratislava. In total, 59 participants from 9 countries from the USA and Europe attended the event.

In addition, a number of smaller meetings focusing on various topics were organized or co-organized by our Institute:

- **SCIENTIFIC WORKSHOP ON DRILLING THE EGER RIFT**: Magmatic fluids driving the earthquake swarms and the deep biosphere (main organizer GFZ Potsdam, Germany), 24-25 January 2019, GFZ Potsdam, Germany;
- **ICDP EGER CORE-SAMPLING PARTY** (co-organized with the Faculty of Sciences, Charles University, Prague), 28-29 November 2019, Ringen Geothermal Research Centre, Litoměřice;
- **SAGA WORKSHOP 1**, followed by COST Action CA17131 (SAGA) Second Joint Working Group Meeting and Third Management Committee Meeting, 30 September – 3 October 2019, Prague;
- **EPOS/TCS GEOMAGNETIC OBSERVATIONS MEETING** with Data Users and Providers and tribute to 180 years of geomagnetic observations on the Czech territory, 18 and 19 June 2019, Prague.

IUGG Assembly 2015: snapshots from the Opening Ceremony (left) and scientific session (right). Courtesy of C-IN Prague.

Studia Geophysica et Geodaetica

Studia Geophysica et Geodaetica (SGEG), published by the Institute of Geophysics since 1956, is an international scientific journal covering all aspects of geophysics, geodesy, meteorology and climatology.

In 2015-2019, the Editorial Board of the journal consisted of 27 experts from 11 countries (see the list below). Electronic and printed versions of the journal are distributed by Springer. In 2015-2019, 477 original works were submitted, of which 183 became published (rejection rate c. 62%). The mean submission-to-acceptance time is about 6 months (it strongly depends on the quality of the submission and willingness of potential referees to review it). Special issues are published on various occasions, usually as proceedings from scientific meetings. In the years 2015-2020, two special issues were compiled and published. Issue 3/2016 presented the first workshop ***Active and Passive Seismics in Laterally Inhomogeneous Media (APSLIM)***, which was held in the Loučeň Castle, Czech Republic, in 2015. Issue 2/2017 published papers presented at the fourth Biannual Meeting of the ***Latin-American Association of Paleomagnetism and Geomagnetism (LATINMAG)*** held in Sao Paulo (Brazil) in 2015.

According to the Impact Factor in 2019 (1.247; 5-year IF 1.200), the journal is ranking as 63^{rd} out of 85 journals in the Web of Science subject group Geochemistry & Geophysics, and 12th out of 40 journals with Impact Factor published in the Czech Republic. The journal is abstracted or indexed in Current Contents: Physical, Chemical and Earth Sciences; ISI Alerting Services; Meteorol. and Geoastrophys. Abstracts and Elsevier/Geo Abstracts.

All the articles published in SGEG since 1956 can be found on the web page: **www.springerlink.metapress.com/content/109194/**

The most cited paper since 2015: Gilardoni M., Reguzzoni M. and Sampietro D.: GECO: a global gravity model by locally combining GOCE data and EGM2008. Stud. Geophys. Geod., 60 (2016), 228-247, DOI: 10.1007/s11200-015-1114-4 (45 citations by August 2020 on Web of Science).

The journal published almost 2400 papers during its lifetime with almost 13000 citations, the h-index of the journal is 39 (as of August 2020, Web of Science).

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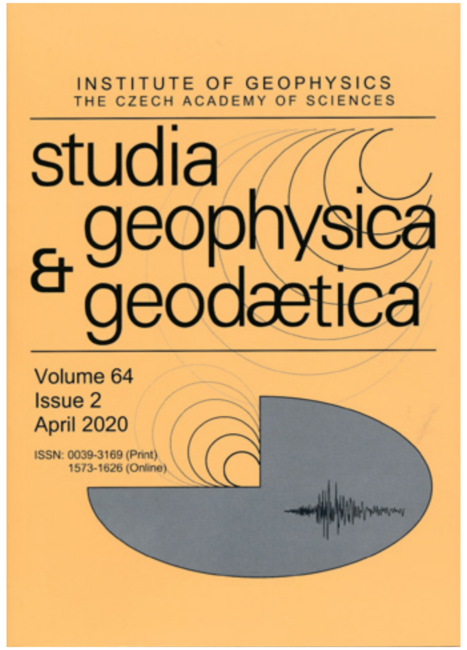


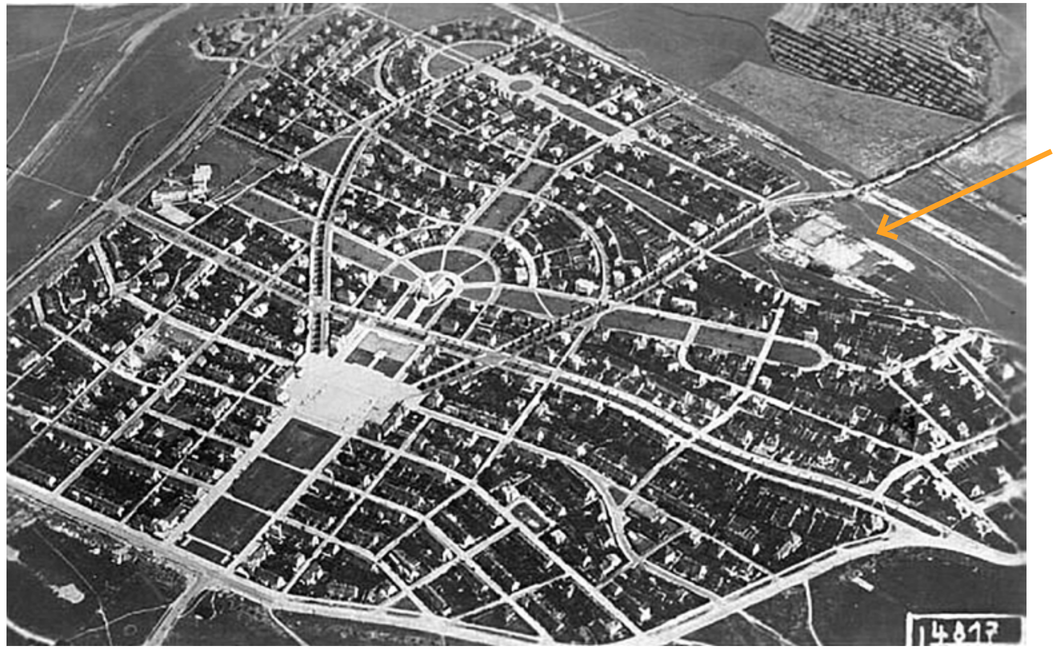
The Spořilov campus: past and future

The Institute of Geophysics is situated in the campus of the Academy of Sciences of an area of 2.5 ha in the eastern part of Prague. The Spořilov district that surrounds the campus is an example of a "Garden City", an architectural concept that was modern and innovative throughout Europe in the beginning of the 20th century. The district that consists of more than 1,000 family houses with small gardens, parks, facilities, and a church, was built based on a comprehensive project of Czech architects J. Bark and J. Bertl between 1926-1929. The district belongs to popular residential sites in Prague.

The campus became a property of then the Czechoslovak Academy of Sciences in 1953, in the year of foundation of the Academy. The institute occupies the main, 3-storey building of the campus. The building was constructed from the very beginning as the seat of the Institute of Geophysics and was finished in the late 1950s. The construction followed a project of architect **Z. Pokorný** whose most valued professional achievement was participation in the successful project of the Czechoslovak pavilion at the world exhibition EXPO '58 in Brussels (together with F. Cubr and J. Hrubý). Later, two smaller buildings were built at the campus – one for the Institute of Atmospheric Physics (1992) and the other for the Astronomical Institute (2011). At the western edge of the capus, its greenest and most remote part was transformed into Geopark in 2003. The Geopark is open daily to the public and its mission is to introduce the fundamentals of geological processes by showcasing a collection of interesting samples of rock types, each complemented by a story that explains the interesting features and a broader context of the sample.

Most recently, necessary renovations of the building and of the entire campus, now over 60 years old, have been designed by architects D. Mareš, J. Hofmeisterová, and colleagues from the "**třiarchitekti**" studio (http://www.triarchitekti.cz/). By now, the renovations include a rebuilding of the lecture hall (2018) and the dining hall (2019). Currently running reconstruction phase, to be completed in April 2021, will, among other changes, transform the former workshop area to a state-of-the-art laboratory of analogue modelling of geological processes. Future plans involve construction of a multi-function pavilion serving all the three institutes of the campus, and a residential building with starting flats for early-career researchers coming from abroad. A comprehensive conceptual study of the campus focuses on sustainable maintenance of the greenery, on optimisation of energy consumption, storage of rain water, and a better conceptual and functional connection to the surrounding district scheme. Opening of the campus to the public proposed by the management of the institute is still undergoing an intense debate among employees of all three institutes of the campus as well as in the neighbourhood.

The roof of the main building is decorated by a large sculpture depicting the globe and some symbols of geophysical exploration. The sculpture, made of sandstone, was placed at the roof probably in 1958 by a helicopter (see photo on the right). Despite all efforts, the author of the sculpture has remained unknown. A plaster model of the sculpture, 90 cm in length, is exhibited at the corridor in front of the lecture hall.



Aerial photo of the Spořilov district, taken in 1938. The future campus of the Academy, including our Institute, is visible in the upper right (arrow).

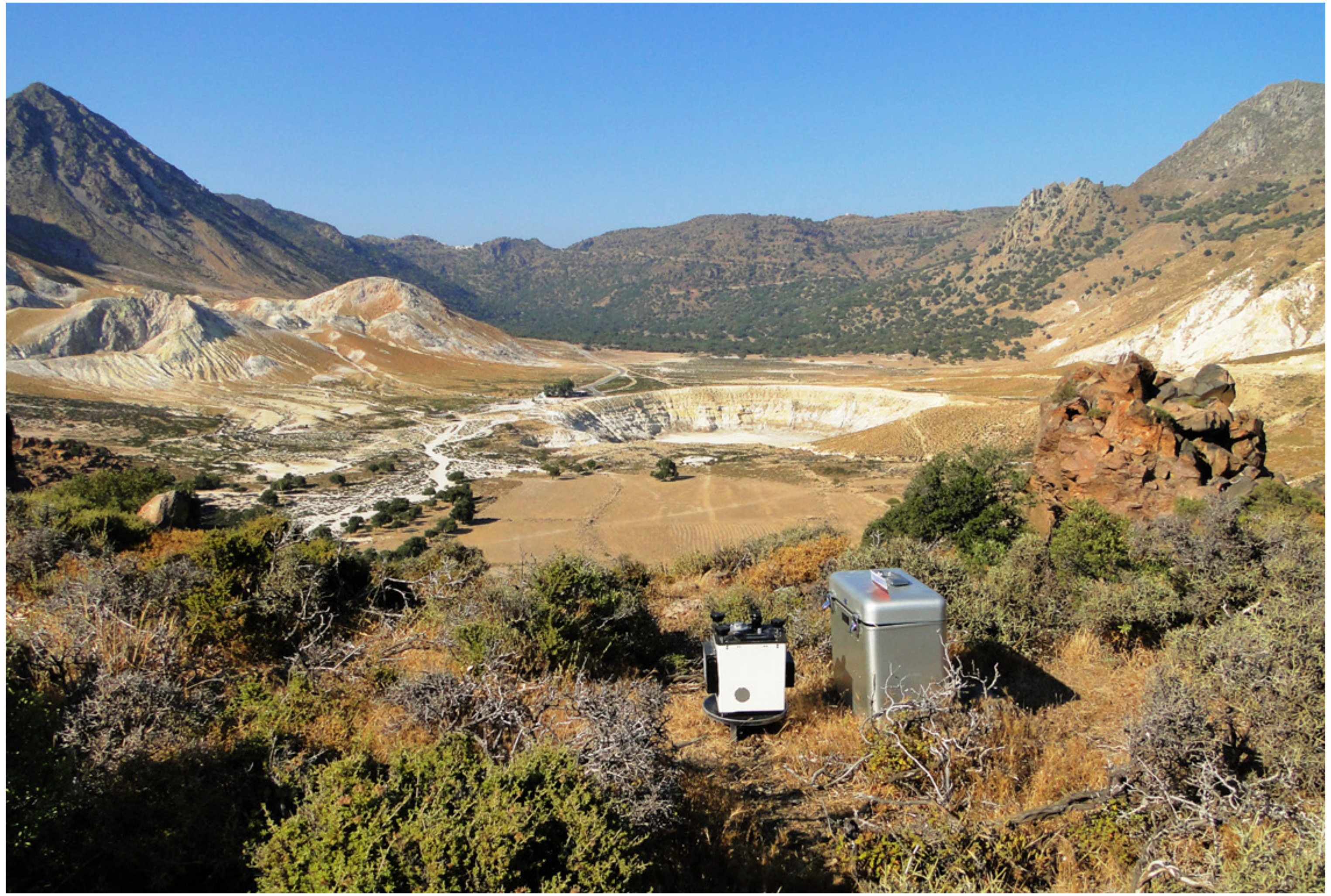
Renovation of the lecture hall, based on a project by the **"třiarchitekti"** studio, represents the most significant upgrade of the Institute's interior in decades. The renovation paid attention to historical details of the architecture as well as to a contemporary feel of the multi-functional space used for meetings, lectures, courses, outreach events as well as art exhibitions (here, exhibition of works of F. Kyncl, spring 2019).

The dining hall of the Institute, after complete renovation finalized in 2019.

Julius Payer: The Starvation Cove (1897), 390x540 cm, Lecture Hall of the Institute of Geophysics. Photograph by Hana Hamplová.

Inside the lecture hall, the Institute houses a masterpiece of realistic painting related to exploration of polar frontiers: oil-on-canvas work "Starvation Cove" by the Austrian geographer, military officer and painter **Julius Payer** (1841 – 1915). The Payer's seminal work, 3.9 x 5.4 meters in size and dated 1897, depicts the tragic end of the polar expedition led by Sir John Franklin between 1845-1847.

The painting became a property of the Institute in 1964 after its former owner, the National Gallery, had declared it "useless", partly because of its huge size and problems with its storage.



Gravity measurements in the volcanic caldera of the Nisyros Island, Greece.

Observatories and data acquisition systems

A significant part of the Institute's mission involves acquisition and sharing of primary geophysical data through a number of observatories and measuring equipment. Continuous observations of physical parameters, mainly magnetic field, gravity, heat flow, and seismicity/ground displacement follow up on a long history of observational activities within the Austro-Hungarian monarchy in the 19th century: geomagnetic field measurements in Prague's Klementinum Astronomical Observatory since 1839, gravity measurements in the mines of Příbram in Central Bohemia since 1882, and seismic recordings in Cheb (Eger) in West Bohemia since 1908. The IG is the only institution in the Czech Republic that performs various geophysical observations systematically. With the absence of a geophysical division within the Czech Geological Survey, the IG plays the role of the state geophysical service.

SEISMOLOGICAL OBSERVATIONS

Seismological Data Centre and Service

The role of the Seismological Service of the Institute of Geophysics is to provide data enabling to follow, in real time, occurrence of even small, unfelt earthquakes all over the territory of the Czech Republic, to identify seismic events induced by industrial activities, namely mining operations, and to point out to stronger, felt earthquakes in the areas neighbouring to Czechia. The Service acquires and archives data from seismic stations of the Czech Regional Seismic Network (CRSN), exchanges the data with European as well as global data centres, and provides various related services to researchers and general society.

The Seismological Service of the IG operates twelve of the total of 27 stations of the CRSN (Fig.1). The interpretations are based not only on recordings from the stations of the CRSN but also on real-time data from about seventy seismological stations in central and southern Europe.

Digital data from all stations of the network – the Czech as well as the virtual ones – are transferred continuously to the IG by Internet, processed by Seismic Handler analysis programme and archived by the Antelope and SeisComP/SeedLink software packages on large raid systems. Digital records and seismic phase readings are exchanged with major international data centers (Internationa Seismolgical Centre (ISC), United Kingdom; NEIC – National Earthquake Information Center (NEIC) of the US Geological Survey, Boulder, Colorado; Incorporated Research Institutions for Seismology (IRIS), Washington D.C.; Observatories & Research Facilities for European Seismology (ORFEUS), De Bilt, The Netherlands; European-Mediterranean Seismological Centre (EMSC), Bruyéres-le-Châtel, France) and a number of neighbouring national centres and observatories.

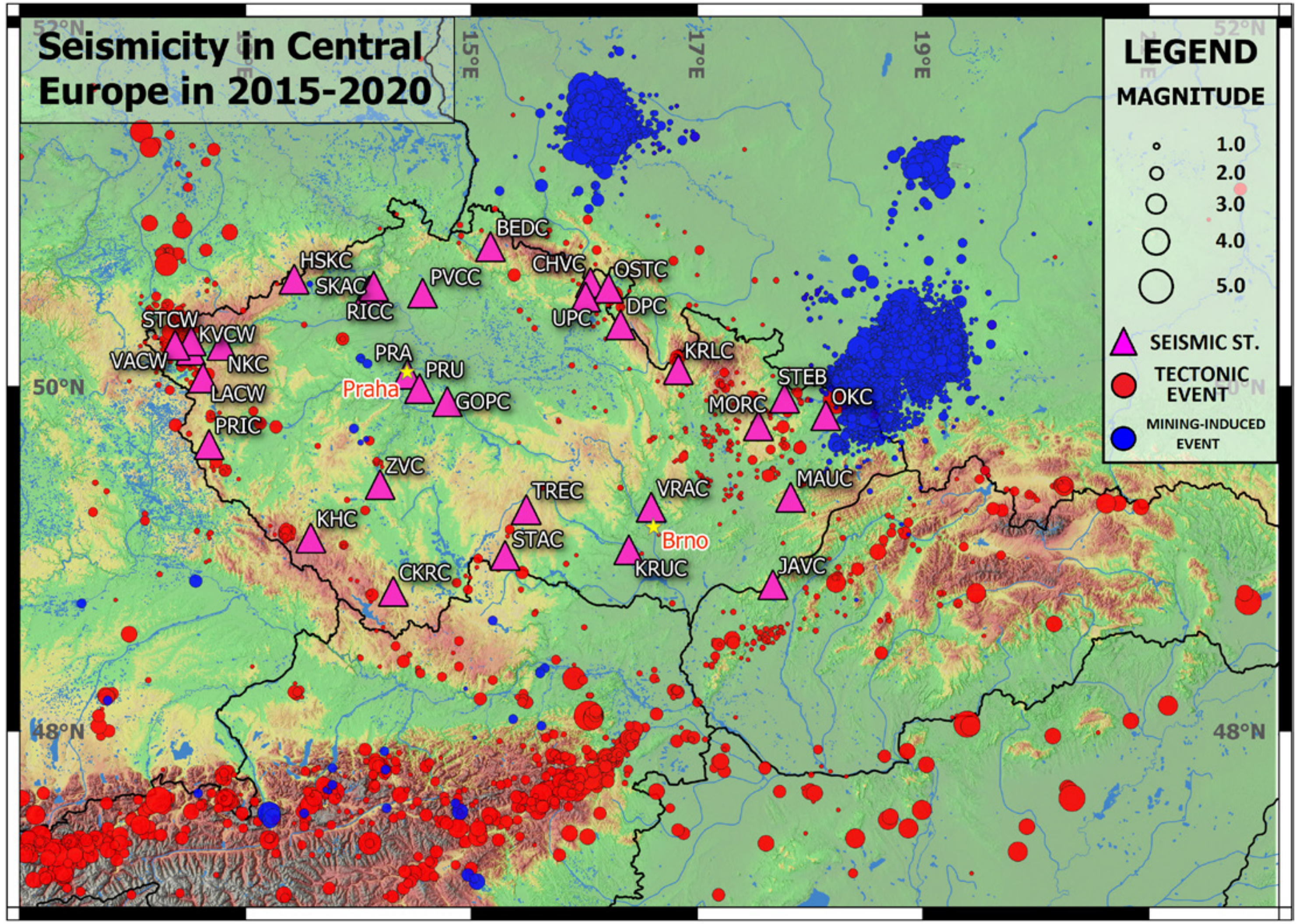


Fig. 1. Map of seismicity in the Czech Republic and surroundings between 2015 and 2020.

Fig. 2. Seismic station Kašperské Hory (KHC) is situated in the gallery "Kristýna", originally a gold-mining gallery of an almost 400 m length.

The Service compiles and publishes seismological catalogues and bulletins on the web of the IG (https://www.ig.cas.cz/en/departments/seismology/seismic-service/), collects and evaluates macroseismic reports about earthquakes felt on the territory of the Czech Republic by means of a questionnaire available at the webpage of the IG (https://www.ig.cas.cz/makroseismicky-dotaznik/ – in Czech) as well as in several mobile phone applications. The Service provides automated and manually revised locations of seismic events and live seismograms of the CRSN stations on the web pages of the IG. Experts of the Service inform the public about strong and devastating earthquakes in Europe and worldwide through the media and web pages of the IG.

Monitoring seismic activity in West Bohemia
The area of West Bohemia and neighbouring Vogtland has probably been the most seismically active region in Central Europe in historical times. Following increased seismic activity on the turn of the 19th and 20th century, one of the earliest Euroopean seismic stations was established in the region already in 1908. Current monitoring has been provided by the WEst Bohemia NETwork (WEBNET), jointly operated by our Institute and the Institute of Rock Structure and Mechanics (IRSM) of the CAS. The network covers an area of about 1000 km² and consists of 24 three-component stations. Supplementary local networks providing relevant, high quality data have been operating in neighbouring NE Bavaria and SE Saxony.

Thanks to up-to-date equipment of seismic stations, WEBNET makes it possible to record high-frequency waves generated by local events, short-period body waves of regional and distant earthquakes, and surface waves excited by quarry blasts fired in the neighbourhood of the region under study. Continuous data from all the stations are transmitted via Internet to the interpreting lab at the Institute in Prague. WEBNET is interconnected with the Czech Regional Seismic Network.

The catalogues and seismograms of all tectonic events recorded by WEBNET since 1992 are archived in a joint digital database that is available at https://www.ig-.cas.cz/en/observatories/local-seismic-network-webnet/. The WEBNET data comprise a reliable database for diverse seismic-source and upper-crust-structure investigations performed not only in our Institute but also by many research teams internationally.

Monitoring earthquake occurrence on Reykjanes peninsula, Iceland
With a decades long experience in operating and maintaining a local network of seismic stations, the team around WEBNET tried to expand abroad to a world-class geological site where the experience and expertise of members of the team should contribute to understanding local/regional seismotectonics, structural relations and mitigating potential geohazards. In summer 2013, a seismic network of 15 stations was built on Reykjanes peninsula in southwest Iceland – the REYKJAnes Seismic NETwork (REYKJANET). REYKJANET provides data to study triggering mechanisms and driving forces of earthquake swarms induced by magma intrusions into the upper crust and to perform a comparative study of intraplate earthquake swarms in West Bohemia/Vogtland and interplate earthquakes in southwest Iceland. Data from several REYKJANET stations have been utilised by the Icelandic Meteorological Office in winter 2019 and spring 2020 when significant seismic activity occurred beneath Reykjanes, with many felt earthquakes and significant ground inflation caused by voluminous magma intrusions.

EARTH TIDE OBSERVATIONS AND TILT MEASUREMENTS

The Institute currently operates three observatories that provide tide and tilt data. The central tidal observatory with an interpretation lab is situated in the mining town of Příbram in Central Bohemia. The observatory is located 90 m beneath the surface in a gallery of an abandoned deep mine of the total depth of 1300 m. The gallery serves also as a site for long-term tests of geo-

Fig. 3. REYKJANET: Station FAF (Fagradalsfjall) is of key importance for Reykjanes seismic observations. The seismic activity has been growing under the Fagradarsfjall volcano since 2017 reaching a magnitude Mw=5 in earthquake swarms of 2020.

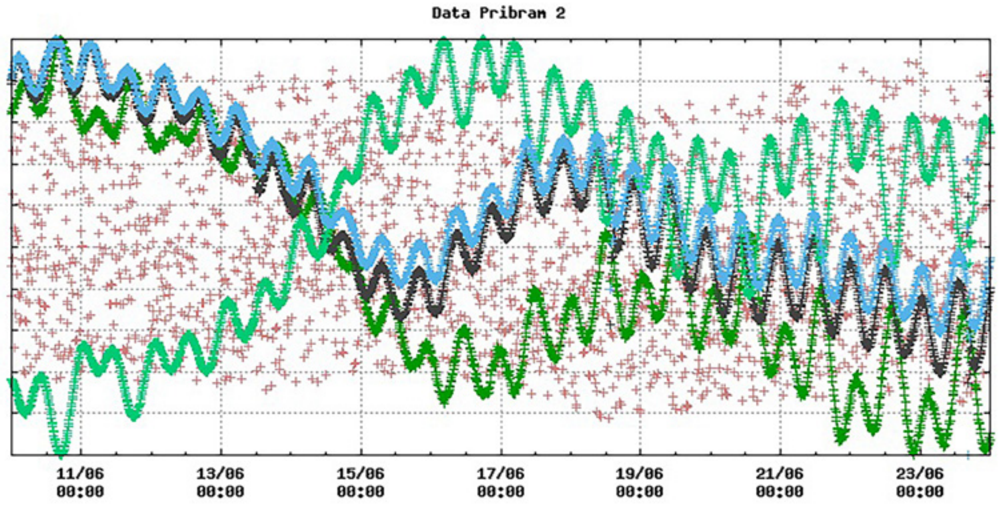


Fig. 4. Tilt data from two independent tiltmeters installed in directions North-South (black and blue lines) and East-West (two green lines). Each line is composed of the Earth-tide wave component (high frequency signal), and tilt component.

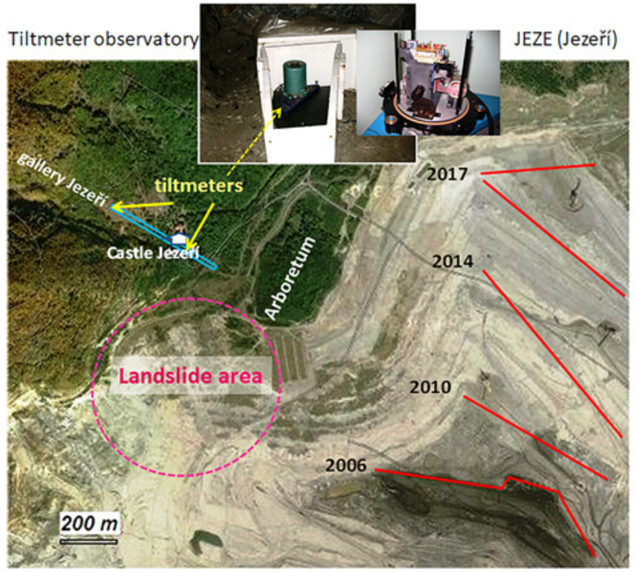


Fig. 5. Location of the Jezeří Gallery at the edge of an open-pit coal mine in North Bohemia. Two tiltmeter stations are established inside the gallery. Red lines show the progress of the mining front, purple circle shows the main landslide area. "Arboretum" is a pillar of sediments left behind during the mining progress in order to support stability of a steep slope with a castle. Inset figures – outer and inner view of a tiltmeter."

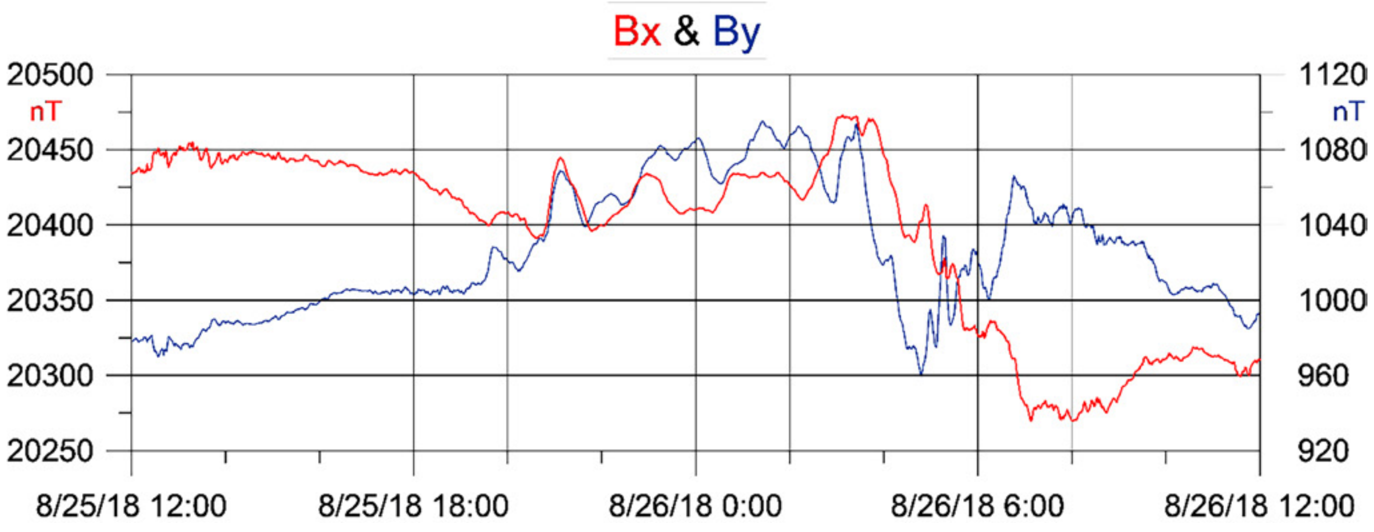


Fig. 6. North (Bx) end east (By) component of geomagnetic field during the magnetic storm on August 25 and 26, 2018; data from Budkov Observatory.

physical equipment such as various types of tiltmeters, gravimeters and seismometers.

The tilt observatory Jezeří in North Bohemia belongs to a measuring system established to control stability of northern edge of a large open-cast coal mine that is situated just beneath steep slopes of the Krušné Hory Mts. The observatory is composed of two sites in a horizontal gallery in the slope above the mine and beneath a historically valuable castle of Jezeří. Differences in tilt values recorded by the two measuring sites could serve as a precursory signal of landslides that represent hazard for the mine and the castle. The costs of operation of the observatory are covered by the mining company.

Tilt measurements in the town of Skalná in the West Bohemia earthquake swarm region have been performed in a geodynamic observatory located in an underground gallery inside a huge granite massif. Permanent tilt and seismic observations are occasionally supplemented by continuous measurements of gravity to record and interpret local changes of the gravity field.

GEOMAGNETIC FIELD OBSERVATIONS

Magnetic field of the Earth is extremely important for life on Earth as it reflects and deviates electrically charged particles and electromagnetic waves from outer space and thus protects the Earth's surface from harmful energy input. Continuous measurements of parameters of the geomagnetic field are thus of importance to the society. The long tradition of geomagnetic observations in Czechia has been evolved in the Budkov observatory, South Bohemia, established in 1967, following previous observations in Prague and nearby Průhonice (since 1839). Currently, the Budkov observatory is equipped with three triaxial variometers and one scalar instrument.

Based on the continuous measurements, daily forecasts of geomagnetic activity for Central Europe has been issued since 1994 and weekly forecasts since 1995. Since 1998 the short term forecasts have been regularly presented by the public TV Česká televize as a part of the daily Weather Forecast. At present, the forecasts, as well as reports of the actual state of the geomagnetic field in our region, are presented on the web pages of the Regional Warning Centre Prague (http://rwcprague.ufa.cas.cz/).

The Budkov Observatory is one of more than 150 observatories of global INTERMAGNET network (www.intermagnet.org), established in the second half of the 1980s.

SUBSURFACE TEMPERATURE RECORDING

The Institute performs continuous subsurface measurements (together with surface and air measurements) at three observatories (Prague, Kocelovice, Svojšice, for details see https://www.czechgeo.cz/en/sections-research-infrastructure-czechgeo/section-geodynamics/geothermal-network-geoclimanet). The measured data are used to study the coupling between air and soil temperature and heat transfer between the surface and the bedrock in various climatic, soil and environmental conditions. The stations are a part of the GeoCLIMANET geothermal network with stations also in Portugal and Slovenia. In all three stations, temperature monitoring is continuously performed at several depth levels beneath the surface. The observations contribute to a serious discussion on warming the subsurface as a consequence of the recent climate change.

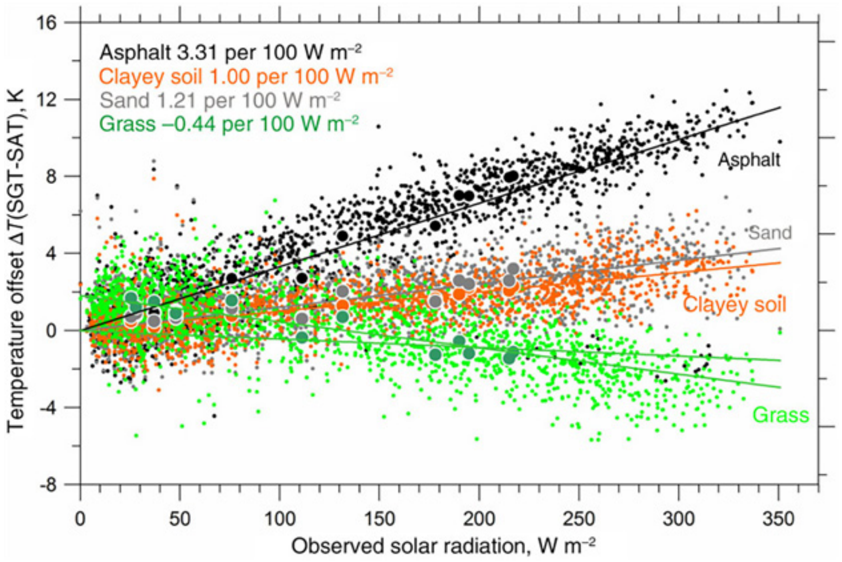


Fig. 7. Relationship of ground–air temperature difference and incident solar radiation at the Geothermal Climate Change Observatory in Prague-Spořilov for the period 2009–2013. Small points represent the daily values of ground–air temperature differences and the observed radiation, large dots are their monthly means. The solid lines characterize the change in ground-air temperature difference between several types of ground material and cover with increasing solar radiation.

OBSERVATIONAL INFRASTRUCTURE SUPPORT

Observational activities had long been supported mainly from the budget of the Institute. Between 2015 – 2020, the observational activities and related infrastructure of the Institute were generously supported by the CzechGeo/EPOS (LM2015079) project funded by Ministry of Education and the CzechGeo/EPOS-Sci (CZ.02.1.01/0.0/0.0/16_013/0001800) project funded by the Czech Operational Programme Research Development and Education based on EU sources. Information on the aims and outcomes of these projects can be found at http://www.ig.cas.cz/en/structure/observatories. From 2020 onwards the role of the Institute in national geophysical service has been recognized by targeted financial support from the Czech Academy of Sciences.

Air-ground temperature monitoring on the campus of the Institute of Geophysics.

Outdoors presentation of “Rocks as magnets” by J. Kadlec, as part of the Earth Day celebration in the Spoři-lov Geopark, 2019

The Institute's director, Aleš Špičák, explaining principles of earthquake formation, as part of the Earth Day celebration in the Spořilov Geopark, 2018

Outreach activities

For a public research institution such as an institute of the Czech Academy of Sciences, it is imperative to inform the broad public audience about the most important research results, as well as to clearly explain the very purpose of scientific work in general. Since 2015, outreach activities of our Institute have further developed and strengthened several lines of communication with the public at all levels of science education. The Geopark Spořilov, founded by the Institute in 2003, has long been a popular spot for outdoors education, along with several popular tourist destinations in West Bohemia.

MEDIA AND SOCIAL NETWORKS

Researchers of the Institute have repeatedly commented on and explained the causes of socially important geodynamic events in the media, especially on public TV. In a press review ordered by the Czech Academy of Sciences, statements of the researchers of our Institute belong to the most frequently cited items. This way of communication with public has been strengthened by fast publication of relevant texts, maps and figures on the Institute’s web page. The Institute uses social networks for PR and outreach activities, such as Facebook, Instagram, a Youtube channel, or Twitter.

ANNUAL OUTREACH EVENTS

The Institute of Geophysics regularly participates in outreach events organized by the Czech Academy of Sciences or other entities, such as the Week of Science and Technology and its Open Days at individual institutes, or the annual Science Fair in Prague-Letňany exhibition centre. Since 2017, we have been preparing the programme of an annual Open Day in collaboration with two other institutes of the CAS residing in the Spořilov campus: the Institute of Atmospheric Physics and the Astronomical Institute. The Open Day includes various activities - lectures, excursions, interactive stands, film, Geopark guided tours, and a competition for children. The number of visitors to events organized by the Institute of Geophysics during the Week of Science and Technology can reach up to 1000 people. In addition, our staff members travel to regional libraries throughout the Czech Republic to give lectures. Participation in the annual Science Fair in Prague-Letňany has become a great opportunity to present our research and Earth Sciences in general: in 2019, the Fair was visited by 30,000 people.

On the occasion of the International Earth Day (April 22), the Institute has regularly organized an outreach event in the Spořilov scientific campus since 2010, under the label “Earth Day with the Czech Academy of Sciences”. Through time this event has developed to include also guests from the Geological Institute of the Academy and neighbouring institutes from the Spořilov campus - the Institute of Atmospheric Physics and the Astronomical Institute as well as companies involved in sustainable technologies. Primary and secondary school students as well as families and individual visitors can visit more than 15 stalls where scientists explain specific natural phenomena and visit guided tour in the Geopark. Topics range from plate tectonic processes and their role in the formation of the landscape of the Czech Republic, volcanoes, earthquakes, to climate change and astronomical observations. The event is visited by 400-600 people every year.

For occasions such as the annual outreach events, our young researchers have developed innovative teaching aids that include, for example, the "barrel organ of plate tectonics" – a manually powered mechanical device that illustrates, in a playful way, the basic elements of plate-tectonic process including aesthenospheric convection. Another way of making basic principles of geophysics accessible to teenage audience is exemplified by the comic book When the Earth Quakes (2020) which explains the origin of seismic waves during earthquakes and their meaning for the study of structures of our Earth.

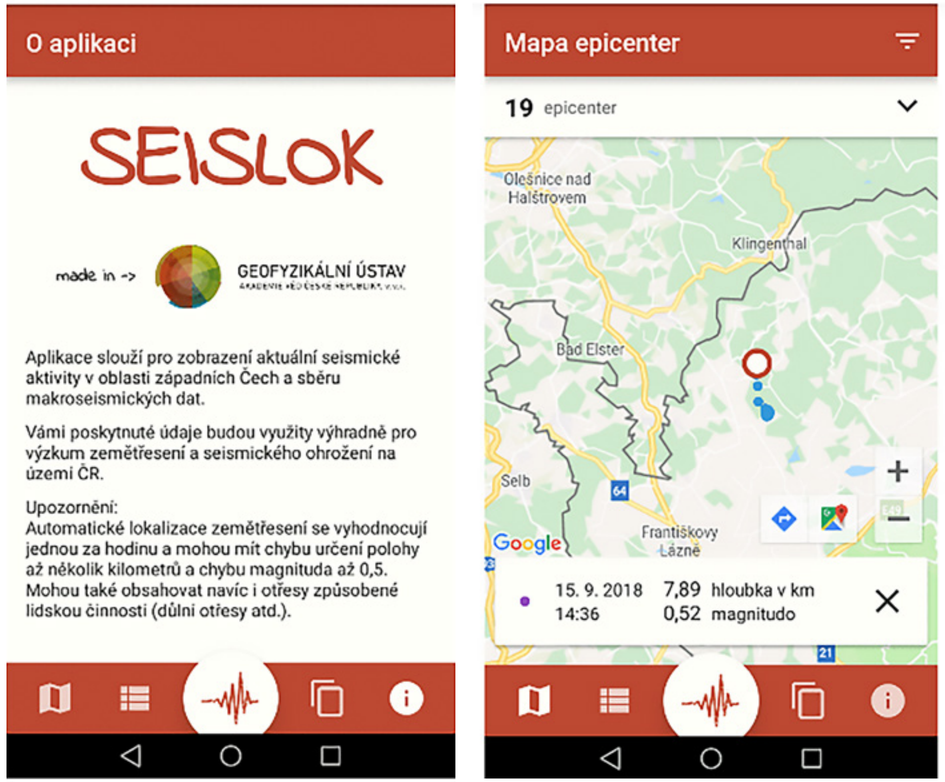
GEOPARK SPOŘILOV AND EXHIBITS OUTSIDE PRAGUE

The publicly accessible Geopark Spořilov has been built on the premises of the Institute in several phases since 2003, with generous support from the Prague 4 municipal council and thanks to enthusiasm of companies that donated many rock specimens. The purpose of our Geopark is not only to show the diversity and beauty of the rocks, but, in the first place, to help visitors understand how and why rocks form, and how they preserve the record of past events in the history of our planet. Currently the Geopark features over 40 large specimens of igneous, sedimentary, and metamorphic rocks from the Bohemian Massif and a collection of magmatic rocks from Western Carpathians. With the help of educational materials posted in the park and on our website, the public thus can gain a better understanding of the long and varied geological evolution of our country, and link it to hands-on experience provided by the rocks themselves. Guided tours are available during regular events as well as on demand. The rock collection of the Geopark became a basis of the book „Geological processes recorded in rocks" produced by the staff of the Department of Geodynamics of the Institute and accompanied by a quiz-game named „The Alchemists' Stone". The popular booklet which introduces basic principles of plate tectonics, Earth's evolution and rock formation is available for free to visitors of the Geopark; its 4th edition is going to be printed in 2021. In addition to rock specimens, a geothermal observational site is situated in a borehole drilled in the Geopark. The last phase of development of the Geopark, in 2018, added several new rock specimens, a flowery meadow and a beetle loggery that add the dimension of a living "urban oasis" to the site.

Outside Prague, our efforts in public education have recently been strengthened by researchers of the Department of Seismology who established the 'Museum of Seismology' in the town of Skalná, West Bohemia, and the 'Museum of Seismometry' at the seismic observatory KHC – Kašperské Hory in southwestern Bohemia – both under the 'Strategie AV21' initiative of the CAS. During the spring 2021, the famous Goethe's adit in the Komorní

As part of efforts to make principles of geophysics accessible to younger teenage generation, the Institute published a comic book "When the Earth Quakes (the Story of a Seismic Wave)".

The Barrel Organ of Plate tectonics helps in presentation on the workings of lithospheric plates.
(Photo from the Earth Day 2019; lectures took place in the renovated Lecture Hall which hosted an exhibition of sculptures by František Kyncl).



Screenshots of the introductory and map pages of the SeisLok application.

In addition to the permanent exhibition of seismic instruments, maps, and explanatory materials, our researchers offer guided tours and lectures to the public in the Museum of Seismology in Skalná. Photo by Petr Němeček.

hůrka Hill, built in the 18th century in order to corroborate its volcanic origin, will be open to the public, as another tourist destination with an interesting scientific story. In collaboration with the town of Skalná, located in the seismically active part of West Bohemia, and its primary school, the Institute founded a Centre of Geophysics as an educational activity, within the framework of a 2020 Regional project of the Czech Academy of Sciences and the Karlovy Vary Region (https://www.ig.cas.cz/pro-verejnost/geofyzikalni-centrum-v-zs-skalna/).

CITIZEN SCIENCE: THE SeisLok APPLICATION

In 2018, the Institute launched the SeisLok application, which continuosly provides up-to-date information on earthquakes in the seismically most active area of the Czech Republic - Western Bohemia. Smartphone owners can download it to their mobile phones for free. Individual earthquakes are displayed on an interactive map together with information about their depth, time of occurrence and magnitude. The application allows the user to send a report of observed shocks, i.e. fill in the so-called macroseismic questionnaire. SeisLok was developed by the Institute of Geophysics with the support of the Strategie AV 21 initiative. The application takes advantage of the data from the WEBNET network, built specifically for seismic monitoring of this area.

Because the application also serves for collection of macroseismic data, i.e. questionnaires, where residents themselves describe the effects of earthquakes as they felt them, it becomes part of the so-called civic or citizen science, where the non-scientific community is involved in scientific projects. Citizens are helping to expand and enrich research projects, which are thus able to achieve better results, and there is a growing general awareness of what scientists are researching and how they can help society. SeisLok thus links education of the public, citizen science and our routine seismological observations.

YEAR 2020 – ADAPTING OUTREACH DURING THE COVID-19 LOCKDOWN

In 2020, due to the COVID-19 pandemic, many events were cancelled, but our staff responded by focusing extra effort to reach out to schools and the general public. In the spring of 2020, the Czech Academy of Sciences project “#veda_na_doma” (“science at home”) was launched, with the aim to make home-schooling easier for parents during the lockdown. Under this hashtag, the institutes of the Czech Academy of Sciences published interesting topics, experiments and teaching materials on websites and social networks. The Institute of Geophysics joined this initiative with online educational materials, including five episodes of video walks through the Geopark Spořilov entitled “When rocks speak”. Lectures were live streamed via the Facebook account of the Czech Academy of Sciences (e.g. How to explore Mars from the living room; When volcanoes explode; etc.), a new cut-out teaching aid "Polarizing MIcroscope" was introduced. An art contest for children entitled “VolcanoMania 2020” was run by two high school students as an internship project in our Institute.

Stanislav Diviš: Inadvertent Touches - Hidden Beauty No. V.13, 2010, acrylic on canvas, 180 x 200 cm. From exhibition at the Institute of Geophysics, March 2017.

Art at the Institute

History of exhibitions of art at the Institute dates back to the year 1999 when the first exhibition took part in the lecture hall of the Institute. The Institute took advantage of a comprehensive collection of pre-photographic illustrations of natural phenomena and old maps of our colleague, seismologist Jan Kozák, and prepared a series of topical exhibitions devoted to earthquakes, volcanic eruptions, landslides, rock bursts in mines, discoveries in the northern Pacific and in Antarctica. Each of these exhibitions that were held between 1999 and 2002 was accompanied with a public lecture and later reminded by a special contribution in the international journal Studia Geophysica et Geodaetica. Such a series of exhibitions close to topics studied at the Institute was crowned by an exhibition at the gothic corridors of the historical building of the Charles University in spring 2003, under auspices of the President of the Czech Academy of Sciences Prof. Helena Illnerová.

Further heading of the focus of exhibitions at the institute was discussed, among others, with Mr. **Jiří Hůla**, an artist, freelance writer and founder of The Fine Art Archive (https://www.artarchiv.cz/en/). He recommended offering the lecture hall of the Institute for exhibitions to contemporary artists whose works apply procedures commonly used in science, such as forethought concept, analogy, variation, similarity etc., and whose efforts are driven by a desire for exploration, discovering, and originality. Such a program of exhibitions was named "ENCOUNTERS" and was launched in 2002 by an exhibition of engravings and etchings of Marie Blabolilová (see e.g. https://www.artlist.cz/en/marie-blabolilova-100588/). By now, 55 artists displayed their works at author exhibitions and many others in three topical, group exhibitions. Many of them are well-known to gallery visitors not only in our country but also outside the Czech Republic: for example Pavel Rudolf, Lubomír Přibyl, Petr Kvíčala, Jan Kubíček, Dalibor Chatrný, Josef Hampl, Stanislav Diviš, Zdeněk Sýkora, František Kyncl, Jindřich Zeithamml or Ivan Kafka. The latter artist mentioned, Ivan Kafka, a representative of land-art and author of many indoor and outdoor instalations, prepared a site-specific instalation in the lecture hall of the Institute called „The Czech ping pong“, ironising the way Czech people understand many standard procedures and institutions.

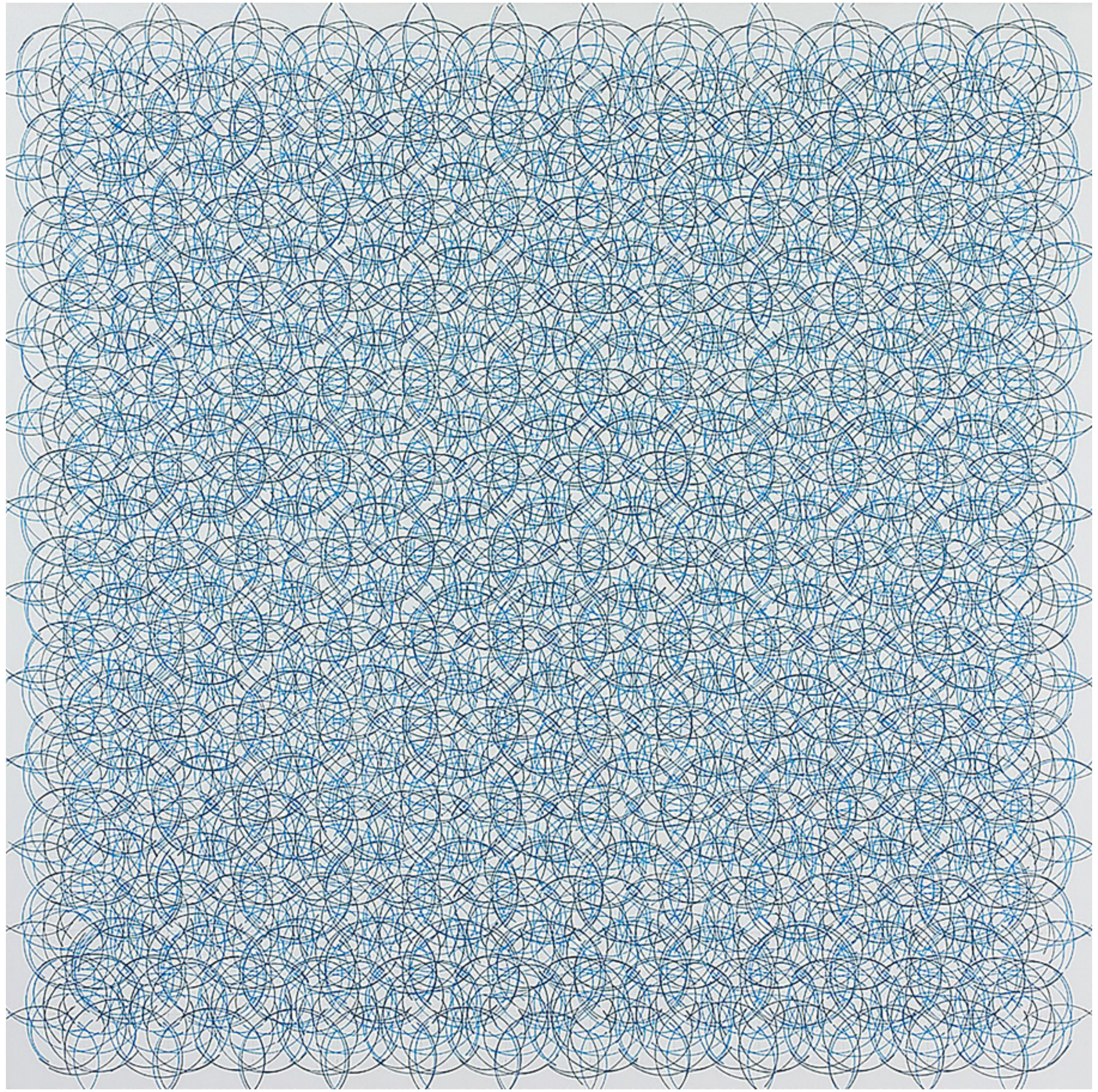
Friendly contacts with the artists that were established during installation of their work and at openings of exhibitions enabled to gradually build up Institute's collection of contemporary Czech art. These are

← Openings of exhibitions are welcome opportunities to discuss the often similar goals of art and science. From left to right: Aleš Špičák, the Institute's director; Jiří Hůla; Denisa Bytelová (Ladislav Sutnar Faculty of Design and Art, Univ. of West Bohemia, Plzeň), Lucie Rohanová (conceptual artist, editor, curator)

↓ Music performance of the saxophone quartet "TyTety" at the opening of the exhibition of paintings of Pavel Rudolf (*1943), painter, graphic artist, photographer, author of installations in space and artists' books, one of the important representatives of the Czech conceptual art and geometric abstraction (https://galeriezavodny.com/pavel-rudolf-1). Lecture Hall of the Institute of Geophysics, March 22 – June 8, 2018.

exhibited permanently in the seminary room of the Institute and in the corridors of the main building.

Occasionally, employees of the Institute and/or of our partner institutions exhibit their non-professional art work. Since 2006, the Institute has annually hosted the "Spořilov Salon" open to non-professional painters of the Spořilov district of Prague where the Institute is located.



Pavel Rudolf: From the cycle "Arrangements", May 25, 2003, acrylic paint on canvas, 65 x 65 cm. From exhibition of P. Rudolf at the Institute in 2018.

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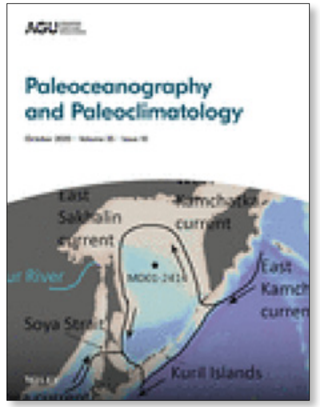

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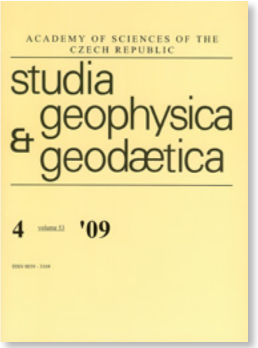

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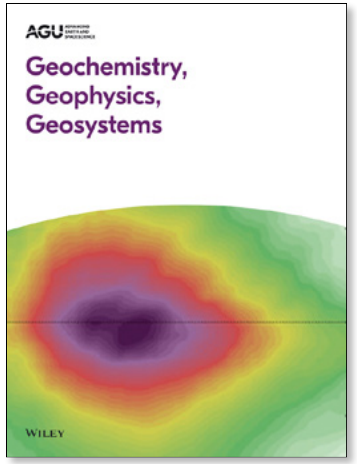

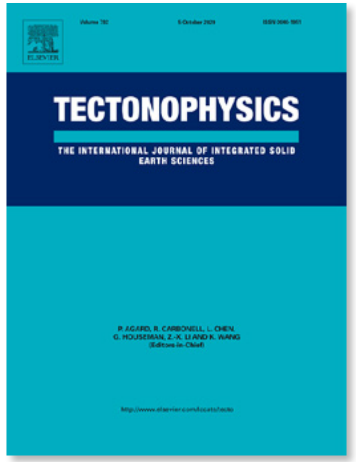

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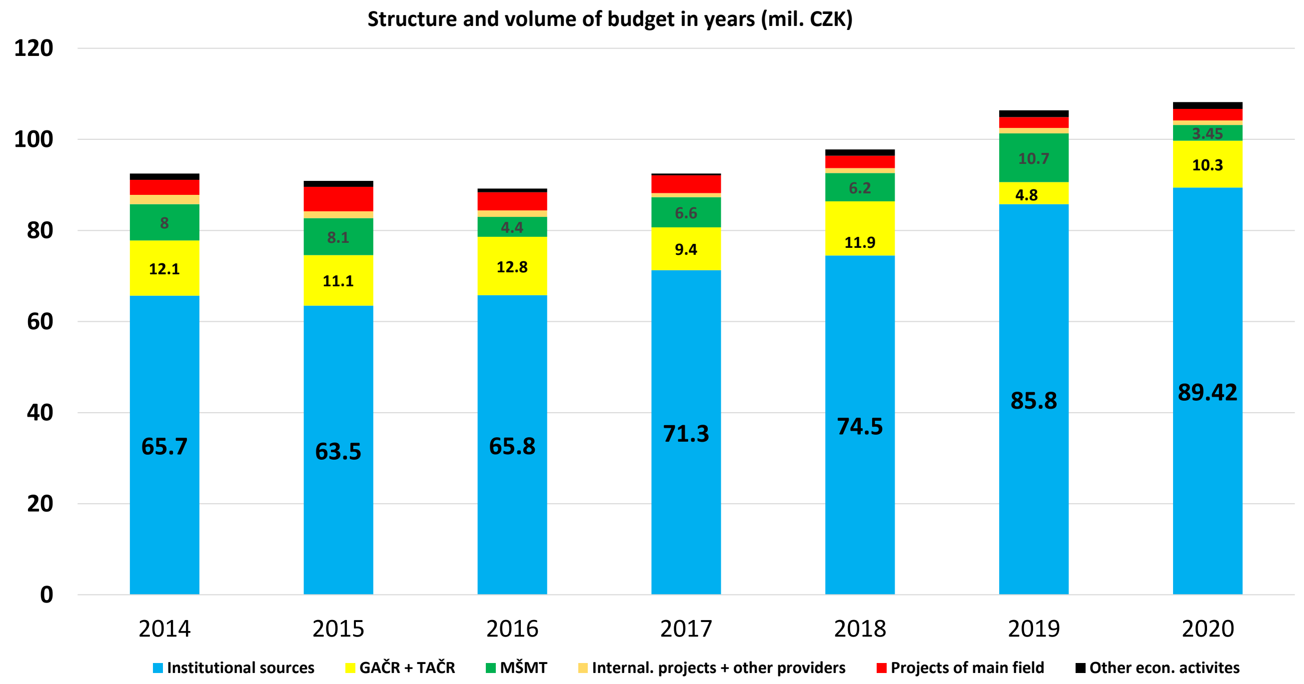
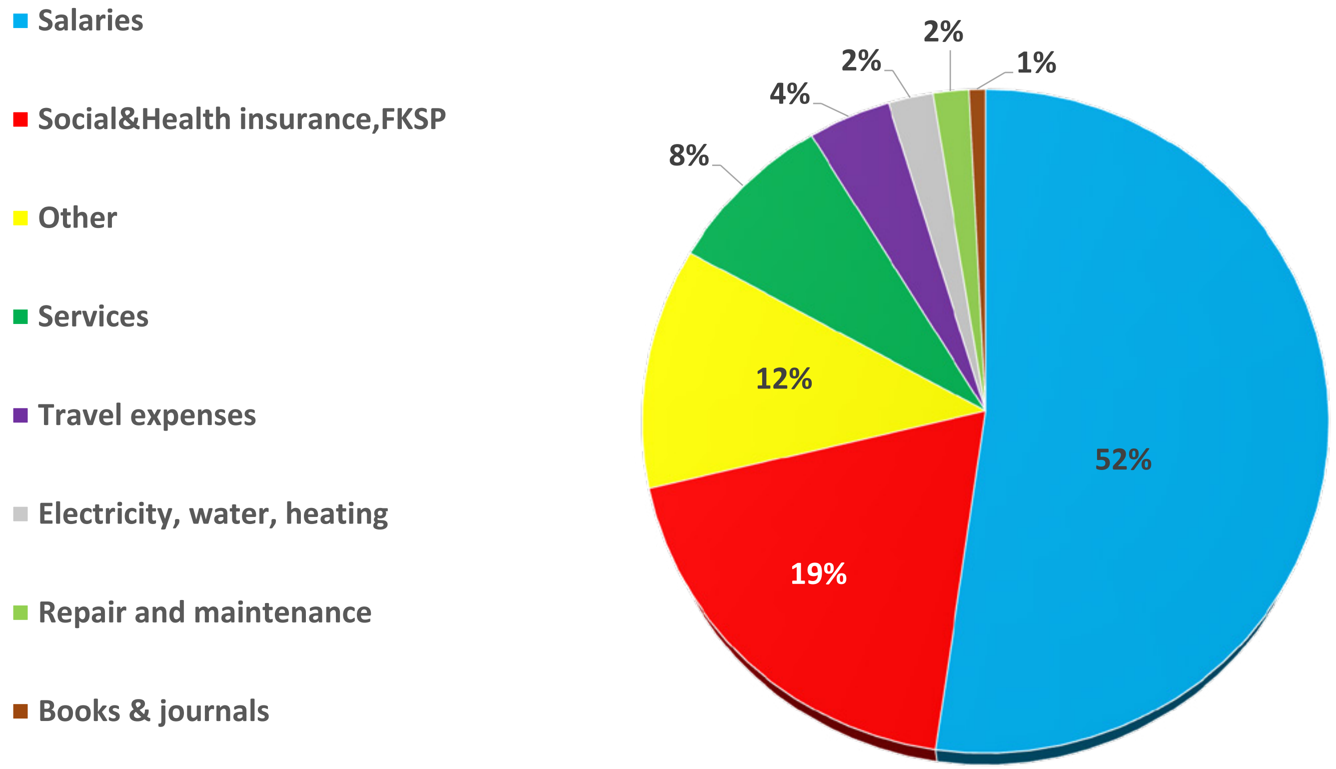
STRUCTURE AND VOLUME OF BUDGET OF THE INSTITUTE OF GEOPHYSICS BETWEEN 2014 AND 2020 (IN MIL. CZK)



STRUCTURE OF THE INSTITUTE'S SPENDING IN 2019 (TOTAL CZK 105.8 MILLION)



The diagram documents the growth of the Institute's budget from 2016 onwards, driven mainly by increasing support from the Czech Academy of Sciences. In 2019, the Institute's total budget was CZK 105.8 million (~ EUR 3.85 M) of which 80 % was sourced from the Academy and 20 % from grants, contracts and services.

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