# Progress report 2012

http://geo.mff.cuni.cz/documents/research_12.pdf
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Department of Geophysics, belonging to the Faculty of Mathematics and Physics, Charles University in Prague, has its roots seated as deep as in the 20's of the last century. Its structure and priorities have evolved from nearly pure seismology and geomagnetism to the present-day broad scope covering nearly all main branches of the physics of the Earth and, most recently, comprising also planetary aspects. Research is tightly coupled with education at the bachelor, master and doctoral levels. In 2011, there were 19 staff members at the department (counting permanent, temporary and part-time positions), and 21 PhD students (8 of them supervised by the staff members).

Research project SW3D, *Seismic Waves in Complex 3-D Structures*, coordinated at the Department of Geophysics since 1993, has continued successfully in 2012. The project has been supported by 5 companies or research institutes (BP America Inc., U.S.A.; Chevron U.S.A. Inc., U.S.A.; NORSAR, Norway; Petrobras, Brazil; Schlumberger Cambridge Research Limited, U.K.) in the framework of the international SW3D consortium. The project commisioned by ESA which aims to develop and test the Swarm Level 2 processing facility started in October 2010. The Charles University, as a member of the SMART consortium, is providing support in development of the time-domain chain for inversion of Swarm data in terms of 3-D mantle conductivity.

Seismic station PRA (created in Prague in 1924), equipped with CMG-3T, is linked with the international data center ORFEUS to provide on-line data transfer to Utrecht. Joint project of the Charles University in Prague and the University in Patras, initiated in 1997, has successfully continued. Current configuration of the jointly operated seismic stations is as follows: SERG (Sergoula), LTK (Loutraki), PYL (Pylos), PDO (Prodromos), ZKS (Zakynthos), ANX (Ano Chora). For details, see http://seismo.geology.upatras.gr/heliplots/. Each site is equipped with a pair of the broad-band and strong-motion instruments. All instruments are of Guralp manufacturer, except ZKS (Nanometrics). The stations became a part of the Hellenic Unified Seismic Network (HUSN), with data sharing by three universities (Athens, Thessaloniki and Patras) and the National Observatory of Athens. The participating institutions in Greece make everyday use of the stations in their earthquake locations. Moreover, the broadband waveforms are used to routinely invert moment tensors at the University of Patras and report them to EMSC. Software ISOLA, continually upgraded (http://seismo.geology.upatras.gr/isola/), is used for this purpose. Consultations to many external users of the software are provided, too. The department also participated in operation of the borehole (60 m deep) broadband CMG-3TD station GOPC located at the Geodetic observatory Pecny (GOPE).

Operation of all these stations is partly supported by the project CzechGeo/EPOS, see http://czechgeo.cz. Within this project the department operates also the CzechGeo/EPOS Seismological Software Centre, see http://epos-eu.cz/ssc.

The Editors or Associated Editors of international journals have been Vlastislav Červený (*Russian Geology and Geophysics*), Luděk Klimeš (*Journal of Seismic Exploration*), Ctirad Matyska (*Journal of Geophysical Research – Solid Earth; Studia Geophysica et Geodaetica*) and Jiří Zahradník (*Journal of Seismology*). Ctirad Matyska has been the member of the editorial board of the journal *Pokroky matematiky, fyziky a astronomie,* which is devoted to popularization of mathematics, physics, astronomy and education in these fields.

The master theses written by David Einšpigel and Jiří Vackář were defended at the Department in 2012.

As in previous years, research at the Department was carried out in three directions: Earthquake and structural studies, Theory of seismic waves, and Geodynamics.

## Earthquake and structural studies (reported by Jiří Zahradník)

**Earthquake sources**

The following events were studied (Mw denotes the moment magnitude): two earthquakes Mw > 5 Efpalio 2010 Greece; two Mw > 4.5 earthquakes of 2009 near Columbo volcano, Aegean Sea, Greece; Mw 6.3 L'Aquila 2009 Italy; and Mw 7.1 Van 2011 Turkey. The two Efpalio mainshocks and the main part of the entire 2010 earthquake sequence in the Corinth Gulf were examined from several viewpoints: (i) source location (Janský et al., 2012), (ii) crustal structure (Novotný et al., 2012), and (iii) source properties (Sokos et al., 2012). The two events from the Aegean Sea served for testing the resolvability of the isotropic source component. The damaging earthquakes of L'Aquila (Gallovič and Zahradník, 2012) and Van (two submitted papers) were investigated in terms of source complexity. Practical consequences of the L'Aquila source model in the high-frequency band of the engineering interest were treated by Ameri et al. (2012), using the Hybrid Integral Composite method, developed at our department in previous years by F. Gallovič and J. Brokešová.

A new method to calculate the space-time slip distribution was developed by F. Gallovič (Gallovič and Zahradník, 2012). The source model consists of Multiple Finite-Extent (MuFEx) subsources. The slip amplitude, rupture velocity, rake and rise time are assumed to be constant within each subsource. The size and location of the MuFEx subsources have to be inferred independently from other methods, e.g., the truncated singular value decomposition, or the iterative multiple-point source deconvolution (ISOLA). Each MuFEx subsource is characterized by an individual set of trial nucleation points, rupture velocities and nucleation times, which are grid-searched. For each combination of these parameters, the subsources' slip is determined by the least-squares approach. This procedure provides not only the best-fitting model, but also a whole range of acceptable models, allowing for the uncertainty analysis.

A new method to calculate uncertainty of the strike, dip and rake of the earthquake source was proposed by Zahradník and Custódio (2012). One of its possible applications demonstrated *ibid.*, is mapping the moment-tensor uncertainty for a given station network, usable for a network design and/or its improvement. The latter has found a practical application in the Irpinia seismic network (diploma thesis by Magdalena Michele, Naples University Federico II, supervised by A. Emolo and S. Custódio). An extension of the method to the non-linear case, where the source position and time belong to the model parameters, was solved with a focus on the probability density function of the isotropic source component. The latter was performed in the framework of the PhD study of D. Křížová, supervised by J. Zahradník (a paper accepted in BSSA, to appear in 2013).

Software ISOLA, developed since 2003 in close co-operation with E. Sokos (Patras University) found a broader application. Since 2012 the code has been in everyday use at the National Observatory of Athens for events over the whole territory of Greece; http://bbnet.gein.noa.gr/NOA_HL/index.php/moment-tensors. The focal mechanisms are reported to the European Mediterranean Seismological Center. Also in 2012, the Iranian Seismological Center (Institute of Geophysics, University of Tehran; http://irsc.ut.ac.ir/tensor.php) has started application of the code for Mw > 5 earthquakes in Iran. The latter usage is supervised by our former PhD student, M. Pakzad. Moreover, numerous e-mail consultations were continuously provided in 2012 to ISOLA users worldwide.

**New instruments**

A new six-degree-of freedom (6-DOF) mechanical seismic sensor "Rotaphone" was developed and tested, including the calibration, linearity, and cross-axis errors (Brokešová et al., 2012a). The instrument records three translational and three rotational ground motion velocity components. The device consists of standard geophones arranged in parallel pairs to detect spatial gradients. The instrument operates in a relatively high-frequency range, above 2 Hz. Its theoretical sensitivity limit in this range is $10^{-9}$ m/s in ground velocity and $10^{-9}$ rad/s in rotation rate. Small size and weight, and easy installation and maintenance make the instrument useful for local-earthquake recording and seismic prospecting.

The calibration method, which is a key point of the Rotaphone development, is explained in detail in Brokešová et al. (2012b). The paper also includes a comparison with a reference sensor (fiber optic gyroscope).

The prototype was subjected to testing at the Albuquerque Seismological Laboratory, U.S. Geological Survey using the rotational shaking table. It was also successfully used to monitor the 6-DOF ground motions from shallow local microearthquakes in various active regions (a seismic swarm area in the Czech Republic, the vicinity of the salt-production factory of Provadia in Bulgaria, and the Corinth Gulf rift zone in Greece).

**Structural studies**

The western part of the Corinth Gulf was subjected to the investigation of the local 1D structural model based on data of the Efpalio 2010 earthquake sequence. The model is based on the minimization of travel-time residuals. A variant of the method of conjugate gradients was used for this purpose. In comparison with several previous models, the new model is characterized by higher velocities up to a depth of about 8 km. The velocity ratio in the model is Vp/Vs=1.83. See Novotný et al. (2012).

The inversion of full waveforms for the same purpose, i.e. construction of a 1D structural model, was tested by V. Plicka (a paper under preparation). The method is based on a combination of the Discrete Wavenumber forward solver of M. Bouchon and O. Coutant, and the optimization Neighborhood Algorithm of M. Sambridge. Elevated values of the Vp/Vs ~ 2 in the topmost 4 km of the Corinth Gulf were detected in the frequency range 0.05-0.20 Hz. An independent validation was obtained from fast long-period dispersive waves studied by J. Vackář in his MS Thesis (and a paper under preparation).

**Seismic stations in Greece**

Joint project of the Charles University in Prague and the University in Patras, initiated in 1997, has successfully continued. Current configuration of the jointly operated seismic station is as follows: SERG (Sergoula), LTK (Loutraki), PYL (Pylos), PDO (Prodromos), ZKS (Zakynthos), ANX (Ano Chora), PVO (Paravola) and FSK (Fiskardo). For details, see http://seismo.geology.upatras.gr/heliplots/ Each site is equipped with a pair of the broad-band and strong-motion instruments. All broad-band channels are continuously transmitted to the Patras hub. The stations belong to the Hellenic Unified Seismic Network (HUSN), with data sharing by three universities (Athens, Thessaloniki and Patras) and the National Observatory of Athens. Data of LTK station are real-time transmitted to the European data center ORFEUS. At the end of 2011 and in 2012, a special network of four strong-motion stations was also established in Messinia (the south-western Peloponnese) to monitor the Agrilos-Arfara fault. The present configuration in Messinia comprises the following sites: PEFK (Pefko), POLI (Poliani), AAMF (Ano Amfia) and LAMP (Lampena); the latter two transmit data to Patras through Internet. Situated near LAMP is the co-operating permanent GPS station VALY (Valyra), belonging to the Geodetic Observatory Pecny, Czech Republic.

**Free oscillations of the Earth**

Zábranová et al. (2012, SGG) analysed synthetic seismograms for several source fast solutions of the 2011 Tohoku earthquake obtained from surface waves and tested them against the observed gravity data from the superconducting gravimeter installed at the GOPE station. Zábranová et al. (2012, GRL) studied radial modes excited by the 2010 Maule and 2011 Tohoku earthquake, obtained new estimates of the quality factors of the modes ${}_0S_0$ and ${}_1S_0$ and corresponding constraints to the $M_{rr}$ component of the seismic moment tensor.

# Theory of seismic waves (reported by L. Klimeš)

**Paraxial ray methods and Gaussian beams in anisotropic media**

The two-point travel times represent the travel times between two points. Assuming that these points are chosen in a paraxial vicinity of the reference ray, Červený, Iversen & Pšenčík (2012: Two-point paraxial traveltimes in an inhomogeneous anisotropic medium, Geophys. J. int., 189, 1597-1610) derived the equations for the paraxial approximation of two-point travel times in heterogeneous anisotropic media.

Waheed, Červený, Iversen & Pšenčík (2012: Tests of two-point paraxial traveltime formula in inhomogeneous anisotropic media, In: Seismic Waves in Complex 3-D Structures, Report 22, Dep. Geophys., Charles Univ., Prague, pp. 113-127), Waheed, Červený, Iversen & Pšenčík (2012: Tests of efficiency of two-point paraxial traveltime formula in inhomogeneous anisotropic media, In: The 15th International Workshop on Seismic Anisotropy (Bahrain), Dhahran Geoscience Society, Dhahran, pp. 82-85), Waheed, Alkhalifah, Pšenčík, Červený & Iversen (2012: Two-point paraxial traveltime in inhomogeneous isotropic/anisotropic media -- tests of accuracy, In: Extended Abstracts of 74th EAGE Conference (Copenhagen), Eur. Assoc. Geoscientists & Engr., Houten, P282), and Pšenčík, Waheed & Červený (2012: Two-point paraxial travel time approximation, In: Kolman, Berezovski, Okrouhlik & Plesek: Advanced Modelling of Wave Propagation in Solids, Institute of Thermodynamics ASCR, Prague, Czech Republic, pp. 109-110) tested efficiency and accuracy of the two-point paraxial travel time approximation in smoothly varying isotropic and also anisotropic velocity models. They demonstrated that, for sufficiently distant points in the studied models, the approximation yields accurate results to a great distance from the reference ray. Application of the approximation to the problem of perturbation of the source and receivers solved recently by the method based on numerical solution of the eikonal equation leads to increased efficiency and accuracy.

Červený, Iversen & Pšenčík (2012: Two-point paraxial travel times using dynamic ray tracing in wavefront orthonormal coordinates, In: Seismic Waves in Complex 3-D Structures, Report 22, Dep. Geophys., Charles Univ., Prague, pp. 129-137) generalized the above mentioned equations for the two-point paraxial travel times to the situation in which the paraxial ray propagator matrix is computed along the reference ray by dynamic ray tracing in wavefront orthonormal coordinates.

**Anisotropic ray theory**

Klimeš (2012: Zero-order ray-theory Green tensor in a heterogeneous anisotropic elastic medium, Stud. geophys. geod., 56, 373-382) simplified the derivation of the zero-order ray-theory Green tensor in a heterogeneous anisotropic medium.

**Coupling ray theory for S waves**

The coupling ray theory is necessary for calculating S waves in heterogeneous weakly anisotropic elastic media by ray-based methods. After many years of their effort, Klimeš & Bulant (2012: Single-frequency approximation of the coupling ray theory, In: Seismic Waves in Complex 3-D Structures, Report 22, Dep. Geophys., Charles Univ., Prague, pp. 143-167) proposed the approximation of the coupling-ray-theory Green tensor by two S waves described by the coupling-ray-theory travel times and the coupling-ray-theory amplitudes. This approximation enables to interpolate the coupling ray theory results within ray cells and to use the coupling ray theory in all applications where we have used the standard ray theory up to now.

The review of the coupling ray theory for S waves was presented by Bulant & Klimeš (2012: S-wave coupling in heterogeneous anisotropic media, In: Kolman, Berezovski, Okrouhlík & Plešek: Advanced Modelling of Wave Propagation in Solids, Institute of Thermodynamics ASCR, Prague, Czech Republic, pp. 35-36).

**Ray-based Born approximation**

Šachl (2012: Effect of caustics on the ray-based Born approximation, In: Seismic Waves in Complex 3-D Structures, Report 22, Dep. Geophys., Charles Univ., Prague, pp. 55-82) continued his work on the ray-based first-order Born approximation, studied the problems with caustics corresponding to the incident ray-theory wave field or to the ray-theory Green tensor from a receiver, and demonstrated the considerable improvement of the accuracy of the reflected wave containing a caustic if the reflected wave is calculated by the Born approximation. Šachl (2012: Born and ray-theory seismograms in 2D heterogeneous isotropic models, In: Seismic Waves in Complex 3-D Structures, Report 22, Dep. Geophys., Charles Univ., Prague, pp. 83-112) then presented his final P-P Born scattering seismograms.

**Structural seismology**

It was determined how the perturbations of a generally heterogeneous isotropic or anisotropic structure manifest themselves in the wave field, and which perturbations can be detected within a limited aperture and a limited frequency band (Klimeš, 2012: Sensitivity of seismic waves to structure, Stud. geophys. geod., 56, 483-520). Perturbations of elastic moduli and density may be decomposed into Gabor functions. The wave field scattered by the perturbations is then composed of waves scattered by individual Gabor functions. If a short-duration broad-band incident wave field with a smooth frequency spectrum is considered, the wave scattered by one Gabor function is composed of only several Gaussian packets with uniquely defined frequencies and directions of propagation. We can thus evaluate to which properties of the structure the recorded wave field is sensitive. The derived approximate solution of the forward scattering problem may be utilized in designing the migration algorithm based on true linearized inversion of the complete set of seismograms recorded for all shots.

The theory describing the sensitivity of seismic waves to the geological structure together with a numerical example were demonstrated by Klimeš (2012: Sensitivity Gaussian packets, In: Kolman, Berezovski, Okrouhlík & Plešek: Advanced Modelling of Wave Propagation in Solids, Institute of Thermodynamics ASCR, Prague, Czech Republic, pp. 71-72).

Jechumtálová & Bulant (2012: Effects of 1-D versus 3-D velocity models on moment tensor inversion in the Dobra Voda locality at the Male Karpaty region, Slovakia, In: Seismic Waves in Complex 3-D Structures, Report 22, Dep. Geophys., Charles Univ., Prague, pp. 17-27) presented their results obtained during the cooperation with Slovak industrial partner ProgSeis within the framework of the European Commission's FP7 project "Advanced Industrial Microseismic Monitoring". They applied the software developed within the SW3D Consortium to smoothing 1-D and 3-D velocity models of the Dobrá Voda locality, and to the calculation of ray-theory amplitudes which they then use within the moment tensor inversion using the software developed by the group lead by Jan Šílený at the Institute of Geophysics, Academy of Sciences of the Czech Republic. Klimeš (2012: Resolution of prestack depth migration, Stud. geophys. geod., 56, 457-482) derived that, for a given source, the migrated section is the convolution of the reflectivity function with the corresponding local resolution function, or the convolution of the spatial distribution of the weak-contrast displacement reflection-transmission coefficient with the corresponding local resolution function.

Bucha (2012: Kirchhoff prestack depth migration in 3-D simple models: comparison of triclinic anisotropy with simpler anisotropies, Stud. geophys. geod., 56, 533-552) demonstrated the behaviour of the 3-D Kirchhoff prestack depth migration in the presence of triclinic anisotropy. He then studied the effects of simplified or incorrectly estimated anisotropy upon the migrated image.

Bucha (2012: Kirchhoff prestack depth migration in velocity models with and without gradients: Comparison of triclinic anisotropy with simpler anisotropies, In: Seismic Waves in Complex 3-D Structures, Report 22, Dep. Geophys., Charles Univ., Prague, pp. 29-40) demonstrated the behaviour of the 3-D Kirchhoff prestack depth migration in the presence of triclinic anisotropy and vertical or horizontal velocity gradients, and studied the effects of incorrectly estimated anisotropy and of simple heterogeneity upon the migrated image.

**CD-ROM with SW3D software, data and papers**

Compact disk SW3D-CD-16 (Bucha & Bulant, 2012: SW3D-CD-16, In: Seismic Waves in Complex 3-D Structures, Report 22, Dep. Geophys., Charles Univ., Prague, pp. 183-184) contains the revised and updated versions of the software developed within the consortium research project "Seismic Waves in Complex 3-D

Structures" (SW3D), together with input data used in various calculations. Compact disk SW3D-CD-16 also contains over 430 complete papers from journals and from the SW3D consortium research reports, and 3 books by V. Červený. The software and papers from compact disk SW3D-CD-16 can be found at "http://sw3d.cz".

# Geodynamics (reported by Ondřej Čadek)

**Planetology**

In the field of planetology, attention has been paid to icy satellites with special emphasis on thermal stability of Enceladus. Using a fully consistent 3d spherical model of thermal convection driven by tidal heating, Běhounková et al. (2012) demonstrated that the present day tidal heat production on Enceladus is not sufficient to explain the heat flux observed at the south pole of the body. They suggested that the present day activity is a consequence of enhanced eccentricity in the past which led to intense melting and disruption of the lid due to volumetric changes in the ice. Kalousová et al. (2012) carefully tested different membrane approximations used to simulate elastic deformation of single-plate terrestrial planets. Besides the shells of constant thickness, traditionally used in planetology studies, they also considered models with uneven thickness and they demonstrated the limits of various thin shell approximations. The role of elastic lithosphere on Mars was also studied in the paper by Golle et al. (2012) where the 3d spherical convection simulations were combined with elastic lithosphere deformation to estimate the dynamic topography of the planet.

Benešová and Čížková (2012) studied the geoid and topography of Venus generated by various models of thermal convection to determine possible viscosity structure of the Venus mantle. They found that the profile proposed by Pauer et al. (2006) is still acceptable and no thick lithosphere is needed to explain the topography and geoid data.

**Tectonophysical modeling**

Maierová et al. (2012a) examined the influence of variable thermal properties on the thermal state of a subducting slab in the top 1000 km of the mantle by combining a kinematic slab model with models of thermal conductivity. We demonstrated that variable thermal diffusivity results in a modest increase of negative buoyancy of the slab. Maierová et al. (2012b) presented a numerical model of exhumation of the orogenic lower crust in the Bohemian Massif during the Variscan orogeny. The model indicates theta the Variscan orogeny of the Bohemian massif resulted from a combined affect of gravitational redistribution in the crust and tectonic compression of the lithosphere.

**Electromagnetic induction research**

In the area of EM induction modeling, Velímský et al. (2012) concluded the study of detectability of large lateral variations of conductivity in D" by means of time-domain EM induction. They demonstrated that failure to detect highly conductive post-perovskite (PPV) in D" by previous 1-D study can be explained not only by the absence of highly conductive phase, but that PPV can be also present in substantial amount not interconnected in the equatorial direction, corresponding to the dominant dipolar polarization of the strongest source of excitation - the magnetospheric ring current. Velímský et al. also tested a new, massively parallel version of the 3-D inversion code on various scenarios. A particular application tailored to inversion of satellite data has become part of the Level 2 processing facility for the upcoming Swarm ESA mission (Velímský; Olsen et al., Earth Planets Space, two manuscripts in review). Velímský also contributed to the GEMINI project (The Global Electromagnetic Modeling INtercomparison Investigation) - a benchmark study comparing the 3-D forward modeling tools developed by different teams. Finalization of the manuscript for Geophys. J. Int. is expected in 2013 with a follow up benchmark of 3-D inverse modeling methods. Besides, Dostal et al. (2012) studied the toroidal magnetic field generated by tidally induced ocean circulation.

**Earth's lower mantle dynamics**

Čížková et al. 2012 used the lower-mantle sinking speed of lithosphere subduction remnants as a unique internal constraint on modeling the viscosity profile. Performing a series of elaborate dynamic subduction calculations spanning a range of viscosity profiles, they selected such profiles that predict the inferred sinking speed of 12 ± 3 mm/yr. This modeling showed that sinking speed is very sensitive to lower mantle viscosity. Good predictions of sinking speed were obtained for nearly constant lower mantle viscosity of about $3\text{-}4\times10^{22}$ Pa s. Viscosity profiles incorporating a viscosity maximum in the deep lower mantle only lead to a good prediction in combination with a weak postperovskite layer at the bottom of the lower mantle, and only for a depth average viscosity of $5\times10^{22}$ Pa s.

Androvičová and Čížková (Studia Geoph. Geod., accepted) studied the processes within subduction zones and their influence on the plate dynamics. Besides control parameters related to the upper mantle describing the composite rheology including diffusion creep, dislocation creep and stress limiter or Peierls creep, they also considered the effect of viscosity contrast across the 660 km upper/lower mantle discontinuity. They found that a step-wise viscosity increase by about an order of magnitude at 660 km depth is necessary to limit the plate velocities to a reasonable value around 5 cm/yr.