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1 History of seismological research in Hungary

1.1 The 150th anniversary of the birth of Radó Kövesligethy (1862-1934)

The Hungarian geophysicists in 2012 commemorated the 150th anniversary of the birth of Radó Kövesligethy, the secretary general of the International Seismological Association – ISA (the official name in German and French was International Seismologische Assoziation and Association Internationale de Sismologie, respectively) between 1906 and 1921. Kövesligethy's earthquake theory was related to the problem of propagation of seismic effects within the Earth. This issue was new during the last years of the nineteenth century, practically not addressed earlier. It should be mentioned that his student Jenő Egerváry (who became later on a worldwide famous mathematician) mathematically proved that Kövesligethy's theory provides results which agree with data obtained from the works of Gustav Herglotz and Emil Wiechert (Varga 2012, Varga and Gráczer 2013).

On the 17th of October 2012, the Hungarian Academy of Sciences held a conference in commemoration of Radó Kövesligethy's scientific work (Mónus and Tóth 2013, Wéber 2013).

2 Observational seismology

2.1 Developments in the Hungarian National Seismological Network since 2011

The MTA CSFK Kövesligethy Radó Seismological Observatory operates the Hungarian National Seismological Network (HNSN). Between 2011 and 2014, the HNSN were extended by six Streckeisen STS-2 and Guralp CMG-3T based broadband stations thanks to the support of the Paks Nuclear Power Plant (AMBH, BSZH, EGYH, MORH, MPLH, TIH) and the Humboldt Foundation (LTVH). With the new deployments, at the end of the year 2014 the HNSN consisted of 12 broadband stations and one short period station.

All the station data is streamed through online connection to the observatory. The data centre of the observatory has been running a SeisComp3 (http://www.seiscomp3.org, 2015-06-04) based automatic hypocentre location service whose results are published on the web (http://www.seismology.hu, 2015-06-04) and simultaneously email alerts are sent to the Hungarian National Directorate General for Disaster Management. The manual phase picking and magnitude determination has been carried out using the Seismic Handler software package (Stammler 1993). The hypocentre location has been performed by the HYPO71PC computer program (Lee and Lahr 1975). In order to increase the quality of earthquake location, data from selected stations of the neighbouring countries are collected, as well.

The annual Hungarian National Seismological Bulletin has been published since 2012. It contains the focal parameters and phase data of the earthquakes occurred in Hungary and its surroundings, the focal mechanism of several earthquakes, the macroseismic characteristics of the felt earthquakes, and the phase data of teleseismic events detected by the stations of the HNSN (Gráczer et al. 2012, 2013, 2014).

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3 Deep structure of the Pannonian basin

3.1 One-dimensional velocity model for Hungary

Based on the first arrival times of local earthquakes, a new one-dimensional P-wave velocity model has been determined for the territory of Hungary (Gráczer and Wéber 2012). During the computations 910 P-wave arrival data of 86 events from the time period between 1985 and 2010 have been used. The applied methodology was a combination of a genetic algorithm based procedure and an iterative linearized joint inversion technique. The preferred velocity profile has been chosen from the best models based on the data of a series of controlled explosions.

The resulting flat-layered model consists of three crustal layers and a half-space representing the uppermost mantle. Its main characteristics are the relatively thick upper crust (16 km, V_p=5.74 km/s) with a 3 km thick sedimentary layer ($V_p = 5.30$ km/s), and a significantly thinner lower crust (7 km, $V_p = 6.29$ km/s). The Moho can be found at a shallow depth of 26 km. Additionally, the V_p/V_s ratio was calculated by the Wadati-method, which gave a value of 1.74±0.05.

3.2 Ambient seismic noise tomography

The Rayleigh wave group velocities beneath Hungary were studied by ambient seismic noise tomography (Szanyi et al. 2013). Seismic noise data recorded at 17 broadband seismological stations in and around the Pannonian basin were used during the computations. In order to determine the Green's functions for the station pairs, cross-correlation functions were calculated in daily segments and stacked over several months. Group velocities belonging to the fundamental mode Rayleigh waves were determined by multiple filter technique.

The dispersion curves for each station pair were measured in a period range of 7–28 s and group velocity distribution maps were computed using a 2D tomography method. Group velocity maps of 7–14 s periods correlate well with regional geology. High group velocities can be observed in the mountains, whereas low velocities can be seen beneath the sedimentary basins. Velocity anomalies observed at 18–28 s reflect the effect of the lower crust and uppermost mantle.

3.3 Complex geophysical probing of the lithosphere beneath the Carpathian-Pannonia Region

The majority of our activities covered the complex geophysical probing of the lithosphere beneath the Carpathian Pannonian region (CPR) by various means of methodologies also in international collaboration. Posgay et al. (2011) demonstrated that there may be lithospheric scale, narrow nappes transacted by the PGT-1 seismic traverse. The integrated interpretation involving geological, geochemical and magnetotelluric results lead to the conclusions that these SSE dipping, lithospheric-scale structures may have formed in the lower Cretaceous by the subduction of one of the Vardar's oceanic branches beneath the Tisza Megaunit.

Kiss and Madarasi (2012) found also SSE dipping structures along the PGT-1 profile many of which penetrated the entire lithospheric column. The authors related some of these structures to magmatic impregnation of possible Cretaceous or younger age.

Janik et al. (2011) investigated the Celebration profiles intersecting the Western Carpathians. The main findings were that the lower sub-Moho velocities in the Pannonian Basin are lower than those beneath the Trans-European suture zone, East European Craton and the Western Carpathians. Sub-parallel reflectors were identified 10-20 km beneath the Moho.

Starostenko et al. (2013) studied the PANCAKE seismic wide angle survey from the Pannonian Basin to the East European Craton through the Carpathians. This study also revealed that the sub-Moho velocities are lower beneath the Pannonian Basin than beneath the Carpathians and the East European Craton. Sub-Moho reflectors were also identified beneath the Pannonian Basin at depths of ~45 and 75 km. The latter of which is attributed to the lithosphere-asthenosphere boundary (LAB).

Oeberseder et al. (2011) revealed the presence of sub-Moho reflectors as well beneath the junction of the Eastern Alps, Western Carpathians and Pannonian Basin at ~55 km average depth dipping toward the mountain belt. The authors attributed the presence of this reflector to layering in the present lithospheric mantle. The shallower layer presumably represents a less anisotropic and more depleted mantle than the deeper part, which may have been added to the lithosphere in the thermal relaxation stage following the Miocene extension. This may be a plausible scenario for the explanation of sub-Moho seismic reflectors found elsewhere in the Pannonian basin.

Kiss (2012, 2013) give a comprehensive gravity and geomagnetic summary of the CPR with special respect to identify the links between anomalies and geological structures. These anomalies were found to correlate rather well with major tectonic lines and the (supposed) distribution of volcanic centres/rocks.

3.4 Studying experimentally the composition of the upper mantle and its geophysical implication

Kovács et al. (2012b) and Green et al. (2014) studied experimentally the effect of water on the phase assemblage of upper mantle peridotites. They showed that the stability of pargasitic amphibole below 3 GPa and 1100°C and instability above may have a drastic effect on the rheological properties of the upper mantle which should be also reflected in geophysical properties. The instability of pargasitic amphibole leads to melting, which could result in lower seismic velocities and higher conductivity. It seems that there is indeed a horizon at ~90 km depth globally (which is called the mid lithospheric reflector) and similar anomalies at shallower depth (referred to as generally the LAB) in tectonically more active areas with higher heat flow ($> 60\text{-}70$ mW/m^2). These may be explained by the instability of pargasitic amphibole and the onset of partial melting at these depths.

4 Earthquake source seismology

4.1 Spectral estimation of source parameters for local earthquakes in Hungary

Source parameters have been estimated for 74 local earthquakes ($0.8 \leq M_L \leq 4.5$) occurred in Hungary in the period of 1995-2011 (Süle and Wéber 2013, Wéber and Süle 2014). The displacement spectra for P- and S-waves were analyzed according to Brune's source model. Observed spectra were corrected for path-dependent attenuation effects using an independent regional estimate of the quality factor Q_S. To correct spectra for near-surface attenuation, the κ parameter was calculated, obtaining it from waveforms recorded at short epicentral distances. The values of the κ parameter vary between 0.01 and 0.06 s with a mean of 0.03 s for P-waves and between 0.01 and 0.09 s with a mean of 0.04 s for SH-waves. After correction for attenuation effects, spectral parameters (corner frequency and low-frequency spectral level) were estimated by a grid search algorithm. The obtained seismic moments range from $1.34 \cdot 10^{11}$ to $3.68 \cdot 10^{15}$ Nm ($1.5 \leq M_W \leq 4.3$). The source radii are between 115 and 1343 m and stress drop spans from 0.14 to 32.4 bars. From the results, a linear relationship of $M_w = 0.73 \cdot M_L + 0.86$ has been established between local and moment magnitudes. The obtained scaling relations show slight evidence of self-similarity violation. However, due to the high scatter of our data, the existence of self-similarity cannot be excluded.

4.2 Source properties of the 2011 M$_L$ 4.5 Oroszlány mainshock and its aftershocks

In the most seismically active region of Hungary, an earthquake of M_L 4.5 occurred near the town of Oroszlány on 29 January 2011. The mainshock was followed by more than 200 aftershocks. This event is the first earthquake in the country above M_L 4 that was recorded on a significant number of three-component digital seismic stations. The source properties of this earthquake sequence have been thoroughly studied by Wéber and Süle (2014).

According to the inversion of arrival times, the hypocenter of the mainshock was at a depth of about 5 km near Oroszlány with horizontal errors of about 1.5 km. The aftershocks were confined to a small region next to the mainshock.

For the main event, we obtained an average moment magnitude of $M_w = 4.2$, P- and S-wave source radii of $r^P = 970$ m and $r^S = 972$ m, and static stress drops of $\sigma^P = 6.67 \cdot 10^5$ Pa and $\sigma^S = 17.60 \cdot 10^5$ Pa from the analysis of P- and S-wave displacement spectra, respectively. The retrieved spectral source parameters for the investigated events agree well with the results of earlier research.

We have also shown that our local waveform inversion method (Wéber 2006, 2009) applied in this study is suitable to estimate the earthquake source mechanism for low-magnitude events using local waveforms exclusively. The moment tensor computed for the mainshock from local waveform data shows a strike-slip mechanism with a NS-striking and an EW-striking nodal plane, agreeing well with regional moment tensor solutions of other agencies.

The source mechanisms of four aftershocks with $M_L \geq 2$ were also successfully estimated. Three of them had strike-slip mechanism very similar to that of the mainshock, whereas the fourth one was a thrust faulting event with some strike-slip component. The sub-horizontal P-axis struck about NE-SW for both the mainshock and all the analyzed aftershocks, coinciding with the general trend of the compressional stress field in the epicentral region.

5 Seismicity and earthquake hazard

5.1 Macroseismic study of the 2013 M_L 4.8 Tenk earthquake

On 22 April 2013, an earthquake of magnitude 4.8 occurred near the village of Tenk (Hungary), which was the strongest Hungarian earthquake since the 4.9 magnitude event near Berhida in 1985. The earthquake was felt in approximately third of the territory of Hungary. The number of incoming macroseismic questionnaires was over eight hundred and damage descriptions for the epicentral area reached almost one thousand. Intensity evaluation was carried out following the European Macroseismic Scale guidelines. Intensities were assigned to 211 places. The earthquake caused non-structural building damages, the epicentral intensity was estimated as VI on the EMS-98 scale. The area of the highest seismic intensities (V or more) is elliptical in shape elongated in the E–W direction. The intensity distribution of the event is very asymmetric, it was widely felt west to the epicentre, but it was much less observed in the east direction (Szanyi et al. 2014).

5.2 Liquefaction occurrences and hazard assessment

Most part of Hungary is low-lying plains covered by young Holocene fluvial sediments with high ground water level. Consequently, the area is disposed to development of soil liquefaction. Despite the moderate seismicity, liquefaction have been observed and documented at least eight times during moderate to larger magnitude historical earthquakes. Their surface manifestations were reported from the Komárom (1763, 1783, 1822), Mór (1810), Érmellék (1829, 1834), Kecskemét (1911) and Dunaharaszti (1956) earthquakes. We have studied contemporary macroseismic observations that demonstrate the occurrence of soil liquefaction. Local subsoil conditions and information regarding ground water level were also studied.

Magnitude of these earthquakes were in the range of 5.4-6.3. The liquefaction was typically confined to the vicinity of the epicenter, and its intensity was mostly small. The exceptions are the two earthquakes stronger than magnitude 6. According to the reports, the 1763 Komárom and the 1834 Érmellék earthquakes caused soil liquefaction which could be extended to a greater extent and a large area. Building or structural damage caused by the phenomenon is proven only in the case of the 1763 Komárom earthquake (Győri 2013). Based on the descriptions, the old castle near to the firth of Danube and river Vágh has suffered severe damage due to lateral spreading. The numerous occurrences of liquefaction in Csallóköz (Žitný ostrov in Slovakia) support the assumption that the epicenter of the earthquake was located probably NW of Komárom.

Because of the lack of strong motion recordings, macroseismic data and analogues of recently recorded earthquakes can be used to estimate the surface motion caused by these earthquakes. Distribution of horizontal ground accelerations possibly caused by these historical earthquakes has been modelled by ShakeMap program. Simulations indicate horizontal PGA of 0.2-0.3 g in areas where liquefaction occurred (Győri et al. 2014b).

Although the seismicity of Hungary is moderate, liquefaction and post-liquefaction settlement as a secondary earthquake effect is one of the main concerns during site characterization of major industrial/nuclear installations. Pore pressure increase and so the liquefaction and surface settlements depend on the characteristics of seismic loading and soil parameters. To quantify the extent of these phenomena is rather difficult. Uncertainties arise both from the probabilistic nature of the earthquake loading and from the simplifications of soil models as well. Significant part of epistemic uncertainties in evaluation of liquefaction and post liquefaction settlement arise from the application of different methods. Therefore we have compared the most important semi-empirical SPT, CPT and Vs based as well as dynamical effective stress methods. Most significant contributors to the uncertainties have been highlighted and particular examples through the investigation of Paks NPP site were given (Győri et al. 2014a). To take into account the uncertainties, a probabilistic procedure has been proposed where the uncertainties are taken into account by applying a logic tree methodology (Győri et al. 2011).

5.3 Seismic microzonation

In 2013, we have started a project about the seismic hazard assessment and microzonation of Budapest. Geological and engineering geological maps necessary for microzonation have been collected and computer programs have been developed to process the map data. Geotechnical data from Budapest and surroundings were collected. We have re-evaluated the intensity distribution of Dunaharaszti earthquake for the whole country and Budapest. We have studied the correlation with geological structures, local soil conditions, built in of the area and with the quality of the buildings.

Vulnerability of building stock largely affects the seismic risk in the capital. The vast majority of buildings in the center of Budapest were built in the 19-20th century according to the architectural (mainly neo-classical and eclectic) styles of that time and to the given technical, civil engineering knowledge and practice. As people did not have experiences in previous earthquakes, the structures were not designed to take into account the earthquake safety. We have studied the older brick buildings in the downtown, and we have found that beside structural problems characterizing a lot of buildings, the lack of maintenance can cause serious problems during a possible earthquake occurring near the city (Völgyesi et al. 2014).

On the basis of different types of geological maps of Budapest, we have delineated areas that were estimated to be liable to resonance. Besides, we have selected some areas where larger damages were experienced during Dunaharaszti earthquake. We have begun microseismic noise measurements in the selected areas, for example in Városliget, Rákospalota, Angyalföld, Kőbánya, Lágymányos, Csepel Island, Gazdagrét, Hűvösvölgy, Óbuda. We could identify areas in Kőbánya, Hűvösvölgy, Óbuda, where soil-structure resonance can occur during earthquakes.

We have performed microseismic noise, active and passive seismic measurements in some parts of the city to determine the S wave velocities of the upper sedimentary layers. We have made MASW and ReMi measurements and we have begun to study the local applicability of the noise cross correlation method.

5.4 Speleoseismology

Suitably shaped (tall, slim and more or less cylindriform), vulnerable, intact stalagmites (STM) in Domica cave were examined in 2011, 2012 and 2013. Some of these STMs are suitable to estimate the upper limit for horizontal peak ground acceleration generated by paleoearthquakes. This research has been the continuation of our previous examination of STMs in Baradla cave, north-east Hungary (Szeidovitz et al. 2008).

The density, the Young's modulus and the tensile failure stress of broken STM samples have been measured in mechanical laboratory, whereas the natural frequency and the heights and diameters of intact STMs were determined by in-situ observation. The value of horizontal ground acceleration resulting in failure and the theoretical natural frequency of STM have been assessed by theoretical calculations.

The age of the samples taken from the STM(2.26m) standing in show part of Domica cave has been determined by Multi Collector – Inductively Coupled Plasma Mass Spectrometry analysis (MC-ICPMS).

The a_g value (the upper limit for horizontal peak ground acceleration) needed to break STM (5 m) in Čertova diera (Ördög-lik) hall coming from theoretical calculation is almost the same (~ 0.059 g) as in case of STM (5.1 m) in Olimposz hall (~0.055 g) of Baradla cave.

According to our measurements and theoretical calculations, in the last 2-5 kyears the geological structures close to Baradla and Domica caves have not generated paleoearthquakes which would have produced horizontal ground acceleration larger than 0.061g. This value can be reached even in moderate size earthquakes. Our result has to be taken into account when calculating the seismic potential of faults near to Domica cave (e.g. Darnó, Plešivec (Pelsőc) and Rožňava (Rozsnyó) lines) (Gribovszki et al. 2013b).

A comprehensive study has also been presented about the non-intrusive in-situ measurements in caves in Hungary, Bulgaria and Slovakia carried out in the last ten years in order to determine the fundamental frequencies and horizontal ground accelerations (HGA) resulting in failure of intact, slim, vulnerable stalagmites (Gribovszki et al. 2013a).

Since the geological structures close to the investigated caves did not excite paleoearthquakes in the determined time period with HGA larger than the determined a_g values, the results of our investigation should be taken into account in seismic hazard assessments of the investigated areas.

5.5 Discrimination of earthquakes and explosions

Recently, due to the increasing number of modern seismological stations, more and more earthquakes and explosions have been recorded and located in Hungary. In the determination of tectonic parameters for different regions, earthquakes should be separated from explosions. This needs to analyse and identify the separation parameters of earthquakes and explosions. The North Hungarian Mountains and the Vértes Hills are typical, where microearthquakes (aftershock sequences) and blasts originated from different quarries are detected regularly. The waveform and spectral properties and diurnal distributions of these seismic events have been analyzed comprehensively (Kiszely 2014).

Most of the explosions in the North Hungarian Mountains and every explosion in the Vértes Hills were executed at workdays. For both areas a time window could be defined when most of the explosions happened. A significant part of the earthquakes (36% for the North Hungarian Mountains and 15% for the area of Vértes) occurred in this time window. The origin time of the event does not provide sufficient information to filter out the explosions from catalogues.

The scalloping of spectra and the time-independent modulations on the spectrograms – caused by the delayed fired technique – were observed in the most case of explosions. The presence of these signs in spectra has proven to be a good indication parameter of quarry blasts.

Based on the correlation waveforms analysis, the explosions of different quarries and aftershocks formed different cluster(s). The clusters of earthquakes and explosions were not mixed with each other. Creating waveform database for each quarry and continuously adding the new blasts, high portion of the explosions will be possible to filter out. The waveform correlation analysis is suitable for classification of several events without calculable hypocentre parameters, due to the few registering stations. We can get more accurate time distribution of aftershocks connecting these events to them (Kiszely 2012, Kiszely and Győri 2013a, 2013b, 2014a, 2014b).

The Fisher-Shannon method was applied to discriminate the quarry blasts from earthquakes based on the informational content of seismograms for the seismic events originated from Vértes Hills (Telesca et al. 2011).

5.6 Spatial and temporal distribution of earthquakes

The aim of the studies by Pődör and Kiszely (2013) and Pődör and Kiszely (2014) were to find possible solutions to represent earthquake catalogue data and design maps. The goal was to visualize all available catalogue data sets in a complex way on a single map, displaying the long-term recurrence times of earthquakes. Therefore, raw data and aggregated data were combined with different cartographic visualization techniques to test the applicability of earthquake maps. Preliminary research demonstrates that aggregation can improve the process of retrieving information from earthquake maps and 3D visualization is useful to find the places of earthquakes of highest magnitude. A second result is that 3D visualization is not effective in the comparison of quantities of released energy and the number of earthquakes.

5.7 Recurrence time of earthquakes

For major earthquakes over the past decades, several significant differences were detected between the predicted and observed PGA values. This is primarily so because Probabilistic Seismic Hazard Assessment (PSHA) and Deterministic Seismic Hazard Assessment (DSHA) suffer from a limited knowledge of seismic prehistory. A further weakness of PSHA is its requirement of homogeneous seismic activity within a seismic zone. Moreover, PSHA and DSHA were developed for seismically active areas and, thus, cannot reliably be used in areas of medium and low activity (Varga 2011a). To overcome this problem an alternative methodology – based on a modified version of Kostrov's equation and the catalogue of seismic moments – was outlined which provides the recurrence time estimate on the basis of common use of geodetic and seismological information. It was found that the recurrence time in a given source zone in case of earthquakes $M_W \geq 9.0$ are of the order of some hundred years. For the large and medium earthquakes the expected time is well above some 10^3 years (Varga 2011b).

6 Geodynamics and tectonophysics

6.1 Mantle dynamics

There has been a long history of studying the endothermic phase change at a depth of 660 km in the Earth's mantle. The goal of our research was to determine the transition between one-layered and two-layered convection and to analyze the dynamics of mantle avalanches using simple two-dimensional numerical models (Herein et al. 2013). A series of numerical calculations have been investigated using different Rayleigh numbers (Ra) and Clapeyron slopes (γ_d). We established that the Rayleigh number effectively influences the dynamics of the phase transition. At higher Rayleigh numbers (more vigorous convection) the hindering effect is stronger; at $\gamma_d < 0$ mantle convection is shifted from one-layered towards a partially layered flow system. From calculating the vertical mass flux at 660 km and analyzing its time series three types of mantle flow were found. The first type is whole mantle convection (one-layered), namely below $Ra=10^5$ and for γ_d = -3, -4.5, -6, -9 MPa/K. The second type is an intermittently layered mantle convection, where the convection is mainly layered but there is a significant, episodically huge mass transfer between the two layers, i.e. above $Ra = 5 \times 10^5$ and for γ_d = -3, -4.5, -6 MPa/K. The third type covers isolated upper and lower mantle convection at γ_d = -9 MPa/K and from $Ra = 10^5$, within which range all of the simulations resulted in two-layered convection. Systematic investigation has been carried out to map the region in the second group where avalanche events can appear. Mantle avalanches have been detected in 12 models from $Ra = 5 \times 10^5$ to $Ra = 10^7$ and at γ_d = -3, -4.5, -6 MPa/K. As a result of a Fourier analysis the characteristic time periods of mantle avalanches have been calculated. Analyzing the amplitude

spectrum of the vertical mass flux at a depth of 660 km two specific time periods were determined. The larger one, at about 580 Myr, may correspond to the large mantle overturns related to Wilson-cycle. The shorter period represents smaller, more frequent mantle avalanches. Studying the influence of the Rayleigh number and the Clapeyron slopes systematically, it has been shown that the characteristic time period of these smaller avalanches depends on Ra, but is independent of γ_d. As Ra increases the time period decreases; the relationship can be well described with a power function. The characteristic time period of small avalanches for mantle-like parameters ($Ra\sim10^7$, γ_d = -3 MPa/K) is about 80-150 Myr, which can be compared to the average time period of episodic flood basalt activity.

In another numerical study the effect of the temperature-dependent viscosity was investigated on the pattern and the characteristic parameters of the thermal convection occurring in the Earth's mantle in two-dimensional cylindrical shell geometry (Kuslits et al. 2014). Systematic model runs established that the viscosity decreasing with the temperature is reduced around the hot core-mantle boundary (CMB) which facilitates the heat transport from the core to the mantle. On the other hand, the viscosity increases near the cold surface which hinders the heat outcome and results in higher mantle temperature and lower surface velocity. A power law relation was revealed between the strength of the temperature-dependence and the observed parameters, such as the velocity, surface mobility, heat flow, average temperature and viscosity. Two additional 'mantle-like' models were built up with extra strong temperature-dependent viscosity to imitate the flow in the Earth's mantle. In model 1, in which the viscosity decreases seven orders of magnitude with the temperature increase, a highly viscous stagnant lid evolves along the cold surface which does not participate in the convection. The existence of the stagnant surface lid reduces the surface heat flow and generates a low viscosity asthenosphere beneath the lid with vigorous small-scale convection. In model 2, in which the viscosity decreases only six orders of magnitude with the temperature and the pressure-dependent viscosity is stronger, does not form a surface stagnant lid, highly viscous 'slabs' submerge to the CMB and effectively influence the hot upwelling plumes. Based on our numerical results it is necessary to implicate the yield stress into the simulations in order to obtain a highly viscous, 'rigid' surface lid, the lithosphere which can be broken up and subduct down to the mantle.

6.2 Tertiary geodynamics of the Carpathian-Pannonian Region

Kovács et al. (2011, 2012a) presented a new geodynamic model to explain the Tertiary geodynamics of the Carpathian-Pannnonian region (CPR). Using data from mantle xenoliths, geology and seismic anisotropy the authors proposed that the extension and extrusion of lithospheric blocks (not just crustal slices) was driven by an eastward directed asthenospheric flow which was generated by the collision in the Alps.

Kiss (2014) in his summary investigated the interrelations of plate tectonics, volcanism and geomagnetic anomalies in the CPR: His results implied that there is a strong link among these geological phenomena which could be, indeed, put into the context of an asthenospheric flow driving the Tertiary geodynamics of the CPR.

6.3 Problems related to geodynamics

For the study of distribution of great seismic events $M \geq 7.0$ (and consequently the released seismic energy) a catalogue for the time interval 01.01.1900 – 30.09.2014 was completed. It is likely that stresses accummulated deeper than 500 km and released by deep $M \geq 7$ earthquakes are connected with resistance due to transition of downward moving plate toward and through the 660 km boundary. When the accurate geographical dimensions of seismic zones on the earth ellipsoid were calculated with use of a software developed for case of different map projections, it was found that the length of the zone of deep events is significantly shorter than that of the shallow ones. The position of very deep ($\geq$ 500 km) earthquake foci indicates where the down-going lithospheric plates conflict with the upper boundary of lower mantle, and where they in some cases cross it. This passage generates compression – elongation inside the slab. This phenomenon is similar to the

Venturi effect known from hydrodynamics. For the study of the fairly uncommon deep earthquakes important additional information was provided by the largest of deep earthquakes, the May 24, 2013 *Mw* 8.3 event under the Sea of Okhotsk. Based on records of Russian and Hungarian national seismological networks it was found that this seismic event was preceded by an earthquake swarm, which consists 58 M ≥ 5 events and occurred between May 15 and 24, 2013 in the higher part of the sinking slab east of Kamchatka in an area of increased historical seismicity. Most probably interaction of two distinct active source zones area took place (Varga et al. 2014).

As a result of investigation of the Earth's inner structure and dynamics, a clear axial co-ordination of radiated seismic energy with maxima at latitudes close to critical (±45°) was detected. This speaks about the presence of external forces that influence seismicity. This external factor is most probably the despinning (reduction of the Earth's angular rotation) of the Earth axial rotation caused primarily by tidal friction due to the Moon (Varga et al. 2012b).

Studies connected to history of development of planetary structure detected that at the present epoch the growth rate of the core comprised between 1 and 10 mm/cy seems to be a plausible guess, leading to a relative decrease of LOD comprised roughly between 10 and 100 µs/cy. Such values do not affect significantly the observed secular increase of LOD caused by tidal braking, which amounts to about 1.79 ms/cy. However, in the remote geological past, before Phanerozoic, the effect of the core growth may have been much more important, because the total change of LOD associated with core formation has been estimated to be 2.4 hours for an initially undifferentiated Earth, and 3.1 hours for an initially undifferentiated hot Earth (Denis et al. 2011).

In order to interpret the change in planetary dynamics close to the border between Proterozoic (Ptz) and Phanerozoic (Pz) a compilation of palaeogeographical maps from the 0.6 Ga BP to Present was analyzed in terms of the (a) ratio between continental to oceanic crust areas (in short continent-to-ocean ratio), (b) length of spreading centres and (c) length of subduction zones. From the constancy of the continent-to-ocean ratio through Pz and from the small size of the continental area above sea level in Ptz it follows that at the border between Ptz and Pz there has been a large change of the length of the shelf zones. This change can explain contemporary change of the despinning rate from about 0.35 ms/century to about 1.79 ms/century. In general this results suggest a change in tectonic regime at the border between Ptz and Pz (Varga et al. 2012a). Similar change in dynamical properties of the Earth was detected when the strength of the geomagnetic field, characterized by the Virtual Dipole Moment (VDM) was investigated. The data bank of virtual dipole moment (VDM) data served as a basis for the analysis. The VDM distribution obtained by the method of a moving average exhibits a positive linear trend from 3.7×10^{22} Am^2 2.6 Ga ago to 5.8×10^{22} Am^2 ~0.6 GaBP, while during the phanerozoic there was no linear trend recognized (Schreider et al. 2011, 2012).

An additional investigation of palaeogeographical maps for the time interval 0.6 Ga BP to Present was carried out for a study of the surface motion of continental plates under the influence of global forces of tidal friction and Eötvös force ("pole-fleeing"). It was concluded that the area of the continents during the Phanerozoic was growing and it exhibited a rate ~0.5 km^3/yr with an average continental crust thickness of 40 km. It was also found that beside the westward oriented tidal frictional forces, the Eötvös force can also play a role in tectonic processes. It was shown that the continental plates on average tend to find a position close to the equator during the whole investigated 600 Ma time Interval (Varga et al. 2014).

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