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A seismic source zone model for the seismic hazard assessment of Slovakia

JOZEF HÓK[1], RÓBERT KYSEL[2,3], MICHAL KOVÁČ[1], PETER MOCZO[2,3], JOZEF KRISTEK[2,3], MIRIAM KRISTEKOVÁ[3,2] and MARTIN ŠUJAN[4]

[1]Department of Geology and Palaeontology, Faculty of Natural Sciences, Comenius University in Bratislava, Ilkovičova 6, Mlynská dolina G, 842 15 Bratislava, Slovakia; hok@fns.uniba.sk
[2]Faculty of Mathematics, Physics and Informatics, Comenius University in Bratislava, Mlynská dolina, 842 48 Bratislava, Slovakia; Robert.Kysel@fmph.uniba.sk
[3]Earth Science Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 840 05 Bratislava, Slovakia
[4]EQUIS Ltd., Račianska 57, 831 02 Bratislava, Slovakia

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Abstract: We present a new seismic source zone model for the seismic hazard assessment of Slovakia based on a new seismotectonic model of the territory of Slovakia and adjacent areas. The seismotectonic model has been developed using a new Slovak earthquake catalogue (SLOVEC 2011), successive division of the large-scale geological structures into tectonic regions, seismogeological domains and seismogenic structures. The main criteria for definitions of regions, domains and structures are the age of the last tectonic consolidation of geological structures, thickness of lithosphere, thickness of crust, geothermal conditions, current tectonic regime and seismic activity. The seismic source zones are presented on a 1:1,000,000 scale map.

Key words: seismotectonic model, seismic hazard, Slovakia, Western Carpathians.

Introduction

The definition of seismic source zones and the derivation of the parameters characterizing seismic activity in each seismic source zone are crucial for a seismic hazard assessment. A seismotectonic model of an investigated territory is a necessary basis for defining seismic source zones. The seismotectonic model relevant for seismic hazard analysis for the Slovak territory has to include adjacent tectonic areas. This means that the eastern part of the Czech Republic, north-eastern part of Austria, northern part of Hungary and the southern part of Poland have to be included in a major area for the analysis.

Probably the first seismotectonic map of Slovakia was produced by Hrašna (1997). The principles applied in this work do not correspond to present requirements. Šefara et al. (1998) defined seismogenic zones within the Alpine–Carpathian–Pannonian region. The zones were represented by the Late Jurassic–Late Cretaceous intraplate and oceanic sutures which were reactivated as fault zones with various kinematics during the Late Tertiary and are still potentially capable of generating earthquakes. Hók et al. (2000) and Kováč et al. (2002) applied similar approaches also including neotectonic stress field and recent vertical movement tendencies. Madarás et al. (2012) defined six seismic active regions on the Slovak territory. They characterized each region by its seismicity, recent vertical movement tendencies and potentially active faults.

Under the seismotectonic model we understand a structured set of available geological, geophysical and seismological data relevant for definition of seismic source zones covering the territory of Slovakia and adjacent regions.

In this article, we start with a general seismotectonic framework of the Slovak territory based on the geological evolution of the Western Carpathians and the lithosphere parameters. We explain a procedure for compiling, homogenizing, declustering and a time-completeness analysis of the new Slovak national earthquake catalogue (2011). We continue with principles of compilation of the seismotectonic model and division of the territory into tectonic regions, seismogeological domains and seismic structures. We made use of earthquake data, crustal thickness, heat flow and other available geophysical data. We conclude with a new model of the seismic source zones covering the territory of Slovakia and adjacent areas.

Seismotectonic framework

Most of the territory of Slovakia belongs to the Western Carpathians. The present day structure of the Western Carpathians contains a number of different allochthonous tectonic units (Biely et al. 1995), displaced during the Alpine orogeny (Fig. 1).

Two decisive phases of the tectonic evolution connected with subduction and collision can be recognized. The Palaeoalpine phase is characterized by subduction, collision and stacking of the groups of nappes in the internal parts of the Western Carpathian arc (Internal Western Carpathians — IWC) accompanied by spreading of oceanic realms in the external parts (External Western Carpathians — EWC) during the Cretaceous. The IWC include three groups of nappes (Hók et al. 2014). The Upper group of nappes, represented by the Gemericum, Meliaticum, Turnaicum and Silicicum tectonic units, was tectonically separated during the Early Cretaceous (ca. 150 Ma). The Middle group of nappes comprises tectonic units of the Veporicum, Fatricum and Hronicum. This group of nappes was structuralized during the lowermost Late Cretaceous (Cenomanian–Turonian i.e. ca. 100 Ma). The Lower group of nappes contains the Vahicum/Penninicum (Plašienka 1995; Schmid et al. 2004, 2008) and Tatricum tectonic units formed during the Latest Cretaceous–Early Palaeogene (ca. 60 Ma).

The Neoalpine phase is characterized by oblique diachronous subduction of the EWC basement along the periphery of the IWC (Kováč 2000). In the collision zone, the Flysch Belt rootless nappes were thrusted onto the European platform margin. The extension connected with the Neogene back-arc type volcanism and the Neogene basins opening and infilling operated during this phase in the IWC. The Neogene intramontane basins and the horst structures of the core mountains are the most expressive morphotectonic phenomena of the IWC. Oblique collision of the IWC with the European platform supported by the roll back effect caused a large counter clockwise rotation of the IWC during the Neogene (e.g., Márton & Fodor 2003). Simultaneously the lateral extrusion of the Carpathians from the Eastern Alpine area (Ratschbacher et al. 1991) and the escape of the Transdanubic and Bükkic terranes from the Southern Alpine and Dinaride realms and their accretion to the IWC occurred. It is assumed that the enigmatic tectonic units covered by the Neogene sediments in south-eastern Slovakia were also shifted together with the Transdanubic and Bükkic terranes (Haas et al. 2001; Márton & Fodor 2003). Recently the EWC have been under compression (Fig. 2) oriented generally perpendicular to the Carpathian arc course (Marsch et al. 1990; Jarosiński 1997, 1998, 2005; Reinecker & Lenhardt 1999; Jarosiński et al. 2009; Olaiz et al. 2009; Ptáček et al. 2012), while the IWC are characterized by orogen-parallel extension (Pešková & Hók 2008; Vojtko et al. 2008; Olaiz et al. 2009; Hók et al. 2010; Králiková et al. 2010; Vojtko et al. 2011) although some parameters of the focal mechanisms showed contradictory orientation in the western part of Slovakia (Cipciar 2001; Fojtíková 2009; Fojtíková et al. 2010; Jechumtálová & Bulant 2014).

The thickness of the lithosphere reaches 120~160 km in the Western Carpathians, 160~240 km and 160~220 km in the Eastern Alps. The lithosphere thickening is generally accompanied by increasing of the crust thicknesses. The lithosphere thickness in the European platform area is 100~140 km (Zeyen et al. 2002; Dérerová et al. 2006; Grinč et al. 2013; Bielik et al. 2014).

The Earth crust thickness and the Moho-discontinuity morphology were studied especially by deep seismic sounding (Mayerová et al. 1985; Šefara et al. 1996). The more precise results were acquired within the CELEBRATION 2000, ALP 2002 and SUDETES 2003 projects (e.g., Brückl et al. 2003; Grad et al. 2008; Janik et al. 2009; Hrubcová et al. 2010; Janik et al. 2011). The European platform, mainly the

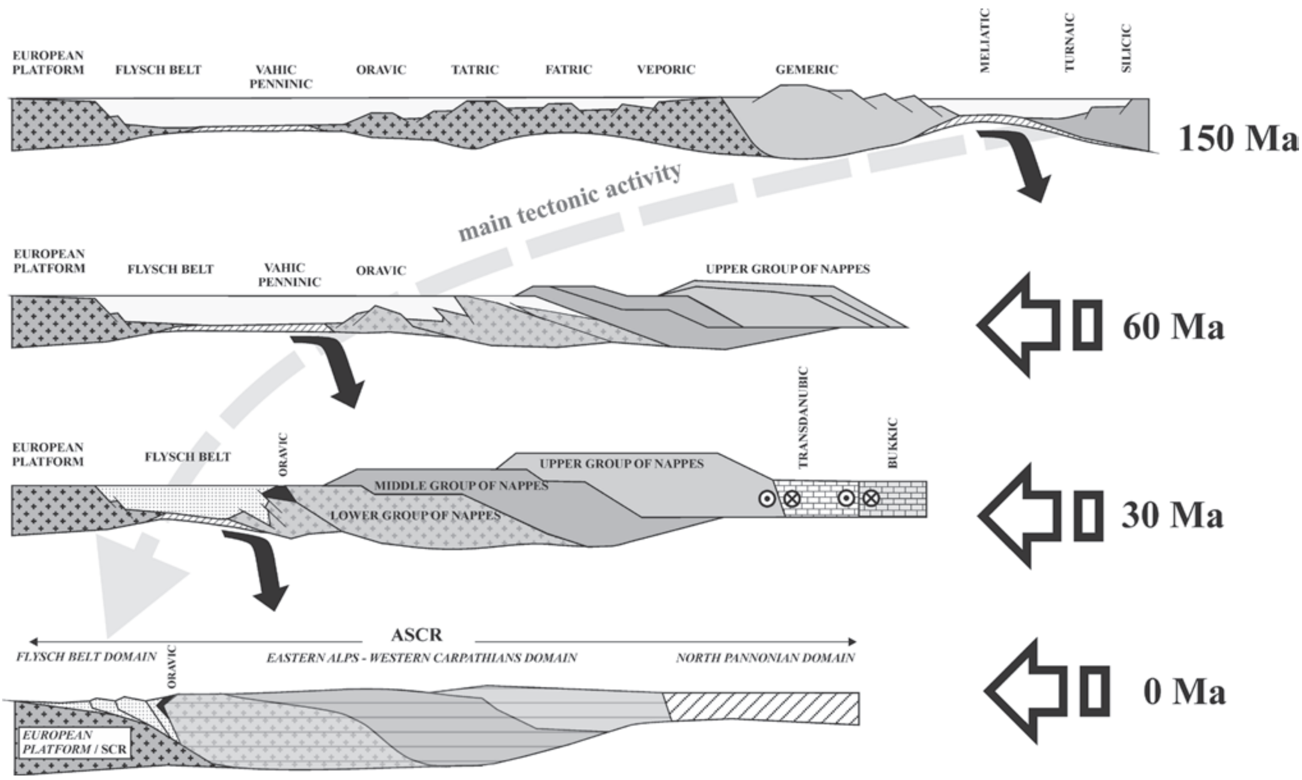

Fig. 1. Simplified tectonic evolution of the Western Carpathians during the last 150 Ma.

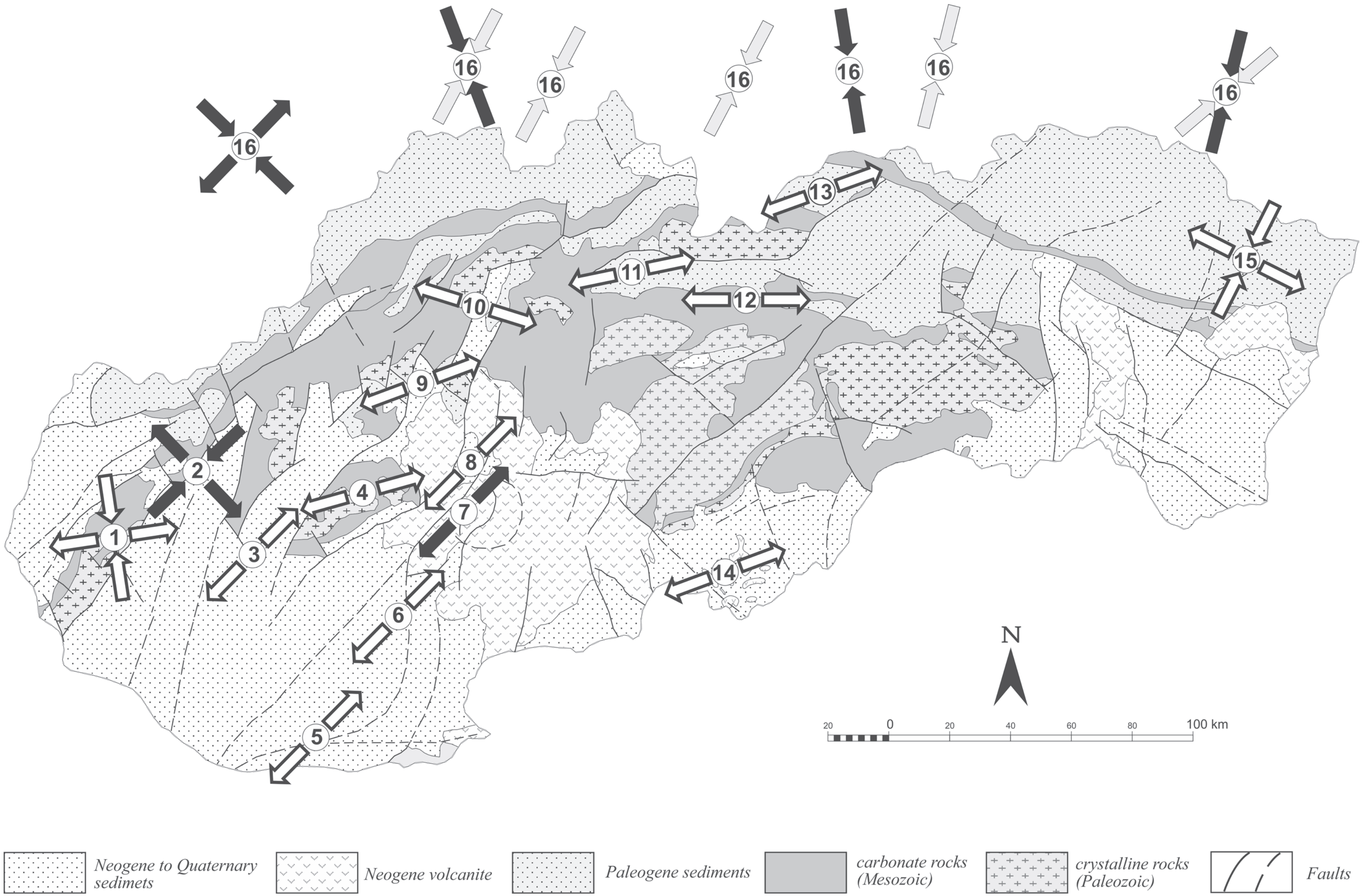

Fig. 2. Simplified geological map of Slovakia with orientation of principal compression and extension during ?Late Pleistocene–Holocene obtained from structural measurements and their interpretations. Black arrows indicate data from interpretation of the focal mechanisms (2) and extensometer (7). Arrows in External Western Carpathians (16) indicate SH_{max} mean direction of the autochthonous basement (black arrows) and the Carpathian nappes (grey arrows). Reference: **1** — Briestenský et al. 2011; **2** — Fojtíková et al. 2010; Jechumtálová & Bulant 2014; **3** — Vojtko et al. 2008; **4** — Hók et al. 2007; **5** — Čepek 1938; **6** — Králiková et al. 2010; **7** — Mentes 2008; **8** — Pulišová 2013; **9** — Vojtko et al. 2011; **10** — Vojtko et al. 2010a; **11** — Pešková & Hók 2008; **12** — Litva et al. 2015; **13** — Vojtko et al. 2010b; **14** — Hók et al. 2011; **15** — Vojtko et al. 2012 **16** — Jarosiński 1998, 2005.

Bohemian Massif is characterized by crust thicknesses of around 34 km. The crust thickness in the Eastern Alps ranges in the interval of 38~44 km, and around 40 km over most of the territory. It is the eastern continuation of the significant Alpine Moho-depression, which reaches even 50 km depths in its central part. The morphology of the Moho varies from 44 km depth in the north of the Western Carpathians area to 26~28 km at the southern contact with the Pannonian basin system. The most distinctive inhomogeneity is a local depression of the Moho course, and significant crust thickening in the northeastern portion of the Slovakia territory. The depression is oriented in a NE–SW direction and runs oblique to the contact of the EWC and IWC (Fig. 3). Its location does not correlate with the most exposed surface topography. The minimum crust thickness of around 30~26 km is found in the Pannonian backarc area. The minimal crust thicknesses follow the deepest Neogene depocentres of the Pannonian Basin system.

Geothermal conditions point to significant differences between the geothermal activity in the Alpine–Carpathian system, Pannonian Basin and European platform (Fig. 4). The temperatures 250 °C and 550 °C were used as decisive in terms of the brittle ductile transitions for limestone (250 °C), granite or feldspar and quartz-rich rocks (550 °C). The temperatures of 350 °C for the quartz-rich (granitic) upper crustal rocks and 450 °C for the quartz-poor (dioritic) rocks were given by Burkhard & Grünthal (2009).

The mechanical strength of the lithosphere is extremely low in the marginal parts of the Dinarides, Eastern Alps, Western Carpathians and adjacent Pannonian Basin area, therefore it is susceptible to deformations, structural reactivation and stress concentration (Bus et al. 2009). The prevailing deformation style from compression through transpression up to transtension (Bada et al. 2001; Olaiz et al. 2009) gradually changes generally from south to north — from the compression zone in the Dinarides towards the Pannonian Basin. The earthquake hypocentres in the wider territory of Slovakia are located in the upper 20 km of the Earth crust. The hypocentral depths between 6~15 km are stated for the marginal parts of the Eastern Alps–Western Carpathians and Pannonian Basin (Tóth et al. 2014). These data correspond to the rheological model of the Pannonian Basin (Lenkey et al. 2002), where only the upper part of the crust (10–14 km thick) can be considered brittle. The lower level of seismicity of the northern and eastern part of the Pannonian Basin confirms that most of the energy coming from the movement of the Adria plate is absorbed by the Dinarides and southwestern part of the Pannonian Basin.

A homogenous earthquake catalogue

A new Slovak earthquake catalogue (SLOVEC 2011) has been developed for the purpose of creating a seismotectonic

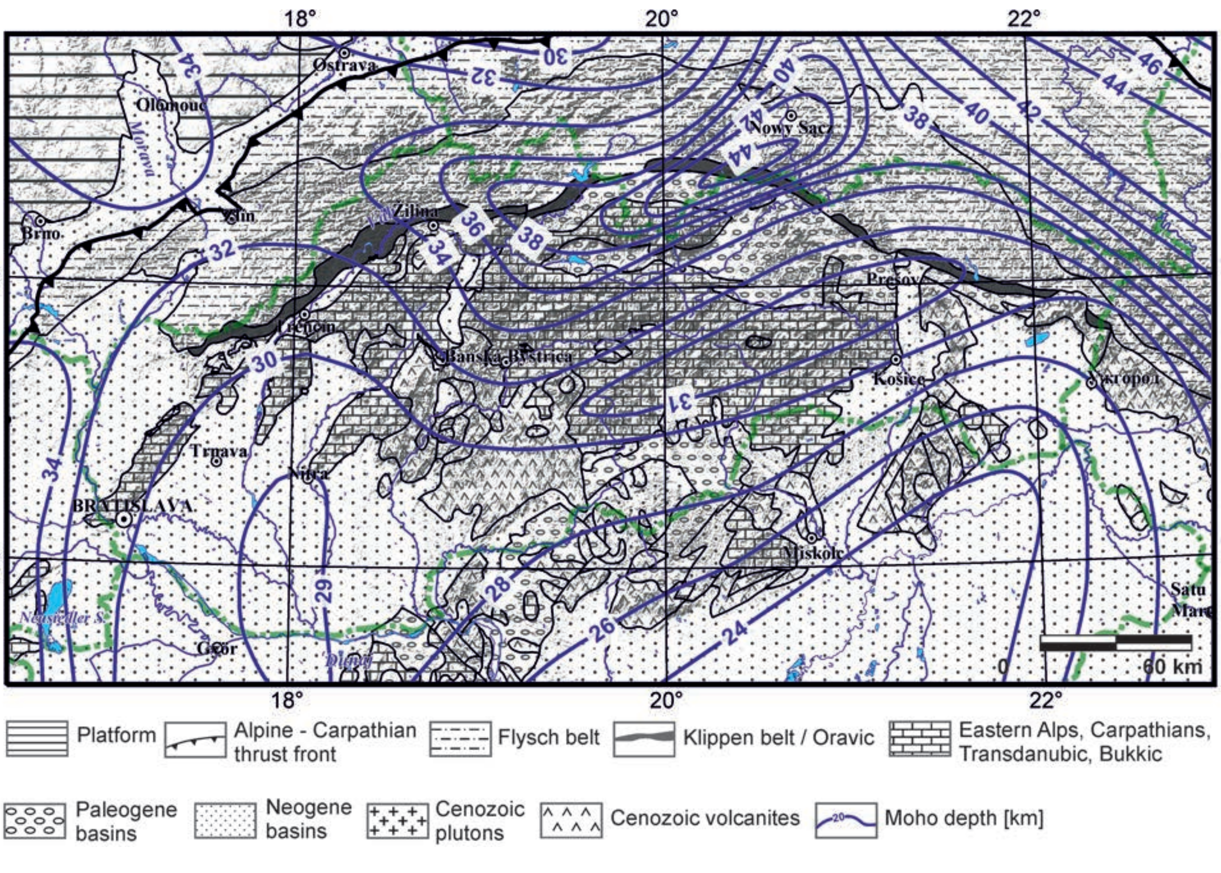

Fig. 3. Map of the Earth's crust/mantle boundary (lower lithosphere) in the wider area of Slovakia (modified after Horváth 1993; Lenkey 1999; Grad et al. 2009; Csicsay 2010; Hrubcová & Środa 2015).

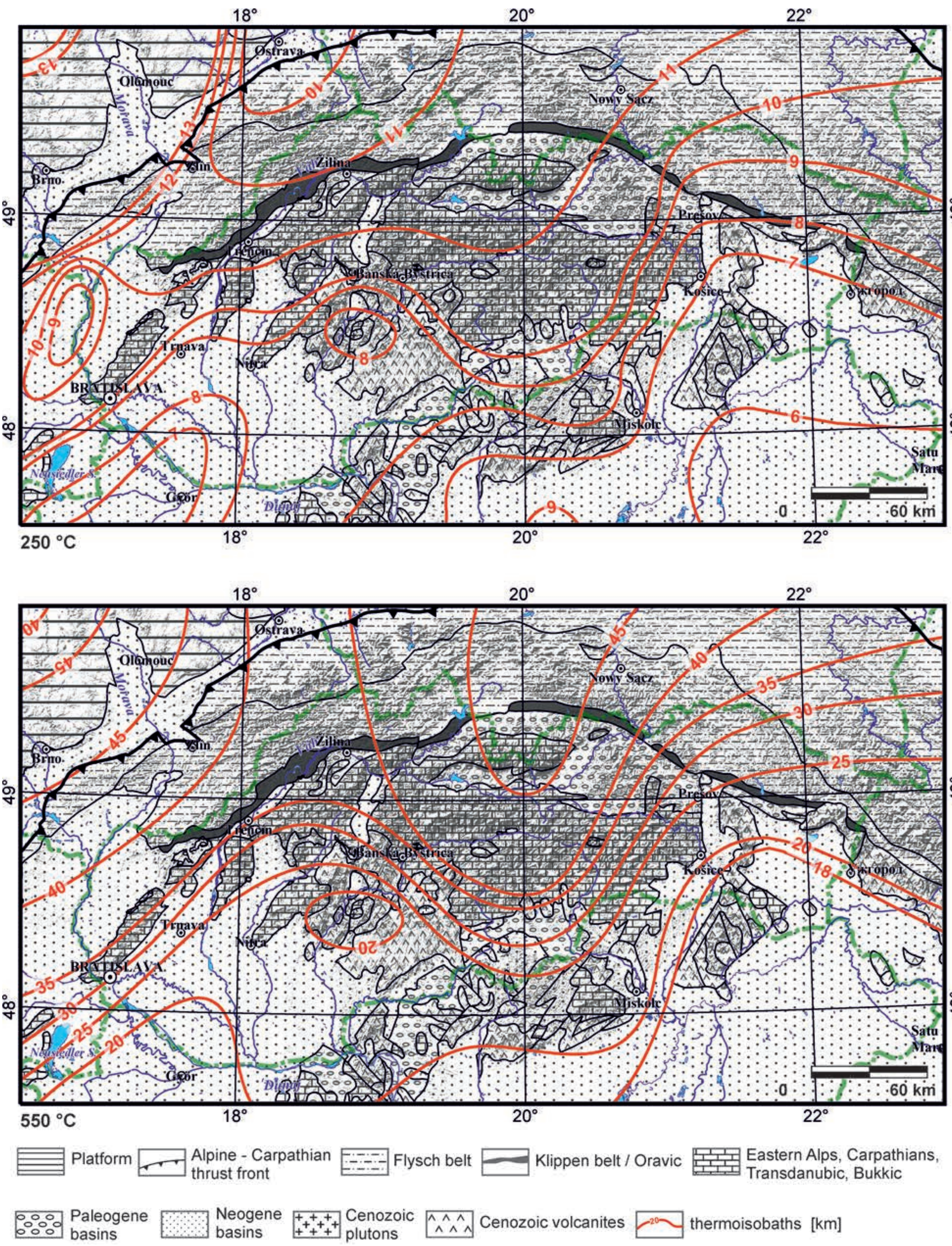

Fig. 4. Maps of the characteristic depths of 250 °C and 550 °C isotherms (original data).

model of the Slovak territory. The catalogue geographically covers the whole territory of Slovakia and the adjacent area. For the compilation of the catalogue, the following earthquake catalogues and databases were used:

(1) previous version of the Slovak national earthquake catalogue (Labák 1998)

(2) CENEC catalogue (Grünthal et al. 2009)

(3) the earthquake catalogue of the local networks of seismic stations situated around NPP Jaslovské Bohunice and NPP Mochovce (Progseis 2010)

(4) the earthquake databases of the Geophysical Institute, Slovak Academy of Sciences.

The earthquake catalogue by Labák (1998) comprises data on historical earthquakes, instrumentally recorded earthquakes and macroseismic observations of earthquakes on the territory of Slovakia and neighbouring parts of Hungary, Austria, the Czech Republic and Poland for the period 1259 to 1997.

The CENEC catalogue (Grünthal et al. 2009) is the unified catalogue of earthquakes in the central, northern and northwestern parts of Europe for the period 1000 to 2004 and magnitudes $M_W \geq 3.50$. The catalogue was compiled from more than 30 national and regional earthquake catalogues, ISC (International Seismological Centre) and NEIC (National Information Earthquake Center) bulletins, and many special studies.

The earthquake catalogue by Progseis (2010) is based on monitoring of microseismic activity in the vicinity of the NPP Jaslovské Bohunice and Mochovce by the local network of seismic stations from 1987 to 2009.

Two earthquake databases of the Geophysical Institute, Slovak Academy of Sciences, provide earthquake solutions from the Slovak National Network of Seismic Stations and macroseismic data for the territory of Slovakia based on evaluation of the macroseismic questionnaires. Both databases cover the period from 1998 to 2009.

The standard procedure was applied for compiling the SLOVEC (2011) catalogue. In the first step, all earthquake catalogues and databases were merged. Subsequently, primary entries were selected and duplicate entries were removed. For earthquakes with epicentres located inside the local seismic networks of Nuclear Power Plant (NPP) Jaslovské Bohunice and NPP Mochovce we considered data on time, location and earthquake size in terms of local magnitude or epicentral intensity from the Progseis catalogue as primary and data from the other sources as subsidiary.

The SLOVEC (2011) catalogue includes data on 1648 events in the period from 1259 to 2009 (882 earthquakes were instrumentally recorded, 609 earthquakes were macroseismically observed, for 104 earthquakes both macroseismic and instrumental data are available, and for 53 earthquakes there is no information on magnitude or epicentral intensity). For each earthquake, the uncertainty in the epicentral location was expertly estimated depending on the time of observation (e.g., uncertainty up to 50 km for historical earthquakes from the late medieval period).

The entire set of earthquakes in the catalogue had to be characterized by the moment magnitude M_W. For the territory of Slovakia, there are no earthquakes with both the moment magnitude M_W and local magnitude M_L determined. Similarly, there are no earthquakes with both the moment magnitude M_W and epicentral intensity I_0 determined. Instead of an attempt to find conversion relation between the moment magnitude and local magnitude or between the moment magnitude and epicentral intensity, we identified 48 earthquakes in the SLOVEC (2011) catalogue for which both the local magnitude M_L and epicentral intensity I_0 were available. Using the least-square method we derived the following conversion relation between the epicentral intensity I_0, local magnitude M_L and hypocentral depth h:

$$I_0 = 1.545(\pm 0.125)M_L - 0.338(\pm 0.304)\log h + 0.206(\pm 0.472)$$

The relation is valid for M_L in the range 2.0~4.7.

We converted the epicentral intensity I_0 to the magnitude using the Kárník et al. (1957) formulas:

$$M_{Io} = 0.55 I_0 + 0.95 \text{ and } M_{Io} = 0.55 I_0 + 0.93 \log h + 0.14$$

where M_{Io} is the so called macroseismic intensity magnitude.

Following Kárník (1968), it was assumed that the surface wave magnitude M_S is equivalent to the intensity magnitude M_{Io}. According to Grünthal & Wahlström (2003) M_S is equivalent to the moment magnitude M_W. Consequently, the homogenization procedure applied to the SLOVEC (2011) catalogue can be characterized by the following scheme:

$$M_{Io} \rightarrow I_0 \rightarrow M_L \approx M_S \approx M_W$$

The map of epicentres from the unified and homogenized SLOVEC (2011) catalogue is shown in Figure 5. The Time-Magnitude distribution for the catalogue is shown in Figure 6. A remarkable increase in the number of documented earthquakes for magnitudes smaller than $M_W = 1.5$ after the year 2004 is due to the modernization of the Slovak national network of seismic stations which was finished that year. For declustering (i.e., identifying of foreshocks, mainshocks and aftershocks in the catalogue) we used the window method. The parameters of the time and distance windows were taken from the PEGASOS project (Burkhard & Grünthal 2009). Earthquakes in the catalogue were regrouped according to their moment magnitudes. In the case that some earthquake occurred within the time and distance windows of an earthquake with larger moment magnitude, the earthquake was marked as a foreshock or aftershock depending on the time of the two events. Using this approach, 993 earthquakes were classified as mainshocks, 149 earthquakes as foreshocks and 506 earthquakes as aftershocks.

The time-completeness analysis of the SLOVEC (2011) catalogue was investigated based on the plots displaying the cumulative number of events versus time, for a given magnitude interval (Fig. 7). The most recent linear segment, indicating a stable seismic rate with time, provides the lower bound of the completeness time interval. The results of the time-completeness analysis of the SLOVEC (2011) catalogue are shown in Table 1.

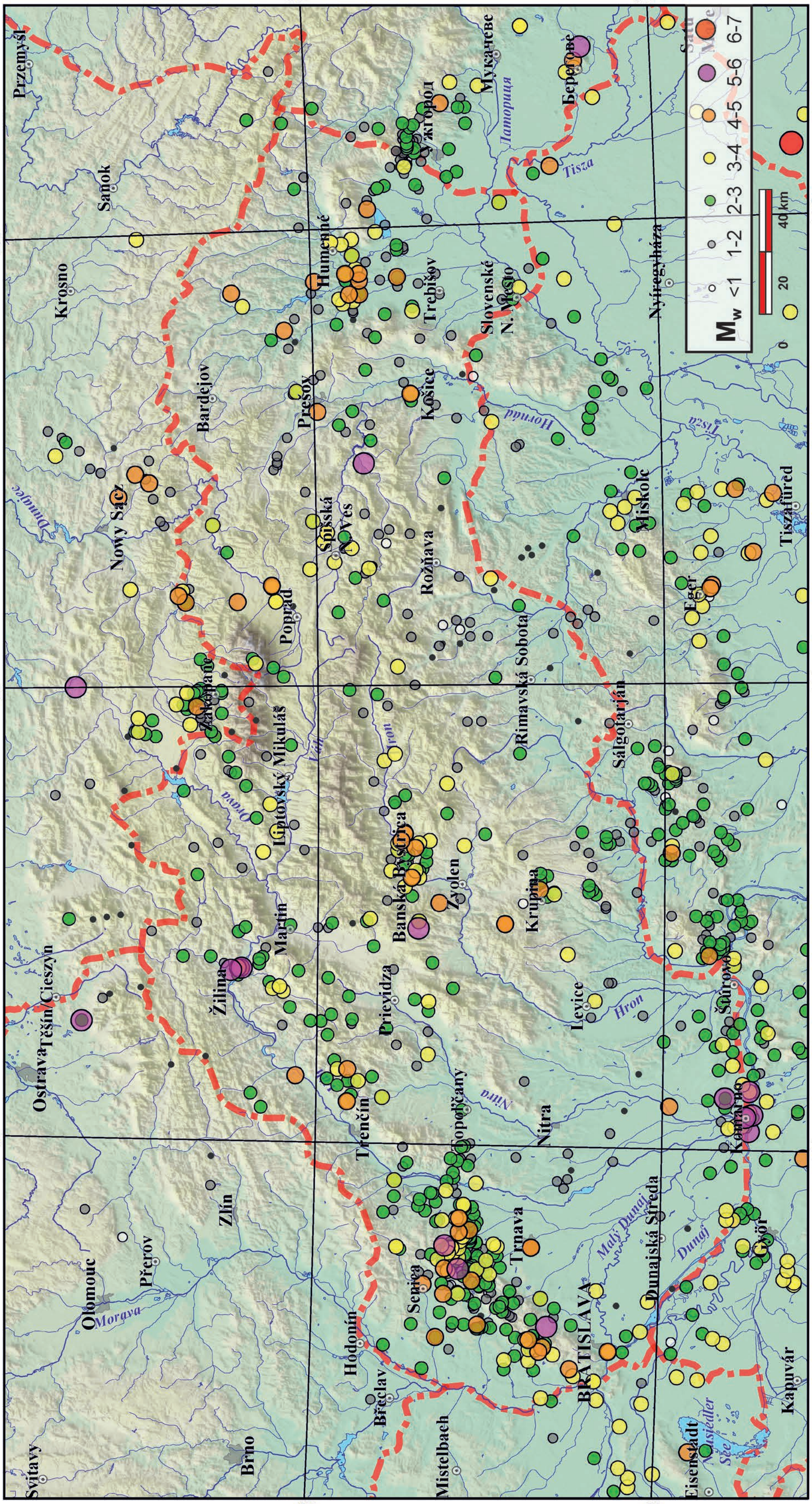

Fig. 5. Map of earthquake epicentres according to the unified and homogenized SLOVEC (2011) catalogue.

Principles of compilation of the seismotectonic model

The construction of the seismotectonic model was based on hierarchical regionalization of geological structures with earthquake occurrence into the tectonic regions, seismogeological domains, seismogenic structure and seismic source zones in the territory of Slovakia and adjacent areas.

The evaluated area has been divided into the stable continental region and the active shallow crustal region (*sensu* Delavaud et al. 2012). The stable continental region (SCR) represents the Caledonian and Hercynian consolidated European platform. The active shallow crustal region (ASCR) region includes the Alpine-Carpathian orogenic system and the pre-Cenozoic basement of the Pannonian Basin system. The SCR and ASCR are separated by a tectonic boundary of the first order, namely the contact of the European platform with the Alpine–Carpathian orogeny.

A **seismogeologic domain** ("the large scale zones") is a spatially defined segment of the Earth's crust with quasi-homogeneous geodynamic characteristics. The uniform age of the last extensive consolidation of the geological and tectonic structure is the main criterion for its allocation. Besides this, there are domains defined by the thickness of lithosphere, thickness of crust and thermal conditions at different depths, neotectonic deformation and seismicity (data from catalogue). Selected seismogeological domains are integral elements of the ASCR (Fig. 8).

(1) The **Flysch Belt Domain** represents the accretionary prism of the Neoalpine nappes of the Alpine–Carpathian orogeny (ASCR) thrusted over the European platform (SCR). The domain forms the northern margin of Slovakia (Figs. 1, 8).

Its basic geophysical characteristics are similar to those of the SCR. The lithosphere thickness is 100~140 km; the crust thickness 30~40 km; thermal conditions at the depth levels of 50 km 600~700 °C, 20 km 350~400 °C, 10 km 200~250 °C and at the depth of 5 km 100~140 °C. Normal faults oriented in the longitudinal and transverse direction with respect to the orogene arc predominate. The last thrusting of the nappes took place in the Middle Miocene, namely 17–11 Ma (Jiříček 1979). This domain has the lowest seismic activity in the territory of Slovakia.

(2) The **Eastern Alps and Western Carpathian Domain** is formed by the tectonic units of the Northern Calcareous Alps, Central Alps and IWC. The rock complexes of the crystalline and sedimentary rocks participate in the Palaeoalpine nappe structures. The Neogene sediments and volcano-sedimentary formations, together with the Palaeogene and partially with the Late Cretaceous sediments represent the post-nappe cover in the IWC. The essential geophysical characteristics of this domain are the lithosphere thickness 200~140 km; the crust thickness 30~44 km; thermal conditions at the depth levels of 50 km 600~1000 °C, 20 km 350~400 °C, 10 km 220~250 °C and at the depth of 5 km 120~160 °C. The normal and strike-slip faults are the

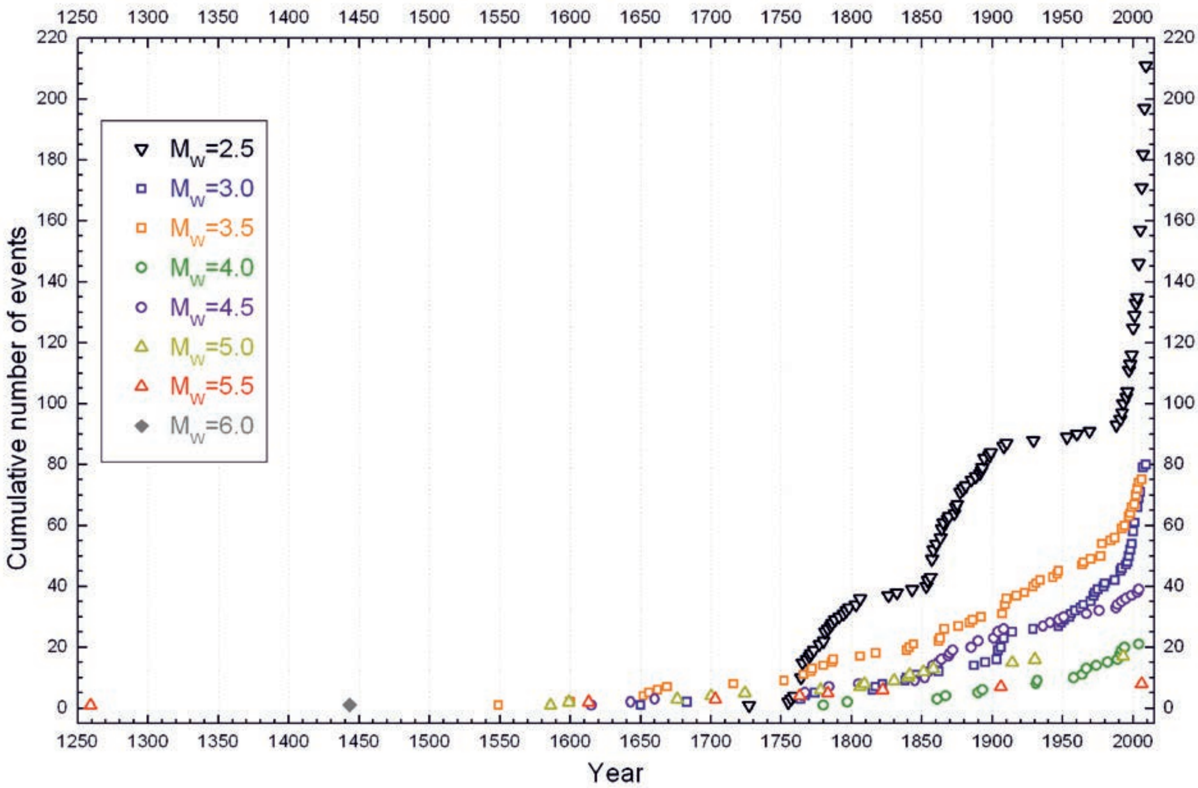

Fig. 6. The cumulative number of events versus time for different magnitude intervals, based on the declustered SLOVEC (2011) catalogue. The increment between the magnitude classes is M_W=0.5.

prevalent phenomena in the tectonic deformation. Termination of the last decisive tectonic events took place in the Early and Middle Miocene, namely 21–9 Ma. This is the most important domain in terms of determining the seismic hazard for Slovakia.

(3) The **Northern Pannonian Domain** is constituted by the Transdanubicum and Bükkicum, namely the Palaeoalpine consolidated lithosphere with affinity to the Southern Alps and Dinarides. The rock complexes of the crystalline and sedimentary, principally Mesozoic carbonate sequences participate in the domain's nappe structure. The lithosphere thickness in the North Pannonian Domain is 100~80 km; the crust thickness is 24~30 km; thermal conditions at the depth levels of 50 km 1000~1100 °C, 20 km 400~500 °C, 10 km ca 300 °C and at the depth of 5 km 160~200 °C. The domain is disturbed mainly by normal faults and strike slip faults. Termination of the last significant tectonic movements took place before 15~13 Ma.

Termination of the last extensive tectonic movements in the form of large listric fault activity in the Danube Basin's deep basement occurred during the Upper Miocene, before ca. 9 Ma.

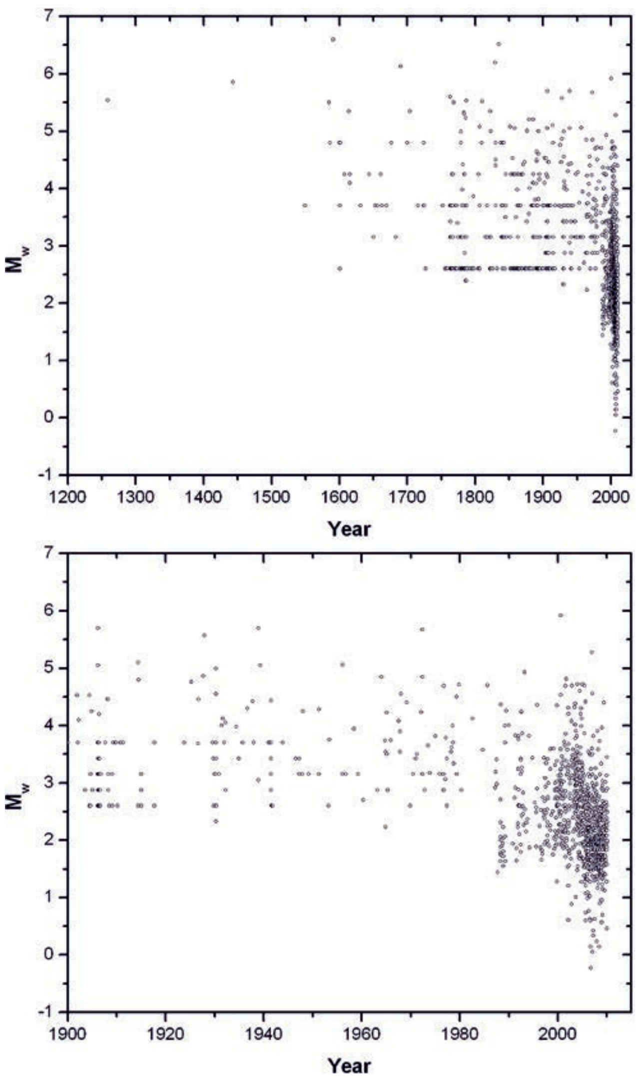

Fig. 7. Time–Magnitude distribution for the unified and homogenized SLOVEC (2011) catalogue.

The domain area extends into Slovak territory at its southern periphery. It is defined by the course of the Rába and the Hurbanovo–Diósjenő lineament (HDL). The most marked seismic activity is connected with the zone along the northern margin of the Transdanubicum and Bükk (Haas et al. 2001; Haas & Budai 2014), south of the (HDL). The domain is important especially in terms of increased seismic activity in the Komárno area.

Seismogenic structures represent faults, fault systems or fault zones associated with the occurrence of earthquakes. The following seismogenic structures are principal for the seismotectonic model in the wider surroundings of Slovakia.

(1) **Mur–Mürz & Vienna Basin Transfer Fault**. The Mur–Mürz fault system disturb the Northern Calcareous Alps in SW–NE direction up to the Vienna Basin area, where it continues by the Vienna Basin Transfer Fault (VBTF) or Vienna Basin fault (VBF) according to Hinsch & Decker (2003) or Beindinger & Decker (2011). The termination of the VBTF is identified gravimetrically as well as in deep seismic profiles at the northwestern margin of the Malé Karpaty Mts., horst (Bielik et al. 2002; Kováč et al. 2002).

(2) **Hurbanovo–Diósjenő Lineament (HDL).** The HDL is considered to be a projection of the flat-lying boundary of the North Pannonian Domain and Eastern Alpine–Western Carpathian Domain or Transdanubicum/Pelso and IWC (Nemesi et al. 1997; Kovács et al., 2000; Kováč et al. 2002). The tectonic boundary is also referred to as the Rába–Hurbanovo–Diósjenő lineament (Balla 1994; Kovács et al. 2000). The HDL is a structure, which limits occurrences of earthquakes towards the north.

A seismic source zone is a defined distinct part of the seismogeological domain with characteristic arrangement of geological structures, tectonic regime and with typical features in its seismic activity. The seismic source zones covering the territory of Slovakia were defined according to the proposed seismotectonic model, while the existing zones resulting from the SESAME project (Jiménez et al. 2003) were accepted with certain modifications for the delimitation of the zones near the border area. The seismic source zones are in principle defined into four groups (see Fig. 9). Zones of the Eastern Alps and Western Carpathian Domain — the Western Carpathian sector — are the zones in the territory of

Table 1: The completeness time windows for the declustered SLOVEC (2011) catalogue.

magnitude interval	time period of completeness	number of events
2.25 – 2.75	1999	98
2.75 – 3.25	1996	33
3.25 – 3.75	1992	19
3.75 – 4.25	1958	12
4.25 – 4.75	1901	17
4.75 – 5.25	1806	11
5.25 – 5.75	1613	7
5.75 – 6.25	1443	1
≥ 2.25		198

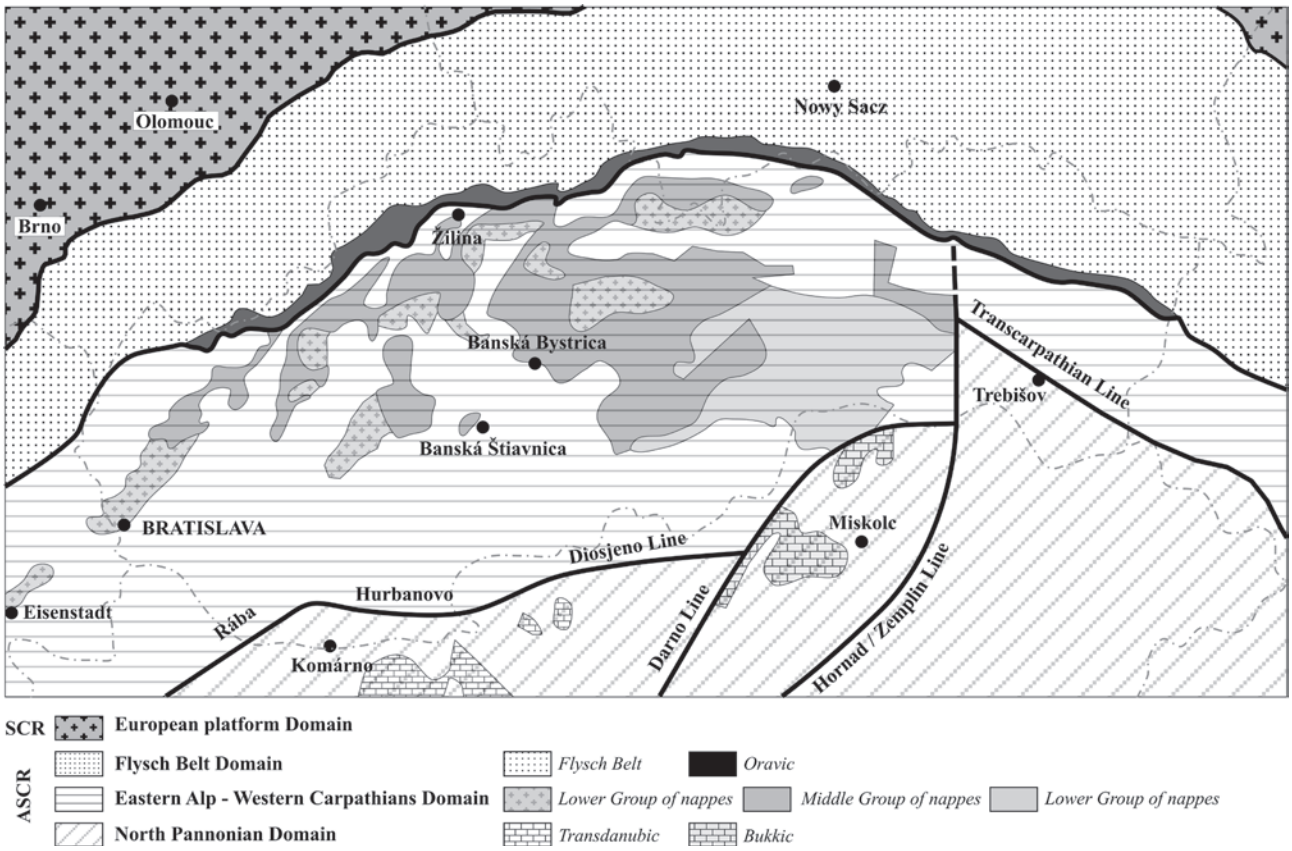

Fig. 8. The Stable Continental Region (SCR), the Active Shallow Crustal Region (ASCR) and Seismogeological Domains (simplified geological background compiled after Hók et al. 2014; Haas & Budai 2014).

Slovakia partially covering eastern Austria and northern Hungary marked as SK1 to SK7. This part of the territory is entirely covered by the catalogue. Zones of the Eastern Alps and Western Carpathian Domain — the Eastern Alps sector marked as A1, A5 and A7, which cover the territory of eastern and south-eastern Austria. Zones corresponding to the North Pannonian Domain, marked as H1 to H8 covering the territory of Hungary. Zones corresponding to the Domain of the European platform (P1 to P3) mostly cover the adjacent territory of the Czech Republic and Poland.

Seismic activity in the defined zones was the subject of mutual comparison on the basis of the parameters derived from the SLOVEC (2011) catalogue and spatial identification of a specific zone. The amount of seismic wave energy per unit area has proved to be the most appropriate comparison parameter. The energy was determined on the basis of the moment magnitudes of earthquakes according to the relationship *sensu* Kanamori (1977). The areal distribution of the emitted energy in the wider territory of Slovakia is documented by a map, constructed by means of the energy summation in clusters of 5×5 km and transfer to $GJkm^{-2}$ (Fig. 10). The amount of seismic wave energy was further normalized to the time through the observation period in an individual zone (subzone) in $MJkm^{-2}$ per year, within the zone's evaluation. As there are considerably different observation periods in the individual parts of the studied territory, intervals resulting from a time-completeness analysis of the SLOVEC (2011) catalogue for individual magnitude classes were used as the time denominator.

Despite the given limitation, the amount of seismic wave energy can be an appropriate parameter in the first approximation, when assessing differences in the seismic activity of defined zones. The density of documented events per unit area was used as a further auxiliary criterion. Descriptive statistics based on the catalogue data, namely moment magnitudes, the earthquakes' hypocentral depths and their distribution in classes, were further used to describe the zones.

Seismic source zones in the territory of Slovakia

SK1 zone (Dobrá Voda): SK1 zone together with the H2 (Komárno) zone is the most significant zone in terms of seismic hazard of Slovakia, with the highest level of seismic activity. Totally 271 earthquakes with M_W from 2.0 up to 5.7 are documented. The hypocentral depths vary in the range 4~18 km with the median value 11 km. The strongest documented event is the 1906 Dobrá Voda earthquake with M_W=5.7. The documented seismic activity is associated with the prevailing strike slip regime of faults (Fojtíková 2009; Fojtíková et al. 2010; Jechumtálová & Bulant 2014).

The thickness of the Earth's crust is 30 km and a gravity field with relatively distinct gradients coincides with margins of the horst structures of the core mountains. There is a conspicuous positive anomaly most probably reflecting the masses of carbonates (dolomite) of the Hronicum tectonic unit. The heat flow at depth 10 km is 220~250°C, at depth 20 km 380~450°C. The steep horizontal gradient of the Earth's crust temperatures can form thermoelastic stresses and contribute to the seismicity initialization. The Palaeoalpine units of the Tatricum, Fatricum, Hronicum, as well as

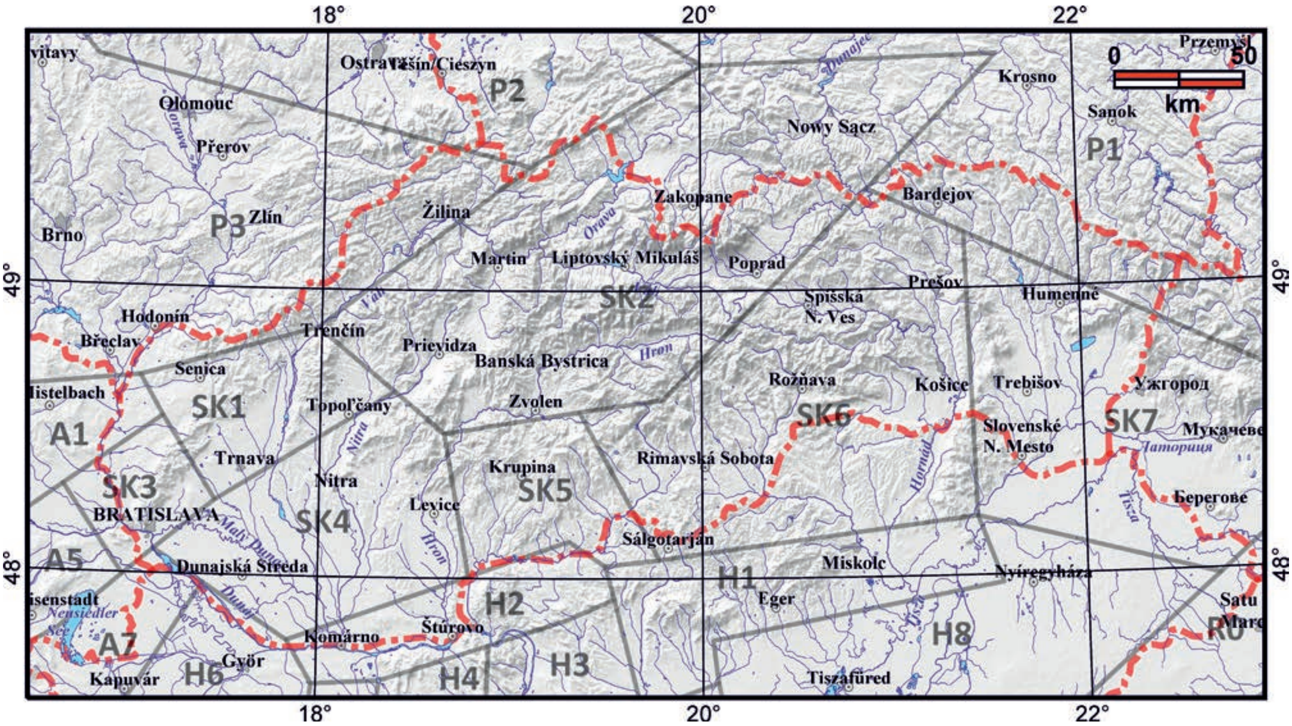

Fig. 9. Division of the territory of Slovakia into seismic source zones.

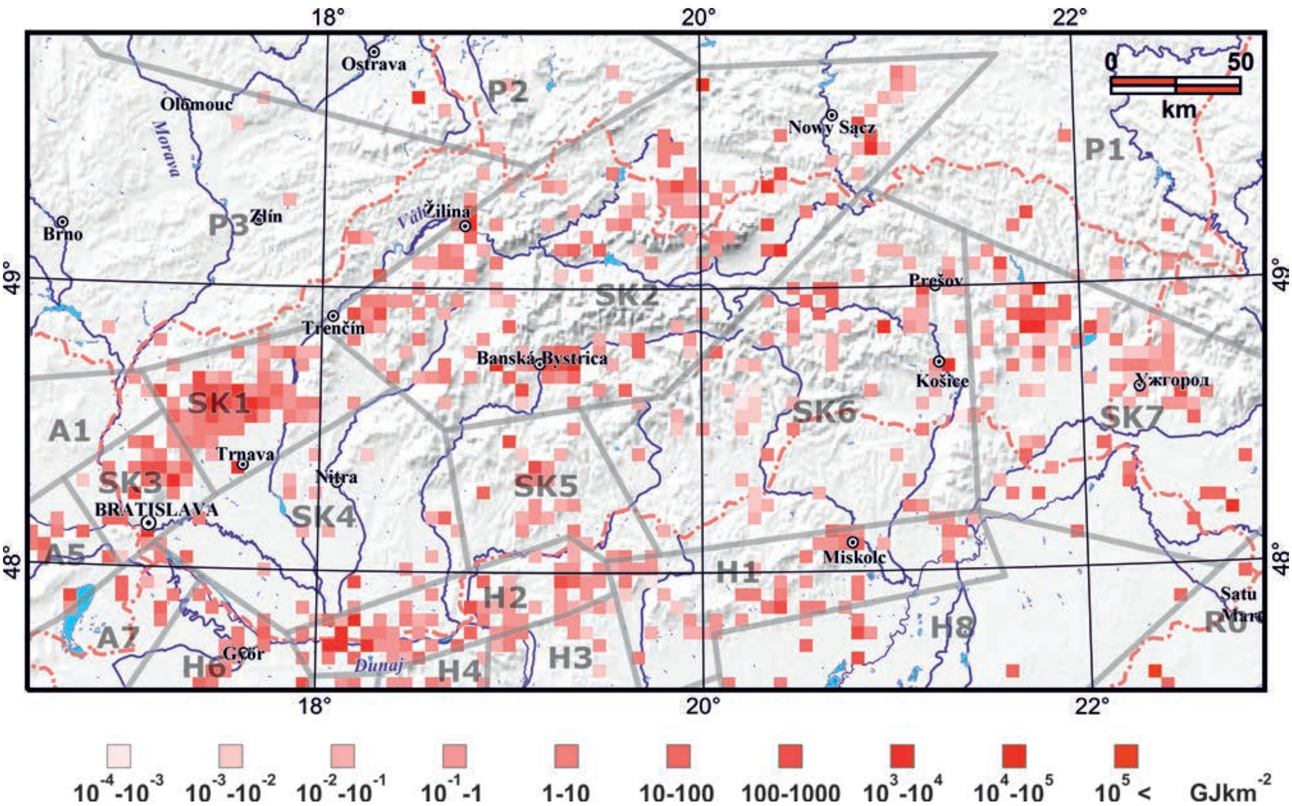

Fig. 10. Map of seismic wave energy according to the SLOVEC (2011) catalogue.

the Klippen Belt are present. The sediments of Late Cretaceous, Palaeogene and towards the Danube Basin also the Neogene sediments participate in its structure. The assumed contact of the IWC with the Bohemian Massif (SCR) is a specific feature in the deep structure of the zone.

SK2 zone (Northern Slovakia): The SK2 zone is formed by the Neoalpine consolidated block, extending to both the IWC and EWC. The Palaeoalpine as well as Neoalpine tectonic units participate in its geological structure. The Neogene sediments occur less frequently in the zone's territory. The zone is characterized by the most distinct morphological differentiation. The thermochronological data (ZFT and AFT data) and derived ages of the crystalline exhumation yielded a range from 9 to 13 Ma (e.g. Králiková et al. 2014a,b).

Seismicity in the Neoalpine consolidated parts of the EWC is low. A total of 196 events with the moment magnitude of $M_W \geq 2.0$ are documented within the zone. The biggest group of documented events reaches small depths of hypocentres up to 5 km, the second largest group of earthquakes reaches the depth 10~15 km, with the median depth of 12 km. Two historical earthquakes in 1613 and 1858 with the magnitudes 5.6 and 5.2, respectively, are the most important events located in the vicinity of Žilina town as well as the 1443 Central Slovakia earthquake with the magnitude 5.7 located in Kremnica town. A moderate increase of the seismic activity is documented in the southern part (the Banská Bystrica area).

The Carpathian gravity low and gravity depressions of the IWC and EWC dominate in the gravity field image, while the field is balanced, without anomalous elements. The territory is characterized by the considerable thickness of the Earth's crust, which increases from 30 km in the southern part to over 40 km in the northeast of the zone. The temperatures reach at the depth 10 km 200~250 °C, at the depth 20 km up to 400 °C. The Banská Štiavnica volcanic field in the southern part of the zone is manifested as a positive geothermal anomaly.

SK3 zone (Malé Karpaty): The SK3 zone covers the southwestern part of the Malé Karpaty Mts., and marginal parts of the Vienna and Danube Basin. 61 events with the moment magnitude $M_W \geq 2.0$ and the strongest earthquake with the value of $M_W = 5.1$ are documented. The distribution of the hypocentral depths is similar to the SK1 zone with the median 12 km.

The thickness of the Earth's crust and geothermal conditions are similarly to those in the SK1 zone, including a considerable horizontal temperature gradient. The gravity field is differentiated, however with less distinct gradients, which define the body of the core mountains. The units of the Tatricum, Fatricum, Hronicum and the Neogene basin infill participate in its structure from the tectonic point of view. A specific feature of the zone is the presence of the VBTF, which is terminated on the western margin of the Malé Karpaty Mts.

SK4 zone (Danube Basin): The seismic activity is very low and so it is comparable to the zones of the stable European platform. A total of 16 earthquakes with the moment magnitude $M_W \geq 2.0$ and highest value $M_W = 4.3$ are documented in this zone. The largest group of earthquakes reaches small depths of hypocentres up to 5 km, another group of earthquakes reaches the hypocentral depth 10~15 km, but the value of the median depth of events in the whole zone is only 2.5 km. The seismic activity in the SK4 zone can be expected especially at its southern border. The SK4 zone is characterized by thickness of the Earth's crust, which decreases below 28 km in the centre. The gravity field image is aligned with the prevailing lows, except the significantly limited positive anomaly of the Tribeč core mountains.

Geothermal temperatures reach at the depth 10 km 250~320 °C, at the depth 20 km 500~550 °C without significant horizontal gradients. The Palaeoalpine tectonic units are present in the deep geological structure. The considerable thicknesses of the Neogene sediments above 7 km in the central depression (Kilényi & Šefara 1989) are an important aspect.

The majority of investigated faults are sealed by the Pliocene sediments. Faultless stress release due to the thermal influence of asthenosphere upwelling is assumed in the Danube Basin area. Similar processes are also expected in the central parts of the Pannonian Basin (Bus et al. 2009).

SK5 zone (Southern Slovakia): The seismic activity is slightly below the average of the evaluated regions. The catalogue comprises a total of 37 earthquakes with the moment magnitude $M_W \geq 2.0$ and the highest value $M_W = 4.5$. The hypocentres are cumulating around 5 km depths and from the range of 10 to 15 km. The Palaeoalpine tectonic units participate in the geological structure. Most of the territory is covered by volcanic products of the Banská Štiavnica stratovolcano and Cenozoic sediments. The Earth's crust thickness is 28~30 km. The gravity field is differentiated, while the positive anomalies corresponding to the Southern Slovakian gravity elevation predominate. Geothermal temperatures reach at the depth 10 km 350 °C, at the depth 20 km around 500~600 °C. The geothermal anomaly related to the presence of the Banská Štiavnica stratovolcano is manifested by significant horizontal gradients in the thermal field at the northwest part of the zone.

SK6 zone (Eastern Slovakia): The seismicity in the zone of the Palaeoalpine consolidated part of the IWC is lower than the average of the SK zones territory. The catalogue of earthquakes comprises 40 events with the moment magnitudes above 2.0 and the highest value of $M_W = 5.4$. The hypocentres of the largest group of earthquakes are situated at the depth up to 5 km. A smaller group reached the depth up to 20 km with the median value 6 km.

The Neogene sediment accumulations are insignificant. The Earth's crust thickness is 28~32 km and the linear elevation with the value 31 km in the SW–NE direction is indicated. The gravity field image reaches predominantly negative anomalies, belonging to the SE margin of the IWC gravity depression. The positive anomalies, belonging to the South Slovakia gravity elevation are more frequent in the direction of the Pannonian Basin. Temperatures reach at the depth 10 km from 250 °C in the northwest up to 350 °C in the southeast and at the depth 20 km 400~600 °C.

SK7 zone (Eastern Slovakia/Trebišov Basin): The zone covers predominantly the Trebišov Basin with its continuation into the Transcarpathian depression. The seismic activity is medium and slightly below average. A total of 104 earthquakes with $M_W≥2.0$ and maximum value of $M_W=5.3$ are documented in the catalogue. The earthquake hypocentres are cumulated around the depths 5 km, the depths of the smaller number of events are localized from 10 to 20 km. A significant subzone with increased seismic activity occurs in the NE of the zone with a continuation to the southeast outside Slovak territory.

The deep structure comprises tectonic units of uncertain tectonic affiliation (Iňačovce and Kričevo units, Zemplinicum). Palaeoalpine tectonic units are present along the northern margin. The basin infill comprises Neogene volcanite bodies as well as Neogene sediments. The positive gravity anomalies are located on the northern and southern boundaries. Both anomalies continue in the southwestern direction into the Transcarpathian depression. The zone is characterized by increased geothermal activity. The temperatures at the depth 10 km are from 250 °C in the northwest up to 350 °C in the basin's centre and at the depth 20 km in the 500~650 °C interval.

Seismic source zones on the borders of Slovak territory (A, H and P zones).

The southern part of the territory of Slovakia is situated on the contact with the Pannonian Basin system, and with the Eastern Alps, where the A and H zones extend partly into Slovak territory. **A1, A5, A7 zones (Eastern Alps)**: The **A1 zone** covers the eastern salient of the Northern Calcareous Alps, molasse foredeep and a part of the Vienna Basin. Seismic activity within the zone is weak. The earthquake (Neulengbach 1590; ACORN (2004) catalogue, also referred as the Ried am Riederberg 1590 earthquake) with the M_W 6.0 represents a specific exception. The **A5 zone** is important in terms of seismogenic potential, even if it does not extend into the evaluated Slovak territory. The SLOVEC (2011) catalogue covers a part of the zone in the vicinity of the Vienna Basin and contains 36 earthquakes with the magnitudes from 2.0 to 4.8 with characteristic hypocentral depths around 8 to 12 km. The strongest earthquake was registered at Ebreichsdorf (2000) with the magnitude 4.8 and hypocentral depth around 10 km (Meurers et al. 2004). The Carnuntum earthquake (350 A.D., Kandler 1989; Decker et al. 2006) with estimated local intensity of 9° EMS-98 is critically discussed by Hammerl et al. (2014). The Carnuntum earthquake was not included in the SLOVEC (2011) catalogue. The south Bohemian basement spur as a major tectonic structure with a high rheological contrast to surrounding units has a strong influence on the stress field and exhibits the highest seismicity at its tip due to stress concentration in this area (Reinecker & Lenhardt 1999). The **A7 East Styrian zone** is characterized by low seismic activity.

The seismic source zones of the North Pannonian Domain (H6, H2) are localized on the southern margin of Slovakia. The **H6 zone** is situated on the boundary between the Eastern Alps and North Pannonian domains. The seismic activity concentrated in the zone coincides with the Rába line at its connection with the Hurbanovo part of the HDL. A total of 32 events with moment magnitudes above 2.0 and with the highest value of $M_W=4.7$ are documented. Hypocentral depths are distributed evenly up to 22 km. The **H2 zone** on the southern margin of southwest Slovakia is particularly important for the seismic hazard of Slovakia. The most significant seismic activity is bounded to the zone along the northern margin of the Transdanubicum, south from the HDL seismogenic structure. The zone comprises the Komárno area including the most important Komárno 1763 earthquake with the moment magnitude $M_W=5.6$ (depth of hypocentre 7 km). Seismic activity is comparable to the SK1 Dobrá Voda source zone. Within the zone 248 events are documented with moment magnitudes above 2.0. The hypocentral depths vary predominantly in the intervals around 5 to 10 km and 20 to 25 km. Observed macroseismic effects of significant historical earthquakes are with high probability affected by site effects because a large part of the zone's area is characterized by the presence of unconsolidated Quaternary (even Holocene) sediments.

P1, P2, P3 zones (Platform and Flysch Belt): The seismic activity in the P1 and P3 zones can be characterized as diffuse (Burkhard & Grünthal 2009) and only the P2 (Sudetes–Labe) zone is manifested as seismogenic (e.g., Špaček et al. 2006). The contribution of the European platform source zone to the seismic hazard of Slovakia is negligible.

Conclusions

The presented seismotectonic model of the Slovak territory and adjacent area includes the eastern parts of the Czech Republic, the northeastern parts of Austria, the northern parts of Hungary and the southern parts of Poland. The seismotectonic model is based on analysis of the geological, geophysical and seismological data and hierarchical regionalization of the investigated territory into the stable continental region and active shallow crustal region (Delavaud et al. 2012), seismogeological domains, seismogenic structures and seismic source zones.

The stable continental region (SCR) includes the European platform tectonically consolidated during the Hercynian orogeny. The active shallow crustal region (ASCR) includes the Alpine consolidated lithosphere of the pre-Cainozoic units of the Internal Western Carpathians and Eastern Alps, the basement of the Pannonian Basin System and the Neoalpine (during the Neogene) consolidated accretionary prism of the External Western Carpathians and Rhenodanubian Flysch Zone.

The uniform age of the last extensive consolidation of the geological and tectonic structures with the quasi-homogeneous geological and geodynamic characteristics was the main criterion for subdividing the seismogeological domains into the Flysch Belt Domain, Eastern Alps–Western Carpathians Domain and Northern Pannonian Domain.

The seismological domains were identified as spatially limited segments with defined thickness of lithosphere, thickness of crust, thermal conditions in various depths, neotectonic deformation and seismicity. The seismogenic structures are specific elements of seismogeological domains with spatially limited significant seismic activity. The identified seismogenic structures are the Mur–Mürz–Vienna Basin transfer fault and the Hurbanovo–Diósjenő Line.

The seismic source zones were defined as distinct parts of the seismogeological domain with characteristic arrangement of geological structures, tectonic regime and with typical features of the seismic activity. In defining the zones we took into account data from the SLOVEC (2011) catalogue for events with the moment magnitude $M_W \geq 2.0$.

Four groups of seismic source zones were identified:

(1) Zones corresponding to the SCR and Flysch Belt Domain which cover approximately the adjacent territory of the Czech Republic and Poland — P1, P2, P3 zones situated externally from the deep-seated contact of the Carpathian orogeny with the stable European platform.

(2) Zones of the Eastern Alps–Western Carpathians Domain — Western Carpathians sector — SK1 (Dobrá Voda), SK2 (Northern Slovakia), SK3 (Malé Karpaty), SK4 (Danube Basin), SK5 (Southern Slovakia), SK6 (Eastern Slovakia), SK7 (Trebišov Basin) situated in Slovakia and partially covering the eastern part of Austria and northern part of Hungary.

(3) Zones of the Eastern Alps–Western Carpathians Domain — the Eastern Alps sector, cover eastern and south-eastern Austria — A1, A5, A7.

(4) Zones corresponding to the North Pannonian Domain — H6 and H2 approximately covering the territory of northern Hungary.

The seismic source zone model formed the input for calculation of seismic hazard of the Slovak territory in terms of peak ground acceleration (PGA) for the return period of 475 years, that is, 10 % probability of being exceeded within 50 years, (Kysel 2014; Kysel et al. under preparation).

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