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SEISMOGENIC ZONES IN THE EASTERN ALPINE-WESTERN CARPATHIAN-PANNONIAN JUNCTION AREA

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Abstract: The newly-defined seismogenic zones in the Alpine-Carpathian-Pannonian (ALCAPA) junction area are correlated with: (1) Paleoalpine deep-seated suture zones, either oceanic or intracontinental, (2) Neoalpine wrench-fault zones following some sutures, and (3) original thrust planes reactivated as low-angle extensional normal faults. 1—The principal West-Carpathian Paleoalpine sutures, from north to south, are: the Penninic-Vahic oceanic suture originated during the Late Cretaceous, the Čertovica intracontinental suture between the Tatric and Veporic thick-skinned sheets locked some 90 Ma ago, and the Meliatic oceanic suture formed in the Late Jurassic, closely related to the Igal-Bükk Zone. These suture zones were partly reactivated during the Late Tertiary and represent weakened zones in the modern upper crust. The concentration of important earthquake epicenters correlates well with these weakened belts which serves as a base for the new seismogenic model of the area. 2—The most important wrench fault zone is situated between the Eastern Alps and Western Carpathians. It reflects the Miocene extrusion of the ALCAPA lithospheric fragment from the Alpine domain as its northwestern boundary. The NE–SW trending wrench fault zone is represented by the Mur-Mürz-Leitha and Považie fault systems. The zone is well expressed by flower structures in many seismic lines. 3—The Miocene back-arc extension driven by the subduction pull in front of the Carpathian orogen and mantle updoming in the Pannonian domain reactivated original Paleoalpine thrusts as crustal detachment planes. In the Danube Basin area, these are accompanied by numerous important faults visible in seismic sections, e.g. the Répce, Rába, Sládkovičovo and Mojmírovce fault systems. The extension regime consequences of the core-mountains uplift during isostatic inversion from the Pliocene are visible in seismic section 2T — along the Čertovica Zone as strong reflector branches. They represent former suture rejuvenated into younger low angle normal faults.

Key words: ALCAPA region, suture zones reactivation, rheology, earthquake distribution, seismogenic model.

Introduction

Seismogenic zones, i.e. zones with increased seismic risk in the Western Carpathians and surrounding areas were derived from geophysically interpreted deep fault zones in the past (Figs. 2 and 3). These were defined by Fusán et al. (1979, 1981, 1987) and Šefara et al. (1987), following the division of the Western Carpathians into neo-tectonic blocks (Fig. 1). This pioneer step in the definition of the neo-tectonic evolution of the Western Carpathians was based on the contemporary knowledge of deep-seated structures supported by refraction seismic lines (DSS) and gravimetry. Moreover, this concept was consistent with the geodetic data on recent vertical movements. It is necessary to emphasize that the above mentioned deep fault zones (Figs. 1, 2, 3) have been used to define the seismogenic zones by seismologists (e.g. Schenk et al. 1986; Šteinberg et al. 1988; Šimůnek et al. 1991) without (or only with partial) analysis of the seismic event generation (e.g. Pospíšil et al. 1985).

The geophysical and geological research in the last decade has brought more exact data which are not consistent with all the originally interpreted deep-seated zones, or they define more precisely their character at depth. The most important of these new data include reflection seismic lines (CDP — Tomek et al. 1989; Tomek & Hall 1993 etc.), magnetotelluric sounding (MTS — e.g. Varga & Lada 1988) and some other results of complex geophysical and geological interpretation (e.g. Šefara et al. 1996). These new results serve as a basis for the new model of seismogenic zones in the Alpine-Carpathian-Pannonian (ALCAPA) junction area presented in this paper.

The previous model of the neo-tectonic block structure of the Western Carpathians and its relationship to deep-seated faults

The principal neo-tectonic blocks of the Central and Inner Western Carpathians, as defined by Fusán et al. (1981), are the Outer Carpathian blocks, the Danube block, the Fatra-Tatra block, the Rudohorie-Pilis block and the Potisie block (Fig. 1). Except for the Potisie block, all the mentioned blocks are represented in the area considered in the present paper.

The principal **Outer Carpathians blocks** (Fig. 1) consist of two parts. The lower part is formed by platform elements partly underthrusting the Central Carpathians; the upper part consists mainly of the flysch nappes of the Outer Car-

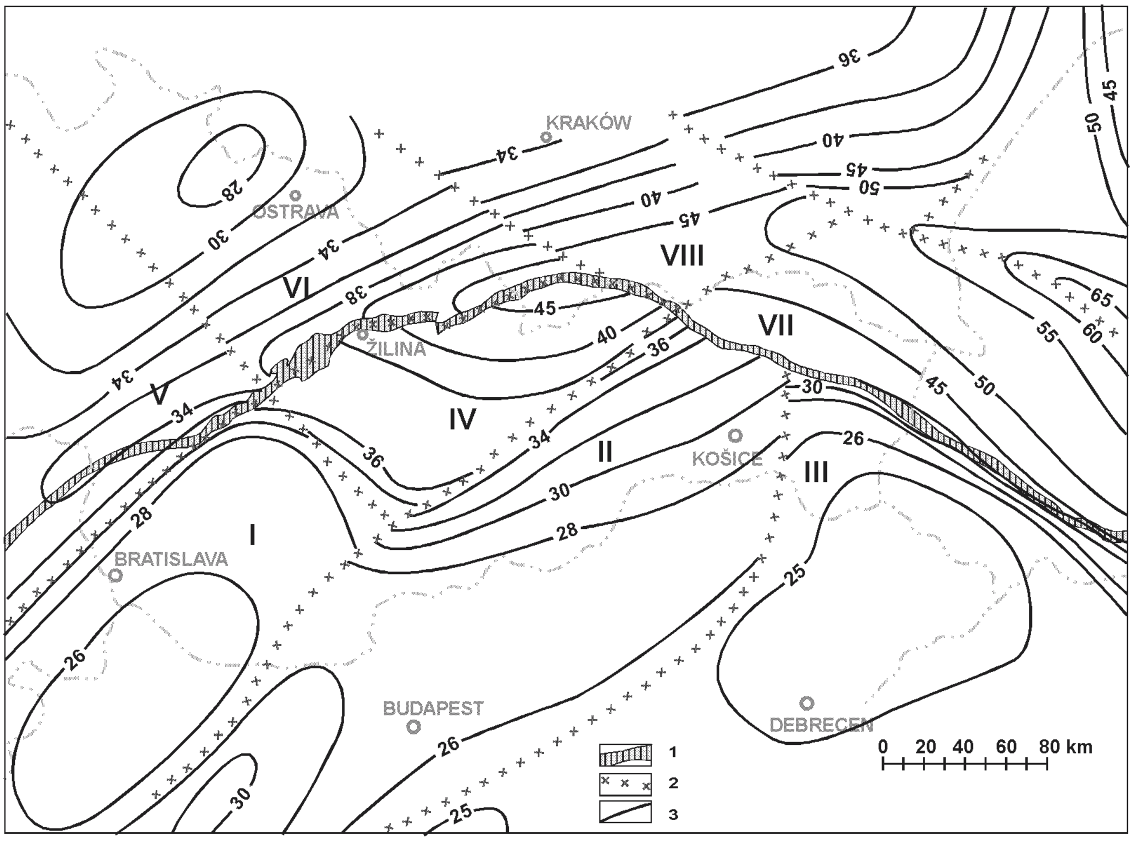

Fig. 1. Neo-tectonic blocks of the Western Carpathians (Fusán et al. 1981). *Legende:* **1** — Pieniny Klippen Belt, **2** — deep seated block boundaries, **3** — Moho discontinuity contours depth in km, Neo-tectonic blocks: **I.** Danube block, **II.** Rudohorie-Pilis block, **III.** Potisie block, **IV.** Fatra-Tatra block, **V.,VI., VII.** and **VIII.** Outer Carpathian blocks.

pathians. In the Slovak-Moravian block, the Mesozoic complexes and the thick Miocene cover are present in the Vienna Basin substratum besides the flysch nappes. An important geoelectric anomaly (MTS, MVS) follows the boundary between the Central and Outer Western Carpathians (Pěčová et al. 1976; Červ et al. 1994).

The **Danube block** was geologically characterized by the presence of thick sedimentary cover and subsidence of up to 3 mm/y in the Danube Basin area. The NW block margin can be partly correlated with the peri-Carpathian lineament which continues along the Pieniny Klippen Belt and follows the suture zone between the Outer and Central Western Carpathians. The originally defined SW continuation of the northern margin of the Danube block (Fusán et al. 1979, 1981, 1987), which passes through the Sopron and Kőszeg areas, was originally determined as a boundary between thick Alpine and thinned Danube Basin crust. From the present point of view, the principal boundary is more likely a deep-seated structure, reflected on the surface as the Mur-Mürz-Leitha seismically active tectonic line, connected with the peri-Carpathian lineament.

The northeast boundary of the Danube block with the Fatra-Tatra block trends in the NW–SE direction. This boundary, surficially defined as the Přerov-Štiavnica fault (Fusán et al. 1981) is geologically very heterogeneous and its activity during the Neoalpine evolution is doubtful. Similarly questionable is the activity of the NW-SE oriented faults that occur in the pre-Tertiary basement of the Danube Basin. Among these are the Dobrá Voda fault zone defining the southern margin of the Považský Inovec Mts. and the Tribeč Mts., continuing further to Nové Zámky and Štúrovo, and two other faults running parallel to this line in the basin basement: one running from Pezinok to Komárno and the second one along the Danube River (Fusán et al. 1981, cf. Figs. 1, 2). From the viewpoint of present knowledge, these should be regarded only as relics of the pre-Neogene tectonics, because they are absent in the sedimentary infill of the basin, as it is well documented by many seismic profiles through the area (e.g. Hrušecký et al. 1996).

The present-day views on the geometry of the Moho discontinuity are also different from those proposed by Fusán et al. (1981) for the model of the West-Carpathian "block structure". For instance, the current opinion is that an elevated neo-Moho in the western part of the Inner Western Carpathians continues as far as the peri-Klippen Belt zone, i.e. it crosses the boundary between the Danube and Fatra-Tatra blocks (Fig. 4).

On the basis of these facts, the so-called Přerov-Štiavnica deep-seated zone and the more southern zones with the same NW–SE trend (e.g. the Dobrá Voda or Pezinok-Komárno fault zones), which were defined mainly on the basis of the original Moho image in this area, are no longer believed to play any important role in Late Tertiary tectonics of the Danube Basin.

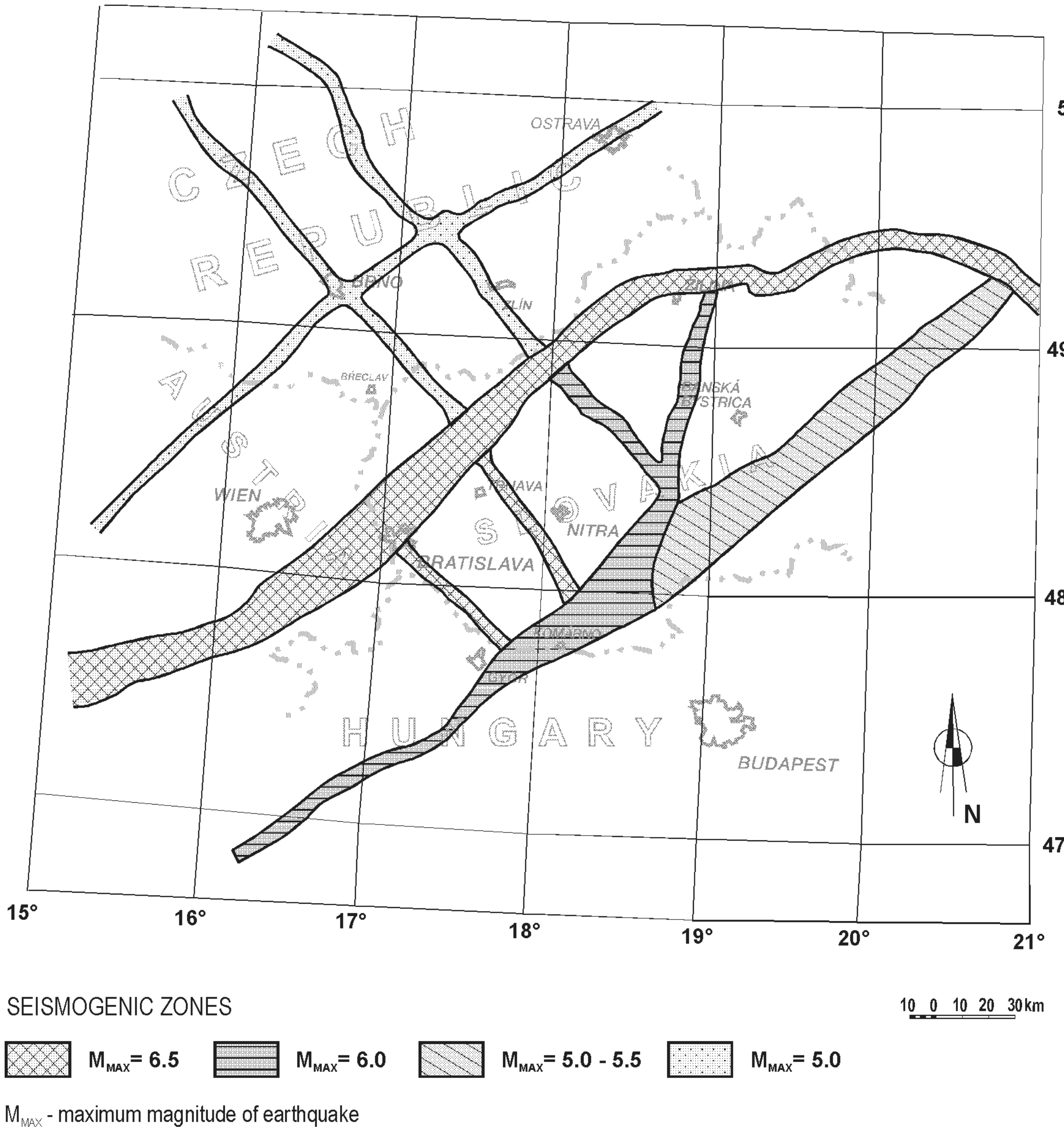

Fig. 2. Zones of possible earthquake generation after Šimůnek et al. 1991.

The **Fatra-Tatra block** is characterized by morphological elevations of the core-mountains and depressions filled by Paleogene and Neogene sediments. The block has an uplifting tendency at a rate of over 2 mm/y. Its northern boundary is represented by the Pieniny Klippen Belt (Figs. 1, 2). In this block, besides the faults defining the core-mountains, the Central Slovak fault system which reaches the lower crustal parts plays a principal role (Fusán et al. 1987; Kováč & Hók 1993). This fault system forms a wide N-S directed fault zone, narrowing downwards, running from the Turčianska kotlina Depression through the Žiarska kotlina Depression and further southwards along the Hron river valley (Figs. 2, 3).

The NE trending boundary of the **Rudohorie-Pilis block** with the Danube and Fatra-Tatra blocks was defined by a density inhomogeneity along the Komárno-Poprad Line (the Vepor deep-seated fault of Fusán et al. 1979), continuing to the Outer Carpathians territories (Fig. 1). In a broader sense this boundary can be correlated with the contact between the Tatric and Veporic basement units, known as the Čertovica Line on the surface.

Only negligible vertical movements were recorded in the Rudohorie-Pilis block, hence this area was considered to be relatively stable (Fusán et al. 1987). However, this is not consistent with the seismic activity probably along the Čertovica Line zone (earthquakes in the Banská Bystrica area) and the Hurbanovo-Diósjenő fault system (earthquakes in the Komárno area).

The **Potisie block** has very indistinct boundaries (Fusán et al. 1987). In the east, it is formed by a N–S trending fault-system in the area of the Slanské vrchy Mts.; in the north-east it is represented by the Pieniny Klippen Belt (Fig. 1).

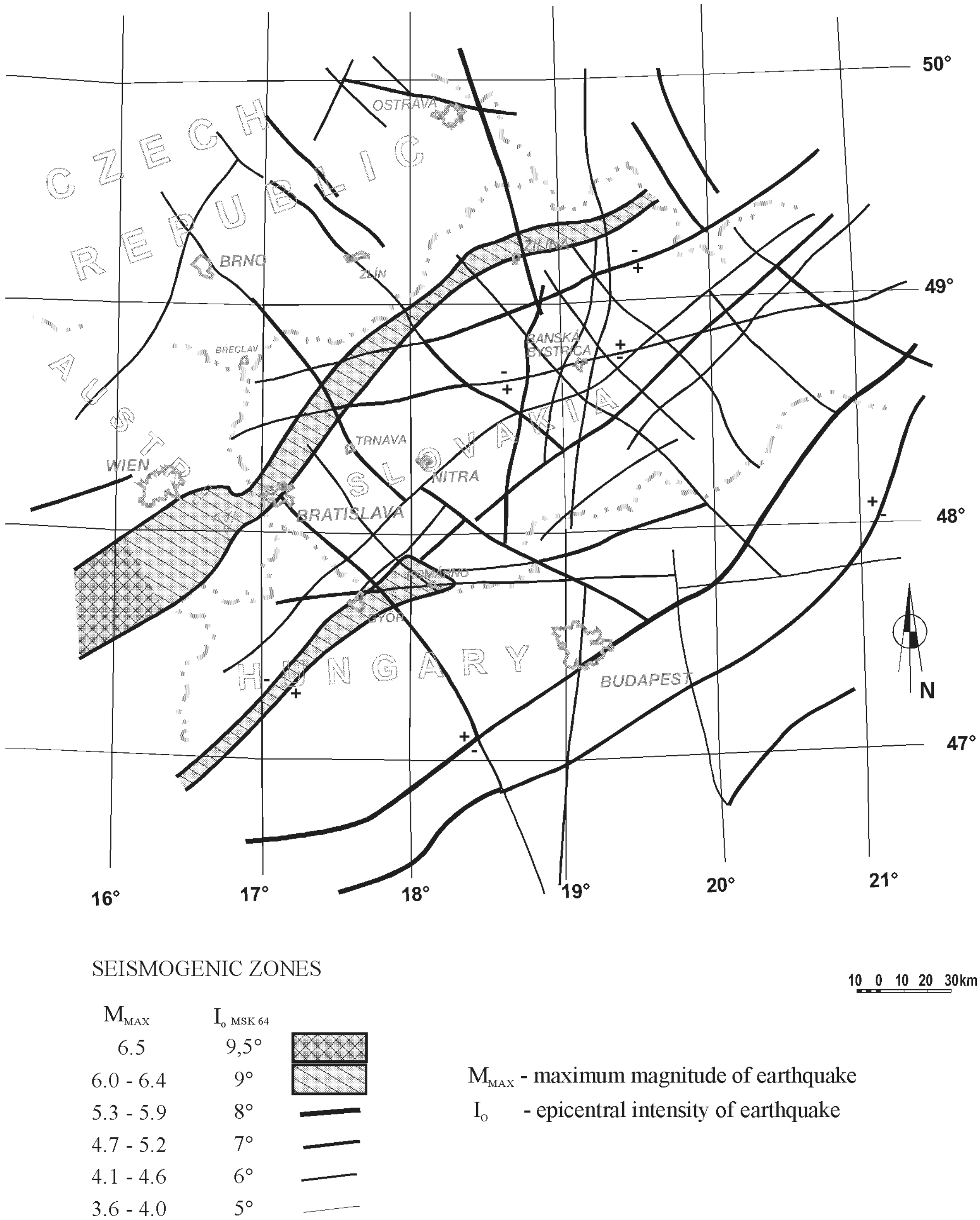

Fig. 3. Zones of possible earthquake generation after Šteinberg et al. 1988.

The block is characterized by a thick Neogene sedimentary cover and subsidence rate of up to 2 mm/y.

Depth and distribution of earthquakes and crustal rheology

Earthquakes deeper than 20–30 km are known only along the front of the Carpathians and/or along the southeastern margin of the Pannonian Basin (Procházková et al. 1994; Labák & Brouček 1996). The only Benioff Zone in the Carpathian arc related to the subduction process is situated in the Vrancea region, where earthquakes occur at depths of 10–180 km (Fuchs et al. 1979). All other earthquakes are shallow and their origin is related to different processes than subduction. A notable West-Carpathian exception is the Kremnica region located within the N-S trending Central Slovak fault zone. Here earthquakes as deep as 30 km have been assumed to occur but by latest the analyses (Labák 1996; Labák et al. 1996) this depth of foci has no real evidence. Elsewhere in the Slovak territory earthquakes generally originate at depths shallower than 15–17 km. This fact can be well correlated with

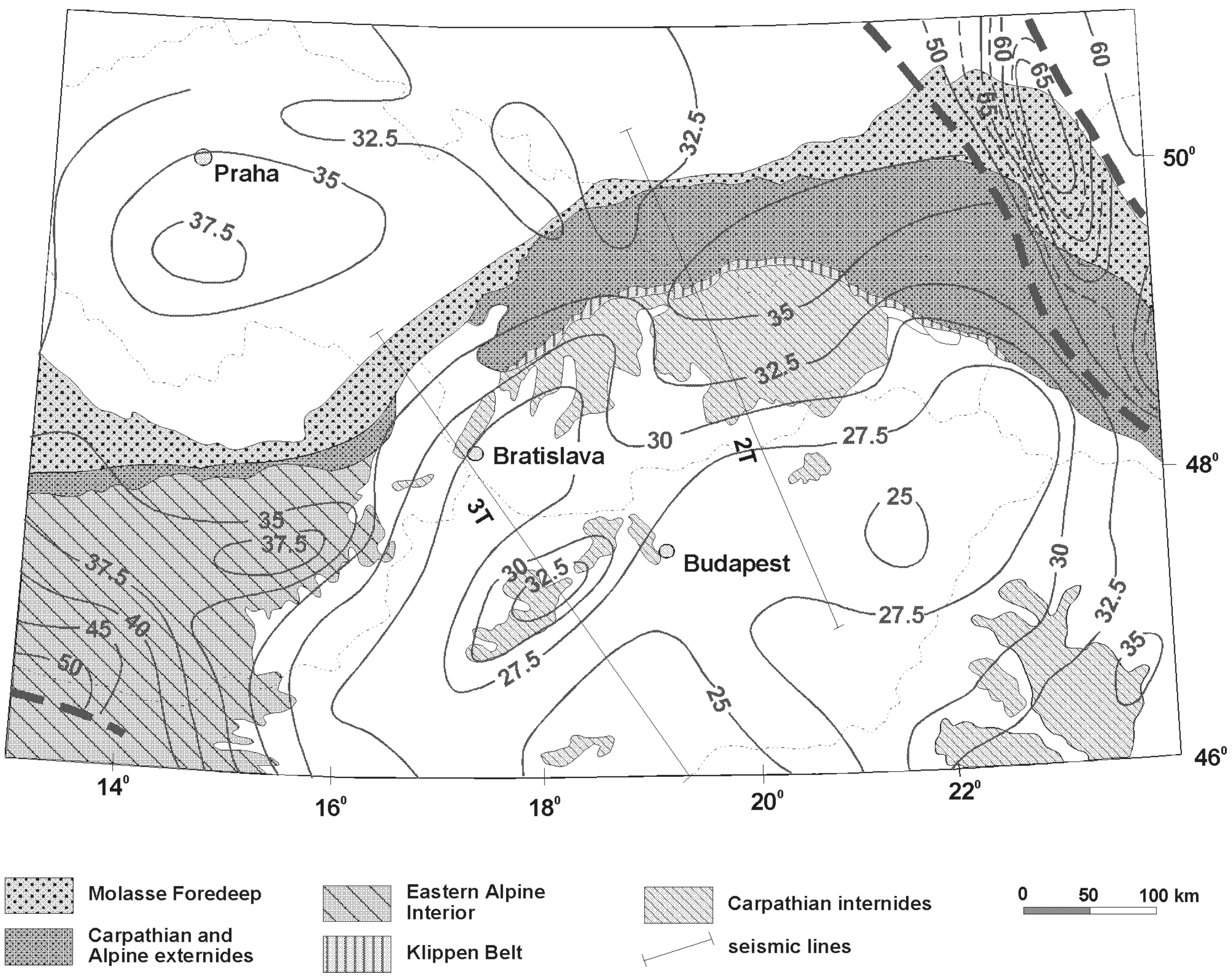

Fig. 4. Thickness of the Earth´s crust in the Carpathian-Pannonian area. Contours in km.

the maximum depth of the brittle crust which is the only zone strong enough to accumulate enough potential strain energy to produce destructive earthquakes.

The thickness of the brittle crust in the Western Carpathians was estimated by Bielik & Stríženec (1994) on the basis of a crustal profile running from the Polish part of the North European Platform to the Carpathians and Pannonian Basin. The maximum estimated thickness along this profile is about 35 km, with 25 km being the more common thickness. However, the high heat flow, particularly in the northern parts of the Pannonian Basin (Fig. 5), indicates an elasto-plastic behaviour of the crust even at depths less than indicated along the above mentioned crustal profile.

According to the rheological model of Lankreijer et al. (1998), the strong area of the Bohemian Massif rapidly loses its strength towards the Carpathians. Nevertheless, the Carpathian foreland area is still relatively strong (Lankreijer 1998). The Vienna Basin is also characterized by a remarkably strong lithosphere. The Danube Basin, typically, only displays lithospheric strength in the uppermost parts of the crust (Fig. 6). Because the substantial part of sedimentary filling also cannot be considered as brittle (upper 3–9 km), only a very thin layer remains for the potential generation of earthquakes. Actually, the central part of the Danube Basin, except for a few small earthquakes on the Hungarian side, is generally aseismic.

The high heat flow and the related thinner brittle crust is also observed in the northern continuation of the Danube Basin, as far as the Pieniny Klippen Belt. This fact is also supported by measured geothermal conditions in the Soblahov-1 borehole. All earthquakes recorded in this area are distributed along the margin of this high heat flow zone (compare Figs. 5 and 13).

A relatively shallow Moho, which is accompanied by an increased heat-flow, is also known in some platform areas, for example in the vicinity of Ostrava (Figs. 4 and 5), or further west in the Ohře rift (Fig. 6). This indicates that crustal

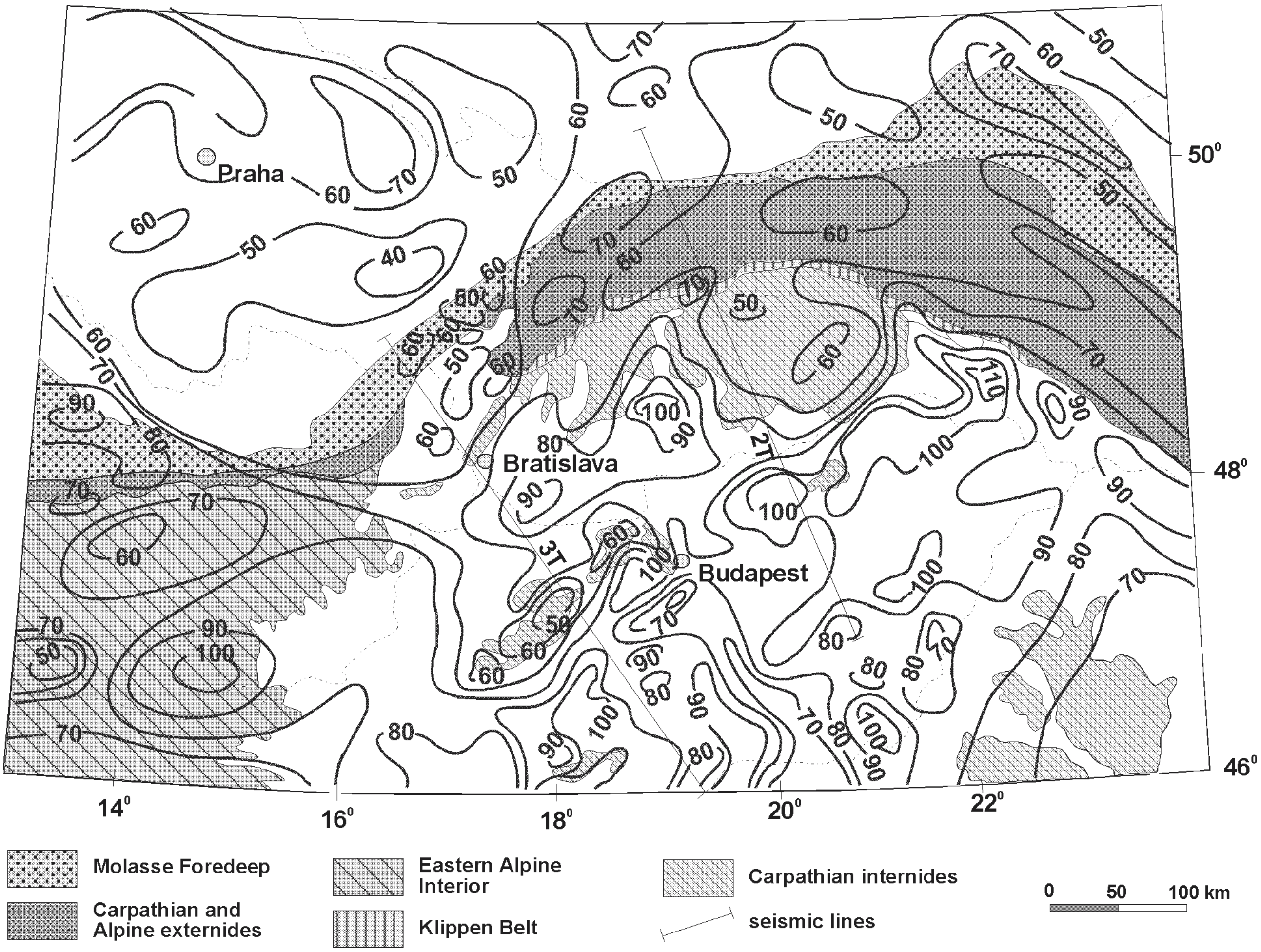

Fig. 5. Heat-flow density map in the Carpathian-Pannonian area. Density contours in mWm^{-2}.

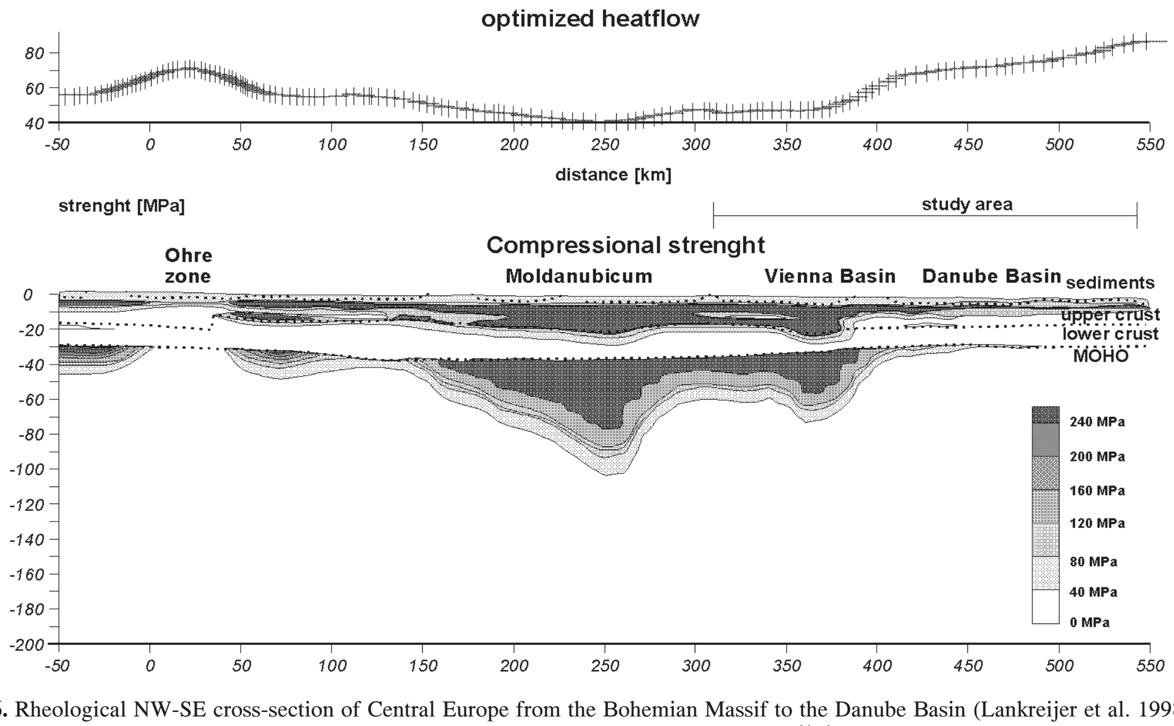

Fig. 6. Rheological NW-SE cross-section of Central Europe from the Bohemian Massif to the Danube Basin (Lankreijer et al. 1998). Interpreted strength contour plot (in MPa) for compressional deformation, at a strain-rate $10^{-14}s^{-1}$.

extension occurred during the Tertiary in foreland areas as well.

The newly defined seismogenic zones of the ALCAPA junction area

The brittle part of the Earth's crust is restricted to the upper 15–35 km in the Western Carpathians. This zone contains some inhomogeneities which originated during the geological evolution of the Western Carpathians. Invoking the principle of minimum energetic expenses, these less competent zones are believed to be utilized as the primary source of the stress release by faulting. These zones are represented by the original Upper Jurassic–Cretaceous intracontinental and oceanic **suture zones (1)** which were often reactivated as fault zones with various kinematics during the Late Tertiary and are still potentially able to generate earthquake events. These reactivated fault zones are mainly **wrench fault corridors (2)** related to the Miocene escape tectonics in the Carpathians and the **low-angle normal faults (3)** occurring below the Neogene basins which accommodated the upper crustal extension and/or isostatic uplift of the orogen.

(1) Principal suture zones of the Western Carpathians

The central and inner zones of the Western Carpathians are marked by stacking of crustal imbricates that originated by northward progradational shortening of heterogeneously thinned epi-Variscan continental crust. Some of the zones attenuated by Triassic-Jurassic rifting graded into domains floored by oceanic crust which were sutured sequentially during the Late Jurassic to Paleogene. Three types of crustal-scale shortening zones were distinguished by Plašienka et al. (1997): (A) original oceanic subduction zones which were succeeded by collisional stacking of mobilized crust of continental margins, as the Meliatic and related sutures of the Inner Western Carpathians; (B) zones of continental and/or oceanic basement underthrusting and stacking within the crust, characteristic for the Central Carpathians — the intracontinental Čertovica suture and originally oceanic Penninic-Vahic suture zone; (C) downbending of the rigid marginal foreland crust of the North European Platform, which was overridden by the Tertiary accretionary wedge of the Outer Carpathians.

Identification of suture zones in the present structure of the Western Carpathians is supported by seismic reflection profiling and by magneto-telluric sounding (MTS), which show the sutures as deep-seated low-resistivity zones. Particularly the high conductivity of the latter zones indicates either ultramylonites, or zones with deep-generated solutions, or other rock types containing clays and/or black shales. A metamorphic process with graphite coating on mineral grains also cannot be ruled out. All these environments have a decreased coefficient of friction, represent weakened or even discontinuous zones within the crust and can potentially produce seismic events.

In the area under consideration, the suture zones defined by Plašienka et al. (1997) include both the oceanic and the intracontinental shortening zones, which have recently acted as weakened seismogenic belts. From north to south, the following zones are depicted (Fig. 7):

(A) The **Penninic-Vahic suture zone** which consumed both the Vahic (i.e. South Penninic) oceanic and the Oravic (i.e. Middle Penninic) continental crust. It originated during the Late Cretaceous to Paleogene (70–50 Ma) and it is younger eastwards. In deep seismic sections, it is indicated by flat reflectors in mid-crustal levels, which underlie the Tatric thick-skinned crustal sheet (Tomek 1993; Vozár et al. 1995) and overlie the underthrust Oravic ribbon continent. The zone is followed by an important Late Tertiary wrench corridor continuing to the Pieniny Klippen Belt NE-ward which controlled the eastward extrusion of the Western Carpathians and evolution of the Vienna Basin. This wrench zone consists of several sections: the Mur-Mürz-Leitha fault zone, the Dobrá Voda area (wrench zone and ENE-WSW trending back-thrusts), and the Váh river valley as far as Žilina (the peri-Carpathian lineament).

The Mur-Mürz-Leitha-Žilina wrench corridor generates earthquakes by movements of two kinematic types. The first one is a horizontal displacement along a sinistral strike-slip fault system accompanied by SW–NE trending flower structures. The second type is contractional, related to older inherited ENE–WSW trending structures (e.g. a wider zone around Dobrá Voda and part of the Pieniny Klippen Belt west of Žilina).

(B) The **Čertovica suture zone** located between the Tatric basement sheet and the Veporic crustal wedge is the dominant feature of the deep seismic line 2T (Tomek et al. 1989; Tomek 1993) where it is indicated by a moderately south-dipping stack of strong reflectors (Fig. 10). The zone originated by the mid-Cretaceous shortening and underthrusting of a thinned continental crust of former Jurassic–Lower Cretaceous basinal area between the Tatric and Veporic elevations. This attenuated, but buoyant crust underplated the Veporic wedge and its sedimentary cover was detached and transported northwards to create the Krížna cover nappe system overriding the Tatric Superunit. The final locking of this zone occurred about 90 Ma ago (late Turonian).

The zone comes to the surface in the area between the towns of Banská Bystrica and Brezno and then obliquely crosses the Nízke Tatry horst. It generates shallow earthquakes, released mostly on the ENE-trending Hron fault system (Fig. 7), which is a superimposed Tertiary phenomenon. It is noteworthy that this system, like the Dobrá Voda fault system, can be clearly identified in the recent morphology and can be easily traced by remote sensing methods (Janků et al. 1984). Earthquakes along the N–S trending Central Slovak fault system in the surroundings of the Turčianska kotlina Depression (with less data) can also be related to this zone, along with its continuation to the Central Slovak neovolcanic area.

(C) The **Meliatic oceanic suture** is closely related to the Igal-Bükk Zone. Both were formed during the Late Jurassic to the earliest Cretaceous (150–120 Ma). The Meliatic suture represents an original subduction zone evidenced by a presence of dismembered ophiolite units, blueschists and

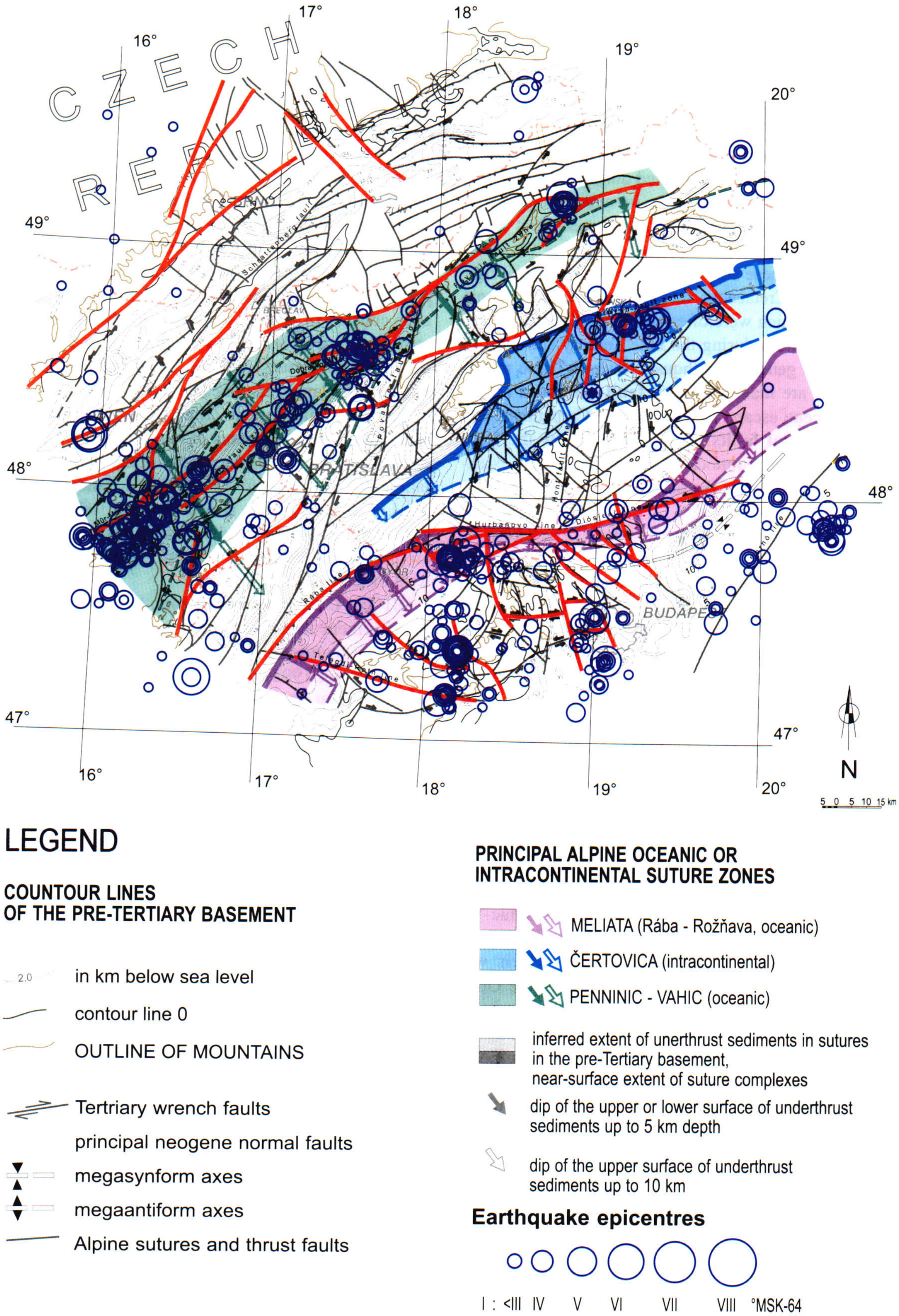

Fig. 7. Principal West-Carpathian suture zones with respect to earthquake occurrences. Historical earthquake epicentres after Labák & Brouček 1996.

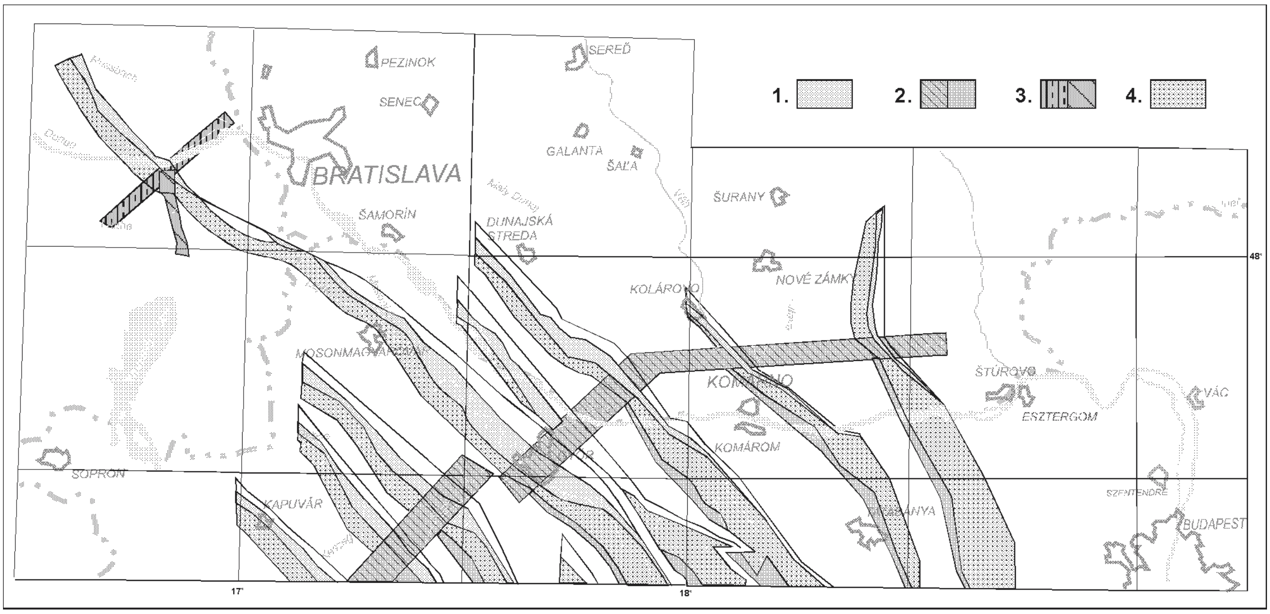

Fig. 8. Magnetotelluric (MTS) profiles in the Danube and Vienna Basins and their interpretation (Nemesi et al. 1997, modified). Important zones of very low resistivity zones are related to: **1** — basin filling, **2** — Rába Line and its shallow depth continuation below the Transdanubian Central Range, **3** — Mur-Mürz-Leitha Line and its steep continuation at depth, **4** — elevated resistivities.

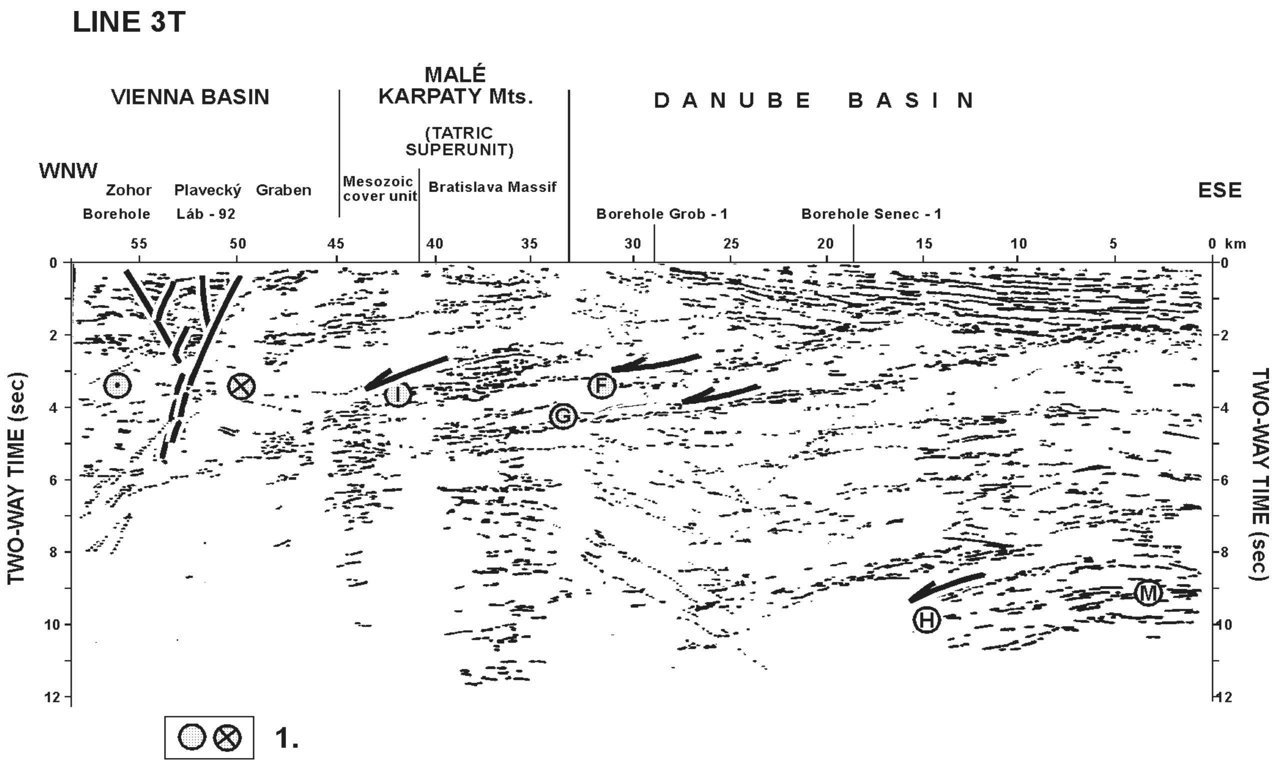

Fig. 9. Seismic time cross-section along the 3T profile (Tomek & Thon 1988, modified). Flower structure in the Zohorsko-Plavecký graben, reflector packages F,G presents normal faults, M—Moho, H—extension in lower crust. 1—sinistral wrench.

coeval calc-alkaline volcanics. The Igal-Bükk Zone was probably formed by closure of a small back-arc oceanic basin (Szarvaskő ophiolites), related to the southward subduction of the Meliatic ocean. Both zones are rather steep (the former south- and the latter north-dipping) to subvertical, but in the western part, below the Neogene Danube Basin, the Meliatic suture is probably flatter. In places, the Meliata suture can be regarded as reactivated by low-angle normal faults (e.g. the Rába Line — Horváth 1993; Plašienka et al. 1997). Some segments of the **Igal-Bükk Zone** were also reactivated as wrench zones during the Late Tertiary (e.g. the Darnó Line). The course of both zones is followed by earthquake epicen-

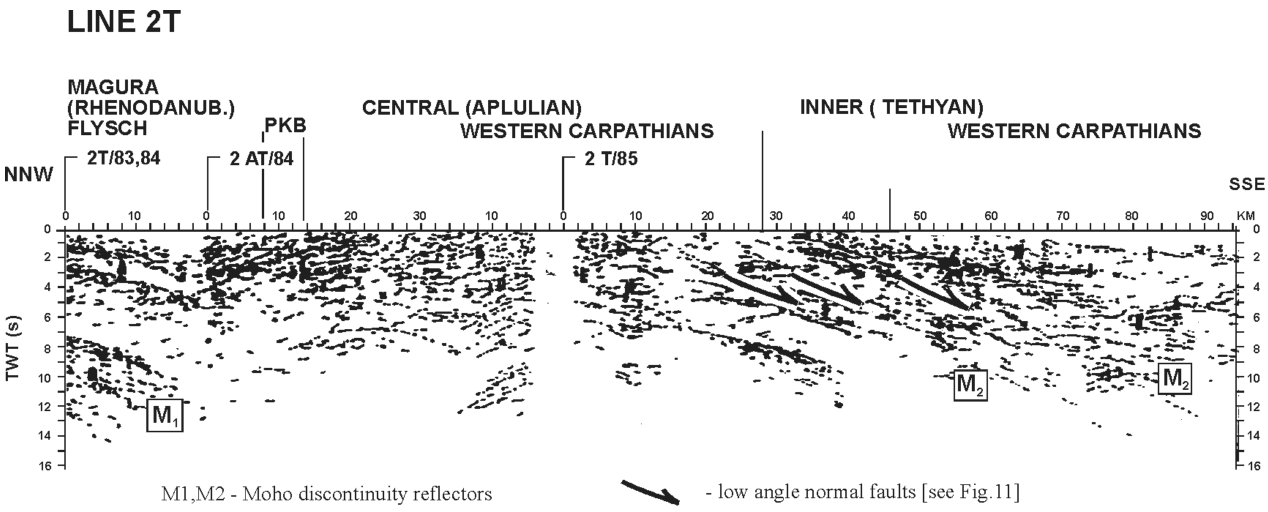

Fig. 10. Seismic time cross-section on the 2T profile (Tomek et al. 1989, modified).

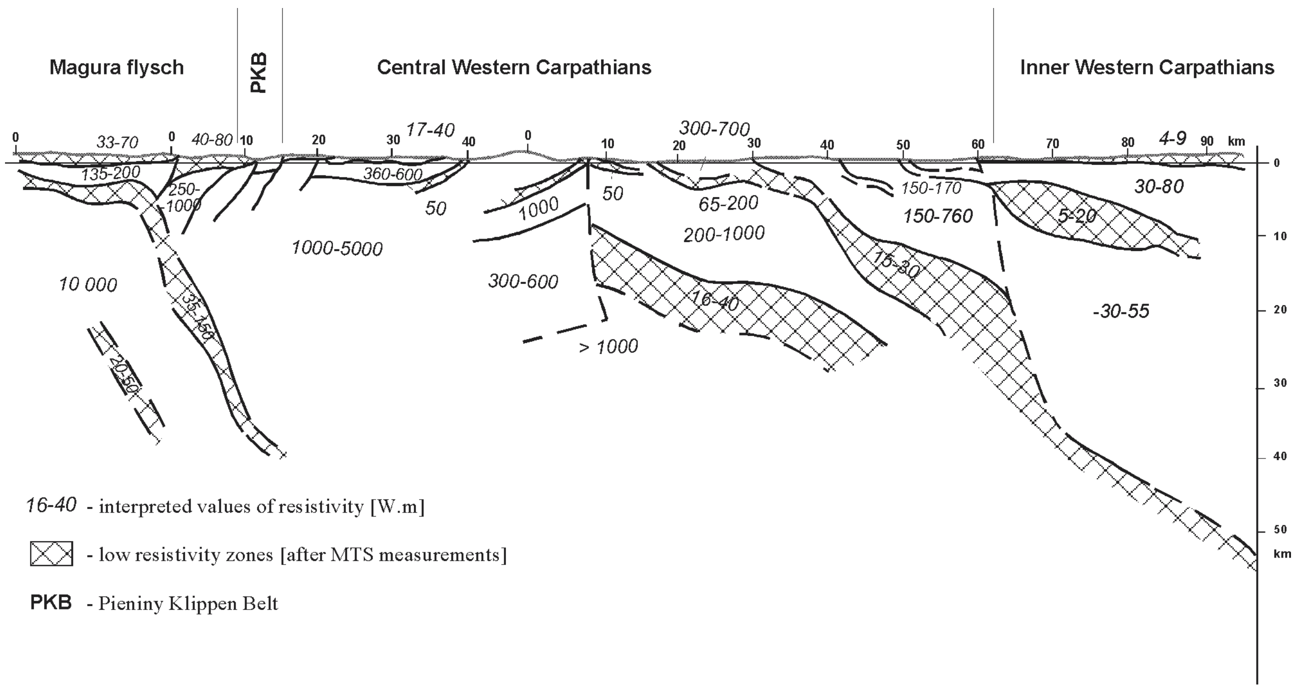

Fig. 11. Interpretation of the magnetotelluric (MTS) measurements (modified after Varga & Lada 1988) along the 2T profile (see also Fig. 10).

ters, especially in areas where they are followed by deep-seated fault systems (Fig. 7).

In the area under consideration, the Meliata oceanic suture is bound to the northwestern margin of the Transdanubian Central Range, an element with comparatively thick crust in the area. Stresses generated along this contact are released by faults surficially represented by the WSW-ENE oriented Hurbanovo-Diosjenő fault zone. This fault system is related to earthquake epicenters mainly at its crossing with smaller transversel fault structures.

(2) Wrench fault zones

Deep-seated zones of very low resistivity have been identified by MTS method along a profile crossing the Vienna Basin, Malé Karpaty Mts. and the Danube Basin (Nemesi et al. 1997, cf. Fig. 8). One of these zones, shown as a flower-structure in seismic lines, occurs in the vicinity of the Schrattenberg fault on the western margin of the Vienna Basin (Červ et al. 1994). Another zone of very low resistivity was identified in the SE part of the Vienna Basin (SE continua-

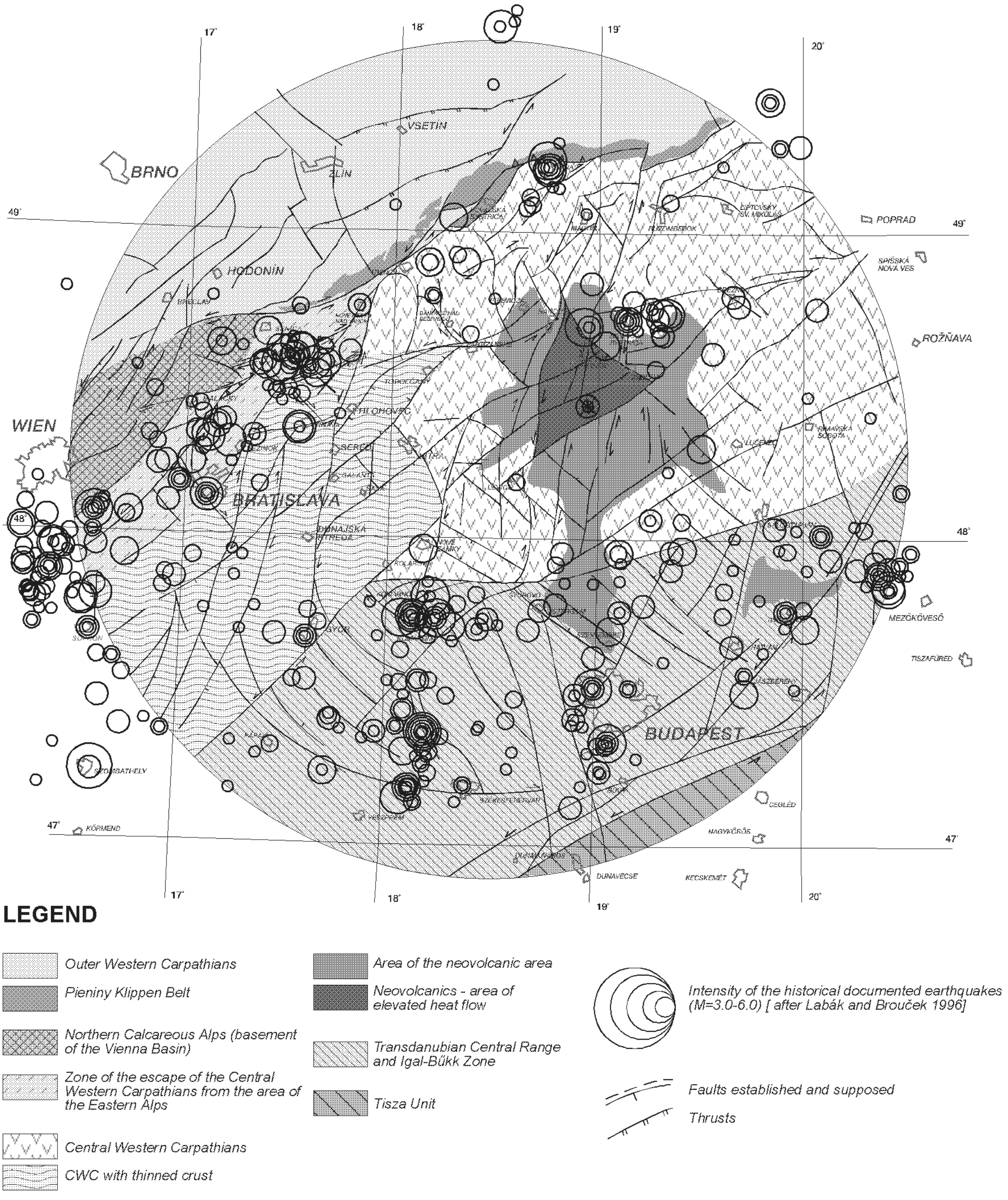

Fig. 12. Seismo-geological domains of the Alpine-Carpathian-Pannonian junction area.

tion of the Malé Karpaty Mts. to Austria). Similar to the first zone, this zone is represented by a seismically identified flower-structure (Tomek & Thon 1988) close to the Malé Karpaty Mts. (Fig. 9).

Based on the coincidence of the deep-seated low resistivity zones and known faults, as well as on the knowledge about the pull-apart opening of the Vienna Basin during the extrusion of the West-Carpathian lithospheric fragment from the Alpine collision zone in the early Miocene (Csontos et al. 1992; Kováč et al. 1993), the low-resistivity zones can be reasonably assumed to be first-order shear zones (Gutdeutsch & Aric 1988). This interpretation is consistent with the young Quaternary structure of the Zohorsko-Plavecký graben which is well documented from the Neogene up to the Quaternary strata.

(3) Extension along the orogenic sutures

The Central Slovak area (the upper part of the Hron river valley), where earthquakes occur more frequently than in other parts of Slovakia is close to the Tatric-Veporic suture

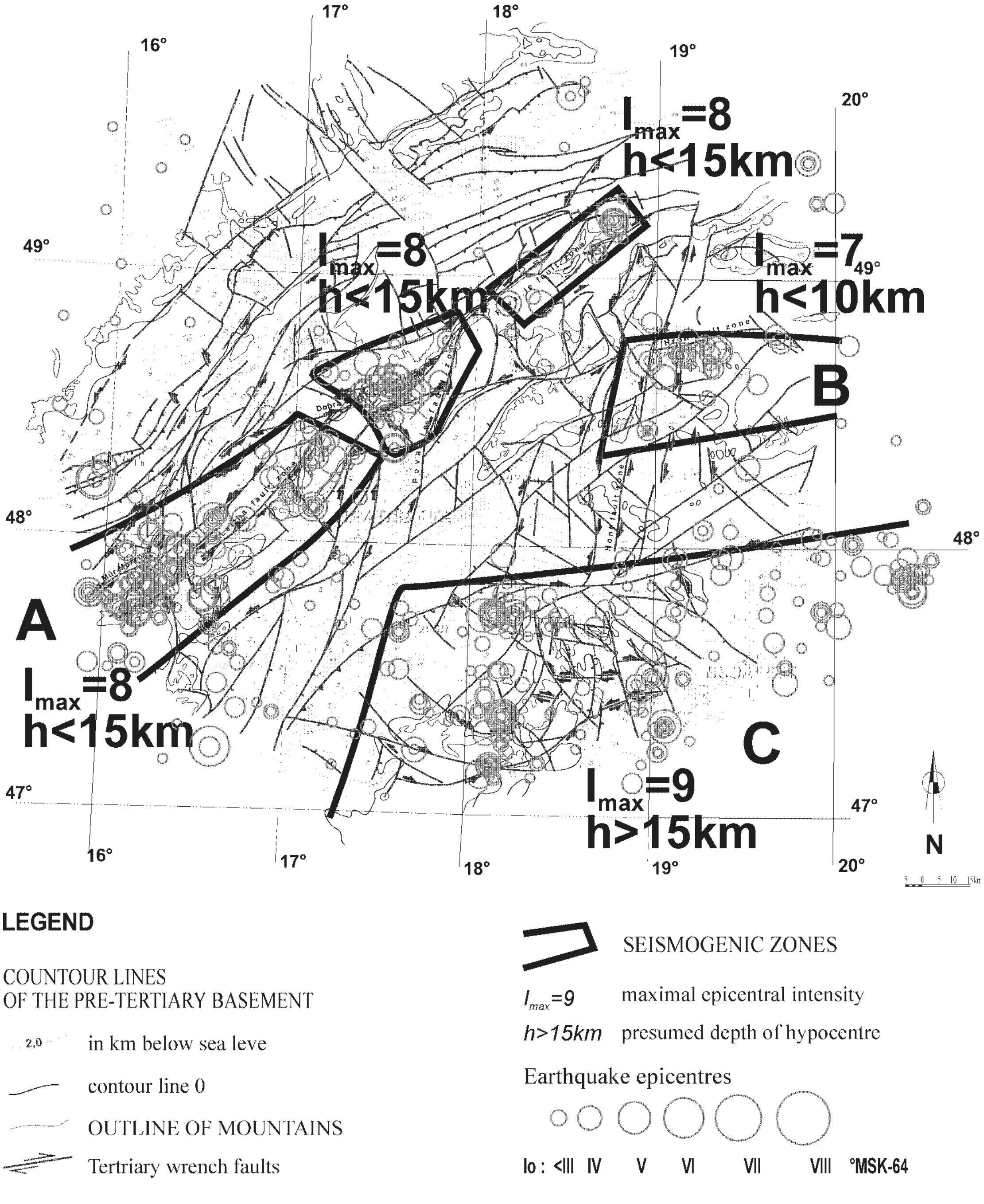

Fig. 13. Seismogenic zones of the Alpine-Carpathian-Pannonian junction area. Historical earthquake epicentres after Labák & Brouček 1996.

zone. Along the 2T seismic profile (Fig. 10), besides the obvious density of SE-inclined reflection boundaries (Tomek et al. 1989) there are some zones of very low resistivity, which are observable in the deeper zones (Fig. 11). The high density of reflections may correspond to a probable extensional reactivation of the Čertovica suture, along which earthquakes are concentrated.

The entire tectonic body of the Transdanubian Central Range is underlain by zones of very low resistivity at 5 to 20 km depths (Nemesi et al. 1997, cf. Fig. 8). This would imply that they represent originally incompetent sutures and that the Transdanubian Range evidently represents an upper unit (a crustal slice) whose movement along these sutures was probably enabled by a low coefficient of friction of the underlying masses (Tari 1996). The stress generated by this movement is believed to be the primary source of earthquakes released on the brittle fault structures in this region e.g. the N-S running transversal Mór graben (Figs. 12, 13).

Seismogenic zones — discussion and conclusions

The rheological aspects of the brittle crust within the East Alpine-Western Carpathian-Pannonian junction, as well as the presence of deep-seated faults, have been taken into account in construction of a model of seismo-geological domains in this area (Fig. 12). Several domains are identified: the SE margin of the Vienna Basin, the Váh river valley, the Central Eastern Alps, the Central Western Carpathians, the area of the thinned crust in the Danube Basin basement, and the Transdanubian Central Range (Fig. 12). These domains were determined on the basis of the earthquake occurrence with respect to the crustal thickness, heat flow and the principal geological units building the domains. In this paper we present the next step — based on definition of zones of weakness in the upper brittle crust, identified as Paleoalpine suture zones reactivated during the Late Tertiary, and we define the seismogenic zones with increased seismic risk in the area considered (Figs. 7, 13):

A (1, 2) The Vahic suture and above it situated wrench fault zone accommodating the Western Carpathians extrusion northeastwards. The main brittle structures generating the earthquakes are the Mur-Mürz-Leitha, the Dobrá Voda and the Považie fault systems. A maximum epicentral earthquake intensity of I_{max} = 8–9^o MSK, at the presumed hypocenter depths as far as 15 km is inferred in this zone.

B (1, 3) The Čertovica suture and above it situated extensional faults which were reactivated during the Miocene back-arc extension and the following Pliocene isostatic uplift of the central part of the orogen. The main brittle earthquake-generating structure is the Hron fault system (surroundings of Banská Bystrica). The zone is characterized by maximum epicentral intensity of potential earthquakes of I_{max} = 8^o MSK, at presupposed hypocenter depths down to 10 km.

C (1, 2, 3) The Meliata suture and along it situated Hurbanovo-Diósjenő fault zone reactivated during the Miocene extension and wrenching along the Igal-Bükk Zone. This seismogenic zone is characterized by maximum epicentral intensity of assumed earthquakes of I_{max} = 9^o MSK, at inferred hypocenter depths exceeding 15 km.

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