SLOVAK NATIONAL CENTENNIAL REPORT

TO

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by

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Contents

ABSTRACT

Territory of the Slovak Republic, covered mostly by the Western Carpathians, can be characterized by a moderate seismic activity. More than 590 macroseismically felt earthquakes with epicenters on the Slovak territory since 1034 are documented in catalogues. Since more than 550 of them occurred after the June 28, 1763 Komárno ($I_o \approx 8-9^\circ$ MSK-64) earthquake, the actual number of the macroseismically felt earthquakes during the documented period must certainly be considerably higher than 590. The Komárno and $I_o \approx 7-8^\circ$ EMS-98 January 15, 1858 Žilina earthquakes strongly stimulated interest in the Austro-Hungarian monarchy (to which the present Slovak territory belonged at that time) in the earthquake activity of the Western Carpathians. On January 1, 1902 recording of earthquakes started at the seismic station in Ógyalla (now Hurbanovo, HRB). Today, the station is still in operation and with its mechanical Mainka seismograph (operating since 1909) is one of the oldest seismic stations in Europe. The earthquake activity, including the $I_o \approx 8-9^\circ$ MSK-64 January 9, 1906 Dobrá Voda earthquake, was then studied mainly by Hungarian seismologists until proclaiming of the Czechoslovak Republic in 1918 when Czech seismologists took over the seismological investigations. The Cabinet of Geophysics of the Slovak Academy of Sciences, established in 1953 and renamed in 1965 as the Geophysical Institute of the Slovak Academy of Sciences, became a national institution for the geophysical and seismological research in Slovakia. Its importance for the Slovak science increased after the split of Czechoslovakia into the independent Czech and Slovak Republics.

At present, seismological research and deep structure research of the lithosphere are carried out by the Department of Seismology and Department of Gravimetry and Geodynamics, respectively, at the Geophysical Institute of the Slovak Academy of Sciences. The Department of Seismology operates national network of seismic stations, participates in monitoring in two local seismic networks; analyses historical and recent earthquake activity within the Slovak territory; performs seismic hazard studies for the whole territory as well as for important localities; develops computational methods for numerical modeling of seismic ground motion and site effects of earthquakes; investigates anomalous seismic motion in local surface geologic structures. Peter Moczo and his colleagues have contributed to the application of the finite-difference method in modeling seismic wave propagation and earthquake ground motion. They have developed efficient computational techniques and optimization procedures in order to facilitate the use of the finite-difference method in seismic ground motion modeling for realistic viscoelastic models of local geologic structures, e.g., large-scale sedimentary basins and valleys. Regarding the deep structure research of the lithosphere, Miroslav Bielik and his colleagues have contributed to the application of 2D and 3D quantitative interpretation of gravity anomalies both in the Western Carpathians and its adjacent regions, development of density modeling methods, calculation of the stripped gravity maps, study of local and regional isostasy in different areas of continental lithosphere, integrated geophysical modeling and rheological predictions of the lithosphere with implications for tectonic scenarios. The results have been used to define seismogenic zones in the region.

The national network includes 6 seismic stations. Except of the historic Hurbanovo (HRB) station, all of them are equipped with 3-component short-period velocimeters and digital registration. The Bratislava (ZST) station is equipped with broad-band instruments and on-line telemetry. The local EBO network (6 stations) and EMO network (7 stations) are deployed around the Jaslovské Bohunice and Mochovce Nuclear Power Plants, respectively. All stations are equipped with 3-component short-period velocimeters and digital registration.

1. SEISMIC STATIONS

BRIEF HISTORICAL REVIEW

Hurbanovo (HRB)

The oldest seismic station in Slovakia which also ranks among the oldest in Europe is situated in the town called now Hurbanovo (historical names: in Hungarian - Ógaylla, in Slovak - Stará Ďala). The recordings started on January 1, 1902 with a pair of the Strasbourg horizontal pendulums by J.&A. Bosch. In 1903, the Vincentini-Konkoly pendulum was installed. Between 1909-1912, the Bosch pendulums were replaced by the Mainka seismograph. The last event recorded with the Vincentini-Konkoly seismograph is of the year 1911 (*Pajdušák* 1997). The World War I caused disturbances due to which the data of the period 1913-1918 was lost. The Mainka seismograph was reconstructed in 1927 and new attenuators installed in 1936. Measurements in Stará Ďala for 1923-1938 are summarized by *Zátopek* (1940). In 1938, the town and thus the observatory were annexed by Hungary. The observations were interrupted due to removal of the attenuators by Czechs, were resumed in 1940 and continued until 1945. However, a major part of the data was destroyed. After the reestablishment of Czechoslovakia, the observations in Hurbanovo started in 1949 and have been ever since going on until present with the old instruments with mechanical registration. The records for the period of 1943-1999 are available at the Geophysical Institute of the Slovak Academy of Sciences in Bratislava.

Skalnaté pleso (SPC)

The second oldest seismic station on the Slovak territory situated on the slopes of the High Tatras was equipped with the horizontal Wiechert seismograph with mechanical registration by Spindler & Hoyer of Göttingen in 1943. This instrument after some improvements was in operation until 1976. In 1958, a 3-component set of the Krumbach seismometers with optical registration was installed. It was in operation until 1965. The observations were then interrupted because of the reconstruction of the pavilion. Afterwards, the Krumbach seismometers were not reestablished. In 1967, the observations started on the vertical-component short-period seismograph VEGIK with galvanometric registration. The observations continued until January 13, 1998 when the station was closed. The records for the period of 1956-1998 are available at the Geophysical Institute of the Slovak Academy of Sciences in Bratislava.

Bratislava (BRA)

The station was situated in the building of the Hydrometeorological Institute in Bratislava and started its operation on May 1, 1956. It was equipped with a 3-component set of the Krumbach seismographs. In 1965 a 3-component set of the VEGIK seismographs with galvanometric registration replaced it. The station was closed in 1977 due to its redundancy in respect to the newly established Bratislava (ZST) station.

Bratislava (ZST)

The station situated in a vault inside of an old quarry in the Little Carpathian Mountains started its operation in April 1976 with a vertical-component short-period seismograph Kirnos

(SKM-3) with galvanometric registration. It was switched off in October 1997. On March 13, 1990, the first Slovak digital seismic station, the ZST station, started telemetric transmission of the data from the acquisition system Lennartz PCM 5800 to the headquarters of the Geophysical Institute of the Slovak Academy of Sciences. During the first period, only three short-period SM-3 seismometers were in operation. In June 1997, the original short-period channels were replaced by improved ones, still based on the SM-3 seismometers, and three broad-band channels based on the Kirnos (SK-D) seismometers were installed. The station has been operating in this configuration until now.

Šrobárová (SRO)

The station was established in 1964. In the period 1963-1965 it was equipped with a three-component set of the short-period VEGIK seismographs with galvanometric registration. In 1966-1967 only two vertical-component short-period VEGIK seismographs were in operation. During the period of 1968-1987 the station was equipped with a three-component set of the medium-period Kirnos (SK-D) seismometers with galvanometric registration. During the period of 1985-1987 along with the medium-period channels, one short-period SKM-3 seismometer was in operation. In 1988-1997 after the removal of the medium-period seismometers, only short-period analog galvanometric registration continues. During the period of 1997-1998 in parallel to the analog galvanometric registration, a new digital station was put in operation. The seismic data acquisition system Lennartz PCM 5800 was first connected only to the Le-3D seismometer, then to the vertical SKM-3 seismometer as well. Finally, all the Le-3D components were replaced by the SKM-3 seismometers. In September 1998 the analog galvanometric registration was switched off. The digital station continues to operate.

Modra

A digital data acquisition system Lennartz PCM 5800 with a 3-component Le-3D seismometer started operation on July 5, 1992. During the period of 1996-1999 the operation was often interrupted because of severe technical difficulties. Since May 1999 the renewed station has been in operation with the improved original equipment.

Košice

An analog vertical-component short-period SM-3 seismograph started operation on January 1, 1990. On May 16, 1991 a digital data acquisition system Lennartz PCM 5800 with a 3-component Le-3D seismometer started operation. The analog registration was switched off in 1992.

Vyhne

An analog vertical-component short-period SM-3 seismograph started operation on July 1, 1990. On November 14, 1991 a digital data acquisition system Lennartz PCM 5800 with a 3-component Le-3D seismometer started its operation. The analog registration was switched off in 1992.

PRESENT

The Slovak national network includes 6 seismic stations (Tab. 1 and Fig. 1): Bratislava (ZST), Šrobárová (SRO), Hurbanovo (HRB), Modra, Vyhne and Košice. With the exception of the historic Hurbanovo (HRB) station, all of them are equipped with 3-component short-period velocimeters and digital registration. The only station with broad-band instruments is Bratislava (ZST).

In addition to the national network two local seismic networks are in operation. The EBO network is deployed around the Jaslovské Bohunice Nuclear Power Plant and consists of 6 stations with 3-component short-period velocimeters and digital registration. The EMO network is deployed around the Mochovce Nuclear Power Plant and consists of 7 stations with 3-component short-period velocimeters and digital registration.

All the data supplied by the Slovak national network and selected data from the local networks is processed at the Geophysical Institute of the Slovak Academy of Sciences in Bratislava.

Slovak National Network November 1999	code ISC (code GPI)	latitude (N)	longitude (E)	eleva-tion (m)	foundation	compo-nents	seismo-meter	T_s (s)	recording	since
Bratislava	ZST	48°11'46''	17°06'09''	250	grano-diorite	Z, N, E	3xSM-3	1.75	dig., trig. telemetry	1976
						Z, N, E	3xSKD	22.5	dig., trig. telemetry	1997
Šrobárová	SRO	47°48'48''	18°18'48''	150	neogenic sediments	Z, N, E	3xSKM-3	1.58	dig., trig. ZIP disk	1964
Hurbanovo	HRB	47°52'25''	18°11'34''	115	neogenic sediments	N, E	2xMainka	ca. 8	analog., cont.	1902
Modra	(MOD)	48°22'23''	17°16'39''	520	quartzite	Z, N, E	Le-3D	1.00	dig., trig. mg. tape	1992
Vyhne	(VYH)	48°29'38''	18°50'10''	450	ryolite	Z, N, E	Le-3D	1.00	dig., trig. mg. tape	1990
Košice	(KOS)	48°43'48''	21°15'01''	206	granite	Z, N, E	Le-3D	1.00	dig., trig. mg. tape	1990

Table 1. The seismic stations of the Slovak National Seismic Network (November 1999)

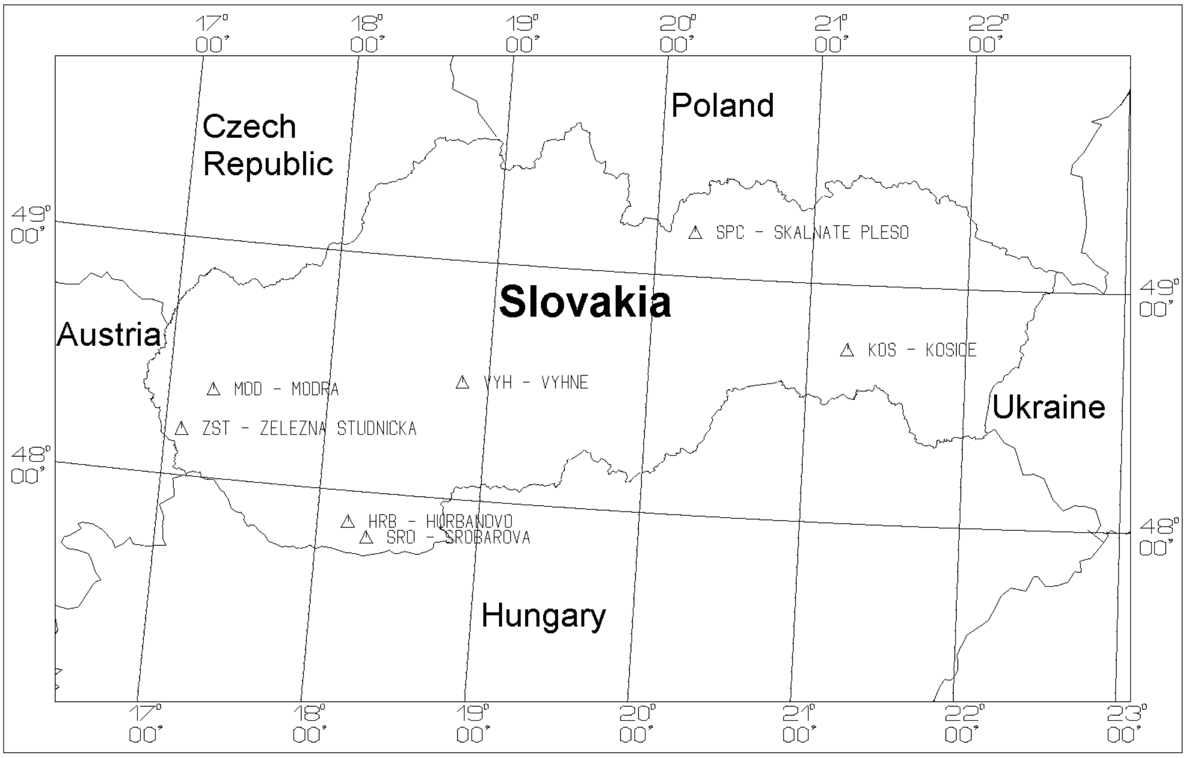

Figure 1. The seismic stations of the Slovak National Seismic Network.

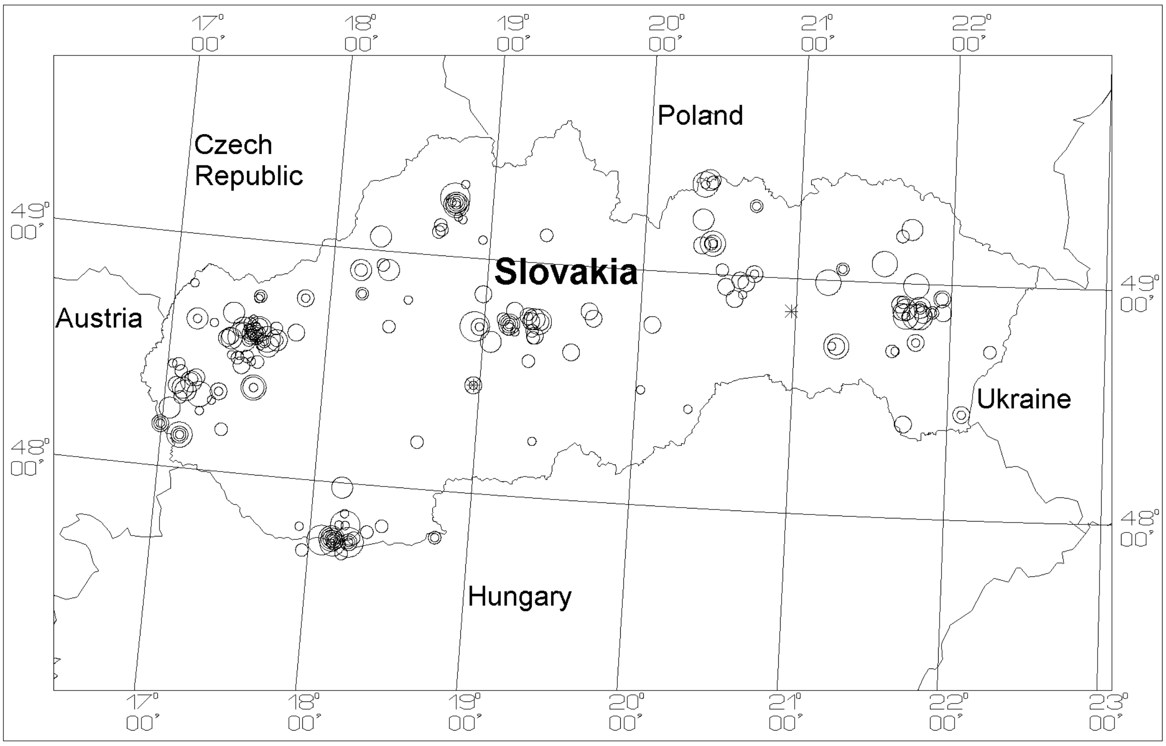

Figure 2. Macroseismically felt earthquakes with the epicenters on the territory of Slovakia since 1034.

2. EARTHQUAKES

EARTHQUAKE ACTIVITY

The territory of Slovakia, which is covered mostly by the Western Carpathians, can be characterized by a moderate seismic activity. This is documented by descriptive and parametric catalogues, as well as several case studies. The first modern earthquake catalogues were compiled by Hungarian seismologist *Réthly* (1952), and Czech and Slovak seismologists *Kárník, Michal & Molnár* (1957). The catalogues include verbal description of the earthquakes, an extensive list of references and earthquake parameters for selected earthquakes. Recent parametric catalogues were compiled by *Schenková & Kárník* (1981) and *Labák & Brouček* (1996). Case studies were performed for crucial earthquakes - e.g., *Szeidovitz* (1987), *Brouček, Eisinger, Farkas, Gutdeutsch, Hammerl & Szeidovitz* (1991), *Labák, Brouček, Gutdeutsch & Hammerl* (1996).

More than 590 macroseismically felt earthquakes with the epicenters within the territory of Slovakia since 1034 are documented in *Labák & Brouček's* (1996) catalogue (Fig. 2). Given the fact that more than 550 of them occurred after the June 28, 1763 Komárno earthquake, it is clear that the actual number of the macroseismically felt earthquakes during the documented period must certainly be considerably higher than 590. In fact, each of the four known crucial earthquakes - the June 5, 1443 Central Slovakia; June 28, 1763 Komárno; January 15, 1858 Žilina, and January 9, 1906 Dobrá Voda earthquakes - stimulated interest in the research of earthquakes in the Hungarian Kingdom to which the present Slovak territory belonged. Consequently, the periods separated by dates of the four earthquakes differ from each other by the number of documented earthquakes, size of the smallest documented earthquakes, and quality of the documents. The numbers of documented earthquakes are given in Tab. 2.

Period \ size	$I_0 \geq 8$	≥ 7 < 8	≥ 6 < 7	≥ 5 < 6	<5	I_0 not assessed	Total no.
1034-1443						3	**3**
1443-1763	3	5	4	14	8	3	**37**
1763-1858	3	9	11	14	159		**196**
1858-1906		1	14	12	92		**119**
1906-1996	1	5	5	27	200		**238**
Total no.	**7**	**20**	**34**	**67**	**459**	**6**	**593**

Tab. 2. The numbers of documented earthquakes of different size in five different periods for the territory of Slovakia. Irregular distribution of the documented earthquakes in time is obvious.

In addition to the macroseismic catalogues, the seismic activity is documented by seismometrically localized earthquakes. 35 earthquakes with a local magnitude larger than approximately 2.5 have been localized for the whole territory of Slovakia since 1956. All data strongly indicate the existence of several earthquake focal zones - Malé Karpaty Mts. (also called Modra-Pernek), Dobrá Voda, Žilina, Central Slovakia, Komárno and Slánske vrchy Mts.

Data on a microseismic activity is, in fact, restricted to the Dobrá Voda focal zone. Since 1987 more than 60 earthquakes with a local magnitude larger than or equal to 1 have been recorded and localized by a local network. Consistent clustering of the macroseismically and instrumentally localized earthquake epicenters in the Dobrá Voda focal zone means that Dobrá Voda is the best spatially defined focal zone on the territory of Slovakia.

For about 10% of the total number of the macroseismically located earthquakes macroseismic focal depths were determined. They range from several kilometers down to approximately 15-18 km. The focal depth interval is confirmed by seismometric hypocenter locations for the period of 1956-1996. The Western Carpathians and the surrounding region can be, therefore, characterized by shallow crustal earthquakes.

The four above mentioned events are key earthquakes in the analysis of seismic hazard for the Slovak territory. The June 5, 1443 Central Slovakia earthquake is the first earthquake for which several earthquake contemporary documents were found (*Labák, Brouček, Gutdeutsch & Hammerl* 1996). The earthquake completely destroyed the mining city of Banská Štiavnica and mining works in the surrounding area, and heavily damaged the city of Kremnica. Casualties and injuries were also reported. The earthquake was also felt in Vienna (Austria), Brzeg and Krakow (Poland), and Brno (Czech Republic). The epicentral intensity of the earthquake was larger than 8° EMS-98.

The June 28, 1763 Komárno earthquake destroyed 7 churches and 279 houses in the city of Komárno. 63 people were killed and 102 injured (*Brouček, Eisinger, Farkas, Gutdeutsch, Hammerl & Szeidovitz* 1991). The earthquake caused panic in Komárno and neighboring villages. Cracks in the ground and sand in the wells were also reported. The earthquake caused damage to buildings also in Budapest (Hungary). An area bigger than the present Slovak territory was shaken. The earthquake was felt also in Beograd (Yugoslavia), Timisoara (Romania), Leipzig (Germany). The epicentral intensity was 8-9° MSK-64. The earthquake stimulated researchers in Hungary to pay more attention to earthquakes and their effects at that time. The 1763 Komárno earthquake was followed by a series of earthquakes in the Komárno focal zone almost over the next one hundred years.

The January 15, 1858 Žilina earthquake is the first earthquake in the Western Carpathians for which a systematic collection of observations and their analysis was performed by the earthquake contemporary researchers (*Labák & Hammerl* 1997). For the first time in the country a kind of macroseismic questionnaire was used to investigate the earthquake. The earthquake caused damage to all houses in the city of Žilina. It was felt as far as in Esztergom (Hungary), Wroclaw (Poland) and in Bohemia. The epicentral intensity was 7-8° EMS-98.

The January 9, 1906 Dobrá Voda earthquake, the biggest earthquake on the territory of Slovakia in the 20th century, is the first instrumentally recorded earthquake with the epicenter on the territory of Slovakia. Several seismic stations in Europe (e.g., Munich, Vienna, Göttingen, Kremsmünster, Trieste, Pola) recorded the earthquake. The earthquake was felt also in Austria, Hungary and Bohemia. The earthquake caused heavy damage in the village of Dobrá Voda. Changes of the water level were reported from several neighboring villages. A new spring was found in the epicentral area. Near the Dobrá Voda village cracks in the ground were found. The epicentral intensity was 8-9° MSK-64. The surface wave magnitude was 5.7.

Epicentral intensities of the three largest documented earthquakes - the June 5, 1443 Central Slovakia; June 28, 1763 Komárno, and January 9, 1906 Dobrá Voda earthquakes - allow for the lower bound estimate of the maximum expected magnitude of M_S=5.7. The recent estimate of the maximum expected magnitude in the Western Carpathians of 6.2-6.8 is determined by *Labák, Bystrická, Moczo, Campbell & Rosenberg* (1998) who performed the integrated seismic hazard analysis for the Bohunice nuclear power plant site.

TECTONIC CHARACTERIZATION OF THE SLOVAK TERRITORY

Geophysical research of the deep lithosphere structure as well as available geologic and tectonic data allows to define seismogenic zones in the Western Carpathians (*Kováč, Bielik, Hók, Kováč, Kronome, Labák, Moczo, Plašienka, Šefara & Šujan* 1999). In most cases the earthquakes can be correlated with fault structures in the Western Carpathians. The most remarkable and important first-order tectonic line is the zone of Pieniny Klippen Belt in the wider surroundings of the Dobrá Voda depression coinciding with the Mur-Mürz-Leitha tectonic line and with the Pericarpathian fault on the NW margin of the Malé Karpaty Mts., respectively. The Pieniny Klippen Belt represents a topographical dissection of contact of the block of the Western Carpathian Internides and the stable European Platform. The Mur-Mürz-Leitha line represents in the area of the Vienna Basin a topographical dissection of contact of the Eastern Alps with the block of the Western Carpathian Internides. Both these tectonic lines represent subvertical boundaries with a probable Tertiary tectonic activity.

The earthquakes concentrated mainly in the area east and SE of cities Banská Bystrica and Brezno in Central Slovakia can be related to the Čertovica line. The Čertovica line is a surface projection of the thrust plane of the Veporicum over the Tatricum. Based on geologic and geophysical data this sector of the Čertovica Line is considered as a recently active due to extensional reactivation. Earthquakes are probably released also on the Hron fault system of the ENE-WSW direction. It is noteworthy that this system, similarly as the Dobrá Voda system, is well distinctive in the recent morphology and can be well traced by the remote sensing methods. This SE inclined source zone can be also related to the earthquake events released on the N-S trending brittle fault deformations surrounding the Turiec Basin (with less data), as well as along the continuation of these faults to the Central Carpathian Neovolcanic area.

A third important geological structure is the Hurbanovo-Diósjenõ fault zone**,** which is most likely a continuation of the Rába line on the Slovak territory. The Rába line in Hungary is of the NE-SW orientation. It probably represents overthrust which separates Austroalpine nappes on the NW and rock masses of the Transdanubian Central Range. On the territory of Slovakia this line continues as the Hurbanovo-Diósjenõ line of the E-W to ENE-WSW orientation which also represents surface projections of the original thrust planes of the Transdanubian units. These thrust planes were reactivated during the Miocene as low-angle extensional faults dipping to the SE. Earthquakes are generated on these low-angle surfaces. These assumptions were proved by several industrial as well as deep seismic profiles correlated with drills and with density modeling which presumed the formation of the Danube Basin to be primarily controlled by a system of low-angle faults. The Rába line (overthrust) is neotectonically reactivated as a partial fault system rooted in the lower crust. Such an interpretation is corroborated by results of recent studies according to which rheology of the lower crust in the Pannonian region is significantly different from that of the upper crust and its characteristic deformation is ductile shear. The position of the normal faults was strongly influenced by the Cretaceous thrust planes because normal faults usually merge with earlier compressional detachment planes at a mid-crustal depth.

3. SEISMOLOGICAL RESEARCH

HISTORICAL REVIEW

Earlier history

The June 28, 1763 Komárno (then Komárom in the Hungarian language) earthquake that killed 63 people, injured 102, damaged hundreds of houses and left many people homeless, stimulated an effort to prepare a first catalogue of earthquakes on the Hungarian part of the territory of the Austro-Hungarian Monarchy. Today's territory of the Slovak Republic (Slovakia) belonged then to the Austro-Hungarian Monarchy. As a result of the effort, Jesuit *J. B. Grossinger* (1783) published the first catalogue in the Latin language. A similar catalogue was compiled by *J. Sternberg* (1786) in the German language. The 1763 Komárno earthquake was followed by a series of earthquakes in the Komárno focal zone almost over next one hundred years. This and $I_o \approx 7-8^\circ$ MSK January 15, 1858 Žilina (then Zsolna in the Hungarian language or Sillein in the German language) earthquakes strongly stimulated interest of Austrian and Hungarian scientists in the earthquake activity of the Western Carpathians.

Modern history

When the Hungarian Geological Society, accepting a proposal by geologist Franz X. Schafarzik, established its Seismological Commission in 1881, today's territory of the Slovak Republic was still a part of Hungary. From the very beginning, the Commission recognized a need to establish seismographic stations at important places of the country. In 1900 a Hungarian seismologist, Professor Radó Kövesligethy (later the first general secretary of the IASPEI), visited the institute in Strasbourg as well as some seismographic stations in the Western Europe in order to acquire more knowledge on seismometry. Eventually, R. Kövesligethy proposed to establish a network of five seismographic stations in Hungary. One of the proposed places was Ógyalla (original Hungarian name for today's Slovak town Hurbanovo) where meteorological observatory existed.

Dr. Miklós Konkoly-Thege, a Hungarian earl, astronomer and science enthusiast, built his private astronomical and geomagnetic observatory in Ógyalla in 1874. In 1890, Konkoly-Thege was named director of the Royal Hungarian Meteorological and Geomagnetic Institute in Budapest, the capital of Hungary. Due to growing industry in Budapest it was decided to move the meteorological and geomagnetic observatory to then small quiet village Ógyalla. F. Schafarzik, R. Kövesligethy and M. Konkoly-Thege attended the first international seismological meeting that was held on April 11-13, 1901 in Strasbourg. The impact of the meeting was immediate and evident: The Royal Hungarian Meteorological and Geomagnetic Institute decided to include seismometric observations into its activities.

Consequently, a new pavilion in the park of the Ógyalla observatory was built in 1901. By the end of 1901 a pair of the Strasbourg horizontal pendulums was installed and on January 1, 1902 the recording earthquakes started. In the following years, earthquake observations in Ógyalla, as well as at other Hungarian stations, were more or less regularly reported by Dr. Antal Réthly in yearly bulletins, e.g., *Réthly* (1907). Today, the Hurbanovo seismic station (HRB) is still in operation and with its mechanical Mainka seismograph (operating since 1909) it is one of the oldest seismic stations in Europe. More details on the HRB station can be found in *Pajdušák* (1997).

After the Czechoslovak Republic - a joint state of Czechs and Slovaks - was established on October 28, 1918, Ógyalla became a part of its territory with a Slovak name Stará Ďala. On December 29, 1920 Institute of Geophysics at Charles University in Prague was founded and Czech seismologist Professor Václav Láska became his first director. Until 1938, operation of the seismic station in Stará Ďala and seismological research on the territory of Slovakia was controlled by Czech seismologists. J. Kaván, J. Sýkora and A. Dittrich served as directors of the observatory and seismic station. In April 1929 the Institute of Geophysics was withdrawn from the competence of the Charles University and renamed as the Czechoslovak Institute of Geophysics. Dr. Alois Zátopek, who joined the institute in 1934, analyzed earthquake observations in Stará Ďala and performed macroseismic studies of several earthquakes felt in the Western Carpathians. Earthquake observations for the period of 1923-1938 are summarized in a special report by *Zátopek* (1940). More details on seismology in Prague can be found in the Czech National Centennial Report.

On November 2, 1938, after the Vienna Arbitration, the Southern regions of the Slovak territory, including Stará Ďala, were annexed by Hungary. Some breaks in operation of the seismic station are reported. During the World War II, probably in 1943, the seismic station Skalnaté Pleso (SPC) in the Vysoké Tatry mountains started its operation with the horizontal Wiechert seismograph.

After the World War II, the southern regions were returned to the Czechoslovak Republic. The Prague Institute, dissolved during the World War II was re-established as the State Institute of Geophysics with Professor Bedřich Šalamon as a director. The Hurbanovo observatory became a State meteorological and geophysical observatory. Joint yearly bulletin of the Czechoslovak seismic stations Prague, Cheb, Hurbanovo and Skalnaté Pleso was issued since 1950, starting with the bulletin by *Zátopek & Vaněk* (1950) for the year of 1949. In 1953 Ing. Alexander Molnár joined the observatory and became, in fact, the first Slovak seismologist. He focused on analysis of earthquakes in the Western Carpathians, contributed to establishment of the Bratislava (BRA) seismic station in 1956, and co-authored an important earthquake catalogue *Kárník, Michal & Molnár* (1957).

The Slovak Academy of Sciences (SAS) was legally established by decision of the Slovak National Council on June 18, 1953. Later in 1953, Presidium of the SAS established Cabinet of Geophysics SAS with the Hurbanovo observatory, including the seismic station, as its basic part. The Skalnaté Pleso (SPC) seismic station was also associated to the cabinet. The cabinet was renamed as the Geophysical laboratory SAS in 1954. Professor Tibor Kolbenheyer became the first director. Geomagnetic and seismometric measurements were the most important scientific activities of the laboratory. In 1962, Ivan Brouček joined the laboratory and focused on analysis of the earthquake activity and seismic hazard in Slovakia. He closely cooperated with Czech, Hungarian and Austrian seismologists on analysis of historic earthquakes, contributed to establishment of the Šrobárová (SRO) seismic station in 1963, and co-authored a comprehensive atlas of isoseismal maps for the Central and Eastern Europe (*Procházková & Kárník, eds.* 1978) and earthquake catalogue *Kárník, Procházková & Brouček* (1981).

In 1965 the laboratory was renamed as the Geophysical Institute of the Slovak Academy of Sciences. In 1967 Klára Mrázová joined the institute. Being specialized in the analysis of seismic records, she introduced the use of computers in data processing from the Slovak seismic stations, twenty years had been editing yearly seismometric bulletins (the first one published in 1972 for the year of 1966), and co-organized regular Czechoslovak seismological workshops. She became the head of the Department of Seismology when it was established within the Geophysical Institute in 1983. Improvement and development of the national seismic network is mainly due to Dr. Pavel Pajdušák who joined the institute in 1973. He contributed to establishing the seismic stations Bratislava-Železná Studnička (ZST) in 1976, Vyhne in 1990, Košice in 1991 and Modra in 1992, and participated in an investigation of structure and anisotropy of the lithosphere conducted by Dr. Vladislav Babuška and Dr. Jaroslava Plomerová of the Geophysical Institute of the Czechoslovak Academy of Sciences in Prague. Since 1988 he had been the head of the Department of Seismology.

Theoretical and computational seismology in Slovakia was introduced by Dr. Peter Moczo, a graduate of the Charles University in Prague, student of Professor Vlastislav Červený and Dr. Jiří Zahradník, who joined the institute in 1981. He focused on development of computational methods, algorithms and computer codes for numerical modeling of seismic ground motion and site effects of earthquakes, and on investigation of seismic motion in local surface geologic structures. In 1983 he started teaching regular courses of seismology and seismic wave propagation at the Faculty of Mathematics and Physics, Comenius University in Bratislava. P. Moczo became head of the Department of Seismology in 1994 and soon he attracted young people to work in the department.

Present

At present, the Department of Seismology is one of five scientific departments of the Geophysical Institute of the Slovak Academy of Sciences. The other departments are Dept. of Geomagnetism, Dept. of Gravimetry and Geodynamics, Dept. of Atmospheric Boundary Layer, and Dept. of Radiation and Climate. Dr. Peter Moczo, Associate Professor of Geophysics, is the head, and Dr. Peter Labák, Mgr. Jozef Kristek, Mgr. Erik Bystrický, Mgr. Miriam Kristeková, Mgr. Monika Kováčová, Ing. Martin Bednárik, Mgr. Andrej Cipciar, Dr. Mária Lucká and Mgr. Alena Bystrická are researchers and PhD. students in the Department of Seismology. The department operates the national network of seismic stations, participates in monitoring in two local seismic networks deployed around the nuclear power plants Jaslovské Bohunice and Mochovce; analyzes historical earthquakes and the recent earthquake activity on the Slovak territory; performs seismic hazard studies for the whole territory as well as for important localities; develops computational methods for numerical modeling of seismic ground motion and site effects of earthquakes; investigates anomalous seismic motion in local surface geologic structures. The research activities will soon also include field measurements and methodology of seismic signal analysis. Future activity will be due to the decision that the Geophysical Institute will serve as a national CTBTO (Comprehensive Test Ban Treaty Organization) data center. P. Moczo teaches seismology and seismic wave propagation at the Faculty of Mathematics and Physics, Comenius University in Bratislava. Researchers of the department participate in several international research grant projects and closely cooperate with seismologists in the Czech Republic, Austria, France, Japan and other countries.

Importance of seismic hazard analysis, especially for localities of crucial importance, is well recognized in the country. This may be illustrated by the fact that P. Moczo serves as a representative of the Slovak Academy of Sciences in the Nuclear Safety Committee of the Slovak Electric Power Plants. Monitoring of earthquakes in the national seismic network is financially supported by the Ministry of Environment of the Slovak Republic in the framework of the project Partial Monitoring System of Geologic Factors of Environment. On the other hand, the financial situation of the country in last decades has not allowed to improve and extend the national seismic network so that it would be capable to cover the whole Slovak territory. The existing network does not cover the northern and eastern regions of Slovakia. Therefore, monitoring and localizing earthquakes as large as $M_L = 2.5 - 3$ in those regions is not possible.

NUMERICAL MODELING OF SITE EFFECTS AND EARTHQUAKE GROUND MOTION

Development of computational methods

Research has been focused on development of methods, algorithms and computer codes for numerical modeling of seismic wave propagation and seismic ground motion in complex realistic models of surface geologic structures including block/layered media with nonplanar interfaces, large velocity contrasts, and realistic model of attenuation. While the asymptotic ray theory was employed in the beginning, the finite-difference method has become a dominant computational method in later effort. Recently, memory optimization procedures have been developed and applied in order to facilitate the use of the finite-difference method in seismic ground motion modeling for large-scale sedimentary basins and valleys.

A method of seismic response analysis of 2D heterogeneous surface geologic structures based on the ray method and on the application of the Debye procedure to include slight attenuation has been developed (*Moczo, Bard & Pšenčík* 1987). The frequency-domain approach to compute the response was applied since it is more efficient than computation in the time domain that includes construction of the ray synthetic seismograms by summation of elementary seismograms. Moreover, the frequency-domain approach allows simple re-computation of time histories for different source-time functions once the frequency response is known.

The computation is performed in two steps. In the first step, rays, travel times, complex-valued ray amplitudes and global absorption factors of individual elementary waves are computed. In the second step, the frequency response (spectral transfer function) and time histories of the response are computed.

The method was applied to the analysis of the SH response of the canonical model of a sedimentary basin. A very good agreement with results of the discrete-wavenumber method has been found. A detailed inspection of elementary waves and the corresponding rays revealed two main types of wave propagation inside the basin: the horizontally propagating local surface waves and the vertically propagating wave in the central part of the basin.

Systematic comparison of the ray and discrete-wavenumber synthetics showed that the approximation of the complex interference wave field by superposition of multiply reflected waves with geometric ray paths fails if wavelengths are larger than the minimum radius of curvature of the basin boundary. Similar comparison for basin with a velocity gradient showed that the ray method can be applied if wavelengths are considerably smaller than $v/|\nabla v|$, where v is a wave propagation velocity. Given the fact that the frequency range 0.5 - 10 Hz has to be considered in practical applications, condition $0.5Hz >> |\nabla v|$ imposes considerable restrictions if a velocity gradient in sediments is to be taken into account.

The ray method was applied to compute a seismic response of a 2D realistic model of weakly laterally heterogeneous geologic structure beneath site of the then planned nuclear power plant Blahutovice (*Moczo & Baňas* 1988). The ray-method results were compared with results of the 1D matrix-method computations applied locally along the 2D profile. Dominant role of the surface sedimentary layer in forming the seismic response was found.

A finite-difference technique for the SH modeling of seismic wave propagation and seismic ground motion was developed (*Moczo* 1989). A displacement finite-difference scheme was used on a rectangular grid with varying size of a grid spacings in both directions. A medium composed of layers and blocks is assumed. A smooth velocity variation is approximated by a piece-wise linear variation that is then strictly taken into account in evaluating effective shear moduli in the horizontal and vertical directions, and density. The technique allows better adjusted modeling of a medium and can yield in many cases more efficient computations as compared to those on a grid with a constant size of grid spacing. The technique gave very good results in the case of grids with a gradual change of size of a grid spacing and grids with an abrupt change of size of a grid spacing.

The technique was extended for a viscoelastic medium by *Moczo & Bard* (1993) in order to account for realistic attenuation. Rheology of the generalized Maxwell body was assumed and *Emmerich & Korn's* (1987) method was applied.

Zahradník, Jech & Moczo (1990b) tested a method of approximate aposteriori absorption correction of seismic response computed for a perfectly elastic medium. Possibility to correct an elastic solution using dissipation operators was known before but decomposition of a wave field into elementary waves was assumed. The method suggested by *Zahradník, Jech & Moczo* (1990a) allows application of an aposteriori attenuation correction in the case of a complex, e.g. interference, wave field not decomposed into elementary waves if a spatially constant quality factor is assumed.

Zahradník, Moczo & Hron (1993) investigated consistency of four SH and P-SV displacement finite-difference schemes at internal material discontinuities and free surface. Theoretical analysis showed principal problems of consistency of P-SV schemes at discontinuities other than horizontal and vertical ones coinciding with grid lines. The importance of harmonic averaging in definition of the effective material parameters was demonstrated in the case of the SH scheme at a horizontal discontinuity not coinciding with a grid line. A P-SV finite-difference scheme for a flat surface was developed. The scheme supplements the *Kummer, Behle & Dorau's* (1987) scheme for interior grid points.

An efficient finite-difference algorithm for computation of the SH seismic ground motion in local geologic surface heterogeneous attenuating structures was developed (*Moczo, Labák, Kristek & Hron* 1996). The algorithm is based on use of the $h \times h\_2h \times 2h$ combined (discontinuous) rectangular spatial grid. The upper part of the computational region is covered with the $h \times h$ grid, while the lower part (with a larger S-wave velocity) is covered with the $2h \times 2h$ grid. The contact of the two grids is not solved by linear interpolation since this would decrease the order of approximation. Instead, having the contact in the homogeneous medium, a sum of both spatial derivatives (i.e., $v_{xx} + v_{zz}$) is directly approximated by a special formula. The algorithm can be also used in the case of $1 < \beta / \beta_{\min} < 2$. It is just necessary to apply the sampling criterion in the homogeneous basement first in order to determine the grid spacing of the $2h \times 2h$ grid.

The algorithm was advantageously used to perform numerical simulations for investigation of a two-dimensional (2D) antiplane resonance (*Moczo, Rovelli, Labák & Malagnini* 1995 and *Moczo, Labák, Kristek & Hron* 1996). The algorithm enabled to save up to 75% of the grid points compared to the regular $h \times h$ grid that would cover the same computational region.

A new hybrid method for computation of the P-SV seismic motion in heterogeneous attenuating local structures with flat free surface was developed (*Zahradník & Moczo* 1996). The two-step method combines the discrete-wavenumber (DW) and finite-difference (FD) methods. In the first step, the DW method is used to calculate the source radiation and wave propagation in a 1D background medium that serves to model path between the source and local surface structure. The local surface structure itself is not included in the model in the first step. The DW method was chosen because it enables to calculate the radiated wave field from dislocation sources accurately and efficiently. Principally, use of other suitable methods is possible. During the first step a complete wave field (that is a superposition of the radiated wave field plus wave field reflected at the free surface) is recorded along two excitation lines that may create three sides of a rectangle that would surround the local heterogeneity. In the second step, the FD method is used to compute wave motion in the local heterogeneity. The computational region usually is smaller than that in the first step. The wave field recorded during the first step is applied along the excitation lines. The source is not directly included in the second step (it is included in the recorded wave field applied at the excitation lines).

The hybrid method enables to compute seismic ground motion for those source-local structure configurations (e.g., the case of a distant source and complex surface sedimentary structure) that could not be computed by a single method due to very large computer time and memory requirements.

While the previous method is applicable to media with a flat free surface, the free-surface topography often should be included since it may have strong influence on seismic ground motion. Therefore, *Moczo, Bystrický, Kristek, Carcione & Bouchon* (1997) developed a generalization of the above method. Their hybrid approach combines the DW, FD and finite-element (FE) methods. It is designed for computation of the P-SV seismic motion in heterogeneous attenuating local geologic structures with the free-surface topography. The role of the DW method is the same as in the above described DW-FD method. The difference is in the second step where, instead of the FD method, a combined FD-FE algorithm is used to compute seismic motion in a local surface topographic/sedimentary structure. The FE method is used to cover fully or partially (e.g., in a narrow strip along the free surface) the topographic feature while the FD method is applied to a major part of the computational region. The FE method is applied along the free surface in order to eliminate principal problem of the FD method to satisfy the traction-free condition in a sufficiently accurate and stable manner. The FD method is applied to a major part of the model in order to avoid large computer time and memory that would be required by the use of the FE method for the whole model.

In developing the FD-FE algorithm for a viscoelastic medium the attenuation corresponding to rheology of two generalized Maxwell bodies was incorporated into the standard FE formulation. A time-integration scheme for the FD-FE algorithm was also developed. The FD-FE algorithm is general and can also be used without the two-step hybrid procedure that includes the DW method if the wave field excitation is solved within the FD-FE algorithm.

A strip of finite elements was shown as a suitable transition zone between the $h \times h$ and $2h \times 2h$ FD spatial grids.

Moczo, Kristek & Lucká (1998) and *Moczo, Lucká, Kristek & Kristeková* (1999) presented a 2^{nd}-order finite-difference scheme for modeling seismic wave propagation and seismic ground motion in 3D heterogeneous media. The scheme is based on the displacement formulation. Contrary to the classical displacement FD schemes the presented scheme makes use of effective material parameters determined as harmonic averages between neighboring grid points. Such averaging was well-known and used for modeling the SH waves. *Zahradník* (1995) suggested a new approximation of the second mixed spatial derivative that is necessary in the P-SV and 3D displacement FD schemes. The presented 3D scheme makes use of *Zahradník's* approximation.

The scheme was shown to be very accurate in media with $\alpha / \beta \leq 2$ and not very high velocity contrast. In such media, the scheme was shown capable to account for a position of an internal material discontinuity more accurately than recent velocity-stress and displacement-stress staggered-grid schemes. This again shows that none of the existing FD schemes is the best and universal scheme for all possible problem configurations.

Applications of the 3D FD modeling to large sedimentary basins require very large computer memory if the modeling covers frequencies up to 1 Hz and larger. Usually, a required large memory is not available. Therefore, the FD algorithms and codes have to be memory-optimized.

The combined memory optimization (CDMO) developed by *Moczo, Kristek, Kristeková & Lucká* (1998); *Moczo, Kristek & Lucká* (1998) and *Moczo, Lucká, Kristek & Kristeková* (1999) naturally comprises core memory optimization and disk memory optimization.

Core memory optimization (presented recently by *Graves* 1996) is based on keeping only a limited number of grid planes in core memory at one time. For such a subset a maximum possible number of time updates is performed. The subset of planes repeatedly moves throughout the entire model space until a desired time window is computed. As the subset of planes repeatedly moves throughout the model space, displacement values (or, generally, wave field characteristics) are successively (plane by plane) and periodically overwritten in disk memory. While the core memory optimization reduces problem with core memory, it may impose considerable problem with disk memory since this is used instead of core memory. In the case of realistic large-scale models the size of required disk space and number of the I/O operations can be too large. Large number of the I/O operations is a serious problem and creates a bottleneck of the computations. Moreover, subroutines performing the I/O operations cannot be parallelized, though a major part of the FD codes can be.

Therefore, the CDMO combines the core memory optimization with disk memory optimization. First, a discrete wavelet transform is applied to the two-dimensional array of the displacement (or particle velocity) - component values in a grid plane that is to be stored in disk. The wavelet transform decreases an information entropy of the array. A data compression is then applied to the set of the wavelet coefficients. Consequently, only relatively small streams of zeros and ones are written and stored in disk.

The combined memory optimization significantly reduces memory requirements and allows for a balanced use of core and disk memory. It is applicable to any explicit FD scheme on a conventional or staggered grid. It makes the FD modeling of large-scale problems and inclusion of a realistic attenuation more affordable. This was clearly demonstrated in the simulation of the Kobe 1995 mainshock (*Kristek, Moczo, Irikura, Iwata & Sekiguchi* 1998).

Moczo, Kristek & Bystrický (1999a) reviewed memory requirements of four basic types of the FD schemes for the 3D seismic ground motion modeling (displacement, displacement-stress, displacement-velocity-stress and velocity-stress) in perfectly elastic and viscoelastic media, and suggested a combination of several memory-optimization procedures for the FD modeling of seismic ground motion in media with realistic model of attenuation.

Moczo, Kristek & Halada (1999) investigated stability and grid dispersion in the 3D 4^{th}-order in space, 2^{nd}-order in time, displacement-stress staggered-grid FD scheme. Though only displacement-stress scheme is explicitly treated, all results also apply to the velocity-stress and displacement-velocity-stress FD schemes. Independent stability conditions for the P and S waves were derived by exact separation of equations for the two types of waves. Since the S-wave group velocity can differ from the actual velocity as much as 5% for the sampling ratio 1/5 (that is usually used in modeling), it is recommended to sample a minimum S wavelength by 6 grid spacings. Grid dispersion is strongest for a wave propagating in the direction of a coordinate axis and weakest for a wave propagating along a body diagonal. Grid dispersion in the 4th-order scheme for the sampling ratios $s = 1/5$ and $s = 1/6$ is smaller than grid dispersion in the 2nd-order scheme for $s = 1/10$ and $s = 1/12$, respectively.

Similarly, *Moczo, Kristek & Bystrický* (1999b) investigated stability and grid dispersion in the P-SV 4th-order staggered-grid schemes.

Numerical modeling of anomalous seismic ground motion

Moczo & Bard (1992, 1993) investigated the SH wave field in a model of a semi-infinite horizontal surface soft layer embedded in a stiffer homogeneous halfspace. The investigation was motivated by consistent macroseismic observations of a significant increase in a damage intensity in narrow strips along strong lateral discontinuities. The wave field was simulated by the displacement FD method. Two basic phenomena are observed: a 1D vertical resonance and an efficient wave diffraction from the discontinuity into the layer. They induce a frequency-dependent amplification and a significant differential motion. The differential motion close to the discontinuity is associated with a complex wave field. Away from the discontinuity, it is associated with the passage of the Love waves. While the amplification of the translational motion is comparable to the 1D value (due to the vertical resonance), the time-domain differential motion always (i.e., for different values of impedance contrast and attenuation, and regardless of the presence of a velocity gradient inside the layer) exhibits a sharp peak close to the discontinuity. For example, in the case of the velocity contrast 1:5, the differential motion reaches a significant value of $3 \cdot 10^{-3}$ for a maximum displacement 1 cm of the incident plane wave in the halfspace. The attenuation mainly affects the amplitude decrease of the differential motion with distance from the discontinuity. The velocity gradient in the layer amplifies both the translational and differential motions. It is concluded that the reported observations of an increased damage near such geologic structures are likely connected with effects of the differential motion on structures.

Zahradník, Moczo & Hron (1992a, b, 1994) participated in the international blind prediction test organized by the Japanese working group on effects of surface geology and the IASPEI / IAEA joint working group on effects of surface geology. In the experiment, all participants were provided with weak-motion records from a rock-outcrop and a surface-sediment stations as well as a standard geotechnical model of the Ashigara valley, Japan, test site. Weak- and strong-motion for determined stations on and in sediments were to be predicted. The FD method (*Moczo* 1989; *Moczo & Bard* 1993) was employed in numerical simulations. The paper by *Zahradník, Moczo & Hron* (1994) presents two approaches of prediction and discusses possible reasons why the prediction was not successful. Generally, however, the prediction belongs to better predictions (as, compared with others), 2D and 3D predictions do not differ much from 1D predictions (likely due to relatively strong attenuation), and numerical predictions for some stations were significantly less successful than for other stations.

The seismic response of the geologic structure beneath the colosseum in Rome was investigated using a 2D SH numerical modeling (*Moczo, Rovelli, Labák & Malagnini* 1995; *Moczo, Rovelli & Labák* 1995). Computations indicate that the southern part of the colosseum may be exposed to a seismic ground motion with significantly larger amplitudes, differential motion and longer duration than the northern part. The significant difference is due to the fact that the southern part of the colosseum is underlain by a sediment-filled valley created by sedimentary filling of the former tributary of the river Tiber. Due to structural uncertainties, two velocity models were considered. In both models, a 2D resonance was observed. Results of the numerical computations together with historical analysis indicate that the earthquakes and site effects are likely responsible for the fact that the southern part of the outer wall of the colosseum is missing while the northern part is relatively well preserved.

Numerical modeling of seismic response of the local geologic structure beneath the colosseum in Rome, Italy, indicated that a 2D resonance can develop in sedimentary valleys that do not satisfy *Bard & Bouchon's* (1985) existence condition. Therefore, an extensive numerical investigation of a 2D antiplane resonance in certain types of surface geologic structures was carried out (*Moczo, Labák, Kristek & Hron* 1996). The models included closed sediment-filled valleys in a homogeneous halfspace, closed valleys embedded in a horizontal surface layer, and a trough at the bottom of the horizontal surface layer.

It was found that a 2D resonance can arise in the valleys embedded in a medium with a horizontal surface layer (whose thickness is a half the maximum valley depth), even in the case when the valley-layer velocity contrast is well below Bard & Bouchon's existence value.

The fundamental and first higher modes are not much sensitive to the presence of the surface layer whose thickness is equal to or smaller than half the maximum valley depth and whose shear-wave velocity is larger than that in the valley and smaller than the velocity in the basement. The differential motion due to the fundamental and first higher modes, and the spectral amplification due to the first higher mode are more sensitive to the valley shape ratio and the shape of the valley than to the valley-basement velocity contrast if the contrast is high enough. Compared to the maximum spectral amplification, the maximum time-domain differential motion due to the fundamental mode is much less sensitive to the valley-basement velocity contrast. The twice smaller valley-basement contrast implies approximately twice smaller spectral amplification, at the corresponding resonant frequencies, but it affects only little the differential motion. This suggests that two valleys with very different levels of the spectral amplification may be „comparably dangerous“ due to close maximum time-domain differential motions.

A simple trough at the bottom of the horizontal surface layer can give rise to the fundamental mode of a 2D resonance whose frequency, spectral amplification, and the maximum time-domain differential motion are very close to those in the closed sediment valley.

The computations confirm that the resonant phenomena are to be expected in many configurations of sediment valleys and basins. The likelihood of the resonance is relatively high since the velocity contrast that determines the occurrence of the resonance seems to be the contrast between the sediments and the bedrock below the valley/basin.

Moczo, Bystrický, Kristek, Carcione & Bouchon (1997) and *Kristek*, *Moczo & Bystrický* (1998) numerically demonstrated an effect of a topography on seismic ground motion in a neighboring sedimentary valley. In most numerical studies the seismic ground motion in sedimentary valleys and basins were studied without inclusion of neighboring topography. However, most of sedimentary valleys and basins are at least partly surrounded by mountain ranges or ridges.

Numerical simulations of the seismic response of the sediment valley with and without neighboring ridge show that the valley response may be considerably affected by the presence of the ridge. This implies that an effect of a neighboring topography should be taken into account in both numerical simulations and interpretations of an observed earthquake ground motion across a sedimentary valley.

On January 17, 1995 Hyogoken-Nanbu (Kobe) earthquake of a moderate magnitude (M_s=6.8) occurred. Despite its moderate size the earthquake was the most destructive in Japan since the 1923 Kanto earthquake. An interesting and dramatic feature of the damage distribution was a relatively narrow damage belt about 1 km from the fault. It is very likely that the coupling of the source-directivity effect and basin-edge effect caused a pronounced damage-pattern irregularity. While such a qualitative explanation is reasonable and acceptable a quantitative ground-motion simulations performed so far are unsatisfactory. Therefore, the Japanese working group on effects of surface geology organized the Kobe simultaneous simulation experiment. The goals of the experiment were recognition of status for theoretical modeling of strong ground motion and understanding the strong ground motion characteristics. 19 teams from around the world participated in the experiment (*Moczo & Irikura* 1999).

Kristek, Moczo, Irikura, Iwata & Sekiguchi (1998, 1999) presented finite-difference simulation of the ground motion. A model of the medium used for the simulation was that constructed by *Iwata, Sekiguchi, Pitarka, Kamae & Irikura* (1998) on the basis of all available geophysical and geologic data. The 3D model covers a western part of the Osaka basin since the goal was to simulate motion for the Kobe region. Dimensions of the model are approximately 57, 13 and 27 km. The sedimentary basin is modeled by three layers with interfaces geometrically conformable with the sediment-basement interface. For simulation of the rupture process a new kinematic fault model by *Sekiguchi, Irikura & Iwata* (1998) was used. The model has five segments with the total number of 310 subfaults. Each subfault was modeled by a point dislocation source. Slip velocity of each point source was modeled as a superposition of six time windows.

A 4^{th}-order displacement-stress FD scheme was used to perform the simulation. Due to very large computer time and memory requirements it was necessary to use a discontinuous spatial grid (combination of the $h \times h \times h$ and $3h \times 3h \times 3h$ spatial grids covering the upper and lower parts of the computational region, respectively) and apply the combined memory optimization (*Moczo, Lucká, Kristek & Kristeková* 1999).

Simulated velocity seismograms do not match the recorded velocity seismograms. It is likely that uncertainties in the models of the basin edge and fault are responsible for disagreement.

ANALYSIS OF SEISMIC HAZARD

Seismic activity on the territory of the Slovak Republic is not very high but certainly is not negligible in terms of seismic hazard. The need of seismic hazard analysis is underlined by the fact that nuclear power plants, large water structures and other important facilities are in operation.

The research in the seismic hazard was focused on the following topics: investigation of historical earthquakes, analysis of macroseismic data, investigation of regional attenuation, seismic hazard analysis for the territory of Slovakia and for the Bohunice nuclear power plant site.

Investigation of historical earthquakes

Data on historical earthquakes is of crucial importance for the seismic hazard assessment in Slovakia. The June 5, 1443, May 25, 1443 and 1441 Central Slovakia, and January 15, 1858 Žilina earthquakes were investigated. The 15th century Central Slovakia earthquakes were candidates for the biggest earthquakes in the Western Carpathians. The January 15, 1858 Žilina earthquake is the first earthquake on the territory of Slovakia for which a systematic collection and analysis of the data was performed by earthquake contemporary researchers. However, epicentral and site intensities in the basic descriptive catalogues and in the Atlas of isoseismal maps for Central and Eastern Europe were inconsistent.

The methods of historical science were used in the investigation of the earthquakes (see for example *Stucchi* 1993). The analysis of ten earthquake contemporary sources for the 15th century Central Slovakia earthquakes was performed by *Labák, Brouček, Gutdeutsch & Hammerl* (1996) in two steps: 1. Establishing of the family tree including the new sources found in the archives in Slovakia, Czech Republic and Austria, 2. Transcription, source criticism and interpretation of the sources. It was found that the 1441 and May 25, 1443 events are fake earthquakes. All the estimated intensities of the June 5, 1443 event are less than 9^0 EMS-92. The sources were good enough for a new intensity estimation only for nine localities. The nine intensity data points allowed only a poor determination of the epicenter for the June 5, 1443 earthquake.

The analysis of the January 15, 1858 Žilina earthquake was performed by *Labák & Hammerl* (1997). The family tree was established from the catalogue sources and from the retrieved Jeitteles' collection (available in the Library of the Austrian Academy of Sciences), which contains 171 contemporary earthquake sources. The earthquake contemporary sources in the basic descriptive catalogues and the documents from the Jeitteles' collection were analyzed. The supplementary character of the primary sources was found and more than 600 localities were identified. For damage estimation a unique questionnaire data was used. The data was found in the Jeitelles´ collection. The EMS-98 scale was used for the estimation of the site intensities. Estimated site intensities were compared with the intensity estimations in the basic descriptive catalogues.

Analysis of macroseismic data

In 1998 a new version of the European Macroseismic Scale (EMS-98) was issued. *Labák, Hammerl & Pospíšil* (1999) analyzed the consistency of the recently used Slovak and Czech macroseismic questionnaires with the scale and analyzed macroseismic data of several earthquakes using the EMS-98 scale. The EMS-98 scale describes effects on humans, objects and nature, and damage to buildings in the form of a plain text for each intensity degree. It was pointed out that this form of the scale is not user-friendly either for the consistency analysis of the questionnaires or for the intensity estimation. Therefore, a new graphic form of the EMS-98 scale was developed. The arrangement of the graphic form of the scale and definition of the quantities is the same as in the original form of the scale. The effects on humans, objects and nature are displayed in the form of tables. The tables include the size of the effects for all intensities. The definition of damage to buildings is displayed in the form of the vulnerability class vs. damage grade table for each intensity degree. The graphic form of the EMS-98 scale was used for the intensity estimation for two recent earthquakes - the April 12, 1998 Slovenia and the September-October 1997 Umbria-Marche earthquakes. The Slovak and Czech questionnaire data was used for the Slovenian earthquake, and the damage data collected by the ESC working group on macroseismology was used for the Umbria-Marche earthquakes. The use of the proposed graphic form of the EMS-98 scale enabled to identify inconsistencies of the old Slovak questionnaire (originally proposed for the MSK-64 scale) with the new EMS-98 scale. A new Slovak macroseismic questionnaire was proposed. It consists of 24 questions clustered into 5 groups - place of the observation, earthquake shaking and sound, effects on people, effects on objects, nature or animals, and damage to buildings.

Investigation of regional attenuation

The macroseismic observations are the only data on moderate to strong earthquakes in the Western Carpathians. *Bystrická & Labák* (1996) and *Bystrická, Labák & Campbell* (1997) investigated the attenuation of macroseismic intensity. Macroseismic observations within 134 km from the epicenter were processed for 38 crustal earthquakes with the epicentral intensities between 4 and 8-9° MSK-64. First, the coefficients in the attenuation relationship $I-I_0 = c_1 + c_2 \log(R) + c_3 R + \varepsilon$ were determined (I_0 is the epicentral intensity, I intensity at the epicentral distance R, and ε is a random error of a regression analysis with mean of 0 and standard deviation of σ). The epicentral distance R was defined in three different ways: isoseismal radius determined in one of 12 directions, mean value of isoseismal radii, and epicentral distance of an intensity data point. It was found that while the shapes of the attenuation curves for the first and third types of distances are the same (the only difference being in absolute values), they differ significantly from that for the second distance. In order to check the dependence of attenuation on I_0, R, and azimuth, and thus the assumption of the above attenuation relationship, the distribution of residuals was analyzed. The analysis showed that the attenuation relationship $I = c_1 + c_2 \log(R) + c_3 R + c_4 I_0 + \varepsilon$, fits the observed data much better than the previous one. It predicts considerably different attenuation than the previous relationship. The difference may be as large as 1° MSK-64.

It was pointed out that only the attenuation relationships with the same definitions of epicentral distances should be used in comparing attenuation relationships. It was found that the attenuation curves for the Western Carpathians have similar shapes as those for the San Andreas Province and Balkan region 1 and 3.

Seismic hazard analysis for the territory of Slovakia and Bohunice Nuclear Power Plant site

The first cross-border earthquake hazard maps for three Central European countries, the Czech Republic, Poland and the Slovak Republic, were prepared within the Global seismic hazard assessment program (GSHAP) by *Schenková, Schenk, Kottnauer, Guterch & Labák* (1998). These preliminary hazard maps were prepared in terms of macroseismic intensity for the 475- and 1000-year return periods. Final hazard maps for the three countries (*Schenk, Schenková, Kottnauer, Guterch & Labák* 1999) were prepared in terms of peak ground acceleration and macroseismic intensity for the 475-year return period.

Labák, Bystrická, Moczo, Campbell & Rosenberg (1998) undertook a comprehensive study of the geology, seismicity, seismic zoning and attenuation characteristics of the region within at least 150 km from the Bohunice Nuclear Power Plant site (BNPP) and performed an integrated seismic hazard assessment. The integrated assessment included probabilistic computation of the seismic hazard and its de-aggregation. The probabilistic computation was chosen due to the necessity to take all random and modeling uncertainties into account.

The seismological and geologic databases allowed to define two areal source zone models in the far region while, due to the higher resolution of the data in the near region, three fault systems were considered. Four alternatives for defining the maximum magnitude for each source zone were used. Two alternatives used the maximum observed magnitude, the third one the Gumbel Type III distribution, and the fourth one used the relationships between fault rupture lengths and magnitude. The cumulative magnitude-frequency relationships were determined for each source zone using the maximum-likelihood method. Several alternatives were considered in selecting earthquakes, determining Gutenberg-Richter b-values and estimating the activity rate. Since there are no strong motion records in the region, the macroseismic intensity attenuation relationships were used. As *Bystrická & Labák* (1996) found, the intensity attenuation is similar to the intensity attenuation in California and the Balkan regions 1 and 3. Based on the similarity, five PGA and spectral acceleration attenuation relationships were developed for these analogous regions.

A logic tree with 1440 branches was constructed. 6 branches were defined for source zonation, 4 branches for maximum magnitude, 12 branches for magnitude-frequency relationships, and 5 branches for attenuation. The hazard computations were performed for each scenario of the logic tree (LT) using the SEISRISK III program. The logic tree was also simulated using 100 000 Monte Carlo (MC) simulations. It was found that the results obtained by the MC simulations are within 5% of those based on the 1440 LT scenarios for the mean and 84% confidence levels. Aposteriori sensitivity tests were also performed in order to investigate the importance of selected parameters.

The mean 10 000-year PGA and spectral acceleration values were used for estimation of the uniform hazard spectrum (UHS). The total seismic hazard for the site (expressed as an annual probability of exceeding a ground motion level) can be de-aggregated in order to obtain both fractional contributions from different magnitude-distance bins, and magnitude and distance of the controlling earthquake. The 0.2s UHS value was de-aggregated. Using the values of magnitude and distance of the controlling earthquake the horizontal and vertical response spectra for the Review Level Earthquake (RLE) were computed. It was found that the RLE spectra are lower than all spectra from the previous deterministic studies. Moreover, the horizontal spectrum is within 15% of the previous probabilistic interim RLE spectrum. Response spectra of five selected sets of accelerograms for the BNPP site were matched to the RLE spectra using the non-stationary time domain spectral matching method.

MONITORING OF EARTHQUAKES

Detection capability of seismic stations in the Central Europe

Kristeková & Skáčiková (1997) determined the 50% and 90% P-wave detection thresholds of 3 Austrian (KMR, OGA, VKA), 2 Czech (KHC, PRU), 5 German (BRG, CLL, HOF, MOX, WET), 1 Hungarian (BUD) and 3 Slovak (SPC, SRO, ZST) seismic stations for four intervals of epicentral distances by a direct method using the maximum likelihood technique. The USGS-NEIC Earthquake Data Reports covering the period from January 1990 to November 1994 were used as the reference system. The differences in both the 50% detection threshold MB50 and 90% detection threshold MB90 between the best and the worst seismic stations are about one m_b magnitude unit for all investigated intervals of epicentral distances. The sequences of the seismic stations according to MB50 differ from those according to MB90. MB50 was found more suitable for comparing the detectability of the seismic stations using the direct method. The detection thresholds estimated using the direct method are less accurate for the seismic stations with lower detection capability. The seismic stations Kašperské Hory (KHC, Czech Republic) and Collmberg (CLL, Germany) have the best detection capabilities. The Hungarian seismic station BUD as well as the Austrian stations are among the stations with lower detection capabilities. The group of German seismic stations displays a large scatter in quality. The Czech seismic stations belong to the best stations. The Slovak seismic stations rank among those with better-than-average detectability.

4. PHYSICS OF THE EARTH’S INTERIOR

DEEP STRUCTURE GEOPHYSICAL RESEARCH OF THE WESTERN CARPATHIANS AND ITS ADJACENT REGIONS

Introduction

Deep structure geophysical research of the continental crust in Slovakia has been carried out at the Geophysical Institute of the Slovak Academy of Sciences. At the beginning, Ing. Miroslav Smíšek and his colleagues performed gravimetric measurements on the Slovak territory which later resulted in a 1:200 000 gravimetric map of Czechoslovakia.

Deep structure geophysical research was initiated by Ing. Jozef Plančár who joined the institute in 1965 and became the head of the Department of Geodynamics and Physics of the Earth’s Interior in 1971. He specialized in interpretation of gravimetric and geodetical data and closely cooperated with Czech geophysicists. He co-edited important monographs on geodynamic investigation and geophysical syntheses in Czechoslovakia (*Vaněk, Babuška & Plančár* 1979; *Zátopek, Petr, Plančár & Vaněk* 1981).

Integrated geophysical modeling of the whole lithosphere in Slovakia was introduced by Dr. Miroslav Bielik who joined the institute in 1982. He focused on the application of 2D and 3D quantitative interpretation of gravity anomalies both in the Western Carpathians and its adjacent regions, development of density modeling methods, calculation of the stripped gravity maps, study of local and regional isostasy in different areas of continental lithosphere, integrated geophysical modeling and rheological predictions of the lithosphere with implications for tectonic scenarios.

The geophysical research of the deep structure of the lithosphere is currently carried out by the Department of Gravimetry and Geodynamics of the Geophysical Institute of the Slovak Academy of Sciences.

Recently, M. Bielik, in cooperation with geophysicists from the Vrije Universiteit in Amsterdam, has investigated the rheology of the Western Carpathians and its surrounding geological units. The approach is based on the extrapolation of failure criteria, gravity and temperature models. Bouguer anomaly, topography and surface heat flow data in the Western Carpathians are analyzed jointly using a finite-element method for calculation of new relief of the thermal lithosphere-asthenosphere boundary.

The results of the deep structure lithosphere research are used for the new definition of the seismogenic zones in the collisional orogen. The next activity will soon also include the largest European lithospheric experiment based on deep seismic refraction sounding (CELEBRATION 2000). This experiment will include the new deep seismic refraction sounding measurements and their interpretation along the transects running across Central Europe. The interpretation of new seismic data will be combined with the interpretation of other geophysical fields.

Gravimetric investigation of structure of the lithosphere

Gravimetric measurements on the territory of Slovakia resulted in a gravimetric map of Czechoslovakia (*Ibrmajer* 1981, *Šefara et al.* 1987). The geological interpretation of the gravity anomalies of the Western Carpathians was accomplished on the scales of 1:500 000, 1:200 000 and 1:25 000. Detailed analysis and interpretation of the gravity anomalies were performed along the international DSS profiles V and VI (*Bielik, Škorvanek, Burda, Hübner, Vyskočil & Fusán* 1987 and *Bielik, Blížkovský, Burda, Fusán, Hübner, Herrmann, Novotný, Suk, Tomek & Vyskočil* 1994). Density models of the Western Carpathians along the profiles running across this region were developed by *Bielik, Fusán, Burda, Hübner & Vyskočil* (1990); *Bielik, Majcin, Fusán, Burda, Vyskočil & Trešl* (1990) and *Vyskočil, Burda, Bielik & Fusán* (1992).

Constructions of the stripped gravity maps initiated the period of the geological filtering of the gravity field using the principle of „processing from known to the unknown". By removing the gravity effects of the known near-surface sources from the gravity map a stripped gravity map has been obtained by *Šefara et al.* (1987) for the Western Carpathians and by *Bielik* (1988a) for the whole intra-Carpathian region. Based on the analysis of the stripped gravity map (*Bielik* 1988b), significant deep density boundaries (linear zones of disturbed gravity field) observable mainly in the NE-SW to ENE-WJW, NW-SE and N-S directions were specified.

A detailed study of gravity anomalies in the stripped gravity map was performed by density modeling along the profiles running across the whole intra-Carpathian region (*Bielik* 1989, *1991*). The Pannonian basin and Transylvanian basin are characterized by large gravity highs (nearly 100 mgal). The gravity field of the Pannonian basin can be divided in the NW and SE parts. They correlate with ALCAPA and TISZA megablocks. It was found that the deepest subbasins (e.g., Békés basin, East Slovakian basin and Danube basin) correspond to the largest gravity highs. The results suggest that their sources are high density masses probably belonging to the lower crust or upper mantle. The apical parts of these bodies are located in a depth of about 10-14 km.

Calculation of a simple density model in local isostatic equilibrium provides a clue to analysis of observed gravity anomaly (*Lillie, Bielik, Babuška & Plomerová* 1994). The method is able to offer and show the contributions of main anomalous layers (zones) to the free-air and Bouguer anomalies. Based on this approach the long-wavelength gravity anomalies in the Carpathians, the Pannonian Basin and the Eastern Alps were studied (*Bielik* 1995; *Bielik* 1998a, b, and *Ádám & Bielik* 1998). The Western and Eastern Carpathians as well as the Eastern Alps represent continental collision regions while the Pannonian Basin and its Békés subbasin are characterized by an extensional type of the continental lithosphere. In spite of different evolution of the lithosphere in studied areas all results indicate clearly that configuration of the lithosphere-asthenosphere boundary is an important component of the observed long-wavelength gravity anomalies. It means that the lithosphere-asthenosphere boundary beneath the European continent is also evidenced as a density boundary. Density contrast of -0.03 gcm^{-3} between the asthenosphere and lower lithosphere was determined. The gravity effect of the asthenosphere must be taken into account in modeling long-wavelength gravity anomalies.

Until 1994, density models had been calculated only for the crust. Thus the deepest density boundary was represented by Moho. *Lillie, Bielik, Babuška and Plomerová* (1994) demonstrated that for the density modeling of the long-wavelength Bouguer anomalies it is necessary to take into account a gravity effect of the lithosphere-asthenosphere boundary. All previous gravity studies that did not account for the asthenosphere must have distributed its effect elsewhere in the mass column (e.g., through combined effects of thicker sediments, lower-density sediments, less relief on the Moho, or a lower density contrast across the Moho). Since a strong variation in crustal and lithosphere thickness is observed in the Carpathian-Alpine-Pannonian region, density models incorporating the lithosphere-asthenosphere boundary were calculated.

Understanding the major contributions for a local isostatic situation helped to analyze problems of the mass lithospheric distribution and strength in terms of deviation from local isostasy. The $2^{1/2}$ D and 3D density modeling were applied to calculate the lithospheric density distribution in the Western Carpathians (*Bielik* 1995, *Bielik* 1998a), the Eastern Carpathians (*Bielik & Mocanu* 1998), and the Békés basin (*Bielik* 1998b).

Integrated geophysical research

Seismogenic zones in the Western Carpathians and surrounding areas were derived from geophysically interpreted deep fault zones in the past. These were defined by *Fusán, Ibrmajer & Plančár* (1979), *Fusán, Ibrmajer, Kvitkovič & Plančár* (1981) and *Šefara et al.* (1987), following the division of the Western Carpathians into the principal neotectonic blocks. This pioneer step in the definition of the neotectonic evolution of the Western Carpathians was based on the contemporary knowledge of deep-seated structures defined by the deep seismic refraction sounding (DSS) and gravimetry. Moreover, a brief description of the neotectonic development of the Western Carpathians based on recent vertical movement tendencies of the Earth's crust in this region was given by *Kvitkovič & Plančár* (1979).

Recently, a large effort is devoted to investigate structure of the continental lithosphere involving integrated application of geophysical, geological and petrological studies. *Bezák, Šefara, Bielik & Kubeš* (1995, 1998), *Šefara, Bielik, Konečný, Bezák & Hurai* (1996), *Kováč, Bielik, Lexa, Pereszlényi, Šefara, Túnyi & Vass* (1998), *Bielik* (1999), *Bielik, Šefara, Soták, Bezák & Kubeš* (1999), *Konečný, Huraiová & Bielik* (1999) and *Šefara, Bielik & Bezák* (1999) developed new models of the structure and geodynamics of the Western Carpathian lithosphere along profiles crossing this orogenic belt.

The models indicate that the interaction between the European platform and the Carpatho-Pannonian block, as well as between the lithosphere and asthenosphere are major factors determining the present lithospheric structure of the Western Carpathians. The latest stage of the evolution of the Western Carpathian arc and the Pannonian Basin was characterized by a lithospheric disintegration which occurred as a consequence of transition from a transpressional to an extensional regime. This process was accompanied by both crustal thinning and, what is more important, by the thinning of the lithosphere. The thinning of the lithosphere was associated with an uplift of asthenospheric, partially molten masses, accompanied by local asthenoliths. The Neogene development of the Western Carpathian intramountain basin was influenced by the subduction and collision processes between the orogene and platform, back-arc rifting, and consequent thermal subsidence in the Pannonian domain.

Based on the interpretation of the deep seismic reflection profiles, gravity and magnetic anomalies, geothermal, seismological and geological data, a lithospheric model of bivergent extension was suggested for the Slovak part of the Danube basin by *Hrušecký, Bielik, Šefara & Kúšik* (1998).

The image of a narrow continental rift was studied by the interpretation of gravity and magnetotelluric measurements taking into account the newest seismic reflection data in detail in the Békés basin (*Ádám & Bielik* 1998). It was found that the large-scale feature of the Buck's mode of a narrow rift must be modified by the intrusion of high-density masses within the lower crust and lower part of the upper crust to obtain a fit between observed and calculated local gravity highs. The gravity high observed over the Békés basin is one of the main geophysical characteristics of this very important region in the Pannonian basin. *Bielik,* *Kohút & Kostecký* (1998) used a finite-element method to calculate the stress field within the lithosphere beneath the narrow rift mode.

The seismogenic zones that generate earthquakes in this orogen can be characterized by a „multifloor structural pattern“. In the deepest level of the brittle crust, these zones (inhomogeneities) are represented by the paleo- and meso-Alpine deep-seated sutures (e.g., the Pienninic-Veporic Suture zone, Čertovica line, Meliata oceanic Suture zone, Rába and Hurbanovo - Diósjenõ units). The middle level of this multifloor structural pattern represents Neo-Alpine brittle deformations and principal displacement zones (Pericarpathian fault system - the Leitha faults, Central Slovakia fault system and Hornád fault system). The uppermost level is formed by the recent active shallow faults corresponding to the neotectonic period (the last 5.4 Ma) for the Western Carpathians. The recent stress field of the Western Carpathians is determined by the main stress sources in the whole Alpine-Carpathian-Pannonian-Dinaric system.

Lankreijer, Bielik, Cloetingh & Majcin (1999) used extrapolation of failure criteria, lithology and temperature models to predict rheology of the lithosphere for two sections crossing the Carpathians and the surrounding regions. Calculations suggest a significant lateral variation in rheology of different tectonic units, with important implications for the tectonic evolution. Mechanically strong behavior of the Polish Platform lithosphere contrasts with the weak lithosphere of the Pannonian basin, indicating that the arcuate shape of the Carpathian orogen is primarily caused by an inherited curvature of an ancient embayment in the foreland, with the Pannonian units passively filling the space. The Polish Platform and the Moesian Platform exhibit a similar rheological anisotropy caused by the NW-SE trending weakness zones paralleling the Tornquist-Teisseyre zone. This anisotropy was the main controlling factor on the behavior of the lithosphere in this area since Cadomian times, as documented by the geological evolution of the Sudety Mts. and the Mesozoic Polish Trough, including the late Cretaceous Alpine inversion and the Neogene development of the Carpathian foreland. This rheological anisotropy appears to have a major controlling impact on the development of at least the eastern part of the European lithosphere.

Rheology predictions for the Bohemian Massif support the idea that the rigid lithosphere of the Bohemian Massif governed the bending of the Alpine-Carpathian transition zone, expressed in the large-scale wrench movements in the Eastern Alps (opening the Vienna Basin) and the northeastern escape of the Western Carpathians units from recent Eastern alpine region. Calculations predict an effective elastic thickness (EET) of about 20-40 km in this area.

In the foreland area, detachment levels are predicted for upper and lower crustal levels, leading to a decoupling of crustal and subcrustal flexure in most areas. An EET of 12 km is predicted for this region based on the strength predictions.

In the Western Carpathians lower crustal strength completely disappears. The lithospheric strength gradually decreases towards the Pannonian Basin. This is a direct result of the increasing temperatures and decrease of the thermally defined lithospheric thickness. An EET of 15-23 km was predicted for the Western Carpathians.

The Pannonian rheological structure is characterized by one relatively thin and strong layer in the uppermost 10 km of the crust and a complete absence of strength in the lower crust and lower lithosphere. The extreme weakness of the lithosphere is the direct result of the high heat flow density and extremely shallow asthenosphere in the Pannonian Basin. An EET is predicted at 5-10 km only.

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