

Seismic activity of the Alpine-Carpathian-Bohemian Massif region with regard to geological and potential field data

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Abstract: The seismicity of the geological complexes of the northern part of the Eastern Alps, the Western Carpathians and the Bohemian Massif is investigated by means of new seismic stations and a review of earthquake catalogues available. Eleven earthquake catalogues are evaluated and checked for multiple entries, fake earthquakes and mistakes. The final data set of earthquakes covers the time span from 1267 to 2004 and comprises 1968 earthquakes in total. The resulting epicentral map provides a very detailed idea of the seismicity of this region. An attempt at a seismotectonic interpretation of earthquakes based on the geological overview of the region is presented. Gravity and airborne magnetometry data in addition to seismic events are collected and cross-border maps are compiled and analysed in order to determine the spatial extent of these geological structures. The Linsser filtering technique is used to trace faults at two depth horizons — 4 and 8 km. Correlation between the epicentres of earthquakes and lineaments derived from gravity data is discussed for major historical earthquakes such as Neulengbach (1590) or Scheibbs (1867). This data set enables us to determine seismically active fault structures and to get an insight into the fault system interaction. The ability to assess the potentially seismically active vertical and horizontal extent of fault structures enables improved hazard assessments in future. The magnetometric map shows a belt of positive anomalies which reflects the presence of magnetized rocks between the Bohemian Massif and the Alpine-Carpathian zone.

Key words: Carpathians, Eastern Alps, Bohemian Massif, seismic monitoring, earthquakes, earthquake catalogue, gravity map, magnetic map, Linsser filtering.

Introduction

Since 1991 the Department of Geophysics, Central Institute for Meteorology and Geodynamics (ZAMG) in Vienna, Austria, and the Institute of Physics of the Earth, Masaryk University (IPE) in Brno, Czech Republic, have been co-operating in seismological studies. This partnership has resulted in a joint project and the establishment of the “Alpine-Carpathian On-line Research Network” (ACORN). The installation of new digital seismic stations with on-line data-transmission to the seismological centres has enabled study of the seismicity across borders.

In 1995–1997, the first phase of the ACORN project focussed on seismic event detection within the Western Carpathians and the Vienna Basin. Based on previous results the second phase commenced in 1998. The area of study was finally enlarged to incorporate the Eastern Alps and a part of the Bohemian Massif to get a broader picture of the region. Hence, the area of interest was chosen to encompass a rectangle ranging from 47.5° to 49.8° in latitude and from 13.0° to 19.0° in longitude, which is referred to as the “ACORN region” hereinafter. During the second and third phase of ACORN project, an earthquake catalogue of the area under consideration was compiled, and further alternative ways of data-transmission were established to secure the data-transfer. In 2004 the project cul-

minated in a geophysical interpretation of gravity data based on the Linsser method.

Seismic monitoring

Integration of new seismic stations

In the early 90's only few seismic stations existed in the area of interest. Data from these stations were available with time delay up to as much as several days and the data exchange between national seismological centres was limited to parametric data, such as time onsets of seismic phases.

Prior to the establishment of the ACORN network, two digital broad band seismic stations Velká Javorina (JAVC) and Moravský Krumlov (KRUC) were built in the Czech Republic in close co-operation between ZAMG and IPE, and were completed in 1995. During the first phase of the project, the seismic station MOA in Molln/Upper Austria was upgraded by the ZAMG to a state-of-the-art broad-band station in 1996. In 1997 another Czech seismic station Moravský Beroun (MORC) could be added to the ACORN network. This station was installed under the co-operation of the IPE and the GeoForschungsZentrum Pots-

dam. After 2000, the international data exchange between European seismological institutions increased mainly due to the MEREDIAN project supported by the EU (Van Eck et al. 2004). The continuous waveform data from other stations situated on the territory of the Czech Republic (Zedník et al. 2004), Slovakia and Hungary were also integrated into the ACORN network.

The data of all these stations are recorded in real time — hence, after a seismic event the data are available for analysis in the national centres at the ZAMG Vienna and at the IPE Brno, with only a few seconds delay. Due to the new seismic stations, the location accuracy based on evaluation of seismograms has substantially improved. Location inaccuracy, previously ranging from 5 to 15 km (depending on the actual position within the Vienna Basin) before data from these stations were available, has improved to less than 5 km. Before the improvement of the network, macroseismic data had to be used in order to mitigate the large inaccuracy of locations, which was caused by the sparseness of the network and the inhomogeneous structure of the crust in this part of Europe. Obviously, this accuracy can be improved even more by installing additional stations.

Recorded events

The seismological data from the stations of the ACORN network were processed in both seismological centres, at the ZAMG Vienna and at the IPE Brno. The time onsets of seismic phases were identified and events that were registered at a sufficient number of stations were located. Locations and identifications were compared in both institutions. Due to the sensitivity of digital stations and the exchange of data across the border even weak microearthquakes could be localized. The analysis of very small tremors that are indicators of seismically active faults — even though they are capable of releasing sufficient energy only in the long term — constitutes an important aspect of seismic studies concerning the seismic hazard.

With regard to improvement of the seismic network, more and more industrial activities such as quarry blasts were detected. The identification of these tremors (a few hundred per year) is time consuming and sometimes

problematic because the released seismic energy is often very small and the recorded seismic signals are extremely weak and difficult to interpret. These events must be discarded when carrying out hazard calculations (Wiemer & Baer 2000). Consequently, many recorded signals from known quarry blasts were analysed to find out some characteristics that could help to verify whether the recorded ground motion originated from an explosion or not. The databases of quarries and blasts were compiled to enable the comparison of registered events with already known signals. Problematic and suspicious events were verified with chief blasters from quarries near the calculated epicentre.

Besides industrial explosions, experimental shots were also registered, especially events registered in the framework of CELEBRATION 2000 (Guterch et al. 2003; Hrubcová et al. 2005), ALP 2002 (Brückl et al. 2003) and SUDETES 2003 (Grad et al. 2003) seismic experiments. The analysis of these events allowed the verification of the location accuracy and improvement of velocity models.

During the ACORN project more than 600 earthquakes were recorded. The strongest and most frequent events originated in Austria in the macroseismically known region between Leoben and Ebreichsdorf (Fig. 1). The strongest earthquakes were recorded on July 11, 2000 near Ebreichsdorf with local magnitudes of 4.8 and 4.5. Other historically known epicentral areas — near Salzburg, Krems, Gmünd, Linz in Austria, Győr and Komárno on the Hungary-Slovakia border, Malé Karpaty Mts and Piešťany in Western Slovakia were active during the ACORN period, too. Weak but frequent seismicity was observed from the north-eastern part of the Czech Republic (Fig. 1).

Earthquake catalogue

During the second and third phase of the ACORN project, an earthquake catalogue of the area under consideration was compiled. The catalogue finally combined 11 individual catalogues (listed in Table 1) which were investigated in terms of fake events, double or conflicting entries and man-made seismic events.

Only entries with coordinates of the epicentre were used. Corresponding events were linked together, one of them was selected as principal and its epicentre was used

Table 1: Catalogues used in the project.

Time span covered	Abbreviation of catalogue	Source
1201 – 2004	A	Catalogue of Austrian earthquakes, ZAMG Vienna, <i>computer file</i>
1995 – 2004	IPE	Seismological catalogue, IPE Brno, <i>computer file</i>
460 – 1956	57	Catalogue of earthquakes of Czechoslovakia. Kárník et al. (1957)
1957 – 1980	81	Catalogue of earthquakes of Czechoslovakia. Kárník et al. (1981)
1800 – 1990	K	Seismicity of Europe and the Mediterranean (M^3 4.5 till 1950, M^3 3.8 since 1950). Kárník (1996)
1991 – 2004	IG	Regional catalogues of GI CAS, Czech Republic. Zedník J. — <i>personal communication</i>
1034 – 1995	SL	Catalogue of earthquakes of Slovakia. Labák P. — <i>personal communication</i>
1984 – 1989	SM	Catalogue of earthquakes of Slovakia. Mrázová (1989)
1991	SA	Catalogue of earthquakes of Slovakia 1991. Kristeková & Labák (1996)
456 – 1986	H	Hungarian earthquake catalogue. Zsiros et al. (1988)
1995 – 2004	HU	Hungarian earthquake bulletins. Tóth et al. (2005)

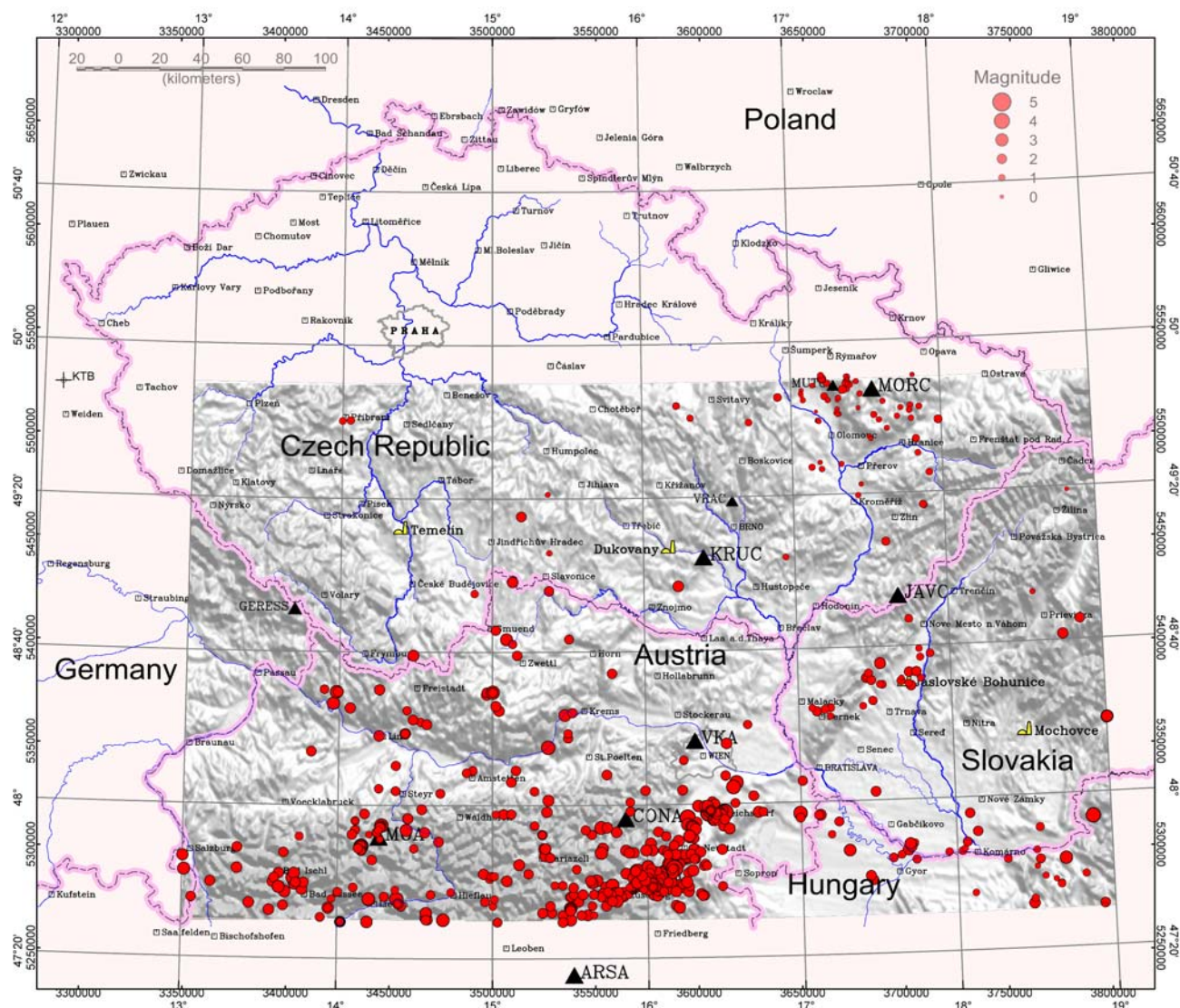


Fig. 1. Epicentres of earthquakes for the period from 1.1.1995 to 31.3.2004 plotted on the grey shaded relief topography map derived from the USGS digital elevation model TOPO 30. The sizes of the red circles are scaled proportionally to the local magnitudes of individual earthquakes. Black triangles show the position of seismic stations.

for plotting maps. Top priority was given to the agency responsible for a particular region. Hence, for example, earthquakes from the Hungarian catalogue (Zsíros et al. 1988; Tóth et al. 2005) in Hungarian territory which did not appear in other catalogues were accepted as genuine earthquakes of this specific region. In case of conflicting entries in terms of dates or times, coordinates, intensities or magnitudes, these entries were investigated, compared and the highest priority was given to the catalogue entry of the respective national agency or institution which also reported the event in its territory. The magnitude of historical earthquakes, for which only an epicentral intensity was known, was computed according to formulae by Kárník et al. (1981) and Shebalin (1958). An example of a part of the catalogue is given in Table 2, and the twelve strongest earthquakes are listed in Table 3.

The catalogue of the ACORN region consists of 1968 earthquakes covering the period from 1267 until March

2004 which are considered to be genuine earthquakes and not blasts or rockbursts (Fig. 2). Events from the ten years of the ACORN period make up around a third of all earthquakes presented in the catalogue (Fig. 3).

Geological and structural setting and their relation to seismic activity

The ACORN region is situated in the Eastern Alps-Western Carpathians-Bohemian Massif junction area (Fig. 4). The Bohemian Massif is situated in the easternmost part of the European Variscan Belt and represents the foreland of the Alpine-Carpathian orogen. The southern and eastern slopes of the Bohemian Massif covered by the molasse sediments of the Alpine-Carpathian Foredeep dip under the Alpine-Carpathian flysch nappes. The Eastern Alps and the Western Carpathians belong to the Alpine-

Table 2: Example of a part of the ACORN catalogue with the earthquake near Molln discussed in Chapter 'Aeromagnetic data'. **M** — multiplicity identifier (P — principal event), **UTC** — Coordinated Universal Time, **Depth*** — typical depth for the area, **Mag.*** — magnitude was estimated from I_0 , I_0 — epicentral intensity, **Cat.** — abbreviation of catalogue (see Table 1). Parameters of principal events used for plotting maps are in upright letters, associated localizations of the same earthquake, if they exist, are written in italics.

M	Origin date	Origin time UTC	Lat. (N)	Long. (E)	Depth (km)	Mag.	I_0	Epicentre	Region	Country	Cat.
P	1967 / 1 / 29	00:12:11.7	47.89	14.25	8	4.6	6.5	Molln	Upper Austria	Austria	A
	1967 / 1 / 29	00:12:11	47.9	14.2		5.0*	7.0			Austria	H
	1967 / 1 / 29	00:12:11.7	47.90	14.20	7	4.8*	7.0	Molln		Austria	81
	1967 / 1 / 29	00:12:12	47.9	14.3	8	4.8*	7.0			Austria	K
	1967 / 1 / 30	05:07	47.89	14.25	6*	2.5*	4.0	Molln-Breitenau	Upper Austria	Austria	A
P	1967 / 2 / 10	06:48	47.70	16.02	7*	2.6*	4.0	Wimpasssing	Lower Austria	Austria	A
	1967 / 2 / 10	06:48	47.7	16.0		2.7*	4.0			Austria	H
	1967 / 2 / 12	23:19	47.89	14.25	6*	2.8*	4.5	Molln	Upper Austria	Austria	A
	1967 / 3 / 6	02:33	47.50	14.74	6*	2.8*	4.5	Zeiritzkappel	Styria	Austria	A
P	1967 / 3 / 31	23:23	47.70	16.02	7*	2.9*	4.5	Wimpasssing	Lower Austria	Austria	A
	1967 / 3 / 31	23:23	47.7	16.0		3.1*	4.5			Austria	H
	1967 / 5 / 10	07:51	47.82	14.16	6*	3.1*	5.0	Klaus/Kirchdorf	Upper Austria	Austria	A
P	1967 / 6 / 7	16:19	47.89	14.25	6*	3.1*	5.0	Molln	Upper Austria	Austria	A
	1967 / 6 / 7	16:19:26.4	47.88	14.29		3.4*	5.0			Austria	K
	1967 / 6 / 13	17:40	47.89	14.25	6*	3.1*	5.0	Molln	Upper Austria	Austria	A
P	1967 / 6 / 17	17:45:36.3	48.58	17.38	8	3.7*	5.0	Dobrá Voda	Malé Karpaty	Slovakia	SL
	1967 / 6 / 17	17:45	48.50	17.40		3.7*	5.0	Buková	Malé Karpaty	Slovakia	81
	1967 / 6 / 17	17:45	48.5	17.4		3.7*	5.0		Malé Karpaty	Slovakia	H
	1967 / 6 / 17	17:45:41	48.54	17.4		3.4*	5.0			Slovakia	K

Table 3: Twelve strongest earthquakes in the ACORN region sorted according to the epicentral intensity I_0 .

Origin date	Origin time (UTC)	Latitude (N)	Longitude (E)	Depth (km)	Magnitude	I_0	Epicentre	Country	Cat.
1590 / 9 / 15	23:50	48.20	15.91	8	6.0	9	Neulengbach	Austria	A
1763 / 6 / 28	04:22	47.82	18.22	7	5.8	8.5	Komárno	Slovakia/Hungary	SL
1906 / 1 / 9	23:07	48.58	17.46	9	5.7	8.5	Dobrá Voda	Slovakia	SL
1443 / 6 / 5	08	48.71	18.94	26	5.9	8	Kremnica	Slovakia	SL
1599 / 10 / 1	08	47.75	18.16		5.6	8	Komárno	Slovakia/Hungary	H
1267 / 5 / 8	02	47.51	15.45	8	5.4	8	Kindberg	Austria	A
1885 / 4 / 30	23:15	47.51	15.45	8	5.4	8	Kindberg	Austria	A
1783 / 4 / 22	02:45	47.75	18.16	7	5.3	8	Komárno	Slovakia/Hungary	H
1613 / 11 / 16	11	49.25	18.75		5.2	8	Žilina	Slovakia	SL
1768 / 2 / 27	01:45	47.83	16.17	6	5.2	8	Bad Fischau	Austria	A
1927 / 10 / 8	19:49	48.07	16.58	6	5.2	8	Schwadorf	Austria	A
1590 / 9 / 15	17	48.20	15.91	4	4.7	8	Neulengbach	Austria	A

Carpathian orogenic belt. They represent a complex, comprising both the outer region of thin-skinned tectonics with Flysch nappes and an inner part of thick-skinned tectonics also containing robust nappes of the pre-Alpine basement.

Bohemian Massif

The Bohemian Massif was formed during at least three orogeneses (Cadomian, Variscan and Alpine). The Variscan structures dominate in the region of the Bohemian Massif. The Moravo-Silesian Unit represents the eastern part of the Bohemian Massif. The basement of this

Variscan unit is formed of the Cadomian crystalline rocks of the Brunovistulicum. Westwards, the Moravo-Silesian Unit dips under the Lugodanubian units (the Moldanubian, Teplá-Barrandian and Lugian Units) of the Bohemian Massif (Suess 1912; Matte et al. 1990; Schulmann et al. 1994). NNE-SSW structures predominate in the Moravo-Silesian Unit, whereas perpendicular WNW-ESE structures predominate in the Lugodanubian units.

The tectonic boundary between the Moravo-Silesian and the Lugodanubian units is formed by the NNE-SSW Moravo-Silesian fault zone consisting of various dislocations, overthrusts and strike-slip zones. Similarly, the N-S to NNE-SSW Rodl-Blanice and Vitis-Přibyslav shear

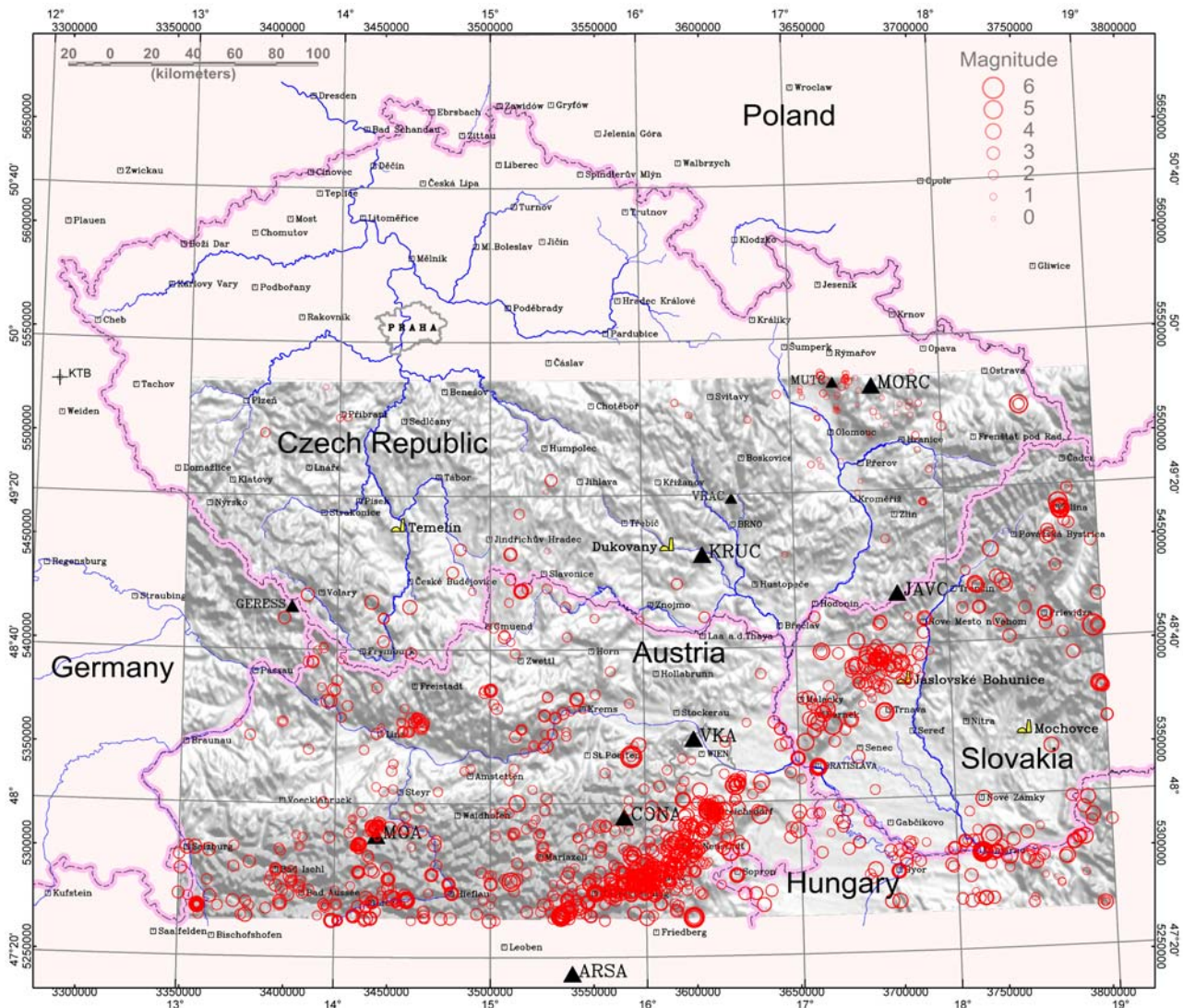


Fig. 2. Epicentres of earthquakes for the period from 8.5.1267 to 31.3.2004 plotted on the grey shaded relief topography map derived from the USGS digital elevation model TOPO 30. The sizes of the red circles are scaled proportionally to the local magnitudes of individual earthquakes. Black triangles show the position of seismic stations.

zones originated during the Variscan orogeny in the Moldanubian Unit. The NW-SE Danube and Pfahl zones were formed as the conjugate systems in respect to these N-S to NNE-SSW shear zones (Brandmayr et al. 1995). In the NW part of the ACORN region, the ENE-WSW Central Bohemian shear zone, injected with the Central Bohemian Pluton, forms the tectonic limit of the Moldanubian Unit and the Teplá-Barrandian Unit.

The NNE-SSW grabens (Boskovice, Blanice and hypothetical Jihlava Grabens) filled by the upper Carboniferous-Lower Permian sediments originated along the Variscan NNE-SSW zones (Veselá 1976; Holub & Tásler 1980). The Boskovice Graben situated near the Moravo-Silesian fault zone represents the most significant Permian-Carboniferous graben in the ACORN region. The NNE-SSW eastern tectonic limit of this graben (the marginal fault of the Boskovice Graben) continues southwards, where it passes into the NE-SW Diendorf fault. The

faults forming the tectonic limits of the Permian-Carboniferous grabens were repeatedly reactivated. The recent seismic activity of the Diendorf fault was discussed by Figdor & Scheidegger (1977). Some known epicentres of weak microearthquakes can probably be attributed to small tectonic movement along the southern segments of the Vitis-Příbyslav fault system and the Rodl-Kaplice-Blanice fault system.

The WNW-ESE to NW-SE fault systems play a significant role in the Bohemian Massif. These fault systems mostly originated already during Variscan orogeny (Brandmayr et al. 1995; Aleksandrowski et al. 1997) and were significantly reactivated during the Cretaceous and the Cenozoic (for instance Grygar & Jelínek 2003). During the Late Cretaceous-Paleogene compression, the crystalline basement thrust over the Upper Cretaceous sediments along some of the WNW-ESE to NW-SE fault systems (for instance the Lužice fault, the Železné Hory fault and the

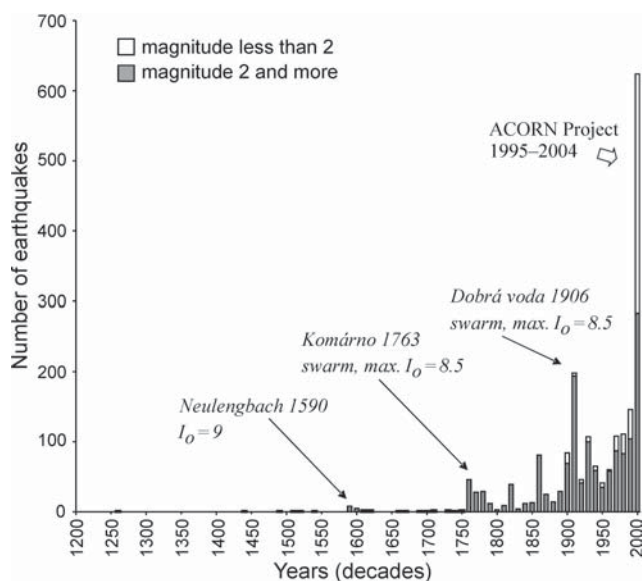


Fig. 3. Number of earthquakes presented in the final ACORN catalogue.

marginal fault of the Blansko Graben — Malkovský 1979, 1987; Coubal 1990; Krejčí et al. 2002). During the dextral Neogene movements of the WNW-ESE to NW-SE faults in the ESE continuation of the Elbe fault system, the Upper Morava Basin was formed (Grygar & Jelinek 2003). These faults intersect the front of the Western Carpathian flysch nappes and several faults also dislocated the Pliocene/Quaternary sedimentary layers of the Upper Morava Basin (Růžicka 1973; Zeman et al. 1980). These facts suggest a young (sub-Recent) reactivation of these faults. Recent natural seismotectonic activity occurring in the NE part of the Bohemian Massif (Fig. 5) is also predominantly connected with the WNW-ESE to NW-SE faults (Kaláb et al. 1996; Skácelová & Havíř 1999; Špaček et al. 2006).

Eastern Alps and Western Carpathians

The Eastern Alps and the Western Carpathians were consolidated during the Alpine orogeny. In the Eastern Alps, the ENE-WSW structures predominate. The Western Car-

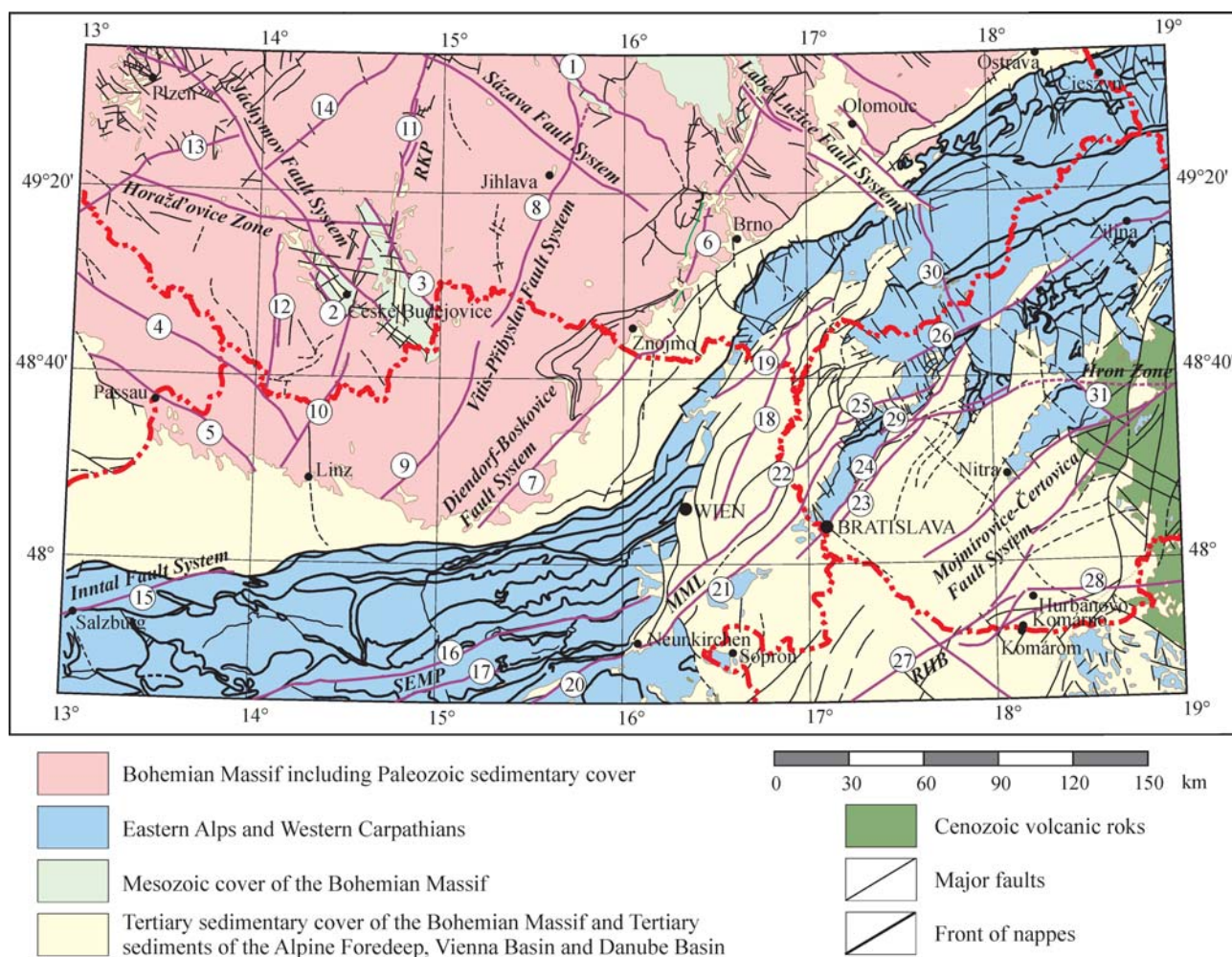


Fig. 4. Scheme of geological and tectonic setting in the ACORN region with marked major fault systems and faults discussed in the article (purple lines) (geological background compiled and simplified after Kodým et al. 1967; Mahel' 1973, marked faults also compiled after

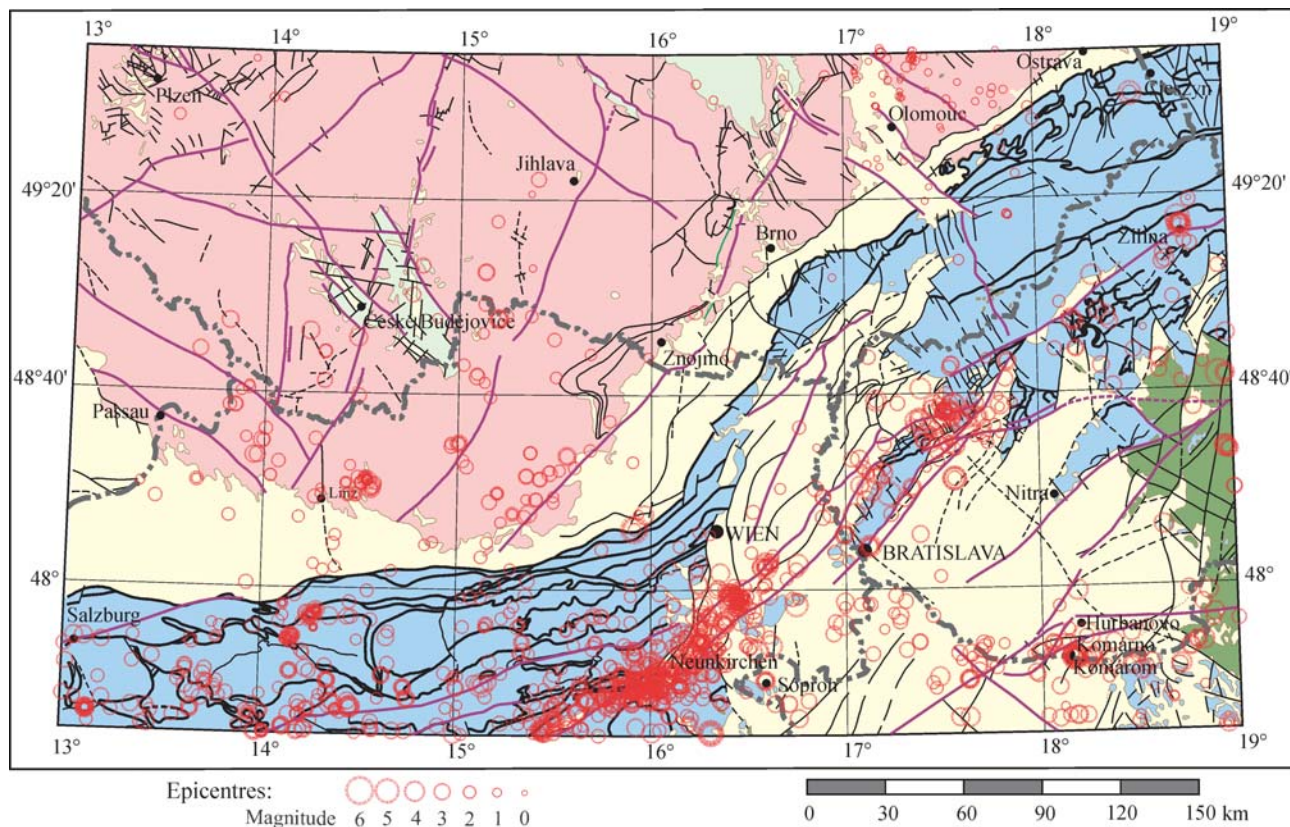


Fig. 5. Distribution of earthquakes in the ACORN region for the period from 8.5.1267 to 31.3.2004 (red circles) on the schematic map of the geological and tectonic setting with marked major fault systems and faults discussed in the article (purple lines) (see Fig. 4 for legend and other explanation).

pathians represent the part of the units which were tectonically extruded towards the NE during the Late Paleogene–Early Miocene (Fodor 1995; Ratschbacher et al. 1991; Peresson & Decker 1997a). The NE-SW to ENE-WSW structures predominate in the western part of the Western Carpathians. Neogene sediments of the Vienna Basin and the Panonian Basin partially cover the easternmost Alps and the SW part of the Western Carpathians. Numerous NE-SW and N-S polyphase faults played a dominant role during the Neogene development of the Vienna and Danube Basins (Fodor 1995; Kováč et al. 1989; Hrušický 1999). Significant volcanic activity occurred during the Tertiary in the Western Carpathians. The volcanic rocks occupy a large area in the easternmost part of the ACORN region.

The lateral extrusion significantly influenced the structural setting of the Eastern Alps (Ratschbacher et al. 1991; Peresson & Decker 1997a,b; Frisch et al. 1998, 2000; Linzer et al. 2002). The ENE-WSW Salzach-Ennstal-Mariazell-Puchberg line (SEMP) separating the Northern Calcareous Alps from the crystalline units situated southwards is the most significant structure connected with this lateral extrusion in the Eastern Alps. The NE-SW to ENE-WSW Inntal fault zone and Traunsee fault zone situated in the Northern Calcareous Alps in the SW part of the ACORN region represents similar dominant structures significantly active during the extrusion (Frisch et al. 1998, 2000; Linzer et al. 2002).

The Mur-Mürz fault system located south of the SEMP is connected with the zone of significant seismic activity

Fig. 4. (Continued from previous page) Suk et al. 1996; Linzer et al. 2002; Kováč & Plašienka 2002). Abbreviations: **RKP** — Rodl-Kaplice-Blanice Fault System; **SEMP** — Salzach-Ennstal-Mariazell-Puchberg Fault System; **MML** — Mur-Mürz-Leitha Fault System; **RHB** — Rába-Hurbanovo-Diosjenő Zone. **Marked major faults:** Bohemian Massif: 1 — Železné Hory Fault; 2 — Dubno Fault; 3 — Eastern Marginal Fault of Třeboň Basin; 4 — Pfahl Fault Zone; 5 — Danube Fault Zone; 6 — Marginal Fault of Boskovice Graben; 7 — Diendorf Fault; 8 — Přibyslav Fault Zone; 9 — Vitis Fault Zone; 10 — Rodl Fault Zone; 11 — Blanice Graben; 12 — Lhenice Graben; 13 — Klatovský Fault Zone; 14 — Benešov Fault Zone. **Eastern Alps and Western Carpathians:** 15 — Inntal Fault Zone; 16 — Ennstal Fault; 17 — Mariazell-Puchberg Fault Zone; 18 — Steinberg Fault; 19 — Schratteberg Fault; 20 — Mur-Mürz Zone; 21 — Pottendorf Fault; 22 — Láb Fault; 23 — Vištuk Fault; 24 — Malé Karpaty Marginal Fault Zone; 25 — Plavecké Podhradie-Dobrá Voda Faults; 26 — Myjava Fault Zone; 27 — Rába Line; 28 — Hurbanovo Line; 29 — Kátlovce Fault; 30 — Nezdenice Fault; 31 — Jastrabie Fault.

(Reinecker & Lenhardt 1999). This seismoactive zone continues NE along the Pottendorf and Láb faults into the Western Carpathians. Both NW and SE tectonic limits of the Malé Karpaty Mts have exhibited recent seismotectonic activity. The epicentres of earthquakes (Fig. 5) significantly concentrate mainly near the NE margin of the Malé Karpaty Mts in the region between the Kátlovce fault and the Myjava fault. Other recent seismic activity has occurred along the Pienniny Klippen Belt, forming the boundary between the Outer Flysch Carpathian nappes and Central Western Carpathian units, at least to the region of Žilina. The discussed ENE-WSW to NE-SW seismoactive zone passing from the Eastern Alps to the Western Carpathians represents the most significant seismoactive zone in the ACORN region (see also Schenková et al. 1995; Šefara et al. 1998; Hók et al. 2000; Bielik et al. 2002; Decker et al. 2005). The seismic activity observed during years 2004–2005 near Zakopane in Poland (Havíř et al. 2006) can be connected with another ENE prolongation of this seismoactive zone.

In the SE part of the ACORN region, the Rába-Hurbánovo-Diosjenő line forming the tectonic boundary between the Transdanubian Range and the Austroalpine nappes (Hrušický 1999; Szafián et al. 1999; Kováč & Plašienka 2002) represents another significant structure connected with a seismoactive zone (Šefara et al. 1998; Hók et al. 2000). The epicentre of the disastrous earthquake which occurred in the region near Komárno in 1763 is situated close to this lineament.

The NW-SE fault zones are less significant in the Western Carpathians. Hrušický (1999) pointed out that the reflection seismic profiles have not confirmed any important NW-SE faults in the Danube Basin. Nevertheless some young NW-SE faults exist in the Western Carpathian region, including faults cutting the front of the Carpathian nappes. The post-kinematic volcanic activity connected with the Nezdenice fault proves the young tectonic activity of this NW-SE structure and its relation with the reactivation of structures in the basement formed by the Bohemian Massif. Thus, the youngest faulting connected with the NW-SE faults situated in the Western Carpathian flysch nappes also has a relation to the reactivation and propagation of the NW-SE to WNW-ESE fault systems already formed during the pre-Alpine stages of the Bohemian Massif. The hypocentres of weak microearthquakes occurring in the basement under the Western Carpathian flysch nappes (recently, during the year 2004, in the Vizovice region close to the Nezdenice fault) show the continuing current activity of these structures on the buried eastern slope of the Bohemian Massif.

Geophysical data

Regional geophysical data from gravity and airborne magnetometry surveys were selected for the analysis of the subsurface extent of geological bodies with contrasting petrophysical properties. Colour shaded relief maps were used to delineate pronounced lineaments whereas the Lin-

sser method (Linsser 1967) was applied to analyse the density contacts at two potentially seismogenic depth horizons.

Gravity data

A new border crossing gravity map was compiled from the observed gravity data from Austria, the Czech Republic and Slovakia. A more detailed description of gravity data sources can be found in Bielik et al. (2006). The gravity map was calculated for a Bouguer reduction density 2.67 g/cm^3 , and the data were adjusted to the International Gravity Standardization Network 1971. The normal gravity formula was derived from the parameters of the geocentric equipotential ellipsoid defined by the World Geodetic System 1984 (WGS84), which is numerically equivalent to the Geodetic Reference System 1980 (GRS80) (Švancara 2004). Gravity data were interpolated into a square grid of $1 \text{ km} \times 1 \text{ km}$. The colour shaded relief gravity map shown in Fig. 6 was plotted by illuminating from the NW at an inclination of 45 degrees. The contour interval was 2 mGal. Epicentres of earthquakes for the period from 8.5.1267 to 31.3.2004 were superimposed on this map as red circular symbols with diameters proportional to the size of their magnitudes.

A dominant feature of the gravity field of the ACORN area is the pronounced negative gravity anomaly of the Eastern Alps in the region of the Salzburgerian Northern Calcareous Alps. Individual gravity minima are situated mainly between Salzburg and Liezen. A distinct negative anomaly can also be found to the west of Vöcklabruck. The prevailing orientation of density contacts and corresponding axis of horizontal gradients of gravity is approximately W-E. A negative gravity field of lower intensity with NW-SE orientation of density contacts characterizes the Alpine Molasse Zone.

The gravity field of the Bohemian Massif is subdivided into several subparallel belts of NE-SW orientation, thus partially matching the observed seismic activity. The NW part of the gravity map of the ACORN area shows a positively disturbed gravity field of the Teplá-Barrandian Zone. The Central Bohemian suture separates this zone from the Moldanubian Zone with a mainly negative gravity field. Light granodiorites and granites of the Bohemian and Moldanubian Pluton predominantly cause individual gravity minima of the Moldanubian Zone. Light granites of Weinsberg type and Freistadt granodiorites give rise to the negative gravity anomalies in the surroundings of Freistadt NNE of Linz.

The most distinct density boundary depicted in the gravity map is the intensive linear gravity gradient cutting across Jihlava and Slavonice to Vitis, Zwettl and Amstetten. This tectonic line separates the Bohemian Moldanubicum to the west from the Moravian and Strážek and Waldviertel Moldanubicum on the east. The northern part of this deep fault zone is called the Přibyslav (mylonite) zone whereas the southern part on Austrian territory is named the "Vitis" shear zone. The positively disturbed gravity field to the east of the Přibyslav-Vitis zone delim-

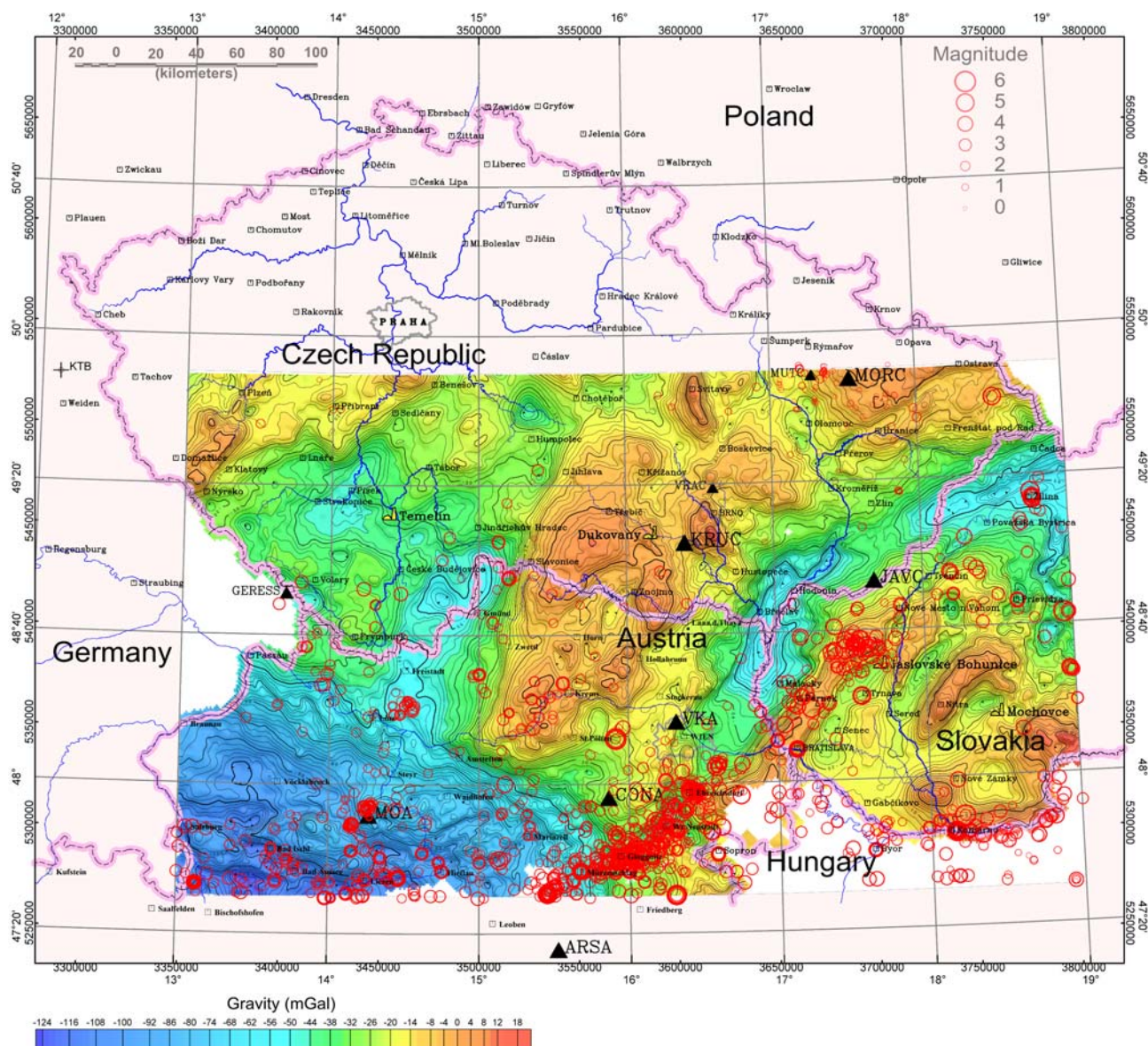


Fig. 6. Colour shaded relief contour map with Bouguer gravity anomalies and epicentres of earthquakes for the period from 8.5.1267 to 31.3.2004. Gravity anomalies were calculated using Bouguer reduction density 2.67 g/cm^3 . The contour interval is $2 \text{ mGal} = 20 \mu\text{m/s}^2$. The sizes of the red circles are scaled proportionally to the local magnitudes of individual earthquakes. Black triangles show the position of seismic stations.

its the Moravo-Silesian block. The most intensive positive gravity anomaly in this region is situated at Moravské Budějovice, SW of Třebíč. The anomaly is caused by high-density metamorphites of the Moravian Moldanubium and probably also by deep-seated huge basic bodies. An interpretation of the refraction profile "Celebration 09" performed by Hrubcová et al. (2005) indicates that the Brunovistulicum (Dudek 1980) is underlain by a broad velocity gradient zone in the lower crust.

The axis "Znojmo–Brno–Ostrava" marks the western margin of the Carpathian Foredeep. In this belt there are several positive gravity anomalies caused by heavy Brunovistulian rocks. A negative gravity anomaly belt between Hodonín and Žilina is called the "West Carpathian gravity low" and is attributed to porous sediments of the

Flysch Belt and the underlying light molasse sediments. A gravity saddle between Zlín and Trenčín weakens the "West Carpathian gravity low", and this anomaly continues in a NW direction to Olomouc in the Hornomoravský úval Lowland. The SSW continuation of the "West Carpathian gravity low" comprises the negative gravity anomaly caused by Tertiary sediments of the Vienna Basin. The western margin of the Vienna Basin is marked by a gravity gradient of the Schratzenberg-Steinberg fault system. An intensive gravity gradient also delimits the eastern margin of the Vienna Basin, especially in the segment Hainburg–Pernek–Sološnica. The sediments of the Vienna Basin reach their maximal thickness of approximately 6000 meters in the Central Moravian/Zistersdorf Depression near the confluence of Thaya (Dyje) and March

(Morava). A second depocentre of the Vienna Basin is situated SE of Vienna near Schwechat. A positive gravity anomaly near Ebreichsdorf separates the Wiener Neustadt Trough from the Schwechat Depression in the Vienna Basin.

In western Slovakia the gravity field delineates the Danubian block with a positive gravity anomaly and the western margin of the Fatra-Tatry block with a negative gravity anomaly. An elongated positive gravity anomaly between Bratislava and Nové Mesto nad Váhom characterizes the Malé Karpaty Mts separating the Vienna Basin from the Danube Basin. East of the Malé Karpaty Mts there are three negative anomalies due to Tertiary sediments of the Piešťany, Topoľčany and Zlaté Moravce bays separated by positive anomalies of Považský Inovec Mts and Tribeč Mts. The positive isometric anomaly in the southern part of the Danubian block (between Gabčíkovo and Nové Zámky) is caused by basic and ultrabasic rocks of the basement of the Danube Basin. The negative gravity field in the surroundings of Žilina can be explained by a superposition of the West Carpathian gravity low and the gravity effect of the Paleogene sedimentary filling of the Žilina valley.

Linsser indications of density contacts

Spatial changes in the density of rocks are responsible for gravity anomalies. Linsser filtering is a unique technique for fault mapping based on analysis of the gravity field. The original technique was proposed by Linsser (1967) and later modified by Šefara (1973). The method is based on the assumption that the gravity profile over a fault or a density contact can be described as a linear combination of a gravity master curve and regional gravity field:

$$\Delta g(x) = E \cdot M(x) + R \cdot B(x)$$

where $\Delta g(x)$ is the measured gravity profile, $M(x)$ is the gravity master curve for specified depth level, E is the amplitude of the fitted gravity master curve, $B(x)$ is the spatial variation of regional field, and R is a multiplicative coefficient describing the regional gravity field.

In addition, the method requires the presence of a steep discontinuity along which a density contrast exists. Strike slip features along which crustal parts of similar density or only horizontal density stratification are displaced cannot be resolved, however.

We have used the approach of Šefara (1973) for the gravity data processing in this article, where the gravity master curve is calculated for the thin sheet model approximating the fault (Fig. 7) while the regional field is considered to be a constant, i.e. $B(x)=1$. The comparison of gravity data — locally re-interpolated to the direction perpendicular to the horizontal gravity gradient — with master curves enables the estimation of a fault amplitude and the regional gravity. The “density contact indication” (DCI) is plotted on a map where the Linsser coincidence criterion C defined in Fig. 7 has a pronounced maximum. An additional requirement for the construction of a DCI is

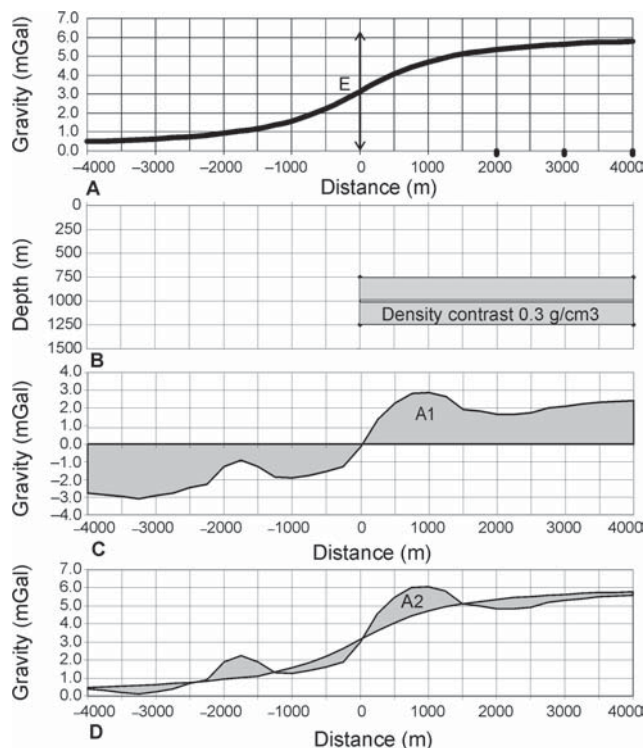


Fig. 7. Principle of the Linsser filtering technique for determination of fault parameters. **A** — Gravity master curve corresponding to the geological model. E is the amplitude of the gravity effect of the master curve. **B** — Cross-section of the density contact model approximated by a 2D horizontal thin sheet. **C** — Measured gravity profile running across the density contact. $A1$ is the area between the regional field and the measured gravity. **D** — Comparison of the measured gravity profile with the gravity master curve. $A2$ is the area between the master curve and the measured gravity. The co-incidence C between the measured gravity and the master curve is defined by the expression $C (\%) = 100 \cdot (A1 - A2) / A1$.

the existence of a common coincidence criterion C on two adjacent parallel profiles. This reduces significantly the fragmentation of the density contact patterns. The size of the symbol is proportional to intensity of the density contact expressed by the product $E \cdot C$ and the azimuth is computed from the horizontal gradient of gravity. Linsser filtering is performed by analysing a set of depth levels using master curves, the length of which is usually 6 times greater than the grid interval.

For the computation of density contacts we have interpolated the Bouguer gravity anomalies in a square grid $2 \text{ km} \times 2 \text{ km}$ with more than 30,900 grid points. The positions of density contacts at the 4 km depth were computed by choosing a Linsser operator totalling 24 km in length, and at 8 km depth we used an operator of 40 km in length. From a formal point of view it is possible to analyse even deeper crustal levels, however, this requires even larger operator lengths, which cause an undesirable integration of gravity anomalies from different geological bodies. For that reason the deepest analysed level was chosen to be 8 km below the surface, although some earthquakes might locate deeper. At the depth level of 4 km the Linsser tech-

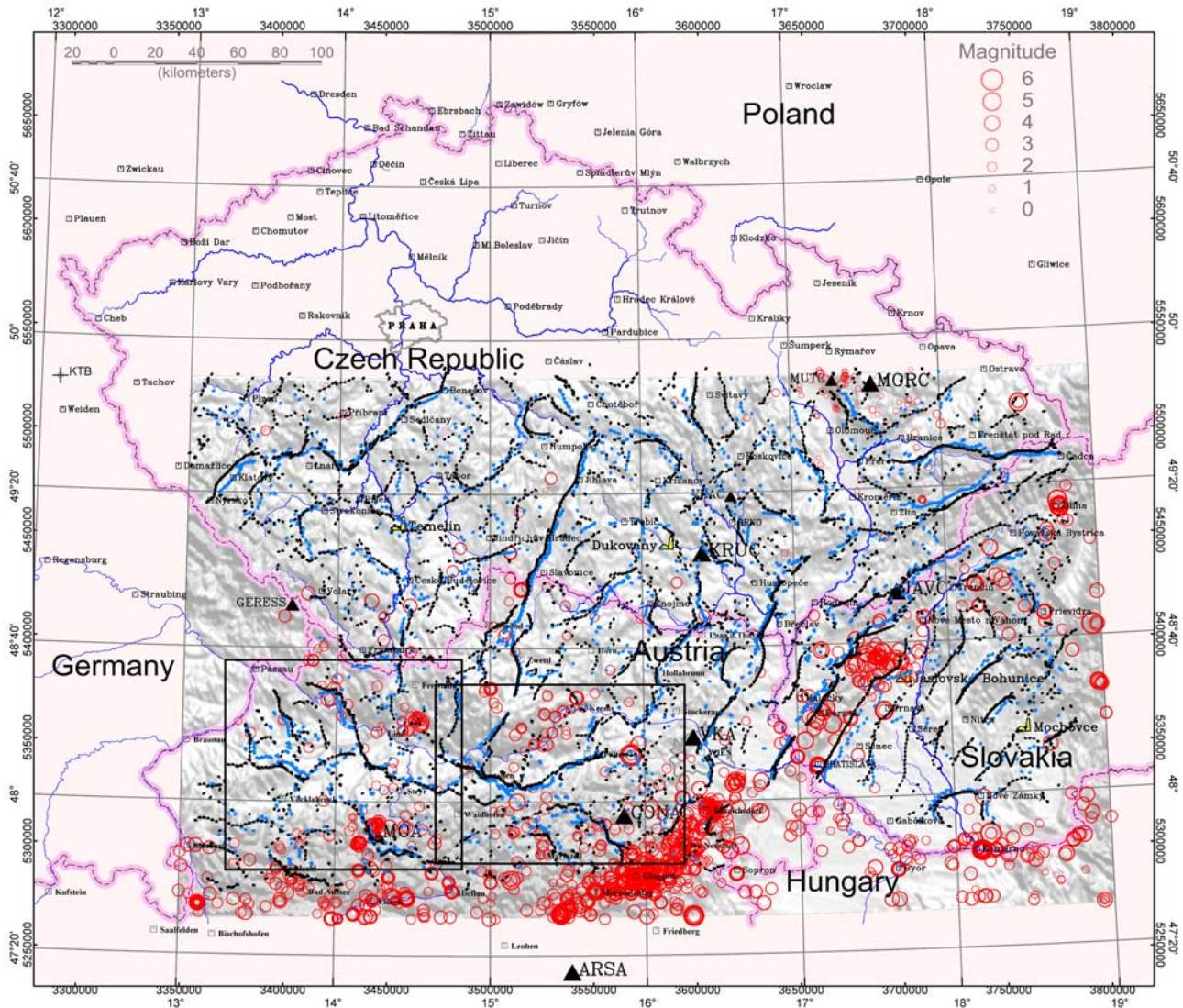


Fig. 8. Positions of density contacts at depth horizons of 4 km (black) and 8 km (blue) below the surface, plotted on the shaded topographic relief map together with epicentres of earthquakes for the period from 8.5.1267 to 31.3.2004. The sizes of the red circles are scaled proportionally to the local magnitudes of individual earthquakes. Black triangles show the position of seismic stations. Details shown in Figs. 9 and 10 are marked by rectangles.

nique determined 3540 positions of density contacts whereas at the depth 8 km below the surface 1840 density contacts could be calculated. The positions of density contacts at depths of 4 km and 8 km were projected on the shaded topographic relief and are plotted in Fig. 8. If a fault dips exactly vertically, both symbols of the Linsser contact plot on top of each other. Slight offsets (e.g. Klatovy fault or Vitis-Přibyslav fault) indicate the fault dip and its direction between the two depth horizons of 4 and 8 km.

Prominent features in Fig. 8 are the NE-SW striking faults, whereas the NW-SE orientated faults are generally less pronounced. This observation can be explained by the nature of NE-SW oriented faults. They can be found in the Moravo-Silesian block as well as to a certain extent in the Bohemian Moldanubicum and reflect Variscan structures accompanied by lithological and density changes.

The Klatovy fault zone and the Benešov fault zone in the NW of the ACORN region and their offset due to the Jáchymov fault system are clearly visible on the density contact map. All these structures cannot be associated with seismic events listed in the catalogue, but have shown small seismic activity (recorded during the recent past with a local network, which is not part of ACORN), however. The same applies to the Lhenice fault on Czech territory. Its southern continuation, which is not apparent on the Linsser map — possibly due to the depth restriction of 8 km — can be associated with numerous events from the catalogue within the Pfahl-Danube fault system on Austrian territory.

The Rodl-Kaplice-Blanice fault system is not pronounced on the Linsser density contact map, indicating negligible density contact. With few exceptions, north of České Budějovice, where the fault system is intersected by

NW-SE trending features like the Dubno fault and the eastern marginal fault of the Třeboň Basin, and in the southern part, north of Linz along the Rodl fault zone, no seismicity is observed.

The seismicity near Pregarten in Upper Austria cannot be associated with one of the major faults. As indicated by the density contact map, the corresponding faults — striking NE-SW and NW-SE — appear only on the shallow 4 km-horizon, hence do not continue further down. This result can be confirmed from past earthquakes, which caused slight damage to buildings at unusually low magnitudes, indicating shallow sources at around 4 km (Reinecker & Lenhardt 1999).

The Vitis-Přibyslav fault zone seems to be relatively aseismic — with an exception at Kautzen — E of Litschau, although the fault appears extremely prominent on the density contact map. A bifurcation of the fault zone towards the south can be observed near Gmünd, possibly commencing already at Kautzen. The western part tends to dip towards the east, whereas the east-part dips vertically and tilts towards the west, thus forming a depression-like structure, which is limited to the south by a pronounced and complex WNW-ESE orientated fault system expressed by the river bed of the Danube.

Further south, near Molln (see “MOA” in Figs. 8 and 9), a clear indication for a NW-SE orientated density contact became apparent. It commences possibly already south of Passau and changes direction just south of Molln (Fig. 9). Its strike coincides with the focal solution (Reinecker & Lenhardt 1999) of the earthquake near Molln in 1967 (see Table 2 for earthquake parameters).

The almost E-W directed density contacts between Salzburg and Bad Aussee appear to be a result of nappes along which small earthquakes occur. Due to their relatively small magnitude, no focal mechanisms could be determined, but the orientation and the N-S orientated stress regime should result in thrust-type mechanisms.

Interestingly enough, the Diendorf-Boskovice fault (Fig. 10) is only very

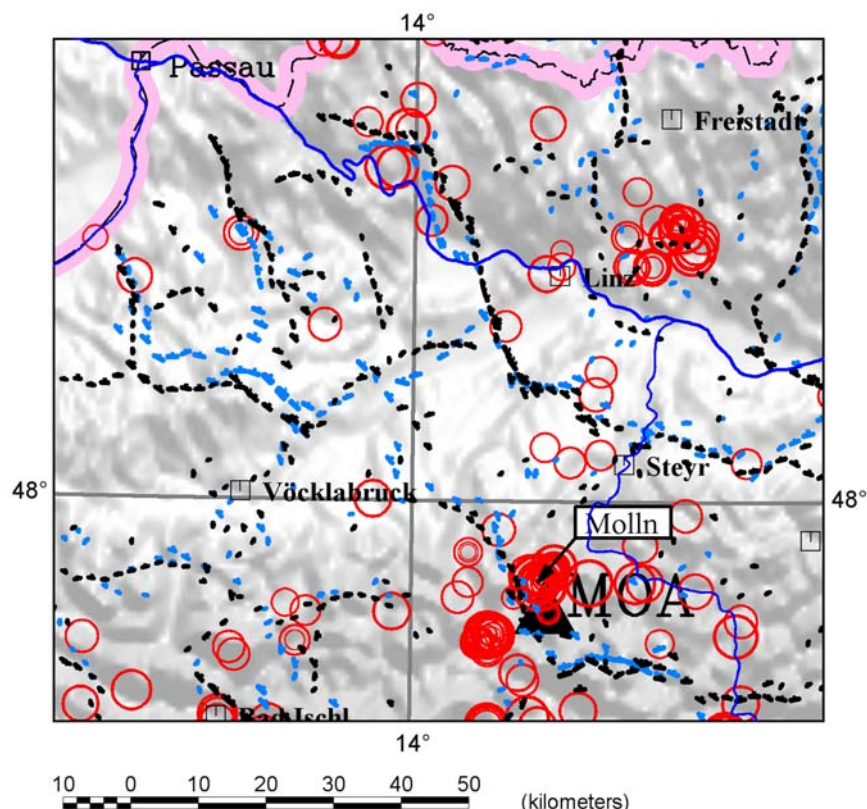


Fig. 9. Detail of Fig. 8 showing the Linsser contact indications near Molln (MOA) in Upper Austria. NW-SE oriented density contact indications between Molln and Passau coincide with the strike of the focal solution of the earthquake near Molln in 1967.

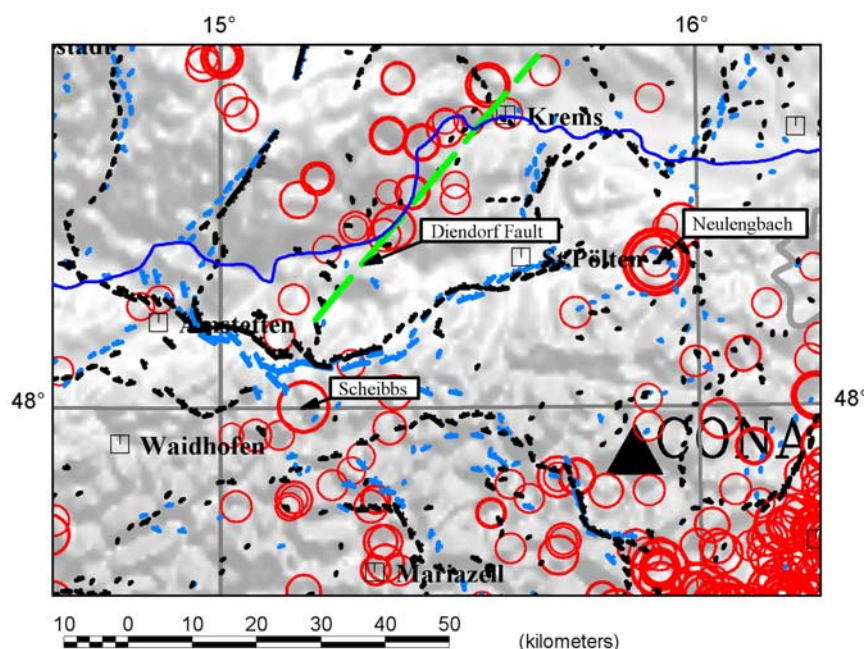


Fig. 10. Detail of Fig. 8 showing the Linsser contact indications near Scheibbs, Diendorf Fault (green) and Neulengbach in Lower Austria. Text balloons mark the possible epicentres of the historic earthquakes near Neulengbach in 1590 and Scheibbs in 1867. (The black triangle depicts the new station at the Conrad Observatory in Lower Austria. The station has only partially come into operation since the end of the project and could not be utilized during the project).

little pronounced in the density contact map. The seismicity is concentrated mainly in the SE portion between Krems and Melk.

Further south, near Mariazell, a NW-SE orientated cluster of earthquakes coincides with strong density contacts. This feature bends towards the west. Slightly north of it, we find Scheibbs (Fig. 10), where a stronger earthquake occurred in 1876. This event is currently under investigation at the ZAMG regarding the exact position of the epicentre and its magnitude.

Another pronounced density contact extends from Amstetten to St. Pölten, terminating at Neulengbach — the possible epicentre of the historic earthquake in 1590. At Neulengbach (Fig. 10) a NW-SE orientated and less pronounced density contact can be seen, which commences already a few kilometers north of the Danube, cutting

across the flysch nappes and possibly continuing even below the Vienna Basin (Wr. Neustadt, epicentre of several historic earthquakes). The Linsser contacts are very diffuse in this part due to sedimentary filling of the basin.

The Pottendorf fault and its continuation towards the east and its parallel faults (Láb fault, Plavecké Podhradie-Dobrá Voda faults, Vištuk fault and the Malé Karpaty marginal fault zone) are clearly visible. In between, a cluster of seismicity (latitude $48^{\circ}35'N$, longitude $17^{\circ}30'E$) can be seen without Linsser contact indications. The seismicity could be a result of the intersection of the Kátlovce fault (WSW-ENE) with a fault in the NW-SE direction.

Additional seismic activity is known from Žilina in Slovakia (e.g. 1858, causing heavy damage to buildings), which can be associated with several faults. One of these (Myjava fault zone) is also visible from the Linsser contacts in Fig. 8.

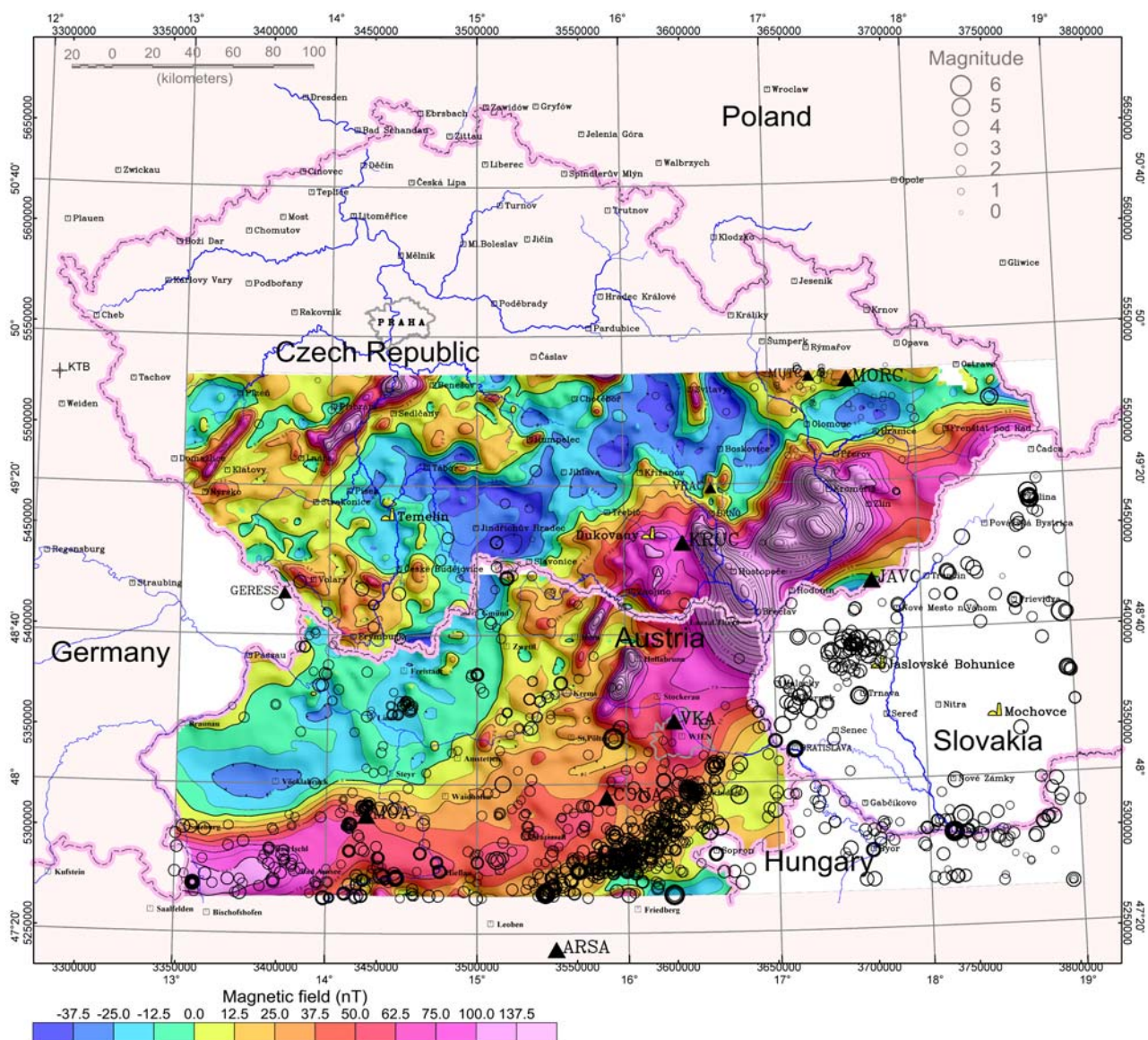


Fig. 11. Colour shaded relief contour map of the total magnetic field upward continued to the level 1600 m with epicentres of earthquakes for the period from 8.5.1267 to 31.3.2004. The contour interval of the magnetic field is 12.5 nT. The sizes of the red circles are scaled proportionally to the local magnitudes of individual earthquakes. Black triangles show the position of seismic stations.

In general, the mapping of density contacts allows a very detailed determination of where faults with high-density contacts exist. Whether these faults are capable of storing enough deformation energy (seismic active) or not (too ductile, aseismic) can only be decided utilizing seismic records.

At the end of this project another approach (Euler 3D deconvolution, Reid et al. 1990) was applied to the data, leading — after filtering — to similar results.

Aeromagnetic data

The cross-border magnetic map was compiled from gridded Austrian aeromagnetic data continued to the level of 1600 m (Oberlercher 1999 — personal communication) and the Czech aeromagnetic and ground magnetic data (Šalanský 1995), which were newly continued upward to the same level. The data were interpolated into a square grid 2 km×2 km using the minimum curvature algorithm. For the computation of the continuation upward we used the MAGMAP module of the geophysical mapping software OASIS Montaj. This software module supports the application of common Fourier domain filters to gridded potential field data. The Fourier domain filtering included pre-processing, filter application and post processing. From the resulting grid the colour shaded relief magnetic map shown in Fig. 11 was constructed with an illumination from the NW at an inclination of 45 degree. The magnetic data stitching should be regarded as a first approach. A major difference between the Austrian and Czech magnetic data was observed in the area of Laa am der Thaya and Břeclav. The reason for this misfit results from the different kinds of magnetic data used; only ground magnetic measurements of the Z component were available from the Czech territory in this part.

The magnetic map (Fig. 11) shows a belt of positive magnetic anomalies extending from Salzburg to Mariazell and Vienna and further to Břeclav, Kroměříž and Čadca. Gnojek & Heinz (1993) call this extensive feature the Central European belt of magnetic anomalies and proposed its geological interpretation. They assume that this belt could be an old basement preserved between the Hercynian consolidated Bohemian Massif and the Alpine-Carpathian zone. Fig. 11 shows some degree of coincidence between the form of the magnetic anomaly and the distribution of epicentres of earthquakes. The correspondence is good in the area of the Northern Calcareous Alps, but continuing eastwards, the epicentres of the seismoactive zone Mur-Mürz-Leitha-Malé Karpaty become increasingly shifted from the maximum of the magnetic anomaly towards the SE.

The data from the total magnetic field will serve as a basis for investigations in future. The cross-border stitching of the magnetic data due to different kinds of data sets available (aeromagnetic, ground survey) and the necessity of choosing the appropriate parameters in the Euler 3D-deconvolution, without being in the position to employ a comparative method (Linsser filtering) to check the outcome in terms of reliability, constrained us from doing so.

In addition, the application of the Linsser method was abandoned, because no correlation between seismic activity and magnetic anomalies became apparent.

Conclusion

The first part of the project dealt with needs of the establishment of the seismic network of ACORN. Incorporation of five seismic stations from neighbouring countries (Czech Republic, Slovakia, and Hungary) resulted in a much higher resolution of seismic activity which is required to study recent tectonic movements. All data are transmitted now in real-time and are shared by national centres. The data were collected not only from recent seismic records but also from historical earthquakes from eleven earthquake catalogues. All entries had to be verified in terms of possible misleading information such as wrong catalogue entries or induced seismic events. Blasts especially turned out to be a challenge, as the denser network enables locating of seismic tremors of much smaller magnitude with greater accuracy than before. This category of tremors — mainly due to quarry blasts — must be flagged in the database to avoid wrong seismic hazard analysis, which would be strongly biased otherwise.

The detection of faults at depth horizons where earthquakes tend to originate is to be considered the main task. In order to do that for such a large area, a method proposed by Linsser was applied to the available gravity data. The method utilizes model curves which represent a certain geological formation underground and their gravity effect on the surface. The difference between the observed and theoretical anomalies is minimized until an optimum agreement has been achieved. This approach was applied to two depth horizons — 4 and 8 km — and numerous faults could be traced well below the surface. These lineaments were finally compared with epicentres of earthquakes from the catalogue, resulting in a good correlation. Moreover, some pronounced lineaments, which cannot be traced on the surface using geological maps, coincide with epicentres of major historical earthquakes, such as Scheibbs (1876) or Neulengbach (1590) thus giving rise to an understanding of the prevailing mechanism involved. In the case of the earthquake of Molln (1967), the strike of the detected structure coincides with one of the planes of the already determined focal mechanism.

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