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REVIEW ARTICLE

The Nysa-Morava Zone: an active tectonic domain with Late Cenozoic sedimentary grabens in the Western Carpathians' foreland (NE Bohemian Massif)

Petr Špaček · Ondřej Bábek · Petra Štěpančíková · Jan Švancara · Jana Pazdírková · Jan Sedláček

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Abstract We give an interpretive review of the geological evolution of the Nysa-Morava Zone (NMZ)—a Late Cenozoic tectonically active region of the NE Bohemian Massif located at its contact with the Western Carpathians' orogenic front. This crustal domain, delimited by generally NW–SE-striking fault system, is characterised by Oligo-Miocene and Plio-Pleistocene volcanic activity, regionally anomalous, weak historical and present-day seismicity and increased CO_2 flux. The NMZ hosts several elongated, mostly NW–SE-trending, graben-like sedimentary basins (Upper Morava Basin System), which are filled by more than 300-m-thick succession of clastic fluvial/lacustrine sediments of Pliocene–Quaternary age. Based on geometric relations, basin architecture, coincidence of seismicity with CO_2 escape and sparse focal mechanism data, a model is proposed, which explains this active domain as a transfer zone developed between major WNW–ESE and NW–SE faults in a right-lateral transpressional setting. It is suggested that slow horizontal slip at these faults resulted in local permutations of the largest and medium stress directions and formation of transtensional crustal domains in the NMZ. Moreover, relation of the NMZ to the Alpine–Carpathian system and sedimentary grabens in its foreland is discussed. The absence of Paleogene and Lower Miocene deposits suggests that subsidence in the NMZ was commenced later than in the European Cenozoic Rift System (ECRIS), which is in agreement with later thrusting in Western Carpathians at ~17 Ma. The quantitative contrasts to the ECRIS in terms of faulting and subsidence rates are explained by the absence of lithospheric/crustal thinning in the NMZ.

Keywords Bohemian Massif · Upper Morava Basin · Tectonic evolution · Seismicity · Sedimentary grabens · Late Cenozoic

Introduction

Active tectonics of slowly deforming crustal domains in intraplate setting is often inexpressive or even cryptic, difficult to study and therefore underestimated in the literature. Yet the data on such domains are useful since they carry important clues for the understanding of stress transfer between plate margins or mobile zones which controls the distribution of seismicity and volcanism in intraplate regions as well as their tectonic uplift and subsidence patterns.

The Variscan Central and Western Europe forms a relatively stable part of Eurasia, which, at the present time, is characterised by very slow tectonic deformation (e.g. Nocquet and Calais 2004; Grenerczy et al. 2005). However, regions of the European Cenozoic Rift System (ECRIS) in the Pyrenean and Alpine forelands display significant Late Cenozoic brittle crustal deformation, basin subsidence and volcanism (Prodehl et al. 1995; Dèzes et al. 2004; Wilson and Downes 2006). The ECRIS evolved due to Oligocene to Neogene passive rifting of European lithosphere related

P. Špaček (✉) · J. Švancara · J. Pazdírková
Institute of Physics of the Earth, Masaryk University,
Tvrdého 12, 60200 Brno, Czech Republic
e-mail: spacek@ipe.muni.cz

O. Bábek · J. Sedláček
Department of Geology, Palacký University in Olomouc,
17. listopadu 12, 77146 Olomouc, Czech Republic

P. Štěpančíková
Institute of Rock Structure and Mechanics, Academy of Sciences
of the Czech Republic, V Holešovičkách 41, 18209 Prague,
Czech Republic

to intraplate stresses generated by the Alpine and Pyrenean collision zones (Ziegler and Dèzes 2007). The Cenozoic volcanism and rift-related uplift of adjacent Variscan massifs are often explained by the activity of small-scale mantle plumes located beneath the Massif Central, north Rhine Graben and Eifel Mts (e.g. Granet et al. 1995). The crustal deformation associated with the ECRIS continues until the present time. It is indicated by generally low-magnitude seismicity (Fig. 1) with occasional moderate to strong earthquakes (Grünthal et al. 2009; Vanneste et al. 2001; Ferry et al. 2005) and relatively thick Pleistocene and Holocene clastic sedimentary successions deposited in major grabens (e.g. the Upper Rhine Graben; Ferry et al. 2005; Gabriel et al. 2013). However, the abundance of these Cenozoic rift-related structures in the Alpine and Pyrenean foreland W of the Bohemian Massif stays in marked contrast with their scarcity in the eastern part of the European Variscides, in particular at their contact with the Western Carpathians.

An exception to these patterns can be the NW–SE-striking fault system at the north-eastern margin of the Bohemian Massif (the Sudetes region), which extends far behind the contact of the massif with the Alpine–Carpathian orogenic system. The eastern part of this region, located in a close proximity of the Western Carpathians' orogenic front, confines a crustal domain herein called the Nysa-Morava Zone (Špaček et al. 2006; Fig. 1b), which shows numerous signs of regionally anomalous, Late Cenozoic tectonic activity. The main manifestations of this young activity include the Late Miocene/Pliocene to Pleistocene alkaline volcanic eruptions (e.g. Ulrych et al. 2013) and tectonic subsidence in a system of graben-shaped basins, the Upper Morava Basin System (UMBS), filled with successions of Pliocene to Quaternary continental clastics, locally >300 m thick (Růžička 1973, 1989). At present, the active domain exhibits a weak seismic activity and regionally increased CO_2 flux (Špaček et al. 2006, 2011). Compared to the wealth of data from ECRIS, which developed in the Alpine foreland, geological information about graben-like structures from the Carpathians' foreland is rather poor (cf. Widera and Haluszczak 2011; Jarosiński et al. 2009). The aim of this review paper wasto summarise the so-far available geophysical, geological and geomorphologic data from this active domain and discuss its tectonic origin on the background of tectonic processes in the Alpine–Carpathian region.

Regional geological setting

Bohemian Massif

The Bohemian Massif is a part of the European Variscides—a tectonic mosaic of continental terranes formed by diachronous accretion of several microcontinents between the colliding Laurussia and Gondwana in the Devonian and Lower Carboniferous times (e.g. Franke 2000). The Variscan basement of the Bohemian Massif is unconformably overlain by post-orogenic, Upper Carboniferous to Lower Permian continental siliciclastics and Triassic to Upper Cretaceous continental and marine sediments (Pešek et al. 2001; Uličný et al. 2008; Ziegler 2005).

Several Variscan suture zones provide structural control for later tectonic reactivation under different deformation regimes during the Permian to Cenozoic times. Most important from the neotectonic point of view are two prominent structures developed in the NW and NE parts of the massif, respectively, the Eger (Ohře) Rift and the Labe-Odra Zone. The Eger Rift is an elongated, SW–NE-trending, >250-km-long zone of Paleogene to Quaternary intraplate volcanic activity hosting a system of Paleogene to Neogene grabens in its central part (Malkovský 1987; Ulrych et al. 2011; Fig. 1). It is traditionally regarded as a part of the ECRIS (e.g. Prodehl et al. 1995; Dèzes et al. 2004; Wilson and Downes 2006; Ulrych et al. 2011). The Labe-Odra Zone is defined here as a ~150-km-wide zone with complex, long-term evolution, which is largely controlled by a system of NW–SE-striking faults between the Elbe (Labe) and Odra fault zones (Figs. 1, 2; cf. Ulrych et al. 2011). It intersects with the NE part of the Eger Rift, and again, it hosts numerous small-volume bodies of Upper Cretaceous/Paleocene to Quaternary intraplate volcanics whose abundance decreases towards the SE (e.g. Badura et al. 2007; Ulrych et al. 2011, 2013; Figs. 1a, 2). The still active SE part of the Labe-Odra Zone is the focus of this paper.

The Labe-Odra Zone as defined in this paper largely coincides with the Sudetes region (e.g. Franke and Zelazniewicz 2000) and its adjacent, faulted units located to the NE and SW, which are covered by Mesozoic and Cenozoic sediments. The Sudetic Mountains at the Czech-Polish state border are developed in the axial part of this zone (Figs. 1, 2). The major NW–SE faults of this region may be regarded as the SE extension of the Elbe fault system sensu Scheck et al. (2002). This major wrench zone played an important structural role already during the Variscan orogeny and controlled the formation of Late Paleozoic volcano-sedimentary basins (Scheck et al. 2002 and references therein; Franke and Zelazniewicz 2000).

The post-Variscan tectonic evolution of the Labe-Odra Zone resulted in a complex block structure, which controlled the Meso/Cenozoic sedimentation. The 80-km-wide downthrown block of the Variscan basement in the northeastern foreland of the Sudetic Mts., which is partly covered by thin Cenozoic sediments, is referred to as the Fore-Sudetic Block (Fig. 2; e.g. Badura et al. 2004). The Sudetic Mts. and the Fore-Sudetic Block are separated

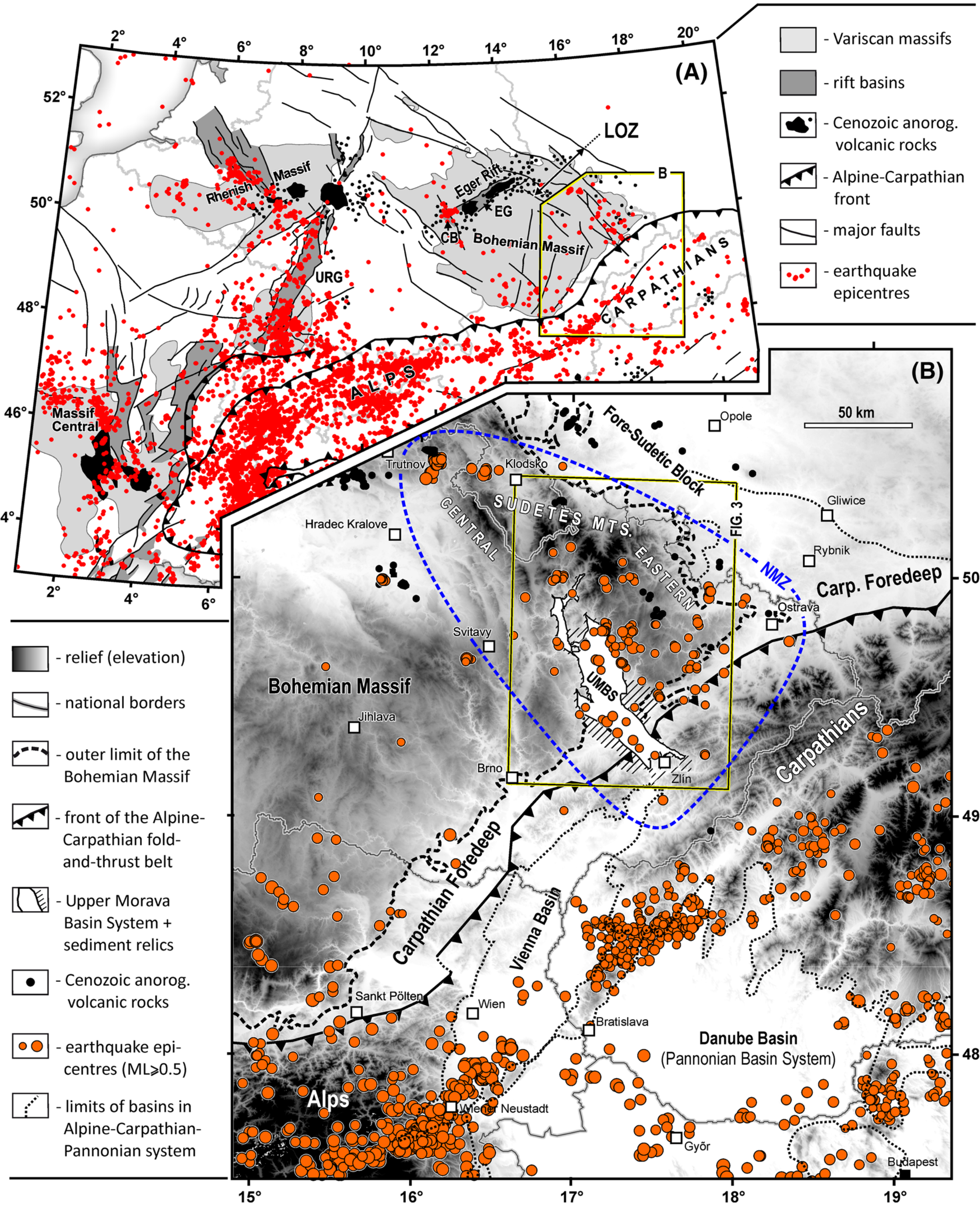


Fig. 1 Position of the studied area and main Cenozoic tectonic features at regional and supra-regional scales. **a** Schematic map showing present-day seismicity and main tectonic features in the Alpine–Carpathian foreland. Sedimentary grabens are based on Dèzes et al. (2004). Epicentres are from EuroMed Catalogue for period 1998–2010, partly revised (see text). *CB* Cheb basin, *EG* Eger Graben, *LOZ* Labe-Odra Zone, *URG* Upper Rhine Graben. **b** Relief map showing the position of the Upper Morava Basin System (UMBS) in the Alpine–Carpathian–Bohemian Massif junction region. Note the location of UMBS in seismically active part of the Carpathian foreland, the Nysa-Morava Zone (NMZ). Earthquake epicentres are from IPE2009 catalogue (2000–2009, $M_L \geq 0.5$; see text). Also shown are the occurrences of Cenozoic alkaline volcanic rocks in the Czech and Polish territories. *Rectangle* delineates the present study region and approximates the extent of Figs. 3, 4 and 5

by morphologically prominent Sudetic Marginal Fault (e.g. Badura et al. 2007; Fig. 2). In these two blocks, the Permo-Carboniferous and Mesozoic sediments are strongly reduced or even absent suggesting a specific uplift history. This stays in contrast to the adjacent Polish basin to the NE and the Bohemian Massif to the SE with thick Upper

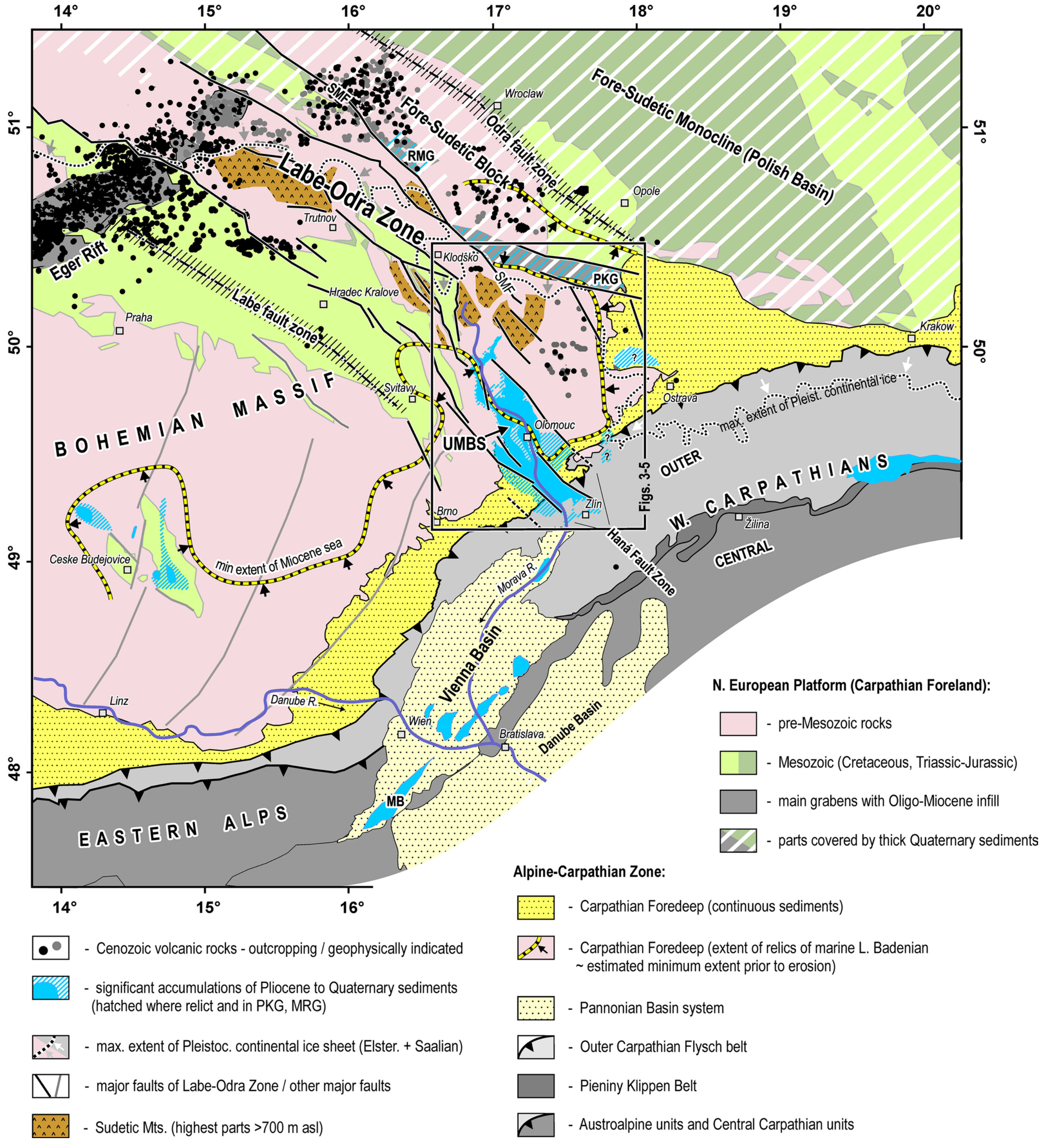


Fig. 2 Simplified geological map of Alpine–Carpathian–Bohemian Massif junction region focused to main neotectonic features. Note the NW–SE-oriented Labe-Odra Zone hosting Cenozoic volcanics and forming a structural elevation with reduced Mesozoic cover. Main grabens with Cenozoic fill are shown in *grey*. Minimum extent of Miocene sea based on relics of Carpathian Foredeep and maximum extent of Pleistocene ice sheet are shown by *dotted lines*. Significant Pliocene and/or Quaternary sediment accumulations are shown in *blue*. *PKG* Paczkow-Kędzierzin Graben, *RMG* Roztoka-Mokrzeszów Graben, *SMF* Sudetic Marginal Fault, *MB* Mitterndorf basin. *Rectangle* delineates the present study region and approximates the extent of Figs. 3, 4 and 5

Carboniferous to Upper Cretaceous sedimentary successions (Pešek et al. 2001; Ziegler 2005; Uličný et al. 2008). In the Sudetic Mts. region, the only Permian/Triassic and Upper Cretaceous sediments are preserved in the intramontane Intra-Sudetic basin and in several minor relics on the flanks of the mountain ranges. Low-temperature cooling age data (Aramowicz et al. 2006; Danišík et al. 2012) indicate large-scale uplift and erosion of the Sudetes during the late Cretaceous to Paleogene times, probably related to Europe–Adria–Africa plate convergence (Danišík et al. 2012). Contrasting evolution of the Sudetes and the Fore-Sudetic Block during Late Cenozoic is suggested by the present-day topography (Fig. 1b) and the presence of NW–SE- to W–E-striking grabens with Late Oligocene and Miocene sediments (Fig. 2; e.g. Dyjor 1983; Jarosiński et al. 2009).

Alpine–Carpathian–Pannonian domain

To the SE, the Variscan Bohemian Massif plunges beneath the outer Western Carpathians of the Alpine–Carpathian orogenic system (Fig. 2)—the Carpathian foreland basin (Carpathian Foredeep in regional terminology) and the external fold-and-thrust belt (Flysch belt).

The Carpathian Foredeep is a relatively narrow foreland basin, located parallel to the Carpathian deformation front and filled with several 100-m-thick, undeformed or slightly deformed late orogenic to post-orogenic, marine and terrestrial deposits of latest Oligocene to middle Miocene (Egerian to Badenian) age (Stráník et al. 1993; Pícha et al. 2006). In addition, numerous relics of Miocene sediments (mostly of Badenian age) are found far to the W, on the Bohemian Massif, within 40 to >130 km distance from the Carpathian deformation front. In tectonic grabens of the eastern Labe-Odra Zone, these relics can be more than 300 m thick (e.g. near Lanškroun north of Svitavy in the Czech Sudetes; Čech and Čtyroká 2012; Paczkow-Kędzierzin Graben in Polish Fore-Sudetic Block; Dyjor et al. 1977; Jarosiński et al. 2009). This indicates that the original extent of Carpathian Foredeep prior to post-Middle Miocene erosion was much larger than today (Fig. 2).

The Flysch belt represents a several-thousand-metres-thick stack of rootless, thin-skinned nappes of the Tertiary accretionary wedge of the Carpathian Orogen, which is thrusted over the Miocene foreland basin. It is composed mostly of siliciclastic deep-marine turbidites, mass-flow deposits and hemipelagic deposits of Jurassic to early Miocene age (Stráník et al. 1993; Plašienka et al. 1997; Pícha et al. 2006).

Farther to the east and southeast, the structure of the orogenic belt continues with the Central Western Carpathian Zone representing a Cretaceous thick-skinned nappe stack of crustal units with pre-Alpine crystalline basement and its Late Paleozoic–Mesozoic sedimentary cover (e.g. Plašienka et al. 1997). The Outer and Central Western Carpathians are divided by the Pieniny Klippen Belt—a narrow zone with sediments of exceptionally variable lithology and mélange-like internal structure formed by Late Cretaceous to early Tertiary thrusting and dextral transpression (e.g. Plašienka et al. 1997).

Gradual arc-parallel collision between the European lower plate and Adriatic (Apulian) upper plate led to the extrusion of the internal Carpathian domains from the Alpine collision zone (Ratschbacher et al. 1991), which was associated with continuous crustal shortening of the orogenic front. The diachroneity of crustal shortening is reflected in lateral eastward migration of molasses and younging of the main thrusting of outer nappes (e.g. Jiříček 1979). In Alpine–Carpathian junction area (Fig. 2), the thrusting of Flysch Belt over the Carpathian Foredeep ended in early to early middle Miocene times (Karpatian to Badenian, ~18–16 Ma) (e.g. Jiříček 1979; Jiříček and Tomek 1981; Pícha et al. 2006; Peresson and Decker 1997a and references therein). The generally N–S-directed shortening in the Eastern Alps and sinistral shearing along the NE–SW wrench fault(s) parallel to Pieniny Klippen Belt continued during Middle and late Miocene times (e.g. Fodor 1995; Marko et al. 1995; Peresson and Decker 1997a) and are still active today as indicated by GPS measurements and regional seismicity (e.g. Grenerczy et al. 2005; Lenhardt et al. 2007; Fojtíková et al. 2010).

The Miocene sinistral wrenching along this NE-trending fault zone lead to opening of the Vienna Basin, a part of the Pannonian Basin System superposed over the junction of the Outer/Inner Carpathians and the Eastern Alps, which is located just south of the region studied here (Figs. 1, 2). Subsidence in the Vienna basin was mainly related to Middle and Late Miocene pull-apart and transtensional deformation phases and resulted in deposition of up to >5-km-thick sedimentary succession (e.g. Jiříček and Tomek 1981; Royden et al. 1983; Fodor 1995; Decker et al. 2005). Since local sedimentation continued throughout Pliocene and Quaternary (Jiříček and Tomek 1981; Decker et al. 2005), this basin brings a regionally important record of Late Cenozoic tectonic evolution in the Alpine–Carpathian junction.

Post-middle Miocene basin subsidence in Labe-Odra Zone

The erosion of Carpathian Foredeep sediments and nearly absent Miocene sediments suggests significant post-Badenian regional uplift of most parts of the Bohemian Massif (cf. Ziegler and Dèzes 2007). However, Miocene sedimentation continued in grabens of the Fore-Sudetic Block (Roztoka-Mokrzeszów and Paczkow-Kędzierzin Grabens; Fig. 2; Dyjor 1983). Subsidence in these grabens was controlled by E–W- to NW–SE-trending faults between the Sudetic Maginal Fault and Odra Fault Zone (Fig. 2). In Paczkow-Kędzierzin Graben, thickness of mostly lacustrine Poznań Series of Sarmatian age is nearly 200 m. The Miocene succession is unconformably overlain by several-dozen-metre-thick accumulations of alluvial and lacustrine Pliocene sediments (Gozdnica Series) and Pleistocene fluvial and glacigenic sediments (Dyjor et al. 1977). Minor accumulations of Pliocene were reported from beneath Quaternary cover in NE Bohemian Massif (Fig. 2; Macoun 1980), while their relation to the Paczkow-Kędzierzin Graben is unclear.

In the southern (Czech) side of the Labe-Odra Zone, the UMBS is by far the most important structure with accumulation of post-Middle Miocene deposits. This system of grabens filled with up to ~300 m succession of lacustrine and fluvial sediments of Late Miocene/Pliocene to Holocene age runs roughly perpendicularly to the Carpathian deformation front, sealing the tectonic contact between the Western Carpathians and their foreland (Figs. 1, 2, 3, 4, 5). Internal structure and evolution of this basin system together with the fault control in the adjacent uplifted regions and the present-day tectonics are the focus of this paper and are described in detail below.

Data sources and methods

This review is based on reassessment of available geological and geophysical data. The map of Bouguer gravity anomalies (Fig. 4) was derived using data from ground gravity surveys carried out by Geofyzika Brno, Charles University in Prague and other state-owned institutions in 1960s–1990s. Point measurements with average distance of 0.5 km were used for most of the studied region except for its westernmost part where average distance was around 2.5 km. All data were processed together using reduction density of 2.67 g/cm^3. Special care was given to the analysis of conspicuous linear horizontal gradient zones, which are potentially associated with large-offset faults.

Morphological analysis was based on high-resolution (10 m grid step) digital elevation model (DEM) interpolated from contour (1–2-m vertical resolution) and point data *ZABAGED* purchased from the Czech Office for Surveying, Mapping and Cadastre, Prague. The occurrence of morpholineaments, river capturing and river segments of enhanced erosion were of special interest.

Having combined these new data with the published papers and available geological maps of the Czech Geological Survey (1:25,000–1:50,000 scale), we reassessed the fault structure of the region. Emphasis was given to the faults with significant Cenozoic activity as indicated by their geological or morphological features.

Several geological profiles and a new model of Plio-Quaternary sediment thickness in the UMBS (Fig. 5) are based on more than 400 boreholes retrieved from the state-owned archive (Geofond/Czech Geological Survey). Of them, nearly 100 reached the base of the Plio-Quaternary suite, while the remaining were used to indicate just the minimum thickness. The interpolation was supported by semi-quantitative assessment of the Bouguer gravity anomalies and the geological maps. Several reflection seismic sections were also used for interpolation in the southern part of the UMBS. It must be stressed here that both the basin depth model and the large-scale profiles are only approximate, since good quality reflection seismic profiles are rare and in some parts of the basin its bottom was not reached by drills. The time-migrated 2D reflection seismic profile shown in Fig. 9 is a composite from two crossing profiles 123/72a and 123/72b performed by Geofyzika Brno (explosive source, CDP 25 m) and reprocessed by M. Novotný (in Dvořáková et al. 1998).

Stratigraphy of the UMBS sedimentary fill and the adjacent fluvial terrace levels is based on a literature review of biostratigraphic data from both surface and subsurface, sediment lithology and provenance data of the terrace levels and their morphostratigraphic position. The literature data are supplemented by a review of core descriptions from several tens of shallow boreholes (Geofond) and a dozen of new ^{14}C ages and electric resistivity tomography (ERT) sections in the active floodplain.

Seismicity in the studied region has been continuously monitored since 1996 using permanent and temporary seismic stations in variable arrangements. Its central part is currently covered by the Moravia Network (MONET), virtual seismic network consisting of nine permanent short-period or broadband stations operated by IPE Brno. Eight more permanent and three temporary stations run by co-operating institutions (IG Prague, IGN Ostrava, IRSM Prague and IGF Warsaw) as well as several stations which are now closed were used for location and inversion of focal mechanisms. Most of the stations are shown in Fig. 5 (including the now closed stations) along with the epicentres of the located earthquakes. For the overview of monitoring network progress, technical specification of stations, velocity model and details on the seismic activity, we refer to Špaček et al. (2006, 2011).

The MONET2012 catalogue comprising 960 local events for 1998–2012 period is used in this study (Fig. 5). Reading of the seismograms, seismic phase identification and picking was performed manually for all stations. All events were carefully revised with regard to mining explosions and underground mining-induced seismicity, which ensures the catalogue to be generally free of non-tectonic events. All events before 2009 were relocated as a part of previous study using seismogram cross-correlation with master events (Špaček et al. 2011). The horizontal relative location error is estimated to <1 km for most events, and the magnitude of completeness of catalogue is close to $M_L = 0.2$ for the region under study.

For regional-scale assessment of seismicity, two other catalogues were used: (1) EuroMed2010 catalogue (EMSC 2010) of European earthquakes for period 1998–2010, cleared of mining-induced events from the territories of Czech

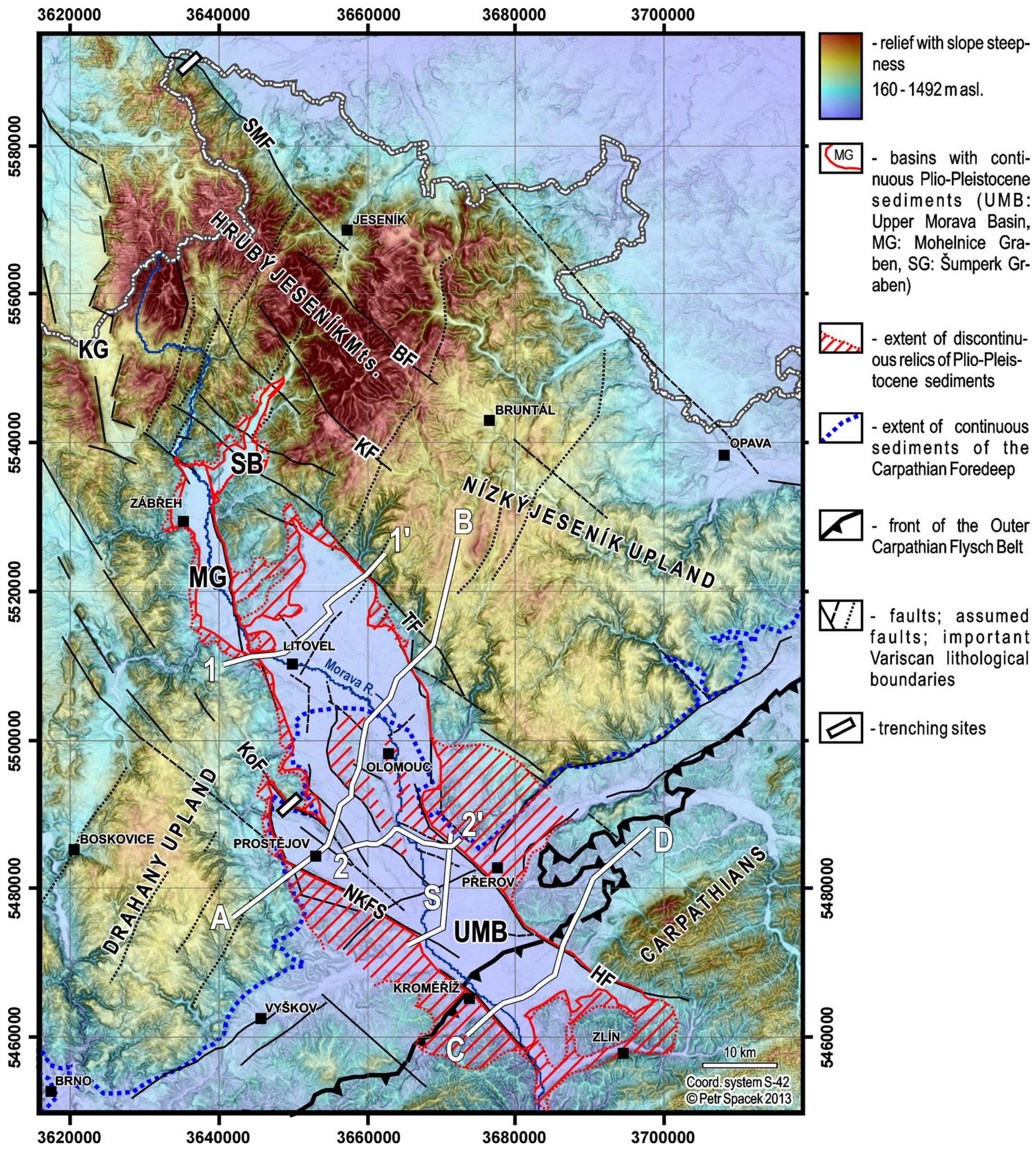


Fig. 3 Relief map of the eastern NMZ and position of UMBS including its erosional relics. *UMB* Upper Morava Basin, *MG* Mohelnice Graben, *SB* Šumperk Basin, *KG* Kraliky—Upper Nysa Kłodzka Graben. Note the en-echelon geometry of UMB, MG and KG. The position of profiles shown in following figures is indicated (A–B and C–D in Fig. 6, 1–1′ and 2–2′ in Fig. 8, seismic profile S in Fig. 9). Faults shown are main faults with assumed Late Cenozoic activity. *SMF* Sudetic Marginal Fault, *BF* Bělá Fault, *KF* Klepáčov Fault, *TF* Temenice Fault, *HF* Holešov Fault, *KoF* Kosíř Fault, *NKFS* Nectava-Kvasice Fault System. Compare with Figs. 4 and 5 showing other features in the same region

Republic, Poland and SE Germany (Fig. 1a); (2) IPE2009 catalogue of ≥ 0.5 events compiled and revised at IPE Brno from the available regional catalogues for period 2000–2009 (J. Pazdírková in Špaček et al. 2011; Figs. 1b, 11). These two catalogues largely overlap in time, and therefore, they can be used to compare the seismic activity at different scales.

Focal mechanisms were calculated for several strongest events by Focmec program (Snoke 2003) using P- and SH-wave polarities and free-surface-corrected displacement amplitude ratios at 11–16 stations as an input.

The Nysa-Morava Zone

In its southeastern part, the Labe-Odra Zone is associated with regionally anomalous, present-day seismic activity,

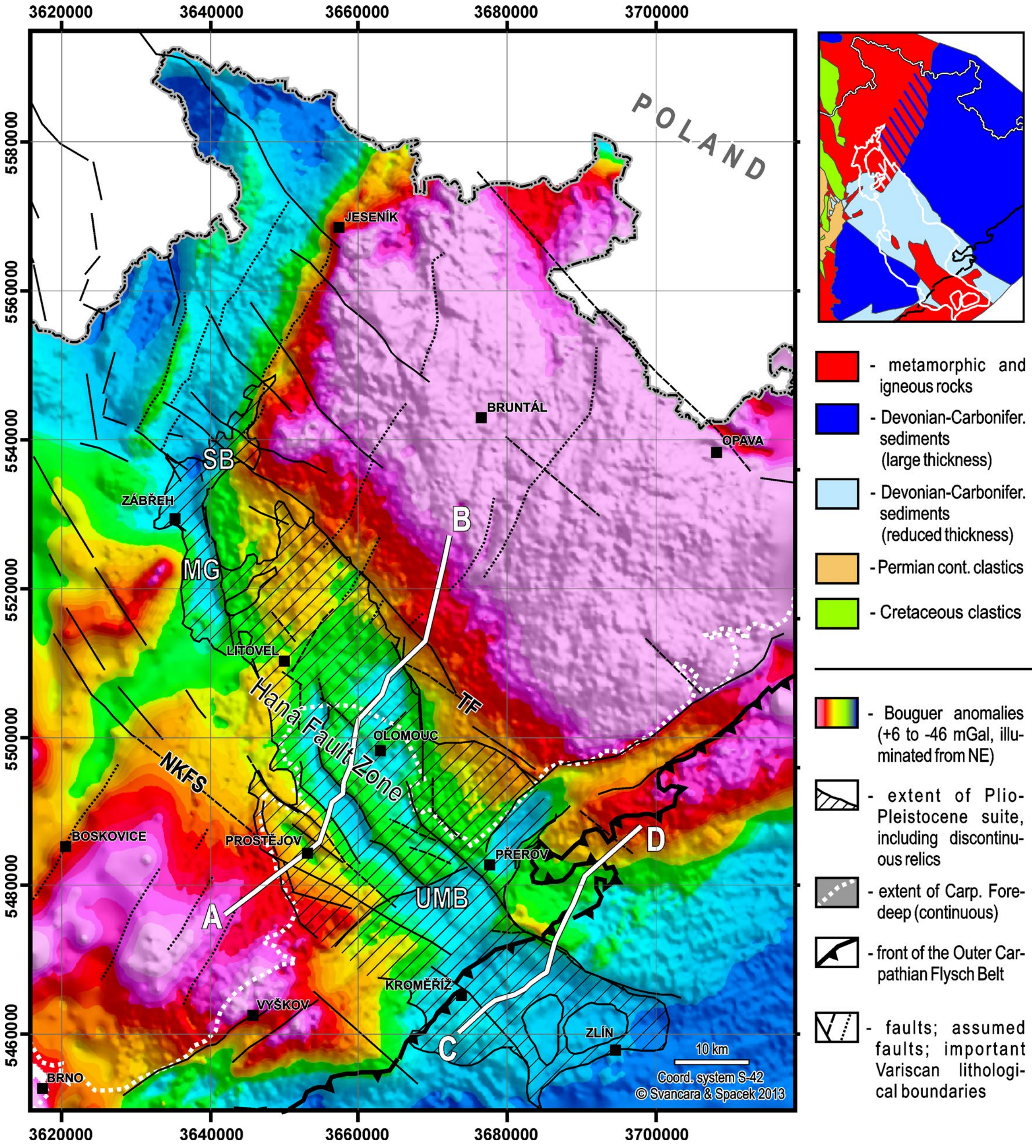


Fig. 4 Bouguer gravity anomaly map of the eastern NMZ. The *inset map at top right* shows simplified pre-Cenozoic geology including substratum of UMBS interpreted from drill cores and gravity. See Fig. 3 for explanation of acronyms. Note the NW–SE-oriented low-gravity area coinciding with UMBS and bounded by marginal faults of the Haná Fault Zone (TF and NKFS). The position of two profiles A–B and C–D shown in Fig. 6 is indicated. Compare with Figs. 3 and 5 showing other features in the same region

which is in sharp contrast with the adjacent parts of the Bohemian Massif and the Carpathians, where seismic events are scarce. This seismogenic domain is herein called the Nysa-Morava Zone (Fig. 1), named after two major rivers whose fault-bounded valleys dominate the relief in its central part (cf. Špaček et al. 2006). The NMZ is delimited by the occurrence of weak tectonic earthquakes instrumentally detected in the last two decades. In a broader sense, the NMZ is confined to the area covering also the epicentres of historical earthquakes, which are assumed to link genetically to the present-day seismogenic zone, located roughly between the towns of Trutnov, Svitavy, Zlín, Ostrava and Kłodzko (Figs. 1, 2).

The grabens of the UMBS filled with Late Cenozoic deposits developed in the central and eastern part of NMZ. Coincidence of these tectono-sedimentary structures with the Late Cenozoic and present-day seismic activity suggests that the tectonics is still alive and the relations

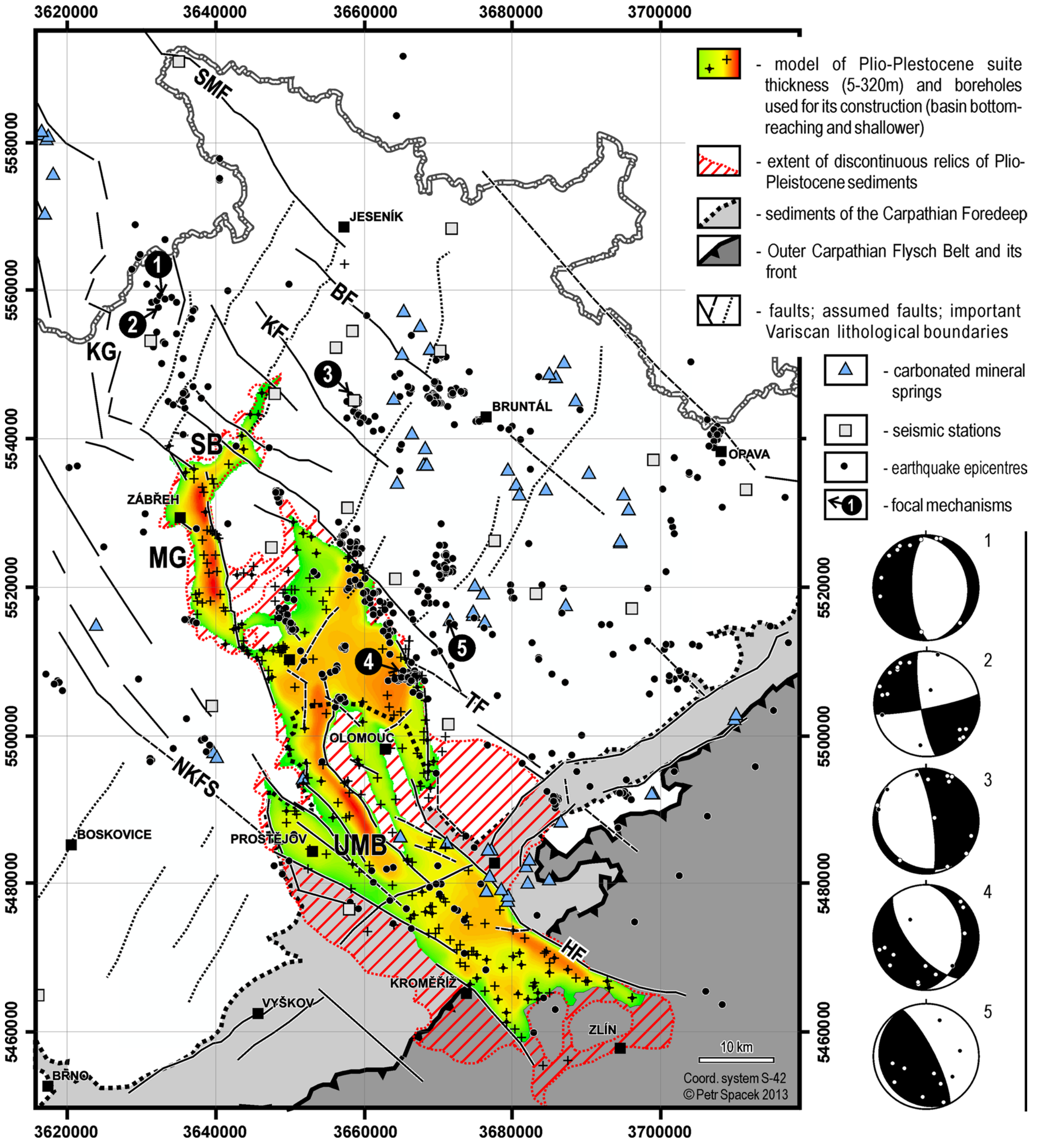


Fig. 5 Map showing the model of thickness of Plio-Pleistocene suite in UMBS and position of earthquake epicentres (MONET2012 catalogue) and carbonated mineral springs in the eastern NMZ. Also shown are the calculated focal solutions for five stronger earthquakes. See Figs. 3 and 4 for explanation of acronyms and comparison of other features in the same region

between the two phenomena are discussed further. Below, we give a more detailed description of geological structure and tertiary to present-day tectonics of the NMZ, which is also shown in Figs. 3, 4 and 5.

Pre-Miocene structure

The basement is composed of high- and medium-grade metamorphics including gneisses, amphibolites and meta-sediments with Variscan cooling ages, mainly in the western part of the region. In the eastern part, slightly deformed to undeformed, syn-orogenic Devonian to Lower Carboniferous clastic-carbonate sedimentary sequences covering the Cadomian crystalline rocks predominate (e.g. Schulmann and Gayer 2000; Kalvoda et al. 2008). The internal structure of the basement including lithological boundaries, thrust faults, cleavage and bedding planes on small scale typically exhibits NNE–SSW trends (locally deflected to N–S or NW–SE trends) and largely variable dips (e.g. Grygar and Vavro 1995; Bábek et al. 2006) In the western parts of the region, the Variscan basement is covered by post-orogenic, Upper Carboniferous to Lower Permian continental siliciclastics, which are unconformably overlain by Upper Cretaceous continental and marine sediments (see inset in Fig. 4).

Generally, NW–SE-trending faults penetrate the whole NMZ (Figs. 3, 4, 5). They are well mapped in the northwest, where they often offset lithological boundaries within the Variscan crystalline basement. In the lithologically uniform, deep-marine Carboniferous siliciclastics (Culm facies) in the NE and SW, these faults are often poorly constrained. Several faults exhibit clear morphological scarps suggesting a Late Cenozoic slip and/or differential erosion associated with lithological contrasts. The Sudetic Marginal Fault, which delimits the Sudetic Mts to the north (Figs. 2, 3), represents the longest and morphologically most prominent fault of the Labe-Odra Zone (e.g. Badura et al. 2007). More to south and southeast, the NW–SE-trending faults (e.g. Bělá and Klepáčov faults) delimit a horst-like uplifted block of the Hrubý Jeseník Mts. (peak at 1,492 m asl) against the low-relief areas of the southern part of NMZ, which is associated with a prominent, 30- to 40-km-wide fault zone coinciding with the Cenozoic UMBS and a distinct negative Bouguer gravity anomaly (Figs. 3, 4, 5). This structure, called the Haná fault zone (HFZ), is a system of NW–SE- to N–S-trending faults with large normal slip component, delimited by the Temenice Fault to the northeast and the Nectava-Kvasice Fault System to the southwest. The SE part of the HFZ is characterised by the absence of Paleozoic (Devonian and Lower Carboniferous) sediments beneath the Cenozoic sediments as indicated by drills, seismic profiles and outcrop observations (e.g. Dvořák 1975). We suggest that this zone of reduced Paleozoic structural layer continues towards NW and is largely responsible for the NW–SE-trending negative Bouguer gravity anomaly associated with the HFZ (Fig. 4). This anomaly is best visible in the central part of HFZ, reaching 10–25 mGal difference relative to the adjacent areas. The main gravity minima correspond to maximum thickness of the UMBS sedimentary infill. However, as the anomaly also covers large areas with only relict occurrence of Cenozoic sediment, it must also reflect the mass deficit in the underlying rocks. The Paleozoic sedimentary rocks, especially carbonates, have generally higher densities than the granitic rocks, which predominate in the underlying Brunovistulian basement (Ibrmajer et al. 1989), and so, the gravity low can be explained by their absence or scarcity in the HFZ. Although additional effect of heterogeneities in the crystalline basement cannot be ruled out (cf. Blížkovský et al. 1977), all available data indicate that the gravity anomalies are mainly caused by the large lateral variability in the thickness of Paleozoic carbonate/clastic sequence, which is lowest in the HFZ.

Fig. 6 Schematic geological, morphological and gravity profiles ▶ showing larger-scale structure of the Upper Morava Basin and its subcrop in northern (A–B; **a**) and southern (C–D; **b**) parts. See maps in Figs. 3 and 4 for location. The subcrop geology is largely conceptual and generalised, interpreted from drills, reflection seismic profiles and gravity. Note the opposite sense of fault slip in pre- and post-Lower Miocene indicated by *arrows*

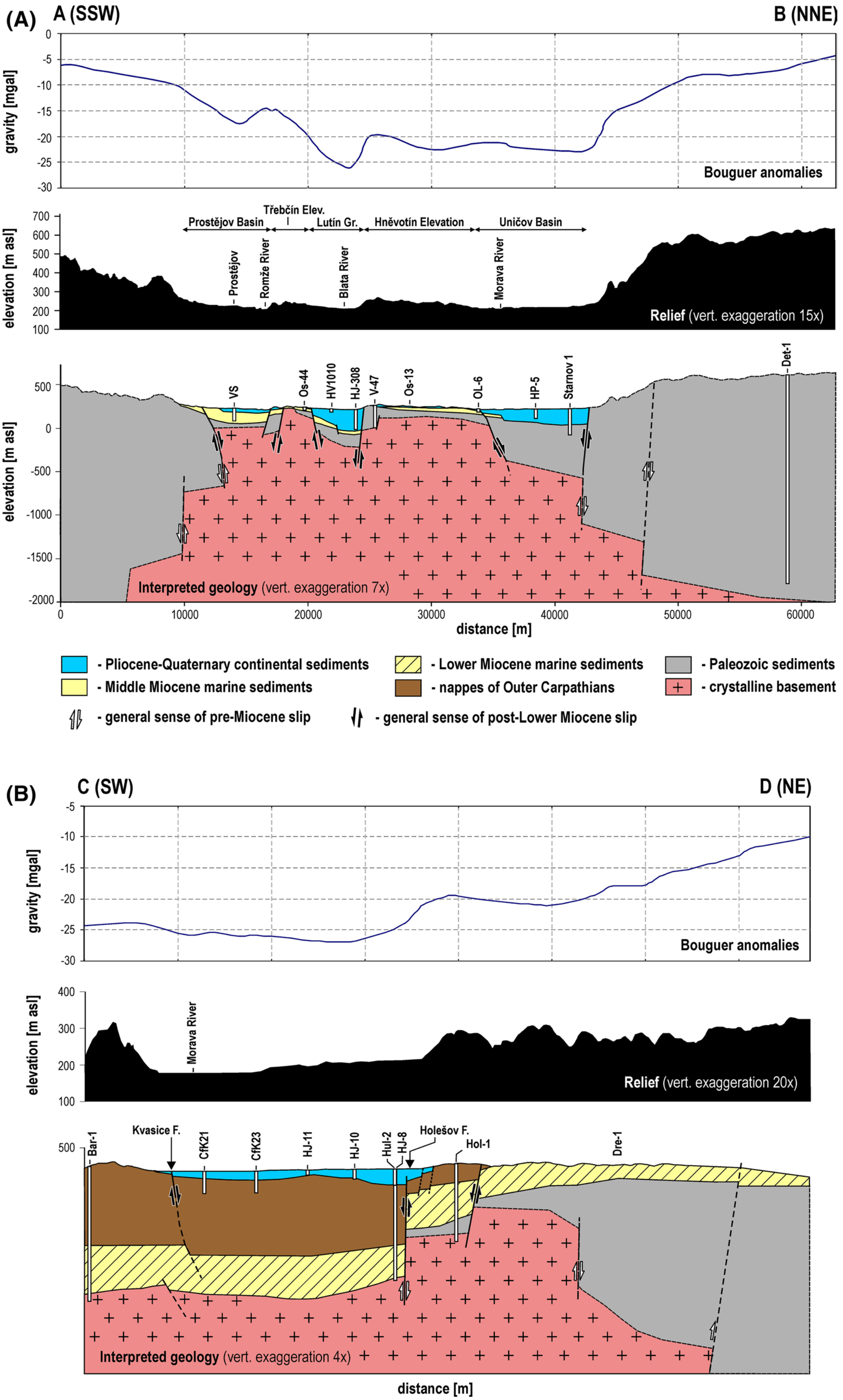
The subsurface structure is illustrated in two schematic geological profiles running across the central and SE part of the HFZ and associated basins of the UMBS (Fig. 6) together with the topography and gravity profiles. In the southeast, the structure is well constrained by drills and seismic reflection profiles from oil exploration (e.g. Dvořák 1975; Krejčí et al. 1999). Interpretation of the deeper parts of the profiles is based on the gravity data and regional geological observations. In the southeastern part of the HFZ, the Paleozoic structural layer is completely absent or reduced only to several hundred metres, while in the adjacent hilly areas to the north (Nízký Jeseník Upland) there is >1,500 m (locally >4,000 m)-thick succession of Paleozoic sediments resting on top the crystalline basement (Čížek and Tomek 1991). The situation in the uplands south of the HFZ (Drahany Upland), which are not explored by deep drilling, is assumed to be similar, as suggested by the gravity data.

The northeastern part of the NMZ hosts another topographic depression trending NNW–SSE, the Králíky-Upper Nysa Kłodzka Graben, which is filled with up to 1-km-thick Upper Cretaceous sediments (Badura and Rauch 2014). This graben and the basins of the UMBS form an echelon-like system of morphological depressions aligned quasi-diagonally within the NMZ. These structures are specifically controlled by NNW–SSE- to N–S-trending faults, which are uncommon in other parts of the NMZ. It is in these domains and in their northern neighbourhood where we see most manifestations of ongoing tectonic activity, and thus, they seem to have been played an important role in the late tectonic history of the region.

The Upper Morava Basin System

Morphology

The UMBS is a group of sedimentary basins with Late Cenozoic sedimentary infill, superposed onto the contact of the Bohemian Massif with the Outer Western Carpathians. It is located in quasi-diagonal position to the main faults of the NMZ, and having an elongated shape with generally NNW–SSE trend, it is nearly perpendicular to the front of Outer Carpathian nappes (Figs. 1b, 2). The low topography of the UMBS was apparently controlled by subsidence along the faults of the Haná Fault Zone (HFZ) and by incision of the present-day Morava River and its tributaries.


(A)
A (SSW)
B (NNE)
gravity [mgal]
0
-5
-10
-15
-20
-25
-30
Bouguer anomalies
elevation [m asl]
700
600
500
400
300
200
100
Třebčín Elev.
Prostějov Basin
Lutín Gr.
Hněvotín Elevation
Uničov Basin
Prostějov
Romže River
Blata River
Morava River
Relief (vert. exaggeration 15x)
elevation [m asl]
500
0
-500
-1000
-1500
-2000
VS
Os-44
HV1010
HJ-308
V-47
Os-13
OL-6
HP-5
Stamov 1
Det-1
Interpreted geology (vert. exaggeration 7x)
0
10000
20000
30000
40000
50000
60000
distance [m]
- Pliocene-Quaternary continental sediments
- Middle Miocene marine sediments
- Lower Miocene marine sediments
- nappes of Outer Carpathians
- Paleozoic sediments
- crystalline basement
- general sense of pre-Miocene slip
- general sense of post-Lower Miocene slip
(B)
C (SW)
D (NE)
gravity [mgal]
-5
-10
-15
-20
-25
-30
Bouguer anomalies
elevation [m asl]
400
300
200
100
Morava River
Relief (vert. exaggeration 20x)
500
Bar-1
Kvasice F.
CfK21
CfK23
HJ-11
HJ-10
Hul-2
HJ-8
Holešov F.
Hol-1
Dre-1
Interpreted geology (vert. exaggeration 4x)
distance [m]

The present-day UMBS is a >90-km-long and 3- to 25-km-wide sedimentary basin with many local depocentres and elevated structural blocks controlled by differential subsidence/uplift patterns. Three major subbasins are distinguished in the UMBS (from SE to NE; Figs. 3, 4, 5).

The *Upper Morava Basin* sensu stricto (UMB) is the largest of the three subbasins, 80 km long and 11–25 km wide, with up to >9-km-wide active floodplain at elevation 180–240 m asl. A pronounced, up to 350-m high morphological step is developed at the Temenice fault constituting the NE margin of the UMB against the Nízký Jeseník Upland (Fig. 3). The morphology of UMB is much less marked in its central part where it cross-cuts the structural depression of the Carpathian Foredeep. Two NNW–SSE-elongated structural elevations with outcrops of Miocene and pre-Mesozoic rocks (Třebčín and Hněvotín elevations) disrupt the flat topography of the floodplain and give the UMB a horst-and-graben morphology with three sub-parallel depressions (Figs. 3, 4, 5, 6a). Discontinuous relics of Pliocene and Pleistocene sediments on elevated platforms adjacent to the UMB (mainly in the Carpathian Foredeep) indicate that the Late Cenozoic sedimentary basin covered almost the entire HFZ. Due to the combination of NNW- to N-trending and NW-trending faults, the basin exhibits quasi-rhombic geometry both on the local and regional scales. In the southeast, the UMB extends as far as to the northern tip of the Vienna Basin (Fig. 2). Today, the two basins are connected by a narrow valley of the Morava River flowing to the SE and S towards the Danube River (Fig. 2). However, the Pliocene and Quaternary deposits are missing in most parts of the Vienna Basin, and they only occur in small subbasins (e.g. Havlíček 1980; Decker et al. 2005; Fig. 2). This suggests rather different subsidence history and perhaps complete separation of the two basins in Pliocene and early Pleistocene.

The NNW–SSE-trending *Mohelnice Graben* (Figs. 3, 4), which is separated from the UMB by a narrow neck of the Morava River, is 4- to 5-km-wide asymmetric graben with remarkably steep, 150- to 200-m high eastern scarp. The floodplain elevation ranges from 240 to 305 m asl, while the adjacent hilly lands reach elevations of 420–600 m asl.

The *Šumperk Basin* (Figs. 3, 4) forms a 2- to 3-km-wide valley (floodplain <1.5 km wide, elevation 290–410 m asl) within a hilly land with mean elevation 500–700 m asl. In contrast to the other basins, it is oriented in NE–SW direction, which corresponds to and was probably inherited from the major structural trend of the Variscan basement. Despite this structural difference and limited data on basin architecture, we include the Šumperk Basin into the UMBS because of the anomalous thickness of its fluvial sedimentary fill (locally >100 m), which implies Late Cenozoic subsidence, and because of the lack of any morphological divide with the adjacent Mohelnice Graben.

Stratigraphy

The sedimentary fill of the UMBS comprises Miocene to Holocene marine and terrestrial, mainly siliciclastic sediments, which rest unconformably on the Precambrian crystalline to Lower Carboniferous basement in the north and on the thrust sheets of the Western Carpathians in the south (Figs. 6, 7). Vast majority of stratigraphic data come from the largest of the three basins, the UMB, and the description below refers mainly to this part of the basin system. Two interpreted geological cross sections (Fig. 8) provide examples of different stratigraphic patterns across the basin.

The oldest sediments, which are preserved in the basin fill are of early Miocene (Karpatian/late Burdigalian) age. These are brackish, shallow-marine and sometimes deep-marine siliciclastics of the Carpathian foreland basin, which were partly folded and partly overridden by the thrust sheets of the Outer Western Carpathians (Flysch Belt) during the end-Karpatian phase of thrusting. Following the thrusting and erosion, sedimentation was renewed in the Middle Miocene (early Badenian/Langhian) times, represented by deltaic, shallow-marine and deep-marine siliciclastics and rare carbonates (Nehyba and Šikula 2007; Doláková et al. 2008). Erosional relics of these sediments were revealed in boreholes and are locally found on surface, mainly in the southern part of the basin. Maximum thickness of the Miocene sediments is about 600 m in the S of the UMBS, while to the N the sediments rapidly wedge out (cf. Figs. 6, 8). Rapid lateral facies transitions in the Miocene deposits of the UMBS point to enhanced tectonic activity compared to the remaining part of the Carpathian Foredeep (Brzobohatý and Cicha 1993).

Since the latest Miocene/Pliocene times, the UMBS evolved as a fully terrestrial sedimentary basin of more-or-less the present-day NW–SE-trending elongated shape. Bounded by a basal angular unconformity (cf. Fig. 9), the uppermost Miocene/Pliocene stratigraphic succession comprises mainly lacustrine and fluvial siliciclastic sediments with scarce peat layers, with maximum thickness of 250 m. In general, this succession shows trends of decreasing grain size from the basin margins towards the basin centre and a fining-upward stratigraphic trend. Lacustrine clays, deposited in the basin centre pass laterally into coarse-grained facies including shoreface, fluvial and colluvial sands and gravels with locally derived clasts suggesting lateral sediment input from the adjacent highs located to the NE and SW (Růžička 1989). The Pliocene age of this succession is based on numerous findings of pollen, fossil plants, ostracods and mammals (Růžička 1989; Zeman et al. 1980; Čtyroký 1995). Rare fossil findings may even indicate late Miocene age of the fluvio-lacustrine succession, which is also supported by its lithological similarity with the uppermost Miocene "Variegated Formation" of the Vienna Basin

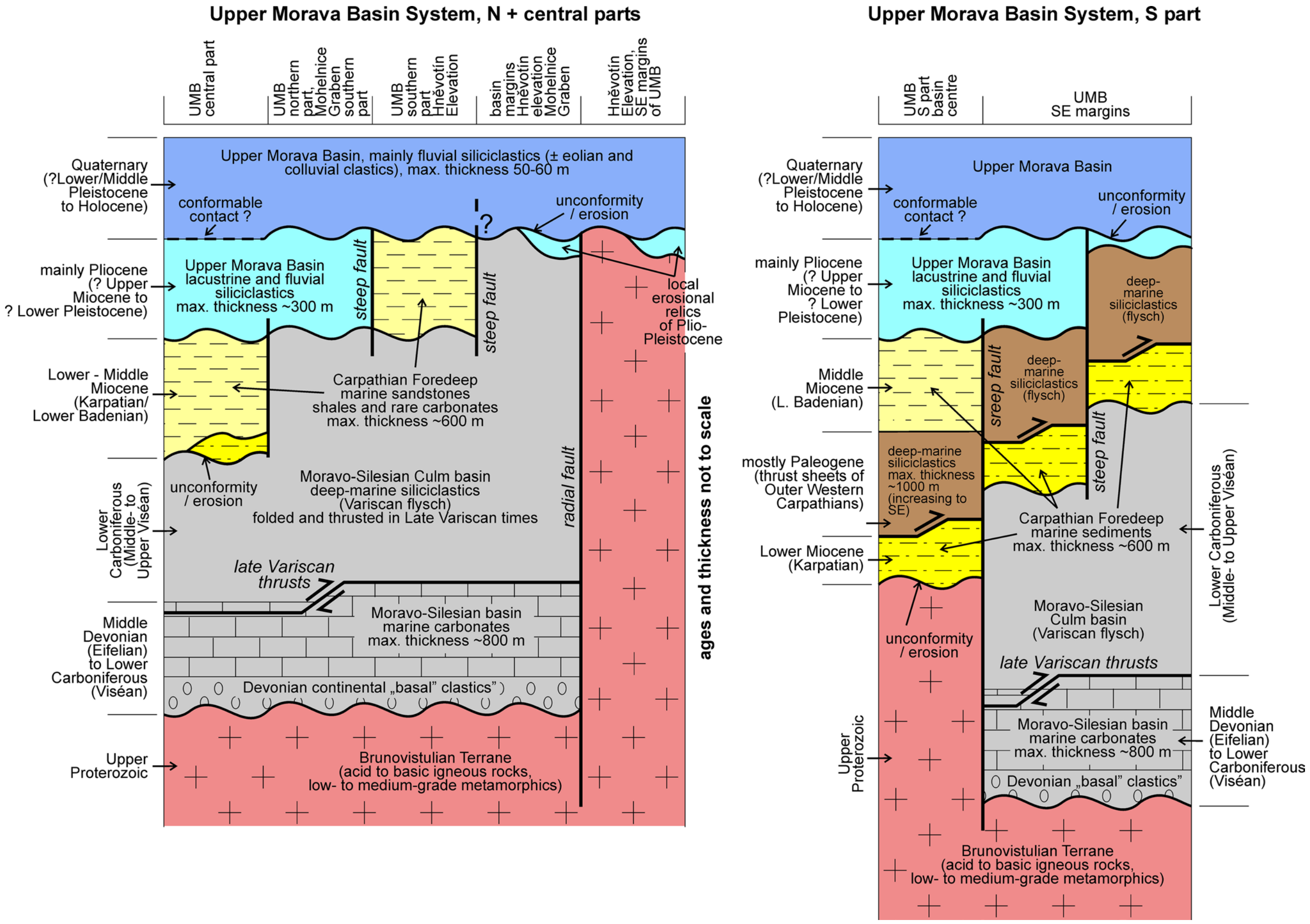


Fig. 7 Lithostratigraphic scheme of sedimentary succession of the Upper Morava Basin System and basement units. Note that ages and thicknesses are not to scale

(Čtyroký 1995). Findings of pollen and rodent teeth (*Mimomys* cf. *stehlini*, *M. polonicus*) enabled to date the upper parts of the succession to early Villafranchian (uppermost Pliocene/lower Pleistocene) (Zeman et al. 1980; Čtyroký 1995).

The overlying Quaternary succession comprises fluviolacustrine and fluvial sands, gravelly sands and gravels, which alternate with thin silty and clayey overbank deposits mainly in the central and southern parts of UMB (Macoun and Růžička 1967; Růžička 1973; Zeman 1971 and Zeman et al. 1980). Relics of the oldest fluviolacustrine sediments are limited to graben-like depressions in the Lutín Graben, Uničov Basin and southeastern part of UMB (Macoun and Růžička 1967; Růžička 1973; 1989). Their age was constrained to Elsterian based on finds of molluscan fauna and morphostratigraphic position (Macoun and Růžička 1967). The fluviolacustrine sediments are also preserved on slopes of the UMB up to the maximum relative elevation of 35 m above the present-day river level (Macoun and Růžička 1967; Růžička 1973). The following incision, probably coupled with differential uplift, resulted in formation of terrace staircases by alternating downcutting and aggradation (Fig. 8b). The age of these fill terraces was constrained to be middle Pleistocene (Late Elsterian) to Holocene based on combined morphostratigraphic and mineral provenance indicators, and correlation with deposits of continental glaciations in the adjacent areas (Macoun and Růžička 1967; Růžička 1973; Tyráček and Havlíček 2009). The terrace levels from upper to lower are as follows: Luková (Early Elsterian), Brodek (Late Elsterian), Kralice (Early Saalian), Nenakonice (Late Saalian) and valley-bottom gravels (Weichselian to Holocene) (Fig. 8b). The Kralice (Main) terrace is an aggradational terrace composed of two superposed accumulations, which are at some places separated by paleosols (Růžička 1973). The valley-bottom gravels form a sheet-like body developed under the present-day floodplain. Its thickness is usually lower than 8–10 m, as indicated by boreholes and ground resistivity imaging (authors' unpublished data). Sediments from shallow depths (<3 m) beneath the active floodplain yielded a broad range of Holocene ages (6.1–0.13 kyr BP, ^{14}C) (Bábek, unpublished data).

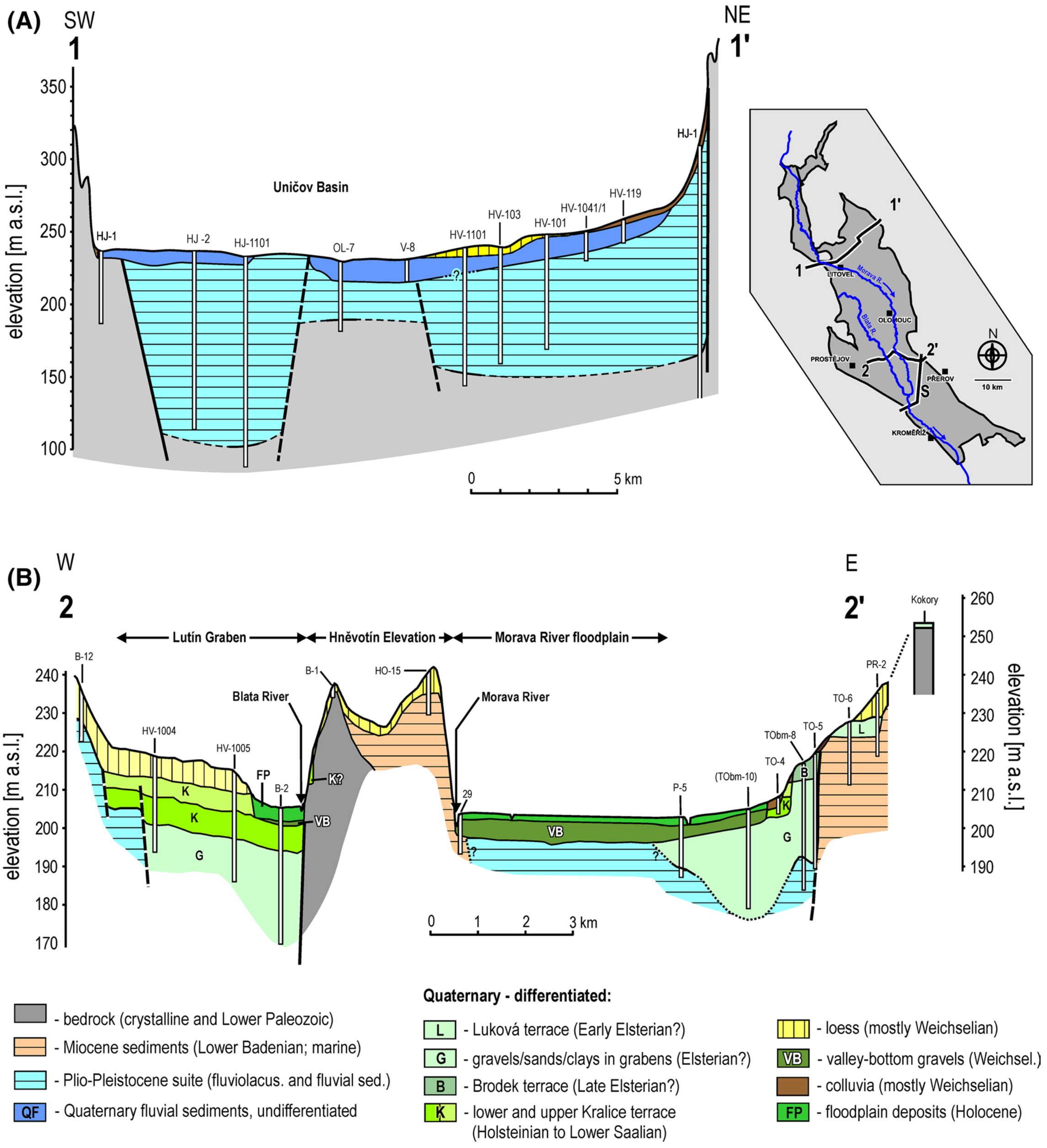


Fig. 8 **a** Lithological section across the northern Upper Morava Basin based on drill core data from Geofond/Czech Geological Survey. **b** Geological profile across Quaternary fluviolacustrine graben fills and fluvial terraces in central Upper Morava Basin. Based on profiles in Růžička (1973) and Macoun and Růžička (1967) and modified. See inset and Fig. 3 for position of both profiles in a map

Subsurface structure

Interpolated model of thickness of the Plio-Pleistocene sediments in the UMBS, based on boreholes, seismic and gravity data is shown in Fig. 5. The structure of the UMB with the inferred fault tectonics is indicated on geological profiles based on drill core data Figs. 6 and 8 and reflection seismic profiles 123/72 (Fig. 9). The thickness is highly variable reaching a maximum of ~300 m in two narrow, NNW–SSE-trending troughs, which are also well visible in the gravity map (Fig. 4). They correspond to the Mohelnice Graben (see “Morphology” section) and the Lutín Graben of the western UMB. In contrast, the northeastern part of the UMB with broad flat bottom (Uničov basin) has only low to moderate thickness (mostly <100 m, locally up to 180 m; Figs. 5, 6a), while in the eastern central UMB (near Olomouc; Fig. 5) the Morava River valley-bottom terrace rests unconformably on the Paleozoic bedrock.

This uneven bedrock topography shows structural fit with the horst-like Třebčín and Hněvotín elevations (see

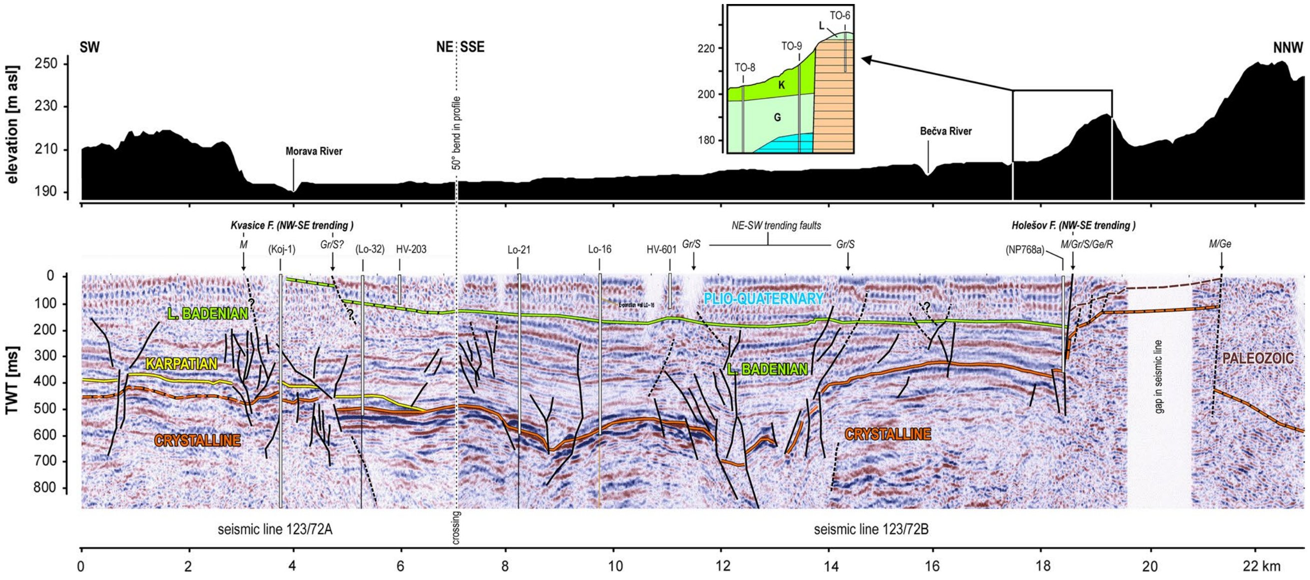


Fig. 9 Composite of two crossing time-migrated 2D reflection seismic sections 123/72A and B (Dvořáková et al. 1998) with new interpretation. See Figs. 3 and 8 for position in a map. Also shown are boreholes used for interpretation (out-of-profile boreholes in parentheses). For selected main faults, the type of indications is given: *Ge* geological, *Gr* gravimetric, *M* morphological, *S* seismic, *R* electrical resistivity. *Inset* shows a simplified geological situation near the top of Holešov Fault; compare with Fig. 8b. *L* Luková terrace, *K* Kralice double terrace, *G* fluviolacustrine sediments in grabens/depressions

"Morphology" section), which can be summarised into a horst-and-graben structure model of the whole basin. A clear structural asymmetry can be observed from the profiles, with general NE-ward tilting of blocks bounded by NW–SE-trending marginal faults controlling the evolution of depressions and grabens (cf. Fig. 6a). At the E and SW margins of the basin, elevated blocks with relatively flat relief are developed hosting relics of post-Middle Miocene sediments (Figs. 3, 5, 7).

The SE margin of the basin is controlled by the major Holešov Fault (Figs. 3, 4, 5, 6b, 9). Drill core data and older seismic profiles in the southern UMB demonstrate that this fault offsets the allochtonous flysch of the Outer Western Carpathians and the underlying Karpatian sediments of the Carpathian Foredeep by a minimum of 700- to 800-m vertical slip (Fig. 6b). In contrast, the Kvasice fault on the opposite, SW side of the basin does not seem to be associated with vertical offset of more than 100–200 m. This larger-scale (basin + subcrop) asymmetry is similar to that observed in the northern UMBS. The seismic section 123/72, oriented generally N–S and located at the intersection of the UMB with the Carpathian Foredeep (Fig. 9), shows a sharp termination of the Badenian and younger sediments against the northernmost part of the Holešov Fault, with estimated SW dip of 60°. The Kvasice Fault, having multiple splays, is unfortunately not well documented in this section.

Low-angle unconformity between the Badenian and overlying Late Mio/Plio-Q strata can be seen in Fig. 9 and in other seismic profiles (Dvořáková et al. 1998). Shorter, high-resolution seismic profiles (not shown) indicate that several normal faults parallel to the Carpathian Foredeep (cf. Figs. 3, 4, 5, 9) were active during the Badenian times and likely reactivated in the Pliocene to Quaternary times.

Active tectonics

Seismicity

Historical records, although not numerous, show weak to moderate macroseismic activity characterised by relatively frequent M3–4 events and only few M4–5 events (e.g. Kárník et al. 1957; Pagaczewski 1972; Guterch 2006; Fig. 12). Apparent distribution of the historical seismicity is probably biased by variable population density in the partly mountainous region. However, it seems that the strongest observed historical events are located near the northern margins of the NMZ, as for example the 1562 $M_w \approx 4.9$ ($I_{\mathrm{EMS}} = 7$; near Kłodzko), 1901 $M_w \approx 4.7$ ($I_{\mathrm{MSK}} = 7$; near Trutnov) or 1931 $M_w \approx 4.2$ ($I_{\mathrm{MSK}} = 6$; near Opava) events. Assignment of 1786 $M \approx 4.4$ event east of Ostrava ($I_{\mathrm{EMS}} = 7$) to the NMZ is unclear, since its epicentre is located in the Outer Carpathians, far beyond the northeastern reaches of the present-day seismic region.

The present-day, low-magnitude seismic activity is concentrated in two sub-domains separated by a 30- to 40-km-wide zone, which is almost aseismic and correlates with the N–S-oriented Králíky-Upper Nysa Kłodzka Graben (Figs. 1b, 5).

The much smaller western sub-domain (approximately 400 km^2) associated with major NW–SE-striking fault (Hronov-Poříčí Fault, see below; Fig. 12) hosted one of the strongest historical events ever recorded in the NMZ ($M_w \approx 4.7$; 1901). The area still produces occasional stronger events (e.g. M_L 3.3; 2005); however, its spatial extent and other details are still relatively poorly known due to currently low activity (cf. Zedník and Pazdírková 2009; Málek et al. 2008).

The eastern sub-domain of the NMZ (Figs. 3, 4, 5) covers much larger area (roughly 8,000 km^2) and continues beneath the flysch belt of the Outer Carpathians to the southeast. The seismic activity is confined to a well-defined region with rhombic shape. The spatial extent of weaker and stronger located events (cf. Figs. 1b, 5, 12) is similar in a long-term perspective, and the present-day extent of the seismically active region is thus well constrained. The northeastern and especially the southwestern limits of this domain are clearly linear, trending NW–SE (Figs. 5, 12). The latter coincides with the Nectava-Kvasice Fault System described above. The NE limit of the sub-domain is located close to the Bělá Fault, while its western termination seems to partly coincide with the NNW–SSE-striking faults parallel to the Mohelnice and Králíky-Upper Nysa Kłodzka Grabens. The eastern limit is more diffuse, which may be partly caused by poor coverage by seismic stations.

The strongest instrumentally recorded event from the eastern NMZ had magnitude $M_L \approx 3.8$ (1986). The magnitude range of 960 events located by MONET network in the period 1998–2012 is $-0.6 < M_L < 2.5$, and the typical hypocentral depths are 9–18 km. Since 2008 (after major upgrade of the network), approximately 200–300 microearthquakes per year are registered from the NMZ, of which 100–180 are routinely located. The cross-correlation analysis (Špaček et al. 2011) showed that majority of the weak, non-located microearthquakes are multiplets of stronger, located events and the repeated occurrence of events in nearly identical foci seems to be characteristic for the NMZ. In spite of relatively large location errors expected for the poorly covered southeastern part of the NMZ, all events there seem to originate beneath the thin-skinned Outer Carpathian nappes, within the crystalline basement of the underlying Bohemian Massif.

The seismicity concentrates in several more-or-less well-defined spatial clusters of epicentres with mostly NNW–SSE to NW–SE orientation (Figs. 5, 12). The orientation of most epicentre clusters is roughly parallel to the known tectonic structures in their neighbourhood, most remarkable being that coinciding with the NE margin of the UMB or the linear zone in the NNW extension of the Mohelnice Graben, which is parallel to the Králíky-Upper Nysa Kłodzka Graben (Fig. 5).

Due to the generally low magnitudes, relatively large extent of the region and limited number of stations operating in a given period, our knowledge on focal mechanisms is still rather poor. Five well-constrained focal solutions calculated for $M \geq 2$ events based on good quality data from 11–16 stations are given in Figs. 5 and 12. The nodal planes with N–S to WNW–ESE strikes (Fig. 12) are assumed to represent real faults since their geometry well corresponds with the orientation of the known faults, morphological steps on surface, surface geology and epicentre clusters on larger scale in the whole NMZ. These solutions correspond to dip-slips on steep to moderately inclined, mostly normal faults and to a dextral strike slip.

Late Cenozoic (post-)magmatic activity

Intraplate magmatic activity affected the Labe-Odra Zone as manifested by numerous bodies of anorogenic alkali basalts and their differentiates (Fig. 1). Similar to the Eger Rift, the main phase of volcanic activity occurred during the Late Oligocene/Early Miocene (syn-rift period sensu Ulrych et al. 2011). Several small-volume volcanic bodies from this period occur mostly in the NE part of NMZ. In the Late Miocene/Early Pliocene and Late Pliocene/Early Pleistocene times, the volcanic activity was renewed in the central parts of the NMZ (Figs. 5, 12). The youngest volcanic bodies near Bruntál were dated by K–Ar method to 0.8–1 Ma (Šibrava and Havlíček 1980; Foltýnová 2003; Ulrych et al. 2013).

The NMZ hosts approximately 80 known cold carbonated mineral springs and one moffete (Květ and Kačura 1976, 1978; Jetel and Rybářová 1979; Dowgiallo 2002), which likely result from the declining magmatic activity in the deeper lithosphere at present. Although most of the springs are small indicating that CO_2 flux is low on regional scale, some of them show very high fluxes with annual release of up to 500 tons of CO_2 (an estimate based on data in Květ and Kačura 1978). An interesting fact to note is the regional-scale spatial co-incidence of the carbonated mineral springs with the seismicity. The occurrence of carbonated mineral springs seems to be specific for the seismically active region. Although the springs and the earthquake hypocentres bring information from different structural levels (surface vs. depths of 8–20 km), they both terminate near the same NW–SE-trending linear structures in the north and in the south (Fig. 12).

Quaternary faulting

In the UMB, Quaternary faulting is mainly documented by the architecture of fluviolacustrine and fluvial sediments. The main accumulations of fluviolacustrine deposits buried beneath the valley-bottom gravels are confined to relatively narrow grabens bounded by NW-striking faults, attaining maximum thickness of 50–60 m in the western part of the UMB (Lutín Graben; Fig. 8b; Růžička 1989 and unpublished data). Comparably large range of heights is observed in the staircase system of fluvial terraces: the base of the valley-bottom gravels is 5–12 m beneath the floodplain, while the terrace relics at relative heights 45–50 m (Kokory), 30–32 and 25–26 m (Luková terrace) are consistently situated on the basin flanks controlled by boundary faults (cf. Fig. 8b).

The estimated ages of the upper terrace levels (Luková and Brodek terraces) and the fluviolacustrine infill of the grabens (both Elsterian; Macoun and Růžička 1967) at least partly overlap. The maximum vertical offset between these fluvial sediments exceeds 100 m, which is difficult to explain simply by river incision and must reflect syn- or post-depositional faulting. Assuming that the age estimates are correct, this situation suggests that during Elsterian stage, rivers in some parts of the UMB degraded leaving behind the succession of fluvial terraces, while in other parts tectonically controlled aggradation resulted in thick succession of sediments buried beneath the active floodplain.

Significant changes of drainage system were suggested by previous authors for the UMB during the Middle Pleistocene. The distribution and provenance of the fluviolacustrine sediments imply that the basin was drained into the Carpathian Foredeep to the SW and not to the Vienna Basin to the south like today. The change in the Morava River course was enabled by uplift of the area SW of the UMB as well as by subsidence of the central and southeastern part of the basin (e.g. Zeman et al. 1980). The spatial extent of the Kralice (Main) terrace suggests that the Morava River flew both through Lutín Graben and via its present-day valley in Holsteinian (Elsterian/Saalian) and older Saalian (Růžička 1973; cf. Figs. 3, 8b). Since Younger Saalian, the Morava River continued to flow only via its present-day valley, possibly due to the interruption of subsidence in the graben.

Pleistocene faulting is indicated by drilling surveys and shallow geophysical profiles, which often show spatial coincidence of remarkable linear morphological scarps with deep reaching faults. An example is given in Fig. 9 showing the Holešov Fault, detected by reflection seismic and electric resistivity surveys, coinciding with the rise of the Luková terrace (cf. Fig. 8b).

The scarcity of outcrops results in a lack of direct mesostructural field evidence on Cenozoic faults in the UMBS, including the slip timing and kinematics. Data on small-scale faults in Quaternary strata are limited to few brief notes given by field geologists, such as the offsets of the Eemian paleosol complexes observed in the now-destroyed exposures in a brickyard pit SW of Prostějov (Zeman 1971). A trenching study aimed at several prominent faults in UMBS is currently carried out to overcome this lack of field data. First observations from the Kosíř fault, a major NW–SE-trending fault located north of Prostějov (Fig. 3), are interpreted as a result of Late Pleistocene tectonic normal faulting overprinted by slope-driven creep and faulting with relatively fast Late Weichselian slip rate (Špaček et al., in prep.).

While the region between the UMB and the NE margin of the Sudetic Mts. is not very well known in terms of Quaternary faulting, the morphologically pronounced Sudetic Marginal Fault has been studied for several decades. Its Quaternary activity has been identified based on reconstruction of river terraces, whose evolution was related to a climate-controlled accumulation and erosion, changing erosional base levels linked with presence of the Elsterian and Saalian ice sheets, and the tectonic and glacioisostatic uplift of the Sudetic Mts. The total uplift of the mountain front controlled by the Sudetic Marginal Fault during the Middle to Late Pleistocene is estimated at 20–30 up to 60–80 m. The biggest portion of the uplift (20–35 m) is younger than the post-Saalian deglaciation as evidenced by truncated fluvial terraces and their occurrence at different altitudes (Migoń 1993; Krzyszkowski and Pijet 1993; Krzyszkowski et al. 1995). Similarly, the post-Saalian 1 (240 ka) uplift with decreasing amplitude towards the Late Pleistocene is indicated in the adjacent Fore-Sudetic block (Štěpančíková et al. 2008).

Recent trenching study shows that Late Pleistocene movements at the Sudetic Marginal Fault had a strike-slip character. The revealed slip-rate acceleration (up to 1.8–2.8 mm/year) was most probably related to glacial loading during Late Glacial Maximum (Štěpančíková et al. 2013). Based on the results of trenching, the fault activity after LGM/Holocene was very low, but in the Polish portion of the fault, some Holocene activity is suggested by geomorphological indications (Krzyszkowski et al. 1995).

Discussion

Evolution of the UMBS

The UMBS shows clear signs of structural inheritance, which is closely linked to the pre-Tertiary HFZ. As discussed above, reduction in thickness of the Paleozoic structural layer must have occurred in some of the older compressional tectonic phases, possibly during regionally important Late Cretaceous/Early Paleogene NE–SW thrusting. The style of reactivation in the late Neogene was opposite to the earlier uplift (cf. Fig. 6). Normal faulting on the N–S- to NNW–SSE-trending faults resulted in the present-day structure of the basin, which is characterised by a system of en-echelon grabens and horsts. Locally, the NE–SW-trending Variscan boundaries were apparently reactivated during the basin formation (e.g. the Šumperk Basin and northeastern margin of the UMB).

The early Miocene thrusting of the Carpathian flysch nappes onto the eastern Bohemian Massif resulted in flexural bending of the lower plate and marine transgression to the west which attained its peak in early Badenian times. The present-day distribution of relic sediments indicates that large parts of the eastern and southern Bohemian Massif were located close to the early Badenian sea level. Some of the relics are found >100 km away from the Carpathian deformation front (Fig. 2) at elevations of up to 500 m asl, which is 200–300 m higher than the present-day surface of Carpathian Foredeep. This indicates a large post-Badenian regional uplift and erosion of the eastern part of the Bohemian Massif, similar as in other regions of central Europe (Ziegler and Dèzes 2007). Significant role of normal faulting resulting from flexural extension can be expected (Zoetemeijer et al. 1999).

The reduced extent of Badenian sediments limits the reconstruction of the Late Cenozoic tectonic evolution of the western part of NMZ. In geological map, the Miocene UMB forms an “embayment” of the Carpathian Foredeep extending about 20 km NW into the Bohemian Massif (Figs. 3, 4, 5). The Lower Badenian succession in the embayment has variable lithology including deep subtidal pelites as well as shallow-marine facies (e.g. Zapletal 2004). However, it is not clear whether the present-day extent of the foredeep is a result of post-Badenian subsidence in the UMB or whether it partly reflects the syndepositional topography of the Badenian sea. Similarly, the absence of Badenian sediments in the Sudetic Mts. (including the parts with lower elevation) can be interpreted as due to a topographic elevation in the Badenian and/or due to post-Badenian fault-related differential uplift. Nevertheless, relics of up to >300-m-thick Badenian succession located in the southwestern NMZ near Svitavy indicate fault slip with a minimum post-Badenian vertical throw of 200 m (Čech and Čtyroká 2012).

Tectonic structure is more clear in the southern part of UMB, at the contact of the Outer Carpathian flysch nappes with the Carpathian Foredeep. The Holešov Fault on the northern margin of UMB (Fig. 6b) offsets the Carpathian flysch and the underlying Miocene (Karpatian) sediments of the foredeep by a minimum of 700–800 m. Boreholes Hol-1, Hul-2 and Bar-1 show that the base of the buried lower Miocene sediments drops from ~440 m bsl in the NE to ~1,500 m bsl in the SW without dramatic change in their thickness (between 370 and 650 m over 20 km distance). The offset of this important marker horizon indicates a significant normal (and/or dextral horizontal) slip on the fault, which post-dates the early/middle Miocene flysch nappe docking. Analogically, a sharp termination of the Badenian and Plio-Quaternary sediments on the Holešov Fault (seismic profile 123/72; Fig. 9) indicates a minimum 250–300 m throw during and after Badenian, of which ~150 m must have post-dated the erosion at the base of Plio-Quaternary. Several seismic profiles show marked faulting and bending within the Badenian succession, and this deformation was likely syndepositional. Furthermore, clear synsedimentary normal faults parallel to the flysch nappe front are observed in the Badenian succession (Fig. 9; Dvořáková et al. 1998). All these deformation features are clearly older than the Plio-Quaternary succession, which rests unconformably on the Badenian deposits and whose deformation is much smaller and more localised.

The thickness map of Plio-Quaternary succession with up to >300-m-deep grabens (Fig. 5) indicates syn- and postsedimentary faulting in the whole HFZ. The low-angle unconformity observed locally between the lacustrine Plio-Quaternary and the fluvial Quaternary deposits suggests Early Pleistocene erosion. The architecture of the fluvial succession indicates significant subsidence in Middle Pleistocene, most markedly in the Lutín Graben (Fig. 8b). Based on the available dating of the sediments and taking into account the above-described changes in the Morava River course, the cumulative Middle Pleistocene to present-day vertical slip between the most uplifted and most subsided parts of the UMB can be estimated to >100 m. Relatively low river incision and alternation of degradation/aggradation phases in the NE part of the Bohemian Massif contrasts with the large incision observed in the central part of the massif (>100 m since early Pleistocene; Tyráček and Havlíček 2009). This is in agreement with local tectonic subsidence at the eastern margin of the massif and suggests its faster relative uplift farther to the west.

The structural setting of the UMB suggests spatially and temporarily inhomogeneous subsidence and uplift controlled by diachronous activity of marginal and intra-basin faults. As discussed above, the field data do not allow to reconstruct stress evolution at the eastern margin of the Bohemain Massif with certainty and with sufficient temporal and spatial resolution. Being aware of the fact that multiphase evolution in changing regional stress regimes is not ruled out (see below), we emphasise here that the structural heterogeneity of the basin can be a result of evolution in a regionally uniform stress field. The geometry of the faults and blocks with common quasi-rhombic patterns, the oblique orientation of basins within the HFZ and the en-echelon alignment of depocentres within the UMBS can be explained by a transtension between dextrally slipping NW–SE faults. Based on morphological analysis, Grygar and Jelínek (2003) interpreted the UMBS as a pull-apart basin. However, to our knowledge, field data do not indicate any large-scale Late Cenozoic horizontal slip on major

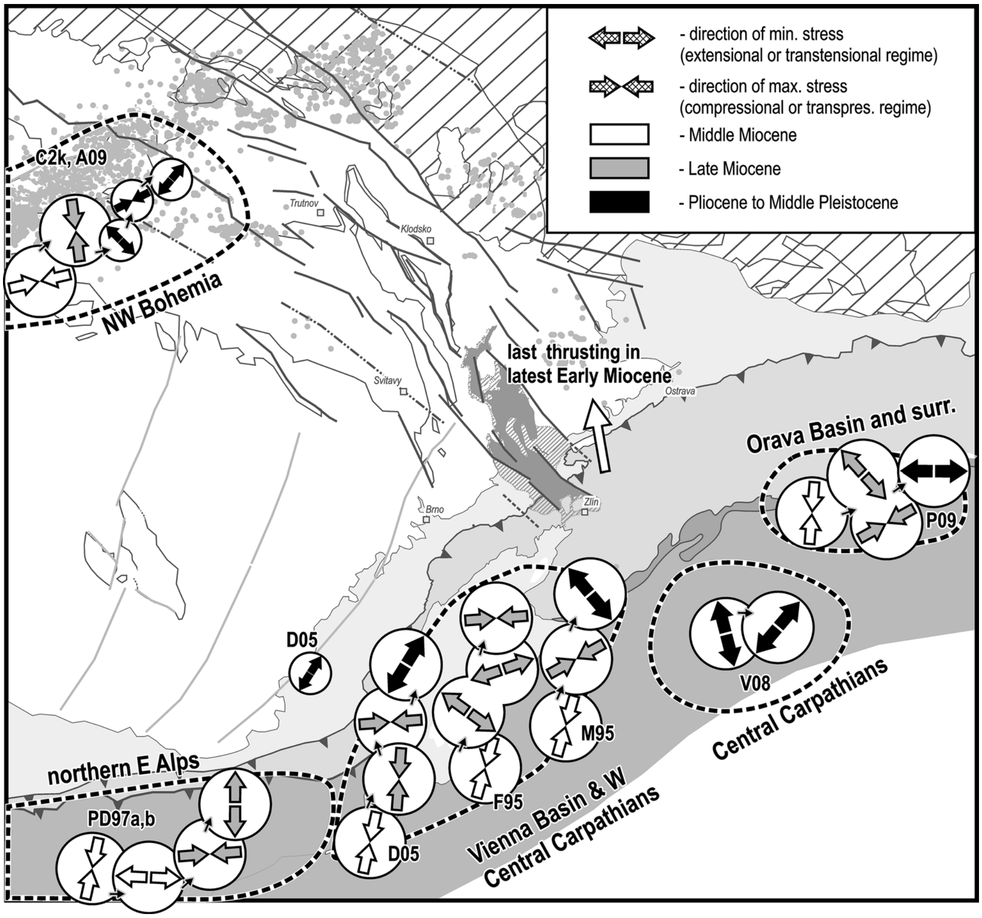


Fig. 10 Simplified map showing main Miocene to Pleistocene paleostress phases in Western Carpathians, Vienna Basin, Eastern Alps and Bohemian Massif. Compare with Fig. 2 which has the same extent. Compiled from Peresson and Decker (1997a, b) (PD97a, b), Decker et al. (2005) (D05), Marko et al. (1995) (M95), Fodor (1995) (F95), Vojtko et al. (2008) (V08), Pešková et al. (2009) (P09), Coubal and Adamovič (2000) (C2k), Ulrych et al. (2011) modified by unpublished results of Adamovič and Coubal (A09). Data are relevant for areas indicated by *dotted lines*. Note that less well-constrained data are shown by *smaller symbols*

faults, which may have acted as master faults. Relatively small deformation with comparable magnitude of strike-slip and normal components can be expected, and we prefer using the broader term transtensional basin.

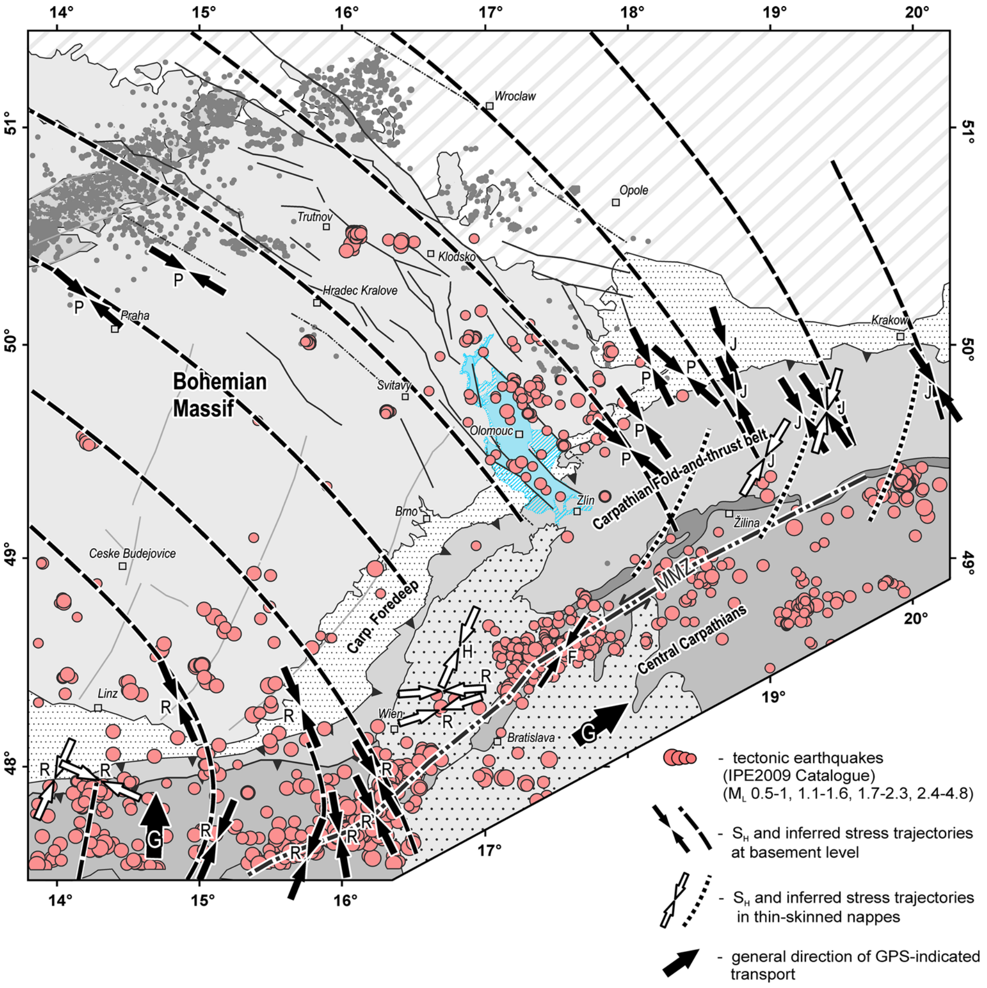
Relations between UMBS and the evolution of Alpine–Carpathian–Bohemian Massif junction

Continuing convergence between Adria and European Platform resulted in postcollisional shortening in the Eastern Alps. We can assume that processes in this collision zone significantly modified the regional stress in the Bohemian Massif. Paleotectonic record from the outer Alpine–Carpathian units at the junction region can therefore bring important clues for understanding of these relations. This is, however, considerably limited by the fragmentary occurrence of Cenozoic sediments in the Bohemian Massif.

The early to middle Miocene (pre-Sarmatian) kinematic data strongly indicate a generally N–S compression both in the northern Eastern Alps and in the Western Carpathians due to northward movement of Adria. Since middle Miocene, a significant change of tectonic evolution and onset of its diversity in time and space is demonstrated from field observations in different parts of the region (Marko et al. 1995; Fodor 1995; Peresson and Decker 1997a, b; see also Fig. 10). This complicated picture is mostly explained by continuing lateral extrusion from the Eastern Alps to the NE along a major sinistral wrench zone parallel to the Pieniny Klippen Belt, continuing pull-apart or transtensional deformation of the Vienna Basin, controlled by this wrench zone, and temporal far-field compressional feedback from the Eastern Carpathians (Marko et al. 1995; Fodor 1995; Peresson and Decker 1997a, b).

The Pliocene and Pleistocene kinematic data indicate extension in different parts of the Alpine–Carpathian junction region (Fig. 10) including the Polish Outer Carpathians (Zuchiewicz et al. 2002), intramontane Orava–Nowy Targ basin at the Central/Outer Carpathian boundary (E–W extension in Pliocene to Quaternary; Pešková et al. 2009) and basins in the Slovak Central Carpathians (NNW–SSE tension in Pliocene and NE–SW tension in Pleistocene; Vojtko et al. 2008). In the Vienna Basin, subsidence persisted locally in small depositional areas during the Pliocene and Quaternary (Fig. 2; e.g. Decker et al. 2005) following the latest Miocene regional inversion. A weak extensional deformation in Pliocene and Early Pleistocene is indicated by large-scale normal fault geometry and rare kinematic data. Nevertheless, the paleostress phases

Fig. 11 Schematic map showing present-day stress, geodetic and seismological indications of active deformation in Alpine–Carpathian–Bohemian Massif junction region. Compare with Fig. 2 with the same extent. Stress data (*double arrow symbols*) are from borehole breakouts [maximum horizontal stress; Peška 1992 (P), Jarosiński 2005 (J), Reinecker and Lenhardt 1999 (R), Heidbach et al. 2008 (H)] and focal mechanisms (total maximum stress; Fojtíková et al. 2010 (F)]. Geodetic GPS-indicated tectonic transport is based on Grenerczy et al. (2005) (G). Earthquake data are from IPE2009 catalogue (2000–2009, $M_L \geq 0.5$; see text). Note the NNW- to NW-oriented maximum horizontal stress in Bohemian Massif including NMZ and its rotations in overlying outer Alpine units. Also note the increased seismicity along the Mur-Mürz-Žilina zone of sinistral shearing (MMZ) parallel to Pieniny Klippen Belt



interpreted by different authors in the Vienna Basin are partly controversial and their timing poorly constrained. Pliocene extension in roughly NW–SE direction was inferred by Marko et al. (1995) from NE-trending normal faults, while Decker et al. (2005) emphasised the NW-striking normal faults and inferred the NE–SW extension for the Pliocene to early/middle Pleistocene (Fig. 10). The deepest of the Quaternary subsidence centres, Mitterndorf basin (Fig. 2), was interpreted by Decker et al. (2005) as a pull-apart basin driven by reactivated sinistral slip on the SE marginal fault of the Vienna basin in Middle Pleistocene. Based on geometry of this basin, they estimated 1.6–2.5 mm/year slip rates in Middle Pleistocene to recent, which is comparable to Miocene ones (Decker et al. 2005).

In the Bohemian Massif, regionally constrained stress models for the Pliocene-Quaternary period are missing and reconstruction of stress transfer between the massif and Alpine orogeny is, therefore, largely speculative. Late Cenozoic stress evolution was proposed for northern Bohemia based on small- to large-scale fault kinematics (Coubal and Adamovič 2000; Fig. 10). In middle to late Miocene, gradual change from WSW–ENE compression to N–S compression was recognised. This was followed by two to three post-Miocene phases: NW–SE extension in Pliocene followed by ENE–WSW compression and NE–SW to NNE–SSW extension in Early to Middle Pleistocene.

The age of sediments in the UMBS (Fig. 7) suggests prevailing subsidence in the early Badenian, latest Miocene to earliest Pleistocene and early middle Pleistocene (Elsterian) times. The unconformities suggest prevailing uplift and/or erosion in the late Karpatian, between early Badenian and latest Miocene and during most of early Pleistocene.

The Miocene angular unconformities are regionally correlated, and they can be explained by the response of the Bohemian Massif to thrusting in the adjacent parts of Alpine–Carpathian system (see above). The onset of subsidence in latest Miocene/Pliocene correlates with the release of far-field regional compression in the Eastern Alpine–Carpathian–Pannonian domain (Peresson and Decker 1997b) and seems to coincide with the onset of extension in the Western Carpathians and northern Bohemia described above (Fig. 7). Sediments of later early Pleistocene age were not found in the UMBS, and the rare

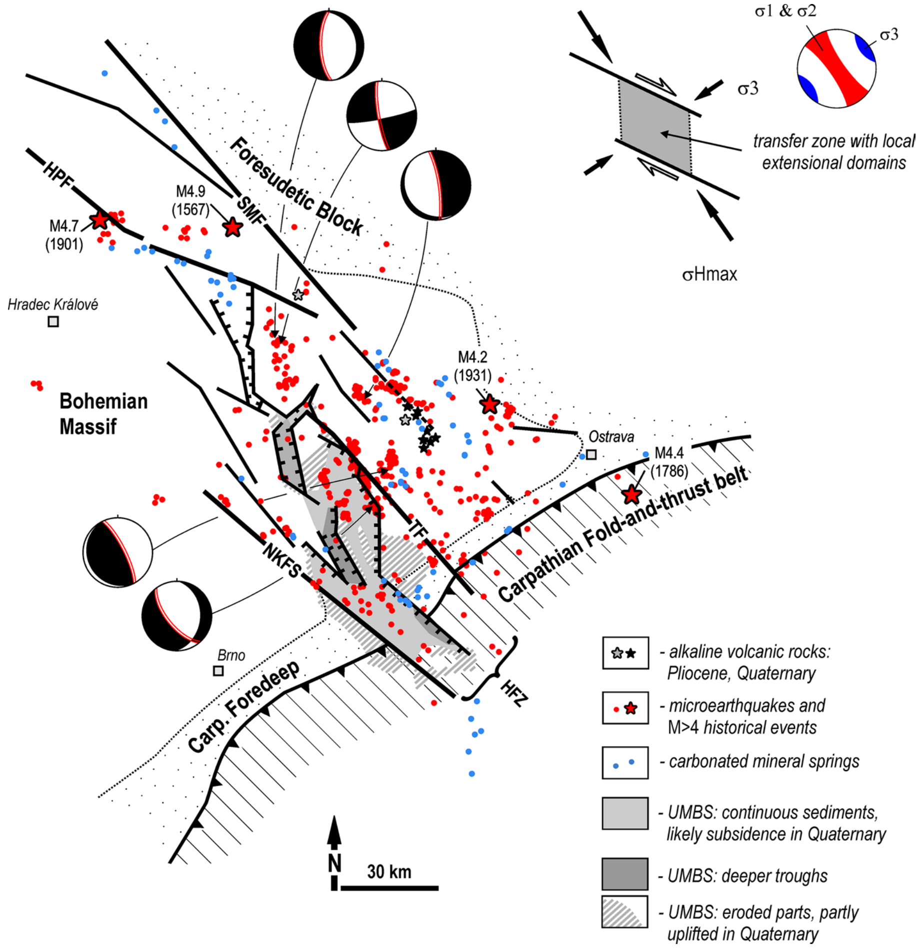


Fig. 12 Simplified tectonic summary of the main features of NMZ. Earthquake epicentres are from the MONET2012 catalogue. The *cartoon in upper right* is a conceptual model explaining the NMZ as a transfer zone with local extensional domains developed between the non-coalesced WNW–ENE- to NW–SE-striking faults. Within this domain, a permutation of maximum (σ_1) and medium (σ_2) stress directions is indicated as shown in a stereodiagram and explained in text. *SMF* Sudetic Marginal Fault, *HPF* Hronov-Poříčí Fault, *TF* Temenice Fault, *NKFS* Nectava-Kvasice Fault System, *HFZ* Haná Fault Zone

observations of low-angle unconformity at the base of middle Pleistocene strata can be explained by local processes. The NE–SW extension reported for northern Bohemia seems to correlate with NE-directed extension inferred from the NW-striking faults in Vienna Basin and isolated small-scale structure in the Austrian foredeep (Decker et al. 2005). Nevertheless, all relevant observations for post-Miocene period are only local and they do not seem to be linked on regional scale. In addition, the paleostress succession inferred for the northern Bohemia and the evolution in the Vienna basin show rather contrasting phases during the times of Pliocene and Quaternary subsidence in the UMBS. Although regional extensional phases cannot be ruled out, their loose expression indicates intermittent character and/or small intensity. To conclude, we still do not have enough data with sufficient time resolution to perform convincing regional-scale correlation of tectonic phases for the post-Miocene period.

Moreover, the Pleistocene stress in the NMZ was potentially influenced by far-field effects of continental ice sheets. The front of North European continental glacier repeatedly approached the northern margin of the Bohemian Massif within a distance of ~200–300 km and reached the Fore-Sudetic Block and northern Sudetes during the Elsterian and Saalian glaciations (e.g. Nývlt et al. 2011; see Fig. 2 for maximum extent). Ice loading and unloading substantially influence lithospheric stress in a broad region adjacent to glaciers, and mathematical models permit virtually any geometry of fault reactivation (e.g. Stewart et al. 2000; Hampel et al. 2010). Although the far-field effect of the Pleistocene ice sheets on stress perturbations and faulting in NMZ is not evidenced by clear observations, it probably took some part and has to be taken into consideration.

Present-day stress and tectonic activity in NMZ and its possible links to the Plio-Pleistocene evolution of UMBS

Regional GPS studies indicate present-day convergence between Adria and Eastern Alps at the rate of 2–3 mm/year, which is largely accommodated by continuing E- to NE-ward lateral escape at the rate of 1–1.5 mm/year (Grenerczy et al. 2005). The resulting sinistral shearing is in accord with Late Pleistocene faulting in the Vienna Basin (Decker et al. 2005; Hintersberger et al. 2013) and increased present-day seismicity in Mur-Mürz-Žilina Zone (Reinecker and Lenhardt 1999; Lenhardt et al. 2007; Fig. 11).

NMZ is situated in the transitional zone between the western European stress domain with NW–SE-oriented first-order maximum horizontal stress (S_H), the fore-Carpathian stress domain with N–S-oriented S_H (Jarosiński 2005; Heidbach et al. 2008) and the Eastern Alpine domain with NNE–SSW to N–S-oriented S_H (Reinecker and Lenhardt 1999). The stress data from borehole breakouts (Peška 1992; Reinecker and Lenhardt 1999; Jarosiński 2005) show prevailing NW–SE- to NNW–SSE-oriented S_H for the Bohemian Massif including its southern and northeasternmost parts, which are buried beneath Eastern Alps and the outer nappes of the Western Carpathians, respectively (Fig. 11). In a narrow spur at the southern margin of the Bohemian Massif beneath the Eastern Alps, a fan-like distribution of NNE- and NNW-oriented S_H axes (Fig. 11) was observed and interpreted by Reinecker and Lenhardt (1999) as a consequence of collision of the Bohemian Massif with Austroalpine basement. Focal mechanisms in the W and NE Bohemian Massif as well as in central and western Europe generally agree with borehole breakouts and the prevailing NW–SE- to NNW–SSE-oriented stress, which is largely explained by Mid-Atlantic ridge push (e.g. Müller et al. 1997; Jarosiński 2005).

Significantly different stress orientations are observed in the alpine units overlying the basement (Reinecker and Lenhardt 1999; Jarosiński 2005). In the flysch nappes of the Outer Western Carpathians, uniform NNE–SSW-oriented S_H is indicated by borehole breakouts (Jarosiński 2005). Likewise, well-constrained earthquake focal mechanisms in the Mur-Mürz-Žilina belt, NE of Vienna Basin, indicate subhorizontal maximum stress with azimuth 30°–40° and subhorizontal minimum stress (Fojtíková et al. 2010). Vertical rotation of S_H in many boreholes brings evidence for mechanical decoupling of the sedimentary cover from its basement in many places of the Alpine orogene. Reinecker and Lenhardt (1999) suggested that in the Eastern Alps, such decoupling occurs within the sedimentary successions of foredeep basin and flysch nappes. Jarosiński (2005) observed gradual stress rotation beneath the Polish Outer Carpathians within the uppermost levels of the basement. In NMZ, we assume that the main decoupling of flysch nappes from basement occurs within the sediments of the Carpathian Foredeep, since in the Paleozoic cover of basement (depths of >900 m) S_H already has the western European orientation (Peška 1992; Fig. 11). This assumption is supported by the observed distribution of seismicity which continues beneath the flysch nappes (Figs. 11, 12) but seems to be restricted to deeper levels, indicating uniform tectonic regime in the basement and different deformation style in the overlying units.

Analogically to the well-documented present-day situation, we can assume that significant mechanical decoupling between the Outer Western Carpathians and the Bohemian Massif persisted for most of Late Cenozoic. Major horizontal stress rotation between the Carpathian domain and its foreland is expected to be located beneath the thin-skinned nappes of the Outer Western Carpathians and at the basement contact near Pieniny Klippen Belt.

The extent of carbonated mineral springs correlates with the rhomb-like seismically active domain of the NMZ (Fig. 12). This zone also accommodates Pliocene to Early Pleistocene basaltic volcanic rocks and areas of long-term subsidence in the UMBS. While the seismic activity and basin formation indicate tectonic deformation in the upper and mid-crustal levels, the volcanic and post-volcanic activity points to the existence of fluid-migration pathways, which are probably associated with steep faults permeable down to the base of the crust. These observations suggest a long-term, whole-crustal extension which is still going on today. On the other hand, geodetic observations in the Sudetic Mts. and the Fore-Sudetic Block do not provide a simple, systematic model of horizontal and vertical velocities (cf. Badura et al. 2007; Štěpančíková et al. 2008; Kaplon et al. 2014). Most likely, this is due to a combined effect of very low tectonic strain rates, measurement errors and near-surface, topography-related distortions.

Based on its structural setting and geodynamic activity, the NMZ can be regarded as a large-scale linkage zone between the WNW–ESE- and NW–SE-striking faults with local extensional domains developed on releasing structures of the complex fault system (Fig. 12). Borehole breakouts from the eastern part of the zone and focal mechanisms from the western part of the Bohemian Massif (e.g. Fischer et al. 2014) indicate NW–SE-oriented maximum horizontal stress (Fig. 11). Fault plane solutions so far available for the NMZ indicate a combination of dextral horizontal shears with normal dip-slips on steeply dipping faults (Fig. 5; cf. Špaček et al. 2006), which is consistent with such model. Although we still do not have enough earthquake data for reliable stress inversion in the NMZ, the focal mechanisms suggest local rotation of maximum compressional stress from sub-horizontal direction to steeper orientations. Preliminary directional statistical analysis of the first motion-amplitude ratios performed on a large dataset of weak events (Špaček, unpublished) gives relatively well-constrained subhorizontal σ_3 with mean NE–SW orientation, while σ_1 and σ_2 are distributed on a subvertical girdle of NW–SE orientation (Fig. 12). This can be explained by spatially heterogeneous stress and small-scale permutations of σ_1 and σ_2, similar to the observations in Rhine Graben and elsewhere in the western and central Europe (e.g. Müller et al. 1997; Hinzen 2003). The low-magnitude multiplet earthquake sequences, which are characteristic for the NMZ today, likely reflect specific local stress perturbations related to complex fault linkage and increased flux of fluids (cf. Fischer et al. 2014).

The remarkably well-defined southwestern and northeastern limits of the NMZ are clearly co-linear with regionally important WNW–ESE- to NW–SE-striking fault structures (Fig. 12): the Nectava-Kvasice Fault system and the system of faults including Hronov-Poříčí fault, Bělá fault and possibly other faults west of Ostrava, respectively. The former, located at the southern boundary of the HFZ, controlled the development of the UMBS, while the latter controlled the long-term evolution in the central LOZ and hosted young volcanic centres and a number of mineral springs. Much of the seismicity is confined to the UMBS: the Temenice fault at the SE margin of the UMB hosts nearly 40 % of all seismic events in the MONET catalogue, and a minor belt of epicentres occurs within the basin, NW of Olomouc and in the southern part of UMB (Figs. 5, 12). Relatively thick accumulations of fluvial gravels and/or colluvia in these parts of the basin with flat topography suggest possible slow subsidence, which is partly compensated by Late Pleistocene to Holocene sediments.

Taking into account the structural and inferred kinematic similarities between the present-day processes and Plio-Pleistocene evolution, we suggest that their deformation styles are largely identical, with the main difference being the lower deformation intensity at present. While the regional stress orientation generally implies strike-slip regime on major NW–SE-oriented faults, local extension persists in some parts of NMZ. In the HFZ, higher strain has lead to long-term Pliocene to Holocene subsidence, while in other parts of the NMZ the Cenozoic strain seems to be much lower and extensional domains are apparently short-lived and diffuse.

Relation to other Cenozoic graben basins in Alpine–Carpathian foreland

Volcanics of the Eger Rift and Labe-Odra Zone form a spatially continuous belt with temporally coherent volcanic production reaching its maximum in Late Oligocene to Early Miocene (“syn-rift” phase; Ulrych et al. 2011, 2013). Although the volcanic activity was weak in NMZ even during this main phase, its resurgence during the Pleistocene, which is comparable only to the western Eger Rift, makes this region anomalous within the Bohemian Massif. These regions are both characterised by Late Cenozoic basin subsidence, present-day seismicity and increased CO_2 flux. The Eger Rift is considered an integral part of ECRIS (e.g. Prodehl et al. 1995; Dèzes et al. 2004; Wilson and Downes 2006; Ulrych et al. 2011). Since the Labe-Odra Zone and ECRIS share similar positions in the foreland of the Alpine orogene and belong to the same province of Cenozoic intraplate volcanism, it is appropriate to briefly discuss their common and/or contrasting features and evolution.

The volcanic activity has similar character (intraplate primitive alkaline series) in western and central ECRIS, Eger Rift and Labe-Odra Zone and exhibits broad range of Paleocene to Quaternary ages (e.g. Wilson and Downes 2006; Ulrych et al. 2011, 2013; Fig. 13). In contrast, sedimentary record in the adjacent tectonic grabens shows a marked diachroneity of subsidence. Most grabens of the western and central ECRIS contain more-or-less continuous sedimentary record from middle Eocene or early Oligocene times until the Late Cenozoic, with relatively short periods of non-deposition or post-depositional erosion (Fig. 13; Sissingh 2006). To the contrary, any indication of Eocene to Early Oligocene subsidence is largely missing in the Bohemian Massif except for its SE slopes belonging to the Carpathian foreland basin. In the Eger Graben (NW part of the Bohemian Massif), the sedimentary record is represented by Upper Oligocene to Lower Miocene fluvio-lacustrine sequence truncated by erosional surface. Only minor relics of older (presumably Upper Eocene) fluvial clastics are preserved. In the SW part of the graben, subsidence was renewed in the NNW–SSE-elongated Cheb Basin (Fig. 1) during the Pliocene to Early Pleistocene as recorded by up to 150-m-thick fluvial–lacustrine succession (Fig. 13; Špičáková et al. 2000). Likewise, sedimentary basins in the Fore-Sudetic Block started to accumulate sediments in the late Oligocene (Roztoka-Mokrzeszów Graben and Zitava Basin) or early Miocene (Paczkow-Kędzierzin Graben) (Dyjor 1983; Jarosiński et al. 2009; Fig. 2). A significant, post-middle Miocene subsidence is indicated by up to 200-m-thick accumulation of lacustrine succession (Sarmatian) and several-dozen-metre-thick Pliocene gravels (Fig. 13; Dyjor et al. 1977; Dyjor 1983; Jarosiński et al. 2009). Paleogene sediments are completely missing in the UMBS, which started to accumulate marine sediments of the Carpathian Foredeep no earlier than in early/middle Miocene. The late depositional phases of the UMBS correspond to the fluvial–lacustrine and fluvial sedimentation of latest Miocene/Pliocene to Pleistocene age.

As discussed earlier, close genetic link with the evolution of the Alpine–Carpathian foreland basin is assumed for the UMBS, similarly as in ECRIS grabens (e.g. Sissingh 2006). It is likely that the diachroneity between the Paleogene and Miocene subsidence in the western/central ECRIS, Eger Graben and grabens of the Labe-Odra Zone (Fig. 13) is partly related to the west-to-east younging of compressional events and the polarity of tectonic styles in the collision zone between Adria and north European foreland (e.g. Jiříček 1979; Ratschbacher et al. 1991; Froitzheim et al. 2008 and references therein). The major role of this convergence is further supported by cessation of Miocene volcanic activity in the Labe-Odra Zone and its significant decline in the whole Bohemian Massif roughly

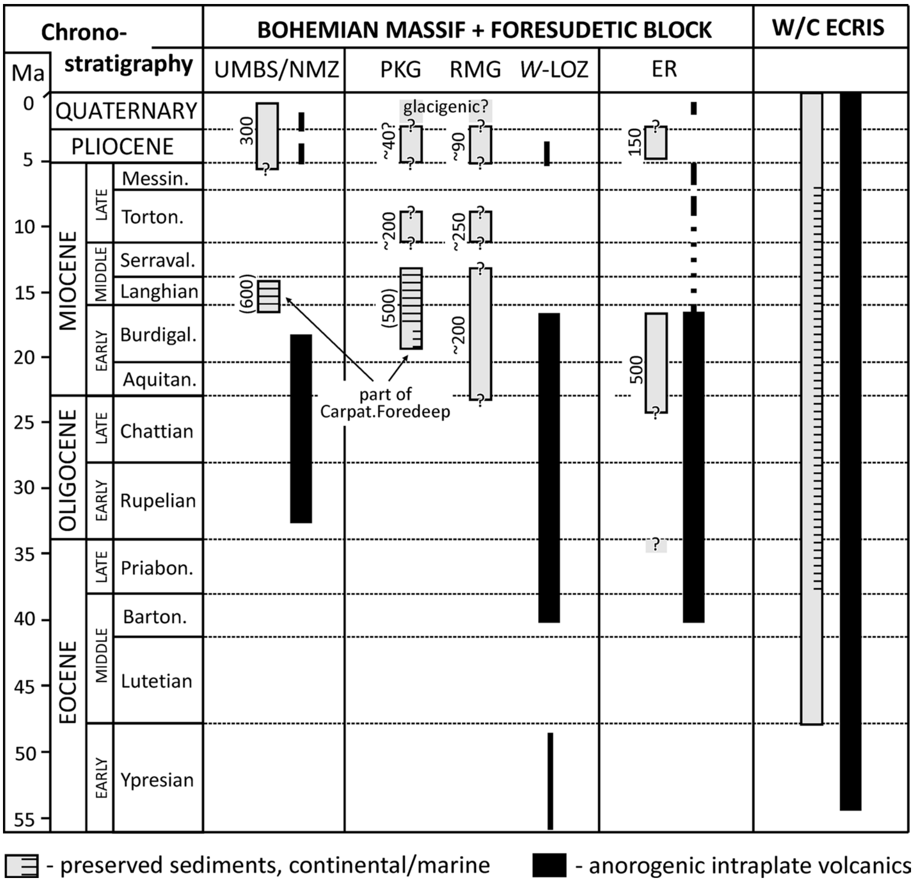


Fig. 13 Schematic chart showing the main phases of sedimentation and volcanic activity in Labe-Odra Zone, Eger Rift and western/central ECRIS. Approximate maximum thickness of sediments (in metres) is given for basins in the Bohemian Massif and Fore-Sudetic Block. Compiled mostly from Dyjor (1983), Dyjor et al. (1977), Sissingh (2006), Špičáková et al. (2000), Schäfer et al. (2005), Ulrych et al. (2011, 2013); Wilson and Downes (2006). *UMBS/NMZ* Upper Morava Basin system and volcanics in Nysa-Morava Zone, *PKG* Paczkow-Kędzierzin Graben, *RMG* Roztoka-Mokrzeszów Graben, *ER* Eger Rift, *W-LOZ* western part of Labe-Odra Zone; cf. Figs. 1 and 2. Note the general younging of the apparent onset of subsidence from W (ECRIS) to E (NMZ)

at the time of final thrusting of external Alpine–Carpathian nappes over its foreland (~18 Ma; Fig. 13).

Large-scale structure and properties of the lithosphere are additional features that make major difference between the NMZ and the Eger Rift and other parts of the ECRIS. Major elements of the ECRIS, the Massif Central, the Rhine Graben, Rhenish Massif with Eifel "hotspot" and the southwestern Eger Rift, are associated with reduced crustal and lithospheric thickness (e.g. Dèzes et al. 2004; Geissler et al. 2008; Plomerová and Babuška 2010) and increased heat flow (e.g. Majorowicz and Wybraniec 2011). The thinning of lithosphere in ECRIS is usually explained as a result of its thermal erosion by upwelling astenosphere or deeper-reaching mantle plumes (Granet et al. 1995). The associated heating and uplift lead to weakening and increased rate of surface erosion, respectively, both resulting in thinning of the crust (e.g. Ziegler and Dèzes 2007). In contrast, the crustal and lithospheric thicknesses in the NMZ are not anomalous in the central European context (30–35 and ~100–140 km, respectively; Geissler et al. 2012; Plomerová and Babuška 2010; Plomerová et al. 2012). Heat flow data show no indication of regional-scale thermal anomaly (50–80 mW/m^2; e.g. Majorowicz and Wybraniec 2011).

While far-field horizontal stresses provide important control on deformation of the ECRIS and the Labe-Odra Zone, the quantitative differences in their Cenozoic deformation are likely caused by generally lower strength of thinned and hotter lithosphere in the former. The latter is associated only with local weakening by whole-crustal wrench zones without any substantial thermal thinning of lithosphere. Accordingly, the maximum preserved thickness of deposits in most ECRIS grabens (>3 km for the Upper Rhine Graben; Sissingh 1998) stays in marked contrast with that in UMBS. The contrasting deposition rates are mainly observed for Oligocene and Miocene (cf. Sissingh 1998), but are also clearly recognised for post-Miocene periods. The Pliocene and Quaternary subsidence in the UMBS and reoccurrence of volcanism in NMZ corresponds with the regional stress growth, which is also demonstrated by increased subsidence rates and volcanic activity in ECRIS (Dèzes et al. 2004; Gabriel et al. 2013). In the Upper Rhine Graben, complex internal faulting and subsidence in Pleistocene and Holocene is documented by large overall thickness of Quaternary sediments (up to >500 m in Heidelberg Basin; Gabriel et al. 2013), by offsets of buried channels in Pleistocene fluvial deposits (Peters and van Balen 2007) as well as by paleoseismological data (e.g. Ferry et al. 2005). The maximum thickness of Pleistocene sediments (50–60 m) and estimated vertical fault slip (min. 100 m) in UMB are at least half-order of magnitude lower than that in Upper Rhine Graben. This suggests that the quantitative contrasts of deformation remained at similar level at least until Late Pleistocene, suggesting average subsidence rates of up to 0.1–0.2 mm/a in Upper Rhine Graben (cf. Gabriel et al. 2013; Peters and van Balen 2007) and <0.05 mm/a in UMBS.

Summary

1. The NMZ is a long-term active crustal domain located in the eastern Sudetes, close to the contact of the NE Bohemian Massif with the Western Carpathians. Its deformation is linked to the generally NW–SE-striking fault system of the Labe-Odra Zone. In Late Cenozoic, repeated weak intraplate anorogenic volcanic activity occurred before (32–18 Ma) and after (6 to <1 Ma) the thrusting of the Outer Carpathian nappes.
2. The UMBS developed in the southwestern part of the NMZ in the early and middle Miocene times, probably forming an embayment of the Carpathian Foredeep. While the pre-middle Miocene evolution is poorly known due to large-scale erosion or non-deposition, a major subsidence phase occurred in early Middle Miocene, soon after the docking of the Outer Carpathian flysch nappes.

A significant boost of tectonic activity in Pliocene and Early Quaternary resulted in further subsidence of the UMBS, formation of graben-like basins and accumulation of fluvio–lacustrine clastic successions, which locally exceeds 300 m of thickness. This succession is superposed onto the frontal limit of the Carpathian Flysch, which is thrusted over the sediments of the Carpathian Foredeep.

In Middle Pleistocene (Elsterian), third significant phase of localised subsidence is indicated by up to 50- to 60-m-thick accumulations of mostly fluviolacustrine sediments in narrow graben-like depressions.

3. The weak present-day tectonic activity is characterised by <M5 macroseismic events and relatively frequent microseismicity of swarm/multiplet nature, which are accompanied by carbonated mineral springs. These features make the NMZ a prominent and spatially well-constrained active tectonic anomaly, which sharply differs from adjacent regions.
4. The occurrence of seismicity and carbonated mineral springs within a rhomb-shaped region with linear NE and SW margins suggests that two major sub-parallel fault structures of NW–SE to WNW–ESE strike control the observed tectonic processes. We assume that the NMZ represents a transfer zone between these faults with strike-slip kinematics. Based on sparse focal mechanism data and preliminary directional statistics of seismograms, we suggest that slow horizontal slip on these faults results in local permutations of the largest and medium stress directions and formation of transtensional crustal domains. This explains the enhanced upward migration of fluids of deeper lithospheric origin and local subsidence. Based on spatial coincidence of the NMZ and UMBS and their tectonic/structural features, we suggest that their present-day- and Plio-Pleistocene deformation styles were similar.
5. On a larger scale, the NMZ represents the easternmost part of extensive region in the Alpine–Carpathian foreland, which was affected by long-term Cenozoic intraplate volcanic activity. Despite their geodynamic similarity with the ECRIS, the NMZ and UMBS significantly differ from ECRIS by substantially later onset of subsidence and its much lower magnitude. This can be explained by the general west-to-east younging of compressional events in the Alpine–Carpathian orogeny and the absence of thermal lithospheric thinning in the NMZ.

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