Chapter 2

Results of previous geophysical, geochemical and petrological research

2.1 Seismicity of the Vogtland/NW-Bohemia swarm earthquake region

The Vogtland/NW-Bohemia region is known for the periodic occurrence of intraplate seismic earthquake swarms of mostly $M_L<3.5$ earthquakes. The general swarm-like character of seismicity has been observed in historical macroseismic reports since 1552 (*Grünthal*, 1989). Primarily, earthquake swarms are a peculiarity of volcanic regions and of mid-ocean ridges. Swarms in intraplate regions and without active volcanism are unusual. However, they may occur in intracontinental regions of increased geodynamic activity such as continental rifts, as shown by *Ibs-von Seht et al.* (2006). They compared the swarm earthquake areas of the Rio Grande, Kenya, and Eger rifts and found major similarities regarding magnitudes and *b*-values as well as the fact that in all three rifts the main swarm activity occurred at graben sections intersected by large-scale fracture zones.

The German expression *Schwarmbeben* ('swarm earthquake') was first used with regard to the Vogtland/NW-Bohemia region by *Knett* (1899) and *Credner* (1900). The term earthquake swarm denotes a group of seismic events strongly clustering in time and space. Earthquake swarms differ from typical mainshock-aftershock sequences mainly by a missing dominant mainshock, and the *b*-value of their magnitude-frequency distribution is usually larger than that of aftershock sequences at plate boundaries (*Lay and Wallace*, 1995).

The swarm earthquake activity in the Vogtland/NW-Bohemia region is generally attributed to the combined influences of tectonic stress, fluid migration and magmatic/volcanic activity (e.g. *Weinlich et al.*, 1999; *Špičák et al.*, 1999; *Špičák*, 2000; *Parotidis et al.*, 2003, 2005; *Bräuer et al.*, 2003, 2005; *Geissler et al.*, 2005). According to *Špičák and Horálek* (2001), many earthquake swarm regions are characterized by Quaternary volcanism, indicating that ascending magmatic fluids trigger earthquakes. They also stress the similarity between the fault plane solutions for the earthquake swarms in the Vogtland/NW-Bohemia region and the KTB borehole, ~50 km away, where fluid injections were carried out (*Zoback and Harjes*, 1997; *Rothert et al.*, 2003). Until recently, the Mariánské Lázně fault was considered to be seismically most active in the region under study. However, *Bankwitz et al.* (2003) propose that in the Cheb basin the N-S trending newly found sinistral Počatky-Plesná zone is identical with the main earthquake line. According to their investigations, evidence from the relocated hypocentres indicate that the Mariánské Lázně fault is seismically inactive.

Fischer and Horálek (2003) classify three types of earthquake activity in the Vogtland/NW-Bohemia region: swarms, micro-swarms and solitary events. *Horálek et al.* (2000a) distinguish seven main epicentral areas (Figure 2.1). The strongest seismic activity is observed in the Nový Kostel focal zone (area 1). Apart from the anomalous deep micro-swarm in February 2004, focal depths in the Nový Kostel area do not exceed 12 km, whereas the focal depths in the whole Vogtland/NW Bohemia region reach up to 23 km (*Horálek et al.*, 2000a). The northernmost earthquake swarm in this region was detected

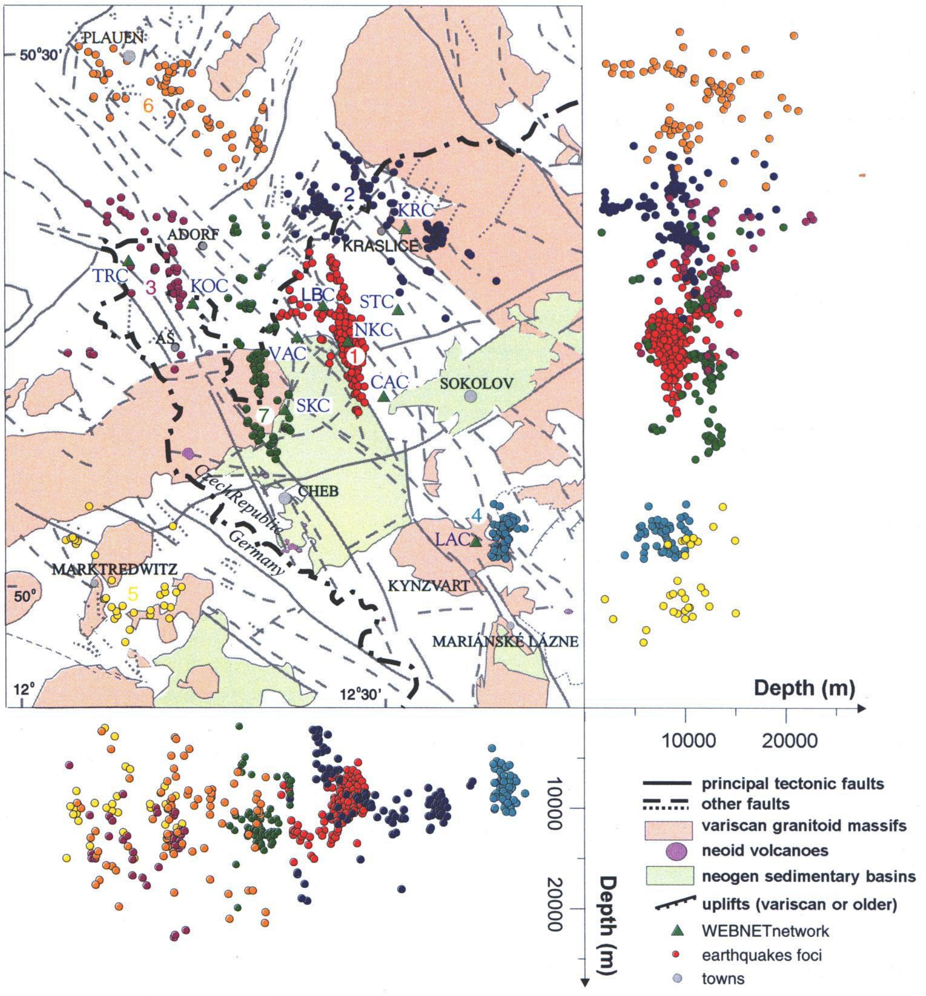

Figure 2.1: Distribution of micro-earthquake foci for the period 1991-1999 in western Bohemia/Vogtland (upper left: map of epicentres, upper right: N-S depth cross-section, lower left: E-W depth cross-section) and positions of WEBNET seismic stations operated by the Geophysical Institute, Academy of Sciences of the Czech Republic, Prague (*Horálek et al.,* 2000a). The colours of earthquake foci represent the seven main epicentral areas distinguished by *Horálek et al.* (2000a). The black dash-dot line marks the state boundary between the Czech Republic (SE) and Germany (NW).

1997/1998 in West Saxony, near Werdau (*Hemmann et al.*, 2003). The hypocenters were located in the area of intersection of the Regensburg-Leipzig-Rostock zone (*Bankwitz et al.*, 2003) and the Gera-Jachimov fault zone. No active fluid processes like in the Vogtland/NW-Bohemia region are known for the area around Werdau, only hints from drillings and geological mapping towards sub-recent upper mantle fluid activity.

Since the start of digital recording of earthquakes, the most prominent swarm in the Nový Kostel focal area occured in 1985/86 with more than 8000 recorded events, the strongest of which reached the maximum magnitude M_{Lmax}=4.5. Further swarms occurred in January 1992 (M_{Lmax}=2.0), December 1994 (M_{Lmax}=2.2), January 1997 (M_{Lmax}=3.0) and August to December 2000 (M_{Lmax}=3.4, more than 10 000 microearthquakes recorded) (*Fischer*, 2003; *Fischer and Horálek*, 2003). Clusters in the Nový Kostel zone show relatively large *b*-values, yet the *b*-value of nearby clusters may vary remarkably (*Neunhöfer and Meier*, 2004; *Neunhöfer and Hemmann*, 2005). While epicentres of swarms are confined to a few subregions, non-swarmlike events are distributed over a larger region.

There exist several models to explain the origin of earthquake swarms:

Mogi (1963) suggested stress concentration in unusually heterogeneous rock and mentioned magma intrusions as one possible cause for the stress accumulation. *Hill* (1977) explained earthquake swarms in volcanic areas by assuming magmatic intrusions in brittle country rock. He also suggests fluid migration as a reason for increased stress difference σ_1-σ_3 which may cause an earthquake swarm. *Yamashita* (1999) proposed that the increase of pore volume due to rupture allows fluids to migrate from high pressure reservoirs into this volume located in the fault zone. A high rate of pore volume increase thus causes a high seismic *b*-value, which corresponds to observations of volcanic earthquake swarms. *Hainzl* (2003) showed that the temporal clustering and magnitude-frequency distribution of swarms can be simulated also without the presence of active fluids but instead with self-organization within the swarm due to local stress transfer and viscous coupling. *Parotidis et al.* (2005) hypothesize that ascending magmatic fluids trigger the Vogtland/NW-Bohemian swarm earthquakes by causing pore pressure perturbations which propagate according to the diffusion equation. They propose that pore pressure diffusion is the main triggering mechanism. *Fischer and Horálek* (2005) investigated space-time relations between consecutive events of the West Bohemian earthquake swarm in 2000 and found indications for a triggering effect of prior earthquakes upon subsequent events. Furthermore, they showed that subsequent events are preferably triggered in the slip direction indicated by the focal mechanisms.

The stress field in the Vogtland/NW-Bohemia does not differ substantially from the known overall SE-NW directed stress field in western and central Europe (*Plenefisch and Klinge,* 2003). The determination of focal mechanisms indicates the presence of an isotropic component in the moment tensors of some of the events, inferring possible fluid activity during the faulting process (*Dahm et al.*, 2000; *Horálek et al.*, 2000b; *Vavryčuk*, 2001, 2002). Many of the swarm events display a multiplet character. Likewise, similar focal mechanisms of the events were found by *Horálek et al.* (2000b) and *Wirth et al.* (2000).

Zoback and Harjes (1997) presented evidence for fluid injection-induced micro-earthquakes at 9 km depth in the nearby KTB deep drilling site. They demonstrated that a relatively small pore pressure perturbation (<1% of the normal) was able to trigger local microseismicity. *Shapiro et al.* (2006) also showed that very weak pore pressure perturbations triggered seismicity at the seismic SE2 reflector during recent hydraulic experiments at the KTB.

2.2 The crust and crust-mantle boundary in seismic studies

From the compilation of results of seismic experiments, *Giese* (1995) created a contour map of crustal thickness in central Europe. It shows crustal thicknesses of 28 to 32 km beneath the Saxothuringian unit and a maximum crustal thickness of 36 km in the central part of the Bohemian Massif. A European Moho map was compiled from several sources by *Dèzes and Ziegler* (2001) (see Figure 2.2) which also shows Moho depths in the range of 28 to more than 36 km in the investigation area. Taken altogether, crustal thickness appears mainly to reflect post-Variscan processes such as Permo-Carboniferous extension and Cenozoic rifting.

Geissler et al. (2005) carried out a receiver function study in the western Bohemian Massif which was one of the initial studies to lead to the passive seismic experiment BOHEMA, the data of which is analysed in this thesis. *Geissler et al.* (2005) observed clear *P*-to-*S* converted phases from the Moho with delay times between 3 and 4.5 s. The calculated crustal thicknesses vary between 27 and 38 km and the v_p/v_s ratios between 1.63 and 1.81. In general, the Moho depth increases from northwest (31 km) to southeast (38

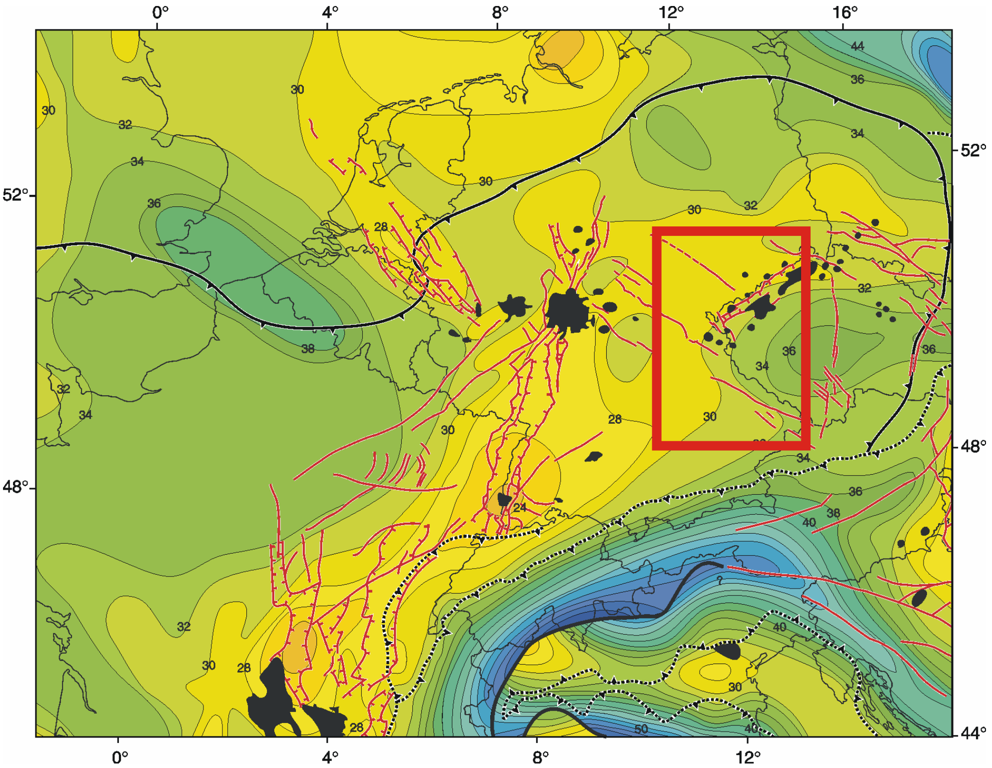

Figure 2.2: Depth map of the Moho discontinuity in central Europe, contour interval 2 km (*Dèzes and Ziegler,* 2001) with major fault systems and graben structures (red lines,) volcanic centres (black fields) and Variscan deformation front (solid black line). The investigation area of this study is marked by a red rectangle. The Moho depth beneath the study area ranges from about 28 to more than 36 km.

km). Beneath the western Eger Rift they found indications of a local Moho updoming up to 27 km with a diameter of approximately 40 km. The area coincides with the location of centres of CO_2 emanations at the surface. At some stations in the area of updoming, the signal from the Moho discontinuity is weak or disappears. In a receiver function study carried out by *Kind et al.* (1995), the Moho at station GRA1 of the Gräfenberg array (also used in this study) is 32 km deep. However, the strongest signal resulted from the bottom of the very low-velocity Mesozoic sedimentary rocks. At station Wettzell, which is also used here, *Kind et al.* (1995) found a weak and very broad Moho conversion, indicating a smooth transition between the lower crust and mantle at approximately 34 km.

Hrubcová et al. (2005) analysed profile CEL09 of the seismic refraction experiment CELEBRATION 2000. They determined two types of crust-mantle transition in the northwestern and central Bohemian Massif, respectively (Figure 2.3): (1) The Saxothuringian has a highly reflective lower crustal layer above the Moho with a strong velocity contrast at the top of the lower crustal layer. This reflective laminated lower crust is located at depths of 26-35 km and was also indicated by data of the deep reflection profile MVE90 as part of the DEKORP investigation (*DEKORP Research Group*, 1994; *Bleibinhaus et al.*, 2003) and the seismic refraction experiment GRANU'95 (*Enderle et al.*, 1998). Such a highly reflective lower crust is a phenomenon frequently observed in Caledonian and Variscan areas (*Warner*, 1990). The Moho in the model by *Hrubcová et al.* (2005) is represented by a thin (about 1 km) gradient zone at 34-35 km depth, which is deeper than in case of GRANU'95 and MVE 90 (30 and 33 km, respectively); (2) The Moldanubian in the central part of profile CEL09 is characterized by the deepest (39 km) and the most pronounced Moho within the whole Bohemian Massif with a strong velocity

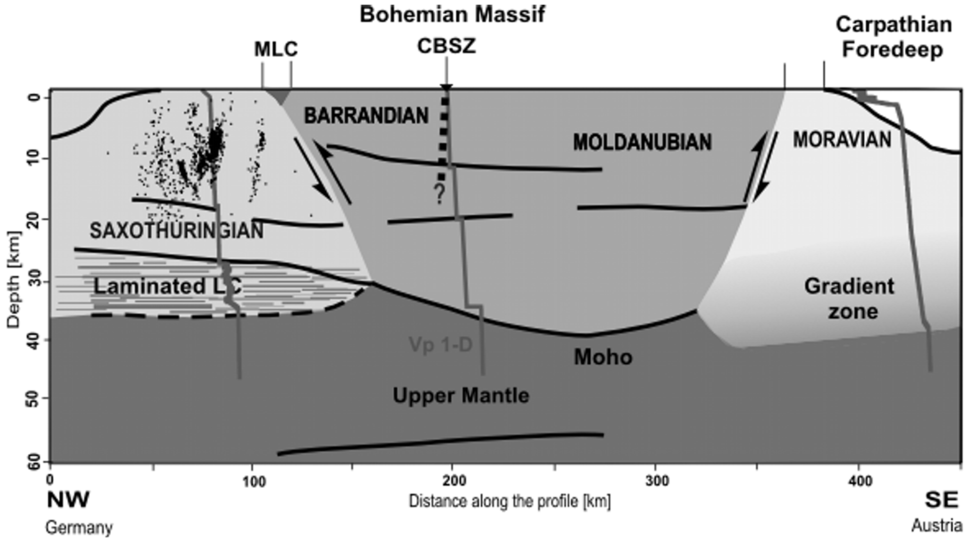

Figure 2.3: Schematic tectonic representation along profile CEL09 (*Hrubcová et al.,* 2005). Dots show locations of hypocentres of the earthquake swarms in the Vogtland/West Bohemia area. Superimposed are 1-D velocity characteristics showing differentiation in the lower crust for different parts of the Bohemian Massif: the Saxothuringian with laminated lower crust dipping southeast; high velocity contrast at the Moho in the Moldanubian; the Moravian with whole-crustal gradient zone. Arrows indicate relative movement along contact zones. MLC – Mariánské Lázně Complex, CBSZ – Central Bohemian Shear Zone. Vertical exaggeration is 1:3.

contrast. In general, *Hrubcová et al.* (2005) found that the average overall compressional velocity of the crust in the Bohemian Massif is about 6.3 km/s.

They furthermore observed reflectors in the middle crust at 7-12 km depth in the Barrandian and partly Moldanubian units, at 17-20 km depth almost throughout the whole model and in the upper mantle at 55-58 km depth in the central part of the Bohemian Massif (Figure 2.3). The latter reflector dips slightly northwest and probably corresponds to a locally sharp reflector found at 56 km depth in the reflection seismic profile 9HR by *Tomek et al.* (1997).

Wilde-Piórko et al. (2005) carried out a receiver function investigation at permanent seismic stations in the Bohemian Massif and surroundings which confirms that the structure of the crust and uppermost mantle differs significantly for the northwestern and southeastern parts of the Bohemian Massif. The crust and upper mantle in the southeastern (~Moldanubian) part have a "normal" structure, without low velocity zones. The crust is 35 to 40 km thick. The crust of the northwestern (~Saxothuringian) part is much thinner (28 to 32 km). Low *S* wave velocities were modelled from receiver functions in the middle crust and in the lower lithosphere. The authors conclude that these features together with recent micro-seismic activity and CO_2 emanation are related to tectonic and magmatic activity in the Eger Rift.

2.3 Lithospheric and upper mantle structure

Lithospheric thickness is a critical parameter in the development of continents. In this study, the seismic definition of the high-velocity Earth's crust and uppermost mantle overlying the low-velocity zone in the upper mantle (asthenosphere) is used for the lithosphere. According to *Babuška and Plomerová* (1992), the lithospheric thickness in the Variscan belt of central Europe varies between about 60 and 150 km with typical values of 100-120 km (Figure 2.4). These depth values were obtained by tomographic studies based on the investigation of relative *P*-wave residuals computed at networks of seismological stations. *Babuška and Plomerová* (1992) furthermore observed a regional thinning of the

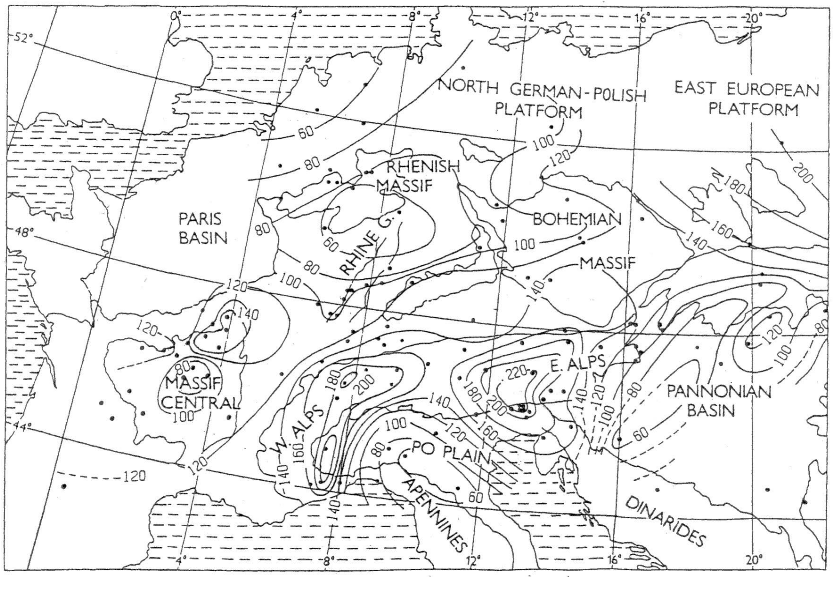

Figure 2.4: Model of lithospheric thickness (isothickness contours in km) beneath central Europe derived from *P*-wave residuals at individual seismological stations (dots) (*Babuška and Plomerová*, 1992).

lithosphere up to about 60-80 km beneath regions of active Tertiary-Quaternary volcanism like the French Massif Central and Rhenish Massif in the Variscan belt of central and western Europe. *Babuška and Plomerová* (2001) introduced a model of thickness and anisotropy of the subcrustal lithosphere of the Bohemian Massif which combines variations of *P*-wave residuals and shear-wave splitting observations (Figure 2.5). In this model the lithosphere is thinning to 80-90 km beneath the contact of the Moldanubian and Saxothuringian units from 90-120 km in the Saxothuringian and 120-140 km in the Moldanubian unit. The model corresponds very well to a model of lithospheric thickness derived from heat flow measurements by *Čermák* (1994). Asthenospheric upwelling beneath the western Eger Rift is also indicated by e.g. *Faber et al.* (1986), *Plomerová and Babuška* (1988), *Passier and Snieder* (1996), and *Plomerová et al. (1998).*

By joint analysis of *P*-wave residuals and shear wave splitting parameters, *Babuška and Plomerová* (1992, 2001) observed large-scale anisotropic structures in the subcrustal lithosphere which are oriented northwestwards in the Saxothuringian and southeastwards in the Moldanubian (Figure 2.5). The authors suggest that the anisotropic structures may represent remnants of successive palaeosubductions of the ancient oceanic lithosphere “frozen” in the subcrustal lithosphere of both units a long time before their Variscan collision. *Babuška and Plomerová* (2001) relate the distinct change in anisotropy to the deep suture which cuts the whole lithosphere thickness and separates the Saxothuringian and Moldanubian units. The observed mixture of anisotropic characteristics within the lower lithosphere south of the surface trace of the Saxothuringian/Moldanubian contact is suggested to reflect underthrusting of a part of the Saxothuringian subcrustal lithosphere beneath the Moldanubian. Alternatively, it could represent a hypothetical remnant of the Early Palaeozoic oceanic lithosphere subducted to the south during collision of the Saxothuringian and Moldanubian units.

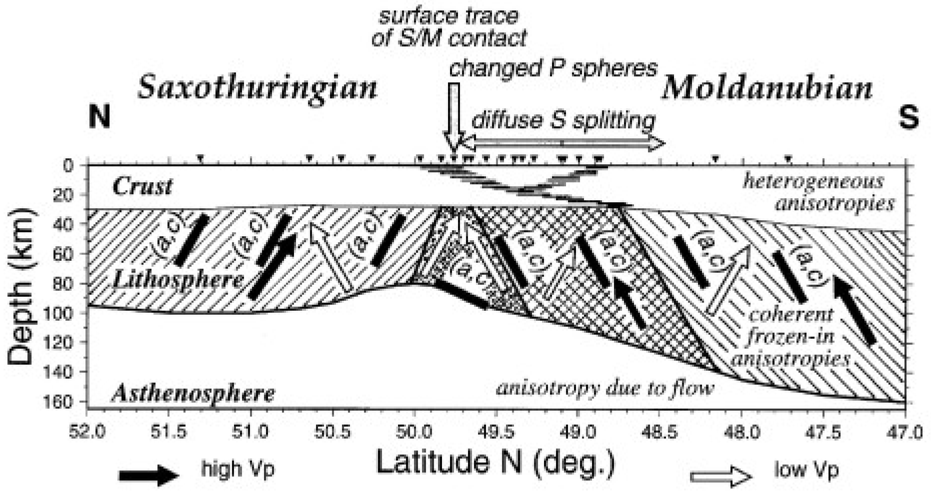

Figure 2.5: Cartoon by *Babuška and Plomerová* (2001) showing a summary of the body-wave observations of anisotropy and their interpretation in terms of large-scale fabric. The regions of “mixed” subcrustal lithospheres of both tectonic units is cross-hatched. A region of lower velocities beneath the surface trace of the Saxothuringian/Moldanubian (S/M) contact is stippled. Thick bars indicate the dipping (a/c) foliation planes of the model peridotite aggregate. DEKORP 4 crustal reflections are schematically shown by dense hatching.

In the receiver function study by *Geissler et al.* (2005) in the western Bohemian Massif, a phase near 6 s delay time was locally observed underneath the region of earthquake swarms and CO_2 degassing which may originate from a discontinuity in approx. 50 to 60 km depth or from a structure within the crust. The authors propose that in the uppermost mantle isolated active magma/fluid reservoirs exist in the depth range of 60 to 30 km (magmatic underplating) (see Figure 2.8).
In two other regions of Variscan origin, namely the French Massif Central and the Eifel (Rhenish Massif), the existence of active mantle fingers was suggested by *Granet et al.* (1995) and *Ritter et al.* (2001), respectively, from seismic tomography studies. *Granet et al.* (1995) suggested that the European Cenozoic Rift System may have a common source of a "plume-like" volcanism in the mantle and predicted the existence of a similar diapiric mantle upwelling also for the Bohemian Massif (Figure 2.6). Active mantle fingers might furthermore be related to release of gas that ascends to the surface. In the French Massif Central, Eifel and western Bohemian Massif, the isotope (He, C, N) composition of ascending gases points clearly to an origin in the European subcontinental mantle. However, structural indications for the existence of a plume beneath the western Bohemian Massif have not yet been clearly observed. Recently, *Achauer et al.* (2005) found indications for an updoming of the asthenosphere beneath the western Eger Rift by teleseismic *P* wave tomography.

Passier and Snieder (1996) obtained a three-dimensional *S* velocity distribution beneath central and southern Germany. It shows low velocities in the uppermost mantle beneath the Eger Rift (80-120 km), the Naab-Pritzwalk-Rostock lineament (80-200 km) and the volcanic Eifel (80-200 km). They suggest the creation of magma in the asthenosphere or at the base of the lithosphere beneath this region.

The upper mantle discontinuity at 410 km depth beneath the western Bohemian Massif was investigated in a receiver function study by *Geissler* (2004). He observed an apparent

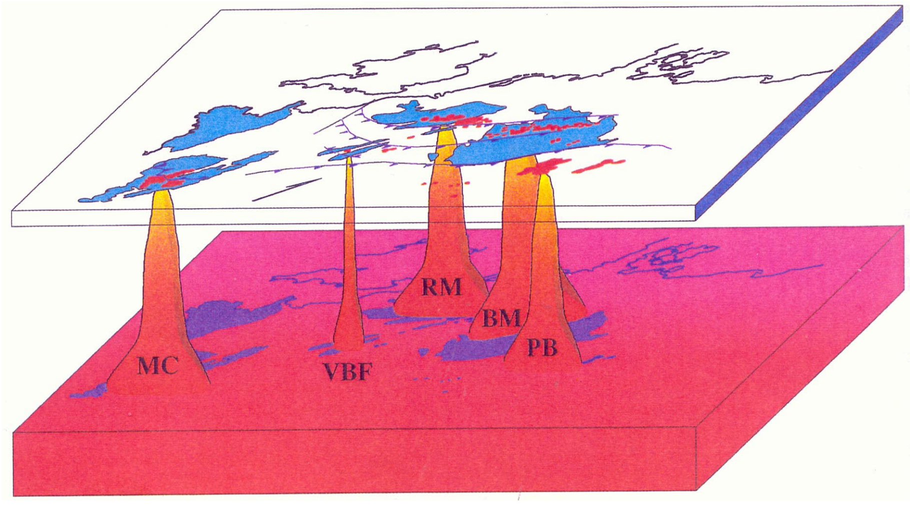

Figure 2.6: Schematic cartoon by *Granet et al.* (1995) showing the upwelling of small-scale mantle fingers beneath the European lithosphere from a thermally and geochemically anomalous layer at ca. 400 km depth. The upper surface of the block shows the distribution of uplifted Variscan basement massifs and Tertiary-Quaternary volcanic fields.

deepening of the 410 km discontinuity, which might be the result of lower seismic velocities in the upper mantle compared to the *IASP91* reference model (*Kennett*, 1991; *Kennet and Engdahl*, 1991). However, a real deepening could not be excluded by his study. Another receiver function study by *Grunewald et al.* (2001) focuses on the Eifel volcanic region in the Rhenish massif of western Germany. They observed a 150 km wide and 20 km deep depression of the 410-km discontinuity in the upper mantle beneath the Eifel region. Their data set extends to the western Bohemian Massif for the discontinuities of the mantle transition zone at 410 and 660 km depth. However, they do not observe any anomaly of the discontinuities of the mantle transition zone in this region.

2.4 CO_2 emanations and fluid investigations

From investigation of the mantle-related CO_2-dominated gas flux in the area of the Cheb basin, *Weinlich et al.* (1999) claimed the existence of a magmatic body in the subcontinental mantle. The fluid activity connected with this body is discussed as a probable trigger mechanism for the earthquake swarms. Evidence for CO_2 degassing from fluid reservoirs in the subcontinental lithospheric mantle was found in three areas of magmatic activity within the European Cenozoic Rift system: the French Massif Central (*Matthews et al.*, 1987), the Eifel volcanic fields (*Griesshaber et al.*, 1992; *May*, 2002) and the western Eger Rift (*O'Nions et al.*, 1989; *Weinlich et al.*, 1999, 2003; *Bräuer et al.*, 2004).

The permeable upper crust beneath the area under investigation enables high permanent CO_2 transport through the upper crust. Hydrological, geochemical and isotope investigations at springs and mofettes in the Vogtland/NW-Bohemia region give evidence of a fluidal response to the seismogenic processes in the swarm earthquake area of Nový Kostel (e.g. *Heinicke and Koch*, 2000; *Bräuer et al.*, 2003; *Koch et al.*, 2003). An increased CO_2 emission is assumed to be responsible for different phenomena such as anomalous behaviour of groundwater level, hydrostatic pressure, free gas flow and radon emission (*Heinicke and Koch*, 2000; *Koch et al.*, 2003).

Weinlich et al. (1999) and *Bräuer et al.* (2005) classify three gas escape centres (Figure 2.7): 1. Cheb basin/Františkovy Lázně, 2. Mariánské Lázně and 3. Karlovy Vary. From the independent behaviour of the $^3He/^4He$ ratios in the three gas escape centres, *Bräuer et al.* (2005) conclude that there might be small isolated magmatic reservoirs present (not a continuous magma body as suggested by *Weinlich et al.* (1999)). The observed increase of the $^3He/^4He$ ratio beneath the Cheb basin degassing centre during the past decade points to an increased magmatic activity and an intrusion of fresh magma into the lower crust and might thus be an indicator of ongoing magmatic processes in this area (*Bräuer et al.*, 2005).

Beneath the presently non-volcanic Mammoth mountain in eastern California, magmatic unrest was detected with similar symptoms as in Vogtland/NW Bohemia, like swarm earthquakes, ground deformation, emission of magmatic CO_2 and fumarole gases with elevated $^3He/^4He$ ratios (*Hill and Prejean*, 2005). The authors suggest that the unrest is caused by the episodic release of a volume of CO_2-rich hydrous magmatic fluid derived from magmatic intrusions at mid-crustal depths.

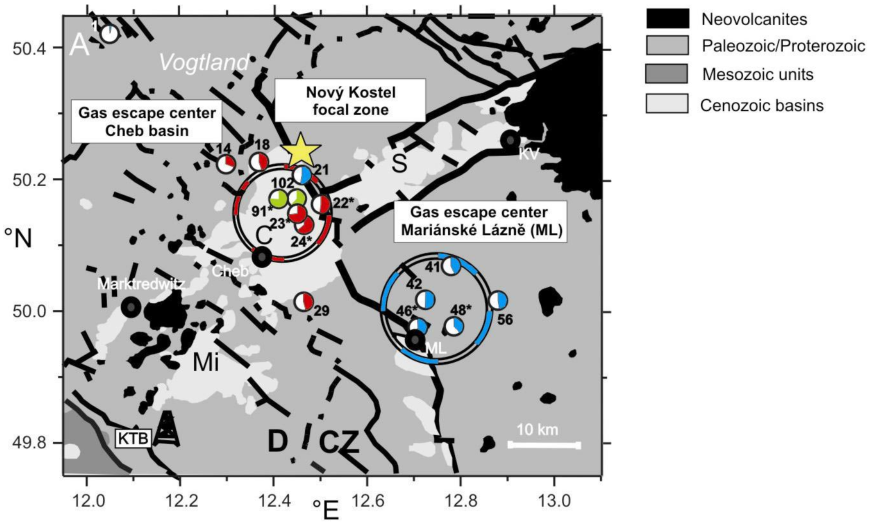

Figure 2.7: Distribution of $^3He/^4He$ ratios in the gas escape centres of the Eger Rift. The locations where $^3He/^4He$ ratios have increased since 1992/93 are shown in red, those with nearly equal values in blue, and two locations which were studied for the first time in green. Symbols and abbreviations: KTB position of the German Continental Deep Drilling site, KV Karlovy Vary, D Germany, CZ Czech Republic, Mi Mitterteich basin, C Cheb basin, S Sokolov basin (*Bräuer et al.*, 2005).

2.5 Xenolith investigations

In a thermobarometric and geochemical study, *Geissler et al.* (2006) analysed upper mantle and lower crustal xenoliths from a Quaternary tephra deposit in Mýtina (age 0.3 to 0.5 Ma) near the Quaternary scoria cone Železna Hůrka. The upper-mantle xenoliths are dominated by wehrlites, clinopyroxenites, and hornblendites, while crustal xenoliths are dominated by rock types similar to crystalline country rock in the surroundings. Only one lower-crustal sample was found. Most of the analysed samples are cumulates of alkaline melts, fragments of pegmatitic veins, or rocks from a metasomatic upper mantle. The metasomatized samples from subcrustal regions give evidence for a lithospheric mantle strongly altered and depth-structured by magmatic/fluid processes. This metasomatism can cause slower than typical uppermost-mantle seismic velocities in a greater area and might help to explain observed seismic anomalies.

2.6 Thermal structure

Relatively low heat flow values of about 50-60 mW/m^2 were observed in the southeastern and central parts of the Bohemian Massif, i.e. in areas where crustal thickness attains its maximum close to 40 km (*Čermák*, 1994). Relatively high heat flow values (70-80 mW/m^2, locally as high as 90 mW/m^2) observed in the Eger Rift are explained by an increased heat supply from below the crust associated with deep seated processes of rejuvenation during the Alpine-Carpathian orogenesis. However, the radiogenic heat of Late Variscan granitic plutons probably contributes here to the observed high heat flow by up to 30-40 mW/m^2 (*Čermák*, 1994). Therefore it is difficult to extrapolate the regional surface heat flow data to depth and to estimate the regional Moho heat flow and temperatures (*Förster and Förster*, 2000).

The heat flow value measured at the KTB superdeep borehole corresponds well to the average background value of about 80 mW/m^2 in southern Germany. However, a considerably higher than expected geothermal gradient was observed. The data show that heat production is controlled by lithology, and there is only a slight overall decrease of heat production with depth (*Emmermann and Lauterjung*, 1997).

In the thermobarometric and geochemical study by *Geissler et al.* (2006), p-T estimates for xenoliths from the Quaternary tephra deposit in Mýtina near the Quaternary scoria cone Železna Hůrka also indicate higher temperatures within crust and uppermost mantle than proposed by regional geotherms by *Čermák* (1994).

2.7 Further models of the investigation area

From receiver function studies, xenolith studies and a compilation of previous studies, *Geissler et al.* (2005) and *Geissler et al.* (2006) developed a model of the present lithosphere for the NW Bohemian Massif (Figure 2.8). It describes the lithosphere-asthenosphere interaction beneath the western Eger Rift with reflectors in the lower crust, fluid reservoirs at subcrustal and possibly lower crustal depth, metasomatic upper mantle, assumed updoming of the asthenosphere and CO_2 channels. According to the model, the crust-mantle boundary is overprinted by magmatic and tectonic processes. A shear wave velocity model is proposed for the western Eger rift area based on receiver function

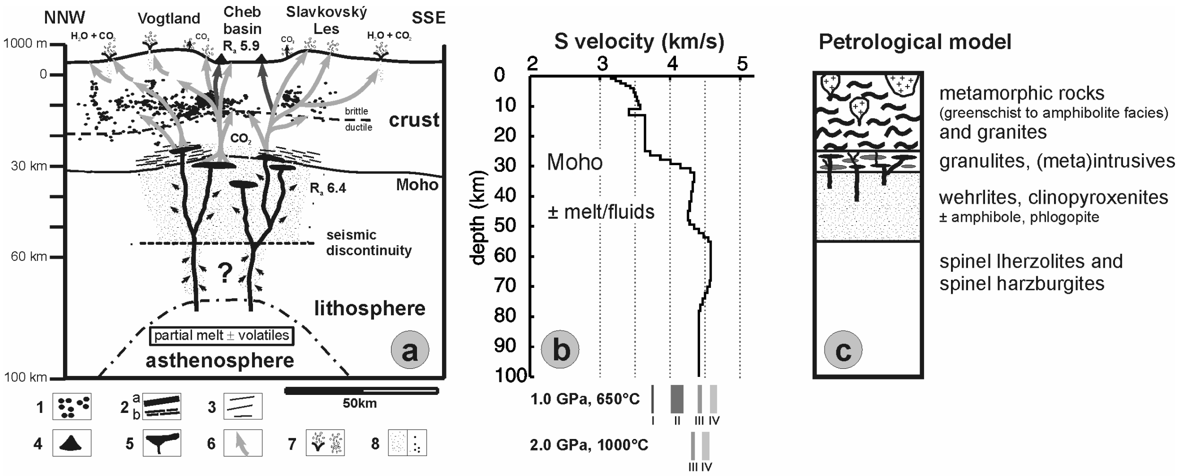

Figure 2.8: Model of the lithosphere beneath the western Eger Rift (*Geissler et al.,* 2006). **(a)** Cartoon illustrating the asthenosphere-lithosphere interaction in the Vogtland/NW-Bohemia region. Legend: 1 - seismogenic zones, 2 – a: Moho, b: disrupted Moho, 3 – reflectors in the lower crust, 4 – scoria cone, 5 – fluid/magma reservoirs, 6 – CO_2 channels, 7 – mineral springs and mofettes, 8 – metasomatic upper mantle. **(b)** Proposed present-day shear wave velocity model beneath the western Eger Rift where an additional phase at 6 s delay time occurs in the receiver function data. Also shown are the ranges of shear wave velocities for different (ultra-)mafic rock types at different temperature-pressure conditions. **(c)** Petrological crustal section derived from the xenolith study and local surface geology.

observations and seismic velocities of the investigated xenoliths. Furthermore, the xenolith study combined with local surface geology led to a petrological crustal and lithospheric model.

Another model was proposed by *Babuška et al*., 2003 (Figure 2.9) demonstrating the complexity of assumed crustal and upper mantle structures, including the suggestion of traces of palaeosubduction zones.

Further models of the region regarding mechanisms of gas emanation were provided by e.g. *Weinlich et al.* (1999) and *Bräuer et al.* (2003).

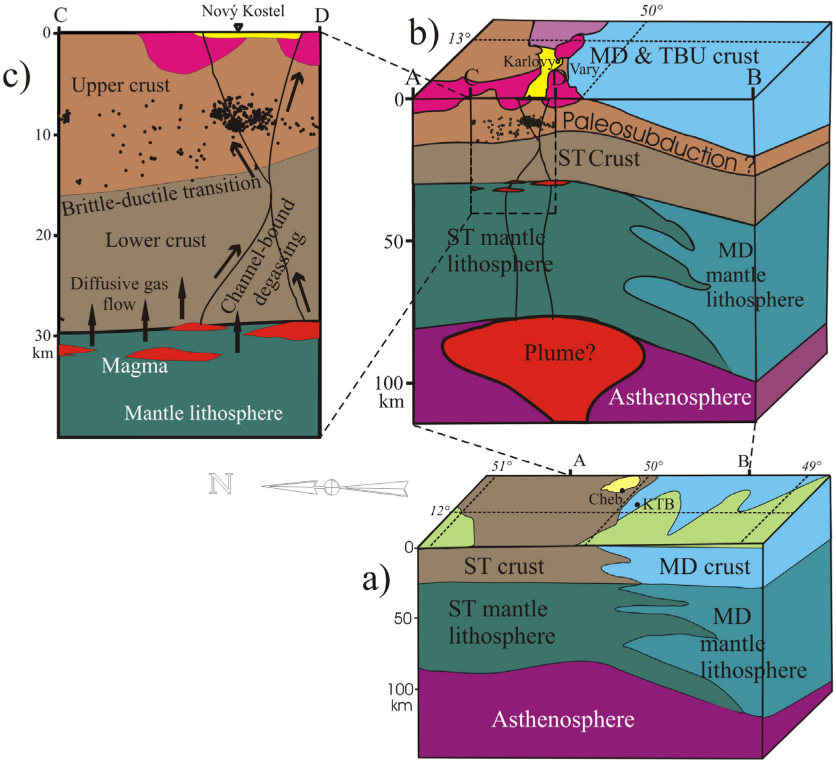

Figure 2.9: Schematic diagrams showing the tectonic situation in the western Bohemian Massif (*Babuška et al.,* 2003). **(a)** N-S section of the deep structure of the Saxothuringian-Moldanubian contact based on observations of seismic anisotropy. **(b)** Close-up of the rear of the lower diagram shows a hypothetical plume head beneath the western Eger Rift, and a hypothetical palaeosubduction of Saxothuringian crust beneath the Moldanubian and Teplá-Barrandian. Granite massifs (red) are also schematically shown. **(c)** Close-up of the distribution of foci of earthquake swarms in Nový Kostel-Kraslice region, as shown in panel (b). Gas flow from the mantle may play an important role in triggering earthquake swarms.