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Upper Cretaceous to Pleistocene melilitic volcanic rocks of the Bohemian Massif: petrology and mineral chemistry

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Abstract: Upper Cretaceous to Pleistocene volcanic rocks of the Bohemian Massif represent the easternmost part of the Central European Volcanic Province. These alkaline volcanic series include rare melilitic rocks occurring as dykes, sills, scoria cones and flows. They occur in three volcanic periods: (i) the Late Cretaceous to Paleocene period (80–59 Ma) in northern Bohemia including adjacent territories of Saxony and Lusatia, (ii) the Mid Eocene to Late Miocene (32.3–5.9 Ma) period disseminated in the Ohře Rift, the Cheb–Domažlice Graben, Vogtland, and Silesia and (iii) the Early to Late Pleistocene period (1.0–0.26 Ma) in western Bohemia. Melilitic magmas of the Eocene to Miocene and Pleistocene periods show a primitive mantle source [$(^{143}Nd/^{144}Nd)_t = 0.51280–0.51287$; $(^{87}Sr/^{86}Sr)_t = 0.7034–0.7038$)] while those of the Upper Cretaceous to Paleocene period display a broad scatter of Sr–Nd ratios. The $(^{143}Nd/^{144}Nd)_t$ ratios (0.51272–0.51282) of the Upper Cretaceous to Paleocene rocks suggest a partly heterogeneous mantle source, and their $(^{87}Sr/^{86}Sr)_t$ ratios (0.7033–0.7049) point to an additional late- to post-magmatic hydrothermal contribution. Major rock-forming minerals include forsterite, diopside, melilite, nepheline, sodalite group minerals, phlogopite, Cr- and Ti-bearing spinels. Crystallization pressures and temperatures of clinopyroxene vary widely between ~1 to 2 GPa and between 1000 to 1200 °C, respectively. Nepheline crystallized at about 500 to 770 °C. Geochemical and isotopic similarities of these rocks occurring from the Upper Cretaceous to Pleistocene suggest that they had similar mantle sources and similar processes of magma development by partial melting of a heterogeneous carbonatized mantle source.

Key words: Bohemian Massif, Cenozoic volcanism, melilitic rock, petrology, mineralogy, isotope geochemistry.

Introduction

Melilitic (>10 vol. % of modal melilite) and melilite-bearing (1–10 vol. % of modal melilite — collectively referred to as melilitic below) olivine rocks generally represent small volume volcanic products (Dunworth & Wilson 1998). These rocks are characterized by unusual chemistry and mineralogy and their origin is subject to debate. According to the model of Wedepohl (1987), the related olivine nepheline and melilite magma in the Hessian Depression was formed at depths of ca. 90 km in the garnet peridotite mantle, at greater depths than other basaltic magmas. These data correspond to the model of generation of the melilitic partial melts from a thermal boundary layer at the base of the lithospheric mantle (Wilson et al. 1995; Dunworth & Wilson 1998).

Melilitic rocks occur in both oceanic and continental environments particularly concentrated in the continental rift setting (e.g. Alibert et al. 1983; Wilson et al., 1995; Keller et al. 2006; Ulrych et al. 2008) and elsewhere. The melilitic rocks in the continental settings are usually represented by olivine melilitites, melilite-bearing olivine nephelinites and rare ultramafic melilitic lamprophyres and olivine melilitolites.

The goal of the present paper is to compare the petrology and mineral chemistry of melilitic rocks of the Bohemian Massif from Late Cretaceous to Pleistocene periods. Further, this paper addresses the problem of the melilitic rock tectonic setting, their magma sources and crystallization history.

Geological setting

Widespread alkaline volcanism in Europe is associated with the major European Cenozoic Rift System (ECRIS — Prodehl et al. 1995). It extends for a distance of 1000 km, from Spain to France, Germany, the Czech Republic and Poland. It is mostly interpreted as a result of the reaction of the Variscan foreland to the effects of the Alpine orogeny (e.g. Ziegler 1994; Prodehl et al. 1995). Rift-related passive asthenospheric upwelling resulted in the generation of large volumes of mantle-derived magmas (e.g. Wilson & Downes 1991; Lustrino & Wilson 2007; Ulrych et al. 2011). The presence of an active magmatic source beneath the Bohemian Massif in the western Ohře Rift area was not confirmed by the seismic studies of Babuška et al. (2003).The Ohře Rift represents a fundamental Variscan boundary between the Saxothuringian and the Teplá-Barrandian units in the Bohemian Massif (Ziegler 1994; Babuška & Plomerová 2010). This graben hosts two extensive Tertiary volcanic complexes: the Doupovské hory Mts and the České středohoří Mts.

Ulrych et al. (2008) interpreted the origin of melilitic rocks in northern Bohemia from a portion of a depleted mantle source overprinted by carbonate-rich fluids probably related to carbonatitic magmatism associated with incipient rifting of the lithosphere of the Bohemian Massif. Abratis et al. (2009) ascertained the CO_2-dominated type of mantle metasomatism for melilitic rocks in Vogtland and western Bohemia.

Melilitic volcanic rocks formed in the Bohemian Massif (Fig. 1) in the Upper Cretaceous and during the whole Cenozoic. Their production culminated in the pre-rift period (Late Cretaceous to Paleocene) in the Ploučnice River region in northern Bohemia (Ulrych & Pivec 1997; Pivec et al. 1998; Ulrych et al. 2008, 2014) and in the late-rift period (Early to Late Pleistocene) in western Bohemia (Ulrych et al. 2000a, 2011, 2013). A non-melilitic ultramafic rock association of Cretaceous age is known from the western part of the Outer Western Carpathians (Szopa et al. 2014). Their concentrations are associated with the junctions of grabens and fault zones. In small quantities, melilitic rocks appear in the Ohře Rift and adjacent areas of the Krušné hory Mts/Erzgebirge, Vogtland (Locality 6 in Fig. 1) and Lusatia, eastern shoulder of the Cheb–Domažlice Graben and the Labe/Elbe–Odra/Oder Fault Zone. These rocks are of Eocene to Miocene age and correspond to the main-rift period of Cenozoic volcanic activity of the Bohemian Massif (Ulrych et al. 2008).

Metasomatism of the lithospheric mantle beneath the Bohemian Massif was ascertained by several studies suggesting mantle enrichment by silicate (e.g. Ackerman et al. 2007, 2014; Puziewicz et al. 2011; Medaris et al. 2014) and/or carbonate-rich melts (Geissler et al. 2007; Matusiak-Malek et al. 2010; Ackerman et al. 2013). The presence of metasomatically transformed upper mantle is further supported by the occurrence of phlogopite-bearing clinopyroxenite xenoliths (Ulrych et al. 2008) and those of lherzolite xenoliths with amphibole and/or phlogopite (Krammer & Seifert 2000; Geissler et al. 2008).

Geological characteristics of sampled localities

Pleistocene volcanism associated with the junction of the Cheb–Domažlice Graben and the Ohře Graben/Rift in the Cheb Basin area, western Bohemia

Pleistocene volcanic activity in western Bohemia is related to the Cheb Fault that bounds the Cheb Basin to the west and

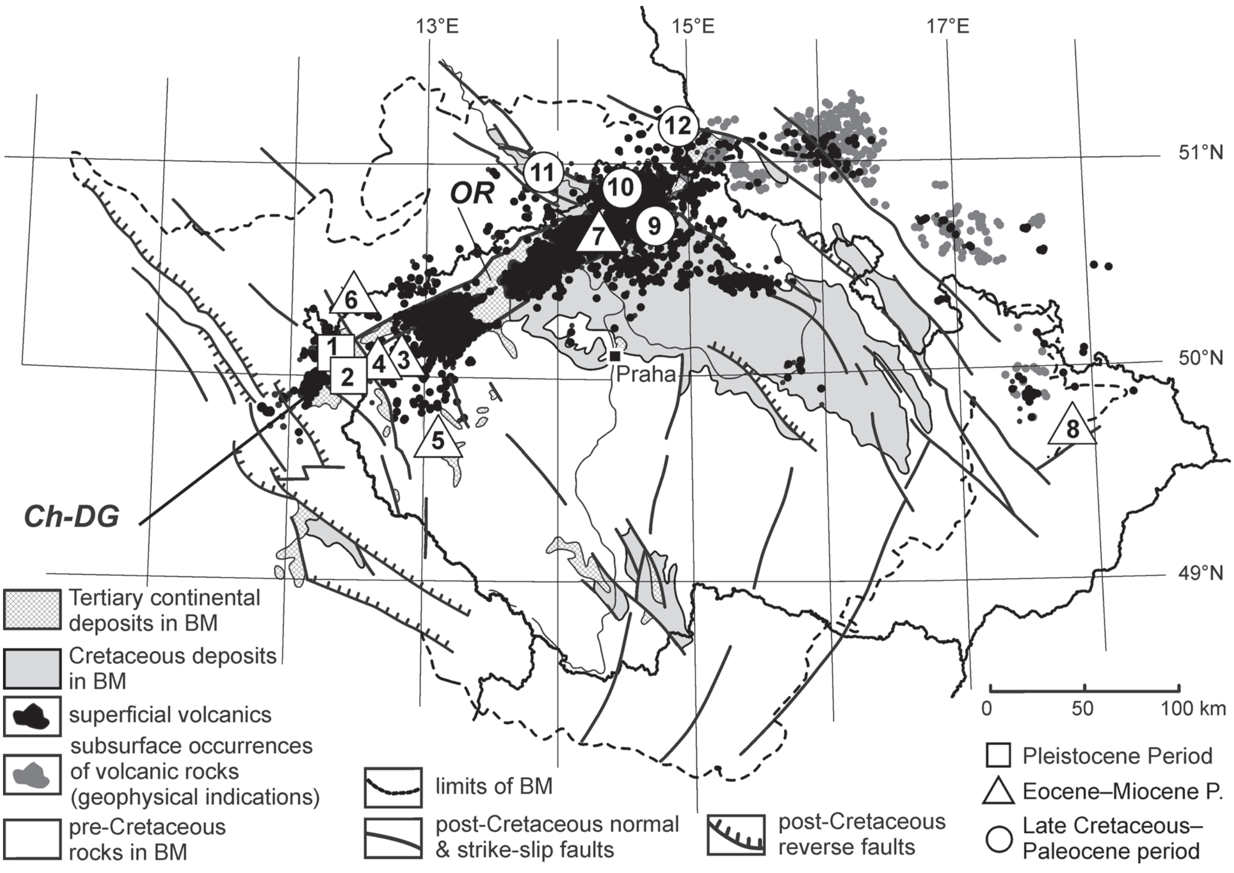


Fig. 1. Geological sketch map of the Bohemian Massif showing occurrences of the Upper Cretaceous and Cenozoic melilitic rocks. **BM** — Bohemian Massif, **OR** — Ohře Rift, **Ch–DG** — Cheb–Domažlice Graben. **Sampling sites:** 1 — Komorní hůrka Hill at Františkovy Lázně, 2 — Železná hůrka Hill and Mýtina near Cheb, 3 — Český Chloumek near Karlovy Vary, 4 — Podhorní vrch Hill near Mariánské Lázně, 5 — Příšovská homolka Hill near Plzeň, 6 — Vogtland, Germany, 7 — Krkavčí skála Hill near Sebuzín, 8 — Pohoř Hill at Odry, 9 — Osečná Complex, near Liberec, 10 — Jiřetín pod Jedlovou and Stožec Hill, 11 — Zeughausgang near Hinterhersmsdorf, Germany, 12 — Pomological Garden in Görlitz, Germany.

limits the Cheb–Domažlice Graben subparallel to the Mariánské Lázně Fault Zone in the east.

Pleistocene melilitic rock series

Komorní hůrka (Locality 1 in Fig. 1) at Františkovy Lázně is a monogenetic Strombolian cinder cone (Hradecký 1994; Gottsmann 1999) with preserved lava-filled conduit and a single lava flow. Both lapilli and lava are composed of melilitic rocks (Ulrych et al. 2013). K/Ar dating of the lava yielded ages ranging from 1.02 Ma (Ulrych et al. 2013) to 0.26 Ma (Šibrava & Havlíček 1980).

Železná hůrka (Locality 2 in Fig. 1) is a cinder cone occurring near Cheb. The Strombolian activity producing stratified tephra to scoria evolved into the Hawaiian type of eruptions represented by coarse-grained black spatter. The youngest sequence is formed by welded scoria (Hradecký 1994; Schwarzkopf & Tobschall 1997). Melilitic scoria yielded a K/Ar age of ~1.0 Ma (Šibrava & Havlíček 1980).

The **Mýtina** (Locality 2 in Fig. 1) locality of pyroclastic deposits lies ~0.5 km E of the Železná hůrka volcano. Geissler et al. (2008) speculated that the Mýtina "tuff-tephra" deposit erupted together with the Železná hůrka scoria cone. Mrlina et al. (2009) interpreted it as part of an independent Pleistocene (~288 ka — Ar/Ar laser dating) maar structure.

Oligocene to Miocene volcanism of the Ohře/Eger Rift, the Cheb–Domažlice Graben including Vogtland, Saxony and the Labe–Odra Fault Zone

The Ohře Rift/Graben

The only known locality of melilitic rocks in the Ohře Rift is **Krkavčí skála** (Locality 7 in Fig. 1) (28.7 Ma — Lustrino & Wilson 2007) at Sebuzín in the České středohoří Mts. The ~100 m long and 6–8 m thick NE–SW-striking dyke(s) of melilite-bearing olivine nephelinite penetrates the Upper Cretaceous sediments in a brecciated zone filled with nepheline basanite.

The Cheb–Domažlice Graben shoulder, western Bohemia

Relicts of a volcanic edifice of melilite-bearing olivine nephelinite to olivine nephelinite composition near **Český Chloumek** (Locality 3 in Fig. 1) (16.5 Ma — Lustrino & Wilson 2007) can be associated with continuation of the Litoměřice Deep Fault.

Melilite-free olivine nephelinite from the **Podhorní vrch** volcano (Locality 4 in Fig. 1) (12.4 Ma — Lustrino & Wilson 2007) lies in the neighbourhood of the Mariánské Lázně Fault. Here, the pegmatoid segregations of ijolite composition in the olivine nephelinite parent contain mineral association of nepheline + diopside + melilite ± olivine, magnetite, apatite and sodalite (Ulrych et al. 2000b).

Melilitic volcanism related to the Cheb–Domažlice Graben continues to Aš in the **Cheb Basin area** and further to the **South Vogtland Trough** in Saxony (Abratis et al. 2009, 2013) where the Lower Miocene (19.5 Ma) melilitic rocks form dykes, rare plugs and diatremes.

The **Příšovská homolka** (Locality 5 in Fig. 1) (5.9 to 7.2 Ma — Ulrych et al. 2013) explosive volcano near Plzeň in the southern part of the Cheb–Domažlice Graben shoulder produced two sequences of pyroclastic products. Younger dykes (0.5 to 1 m thick) of basanite to olivine nephelinite composition penetrate the tuffites. The presence of altered melilite in the rock, discussed by Ulrych et al. (2013), has not been confirmed yet.

The Labe–Odra Fault Zone

The occurrences of melilitic rocks in Moravia and Silesia are very rare. The only currently accessible body is the basaltic dyke of **Pohoř Hill** at Odry (Locality 8 in Fig. 1) (32.3 Ma — Ulrych et al. 2013).

Late Cretaceous to Paleocene volcanism of the Ploučnice River region (the Osečná Complex), northern Bohemia

Dykes of melilitic rocks, including ultramafic melilitic lamprophyres–polzenites, occur in the **Ploučnice River region** in northern Bohemia, e.g. Osečná Complex (Locality 9 in Fig. 1 — Ulrych et al. 2008), **Jiřetín pod Jedlovou** and near **Stožec Hill** (Locality 10 in Fig. 1) and **Zeughausgang** near Hinterhermsdorf (Locality 11 in Fig.1 — Seifert et al. 2008), and **Pomological Garden in Görlitz** (Locality 12 in Fig. 1 — Seifert et al. 2008) mostly associated with the Lusatian Fault. These rocks are concentrated in the **Osečná Complex** (Locality 9 in Fig. 1) situated at the intersection of the Lusatian Fault with the Ohře Rift (Ulrych & Pivec 1997; Ulrych et al. 2008, 2014). The Osečná Complex is formed by a central lopolith-like intrusion (Ulrych & Pivec 1997). The central part is composed of medium-, rarely coarse-grained to porphyritic olivine melilitite with rare pods and dykes of melilitic pegmatoids, glimmerites and ijolites. The dykes of the **Devil's Walls Dyke** swarm of porphyritic melilite-bearing olivine nephelinite to olivine melilitite composition are spatially associated with the Osečná Complex.

Analytical procedures

Whole-rock major element concentrations were determined using the wet chemical method. Analyses of the USGS international rock standard BCR-2, and duplicate analyses of the samples, yield total procedure errors of ±10 % (2 σ). A quadruple-based ICP-MS (Thermo XSeries) was used for determination of REE and other trace elements using the methods outlined in Strnad et al. (2005). The in-run precision of the analysed elements was always better than ±5 % (2 σ). The accuracy of the analyses was monitored by replicate analyses of the USGS international reference material BCR-2 and was better than ±10 % (2 σ).

Mineral analyses were carried out on a CAMECA SX 100 wavelength-dispersive electron probe microanalyser. Analytical conditions were as follows: 15 kV accelerating voltage, 10 nA beam current and 2 μm beam diameter. Synthetic phases and natural minerals were used as standards.

The Sr/Nd isotope compositions were determined according to the procedures outlined in Hegner et al. (1995). The Sr/Nd isotopic compositions were determined with a Finnigan MAT 261 using a dynamic triple mass method for $^{143}Nd/^{144}Nd$ ratios measurements and dynamic double mass method for $^{87}Sr/^{86}Sr$ ratios.

The K/Ar age determinations were carried out using the instruments and methods described in Balogh (1985). The accuracy and reliability of the measurements were shown by the results of an interlaboratory calibration project published by Odin et al. (1982). The K/Ar results presented in this study have been calibrated using standards LP-6, HD-B1 and Asia 1/65, as well as atmospheric argon.

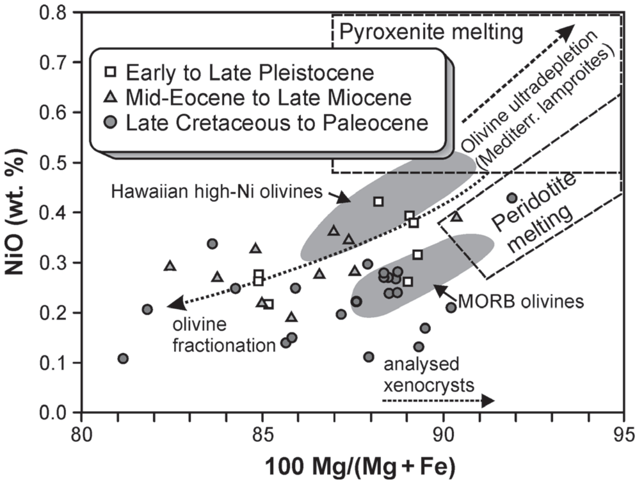


Fig. 2. Olivine from melilitic rocks of the Bohemian Massif in terms of 100 Mg/(Mg+Fe) vs. NiO (wt. %) compared with the Hawaiian high-Ni olivine and MORB olivine, along with olivine fractionation and ultradepletion trend (compiled by Prelević et al. 2013). The peridotite melting box is from Herzberg (2011), pyroxenite melting box from Straub et al. (2008).

Results

Petrography

Concise petrographic and geological characteristics of the Upper Cretaceous to Pleistocene melilitic and melilite-bearing rocks are presented in Table 1. The samples are mostly micro-porphyritic with a fine-grained groundmass and chemically homogeneous. Most of them have a common simple modal composition. A brief presentation of the main rock-forming minerals in individual rock samples is presented in Table 1. The results of the study of the main rock-forming minerals are listed in the following section.

Main rock-forming minerals

Representative analyses of the minerals of the studied melilitic rocks from the Bohemian Massif are presented in Supplement 1 (Supplements 1–3 available online at *www.geologicacarpathica.com*). Analyses of rock-forming minerals of melilitic rocks from the Ploučnice River region published by Ulrych et al. (1986, 1988, 1991, 1994) and from Vogtland published by Abratis et al. (2009) were used for comparison. Mutual spatial relationships of selected fundamental minerals as shown in optical micrographs and back-scattered electron images are presented in Supplement 2.

Olivine was observed prevalently in the form of weakly corroded euhedral to subhedral hopper-like rarely aggregated phenocrysts passing to rare grains of groundmass size. In scoria and lapilli from the Železná hůrka and Komorní hůrka cinder cones, olivine occurs as corroded (micro)phenocrysts with tiny glass inclusions. Titanian magnetite grains often concentrate at the contact between olivine phenocrysts and groundmass.

Phenocrysts exhibit a normal type of compositional zoning with subhedral Mg-rich cores and Fe-rich rims. Forsterite (Fo) contents usually vary between 82 and 89 mol %. Besides typical magmatic olivine, variably corroded crystals with high Fo (~90; up to 92 mol %) were found in cores of phenocrysts, rarely as independent xenocrystic grains. Compositional trends of olivine phenocrysts and xenocrysts are visible in the 100 Mg/(Mg+Fe) vs. NiO diagram (Fig. 2). Olivine xenocrysts show markedly elevated NiO contents (up to 0.55 wt. %), whereas phenocrysts follow a fractionation trend characterized by decreasing NiO and MgO contents from cores to rims. Low CaO contents (usually below 0.2 wt. %) are characteristic for xenocrysts.

Monticellite occurs as rims of olivine and rarely also occurs as individual grains in ultramafic lamprophyres (polzenites) and olivine melilitolite of the Osečná Complex. Additionally, this mineral was identified in the altered polzenite from Jedlová railway station.

Clinopyroxene forms (i) subhedral prismatic (micro)-phenocrysts or (ii) subhedral to anhedral grains and columns forming the prevailing part of the groundmass. In rare cases clinopyroxene rims olivine. Clinopyroxene analyses correspond mostly to aluminian, ferrian, ±ferroan, ±titanian, ±chromian, subsilicic diopside following the nomenclature of Morimoto (1988); see Fig. 3. Phenocrysts show different combinations of concentric and rare sector-zoning (e.g. lava from Komorní hůrka and scoria from Železná hůrka). The majority of crystals display normal compositional zoning: Ti, Al, and Fe^{3+}contents and $^{[4]}Al$ /$^{[6]}Al$ ratios increase whereas Si, Mg and Na contents decrease from core to rim. Sodium content increases from centre to rim (Na_2O from 0.26 to 0.44 wt. %) in rare late magmatic clinopyroxenes in scoria from Železná hůrka whereas those in lava from the Komorní hůrka show opposite trends (from 0.64 to 0.24 wt. %). The analysis of a clinopyroxene phenocryst from Krkavčí skála provided an exceptionally high K_2O content of 0.23 wt. %.

Rhönite was found in homogeneous microphenocrysts spatially associated with clinopyroxene clusters in the melilite olivine nephelinite of Krkavčí skála and tuffite of Příšovská homolka.

Melilite occurs mostly in the form of lath-shaped 10–400 μm thick and 0.1–1.3 mm long subhedral to euhedral microphenocrysts in the studied melilitic rocks. Sector zoning is locally present (e.g. scoria from Železná hůrka). Laths of melilite are surrounded by nepheline and rimmed by tiny magnetite and

Table 1: Geological and petrographic characteristics of melilitic rocks from the Bohemian Massif. **Data sources:** 1 — this study, 2 — Ulrych et al. (2011), 3 — Ulrych et al. (2000b), 5 — Ulrych et al. (2008).

Age	Data sources	Samples	Location (and geological setting)	Latitude, N Longitude, E	Rock type	Petrographic characteristic
Early to Late Pleistocene	2, 1	68, Ul-Pr-2, 6.13.	Komorní hůrka Hill at Františkovy Lázně (conduit and porous lava flow of the cinder cone)	50°06'02" 12°20'14"	Nepheline olivine melilitite	Massive, holocrystalline, microporphyritic with aphanitic groundmass. Phenocrysts: olivine Fo_{89-74}, clinopyroxene. Groundmass: nepheline, melilite, (phlogopite in 6/13 only), Cr–Al-spinel, magnetite, apatite
	2	69	Komorní hůrka Hill at Františkovy Lázně (vesiculated lapilli (25×15 ×10 mm) in bedded scoria)	50°06'02" 12°20'18"	Haüyne-bearing olivine melilitite	Porous, hemicrystalline, numerous phyllite xenoliths. Microphenocrysts: olivine, clinopyroxene, melilite, haüyne, nepheline, magnetite, Cr–Al-spinel
	2	67/1, 2, 3, 4	Železná hůrka Hill near Cheb (coarse-grained spatter layer of cinder cone)	49°59'31" 12°26'35"	Haüyne-bearing olivine melilitite	Highly vesiculated scoria layer, porous, hemicrystalline, rare peridotite xenoliths. Microphenocrysts: olivine, Fo_{85-75}, clinopyroxene. Groundmass: olivine, clinopyroxene, melilite, haüyne, nepheline, magnetite, Cr–Al-spinel, apatite, glass. Megacrysts: olivine, clinopyroxene, phlogopite, amphibole
Mid Eocene to Late Miocene	2	Z-16	Český Chloumek, abandoned quarry (dyke)	50°07'09" 13°56'56"	Melilite-bearing olivine nephelinite to olivine nephelinite	Massive, holocrystalline, porphyritic with aphanitic groundmass. Phenocrysts: olivine Fo_{85-80}, clinopyroxene. Groundmass: clinopyroxene, melilite, nepheline, haüyne?, magnetite, apatite, glass
	3	WB-22/1, 3, 8	Podhorní vrch, abandoned quarry (lava flow)	49°58'28" 12°46'02"	Olivine nephelinite	Massive, holocrystalline, porphyritic with aphanitic groundmass. Phenocrysts: olivine Fo_{85-80}, clinopyroxene. Groundmass: clinopyroxene, nepheline, magnetite, apatite
	3	WB-22/4, 5, 6, 7	Podhorní vrch, abandoned quarry	49°58'28" 12°46'02"	Pegmatoids of ijolite to turjaite composition in olivine nephelinite	Coarse-grained (2–10 mm) formed by nepheline + diopside + melilite/leucite, sanidine ± olivine, magnetite, apatite, sodalite clinopyroxene > melilite (leucite) > sodalite > magnetite
	2	Ul-Pr-12	Příšovská homolka Hill at Příšov near Plzeň, abandoned quarry (relicts of an exhausted dyke cutting the tuff)	49°49'05" 13°17'43"	Nepheline basanite	Massive, hemicrystalline?, porphyritic with aphanitic groundmass. Phenocrysts: olivine (altered), clinopyroxene. Groundmass: clinopyroxene, sanidine to anorthoclase, magnetite, apatite
	1	7.13.	Krkavčí skála Hill at Sebuzín, (morphologically positive outcrop of the dyke (length ~150 m))	50°35'09" 14°4'47"	Melilite-bearing olivine nephelinite in nepheline basanite	Massive, holocrystalline, porphyritic with aphanitic groundmass. Phenocrysts: olivine Fo_{85-80}. Groundmass: clinopyroxene, rhönite, nepheline, magnetite, apatite, glass
	1	8.13.	Krkavčí skála Hill at Sebuzín, (boulders; host rock of melilite-bearing olivine nephelinite)	50°35'07" 14°4'43"	Nepheline basanite	Massive, holocrystalline, porphyritic with aphanitic groundmass. Phenocrysts: olivine Fo_{80-78}, clinopyroxene. Groundmass: clinopyroxene, nepheline, phlogopite, magnetite, apatite
	2	Ul-Pr-4	Pohoř Hill at Odry (dyke (length ~600 m))	49°39'05" 17°50'56"	Melilite-bearing olivine nephelinite	Massive, holocrystalline, porphyritic with aphanitic groundmass. Phenocrysts: olivine Fo_{85-88}, clinopyroxene. Groundmass: clinopyroxene, olivine, melilite, nepheline, haüyne, magnetite, apatite, glass
Late Cretaceous to Paleocene	5	POL-2, 10, 15, 119	Osečná Complex (in boreholes only) (hidden lopolith-like (sill) intrusion (20 to 60 m)) Contains numerous:		Olivine melilitolite	Massive, medium-grained to porphyritic, nepheline, melilite, phlogopite ± sodalite, zoned spinels, apatite
		POL-69, 70	— pegmatoid pods and dykes		Leuco-olivine melilitolite	Coarse-grained olivine melilitolite enriched in nepheline, phlogopite, garnet, apatite, spinels
		POL-71	— ijolite dykes		Ijolite to turjaite	Medium-grained rich in nepheline, clinopyroxene, carbonate with minor pectolite, phlogopite, melilite, garnet, spinels, apatite
		POL-3, 69, 71	— glimmerites pods		Phlogopitite	Olivine melilitolite sunbstantially enriched in phlogopite and garnet
	5	POL-12, 21, 26, 27, 34, 37, 57, 1, 14, 4, 13, 18, 39, 9	Osečná Complex (dykes)		Ultramafic lamprophyres-polzenites	Massive, porphyritic mostly pyroxene-free, nepheline, melilite, phlogopite ± sodalite, zoned spinels, apatite, rarely clinopyroxene
	5	POL-20, 23, 28, 29, 40, 59	Osečná Complex (dykes)		Melilite-bearing olivine nephelinite to olivine melilitite	Massive, porphyritic clinopyroxene, nepheline, melilite, phlogopite ± sodalite, zoned spinels, apatite
	1	POL-181	Jiřetín pod Jedlovou, abandoned quarry near the railway stop Jedlová (dyke)	50°33'06" 13°51'41"	Ultramafic lamprophyre-polzenite (altered)	Massive, holocrystalline, porphyritic with aphanitic groundmass. Phenocrysts: olivine Fo_{88-82}, clinopyroxene. Groundmass: clinopyroxene, phlogopite, nepheline, melilite?, phlogopite, magnetite, apatite
	1	POL-182, 183	unnamed elevation near Stožec Hill at Jiřetín pod Jedlovou (xenoliths in a volcanic breccia filing a chimney)	50°33'06" 13°51'41"	Ultramafic lamprophyre-polzenite (altered)	Massive, holocrystalline, porphyritic with aphanitic groundmass. Phenocrysts: olivine Fo_{88-82}, clinopyroxene. Groundmass: clinopyroxene, phlogopite, nepheline?, magnetite, apatite

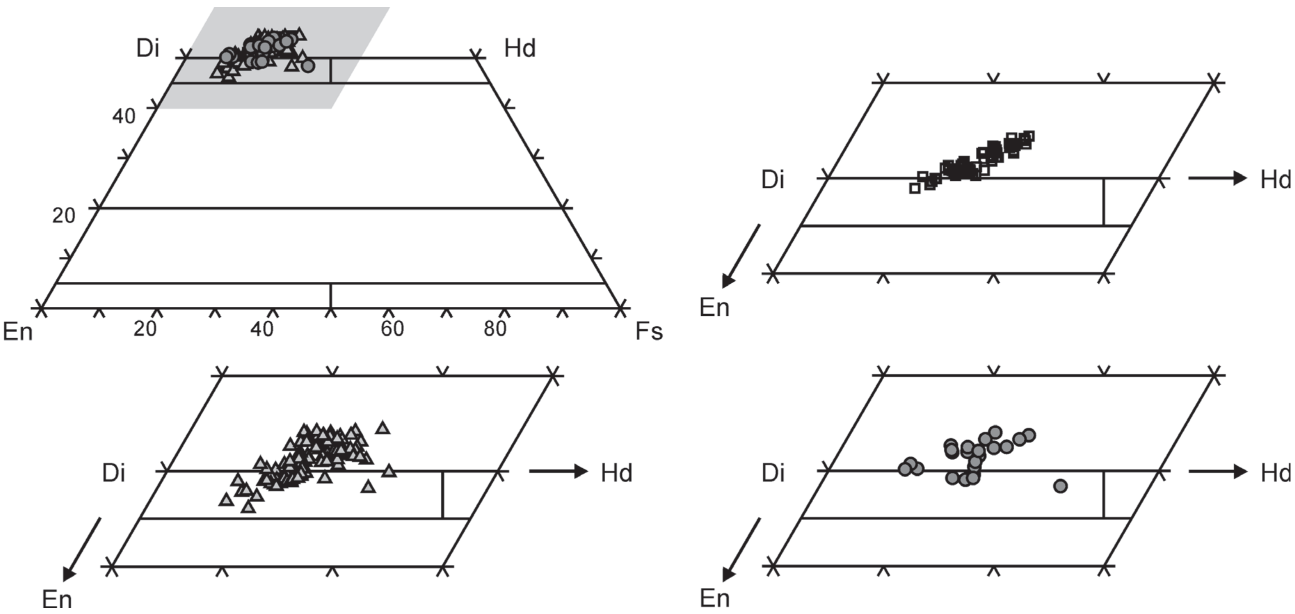
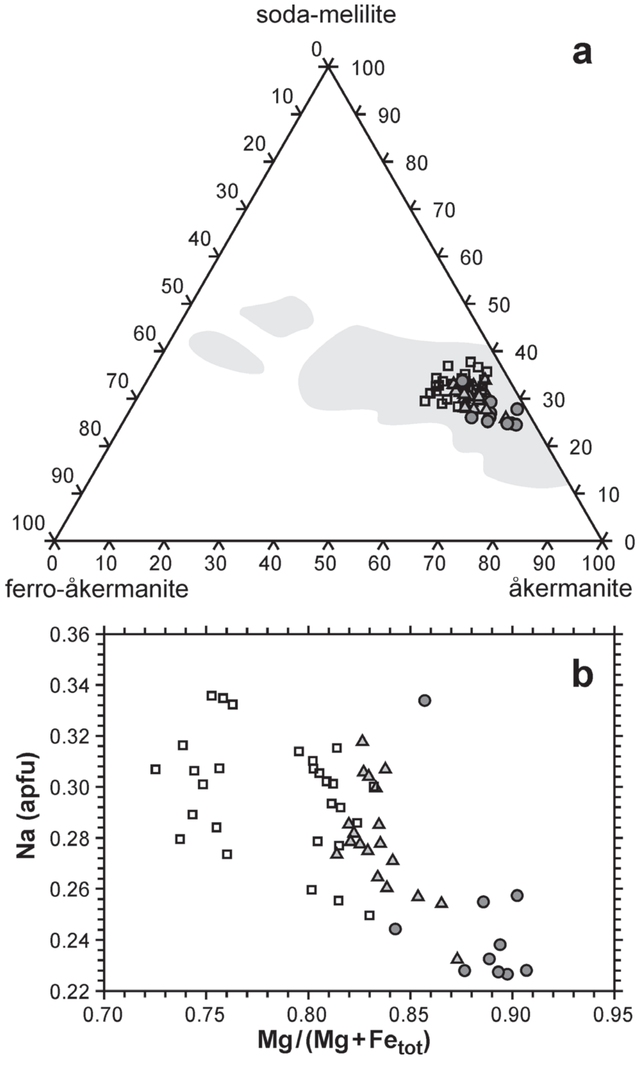


Fig. 3. Clinopyroxene from melilitic rocks of the Bohemian Massif in the quadrilateral diagram of Morimoto (1988). Symbols as in Fig. 2.



rarely perovskite grains. Their bundles in the groundmass follow the fluidal arrangement in some cases. A peg structure of melilite is emphasized in melilitic rocks from the Osečná Complex and Pohoř only in association with the late-magmatic hydrothermal phase (Ulrych et al. 1991).

The studied melilites show a narrow variation in chemical composition. Dominant end-members of these melilites are åkermanite and soda-melilite accounting for 80 mol % or more. The contents of the soda-melilite component are higher in melilites of the youngest rocks and lower in Upper Cretaceous to Paleocene rocks. Other components are less important, yet ferro-åkermanite displays the highest contents among them in general (Fig. 4a). Aluminium content in T1 site is high, but does not attain the level substantiating the presence of alumo-åkermanite (Fig. 4a). The studied melilites also commonly show a zoning pattern characterized by an increase of the soda-melilite component and Al content and a decrease of Mg from core to rim. The Na vs. Mg/(Mg+Fe) ratio (Fig. 4b) shows a separation of melilites into several groups, partly correlating with age.

Nepheline, haüyne and **sodalite** are the dominant feldspathoids of groundmass, yet they rarely also form microphenocrysts.

Nepheline is a common feldspathoid of the melilitic rocks studied. It occurs as rare microphenocrysts and/or anhedral fillings/grains in groundmass rich in Na_2O. It locally replaces melilite. However, it is missing or very rare in scoria from

Fig. 4. Melilite from melilitic rocks of the Bohemian Massif in the åkermanite–ferro-åkermanite–soda-melilite (mol %) diagram (**a**). Shaded regions illustrate the composition of melilites from common volcanic rocks as defined by El Goresy & Yoder (1974). Diagram Na vs. Mg/(Mg+Fe) (**b**) shows separation of analytical data into several groups correlated partly with the age. Symbols as in Fig. 2.

the Komorní and Železná hůrka. End-members in the Ne–Ks–An–Qz tetrahedron were recalculated adopting a procedure described in Blancher et al. (2010). The studied nephelines are chemically quite variable; the content of nepheline end-member varies between 65 and 83 mol %, the content of kalsilite component between 9 and 29 mol %, silica end-member between 0.5 and 9 mol %, and anorthite component was found to be between 0 and 11.5 mol %. The highest chemical variability was recorded for Upper Cretaceous–Paleocene rocks; Pleistocene volcanic rocks display the lowest variability (Fig. 5). Projection onto the Ne–Ks–Qz plane shown in Fig. 5 demonstrates that nephelines are mostly Ne-depleted with a considerable number of data plotting away from the "Barth join" representing natural nephelines (Dollase & Thomas 1978). The temperatures of nepheline crystallization concentrated mostly between 500 and 700 °C were estimated from the isotherms defined in Hamilton (1961).

Analyses of **sodalite group** minerals are shown in a diagram after Lessing & Grout (1971) in Fig. 6. In microphenocrysts, haüyne forms the centres being rimmed by sodalite on margins. The intermediate members chemically close to noseane are present in the olivine melilitolites and micromelilitolites of the Osečná Complex (Ulrych et al. 1991) and melilitic pegmatoids of the Podhorní vrch volcano (Ulrych et al. 2000b). Corroded and chemically heavily altered haüyne microphenocrysts are dispersed as a minor phase in groundmass of scoria and lapilli from the Železná hůrka and Komorní hůrka volcanoes; haüyne is missing in the lava from the latter locality. Haüyne has been also described as microphenocrysts from melilitic rocks from Vogtland by Abratis et al. (2009).

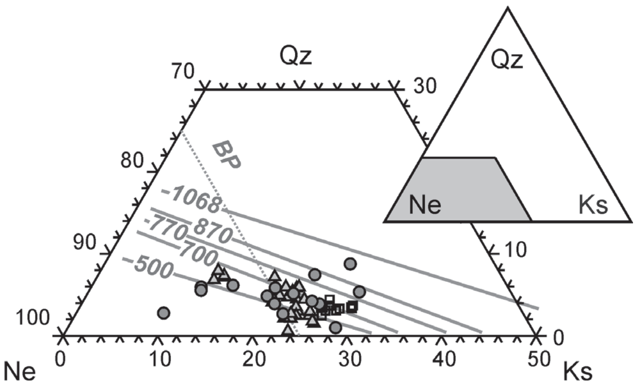


Fig. 5. Nepheline from melilitic rocks of the Bohemian Massif in the Ne–Ks–Qz diagram (in mol %). The dashed line identifies "Barth join" defined by Dollase & Thomas (1978). Tie-lines illustrate limits of nepheline solid solution at the shown temperatures and approximate limit at 1068 °C and 10 MPa (modified after Hamilton 1961 and Blancher et al. 2010). Symbols as in Fig. 2.

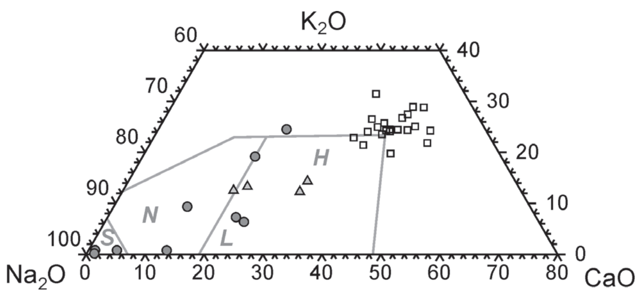


Fig. 6. Sodalite-group minerals including their alteration products from melilitic rocks of the Bohemian Massif in K_2O–Na_2O–CaO diagram. Field for haüyne (**H**), sodalite (**S**), nosean (**N**), and lazurite (**L**) after Lessing & Grout (1971). Symbols as in Fig. 2.

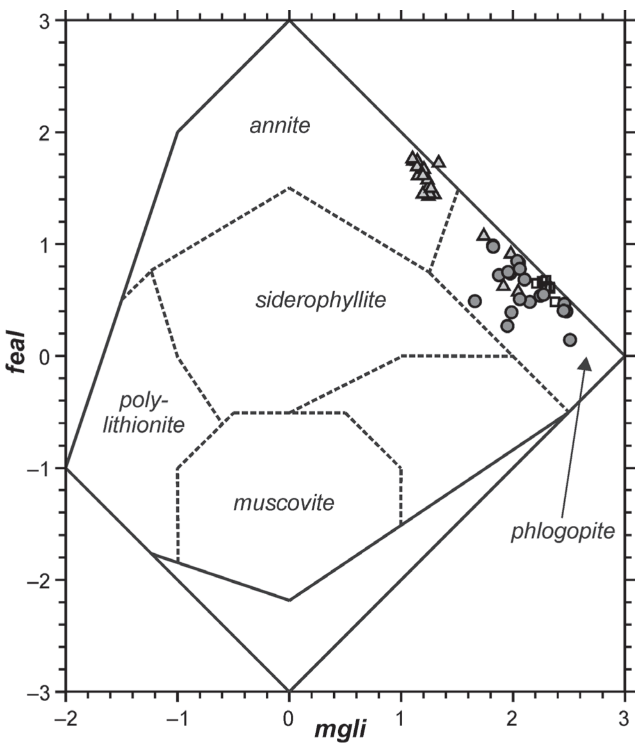


Fig. 7. Classification diagram of Tischendorf et al. (2007) for micas from melilitic rocks of the Bohemian Massif. Symbols as in Fig. 2.

Following the classification diagram of Tischendorf et al. (2007), the studied **micas** belong to the phlogopite–annite series (Fig. 7). They occur rarely as irregular fragments of lamellae in melilite-bearing olivine nephelinites. Abratis et al. (2009) reported subhedral microphenocrysts of phlogopite from similar melilitic rocks from Vogtland. Phlogopite was also found as uneven fragments in the porous upper part of the Komorní hůrka lava flow, concentrated along the rims of olivine microphenocrysts. These phlogopites are generally high in Mg (average Mg# = 0.78), Al (~1.7–3 apfu with average ~2.6) and low in Si (~4.5–5.8 apfu with average ~5.3; see Fig. 8, Supplement 1).

Phlogopite is present in substantial amounts in the groundmass of olivine melilitolites and polzenites of the Osečná Complex. At this locality, phlogopite occurs in at least two generations, which differ in composition (Pivec et al. 1998). Early phlogopite is characterized by high Mg# values (Mg/Mg + Fe; ~0.9) and low Ba and Ti contents. It is partly replaced by newly formed phlogopite, which has a lower Mg# value (0.81–0.87) and high Ba and Ti contents. High BaO concentration (up to 16 wt. %) consistent with almost 50 mol % content of kinoshitalite end-member was observed mostly at the margins of phlogopite flakes from the Komorní hůrka lava.

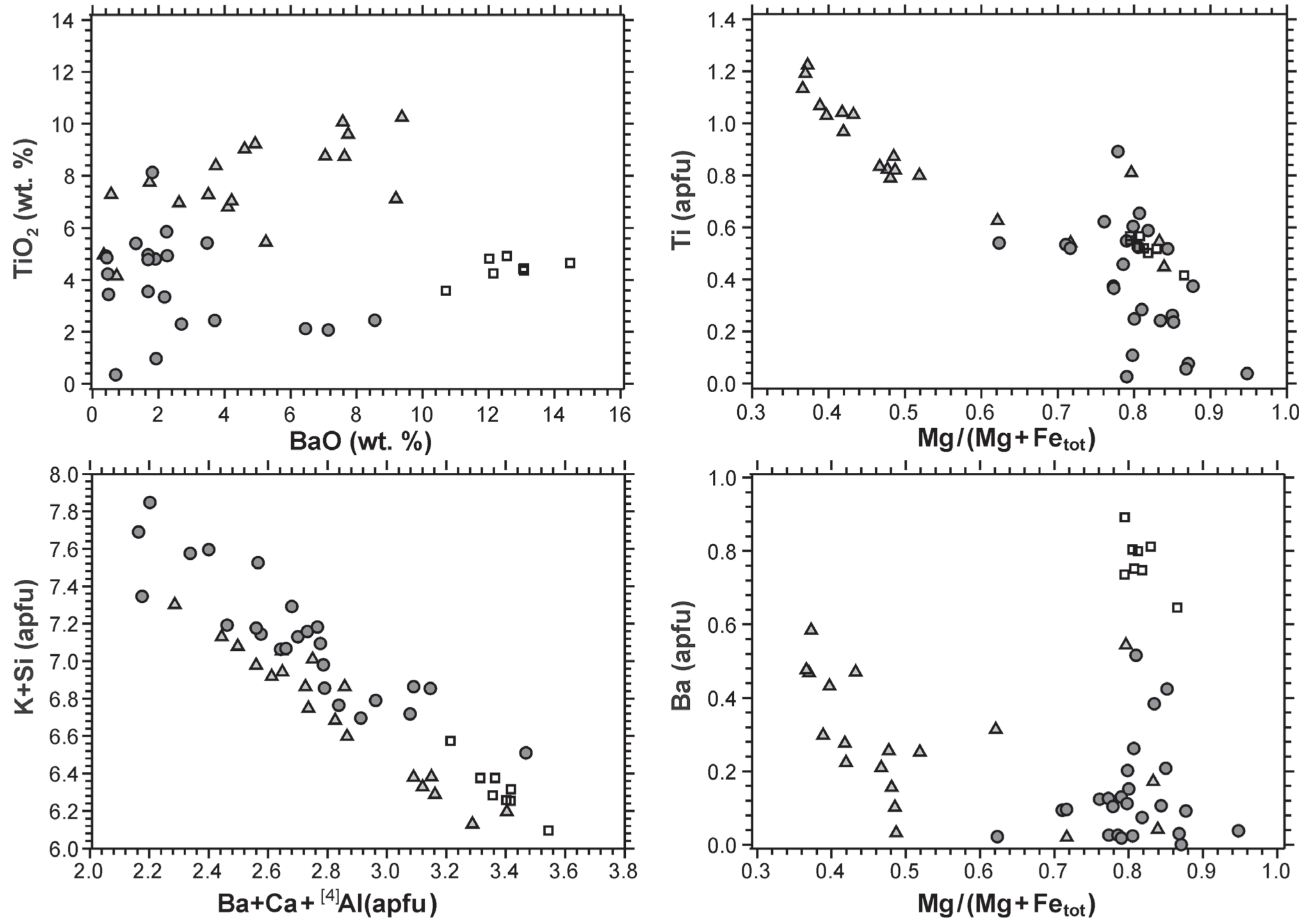


Fig. 8. Chemical composition of studied micas showing their compositional variability. Symbols as in Fig. 2.

Garnet occurs exclusively in olivine melilitolites, their pegmatoids and glimmerites of the Osečná Complex as a typical late-magmatic phase (Ulrych et al. 1994). Zirconium rich melanite cores are rimmed by oscillating zones of (F,OH)-bearing Ti-poor andradite, (F,OH)-bearing titanian andradite and Ti-rich andradite.

The **spinel-group minerals** of the melilitic rocks are represented by the spinel series, consisting of only slightly resorbed Cr–Al-spinel cores overgrown by Mg–Al-titanian magnetite (cf. Dunworth & Wilson 1998; Abratis et al. 2009), see Fig. 9. Titanian magnetite of several generations occurs mostly as tiny isometric euhedral, subhedral and more rarely anhedral grains often concentrated at the contact of olivine phenocrysts and groundmass. Cr–Al-spinel occurs as euhedral to subhedral microphenocrysts forming numerous inclusions in the olivine phenocrysts. Abratis et al. (2009) reported a similar spinel-group minerals association from melilitic rocks from Vogtland, and Seifert et al. (2008) from Görlitz and Zeughausgang. Spinel grains from olivine melilitolite, polzenite and melilite-bearing olivine nephelinite of the Osečná Complex show two distinct zones; an (Mg,Fe)–Al-chromite core and an Al–Ti-magnetite margin. Spinels of the olivine micro-melilitolites display three zones with a transitional "pleonaste" intermediate zone between core and margin (Ulrych et al. 1986).

Perovskite occurs very rarely (e.g. Pohoř) in the melilite-bearing olivine nephelinites and olivine melilitites, or is completely missing. Numerous subhedral to euhedral perovskite crystals occur only as microphenocrysts (3–5 vol. %) in rare olivine melilitite from Vogtland (Abratis et al. 2009). Abundant perovskite (1–5 vol. %) with normal zoning is present in all melilitic rocks of the Osečná Complex (Ulrych et al. 1988). The most abundant late-magmatic perovskite is characterized by high Nb_2O_5 (up to 1.2 wt. %) and REE (up to 1.3 wt. %) contents in olivine melilitolite pegmatoids. The postmagmatic light-coloured perovskite overgrowths and incompletely rims titanian magnetites. It is very low in incompatible elements, e.g. Nb_2O_5 content is about 0.05 wt. %.

Geochemical characteristics

Whole-rock geochemistry

Major and trace element analyses of the melilitic rocks from the Bohemian Massif are given in Supplement 3. The low SiO_2 and Al_2O_3, medium alkali ($Na_2O > K_2O$) and high CaO and MgO contents correspond to common geochemical characteristics for melilitic rocks (e.g. Brey 1978; Dawson et al. 1985; Dunworth & Wilson 1998; Keller et al. 2006; Melluso et al. 2011). The lowest SiO_2 contents were found in majority of rocks from the Osečná Complex (down to 29.9 wt. %) whereas the highest SiO_2 concentrations were

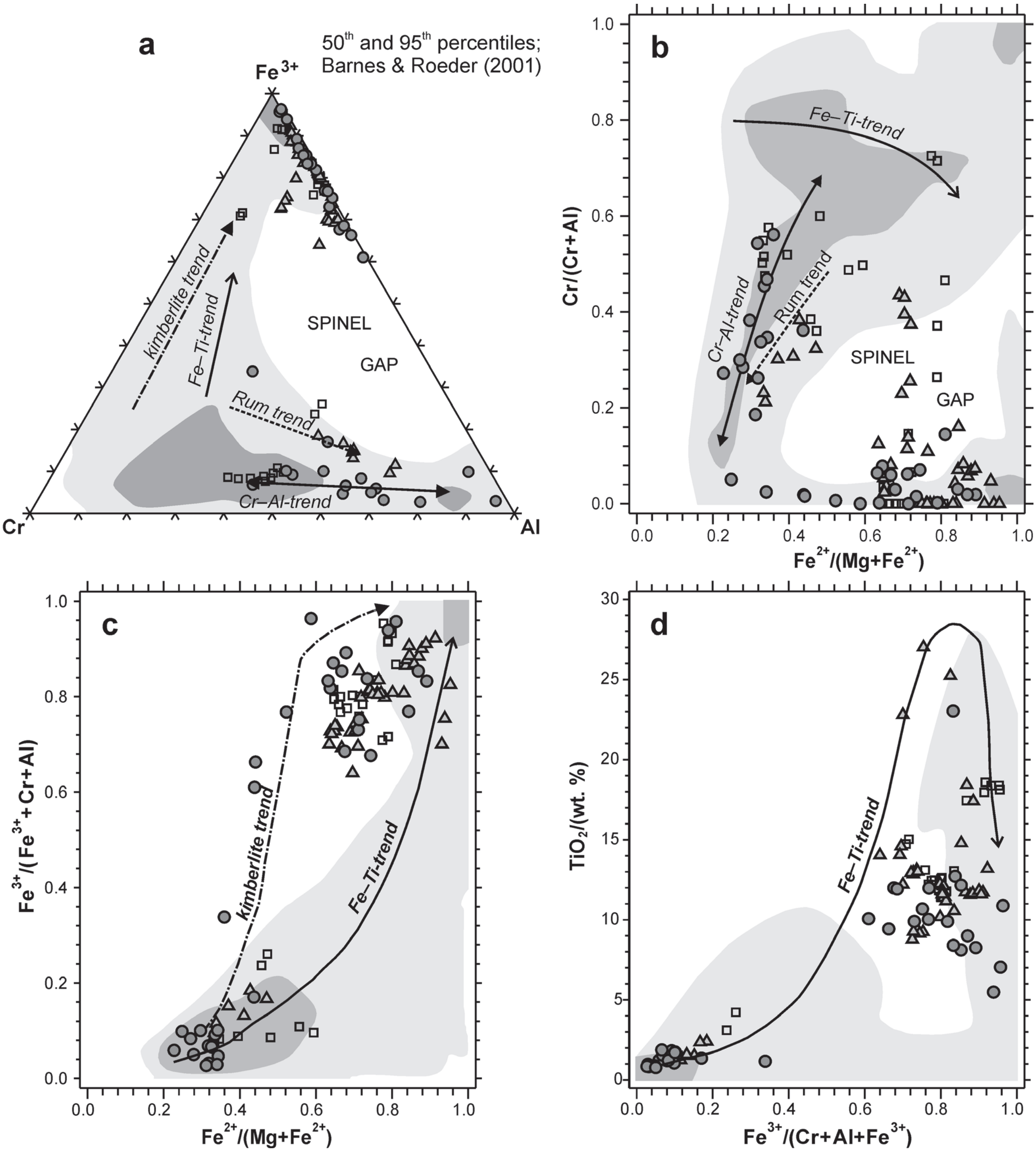


Fig. 9. Spinel-group minerals from melilitic rocks of the Bohemian Massif displayed in plots after Barnes & Roeder (2001) compared to the most common terrestrial spinel compositions. Symbols as in Fig. 2.

met in the Železná hůrka scoria (up to 41.6 wt. %). On the contrary, CaO contents are highest in rocks of the Osečná Complex (up to ~24.7 wt. %), while the lowest values occur in the scoria of the Železná hůrka (~12.3 wt. %). In the TAS (total alkali–silica) diagram of Le Maitre (2005) (Fig. 10), the studied melilitic rocks plot to the lower part of the foidite field except for the melilite-bearing pegmatite in olivine nephelinite from Podhorní vrch, which is very rich in alkalies (Na_2O+K_2O ~9.2 wt. % with Na_2O/K_2O ~3.2). The melilitic rocks are ultramafic, larnite-normative and contain the primary olivine+nepheline+melilite/clinopyroxene+spinel±carbonate mineral association. High Mg# (Mg# = [100×Mg/(Mg + Fe^{2+})], for Fe^{3+}/Fe = 0.15) ranges between ~58 to ~79. The samples are characterized by wide variations in the contents of compatible elements like Cr (44–969 ppm), Ni (57–370 ppm), Co (20–63 ppm) and Sc (10–68 ppm), see Supplement 3. Nevertheless, minor geochemical differences exist among the individual groups of the melilitic rocks of different age. The Pleistocene and Eocene to Miocene volcanic rocks are characterized by relatively low Mg# values (<74) and compatible

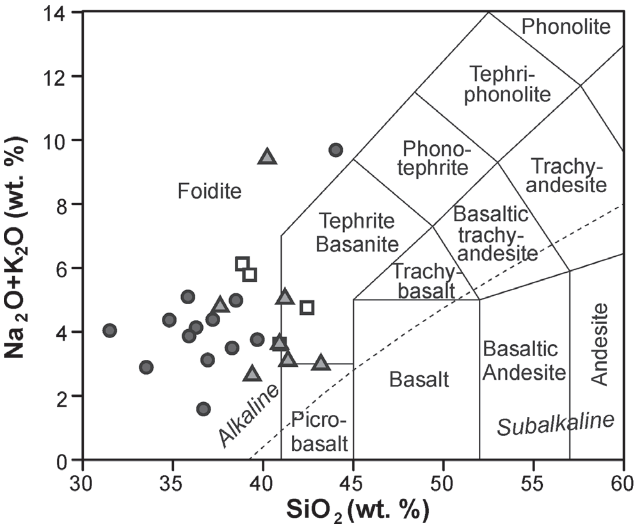


Fig. 10. TAS (total alkali-silica diagram — Le Maitre 2005) for the melilitic rocks of the Bohemian Massif. Symbols as in Fig. 2.

element concentrations whereas the Upper Cretaceous to Paleocene rocks have the composition of primitive ultramafic rocks with a wide scatter, mostly high values of Mg# (up to ~79) and compatible element contents (Supplement 3). The melilite-bearing olivine nephelinites to olivine melilitites of the Devil's Walls dykes associated with the Osečná Complex are characterized by particularly high Cr, Ni, Co and Sc contents compared to olivine melilitolites and ultramafic lamprophyres–polzenites of the Osečná Complex. Olivine-bearing melilitite (polzenite?) of the Pomological Garden in Görlitz has a similar geochemical signature (Mg# 78) to the rocks from the Osečná Complex while that from Zeughausgang is relatively more differentiated (Mg# 75) and enriched in incompatible trace elements (Seifert et al. 2008). In the major element variation diagram (Fig. 11), the studied rocks exhibit a wide scatter in the MgO vs. SiO_2 and MgO vs. CaO plots, yet a weak negative correlation exists between MgO and Al_2O_3. Furthermore, a prominent positive correlation exists between MgO and Cr, pointing to a similar compatible behaviour of these elements.

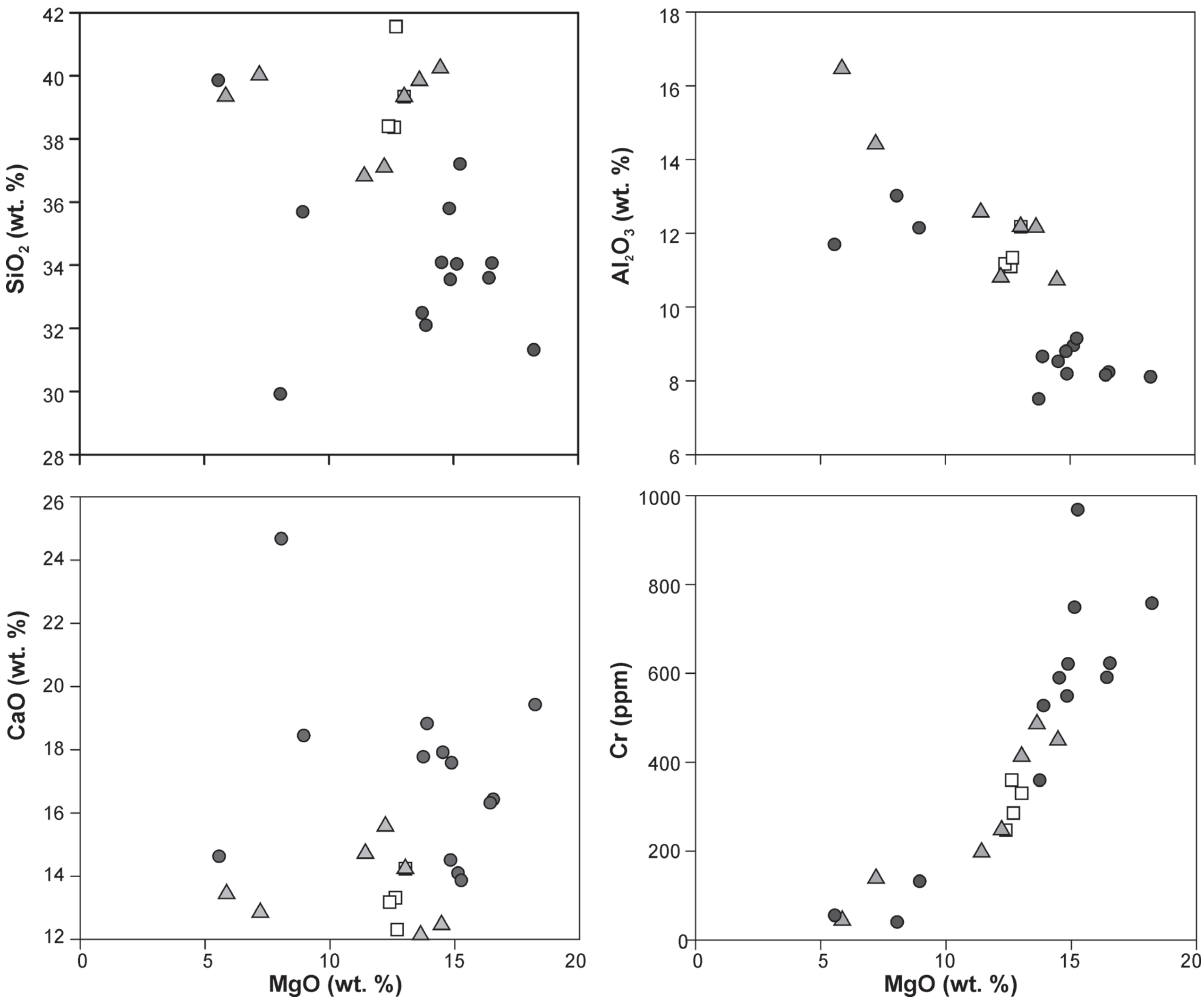


Fig. 11. MgO vs. SiO_2, Al_2O_3, CaO (all in wt. %) and Cr (ppm) variations for the melilitic rocks from the Bohemian Massif. Symbols as in Fig. 2.

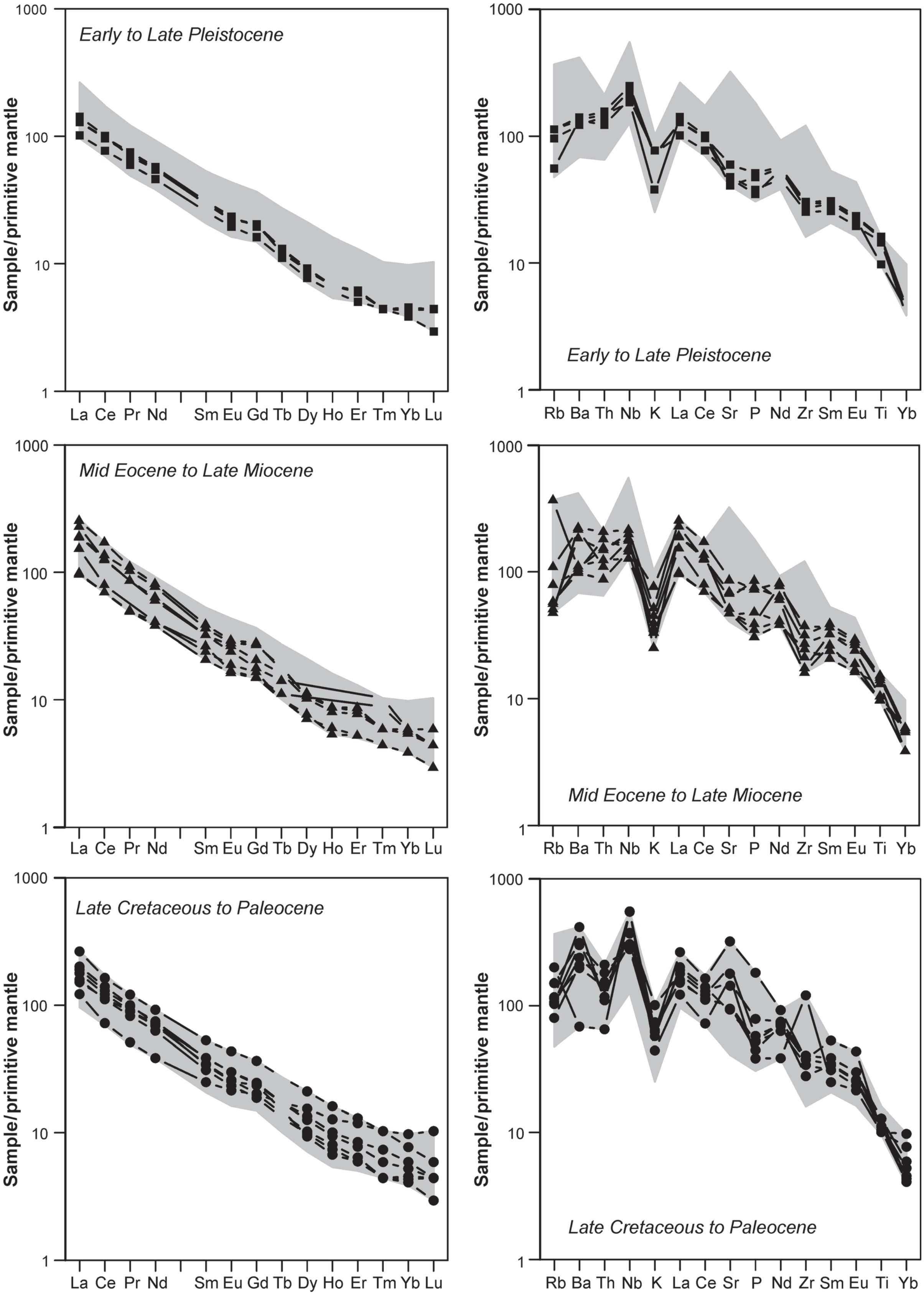


Fig. 12. Primitive mantle-normalized rare earth element (REE) and incompatible element diagrams for the melilitic rocks of three volcanic periods in which they occur in the Bohemian Massif. Normalizing values after McDonough & Sun (1995). Shaded field represents the compositional range of all rock types.

Primitive mantle-normalized incompatible trace element plots for the melilitic rocks of the Bohemian Massif are given in Fig. 12. The rare earth element (REE) patterns are similar for all rocks without any significant variations between those of different age, but La_N/Yb_N ratios are highly variable between 25 and 71 with the highest values found in the ultramafic xenoliths near Jiřetín pod Jedlovou. The highest concentrations of light REE (LREE) are associated with late-stage processes resulting in the formation of pegmatoids of the Osečná Complex, Podhorní vrch Hill and xenoliths from Stožec Hill near Jiřetín pod Jedlovou. While all melilitic rocks show distinct negative K anomalies, extended trace element patterns reveal some important differences between rocks of different age. The Eocene to Miocene volcanic rocks have trace element patterns similar to the Pleistocene rocks, however, they display much higher variation in concentrations and more pronounced negative Zr anomalies. On the other hand, the Upper Cretaceous to Paleocene rocks exhibit very high Ba, Nb and Sr contents producing significant positive anomalies in the trace element patterns (Fig. 12).

Sr/Nd isotopic compositions

The Sr/Nd isotopic ratios of the melilitic rocks from the Bohemian Massif (Table 2) are similar to those reported for melilitic rocks throughout the CEVP (e.g. Massif Central, Vosges, Urach, Hegau — Alibert et al. 1983; Hegner et al. 1995; Lustrino & Wilson 2007; see Fig. 13).

The Sr/Nd isotopic ratios of most melilitic rocks of the Pleistocene and the Eocene to Miocene periods show high $(^{143}Nd/^{144}Nd)_t = 0.51280–0.51287$ and low $(^{87}Sr/^{86}Sr)_t = 0.7034–0.7038$ ratios. However, the volcanic bomb (MR-1) from the Pleistocene maar locality of Mýtina (Ulrych et al. 2013) yielded high $^{87}Sr/^{86}Sr$ of ~0.7041. On the contrary, the Late Cretaceous to Paleocene melilite-bearing rocks (Osečná Complex) display a broad scatter of Sr/Nd isotopic ratios with $(^{143}Nd/^{144}Nd)_t$ between 0.51272–0.51282 and $(^{87}Sr/^{86}Sr)_t$ of 0.7033–0.7049. The melilite-bearing rocks of the Devil's Walls dykes with low $^{87}Sr/^{86}Sr$ (0.7033–0.7034) and transitional $^{143}Nd/^{144}Nd$ (0.51283) plot between the Upper Cretaceous to Paleocene rocks (Osečná Complex) and younger Pleistocene and Eocene to Miocene rocks; see Fig. 13.

Table 2: Representative Sr/Nd isotopic data for the melilitic rocks from the Bohemian Massif.

Data sources	Sample	Locality	Rock type	Age (Ma)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$(m.)*	$^{87}Sr/^{86}Sr$(t)	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$(m.)*	$^{143}Nd/^{144}Nd$(t)	εNd(t)⁺
Early to Late Pleistocene															
2	11.1.	Komorní hůrka Hill	HOM	0.43	59	953	0.179	0.703500 ± 11	0.703500	57.6	10.1	0.105	0.512864 ± 12	0.512864	4.4
2	12.2	Železná hůrka Hill	NOM	1.01	67.9	1183	0.166	0.703438 ± 10	0.703440	68.3	11.6	0.103	0.512868 ± 12	0.512867	4.5
Mid Eocene to Late Miocene															
1	5/13	Český Chloumek	MON–ON	16.5	65.4	955	0.198	0.703388 ± 10	0.703363	51.1	9.65	0.115	0.512836 ± 06	0.512815	5.1
2	10.2.	Příšovská homolka	MON?–ON	7.23	11.6	124	0.271	0.703556 ± 12	0.703550	11.8	18.1	0.0930	0.512829 ± 12	0.512825	3.8
1	3/13	Krkavčí skála Hill	MON	26.9	28.6	1773	0.0467	0.703396 ± 12	0.703378	102	15.8	0.111	0.512791 ± 06	0.512796	3.7
2	13.1.	Pohoř Hill at Odry	MON	32.3	30.5	1396	0.0632	0.703811 ± 11	0.703782	79.7	13.1	0.0992	0.512864 ± 06	0.512843	4.8
Late Cretaceous to Late Paleocene															
5	POL-119	Osečná borehole	OME	65	89.0	2210	0.120	0.703896 ± 11	0.704170	83.1	14.6	0.106	0.512823 ± 11	0.512778	4.4
5	POL-37	Děvín Hill at Hamr	UML–POL Vesecite type	68	83.0	2050	0.080	0.703417 ± 11	0.703300	115	18.2	0.0961	0.512797 ± 11	0.512756	3.9
5	POL-4	Zlatá výšina Height	UML–POL Modlibovite type	63	67.0	1040	0.040	0.704206 ± 10	0.704170	81.6	13.4	0.0991	0.512823 ± 11	0.512789	4.6
5	POL-9	Suchý Janův Důl	UML–CPOL Luhite type	63	21.0	1470	0.040	0.704244 ± 11	0.704210	87.6	12.9	0.0890	0.512754 ± 11	0.512716	3.2
5	POL-28	Great Devil's Dyke	MON	62	48.0	710	0.190	0.703522 ± 11	0.703350	46.0	8.48	0.111	0.512867 ± 11	0.512820	5.2
1	POL-181	Jiřetín pod Jedlovou	UML–POL	68.8	44.3	1102	0.116	0.703482 ± 9	0.703368	85.3	14.3	0.101	0.512783 ± 06	0.512738	3.7
1	POL-182	Stožec Hill	UML–POL	60.5	24.9	1709	0.0421	0.703409 ± 13	0.703373	105	16.1	0.0925	0.512766 ± 08	0.512729	3.3

Abbreviations: HOM — haüyne olivine melilitite, NOM — nepheline olivine melilitite, MON — melilite olivine nephelinite, ON — olivine nephelinite, OME — olivine melilitolite, UML — ultramafic lamprophyre, POL — clinopyroxene-free lamprophyre-polzenite, CPOL — clinopyroxene lamprophyre-alnöite ("polzenite").

Data sources: 1 — this study, 2 — Ulrych et al. (2013), 5 — Ulrych et al. (2008).

Explanations: * Error (2SE) refers to the last digits of ratio. ⁺εNd calculated with the parameter of Bouvier et al. 2008. The $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$ and $^{147}Sm/^{152}Sm = 0.56081$. The $^{143}Nd/^{144}Nd$ ratio of the in-house Ames Nd standard solution was 0.512142 ± 12 (n = 35), corresponding to 0.511854 in the La Jolla Nd reference standard material. The εNd(t) values were calculated with the parameters of Jacobsen & Wasserburg (1980). Present-day ratios for the chondrite uniform reservoir (CHUR) were: $^{147}Sm/^{144}Nd = 0.1967$, $^{143}Nd/^{144}Nd = 0.512638$ (Jacobsen & Wasserburg 1980; $^{143}Nd/^{144}Nd$ re-normalized to $^{146}Nd/^{144}Nd = 0.7219$). $^{87}Sr/^{86}Sr$ ratios were determined with a dynamic double mass method, monitoring ^{85}Rb, and normalized to $^{86}Sr/^{88}Sr = 0.1194$. The NIST 987 reference material yielded $^{87}Sr/^{86}Sr = 0.710230 \pm 11$ (n = 22).

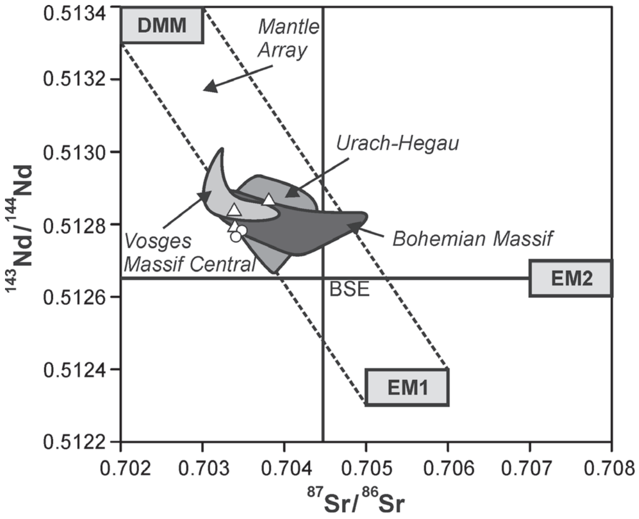


Fig. 13. Measured $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios of the melilitic rocks from the Bohemian Massif compared to data published by Lustrino & Wilson (2007), Haase & Renno (2008), Ulrych et al. (2008, 2013, 2014). Note the very large variation and in some cases very high $^{87}Sr/^{86}Sr$ indicating melting of enriched mantle sources. Fields for melilite-bearing rocks from Urach and Hegau (Alibert et al. 1983; Hegner et al. 1995; Lustrino & Wilson 2007) and Voges and Massif Central (Alibert et al. 1983) are plotted for comparison. **DMM** — Depleted MORB Mantle, **EM I** — Enriched Mantle type I, **EM II** — Enriched Mantle type II (from Lustrino & Wilson 2007). Symbols as in Fig. 2.

K/Ar geochronology

K/Ar ages, both new and previously presented (Ulrych et al. 2008, 2014), show that the melilitic rocks of the Bohemian Massif formed during the broad period from the beginning in the Late Cretaceous and continuing to the Pleistocene (Table 3). The melilite-bearing olivine nephelinite (26.9 ± 1.1 Ma) from Krkavčí skála at Sebuzín in the České středohoří Mts and olivine nephelinites from Podhorní vrch at Mariánské Lázně (18.3 ± 1.2 Ma — flow and 17.0 ± 0.8 Ma went) are the only newly dated rock samples of the Eocene to Miocene period. The olivine basanite intrusion from the Krkavčí skála is substantially younger (17.1 ± 1.0 Ma). The first K/Ar data from ultramafic lamprophyre (polzenite) from a quarry near the Jedlová railway station (68.8 ± 3.3 Ma) and a similar ultramafic xenolith in the pipe breccia from Stožec Hill (60.5 ± 3.3 Ma) in the Lusatian Fault area confirm their affinity to the pre-rift melilitic magmatism.

Discussion

Melilitic rock setting and age considerations

The melilitic volcanic rocks were formed in the Bohemian Massif over a wide time period of about 80 Ma. The formation of these rocks culminated during the initial pre-rifting Late Cretaceous to Paleocene period and in the late-rifting Pleistocene volcanic episode of the Cenozoic volcanism (Ulrych et al. 2011). The occurrence of melilitic rocks among volcanic rocks of the most widespread Eocene to Miocene syn-rift period is marginal. The volcanism of both periods when melilitic rocks predominantly formed is associated with junctions of the graben structures.

The setting of the Upper Cretaceous–Paleocene melilitic rocks of the Ploučnice River region represented exclusively by dykes and solitary lopolith (sill) are concentrated in the Osečná Complex associated with the intersection of the Ohře Rift and the regional Lužice Fault. The volcanism of this period predates the activation of the Ohře Rift and occurred in the rift external blocks of the graben, which formed later dur-

Table 3: Representative K/Ar isotopic age data for the melilitic rocks from the Bohemian Massif. **Abbreviations:** NOM — nepheline olivine melilitite, ON — olivine nephelinite, OB — olivine basalt, MON — melilite olivine nephelinite, OME — olivine melilitolite, UML — ultramafic lamprophyre, POL — clinopyroxene-free lamprophyre–polzenite, CPOL — clinopyroxene lamprophyre–alnöite (“polzenite”). **Data sources:** 1 — this study, 2 — Ulrych et al. (2013), 5 — Ulrych et al. (2008), 6 — Ulrych et al. (2014).

Data sources	Sample	Locality	Rock type	K (wt. %)	^{40}Ar (rad) cc STP/g	^{40}Ar (rad) (%)	Age ± 1σ (Ma)
Early to Late Pleistocene							
2	Ul-Pr-2	Komorní hůrka Hill	NOM	1.854	0.073×10^{-6}	20.8	1.01 ± 0.1
Mid Eocene to Late Miocene							
1	WB-22a	Podhorní vrch Hill	ON — feeding channel	0.722	4.778×10^{-7}	45.2	17.0 ± 0.8
1	WB-22b	Podhorní vrch Hill	ON — flow	1.180	8.405×10^{-7}	23.7	18.3 ± 1.2
2	10.1.	Příšovská homolka	MON?–ON — tuff	0.671	0.154×10^{-6}	33.3	5.89 ± 0.30
2	10.2.	Příšovská homolka	MON?–ON	0.333	0.094×10^{-6}	13.2	7.23 ± 0.77
1	3/13	Krkavčí skála Hill	MON–ON	1.340	1.413×10^{-6}	56.8	26.9 ± 1.1
1	4/13	Krkavčí skála Hill	OB	0.896	5.975×10^{-7}	26.2	17.1 ± 1.0
2	13.1.	Pohoř Hill at Odry	MON	0.775	0.981×10^{-6}	51.1	32.3 ± 1.4
Late Cretaceous to Paleocene							
5	POL-119	Osečná, borehole	OME	1.829	4.691×10^{-6}	56.7	64.8 ± 2.6
6	POL-57	Děvín Hill at Hamr	UML–POL Vesecite type	0.971	3.067×10^{-6}	47.7	79.5 ± 3.5
6	P-2	Modlibohov	UML–POL Modlibovite type	1.318	3.636×10^{-6}	40.9	69.5 ± 3.0
6	P-10	Luhov	UML–CPOL Luhite type	1.102	2.672×10^{-6}	43.9	61.3 ± 2.6
5	POL-28	Great Devil’s Dyke	MON	1.241	3.053×10^{-6}	66.9	62.2 ± 2.4
6	P-4	Mazova horka Hill	MON	1.142	1.142×10^{-6}	60.7	61.9 ± 2.4
1	POL-181	Jiřetín pod Jedlovou	UML–POL	1.174	3.200×10^{-6}	37.1	68.8 ± 3.3
1	POL-182	Stožec Hill	UML–POL	0.745	1.783×10^{-6}	30.6	60.5 ± 3.3

ing the evolution of the rift system. A magmatic event related to the initial pre-rift period of Cenozoic rifting of the Bohemian Massif proceeded in the range of 80–59 Ma in the Ploučnice River region. On the basis of whole-rock K/Ar determinations, a number of authors (e.g. Lippolt 1983; Pivec et al. 1998; Ulrych et al. 2008, 2011, 2013) suggested that the intraplate volcanic cycle associated with the Alpine Orogeny already started in the Late Cretaceous.

The most voluminous syn-rift alkaline volcanism is associated with the main stage of the rifting and concentrates in the Ohře Graben. Individual melilitic dykes are only rarely present in the Ohře Rift, within the eastern shoulder of the Cheb–Domažlice Graben and its continuation in Vogtland and the Labe–Odra Fault Zone.

Cinder cones with melilitic scoria and lava products associated with the Early to Late Pleistocene final volcanic episode (1.0–0.26 Ma) occur in the Cheb Basin area where the thickness of the seismic lithosphere is reduced to ca. 80–90 km (Babuška & Plomerová 2010).

Prominent association of melilitic magmas with regional faults and block tectonics of the Bohemian Massif suggests reactivation of deep lithospheric fracture zones. Such old inhomogeneities may have facilitate the regional stress in intraplate settings and thus contribute to generation of magmatic processes — asthenospheric upwelling, ascent of magma and migration of late- and postmagmatic fluids (Adamovič & Coubal 1999). The space- and time-dispersed melilitic magmas of the Bohemian Massif (Table 4) were probably generated in specific conditions of adiabatic decompression melting of the mantle associated with asthenospheric upwelling, which might have been triggered by lithospheric extension (Wilson et al. 1995)

Melilitic magma generation and its sources

Melilitic magma is a typical small volume volcanic product characterized by its peculiar chemical composition (Dunworth & Wilson 1998). The geochemical signatures of the Late Cretaceous to Pleistocene melilitic rocks of the Bohemian Massif resemble those from continental intraplate settings of ECRIS in Western Europe (Alibert et al. 1983; Wilson et al. 1995; Dunworth & Wilson 1998; Lustrino & Wilson 2007). These rocks are commonly interpreted as near-primary melts originating by low degree melting of heterogeneous mantle sources, including both lithospheric and asthenospheric mantle components (Lustrino & Wilson 2007).

The chemical composition of the melilitic rocks of the Bohemian Massif fully corresponds to common features of melilitic melts characterized by low SiO_2, Al_2O_3, $Na_2O > K_2O$ contents accompanied by high CaO, MgO, and CO_2 contents as well as high (Ca+Na+K)/Al ratio (Wilson et al. 1995; Di Battistini et al. 2001; Keshav & Gudfinnsson 2004; Ulrych et al. 2008). High Mg# and broad variations in the contents of compatible elements were interpreted by Frey et al. (1978) to reflect primitive, near-primary upper mantle melts which typically underwent only limited low-pressure fractional crystallization.

Regardless of their age and place of occurrence in the Bohemian Massif, the melilitic rocks are enriched in both compatible and incompatible elements, which is a characteristic feature of melilitic rocks worldwide (Dunworth & Wilson 1998). The highest La_N/Yb_N ratios (~70) of xenoliths from Stožec Hill near Jiřetín pod Jedlovou are comparable with those of ijolite xenoliths (~55–65) from the Loučná–Oberwiesenthal Volcanic Centre associated with the Ohře Rift (Ulrych et al. 2005). The steep slope of the REE patterns and the high La_N/Yb_N ratios (~30–70) of the melilitic rocks, which are similar to those of OIB, indicate the presence of residual garnet in the source (Wilson et al. 1995; Dunworth & Wilson 1998; Lustrino & Wilson 2007). The enrichment in Nb relative to La and Th and an enrichment in La relative to Ce suggests that these rocks cannot be readily generated from a primitive mantle source but require a metasomatized source, enriched in strongly incompatible trace elements (Hofmann 1986). The distinct negative K, Rb and P anomalies on the primitive mantle-normalized incompatible element diagrams of the melilitic rocks have usually been interpreted as implying the presence of residual phlogopite and apatite within the mantle source (Wilson et al. 1995; Dunworth & Wilson 1998). Nevertheless, the interpretation of Dunworth & Wilson (1998) suggested that the relative K depletion in these rocks is in part due to the presence of carbonate in the mantle source, which enhances the stability of phlogopite (Rogers et al. 1992). This interpretation of the source of melilitic rocks seems to be realistic also in the Bohemian Massif.

Carbonate mantle metasomatism preferentially enriches LREE relative to Hf (e.g. Yaxley et al. 1991; Rudnick et al. 1993). The lower Hf/Sm ratio in the melilitic rocks (~0.3–0.6) compared to the primitive mantle (~0.70 — McDonough & Sun 1995) may thus suggest that the source of melilitic volcanic rocks can be modified by carbonate-rich melts. The variations of initial Sr isotopic ratios ($^{87}Sr/^{86}Sr = 0.7033–0.7049$) found in the Osečná Complex can also be interpreted as the result of the late-magmatic to postmagmatic hydrothermal alteration (Ulrych et al. 2008). The $^{87}Sr/^{86}Sr$ ratio ~0.7041 determined for the volcanic bomb from the Pleistocene maar locality of Mýtina may reflect contamination of the primary magmas by Variscan phyllites.

The Sr/Nd isotopic ratios of most melilitic rocks of the Pleistocene and the Eocene to Miocene periods suggest primitive mantle sources. The high positive initial ε_{Nd} values (3.2–5.1) of the melilitic rocks of the Bohemian Massif are interpreted as indications of the melting of depleted and moderately heterogeneous mantle sources precluding significant crust contamination.

The primitive nature of the chemical composition of the melilitite rock can be used to constrain the compositional characteristics of the mantle sources (e.g. Dawson et al. 1985; Dunworth & Wilson 1998; Keller et al. 2006; Lustrino & Wilson 2007; Melluso et al. 2011). The melilitic magma is generally believed to be formed by partial melting of a carbonated mantle peridotite/clinopyroxenite at the base of the lithosphere (the thermal boundary layer of Wilson et al. 1995; Dunworth & Wilson 1998). Similarly Brey (1978) and Keshav & Gudfinnsson (2004) concluded that melilitites and nephelinites are partial melts of carbonated lherzolites at 3 GPa (or higher). In the experiments of Gudfinnsson & Presnall (2005), the melilitite melts resembling natural me-

Table 4: Comparison of geological, petrographic and geochemical characteristics of melilitic rocks of the Bohemian Massif.

	Early to Late Pleistocene		Mid Eocene to Late Miocene				Late Cretaceous to Late Paleocene			
	Cheb Basin, western Bohemia		Ohře/Eger Rift	Cheb–Domažlice Graben, western Bohemia	Vogtland, Saxony	Labe–Odra Fault Zone, Silesia	Ploučnice River area, northern Bohemia		Lusatian Fault area, northern Bohemia	Saxony and Lusatia
							Osečná Complex	Devil's Dykes		
Data sources	2	2	1	1, 3	4	2	5, 6	5, 6	1	7
Age (Ma)	0.43	1.01–0.26	26.9	18.3–17.0 (ON)[c] 5.89 (MON?)[d]	Tertiary	32.3	61.1–79.5	59.2–63.6	60.5–68.8	71.3
Geological occurrence	scoria/lapilli	lava flow	dykes	dykes and flows (ON)	dykes	dykes	sill and dykes	dykes	dykes/xenoliths	dykes
Rock type	HOM	NOM	MON	ON/MON	MON and NOM	NOM to MON	OME/UML–POL	MON to NOM	UML–POL	POL/MON?
Texture	micro-porphyritic hemicrystalline[a]/ glassy matrix[b]	micro-porphyritic hemicrystalline matrix	micro-porphyritic hemicrystalline matrix	micro-porphyritic holocrystalline/ hemicrystalline matrix	micro-porphyritic holocrystalline matrix	micro-porphyritic holocrystalline matrix	medium-grained to porphyritic holocrystalline matrix	micro-porphyritic holocrystalline matrix	altered	(micro)-porphyritic holocrystalline matrix
Mineral assemblage										
clinopyroxene	common	common	common	common	common	common	no/very rare	common	common	common/very rare
melilite	common	common	common	rare	common	common	common	rare	altered?	common
nepheline	rare	common	common	common	common	common	common	common	altered?	rare
sodalite/hauyne	common	no	very rare	very rare	rare	common	very rare	rare	altered?	rare
monticellite	no	no	common	common	no	no	common	no	common	no
perovskite	no	no	no	no	common	no	common	very rare	very rare	very rare
Late-magmatic crystallization										
melilite in pegmatoids	no	no	no	rare in ON flow	no	no	common	very rare	no	no
ijolite dykes	no	no	no	no	no	no	rare	no	?	no
glimmeritization	no	no	no	no	no	no	common	very rare	no	no
Chemical composition										
Mg#	71–72[a] / 69[b]	68–70	66	69–70	?	71–72	71–81	69–78	76–79	75–78
SiO_2	40.1–43.9[a] / 38.4[b]	38.1–39.2	36.8–37.0	39.2–39.7	?	36.9–37.1	29.5–35.0	36.3–39.5	31.3–33.6	33.2–35.8
CaO	10.5–13.6[a] / 13.2[b]	12.9–13.6	14.7–15.2	15.1–15.8	?	14.5–15.6	14.9–21.1	12.1–15.7	16.3–19.4	14.5–17.9
Ni	180–280[a] / 160[b]	170–250	130–140	210–220	?	160–230	170–670	190–610	317–321	260–330
Cr	270–460[a] / 250[b]	290–400	140–200	220–410	?	250	420–890	580–1290	591–758	550–1180
REE	290–310[a] / 380[b]	370–410	620–640	280	?	480–520	340–650	220–500	453–581	320–480
La_N/Yb_N	28–29[a] / 31[b]	31–36	45–46	27	?	33–37	27–69	19–34	51–74	45
Isotopic composition										
$^{87}Sr/^{86}Sr(t)$	0.7035–0.7036	0.7034	0.7034	0.7034–0.7035[c]/ 0.7036[d]	0.7032–0.7036	0.7038	0.7033–0.7049	0.7033–0.7034	0.7034	?
$^{143}Nd/^{144}Nd(t)$	0.51285–0.51286	0.51287	0.51280	0.51282–0.51286[c]/0.51281[d]	0.51282–0.51287	0.51284	0.51272–0.51279	0.51281–0.51282	0.51273–0.51274	?

Abbreviations: HOM — haüyne olivine melilitite, NOM — nepheline olivine melilitite, MON — melilite olivine nephelinite, ON — olivine nephelinite, OME — olivine melilitolite, UML — ultramafic lamprophyres, POL — clinopyroxene-free lamprophyre-polzenite. Mg# = 100 Mg/Mg + Fe^{2+}, for Fe^{3+}/Fe = 0.15.
Data sources: 1 — this study, 2 — Ulrych et al. (2013), 3 — Ulrych et al. (2000b), 4 — Abratis et al. (2009), 5 — Ulrych et al. (2008), 6 — Ulrych et al. (2014), 7 — Seifert et al. (2008).
Notes: [a] — data for scoria, [b] — data for lapilli, [c] — data for olivine nephelinite, [d] — data for melilite olivine nephelinite.

lilitite whole-rock compositions were produced only at pressures <4 GPa; at higher pressures and temperatures they grade into kimberlitic melts. Modelling of the melting of the garnet lherzolite phase assemblage containing 0.15 wt. % CO_2 indicates that melilitites are produced by <1 % melting. In a discrimination diagram of MgO/CaO vs. SiO_2/Al_2O_3 of Gudfinnsson & Presnall (2005) our analytical data plot mostly to or close to a field for melilites near the 3 GPa isobar, yet some are located outside the field at considerably lower pressures. Falloon & Green (1990) estimated the formation of the olivine melilitite magma in equilibrium with garnet–phlogopite lherzolite within the dolomite stability field as 1020 °C at pressures >2.5 GPa. The parental magma of the region with prominent occurrence of melilitic rocks, the Osečná Complex, was probably derived from a heterogeneous veined(?) metasomatically enriched carbonate- and phlogopite-bearing garnet lherzolite (Ulrych et al. 2008). The geochemical and isotopic similarity of melilitic rocks occurring from the Late Cretaceous to the Pleistocene in the Bohemian Massif suggests that their magma originates from compositionally very similar mantle sources.

The $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios of the melilitic rocks are similar to common mafic volcanic rocks from the Ohře Rift. In contrast, the volcanic rocks in the Lusatian Fault area represented by the Osečná Complex display more radiogenic $^{87}Sr/^{86}Sr$ isotopic composition at given similar $^{143}Nd/^{144}Nd$, which can be explained by mantle sources with decoupled Sr/Nd isotopic compositions (e.g. due to selective modification by radiogenic $^{87}Sr/^{86}Sr$ hydrous and/or carbonate-rich fluid).

Crystallization history of melilitic rocks

The ultramafic melilitic volcanic rocks of the Bohemian Massif are characterized by the early-magmatic mineral association of olivine + melilite + Cr–Al-spinels ± clinopyroxene, which became unstable under later hydrothermal conditions. Products of the following main-magmatic crystallization are represented by alkali-rich phases such as nepheline + sodalite–haüyne and concentrate mostly in the groundmass. The residual fluids of the late-magmatic hydrothermal stage are enriched in large ion lithophile elements (LILE), high field strength elements (HFSE) and volatile elements. The number of rare minerals such as Ba-rich phlogopite, Zr-bearing (F,OH)-andradite, perovskite, calzirtite and bartonite crystallized in these stages (Ulrych et al. 1991).

Olivine with Fo contents of ~90 mol %, which we observed as corroded xenocrysts, is typical for mantle xenoliths from the Bohemian Massif (e.g. Konečný et al. 2006; Ackerman et al. 2007, 2013, 2014; Špaček et al. 2013). The Mg-rich olivine may therefore represent xenocrystic cores being overgrown by Mg-poorer olivine crystallizing from the melt.

The studied ***olivines*** exhibit the normal type of compositional zoning, which differs from the predominant reverse zoning recorded from melilitic rocks of the SW German Tertiary Volcanic Province (Dunworth & Wilson 1998). A characteristic feature observed both in crystallization cores of olivine phenocrysts and cores corresponding to relicts of xenocrysts is increased NiO concentration positively correlated with forsterite component content. High Ni contents in olivine can be explained by partial melting of pyroxenite-rich mantle domains (Sobolev et al. 2005).

Monticellite rims around olivine phenocrysts restricted to rare melilitic rocks from the Osečná Complex and Jiřetín pod Jedlovou area are related to a late-magmatic stage (cf. experimental data of Yoder 1979). The possible metasomatic origin is supported by increased LREE, U, Th, Hf contents (Ulrych et al. 1991).

Clinopyroxene phenocrysts of the melilitic rocks show similar core-to-rim compositional trends illustrated by simultaneous increase in Al and Ti content. This indicates similar alkalinity of studied melilitic volcanic systems, as the Al contents of the clinopyroxenes are in general directly proportional to the alkalinity of their parent melts (e.g. Mitchell & Bergman 1991). Typical "green cores" presented from Cenozoic basaltic rocks from, for example, Germany (Duda & Schmincke 1985; Abratis et al. 2009) have not been ascertained. Occurrence of resorbed cores of Cr-rich diopside characteristic for melilitic rocks of the SW German Tertiary Volcanic Province (Dunworth & Wilson 1998) implying their origin from mantle xenoliths was also not found at the localities studied. Dunworth & Wilson (1998) emphasized the role of the polybaric crystallization as the low-viscosity, high-temperature melilitic magmas are likely to have cooled rapidly as they rose through the relatively thick lithosphere of Central Europe.

Procedure proposed by Putirka (2008) suggests crystallization pressures for clinopyroxene in a wide range between 2 GPa for crystal cores and 1 GPa for groundmass microphenocrysts. These crystallization pressures are also supported by clinopyroxene phenocrysts from Krkavčí skála highly enriched in K_2O (up to 0.23 wt. %) since entry of potassium into clinopyroxene structure is pressure-dependent. According to the model of Soesoo (1997), most of the clinopyroxene analyses produce crystallization temperatures between 1000 and 1200 °C with majority of them clustering around the 1150 °C isotherm.

The analysed ***(Mg,Fe)–Al-chromite*** cores display high TiO_2 contents (0.8–2.4 wt. %), which are generally higher than those reported for primary spinel from peridotite xenoliths in the Bohemian Massif that usually have only 0.1 to 0.7 wt. % TiO_2 (Ackerman et al. 2007, 2014; Medaris et al. 2014). ***Titanian magnetites*** are characterized by variable contents of Cr_2O_3 (0.3–6.6 wt. %), MgO (2.0–9.3 wt. %) and Al_2O_3 (2.1–9.0 wt. %) (Sebuzín, Český Chloumek, Pohoř) manifesting most likely a remobilization from (Mg,Fe)–Al-chromite cores. In terms of the classification of Barnes & Roeder (2001), spinels follow mostly Cr-Al trend modified by incorporation of a component produced during fractionation or contamination by host magma.

Melilite belongs to minerals of the early-magmatic phase of the rock crystallization sequence. Moore & Erlank (1979) pointed out that melilite is unstable at the solidus temperature of mafic igneous rocks, although it may be preserved in volcanic rocks if cooling is rapid. The composition of the melilite from the melilitic rocks of the Bohemian Massif fits the trends delineated by El Goresy & Yoder (1974) for volcanic rock associations in general and particularly the trends observed for olivine melilites from, for example, the

Rhinegraben–Urach–Hegau volcanic areas presented by Dunworth & Wilson (1998).

Since the (Ca + Na + K)/Al ratio in the melilitic rocks we studied is high, melilite formation in them is most possibly associated with the carbonate–silicate-magma reaction processes as suggested by Dunworth & Wilson (1998) and Di Battistini et al. (2001). Mixing of mafic silicate magma and carbonate melt promoted melilite crystallization. The idea that melilitic rocks are derived from a Ca-rich melt produced at deep levels of the upper mantle has been formulated by Rass (2008).

Hamilton (1961; Fig. 5) calibrated the ***nepheline*** compositions so that they can be used as a temperature indicator. Nepheline crystallization temperatures in Pleistocene rocks cluster around 700 °C, most of Eocene to Miocene nephelines typically display slightly lower crystallization temperatures (below 700 °C) although those with higher Ne contents show the same temperatures of crystallization as younger nephelines. The most scattered values were recorded for nephelines from Upper Cretaceous to Paleocene rocks, which display crystallization temperatures in a wide range from below 500 °C up to almost the limit of nepheline stability at 1068 °C. According to Abratis et al. (2009), nephelines of melilite-bearing olivine nephelinites from Vogtland crystallized at temperatures of about 700 °C.

The studied rocks are characterized by the progressive manifestation of the low-temperature hydrothermal phase with changing activities of volatile components starting with high concentrations of chlorine to final phase with prevalence of sulphur in minerals of the ***sodalite group***. There is a chemical zoning present in the microphenocrysts following the pattern with increasing SO_3 content compensated by a decrease in Cl from core to rim.

Early ***phlogopite*** crystallized during the late-magmatic period. Intermediate phlogopite is the reaction product of postmagmatic fluids with olivine, monticellite and early phlogopite. The late-magmatic processes (glimmeritization) of the olivine melilitolite sill from Osečná result in the formation of bimineral rock — garnet glimmerites.

The youngest population of micas in polzenites is represented by rims of phlogopites enriched in the tetra-ferriphlogopite end-member (Pivec et al. 1998). The tetra-ferriphlogopite is also present in melilitic dyke rocks of Urach and Hegau in Germany (Dunworth & Wilson 1998) and the Komorní hůrka lava (Seifert & Kämpf 1994). Edgar (1992), Seifert et al. (2008) and Abratis et al. (2009) reported the presence of Ba-rich phlogopite from melilitic rocks of the West Eifel, Komorní hůrka, Görlitz and Vogtland, respectively, suggesting an enrichment of the late-magmatic hydrothermal fluids in barium.

Low temperature hydrothermal reactions are documented by the presence of the abundant late-magmatic ***perovskite*** rich in incompatible elements and by postmagmatic light-coloured perovskite very low in incompatible elements rimming titanian magnetites (Ulrych et al. 1988).

Dunworth & Wilson (1998) noted that crystallization of minerals in melilitic magmas is influenced by variable proportions of H_2O and CO_2 and Ca saturation. Late-stage crystallization of phlogopite and carbonate in melilitic rocks is related to high contents of H_2O and CO_2 while the crystallization of melilite is enhanced by low H_2O/CO_2 but high (Ca + Na + K)/Al in melts (Di Battistini et al. 2001). This interpretation can be demonstrated in particular in the Osečná Complex.

Conclusions

Melilitic rocks are relatively widespread in the Bohemian Massif during the Late Cretaceous and Cenozoic. The Osečná Complex together with the surrounding Ploučnice River region in northern Bohemia located at the intersection of the Ohře Rift and the Lusatian Fault, and adjacent territories of Saxony and Lusatia host mostly dyke melilitic rocks dated to the Late Cretaceous to Late Paleocene period (80–59 Ma). The dominant Mid Eocene to Late Miocene (32.3–5.9 Ma) volcanic period in the Bohemian Massif is very poor in melilitic dyke rocks (the Ohře Graben, the Cheb–Domažlice Graben and its continuation in Vogtland and the Labe–Odra Fault Zone). Cinder cones of extrusive melilitic rocks (scoria and lava) occur at the junction of the Ohře Rift and the Cheb–Domažlice Graben in the Cheb Basin area. They belong to the Early to Late Pleistocene volcanic episode (1.0–0.26 Ma) of the Bohemian Massif.

The mineral, geochemical and Sr/Nd isotopic similarities of melilitic rocks occurring in the Bohemian Massif from the Late Cretaceous to the Late Pleistocene suggest that their unusual magma evolved from compositionally very similar mantle sources and those magmas also underwent similar processes of their formation. Only the melilitic rocks of the Osečná Complex influenced by late-magmatic and postmagmatic fluids partly differ in Sr isotopic characteristics, showing more radiogenic $^{87}Sr/^{86}Sr$ values. However, their tectonic (grabens and fault zones) and geological (dykes, sills, flows, scoria cones) settings and petrographic (melilite olivine nephelinite to nepheline olivine melilitite, haüyne olivine melilitite, ultramafic lamprophyres — polzenite and alnöite, olivine melilitolite and its pegmatoid segregations) characteristics are partly different.

The ultramafic melilitic rocks are characterized by the primary olivine + melilite + Cr–Al-spinel/clinopyroxene mineral association, which became unstable under late-magmatic conditions. The low Cr_2O_3 contents in diopside (< 0.5 wt. %) and high TiO_2 contents in Cr–Al-spinels (0.8–2.4 wt. %) do not correspond to the primary composition of mantle xenoliths. The specific mineral association with rare minerals such as Zr-rich (F,OH) andradite, calzirtite and bartonite is characteristic only for the Osečná olivine melilitolite intrusion strongly influenced by late-magmatic fluids concentrating LILE, HFSE and volatile elements.

On the basis of major- and trace elements and the Sr/Nd isotopic characteristics, the melilitic rocks of the Bohemian Massif should be interpreted as melts originating by low melting of heterogeneous mantle sources, including both lithospheric and asthenospheric mantle components. The heterogeneous lithospheric source was probably veined carbonated mantle peridotite/clinopyroxenite.

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