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Cenozoic alkaline volcanic rocks with carbonatite affinity in the Bohemian Massif: Their sources and magma generation

JAROMÍR ULRYCH and JANA ŠTĚPÁNKOVÁ-SVOBODOVÁ†

Institute of Geology v.v.i., Acad. Sci. Czech Rep., Rozvojová 269, 165 00 Praha 6, Czech Republic; ulrych.@gli.cas.cz

Dedicated to the memory of Jana
†died on June 30, 2002

Abstract

Melilitic alkaline rock suite of the Osečná Complex and mildly alkaline rock suite of the Roztoky Intrusive Complex, both with carbonatite affinity, were studied to determine the source of magma for alkaline volcanism in the Cenozoic Central European Volcanic Province. No significant correlation in primary chemical composition exists between element contents in the extremely SiO_2-undersaturated melilitic rock suite of the Osečná Complex. All geochemical variations can be explained by metasomatic overprinting. The rocks represent a product of primitive mantle-derived magma. Enrichment in incompatible elements, high Zr/Hf, Ce/Pb ratios, relative depletion in HREE and negative K and Rb anomalies in the PM-normalized multielement variation diagrams point to a metasomatized mantle source with amphibole and/or phlogopite and garnet in the residuum.

The rocks of the essexite – monzodiorite – sodalite syenite series and associated differentiated dykes of the Roztoky Intrusive Complex, characterized by mean SiO_2 contents, are depleted in compatible elements, and their magma represents an evolved melt. Negative correlations between SiO_2 and MgO, TiO_2, P_2O_5 and CaO, and positive correlations between SiO_2 and K_2O, Na_2O and Al_2O_3 point to fractional crystallization of olivine, clinopyroxene, Fe-Ti oxides and apatite. The rocks geochemically correspond to the trachybasaltic lavas of the České středohoří Mts., and the same magma source can be presumed, i.e. mantle-related magma that was affected by some crustal assimilation.

Based on the presence of negative K and Rb anomalies in the PM-normalized multielement variation diagram in the Lower Paleozoic magmatic rocks of the Bohemian Massif we suggest that metasomatism of mantle lithosphere started already in the Early Cambrian. HIMU-OIB like Sr and Nd isotopic composition of the rocks of the Osečná Complex and variations in chemical composition of the volcanic rocks of the Central European Volcanic Province can be explained by continuous melting and subsequent metasomatism of mantle lithosphere. Geochemical similarities of ultramafic rocks from different world magmatic complexes show that subcontinental metasomatized mantle lithosphere is probably more homogeneous than sometimes presumed.

Key words: alkaline volcanic rocks, melilitic rocks, carbonatites, magma generation, metasomatism, Cenozoic, Bohemian Massif

Introduction

Carbonatite and associated alkaline rocks represent special products of mantle-derived magmas, the origin of which remains still under debate (e.g., Kaiserstuhl and Delitzsch Complex in the Cenozoic Central European Volcanic Province – CEVP; Wimmenauer, 1974; Ulrych et al., 1988; Krüger et al., 2012). Melilitic rocks as representatives of strongly undersaturated alkaline rock types are often associated with carbonatite complexes. Kresten et al. (1981), Dawson et al. (1985), Krüger et al. (2012) and others presumed that metasomatized melilitolite complexes are genetically associated with, or even underlain by, hidden carbonatite bodies. However, carbonatite rocks not always have been proved in the alkaline complexes.

Melilitic magma is usually believed to be small-volume partial melt of lithospheric mantle (Brey and Green, 1977; Brey, 1978; Alibert et al., 1983; Dautria et al., 1992; Dasgupta et al., 2007; Rass, 2008). Melilitic rocks are substantially enriched in incompatible trace elements. There are several possible ways of such enrichment: Wilson and Downes (1991), Wilson et al. (1995), Cullers and Graf (1984), Zinngrebe and Foley (1995) explained the enrichment by input of incompatible elements by interaction of the magma and wall rock during magma ascent (steady zone model), while Menzies and Murthy (1980), Bailey (1982), McKenzie (1989), Hegner et al. (1995), Furman (1995) presumed that alkaline magmas formed by partial melting of enriched source, represented by metasomatized subcontinental lithospheric mantle.

Metasomatic transformation of the lithospheric mantle can be generated by several mechanisms:

– metasomatism by hydrous fluids released from the subducting lithosphere (Basu et al., 1991; Tatsumoto et al., 1992; Wedepohl et al., 1994)

– metasomatism by alkali-rich carbonatite melts (Egorov, 1970; Green and Wallace, 1988; O´Nions and McKenzie, 1988; Hunter and McKenzie, 1989; Hauri et al., 1993)

– freezing of mantle-plume or metasomatism by asthenosphere-derived melts (Fitton et al., 1991; Johnson and Thompson, 1991; Menzies et al., 1991; Hegner et al., 1995)

– K or Na metasomatism of mantle wedge by interaction with slab-derived fluids in subduction environment (Kepezhinskas et al., 1995).

The aim of this study was to determine the source of parental magma for alkaline rock suites of presumable carbonatite affinity of the Roztoky and Osečná complexes, Bohemian Massif. Both complexes are related to the CEVP. The genesis of parental magma of ultramafic rocks of the CEVP was dealt with in a number of papers. Pivec et al. (1998a) considered that parental magma of melilitic rocks of the Osečná Complex was derived from sublithospheric mantle and was enriched in incompatible elements *en route* to the surface. On the basis of major and trace element compositions and Sr–Nd–Pb isotope ratios, Wilson et al. (1994) and Ulrych et al. (2000a, 2005) presumed the involvement of both lithospheric and asthenospheric mantle sources with HIMU-OIB affinities for primitive Cenozoic alkaline rocks (incl. olivine melilitites) of the Bohemian Massif. Hegner et al. (1995) suggested that parental magma of melilitic rocks of the Urach volcanic field (SW Germany) was derived from metasomatized lithosphere that was very recently enriched by the effect of melts derived from the old OIB source. Wilson and Downes (1991) presumed that molten subducted lithosphere of the Variscan age was involved in the source of parental magma of olivine melilitites of the CEVP. In a later study, Wilson et al. (1995) suggested that parental magma of Cenozoic melilitic alkaline rocks in Germany and France was derived from a metasomatized thermal boundary layer.

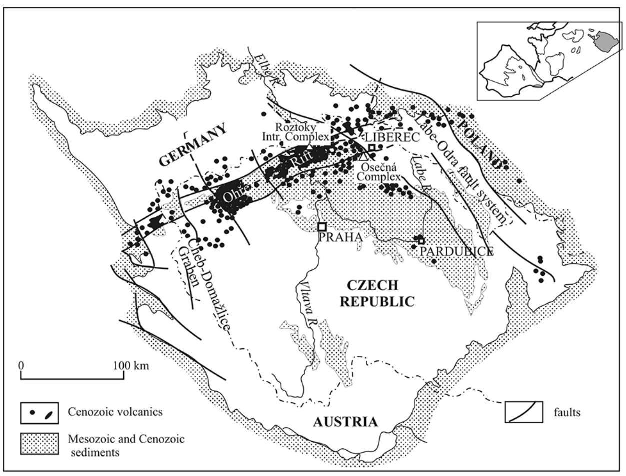

Fig. 1. Geological sketch map of the Bohemian Massif with indicated extent of Late Cretaceous to Cenozoic volcanic products. Modified after Ulrych et al. (1999). The position of the Osečná and Roztoky complexes are shown in the map.

Geological setting

The Osečná and Roztoky complexes were formed during the Upper Cretaceous to Tertiary volcanic activity related to the continental rift system in the foreland of the Alpine––Carpathian orogenic arc (Wimmenauer, 1974; Prodehl et al., 1995; Dèzes et al., 2004). Magma generation and ascent were controlled by major structural Variscan inhomogeneities of the basement. Young volcanism is associated with the following structures in the Bohemian Massif: the Ohře (Eger) Rift, the Labe/Elbe–Odra fault system and Cheb–Domažlice Graben (Ulrych et al., 2011; Fig. 1).

Two main Neoidic volcanic phases were recognized in the Bohemian Massif already by Ulrych and Pivec (1997), later specified by Ulrych et al. (2011): (1) pre-rift volcanism (79–49 Ma) in northern Bohemia, in the vicinity of the Lusatian Fault, in shoulder blocks of the later Ohře Rift, and (2) the syn-rift volcanism concentrated to the Ohře Rift with an older major episode (42–17 Ma) and a (3) younger minor one (13–9 Ma). Quaternary volcanic activity (4) was concentrated to limited areas only. Majority of magma (almost 99 vol. %) was extruded during the older rifting periods.

Cenozoic volcanism in the Bohemian Massif is represented by four principal rock series (Ulrych et al., 1999; classification of Le Maitre (ed.), 2002):

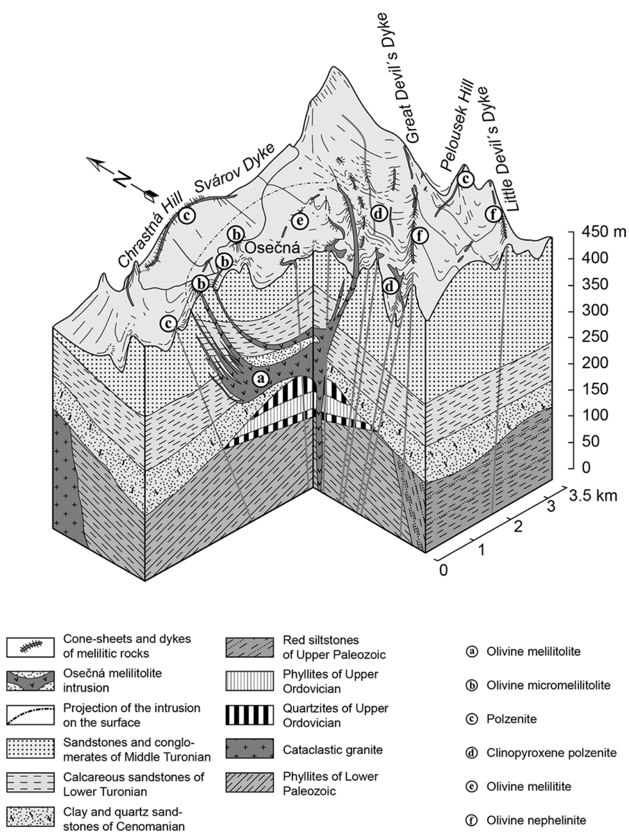

Fig. 2. A block diagram of the Osečná Complex. Modified after Rutšek in Ulrych et al. (1988).

(i) unimodal olivine melilitite/olivine nephelinite – melilitic lamprophyre (polzenite) rock suite of the pre-rift period (northern Bohemia),

(ii) bimodal olivine nephelinite/basanite/trachy basalt – trachyte and coeval nephelinite/tephrite – phonolite series of the syn-rift period (České středohoří Mts. in northern Ohře Rift and the Labe/Elbe–Odra fault system in northern Bohemia and Moravia, Saxony, Lusatia and Silesia),

(iii) mostly unimodal, (olivine) nephelinite/basanite– –tephrite/(trachy)basalt – trachyte (rare) series of the syn- -rift period (Doupovské hory Mts. in the western Ohře Rift),

(iv) bimodal tephrite/basanite – phonolite and coexisting trachybasalt – trachyte/rhyolite series of the syn-rift period (Cheb–Domažlice Graben, western Bohemia).

The ***Osečná Complex*** is situated on the eastern flank of the Ohře Rift and represents the principal centre for the Upper Cretaceous to Paleocene ultramafic ultraalkaline (melilite/nepheline) volcanism in the northern Bohemia, formed during the pre-rifting period (Pivec et al., 1998a; Ulrych et al., 1998, 2011). The central intrusion of the Osečná Complex (Fig. 2) is formed by olivine melilitolite that intruded into the Upper Cretaceous epicontinental sediments (12.5 km^2 with the apparent thickness of 20 to 60 m). The main melilitolite body is locally metasomatized by pegmatoids and phlogopitites, and penetrated by ijolite dykes. In the marginal parts, olivine melilitolite changes into porphyritic olivine micro-melilitolite of chilled margins and often forms finger-like apophyses. The dip angles of the Osečná saucer-shaped sill and flat-lying sheets is low (up to 30°) but steepen to as much as 70–80° on the edges of the saucer, forming finger-like apophyses (cf. similar steepening from the Cape Province, South Africa, Whin Sill, England and Midland Valley Sill, Scotland in Hall, 1995). Independent dykes of lamprophyric ultramafic rocks – polzenites (Scheumann, 1913, 1922), usually of porphyritic olivine micro-melilitolite composition, are associated with the intrusion (polzenite formation sensu Shrbený, 1995). Nevertheless, the Osečná intrusion is associated with steeply inclined, partly younger dykes of olivine nephelinite to olivine melilitite composition of the pre-rifting volcanic phase. Both, the mantle (lherzolites, harzburgites, and clinopyroxene phlogopitites) and the upper crustal xenoliths were described from the olivine melilitolite and olivine nephelinite/melilitite rock suite of the Osečná Complex (Ulrych et al., 2000c).

The ***Roztoky Intrusive Complex*** is situated in the centre of volcanic activity of the České středohoří Mts. It represents the second largest erosional relict of the Cenozoic volcanic complex within the Ohře Rift. The Roztoky Intrusive Complex (Fig. 3) is situated at the intersection of the hypothetical central fault of the Ohře Rift and the fault parallel to the Labe/Elbe–Odra fault system. The geophysical survey of Mrlina and Cajz (2006) found that essexite and monzodiorite intrusions of the Roztoky Intrusive Complex form a single deep body that has a few protrusions reaching to the surface. The centre of the complex is formed by a crater vent filled with carbonate- -rich trachytic breccia. Kopecký (1987) presumed a hidden carbonatite body in deep parts of the pseudotrachyte-filled "caldera" structure, however, no unequivocal carbonatite rocks have been documented in this region (Ulrych and Balogh, 2000). A number of hypabyssal and subvolcanic dyke bodies of different rock types occur in the surroundings of the intrusive centre. Mostly radially oriented differentiated dyke swarm is associated with the Roztoky Intrusive Complex. Ulrych (1998), Ulrych et al. (2000b) and Skála et al. (2012) described the following rock series in the Roztoky Intrusive Complex:

– medium alkaline hypabyssal series formed by essexite – monzodiorite – sodalite syenite,

– weakly alkaline dyke series represented by camp- tonite/monchiquite – maenite ("gauteite" and bostonite),

– strongly alkaline dyke series composed of "tinguaite" and porphyric "tinguaite" of phonolitic composition.

The dyke swarm includes lamprophyric and light derivatives (of maenite type sensu Rock, 1991) as well as common basaltic rocks and trachytic/phonolitic dyke rocks (Hibsch, 1930; Ulrych and Balogh, 2000).

Although no carbonatites were found either in the Osečná and the Roztoky complexes, concentric and radial complex arrangement, chemical composition of the rocks (enrichment in incompatible elements), chemistry of rock- -forming minerals (kimzeyitic garnet, Mn-bearing ilmenite in olivine melilitolite, carbonate in both complexes) and extended metasomatic phenomena relate both complexes

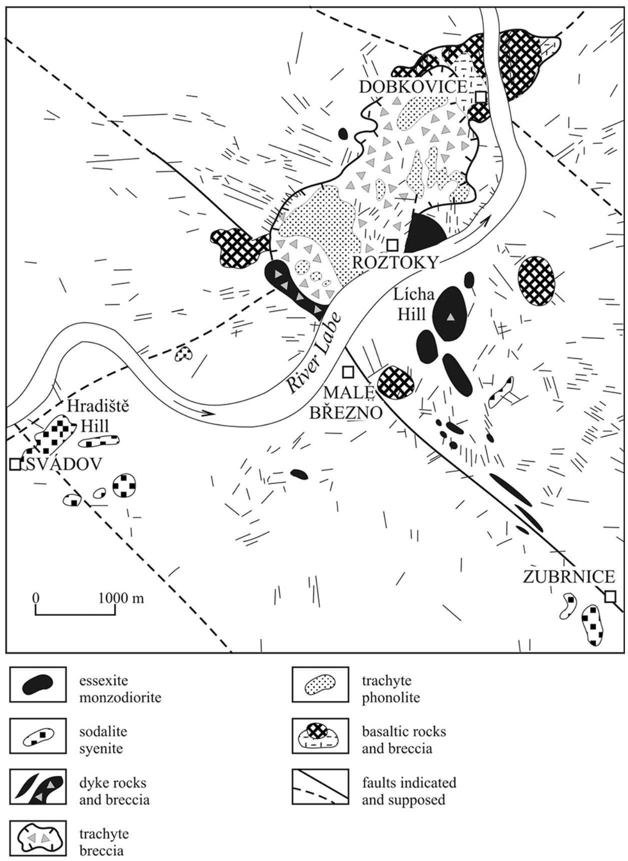

Fig. 3. A sketch map of the Roztoky Complex. Modified after Ulrych (1998).

to those with carbonatite affinity. The subject of our study represents rocks genetically related to carbonatite melts: (i) hidden carbonatite body (?) of the Roztoky Intrusive Complex, or (ii) ultramafic mantle melts of strongly alkaline rocks in the Osečná Complex. In the Osečná Complex such rocks are represented by olivine melilitolite with the olivine micro-melilitolite facies and metasomatic derivatives, e.g. pegmatoids, phlogopitites and ijolites. Kopecký (1987) presumed that a hidden carbonatite body with an albitite aureola in the Roztoky Intrusive Complex, located in the pseudotrachytic breccia of the "caldera" filling, is genetically related to differentiated alkaline dyke rock suite (camptonite/monchiquite – "tinguaite") and epithermal Pb–Zn–Cu–(Ag, Te) ore veins with carbonate gangue.

Petrological characteristic

Detailed petrographic characteristic of rocks of the ***Osečná Complex*** were presented by Ulrych et al. (1988) and Pivec et al. (1998a). The following rocks are typical for the Osečná Complex:

– olivine melilitolite, medium- to coarse-grained with gabbroophitic to poikiloophitic texture forming the central Osečná lopolith-like intrusion. The mineral paragenesis is melilite + olivine + nepheline + phlogopite ± spinel, garnet, monticellite, carbonate, perovskite and apatite. Melilite is one of the most important primary minerals. It is often altered into a mixture of fibrous Ca-rich silicates (as pectolite, wollastonite, tobermorite) denoted as "cebolite". Mg-rich olivine (Fo_{88-91}), often with a xenocrystic core, is accompanied by, and homoaxially overgrown with, monticellite. Nepheline, forming anhedral filling among melilite laths, is associated with carbonate. The bizonal developed spinels and perovskite represent also primary minerals. Phlogopite is developed in two generations. The rare older generation I belongs to primary minerals, however, the totally prevailing poikilitic generation II represents, together with titanian andradite, products of the late magmatic metasomatic phase. In the strongly hydrothermally affected parts of the body, metasomatic derivatives were formed, such as:

– pegmatoids forming a system of irregular schlieren and nests and vertically zoned dykes (10–60 cm) formed by coarse-grained melilitolite pegmatoid (nepheline + melilite + phlogopite + garnet + spinel ± apatite, perovskite, calzirtite);

– ijolites forming rare dykes (5–20 cm) concentrated in the central part of the intrusion near the feeding channel. They are medium-grained ijolite/melteigite in composition with transitions to turjaite (nepheline + clinopyroxene + calcite ± melilite, /Ti, Zr-rich/ garnet, apatite);

– phlogopitites forming irregular bodies and rims of pegmatoid and ijolite bodies gradually passing to the host rock. The medium-grained rock is of bimineral (phlogopite + garnet) composition ± olivine, melilite, apatite, rasvumite (potassium sulphide);

– polzenite dykes (totally prevailing) of the olivine micro-melilitolite character (free of clinopyroxene) being porphyritic (olivine ± clinopyroxene and poikillitic phlogopite) in fine-grained matrix of trachytic texture. Chemical composition of the dykes and their minerals is the same as in olivine melilitolite (see above);

– clinopyroxene "polzenite" (correctly alnöite) dykes revealing the same textural characteristic as olivine micro-melilitolite (see above). The mineral association is: melilite + olivine + monticellite ± phlogopite, clinopyroxene, haüyne, calcite, spinel, perovskite and apatite. Clinopyroxene polzenites contain substantial amounts of clinopyroxene (10–20 vol. % and about 10 vol. % carbonate);

– melilite-bearing olivine nephelinite to olivine melilitite, and olivine nephelinite forming dykes of the Devil´s Walls (see Fig. 3), 1–3 m thick with horizontal, thick-columnar jointing. They are microporphyritic (olivine, clinopyroxene) with a very fine-grained holocrystalline matrix and mineral paragenesis of clinopyroxene + nepheline + olivine ± melilite, spinel, apatite and perovskite.

Petrography of the hypabyssal and dyke rocks of the ***Roztoky Intrusive Complex*** was described by Ulrych et al. (1983), Jelínek et al. (1989) and Ulrych (1998). The following mineral parageneses are characteristic of the studied rocks:

– monzodiorite to (diorite/gabbro) is equigranular fine- to medium-grained more rarely coarse-grained and porphyritic with hypautomorphic texture. Mela-monzodiorite and leuco-diorite vertical layering together with monzonite to monzosyenite dykes are characteristic features of the inhomogeneous Roztoky intrusive body with signs of crystallization of cumulate type. Mineral association is plagioclase + K-feldspar + biotite/clinopyroxene ± amphibole, magnetite, ilmenite, calcite and apatite. Lath-shaped plagioclase forms a framework filled with K-feldspar, clinopyroxene, poikilitic phlogopite and problematic carbonate grains. Dark minerals show tendency to cluster. Amphiboles form anhedral grains and rare pyroxene rims;

– essexite stocks with petrographic characteristic similar to monzodiorite: plagioclase + K-feldspar + nepheline + pyroxene + amphibole/biotite ± magnetite, apatite, carbonate; presence of nepheline and rare carbonate is typical;

– sodalite/analcime (micro)syenite to sodalite/analcime (micro)monzosyenite forming stocks and a small laccolith are porphyritic (clinopyroxene, amphibole) with fine-grained prismatic granular texture. Spaces between laths of feldspar are filled with abundant mineral of sodalite group, mostly replaced by analcime (± calcite, nepheline). The most abundant mafic minerals are clinopyroxene and hornblende (xenocrysts? from decomposed hornblendite cumulates) forming independent individuals. Mineral paragenesis is K-feldspar + sodalite (replaced by analcime) + pyroxene + amphibole ± plagioclase, titanite, apatite;

– sodalite/analcime-bearing (micro)monzosyenite forming stocks of the Býčkovice body (15 km south of the centre of the Roztoky intrusive complex) is of transitional character between sodalite syenite and essexite: K-feldspar + sodalite (replaced by analcime) + pyroxene ± plagioclase, titanite, apatite;

– hornblendite (to clinopyroxene hornblendite and rare gabbro) cumulates in sodalite syenite and lamprophyres contain kaersutite + diopside + apatite ± plagioclase, olivine, magnetite, titanite;

– camptonite and monchiquite dykes: phenocrysts (hornblende, biotite ± clinopyroxene, plagioclase); matrix (clinopyroxene, hornblende, plagioclase phlogopite, sodalite, analcime ± glass);

– "gauteite" (local name for felsic derivatives belonging to maenite of Rock, 1991) dykes with transitions to bostonites and "mondhaldeites": phenocrysts (hornblende, clinopyroxene, biotite, plagioclase ± sodalite); matrix (plagioclase, K-feldspar, hornblende, clinopyroxene ± glass);

– "tinguaite" and porphyric "tinguaite" dykes: phenocrysts (K-feldspar, nepheline ± sodalite, plagioclase, Na-rich diopside, amphibole); matrix (K-feldspar, sodalite, Na-rich diopside);

– epithermal Pb–Zn–Cu–(Ag, Te) veins penetrating the monzodiorite body with sphalerite > galena >> chalcopyrite > tetrahedrite mineralization. The gangue is formed by rhodochrosite > dolomite > calcite > chalcedony, quartz and barite. Hessite represents a source of Ag-mineralization in galena and tetrahedrite.

Geochemical characteristic

A number of studies have been dealing with the geochemistry of both studied complexes. Major and trace elements, together with isotopic geochemistry of melilitic rocks of the Osečná Complex, were studied by Ulrych et al. (1988), Ulrych et al. (1997), Pivec et al. (1998a). Geochemistry of the Roztoky Intrusive Complex was presented by Ulrych (1998) and Ulrych and Balogh (2000).

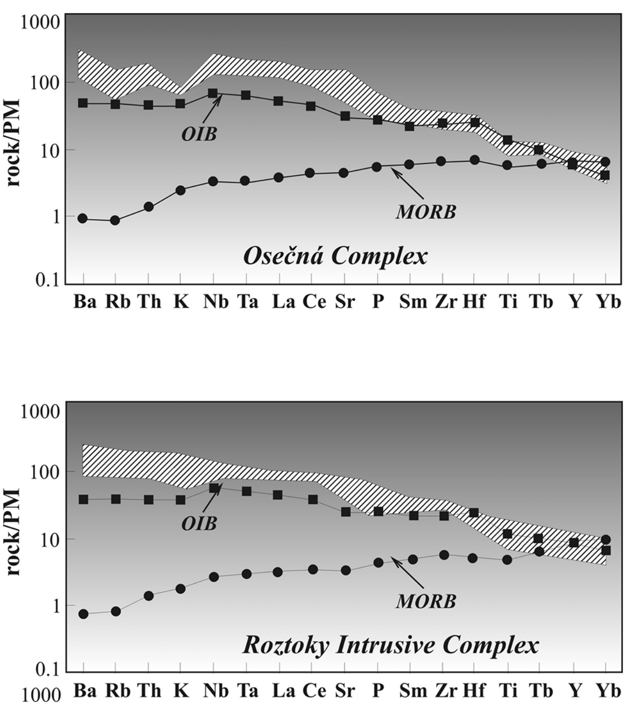

Fig. 4. Mantle-normalized incompatible trace element diagrams of melilitic rocks of the Osečná Complex and mildly alkaline rocks of the Roztoky Intrusive Complex. Normalizing values after Sun and McDonough (1989); OIB and MORB (Sun and McDonough, 1989) are plotted for comparison.

Geochemical data sets were presented in Ulrych et al. (2008) and Skála et al. (2013). Representative analyses of the studied rocks are summarized in Tab. 1.

Melilitic rocks of the ***Osečná Complex*** have high MgO (12.7–19.5 wt. %) and low SiO_2 (29.5–38.5 wt. %). The rocks belong to the sodic series with K_2O/Na_2O ratios in the range of 0.5–1.1. No substantial correlations between major and trace element contents in the rocks were recognized.

Compatible trace element concentrations are mostly also high (160–660 ppm Ni, 420–1 210 ppm Cr, 25–38 ppm Sc). The rocks are enriched in incompatible elements when compared to the PM (primitive mantle), the OIB (ocean island basalts) and the MORB (mid-ocean ridge basalts), see Fig. 4. The PM-normalized multielement variation diagrams show a relative depletion in Rb, K and Ti (Fig. 4). The rocks are characterized by lower Pb/Ce (0.01–0.04), Rb/La (0.3–1.0), Rb/Sr (0.01–0.05), Ti/Eu (3 300–4 300) and higher Zr/Hf (40–60) ratios than the OIB, MORB and PM (Sun and McDonough, 1989). Chondrite-normalized REE patterns are steep with high relative enrichment in LREE (La/Yb = 30–70) and only a minor europium anomaly (Eu/*Eu 0.84–0.97 – Ulrych et al., 2008, and 2014).

Initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of the melilitic rocks of the ***Osečná Complex*** are 0.7033–0.7049 and 0.51275–0.51287, respectively (Pivec et al., 1998a; Ulrych et al., 2008). They plot partly below the mantle array and correspond to the mantle source with the asthenospheric HIMU-OIB component (Fig. 5). As the Sm-Nd isotopic system is robust during the low-temperature and autohydrothermal alteration (cf. Hegner and Vennemann, 1997), the $^{143}Nd/^{144}Nd$ ratios values are interpreted to indicate melting of depleted and moderately heterogeneous mantle sources. In contrast to the relatively uniform Nd isotopic compositions, the initial $^{87}Sr/^{86}Sr$ ratios show a wide range of values.

A preferred explanation for a wide range of the Sr--isotopic ratios in the melilitic rocks of the Osečná Complex is melting of a veined mantle. Such a veined source produced

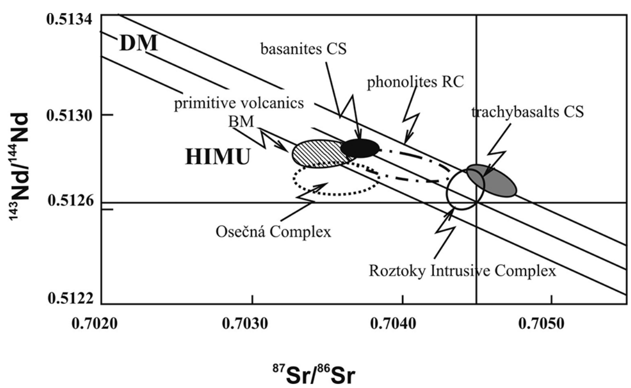

Fig. 5. Initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios for rocks of the Osečná and Roztoky complexes Isotopic data for Cenozoic volcanic rocks of the Bohemian Massif are plotted for comparison. Data sources: České středohoří Mts. (CS) (Cajz et al., 1999), Cenozoic primitive mafic rocks of the Bohemian Massif (basanites, trachybasalts – BM) (Wilson et al., 1994; Ulrych et al., 2011), Osečná Complex (Pivec et al., 1998; Ulrych et al., 2008), Roztoky Intrusive Complex (Ulrych et al., 2000b, 2006; Skála et al., 2013).

Tab. 1
Representatite chemical analyses of the melilitic rocks of the Osečná Complex and mildly alkaline rocks of the Roztoky Intrusive Center

Locality	Osečná	Osečná	Osečná	Osečná	Holičky	Vesec	Pelousek	Suchý	Roztoky	Lícha Hill	Hradiště	Křížový v.	Těchlovice	Těchlovice	Těchlovice	Skrytín at
	borehole	borehole	borehole	borehole	borehole	at	Hill at	Janův Důl	railway	at Velké	Hill at	Hill at	active	active	active	Roztoky
	159 152/	159 146/	063 160/	159 146/	047 112/	Světlá p. J.		trench	cut	Březno	Svádov	Býčkovice	quarry	quarry	quarry	road cut
	254 m	251 m	212 m	251 m	226 m			BK-239								
Latitude	50°41´2´´	50°41´25´´	50°40´24´´	50°41´25´´	50°40´45´´	50°42´10´´	50°40´41´´	50°41´56´´	50°41´15´´	50°40´39´´	50°39´59´´	50°33´43´´	50°42´38´´	50°42´38´´	50°42´26´´	50°41´41´´
Longitude	14°56´10´´	14°56´05´´	14°54´46´´	14°56´05´´	14°53´49´´	14°58´59´´	14°58´09´´	14°57´33´´	14°11´12´´	14°11´24´´	14°16´58´´	14°13´07´´	14°11´34´´	14°11´34´´	14°12´04´´	14°10´53´´
Rock type	OM	PEG	IJ	PHL	OMM	POL	POL	CPOL	MD	E	SS	SMS	M	C	G	TI
SiO_2 (wt. %)	34.51	30.72	39.86	30.74	31.50	29.50	35.02	34.38	46.62	45.72	48.88	49.96	45.88	47.84	53.68	53.26
TiO_2	2.48	1.62	2.03	2.75	2.57	1.93	2.10	2.15	2.64	3.08	1.68	1.78	3.22	2.13	1.78	0.79
Al_2O_3	8.14	12.42	11.70	7.46	8.65	7.25	8.68	8.09	17.94	15.47	18.53	18.18	14.99	16.15	17.53	20.66
Fe_2O_3	4.16	7.79	4.63	7.13	7.57	6.06	6.03	9.12	5.32	4.25	4.57	6.40	7.25	6.67	4.92	2.53
FeO	6.22	2.51	2.47	2.63	2.81	4.49	5.41	5.29	4.36	5.45	2.00	0.64	3.44	1.50	1.75	1.67
MnO	0.20	0.13	0.09	0.17	0.17	0.16	0.22	0.19	0.21	0.15	0.21	0.14	0.16	0.16	0.14	0.20
MgO	13.57	8.94	5.56	13.33	13.38	15.34	15.27	15.96	3.76	5.68	1.95	2.42	4.91	2.48	2.32	0.70
CaO	18.01	23.79	14.63	20.18	17.89	21.06	18.38	14.47	8.28	10.36	6.61	6.39	8.79	7.35	3.83	3.68
Na_2O	3.22	2.03	7.49	0.14	0.22	0.91	1.76	2.39	4.34	3.65	6.13	4.85	2.92	3.70	5.25	8.98
K_2O	2.31	1.65	1.28	3.51	1.98	1.15	1.39	1.83	2.37	3.92	4.00	4.47	4.09	4.07	4.89	4.73
P_2O_5	0.92	3.24	0.79	1.49	0.95	1.62	1.10	0.86	0.87	0.47	0.48	0.53	0.47	0.52	0.35	0.13
H_2O^+	3.06	3.87	4.31	2.35	4.66	5.71	3.34	1.64	1.09	1.25	3.11	1.74	2.99	2.28	2.96	1.47
H_2O^-	0.58	0.44	0.60	1.13	1.92	0.63	0.20	0.92	0.26	0.08	0.26	0.54	0.22	1.02	0.22	0.16
CO_2	1.46	0.69	4.02	6.69	5.39	3.82	0.44	2.87	1.75	0.11	1.35	1.69	0.23	3.56	0.11	0.25
F2	0.16	0.28	0.12	0.86	n. d.	0.15	n. d.	0.09	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.
S	0.10	n. d.	n. d.	n. d.	n. d.	0.19	n. d.	0.32	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.
Total	99.00	100.00	99.53	100.20	99.74	99.86	99.64	100.45	99.81	99.64	99.76	99.73	99.56	99.43	99.73	99.21
Ni (ppm)	187	99	56.0	74.0	216	323	321	195	10.6	37.9	22.2	5.30	22.3	14.8	10.0	9.00
Cr	550	32.0	55.0	48.0	700	675	559	600	6.60	74.2	2.30	3.60	27.2	15.8	11.7	3.10
Co	48.0	26.0	6.00	30.0	47.0	54.0	56.0	64.0	16.2	31.3	10.2	10.0	30.6	16.5	13.8	4.60
Sc	28.4	35.0	67.8	41.0	21.8	28.3	29.9	35.0	8.38	26.4	3.82	4.52	24.0	9.50	9.30	1.86
Rb	84.2	79.6	120	59.7	65.0	31.1	45.0	48.8	55.0	96.5	101	90.4	81.0	117	122	182
Sr	2 429	4 332	3 300	8 430	1 277	1 978	2 225	1 750	1 490	820	1 690	1 310	641	1 000	505	1 270
Y	30.6	54.4	46.7	59.5	29.0	26.6	41.0	21.9	25.7	19.9	30.6	24.6	20.8	25.4	22.5	20.0
Zr	560	433	1 268	357	345	275	379	289	243	236	491	355	359	576	408	878
Nb	224	341	363	386	125	204	179	193	99.0	80.0	189	87.0	94.0	123	107	141
Cs	2.66	1.82	28.9	3.04	3.03	0.91	0.74	1.23	0.96	1.64	1.82	1.30	0.90	1.50	1.50	2.98
Ba	1 069	2 669	451	3 072	754	533	2 115	1 521	976	813	1 290	1 270	781	937	1 420	1 176
La	95.6	137	79.2	198	83.6	158	158	134	70.8	44.8	121	81.0	48.7	76.9	72.0	117

Tab. 1 – continued

Locality	Osečná	Osečná	Osečná	Osečná	Holičky	Vesec	Pelousek	Suchý	Roztoky	Lícha Hill	Hradiště	Křížový v.	Těchlovice	Těchlovice	Těchlovice	Skrytín at
	borehole	borehole	borehole	borehole	borehole	at	Hill at	Janův Důl	railway	at Velké	Hill at	Hill at	active	active	active	Roztoky
	159 152/	159 146/	063 160/	159 146/	047 112/	Světlá p. J.		trench	cut	Březno	Svádov	Býčkovice	quarry	quarry	quarry	road cut
	254 m	251 m	212 m	251 m	226 m			BK-239								
Latitude	50°41´2´´	50°41´25´´	50°40´24´´	50°41´25´´	50°40´45´´	50°42´10´´	50°40´41´´	50°41´56´´	50°41´15´´	50°40´39´´	50°39´59´´	50°33´43´´	50°42´38´´	50°42´38´´	50°42´26´´	50°41´41´´
Longitude	14°56´10´´	14°56´05´´	14°54´46´´	14°56´05´´	14°53´49´´	14°58´59´´	14°58´09´´	14°57´33´´	14°11´12´´	14°11´24´´	14°16´58´´	14°13´07´´	14°11´34´´	14°11´34´´	14°12´04´´	14°10´53´´
Rock type	OM	PEG	IJ	PHL	OMM	POL	POL	CPOL	MD	E	SS	SMS	M	C	G	TI
Pr	22.5	24.3	13.0	36.0	19.9	31.4	27.5	25.2	16.1	10.7	21.3	15.2	11.8	16.4	13.8	10.8
Nd	86.8	92.3	48.1	135	77.2	115	98.3	87.9	61.8	41.7	72.1	54.5	45.8	59.3	48.9	31.7
Sm	14.4	18.1	10.1	24.5	13.4	16.8	16.5	11.9	10.5	7.59	11.1	8.81	8.58	9.84	8.06	5.01
Eu	4.05	5.73	3.34	7.43	3.85	4.76	4.94	3.31	3.18	2.32	3.19	2.59	2.48	2.89	2.25	1.52
Gd	11.3	17.7	10.9	21.6	13.9	13.5	18.3	9.27	9.78	7.18	11.0	8.72	8.21	9.88	8.01	2.40
Tb	1.44	2.46	1.75	2.82	1.62	1.60	2.10	1.15	1.16	0.90	1.27	1.04	1.03	1.23	0.99	0.53
Dy	7.23	13.30	10.40	14.6	6.28	7.68	8.38	5.76	5.50	4.32	6.01	5.04	4.84	5.62	4.66	4.01
Ho	1.27	2.27	1.94	2.42	0.97	1.16	1.41	0.93	0.96	0.75	1.11	0.91	0.85	1.00	0.86	0.80
Er	3.23	5.57	5.24	5.55	2.87	2.56	3.93	2.21	2.69	2.11	3.32	2.68	2.35	2.88	2.56	2.39
Tm	0.41	0.66	0.70	0.63	0.29	0.29	0.42	0.27	0.32	0.26	0.43	0.34	0.28	0.36	0.32	0.36
Yb	2.57	3.49	4.32	3.20	1.82	1.52	2.54	1.61	2.00	1.58	2.73	2.16	1.81	2.37	2.26	2.34
Lu	0.33	0.44	0.65	0.38	0.25	0.18	0.33	0.20	0.30	0.23	0.41	0.32	0.27	0.34	0.33	0.29
Hf	10.2	9.35	30.0	7.58	7.77	5.41	8.67	6.27	6.61	6.47	10.1	8.14	9.19	12.4	9.34	11.7
Ta	8.85	13.4	7.89	7.58	7.73	9.06	8.11	7.39	4.09	3.46	7.45	3.64	4.84	6.13	5.10	3.28
Th	11.3	7.22	5.21	10.1	10.2	19.3	19.5	19.8	7.01	7.72	17.0	12.3	8.90	11.8	14.5	22.9
U	5.01	7.85	10.0	7.40	2.49	4.93	5.63	5.92	1.83	2.18	4.88	3.12	2.00	3.40	3.00	7.20
# Mg	74.1	66.3	63.7	75.6	74.5	76.4	74.7	71.3	46.3	56.2	40.1	44.2	50.8	41.0	44.1	27.1
K/Rb	228	172	89	488	253	307	256	311	358	337	329	410	419	289	333	216
Rb/Sr	0.035	0.018	0.036	0.007	0.051	0.016	0.020	0.028	0.037	0.118	0.060	0.069	0.126	0.117	0.242	0.143
ΣREE	439	544	311	781	403	626	623	504	328	218	471	331	238	336	296	329
LaN/YbN	26.7	28.2	13.2	44.4	32.9	74.6	44.6	59.7	25.4	20.3	31.8	26.9	19.3	23.3	22.9	35.9
Eu/Eu*	0.94	0.97	0.97	0.97	0.86	0.94	0.87	0.93	0.94	0.95	0.87	0.89	0.89	0.89	0.85	1.18
Zr/Hf	54.9	46.3	42.3	47.1	44.4	50.8	43.7	46.1	36.8	36.5	48.6	43.6	39.1	46.5	43.7	75.0
Th/U	2.26	0.92	0.52	1.36	4.10	3.91	3.46	3.34	3.83	3.54	3.48	3.94	4.45	3.47	4.83	3.18
Nb/Ta	25.3	25.4	46.0	50.9	16.2	22.5	22.1	26.1	24.2	23.1	25.4	23.9	19.4	20.1	21.0	43.0
Nb/U	44.7	43.4	36.3	52.2	50.2	41.4	31.8	32.6	54.1	36.7	38.7	27.9	47.0	36.2	35.7	19.6
La/Nb	0.43	0.40	0.22	0.51	0.67	0.77	0.88	0.69	0.43	0.40	0.22	0.51	0.67	0.77	0.88	0.69
Ba/Nb	4.77	7.83	1.24	7.96	6.03	2.61	11.8	7.88	9.86	10.2	6.83	14.6	8.31	7.62	13.3	8.34

Osečná Complex (Ulrych et al., 2008): OM – olivine melilitolite; PEG – pegmatoide in OM; IJ – ijolite in OM; PHL – phlogopitite-glimmerite in OM; OMM – olivine micromelilitolite in OM; POL – polzenite (vesecite type of Scheumann, 1913); POL – polzenite (modlibovite type of Scheumann, 1913); CPOL – clinopyroxene "polzenite" (luhite type of Scheumann, 1913). *Roztoky Intrusive Complex (Ulrych et al., 2006; Skála et al., in press):* E – essexite; MD – monzodiorite; SS – sodalite syenite; SMS – sodalite monzosyenite; M – monchiquite; C – camptonite; G – "gauteite" – maenite; TI – "tinguaite"; # Mg = 100 Mg/Mg + Fe^{2+}, for Fe^{3+}/Fe = 0.15; n. d. = not determined.

by carbonate-rich fluids, with very high Sr concentrations, is supported by the high CO_2 and Sr concentrations in the rocks. These metasomatic fluids had high concentrations of isotopically enriched Sr but low concentrations of Nd and thus little influence on the Nd inventory of the source (depleted mantle).

Phlogopite-bearing mantle xenoliths present in the melilitic rocks of the complex indicate that the mantle was also overprinted by hydrous fluids. Phlogopite-bearing veins would also produce highly radiogenic Sr. Changes in the $^{143}Nd/^{144}Nd$ isotopic compositions produced by such a process would be much smaller and possibly not discernible within the analytical error of the ratio. Consequently, hydrous as well as carbonate metasomatism may explain the enriched Sr-isotopic compositions of some of the samples. However, taking into consideration the evidence for melting of carbonate-bearing and Sr-rich mantle sources, we prefer to attribute the enriched Sr isotopic compositions to carbonatite-related magmatism associated with initiation of the Ohře Rift.

According to Ulrych et al. (1997) distinctive generations of carbonates in the olivine melilitolites and associated metasomatic derivatives show partly different $\delta^{13}C$ PDB values. Carbonate inclusions in silicates and in the matrix of olivine melilitolites and their metasomatic derivatives have $\delta^{13}C$ values –5 to –9 ‰ PDB (Ulrych et al., 1997, and Pivec et al., 1998a) comparable to primary igneous carbonatites (PIC of Taylor et al., 1967). Values of carbonate veinlets in altered rocks incline to higher $\delta^{13}C$ values (–4 to +1 ‰ PDB; Pivec et al., 1998). Despite of relatively low $\delta^{13}C$ PDB of some carbonates, all of them have high $\delta^{18}O$ 14 to 21 ‰ SMOW, too high for primary igneous carbonatites (Ulrych et al., 1997, and Pivec et al., 1998a).

All the studied rocks of the ***Roztoky Intrusive Complex*** show higher silica contents (45–67 wt. % SiO_2) as compared with olivine melilitolites of the Osečná Complex. The rocks of the Roztoky Intrusive Complex are depleted in compatible elements (<6 wt. % MgO, <10 ppm Ni, <30 ppm Cr) and enriched in incompatible elements relative to the PM, MORB and OIB (Fig. 4). There are significant correlations between silica and other major and trace element concentrations. MgO, TiO_2, CaO, P_2O_5, Ni, Cr and Sc decrease and Al_2O_3, Na_2O, K_2O, Rb, REE and Zr increase with rising SiO_2 contents.

Initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of hypabyssal rocks of the Roztoky Intrusive Complex show a large variation ranging from 0.7037 to 0.7047 and 0.51264 to 0.51278, respectively (Ulrych et al., 2000; Skála et al., 2013) – i.e., close to Bulk Earth composition (Fig. 5). The $^{87}Sr/^{86}Sr$ (~0.7050) and $^{143}Nd/^{144}Nd$ (~0.51269) ratios of the Býčkovice sodalite monzosyenite body are similar. Lamprophyric dykes have Sr-Nd isotopic compositions overlapping those of hypabyssal rocks except of "tinguaites" ($^{87}Sr/^{86}Sr$: 0.7034 to 0.7042 and $^{143}Nd/^{144}Nd$: 0.51270 to 0.51282; Ulrych et al., 2006).

The $\delta^{13}C_{fluid}$ (–5 to –3 ‰) of carbonates (rhodochrosite, dolomite, calcite) from Tertiary epithermal base metal veins penetrating the hypabyssal monzodiorite body (Ulrych et al., 1997; Pivec et al., 1998b) indicate the influence of deep-seated CO_2 but the O isotopic composition of hydrothermal fluids (calculated $\delta^{18}O_{fluid}$ values from –3 to –7 ‰ SMOW) shows the dominance of water with relatively shallow circulation. Kopecký et al. (1987) interpreted these veins as products of residual solutions derived from a supposed hidden carbonatite intrusion (late-magmatic carbonatites C4 of Le Bas, 1977).

Origin and evolution of the magma

Our conclusion on the magma source and magma evolution of the studied rocks of both – the Osečná and Roztoky complexes is based on the study of trace and major elements and Nd and Sr isotopic bulk-rock geochemistry.

The following criteria (Pivec et al., 1998a) relate melilitic rocks of the Osečná Complex to products of primitive undersaturated mantle magma (sensu Frey et al., 1978):

– Mg # in the range of 69 to 81 (75 on average),

– high concentrations of compatible elements (Cr, Sc, Ni) and low SiO_2 activity in bulk-rock geochemistry,

– presence of mantle (lherzolite) and metasomatized mantle (mica clinopyroxenite) xenoliths in the rocks (Ulrych et al., 2000c).

Evolution of the rock suite of the Osečná Complex is not very clear. Compositional trends (particularly that of olivine melilitolite) are obscured by the later metasomatism; however, the pattern of the PM-normalized multielement variation diagrams (Fig. 4) suggests uniform-source material of melilitic rocks of the Osečná Complex. The rocks probably represent products of crystallization of primitive, near-primary silica-deficient magma (Keshav and Gudfinnsson, 2004).

Incompatible trace element ratios and Sr and Nd isotopic compositions usually reflect chemistry and residual mineralogy of the magma source. Negative K and Rb anomalies in the PM-normalized multielement variation diagrams and low Pb/Ce can be attributed to the presence of amphibole and/or phlogopite in the residuum (Rosenbaum, 1993; Hegner et al., 1995). Phlogopite-bearing ultramafic rocks as mica clinopyroxenite to glimmerite were described among xenoliths in olivine melilitolite rocks (Ulrych et al., 2000c). Steep REE pattern indicates the presence of garnet in the residuum (Ulrych et al., 2008; Skála et al., 2013).

The enrichment in incompatible elements, relative depletion in K and Rb, low Pb/Ce, Rb/La, Rb/Sr ratios and $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios (for values see above) are consistent with the presence of the HIMU-OIB asthenospheric source characteristics (Zindler and Hart, 1986; Weaver, 1991a, b; Chauvel et al., 1992). However, the same characteristics are typical for magmas derived from metasomatized lithospheric mantle and these two sources can be hardly distinguished from each other.

The presence of carbon of deep origin, as inferred from C isotopic data, is typical for lithosphere metasomatized either by carbonatite melts or by CO_2-saturated silica melts in both the ocean and continental environments (Menzies et al., 1985; Green and Wallace, 1988; Yaxley et al., 1991, 1998).

Carbonatite metasomatism produces anomalously high Zr/Hf, low Ti/Eu ratios and relative Nb and Sr depletion

(Dupuy et al., 1992; Rudnick et al., 1993; Nelson et al., 1988; Yaxley et al., 1991, 1998). Zr/Hf and Ti/Eu ratios of the olivine melilitolite of the Osečná Complex slightly differ from those of the MORB and OIB; however, they do not reach values postulated for xenoliths that underwent strong carbonatite metasomatism (Zr/Hf = 100, Ti/Eu = 215–3 500; Dupuy et al., 1992; Rudnick et al., 1993; Nelson et al., 1988; Yaxley et al., 1991, 1998). This fact, along with the absence of negative Sr and Nb anomaly in PM-normalized multielement variations diagrams, contradicts the pure carbonatite-metasomatized lithosphere as a possible source of the magma.

Ultramafic magma of the OC probably originated by mixing of partial melts from the convecting asthenosphere and from the mantle lithosphere. The asthenospheric component shows signs of the HIMU-OIB source and mantle-lithosphere metasomatized either by fluids from the mantle-derived magma or by fluids released from the subducting slab in the past (sensu Wilson and Downes, 1991; Lustrino and Wilson, 2007).

The rocks of the ***Roztoky Intrusive Complex*** represent products of evolved magmas (according to high SiO_2 and FeO/MgO ratio and low MgO contents). Geochemical variations and correlation between major elements can be explained by low-pressure fractional crystallization. Negative correlation between MgO–SiO_2, TiO_2–SiO_2, P_2O_5–SiO_2 and CaO–SiO_2 and positive correlation between K_2O–SiO_2, Na_2O–SiO_2 and Al_2O_3–SiO_2 point to fractionation of ferromagnesian minerals (olivine, clinopyroxene), apatite and Fe-Ti oxides, whereas fractionation of plagioclase played only a minor role. This idea is supported by the trace element evolution (negative correlation between Ni–SiO_2, Cr–SiO_2 and positive correlation between Ba–SiO_2 and Rb–SiO_2 pairs).

The PM-normalized multielement variations diagrams and Sr and Nd isotopic ratios differ from those of the melilitic rocks of the Osečná Complex. The studied rocks of the Roztoky Intrusive Complex are geochemicaly (according to trace element and Sr and Nd isotopic data) very similar to the trachybasaltic lavas (Děčín Formation of Cajz et al., 1999) of the České středohoří Mts. (Fig. 5).

Parental magma of trachybasaltic lavas was derived from partly enriched mantle source and magma evolved by the assimilation – fractional crystallization (Ulrych et al., 2002). The same origin can be supposed for the studied rocks of the Roztoky Intrusive Complex. However, fractional crystallization processes alone cannot explain all compositional variations within the Roztoky Intrusive Complex rock suite, particularly the variations of trace elements and Sr-Nd isotopes. The high contents of incompatible trace elements as LREE, Th and Ba in the sodalite syenites suggest that it is unlikely that these rocks are simply products of continuous fractional crystallization of alkaline basaltic magma and may point to assimilation of some crustal material. The fractional crystallization and/or assimilation – fractional crystallization was likely accompanied by, e.g., a late-magmatic transfer of volatile fluids containing Zr, U, Th and REE as implied by the occurrence of rare Zr-minerals, which concentrate these elements in the sodalite syenite and "tinguaites" (Ulrych et al., 1992).

The carbonates of veins penetrating the monzodiorite body at Roztoky represent products of hydrothermal fluids with dominance of water of shallow circulation and influence of deep-seated CO_2 (Pivec et al., 1998b).

However, variations in the Sr-Nd isotopic compositions of individual rock types, in spite of their similar petrography and whole-rock chemistry, suggest variable crustal contributions and/or a heterogeneous mantle source. Numerous gneissic and granite xenoliths, as well as metasomatized mantle xenoliths in volcanic rocks of the České středohoří Mts. play a substantial role in geochemical variations of hypabyssal and dyke rocks of the Roztoky Intrusive Complex (Skála et al., 2013).

Metasomatism of mantle lithosphere beneath the Bohemian Massif

Parental magma of the melilitic rocks of the Osečná Complex was probably derived from a mantle enriched in incompatible elements and/or produced by very low-degree partial melting of the mantle source. To find the time of formation of such anomalous mantle segment we studied geochemical features of magmatic rocks of older magmatic episodes in the Bohemian Massif (the Early and Late Paleozoic). For such purpose, we used data for the Upper Paleozoic volcanics (Ulrych et al., 2006; Svobodová, 1999; Patočka et al., 1993) for the Lower Paleozoic magmatic rocks.

Whereas the Upper Paleozoic volcanics geochemicaly differ from the melilitic rocks of the Osečná Complex, some geochemical features of the Lower Paleozoic (Cambrian) gabbroic and dioritic rocks of the Orlovice Complex, southwestern Bohemia (Svobodová, 1999) are similar to those of melilitic rocks of the Osečná Complex. Principal common features of these two complexes are negative Rb and K anomalies in the PM-normalized multielement variation diagrams. Nevertheless, we presume that the parental magma of the Orlovice Complex could have been probably derived from the ocean lithosphere source (Depleted MORB Mantle – DMM-like) or from an amphibole- and/or phlogopite-bearing mantle source.

Nd and Sr isotopic ratios of the Cambrian rocks of the Orlovice Complex correspond to depleted mantle (Svobodová, 1999). Metasomatism induced by fluids derived from the subducted slab or by plume-derived magmas should shift the Sr isotopic composition in the direction to the Bulk Earth and cause the decoupling of Sr-Nd isotopes. We dispute this type of metasomatism as being the universal way of enrichment of lithospheric mantle beneath the Bohemian Massif. As inferred from Nd and Sr isotopic ratios of the Cambrian rocks of the Orlovice Complex, both the unaffected lithosphere and the metasomatizing agent must have had Nd and Sr isotopic compositions similar to that of depleted mantle.

Our idea on the formation of the anomalous mantle segment in the Early Cambrian is supported by the T_{DM} Nd-model ages of some Bohemian melilitic rocks (Chrastenský vrch Hill, 518 Ma – Pivec et al., 1998a).

Cambrian magmatism in the Bohemian Massif was probably related to active rifting in the ocean environment (Patočka et al., 1993, 1994). Metasomatism could have resulted from either (1) partial melting of the lithosphere and formation of metasomatized domains or (2) interaction of rising asthenospheric magma.

Metasomatism of the mantle lithosphere can increase the Rb/Sr ratio (McKenzie, 1989). Through time, $^{87}Sr/^{86}Sr$ isotopic ratio increases and the initial isotopic ratio moves inside the mantle array to the bulk Earth composition. However, a simple metasomatic process cannot shift isotopic ratios below the mantle array, as observed in melilitic rocks of the Osečná Complex. This can be explained by a decrease in the Rb/Sr ratio in the source. The Rb/Sr ratio decreases during partial melting of an amphibole- and/or phlogopite-bearing source. We therefore suppose that the mantle source was affected by partial melting some time prior to the Osečná Complex emplacement (cf. Lustrino and Wilson, 2007). It cannot be excluded that melting and metasomatism was a continuous process and that anomalous mantle domains were not formed during a single event.

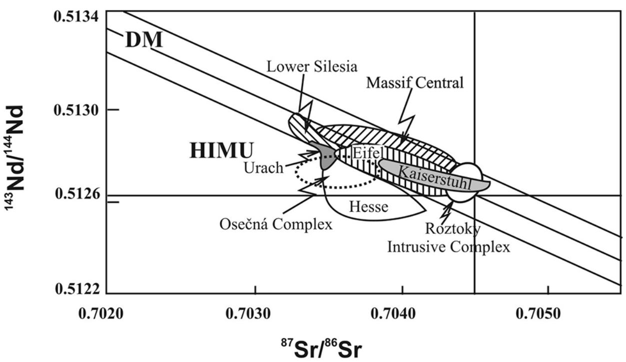

Fig. 6. Initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios for rocks of the Osečná and Roztoky complexes. Isotopic data for Cenozoic volcanic rocks of the Central European Volcanic Province are plotted for comparison. Data sources: Urach (Hegner et al., 1995), Massif Central (Downes, 1984; Chauvel and Jahn, 1984), Eifel and Hesse (Kramers et al., 1981; Worner et al., 1986; Wedepohl et al., 1994), Kaiserstuhl (Nelson et al., 1988), Lower Silesia (Alibert et al., 1987; Blustztajn and Hart, 1989), Osečná Complex (Pivec et al., 1998; Ulrych et al., 2008), Roztoky Intrusive Complex (Ulrych et al., 2000b; Skála et al., 2013).

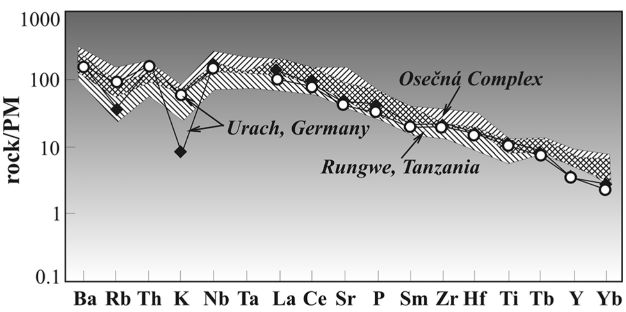

Fig. 7. Mantle-normalized incompatible trace element diagrams of melilitic rocks of the Osečná Complex. Data for Recent melilitic volcanic rocks from Rungwe, Tanzania (Furman, 1995) and Tertiary melilitic volcanic rocks from Urach volcanic field, SW Germany (Hegner et al., 1995) are plotted for comparison. Normalizing values after Sun and McDonough (1989).

Homogeneity or heterogeneity of mantle lithosphere?

Nd and Sr isotopic ratios of magmas extruded in the CEVP show a wide variation (Fig. 6): Urach (Hegner et al., 1995), French Massif Central (Downes, 1984; Chauvel and Jahn, 1984), Eifel and Hesse (Kramers et al., 1984; Wörner et al., 1986; Wedepohl et al., 1994), Kaiserstuhl (Nelson et al., 1988), Lower Silesia (Alibert et al., 1987; Blusztajn and Hart, 1989), Osečná Complex (Wilson et al., 1994; Pivec et al., 1998a; Ulrych et al., 2008), Roztoky Intrusive Complex (Wilson et al., 1994; Ulrych et al., 2000b; Skála et al., 2013). Such isotopic inhomogeneity can be explained by mixing of at least three different magma sources (cf. Haase and Renno, 2008). However, if we compare geochemical signatures of melilitic rocks of the Osečná Complex and those of the Urach volcanic field, SW Germany (Hegner et al., 1995), we find a very similar pattern in the PM-normalized multielement variation diagrams (Fig. 7) of the two mentioned groups of melilitic rocks. Steep REE pattern in the melilitic rocks of the Urach volcanic field (Hegner et al., 1995) can be explained by a higher amount of residual garnet, lower partial melting, or an enriched lithospheric mantle source. Similar geochemistry of the mantle source can be supposed. The above proposed model of continuous partial melting can explain the isotopic heterogeneity of extruded magmas, although plume component in some of them was present, too (Hegner et al., 1995).

We also compared melilitic rocks of the Osečná Complex to other classical occurrences of melilitic rocks in the world (Rungwe, Tanzania; Furman, 1995). The studied olivine melilitolites of the Osečná Complex have trace element compositions comparable to those of recent melilitic rocks of Rungwe, Tanzania (Furman, 1995). We therefore conclude that metasomatized mantle lithosphere is a common feature of sublithospheric mantle. It is probably geochemically more homogeneous than sometimes supposed, occurring more commonly in the continental environment than in oceanic environment.

Rare melilitic rocks occur along the margin of the Cenozoic Ohře Rift zone (Eger Graben), which runs parallel to the major inhomogeneity within the Variscan Bohemian Massif which was reactivated during the Alpine orogenic movements. The melilitic rocks are a result of the initial stages of continental rifting during Late Cretaceous to Early Paleocene.

Conclusion

1. Parental alkaline magmas of the Osečná Complex and the Roztoky Intrusive Complex were derived from the convecting asthenosphere and from the mantle--lithosphere by mixing of partial melts. The asthenospheric component shows similarities to the source of the HIMU--OIB type. Melilitic magma of the Osečná Complex should be derived from metasomatized-sublithospheric mantle with garnet, phlogopite and/or amphibole in the residuum. Mildly alkaline hypabyssal rocks of the Roztoky Intrusive

Complex were generated from an enriched mantle source affected probably by assimilation of some crustal material.

2. Parental magma of the melilitic rocks of the Osečná Complex was of near-primary mantle-derived composition. The major and trace elements and in particular the Nd-Sr isotopic compositions of the melilitic rocks suggest melting of a heterogeneous veined mantle source. This may have resulted from carbonate metasomatism related to carbonatitic magmatism during incipient rifting of the lithosphere.

3. Parental magma of the mildly alkaline rocks of the Roztoky Intrusive Complex was moderately evolved by fractional crystallization of olivine, clinopyroxene, apatite and Fe-Ti oxides, and assimilation-fractional crystallization (AFC) processes could have played an important role in the evolution of these rocks. The essexite, monzodiorite and monzosyenite dykes and most of the lamprophyric dykes can be best explained by ~8–50 % crystallization of essexite parent magma with a limited contribution of crustal material. The carbonate veins in the Roztoky monzodiorite body are of common hydrothermal character generated from water of shallow circulation mineralized by deep-seated CO_2.

4. Metasomatized sublithospheric mantle was probably formed during the Lower Cambrian magmatic episode in the Bohemian Massif. Melts that formed by partial melting of either asthenospheric or lithospheric depleted mantle probably acted as metasomatizing agents.

5. Metasomatized lithospheric mantle is a common feature of subcontinental lithosphere including lithosphere beneath the CEVP. It is probably formed by a more complex continuous process involving partial melting and subsequent metasomatism of mantle lithosphere.

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Kenozoické alkalické vulkanické horniny s karbonatitovou afinitou v Českém masívu: zdroje a vývoj magmatu

Za účelem stanovení zdrojů alkalických magmat kenozoické Středoevropské vulkanické provincie byly studovány melilitické alkalické horniny osečenského komplexu a slabě alkalické horniny roztockého intruzivního komplexu, obou se znaky karbonatitové afinity. V extrémně SiO_2-podsycených melilitických horninách osečenského komplexu nebyly zjištěny významné korelace mezi obsahy prvků jejich primárního chemického složení. Všechny existující geochemické variance v nich lze vysvětlit následnou metasomatickou přeměnou. Horniny reprezentují produkty primitivního plášťového magmatu. Obohacení inkompatibilními prvky, vysoké hodnoty Zr/Hf, Ce/Pb poměrů, relativní ochuzení o prvky těžkých vzácných zemin (HREE – Heavy Rare Earth Elements) a negativní K a Rb anomálie v primitivním plášťěm (PM-primitive mantle) normalizovaných multielementních variačních diagramech ukazuje na metasomatizováný plášťový zdroj s amfibolem a/nebo flogopitem a granátem v reziduu. Horniny řady essexit – monzodiorit – sodalitický syenit a s nimi spjaté diferenciované žilné horniny roztockého intruzívního komplexu se středními obsahy SiO_2, jsou ochuzené o kompatibilní elementy a jejich magma reprezentuje vyvinutou taveninu. Negativní korelace mezi SiO_2 a MgO, TiO_2, P_2O_5 a CaO a pozitivní korelace mezi

SiO_2 a K_2O, Na_2O a Al_2O_3 ukazuje na frakční krystalizaci olivínu, klinopyroxenu, Fe-Ti oxidů a apatitu. Horniny této řady geochemicky odpovídají trachybazaltickým lávám Českého středohoří a lze předpokládat jejich společný zdroj v plášťovém magmatu ovlivněném jistou korovou kontaminací. Na základě přítomnosti negativní K a Rb anomálie v primitivním pláštěm (PM-primitive mantle) normalizovaných multielementních variačních diagramech spodnopaleozoických magmatických hornin Českého masívu předpokládáme, že metasomatóza plášťové litosféry započala již v raném kambriu. Sr a Nd izotopické složení hornin osečenského komplexu se znaky HIMU--OIB a variance chemického složení vulkanických hornin Středoevropské vulkanické provincie mohou být vysvětleny průběžným tavením a následnou metasomatózou plášťové litosféry. Geochemická podobnost ultramafických hornin z různých magmatických komplexů ve světě ukazuje na skutečnost, že subkontinentální metasomatizovaná plášťová litosféra je patrně homogennější, než jak se mnohdy předpokládá.