Cenozoic intraplate volcanic rock series of the Bohemian Massif: a review

Jaromír ULRYCH[1], Edvín PIVEC[1], Miloš LANG[1], Kadosa BALOGH[2] and Vladimír KROPÁČEK[3]

[1] *Institute of Geology, Academy of Sciences of the Czech Republic, Rozvojová 135, 165 02 Praha 6 - Suchdol, Czech Republic*
[2] *Institute of Nuclear Research, Hungarian Academy of Sciences, P.O. Box 51, H-4001 Debrecen, Hungary*
[3] *KROVE, Družstevní ochoz 3, 140 00 Praha 4, Czech Republic*

ABSTRACT. The young intraplate volcanism of the Bohemian Massif is an integral part of the Cenozoic Central European Volcanic Province associated with a rift system originated as a repercussion of the Hercynian foreland to the collision of the African and Eurasian plates. The alkaline volcanism was initiated by adiabatic decompression of updomed asthenospheric mantle developed in association with the Alpine Orogeny. The continuous Late Cretaceous to Quaternary volcanism of 79 (87?) to 0.26 (0.11?) Ma ages of the Bohemian Massif displays two principal maxima: (i) the pre-rifting event producing ultra-alkaline volcanism (79–49 Ma) and (ii) riftogenic event with alkaline volcanism (42–0.26 Ma). The bimodally distributed riftogenic volcanism is formed by two coexisting differentiation series: olivine nephelinite/basanite-trachyte and nephelinite/tephrite–phonolite. The volcanism of the Bohemian Massif is concentrated (more than 99 vol.%) in the Ohře (Eger) Rift (ENE–WSW) in addition to transverse structures such as the Labe and Odra Tectono-Volcanic Zones (WNW–ESE) and the Cheb–Domažlice Graben (NNW–SSE). Approximate volume and areal extent of the preserved volcanic products is about 180 km^3 and 1,100 km^2, respectively.

KEY WORDS: alkaline volcanics, Late Cretaceous–Cenozoic, Bohemian Massif, Central European Volcanic Province, Ohře Rift.

Introduction

The Late Cretaceous to Cenozoic (hereafter Cenozoic only) intraplate alkaline volcanism of the Bohemian Massif (Bohemian Massif Volcanic Subprovince – BMVS) is an integral part of the Cenozoic Central European Volcanic Province – CEVP (sensu Wimmenauer 1974; Kopecký 1978; Ziegler 1982). In the sense of Hoernle et al. (1995) the CEVP includes also the Western European Volcanic Province in France (Wimmenauer 1974). The CEVP is spatially and genetically associated with the Cenozoic rift system of Neoeurope which evolved as a repercussion of Variscan foreland to the later phases of the Alpine Orogeny (Sengor 1976; Laubscher 1988; Wedepohl 1994). The volcanism may be related to lithosphere flexuring associated with the orogenesis or to development of several small mantle hot spots. Presence of several smaller mantle plumes (600 km) in Central and Western Europe (Wilson and Downes 1991) is more consistent with the highly variable geochemical characteristics and the localized nature of both uplift and volcanism across the province than a single big hot spot of 2,000 km in diameter. However, results of seismic tomography suggest the existence of a large, sheet-like region of upwelling in the upper mantle which extends from the eastern Atlantic Ocean to central Europe and the western Mediterranean. A belt of extension and rifting in the latter two areas appears to lie above the intersection of the centre of the upwelling region with the base of the of lithosphere (Hoernle et al. 1995).

The volcanism manifested in the foreland of the Alpine–Carpathian system near the contact of the West European and East European Platforms is clearly associated with Cenozoic taphrogenic structures. Nevertheless, the "Cenozoic volcanism" of the BMVS (also in other subprovinces of CEVP) had started already during the Late Cretaceous (79 Ma – Ulrych and Pivec 1997 or even 87? Ma – Kopecký 1987–1988) as a precursor of rifting in association with earlier phases of the Alpine Orogeny or an independent mantle plume? The Late Cretaceous to Lower Eocene volcanism of the BMVS corresponds both in structural position and geochemical character to ultra-alkaline magmatism occurring in no association to rifting as described by Le Bas (1987a) from Eastern Africa and Rhine Graben. Rejuvenation of NW–SE transform faults in the BM between the Labe and Odra lineaments in the Jurassic to Early Cretaceous time was mentioned by Mísař (1987). Characteristically, the Late Cretaceous to Paleocene volcanism occurs exactly in the same area, i.e. in the Labe (LTVZ) and Odra (OTVZ) tectono-volcanic zones outside the OR. Both regions with pre-rifting volcanism in the BMVS, i.e. the Osečná Complex in N Bohemia (Pivec et al. 1986, 1998; Ulrych et al. 1988; Ulrych and Pivec 1997) and the Dvůr Králové n.L. Complex in E Bohemia (Ulrych et al. 1996), occur in spatial association with the Lusatian Fault which represents the northern master fault of the LTVZ. Kopecký (1997–1988) listed the oldest Upper Createaceous volcanics of the BM (87 Ma) also from the OTVZ in Poland.

Cenozoic volcanism of the Bohemian Massif Volcanic Subprovince

The young volcanism of the BMVS is mostly Tertiary in age (prevalently Late Eocene– Miocene), much less is Late Cretaceous to Early Eocene or of Pliocene to Pleistocene ages. The youngest volcanic products are dated as 0.26 (Šibrava and Havlíček 1980) and 0.42 (0.11?) Ma (Wilson et al. 1994), respectively. The new independent alpha-recoil track, TL, ESR and fission track chronometry of Wagner et al. (1998) confirms the age span of the young BM volcanism as 0.90–0.17 Ma.

The continuous intraplate volcanism of the BMVS displays two principal maxima according to K/Ar dating:

(i) the pre-rifting volcanic event producing ultra-alkaline volcanism in lateral blocks of the later Ohře Rift – OR (79–49 Ma) in association with the older structure of the LTVZ (Mísař 1987), see comment above,
(ii) the riftogenic volcanic event producing a broad spectrum of alkaline volcanic products with the following main episodes
  - 43 to 16 Ma – the main Eocene to Miocene episode,
  - 13 to 9 Ma – the minor (about 1 vol.%) regionally limited (the Teplice–Bílina area inside the OR) Late Miocene episode,
  - 5.0 to 0.26 Ma – the final regionally limited (the Cheb

area in the OR and the Nízký Jeseník in N Moravia) Plio-Pleistocene episode.

The origin and space distribution of the Cenozoic volcanism in the BM is mostly explained by the taphrogenic model of the Bohemian Massif (Fig. 1). The volcanic products of the BMVS are, according to Kopecký (1978), associated with:

(i) the Ohře (Eger) Rift (ENE–WSW) in W and N Bohemia, Germany and Poland representing active, mostly low-volcanicity type rift (sensu Barberi et al. 1982; Ulrych and Pivec 1997),
(ii) the Labe (Elbe) Tectono-Volcanic Zone (ESE–WNW) prevalently in E and central Bohemia, and extending into Saxony,
(iii) the Odra Tectono-Volcanic Zone (WNW–ESE) found mostly in Poland, with only sporadic occurrences in N Moravia and Silesia in the Czech Republic,
(iv) the Cheb–Domažlice Graben (NNW–SSE) in W Bohemia.

Cenozoic volcanism of the BMVS survives as relicts only, represented mostly by extrusive products, uncovered feeding apparati and high-level intrusive bodies. The maximum inferred present-day thickness of the volcanic products reaches 400 m in the České středohoří Mts. and 500 m in the Doupovské hory Mts. (Shrbený 1995). Approximate volume and areal extent of the preserved volcanic products (volcanics only!) of the BMVS is according to Shrbený (1995):

- Doupovské hory Mts. 123/594
- České středohoří Mts. 52/472
- Other (central Bohemia, N Bohemia, N Moravia) 0.9/12
- Total BMVS, approx. 180 km^3/1,100 km^2

The data on areal extent and age of volcanics of the BMVS are comparable with other volcanic areas of the CEVP (cf. Wedepohl et al. 1994 – the total volcanic area extent including non-volcanic rocks!): Hegau (300 km^2/15–7 Ma), Kaiserstuhl (90/18–14), Vogelsberg (2500/24–9), Westerwald (1200/30–5), Rhön, Heldburg (1300/42–11), Hessian Depression (5200/20–8), Siebengebirge (900/28–6), W Eifel (1800/45–24), E Eifel (400/0.7–0.01).

The age distribution of volcanics of the Cenozoic BMVS determined from a set of 250 (partly unpublished) K/Ar determinations is shown in Fig. 2: it spans the interval of 79–0.26 Ma. This figure exhibits a coherent distribution of volcanic activity after 43 Ma with several separate pre-rift Late Cretaceous to Early Eocene volcanic episodes (79–49 Ma). The presence of a quantitatively significant age peak for the Plio-Pleistocene episode results from the relatively high accumulation of age data for these very attractive young volcanic products in W Bohemia and N Moravia and Silesia.

The complete set of Upper Cretaceous and Cenozoic volcanic rocks of the BMVS is presented in the TAS diagram (Le Maitre ed. 1989) and three-D histogram in Fig. 3 A, B. Two main maxima in Fig. 3 A (field I) and peaks (Fig. 3 B) correspond to the bimodal riftogenic series (ii), the small maximum in Fig. 3 A (field II) and peak (Fig. 3 B) to the unimodal pre-rift series (i). A statistical analysis (1,332 chemical analyses of Cenozoic volcanic rocks of the BMVS) of the main rock-forming oxides (at significance level of 0.05) results in a normal distribution (Kropáček 1985). Processing the whole set of chemical data, expressed as average chemical compositions of 28 main rock

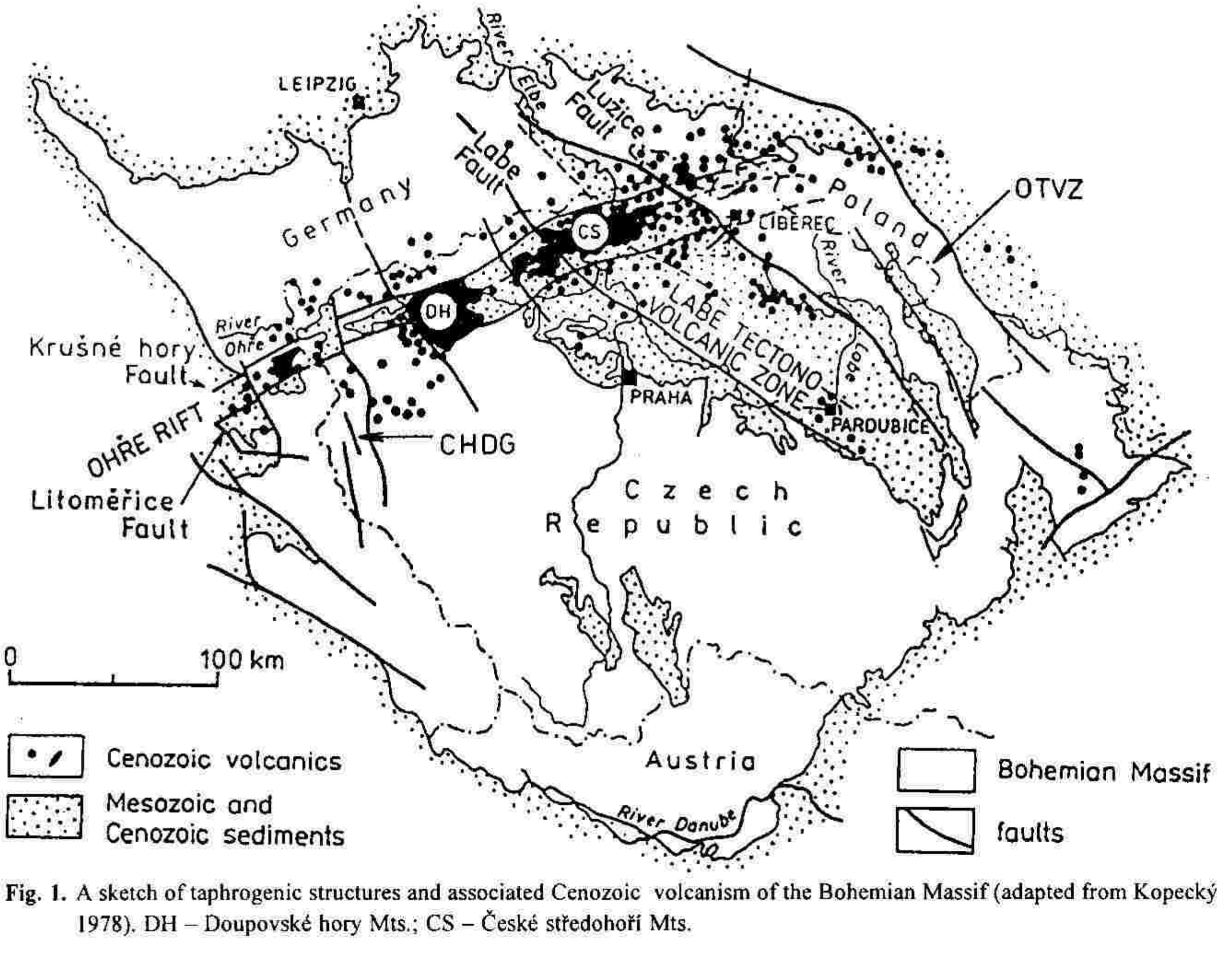

Fig. 1. A sketch of taphrogenic structures and associated Cenozoic volcanism of the Bohemian Massif (adapted from Kopecký 1978). DH – Doupovské hory Mts.; CS – České středohoří Mts.

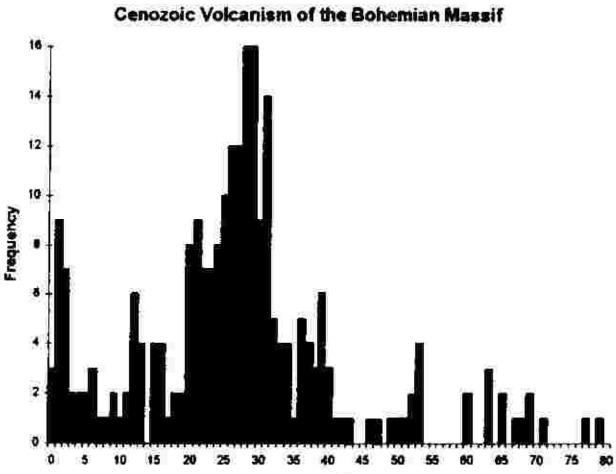

Fig. 2. Age distribution of the Cenozoic volcanic rocks of the Bohemian Massif Volcanic Province based upon a set of 250 K/Ar analyses (partly unpublished); vertical axis – frequency of K/Ar experimental data.

types of the BMVS (see Table 1), reveals the presence of two differentiation series (confirmed by cluster analysis – Kropáček 1985):

- olivine series (with normative olivine in mafic rock types) can be described by the equation (oxides in wt.%); correlation factor (0.94)

  $Na_2O + K_2O = - 0.8714 + 0.0169\ SiO_2 + 0.00297 * (SiO_2)^2$ comprising 15 rock types (in particular: polzenite–olivine melilitite/olivine nephelinite–basanite–alkali olivine basalt–camptonite/monchiquite–trachyandesite–trachyte/quartz trachyte) of both fundamental differentiation series of the BM (i) – pre-rift association (ultramafic members) and (ii) – rift association forming the weakly alkaline olivine nephelinite/basanite–trachyte series (WAS)
- olivine-free series described by the equation; correlation factor (0.97)

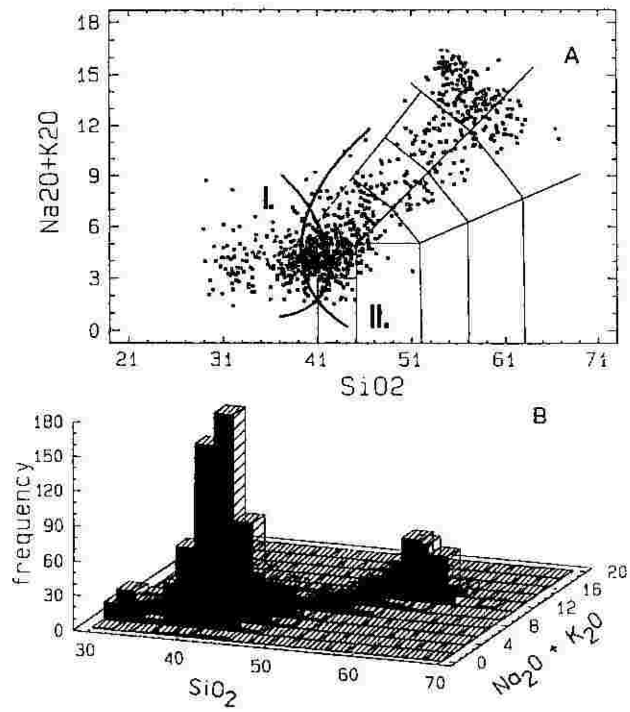

Fig. 3. Cenozoic volcanic rocks of the Bohemian Massif Volcanic Province (1,332 chemical analyses) in: (A) SiO_2 vs. $Na_2O + K_2O$ diagram (Le Maitre ed. 1989) and (B) 3-D histogram; vertical axis – frequency of chemical analyses. All chemical data in wt.%. Two main maxima (field I) in Fig. 3 A and peaks in Fig. 3 B correspond to the bimodal riftogenic series (ii), the small maximum (field II) in Fig. 3 A and peak in Fig. 3 B to the unimodal pre-rift series (i).

$Na_2O + K_2O = 38.5036 - 1.8414\ SiO_2 + 0.02504 * (SiO_2)^2$ comprising 10 rock types (in particular: melilite nephelinite/nephelinite–tephrite–alkali basalt–trachybasalt–gauteite–phonolite) related exclusively to (ii) – rift association form-

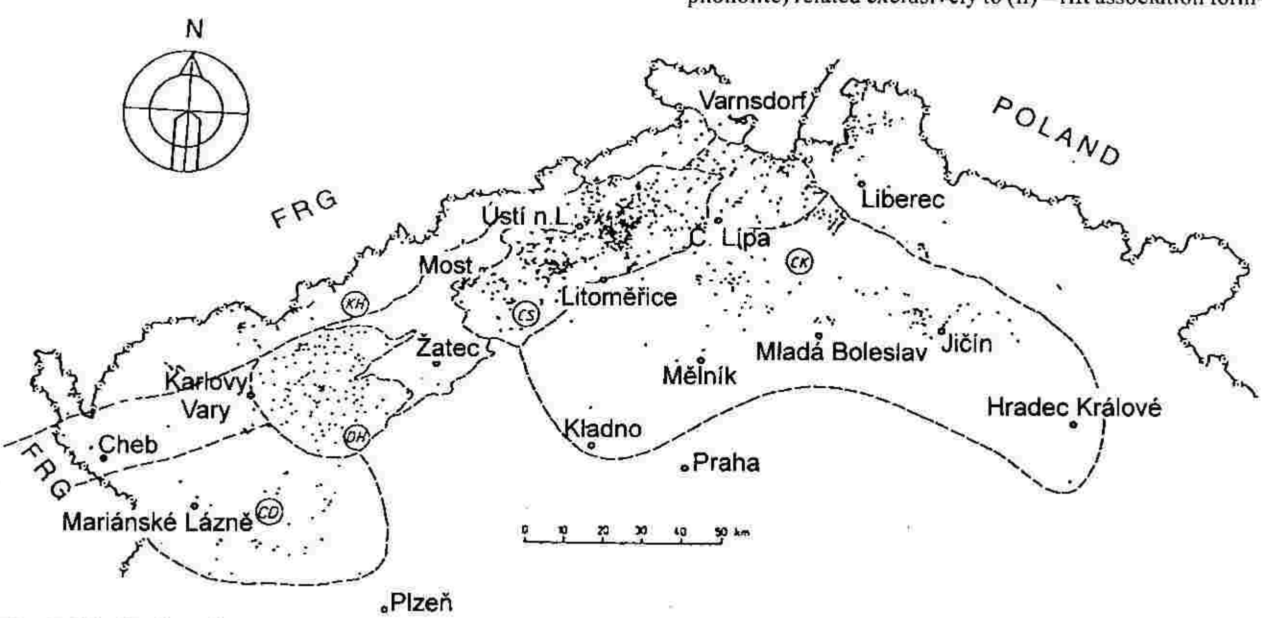

Fig. 4. Distribution of the Cenozoic volcanism of the Bohemian Massif Volcanic Province into the characteristic areas (adapted from Shrbený 1995). CD – Cheb–Domažlice Graben; DH – Doupovské hory Mts.; KH – Krušné hory Mts.; CS – České středohoří Mts.; CK – Bohemian Cretaceous Basin.

ing the strongly alkaline nephelinite/tephrite–phonolite series (SAS).

Areas of Cenozoic volcanism of the Bohemian Massif Volcanic Subprovince

The Cenozoic volcanism of the BMVS is concentrated in particular in the following areas (Fig. 4 – adapted from Shrbený 1995) represented by characteristic rock series:

The Ohře Rift

I. Area N of the Lužice/Lusatian Fault continues up to Lusatia and occurs mostly along the border with Germany and Poland. Products here are very similar to rock series II (a) and (b) (described below). Of the two subgroups, the widespread effusive products of rock association (b) (41–20 Ma) are most characteristic (Pfeiffer et al. 1984; Kaiser and Pilot 1986; Alibert et al. 1987).

II. Northernmost part of the rift (in particular between the České středohoří Mts. and the Lusatian Fault (Fig. 5 A, B):

(a) unimodal polzenite – olivine melilitite/olivine nephelinite series with hypabyssal olivine melilitolite (Fig. 5 A, field I – Osečná Complex of Pivec et al. 1986, Ulrych et al. 1988, Polzenite Formation of Shrbený 1995) – precursor of the Ohře Rift formation (79–49 Ma – Ulrych and Pivec 1997, Pivec et al. 1998). Cognate Zeughausgangzug in Saxony formed by polzenites was dated at 71 Ma, Pfeiffer 1994),

(b) bimodal basanite/olivine nephelinite – phonolite series (Fig. 5 A, field II partly overlapping with field I) of rift association (40–24 Ma; 34 Ma – Pivec et al. 1998 in the Osečná Complex); presence of two groups of phonolitic derivatives was established

- group I (sensu Le Bas 1987) originated by differentiation of plagioclase from a basanitic magma (low in Sr, Ba and high in Rb, Th) and corresponds mainly to aphyric type A phonolite (Wilson et al. 1995) which is similar to rhyolite and is generated by extreme differentiation of type B phonolite,
- group II (sensu Le Bas 1987) originated by fractionation of olivine-poor to olivine-free nephelinites and is often associated with carbonatites and ijolites (high in Sr, Ba and low in Rb, Th) and corresponds most closely to porphyritic type B (Wilson et al. 1995) which is similar to trachyte,

Rock type	P		OMN		Ne		Ha		An		ON		Pb	
No. of samples	20		31		56		17		36		136		14	
	x_o	s_x	x_o	s_x	x_o	s_x	x_o	s_x	x_o	s_x	x_o	s_x	x_o	s_x
SiO_2 (wt.%)	34.01	2.56	38.14	1.02	38.17	1.59	40.13	1.29	40.15	1.50	40.61	1.39	42.28	0.79
TiO_2	2.26	0.27	2.58	0.42	4.43	0.83	3.77	0.91	4.22	0.53	2.94	0.69	1.80	0.58
Al_2O_3	8.43	1.54	9.77	1.70	11.44	1.76	13.55	2.32	11.99	1.30	12.11	2.10	7.09	1.23
Fe_2O_3	5.00	0.79	4.70	1.92	7.81	1.39	7.32	1.67	7.28	1.48	5.34	1.54	3.48	0.30
FeO	6.19	0.91	7.28	1.08	6.81	0.96	5.4	1.55	5.94	1.08	6.84	1.30	7.12	1.63
MnO	0.22	0.02	0.22	0.07	0.28	0.18	0.27	0.13	0.23	0.04	0.22	0.08	0.22	0.14
MgO	17.35	1.57	15.67	2.97	7.79	1.45	6.26	1.53	7.00	0.88	11.19	2.31	19.79	3.22
CaO	14.75	3.35	13.11	1.52	14.80	2.07	13.11	1.08	13.72	1.03	12.61	1.64	11.15	2.88
Na_2O	1.97	0.93	2.55	0.84	2.59	0.75	3.2	1.22	2.83	0.54	3.29	1.01	1.48	0.63
K_2O	1.77	0.36	1.41	0.29	1.26	0.61	1.67	0.72	1.03	0.53	1.03	0.37	0.87	0.44
P_2O_5	1.25	0.49	0.96	0.32	0.85	0.31	0.88	0.26	0.83	0.25	0.83	0.29	0.77	0.76
Σ	93.20		96.40		96.22		95.56		95.21		97.01		96.04	

Rock type	OB		Bn		B		Te		TA		Ph		Tr	
No. of samples	95		164		37		64		11		134		82	
	x_o	s_x	x_o	s_x	x_o	s_x	x_o	s_x	x_o	s_x	x_o	s_x	x_o	s_x
SiO_2 (wt.%)	42.74	1.77	42.70	1.55	45.88	2.10	46.35	2.83	52.70	2.83	55.95	1.63	56.94	3.04
TiO_2	2.78	0.62	3.08	0.64	2.86	0.68	2.21	0.63	1.71	0.55	0.28	0.13	0.59	0.38
Al_2O_3	13.48	1.74	12.97	1.38	15.21	1.21	16.86	1.51	17.50	2.15	21.25	2.41	19.63	1.09
Fe_2O_3	5.40	1.92	5.32	1.47	5.66	1.61	5.40	1.11	4.34	1.57	1.56	0.56	2.16	1.05
FeO	6.78	1.54	6.60	1.23	5.94	1.02	4.26	0.82	2.57	1.08	1.35	1.11	1.71	1.04
MnO	0.23	0.12	0.22	0.23	0.22	0.03	0.30	0.04	0.21	0.08	0.28	0.28	0.25	0.21
MgO	9.97	2.46	9.42	2.55	5.36	1.40	3.82	0.71	2.48	0.96	0.33	0.38	0.63	0.52
CaO	11.30	1.36	11.64	1.37	10.10	1.00	9.12	1.64	6.28	2.11	1.29	0.61	2.83	1.52
Na_2O	3.00	0.68	3.02	0.58	3.54	0.61	4.39	0.86	4.86	1.25	9.06	1.10	6.68	1.41
K_2O	1.25	0.52	1.25	0.49	1.94	0.65	2.56	1.22	3.71	0.63	5.29	0.56	5.36	0.72
P_2O_5	0.07	0.25	0.69	0.25	0.75	0.26	0.65	0.23	0.70	0.71	0.07	0.13	0.16	0.20
Σ	96.99		96.91		97.44		95.93		97.06		96.70		96.94	

Table 1 Average chemical composition of main Cenozoic volcanic rock types of the Bohemian Massif. P – polzenite; OMN – olivine melilite nephelinite; Ne – nephelinite; Ha – hauynite; An – analcimite; ON – olivine nephelinite; Pb – picrobasalt; OB – olivine basalt; Bn – basanite; B – basalt; Te – tephrite; TA – trachyandesite; Ph – phonolite; Tr – trachyte; x_o – arithmetic mean; s_x – standard deviation.

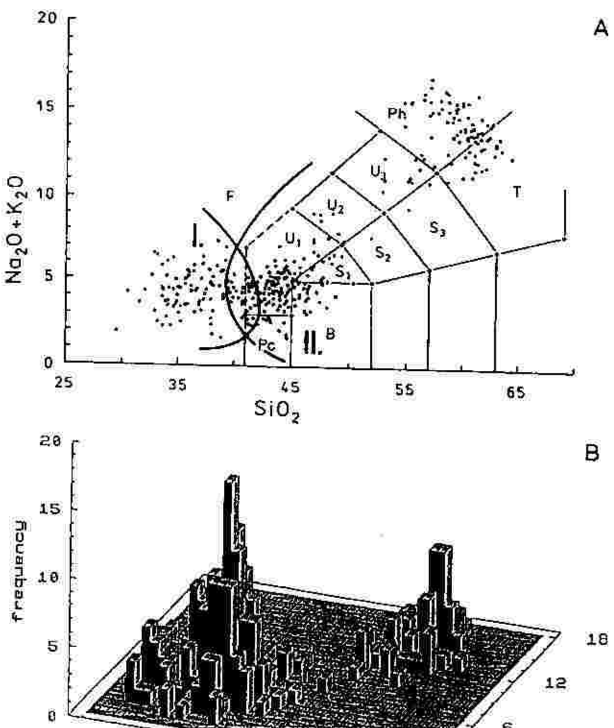

Fig. 5. Cenozoic volcanic rocks of the northern part of the Ohře Rift between the České středohoří Mts. and the Lusatian Fault in: (A) SiO_2 vs. $Na_2O + K_2O$ diagram and (B) 3-D histogram; vertical axis – frequency of chemical analyses. All chemical data in wt.%. Two main maxima (field I) in Fig. 5 A and peaks in Fig. 5 B correspond to the bimodal riftogenic series (ii), the small maximum (field II) in Fig. 5 A and peak in Fig. 5 B to the unimodal pre-rift series (i).

(c) picrobasalt unimodal series (9 Ma) association connected with the Lusatian Fault and basanite/olivine nephelinite association of the Kozákov volcano group (6.6–4.0 Ma) in the Labe Tectono-Volcanic Zone (see below).

III. České středohoří Mts.
  (a) two simultaneous series (polymodal association?) of the main volcanic phase (43–16 Ma); for age distribution of volcanic rocks within the OR see Fig. 6):
    - weakly alkaline series (WAS) olivine nephelinite/basanite/trachybasalt – trachyte represents the prevailing and most characteristic rift association occurring together with the hypabyssal association (HA, 31–26 Ma) mostly of transitional character to the SAS (monzodiorite/essexite – analcimized sodalite syenite – mafic and salic dyke differentiates of both WAS and SAS) associated with the Roztoky Volcanic Centre,
    - strongly alkaline series (SAS) (olivine-poor) nephelinite/tephrite – phonolite,
  (b) unimodal basanite (often analcimized) association of the Late Miocene (13–9 Ma) minor volcanic phase; estimated volume about 1 vol.%.

IV. Doupovské hory Mts. (Fig. 7 A, B)
  (a) unimodal olivine-poor nephelinite/tephrite/trachybasalt (28–22 Ma) association (strongly analcimized) with hypabyssal association (HA) theralite/monzodiorite/essexite – mafic dykes differentiates associated with the Doupov Volcanic Centre.

V. Southernmost part of the rift (between the Doupovské hory Mts. and the Franconian Line in Bavaria, Germany)
  (a) unimodal basanite – olivine nephelinite association (29–19 Ma, Lüttig 1998),
  (b) unimodal olivine melilitite/olivine nephelinite association (?5.0–0.26 Ma) present in the Cheb Basin and its environs, western Bohemia, only,

VI. Krušné hory (Erzgebirge) Mts. (region associated with the OR)
  - bimodal (olivine-poor) nephelinite (very rich in Ti)/tephrite – rare phonolite association (28–18 Ma) with differentiated Loučná–Oberwiesenthal ijolitic eruptive centre (52–31 Ma; Jiránek 1974; Pfeiffer et al. 1990) and K-rich dyke of "leucitophyres".

Labe Tectono-Volcanic Zone

(a) unimodal (olivine) clinopyroxenite/alkali clinopyroxenite intrusive association of the Dvůr Králové n.L. Volcanic Centre, E Bohemia (69 Ma – Ulrych et al. 1996) and others (Prosečné, Kopecký 1978) connected with the continuation of the Lusatian Fault. The age distribution of volcanic rocks within the Labe and Odra Tectono-Volcanic Zones and the Cheb–Domažlice Graben is given in Fig. 8,

(b) bimodal olivine-poor nephelinite – phonolite series (typically developed in the central Bohemia, 36–21 Ma),

(c) unimodal basanite/olivine nephelinite association connected with the Lusatian Fault – Kozákov volcano group (6.6–4.0 Ma); the Elbtalzone, Saxony (14–8.3 Ma; Pfeiffer et al. 1984; Kaiser and Pilot 1986).

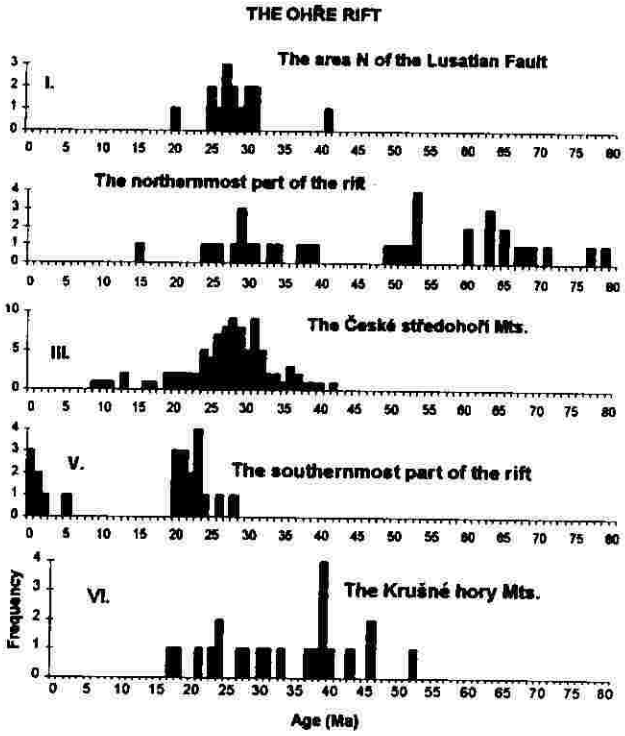

Fig. 6. Age distribution of Cenozoic volcanic rocks within the Ohře Rift. The Doupovské hory Mts. are not included due to the low number of data (22–25–28 Ma); vertical axis – frequency of K/Ar experimental data.

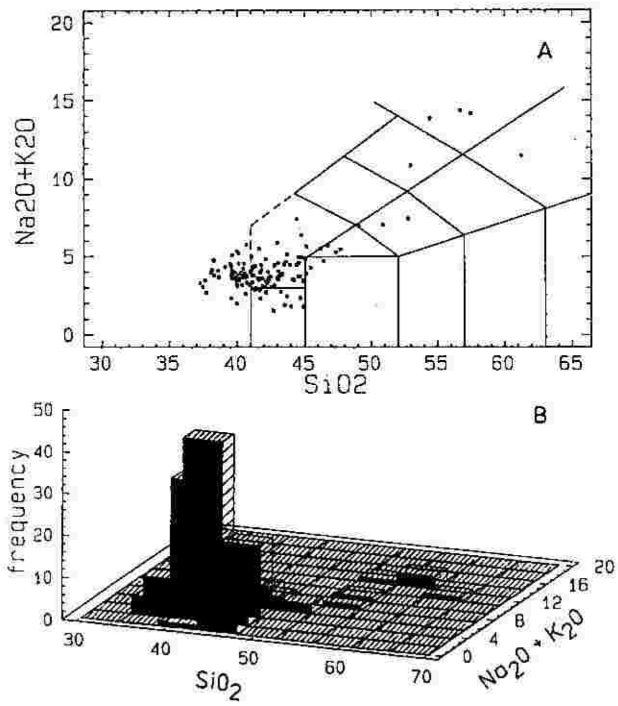

Fig. 7. Cenozoic volcanic rocks of the Doupovské hory Mts.: (A) SiO_2 vs. $Na_2O + K_2O$ diagram and (B) 3-D histogram displaying a unimodal rock association; vertical axis – frequency of chemical analyses.

Odra Tectono-Volcanic Zone

(mostly in Lower Silesia – Poland, partly in northern Moravia and Silesia – Czech Republic)

(a) unimodal olivine nephelinite/basanite – trachybasalt association with rare trachytes and phonolites (28–15 Ma; Kruczyk et al. 1977; Blusztain and Hart 1989; Kononova et al. 1991),

(b) unimodal olivine nephelinite (4.6–0.91 Ma) association, only in the Nízký Jeseník Mts., Moravia.

Cheb–Domažlice Graben (western Bohemia)

(a) unimodal olivine nephelinite/olivine melilitite – basanite association (30–16 Ma),

(b) two simultaneous weakly (WAS) and strongly alkaline (SAS) series of the Late Miocene phase (Pivec et al. in press):

- trachybasalt – trachyandesite – trachyte – rhyolite (12.9–11.4 Ma) weakly alkaline series,

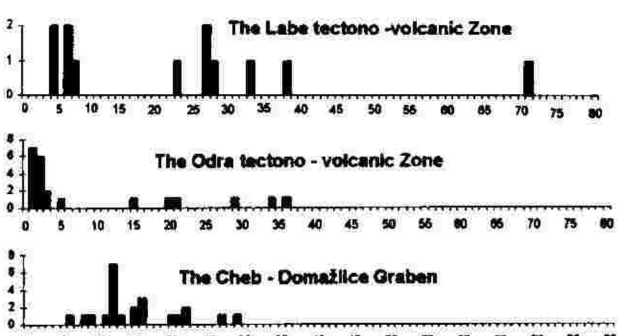

Fig. 8. Age distribution of Cenozoic volcanic rocks within the Labe and Odra Tectono-Volcanic Zones and the Cheb–Domažlice Graben; vertical axis – frequency of K/Ar experimental data.

- (olivine-poor) nephelinite/(olivine-poor) melilitite – tephrite/(basanite) (12.5–8.3 Ma) strongly alkaline series.

Conclusions

Chemical composition of young intraplate volcanism of the BM developed from the (i) pre-rift ultramafic, ultraalkaline magmas forming unimodal olivine melilititic/olivine nephelnitic series (Upper Cretaceous to Paleocene) to (ii) riftogenic olivine nephelinite/basanite – trachyte and (olivine-poor) nephelinite/tephrite – phonolite alkaline rock series (locus typicus of Atlantic province of Becke 1903 and Atlantic suite of Harker 1909) of both bimodal and unimodal characters (Eocene to Miocene) terminated by unimodal olivine melilititic/nephelinitic series (Pliocene to Quaternary) present in limited areas only.

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