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Late Miocene volcanic activity in the České středohoří Mountains (Ohře/Eger Graben, northern Bohemia)

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Abstract: First occurrences of superficial bodies of Late Miocene volcanic activity were found in the western part of the České středohoří Volcanic Complex (CSVC) and extended our knowledge of its volcanostratigraphy. Their K-Ar ages (9.59, 9.61 and 11.36 Ma) correspond to the age of alkaline basaltic rocks of the youngest known Intrusive Suite of this area. Unlike the previously known subvolcanic bodies of this system, the newly observed bodies are represented by superficial products: two scoria cones with remnants of lava flows and one exclusive lava flow produced from a lava cone. The magmas forming all three occurrences are basanitic. Their primitive chemical composition Sr (0.70347–0.70361) and Nd (0.51279–0.51284) isotope ratios are similar to the products of the first and third volcanic formation of the CSVC. The proved existence of superficial products of the youngest volcanic formation, together with clear superposition relations to sedimentary formations and the chemical character of the youngest magmas in the central part of the Ohře (Eger) Graben support the stratigraphic scheme of volcanic activity in the České středohoří Mts. The eruptive style of the youngest formation volcanoes was purely magmatic (Strombolian) with no phreatic influence.

Key words: Upper Miocene, České středohoří, Štrbice Formation, volcanostratigraphy, geochemistry, K-Ar dating, cinder cone, basanite.

Introduction

The České středohoří Volcanic Complex (CSVC) is a classical area where volcanic rocks have been studied for at least 200 years. Nevertheless, its magmatic and eruptive history has not been completely reconstructed yet. The post-Variscan, intra-plate alkaline volcanism in the Bohemian Massif dates from the Late Cretaceous to Quaternary. It represents the easternmost extension of the Central European Volcanic Province (*sensu* Wilson & Downes 1991), developed in the northern foreland of the Alps. Two main volcanic complexes, the Doupovské hory Mts and the České středohoří Mts, dominate the Ohře (Eger) Graben (OG) in northwestern Bohemia (Fig. 1a), where the principal volcanic activity initiated in the latest Eocene and continued until the Early Miocene. Basaltic lavas and concomitant volcaniclastics (generated predominantly by auto- or hyaloclastesis — Cajz 2000) represent superficial products of both volcanic complexes. This volcanic period was followed by a major sedimentation period, filling the Most Basin between the České středohoří Mts and the Doupovské hory Mts volcanic complexes (e.g. Malkovský 1987; Rajchl et al. 2008). After the main sedimentation period (including coal deposition), the volcanic activity was reactivated, not only in the CSVC, with a much lower intensity.

The lithostratigraphic subdivision of superficial volcanic products of the CSVC has been proposed by Cajz (2000). Based on detailed fieldwork, it reflects superposition of lithostratigraphic units differing in their volcanology and petrography. This lithostratigraphic scheme is also supported by bulk-rock geochemistry and Sr/Nd isotopic composition of lavas (Cajz et al. 1999; Ulrych et al. 2001). The following four units were defined: (1) Ústí Formation, represented by olivine foidites–basanites; (2) Děčín Formation, formed mainly by tephrites and trachybasalts; (3) Dobrná Formation, represented again by effusions of olivine foidites–basanites; and (4) basanitic Štrbice Formation.

The Upper Miocene Štrbice Formation thus represents the youngest lithostratigraphic unit of the CSVC. Volcanic activity was restored after a period of magmatic quiescence, and the basaltic magmas of the Štrbice Formation penetrated Miocene sediments of the Most Basin. The age of the Štrbice Formation was deduced from its geological position and later supported by K-Ar radiometric dating (Shrbený & Vokurka 1985; Cajz et al. 1999). Despite the thorough documentation (Cajz 2000), this formation has not been accepted by some authors (e.g. Kukal in Šalanský 2004), as no corresponding superficial products were known. Volcanic bodies of this late magmatic activity are scarce and small in scale, their superficial products have mostly been destroyed by erosion, and the pertinence of

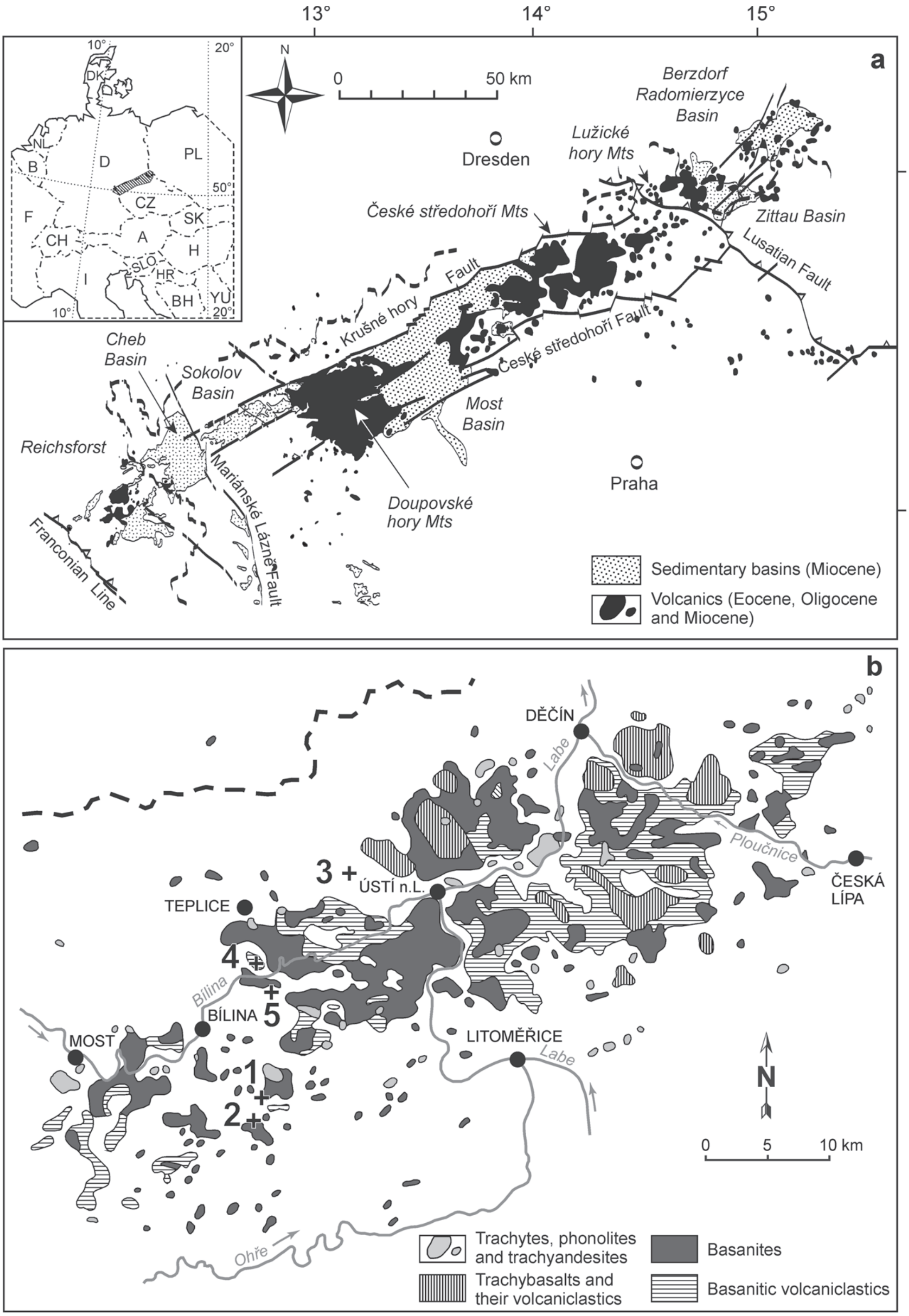

Fig. 1. **a** — Location of the České středohoří Volcanic Complex (CSVC) in the Ohře (Eger) Graben, NW Bohemia. Volcanic complexes and solitary bodies marked in black. **b** — The studied sites and their position in the CSVC: 1 — Ostrý, 2 — Hradišťko, 3 — Úžín, 4 — Křemýž, 5 — Štrbice-Světec feeder-and-sill system.

the below described relics to the youngest volcanic activity of the region has not been recognized before. Our paper has an ambition to fill this gap because these latest volcanics are important for the late tectonomagmatic evolution of the central part of the OG.

This study aimed at detailed description of volcanic products and their relations to ambient rocks, petrology, bulk-rock (incl. trace and rare earth elements) and mineral chemistry, isotopic composition and K-Ar radiometric dating.

Analytical methods

Bulk-rock analyses of the major oxides and selected trace elements (Cr, Ni, Cu and Zn) were performed in the labs of the Czech Geological Survey by combination of titration, FAAS, photometry, coulometry and X-ray fluorescence. The larger set of trace elements (including REE) were analysed in the Activation Laboratories Ltd., Ancaster, Canada, using lithium metaborate/tetraborate fusion and Inductively Coupled Plasma Mass Spectrometer detection.

For the isotope study, samples were dissolved using a combined HF-HCl-HNO_3 attack. Strontium was isolated by exchange chromatography techniques using Sr.spec Eichrom resin, Nd with TRU.spec and Ln.spec Eichrom resins. Isotopic analyses were performed on a Finnigan MAT 262 Thermal Ionization Mass Spectrometer in a dynamic mode using a double Re filament assembly. The $^{143}Nd/^{144}Nd$ ratios were corrected for mass fractionation to $^{146}Nd/^{144}Nd = 0.7219$, $^{87}Sr/^{86}Sr$ ratios assuming $^{86}Sr/^{88}Sr = 0.1194$. External reproducibility was set by repeated analyses of the La Jolla ($^{143}Nd/^{144}Nd = 0.511852 \pm 14$ (2σ; n = 23)) and NBS 987 ($^{87}Sr/^{86}Sr = 0.710247 \pm 26$ (2σ; n = 25)) isotopic reference materials. For further details see Míková & Denková (2007).

The K-Ar age determinations were made on bulk-rock samples, the same powders having been used for potassium determination. Potassium was determined by flame photometry using a CORNING 480 machine, sample solutions being bracketed by standards. Argon was extracted by fusion under vacuum conditions, with pure ^{38}Ar added as a "spike". The isotopic ratios were measured on a 15 cm radius magnetic sector-type mass spectrometer under static mode, built in Debrecen, Hungary. Details of the instruments, the applied methods and results of calibration have been published by Balogh (1985) and others. The atomic constants suggested by Steiger & Jäger (1977) were used for the calculation of ages. The analytical errors are quoted for the 68% confidence level (one standard deviation).

The analyses of rock-forming minerals were performed using a CAMECA SX-100 electron microprobe. They were carried out in wavelength dispersive spectrometers with beam diameter of 2 μm and accelerating potential of 15 kV. A beam current of 10 nA was measured on a Faraday cup. Counting time 10 s was used for all elements. The standards used were: SiO_2 [Si Kα], Al_2O_3 [Al Kα], diopside [Ca Kα], Fe_2O_3 [Fe Kα], barite [Ba Lα] and [S Kα], celestite [Sr Lα]. Data were reduced using the X-PHI correction.

Geochemical calculations and visualization of analytical data were performed using GCDkit software (Janoušek et al. 2006).

Geological setting

The youngest volcanic activity of the CSVC, postdating the Miocene lacustrine sedimentation, was first described by Pelikan (1895) from a lignite mine N of Bílina. Since then, several bodies in subvolcanic position have been discovered during lignite exploration and exploitation (e.g. Brus & Hurník 1984).

A system of intrusions in Miocene sediments was described by Macák (1963) from drill cores in an erosional relict of the Most Basin near Křemýž (Fig. 1b). Unfortunately, no cores were archived from these drillings, thus no material is available for detailed petrological and radiometric examinations. An Upper Miocene feeder-and-sill system is known from the wider area (about 6 km^2) around Štrbice and Světec villages with the central conduit at Pohradická hora Hill (13.0 ± 1.1 Ma in Cajz et al. 1999). Several sills have been reported from abandoned and reclaimed coal pits at Světecká výšina Hill and in the Štrbice sandpit (12.0 Ma in Shrbený & Vokurka 1985; 9.0 Ma in Kopecký 1987–1988; neither of these ages give analytical errors). A new detailed survey showed other sills and a possible parasitic dyke-modified vent of Hůrka Hill between Štrbice and Kostomlaty. Although the production of superficial volcanics is highly probable, no lava or pyroclastic facies of these conduits have been preserved.

All previously described Upper Miocene basalts are present in the form of subvolcanic bodies, with no superficial products preserved. Within the present detailed geological survey on the western margins of the CSVC, three Upper Miocene basaltic occurrences were newly observed. The first two are remnants of monogenic Strombolian cones with relics of lava flows emitted; the last one is a lava flow overlying the Miocene sediments.

Newly documented sites

Ostrý Hill (50°29′50″N, 13°51′38″E)

The basanitic vent of ***Ostrý Hill*** (9.6±0.5 Ma) located near the Měrunice village (Fig. 2) SE of Bílina most probably produced lavas now overlying the sands of the Most Formation preserved on Hradišťany Hill, NNE of the vent. The 30–60 meters difference in altitude of the lava and the recent top of the feeder (well documented in the cross-section) can be explained by different erosion of mostly loose cinder cone material and solid tabular lava body — the altitude of the real place of lava production from the cone should have been higher than the recent top. Nevertheless, we suppose younger tectonic activity which caused uplift of northern block(s) in the first tens of meters. The lavas also reached the areas to the NW of the vent where sand-dominated sediments are also overlain by relics of coherent basanitic bodies (Fig. 3).

Fortunately, a near-vent superficial pyroclastic rock surrounding the compact conduit has been preserved, nested on the sands of the Most Formation. It was formerly interpreted as a diatreme facies of a maar volcano (Kopecký 1987–1988). Pyroclastic deposits consist of irregular vesiculated scoria fragments reaching 3 cm in size. Scoria fragments show no

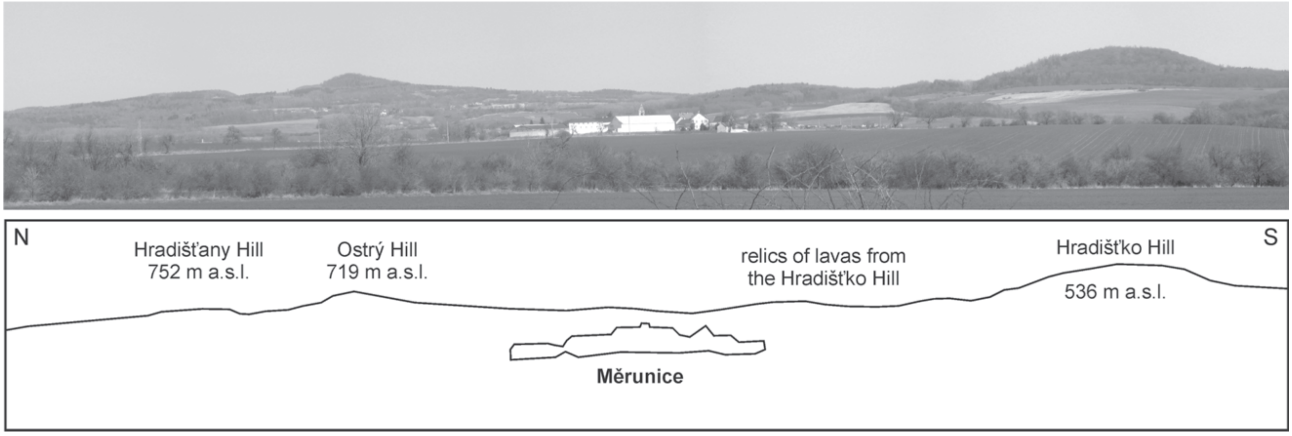

Fig. 2. A panoramic photo of the Ostrý and Hradišťko remnants of scoria cones. A view from the west.

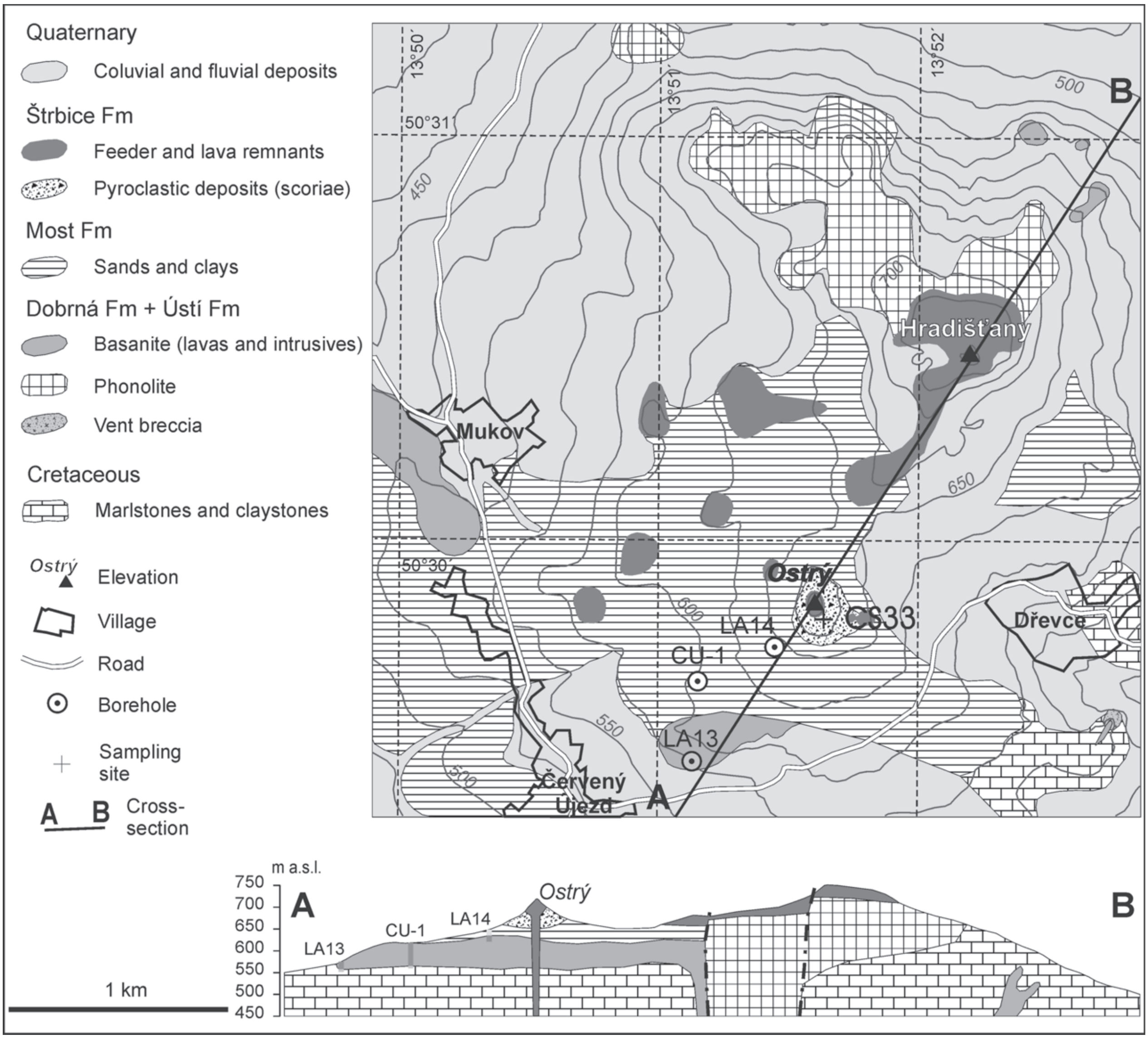

Fig. 3. A schematic map of the Ostrý scoria cone, the source of the Hradišťany Hill lava. Supposed faults indicated in the cross-section are not shown on the map because of the lack of indications of their course. Basanites of the older Ústí Formation in the cross-section also comprise bentonitized facies.

welding patterns; therefore, this deposit is interpreted as a product of Strombolian activity. Few unique cow-dung bombs, welded upon accumulation of non-welded scoria fragments, were observed (Fig. 4). The combination of non-welded scoriae with few cow-dung bombs suggests that these deposits represent upper-crater facies of a former cinder cone (e.g. Rapprich et al. 2007). The position of this scoria cone penetrating and resting upon Miocene sediments proved that the magmatic activity constituted a volcano after the deposition of the Most Formation sediments. No evidence for previous phreatomagmatic activity was found. On the other hand, a remnant of an older scoria cone buried by Miocene sands can be seen in a nearby stream-gorge. Pyroclastic deposits of the older volcano consist of strongly altered, periclinally bedded scoriae. No further analyses or radiometric dating could be obtained due to the high degree of weathering. Based on the geological setting and on analogy with the surrounding bodies, this older scoria cone can be assigned to the preceding Dobrná Formation.

Fig. 4. A cow-dung bomb welded upon non-welded scoriae at Ostrý Hill.

Hradišťko Hill *(50°28′27″N, 13°50′26″E)*

The ***Hradišťko Hill*** between the villages of Řisuty and Měrunice (see Fig. 2) represents a multiphase coherent conduit. The Upper Miocene (9.6 ± 0.4 Ma) scoria cone with a basanitic feeder overlies a remnant of Lower Miocene (20.72 ± 0.94 Ma) picrobasalt-basanite feeder. The earlier picrobasalt-basanite activity was significantly more widespread; this event is represented by several remnants of lavas, coherent and clastic conduits (Fig. 5). The age of the volcanic activity corresponds well with the age of lava excavated in a nearby quarry on Stříbrník Hill (19.2 Ma — Lustrino & Wilson 2007; no errors given). This lava could also be assigned to an early Hradišťko source-vent.

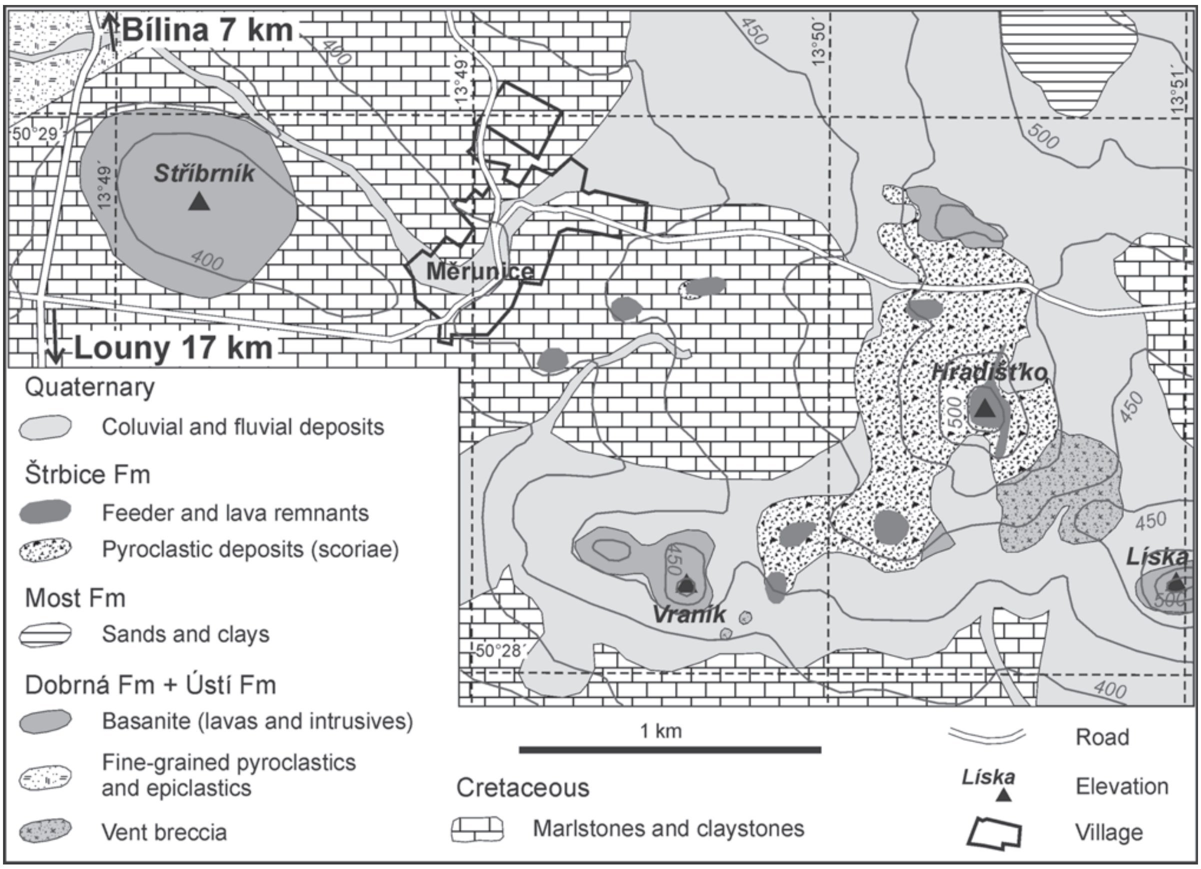

Fig. 5. A schematic map of the Hradišťko scoria cone and erosional remnants of lavas emitted to the west.

Younger basanitic volcanism is preserved in the form of a scoria cone relict. Pyroclastic deposits consist of highly vesiculated and non-welded, undeformed solid scoria fragments with significant inter-clast voids (Fig. 6). The diameter of common scoria fragments ranges from 1 cm to 10 cm. Scarce bombs are of spindle shape. Bedding planes are poorly visible but appear to dip outward, corresponding to a proximal wall facies on outer volcano slopes. In a unique sample, a small piece of silicified wood was observed within the scoria deposit (Fig. 7).

Fig. 6. Non-welded scoria fragments at the Hradišťko scoria cone. Note the preserved voids among individual fragments. A 1 Euro coin represents the scale.

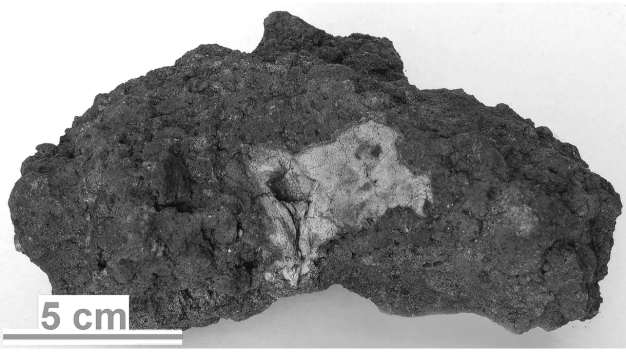

Fig. 7. A silicified wood fragment in scoriae of Hradišťko Hill.

Lava flow near Úžín (*50°41′14″ N, 13°57′08″ E*)

The construction of a new segment of highway from Prague to Dresden (D8, Exit 74), touching the NW margin of Ústí nad Labem, required excavations in the extreme NE part of the Most Basin, where the basin adjoins the northern part of the CSVC. Deposits of wasted clayey material most probably produced at the beginning of mining activities for lignite were exposed during construction. The oldest geological maps (Hibsch 1926) already document this waste deposit and not the lava beneath. Columnar-jointed basanitic lava (11.4 ± 0.4 Ma) overlies clayey sediments of the Most Basin (Fig. 8). The columns are vertical, 40–80 cm in diameter and relatively regular 5- to 6-angular. The preserved thickness of the lava flow reaches maximum 3 m (Fig. 9). A maximum 30 cm thick layer of hyaloclastic-type breccia is present at the bottom of the flow. Hyaloclastesis was caused by an interaction of lava with the underlying water-saturated sediments. These sediments are well-stratified clays to sandy clays of two different colours. Greyish blue fine clay in 5–10 cm thick layers alternates with brownish red clays to sandy clays in layers 20–30 cm thick (see Fig. 8 for details). This stratified sequence was excavated to the depth of 2 m below the base of the lava flow but its base was not reached. Its origin can be explained by changing source areas for the sedimentary material. The bluish clay is typical for the Most Formation and originated from material transported over a longer distance in the ba-

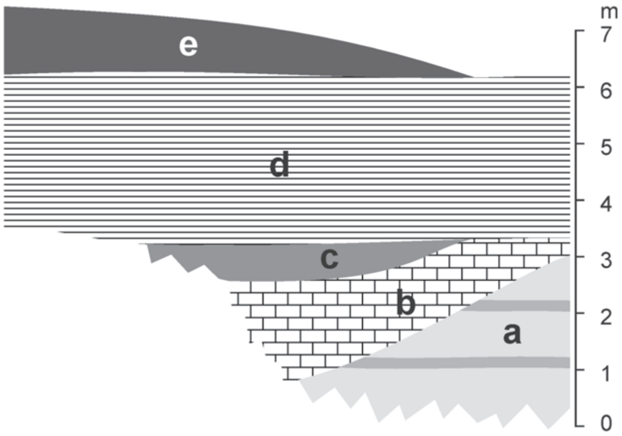

Fig. 8. A schematized section of the volcanic and sedimentary deposits exposed during the construction of highway D8 at Úžín. **a** — alternation of yellow volcaniclastic clays (each of 3 layers is ca. 80 cm in thickness) and light grey lacustrine clays of the Miocene Most Basin (approximately 20 cm thick — two intercalations were exposed); **b** — 1.5 m of greenish volcanogenic clays filling a paleo-valley; **c** — 0.7 m of greyish-violet clay overlying the green volcanogenic clay and filling the rest of the paleo-valley; **d** — 3–4 m of greyish-yellow volcanogenic sandy clays burying the flat paleo-relief; **e** — an olivine basalt lava flow.

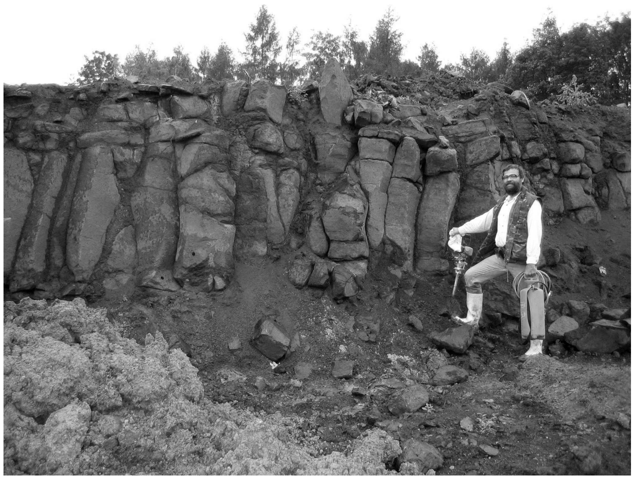

Fig. 9. Columnar-jointed basanitic lava excavated during the construction of highway D8. (See first author serving as a scale.)

sin. The latter material is supposed to be a product of multiple events of re-sedimentation of hyaloclastics that belong to the Ústí Formation (the oldest volcanism of the CSVC) and were exposed only a few hundred meters to the SW.

The lava flow exposed near Úžín was most probably emitted from the vent located on Jedlová hora Hill, some 3 km to the NE. This elevation is now covered by basanitic lava blocks reaching up to 1.5 m in diameter (Fig. 10), but no outcrop can be found. No pyroclastic deposits were observed — probably due to the activity of volatile-poor magma, producing solely lava flows with no concomitant eruptive activity (Head & Wilson 1989). Alternatively, pyroclastic deposits may already have been eroded. The Jedlová hora Hill conduit partly penetrates older basaltic sequences of the Ústí Formation. Its magmatic material, corresponding to the Úžín lava in its petrology, ascended along the fault cutting older volcanic products and constituting their limit against Cretaceous sediments.

Fig. 10. Basanitic lava disintegrated into blocks at Jedlová hora Hill.

Petrography and geochemistry

Petrography and mineral chemistry

All the studied rocks are of similar petrography. They are classified as basanites and consist (in order of decreasing abundance) of clinopyroxene, olivine, Ti-magnetite, plagioclase and nepheline. The rocks are fine-grained with phenocrysts reaching some 2 mm and scarcely 5 mm. The phenocrysts are represented solely by olivine and clinopyroxene.

Olivine phenocrysts are common in the rocks of the Úžín lava and Hradišťko cinder cone, maximum 5 mm in diameter. On the other hand, olivine in the conduit of Ostrý Hill is present only in the form of small crystals in matrix. Olivine crystals from different sites vary in their composition, reflecting slight differences in bulk-rock chemistry and crystallization history (Table 1). The most magnesian olivines are present in the silica-poorest rock at Ostrý Hill, with forsterite component varying from Fo_{92} in the cores to Fo_{85} in the rims. More differentiated olivine crystals at Hradišťko Hill range from $Fo_{90.5}$ in cores to Fo_{75} in rims. A slight differentiation was documented on scarce fresh olivine crystals from the Úžín lava. Olivine crystallization initiated with the composition of Fo_{87} in the cores and terminated with Fo_{77} in the rims.

Clinopyroxene is the most abundant mineral in the studied basanites. Its composition is relatively uniform and independent of the sampling site. A slight increase in ferroan component towards the rims was documented in all crystals (Fig. 11). A large portion of the data fit within the immiscibility field above the 50 % wollastonite limit in the common classification diagram recommended by IMA (Morimoto 1988 — Fig. 11a), mainly due to the presence of Ca-Tschermak's molecules. This is in disagreement with the real chemical composition of the analysed minerals, where Ca contents range between 0.87 and 0.93 *apfu* (Table 2, Fig. 11b and 11c in detail). Ca and Al (reaching 0.4 *apfu*)

Table 1: Olivine composition of the studied rocks.

Sampling site		**Ostrý**			**Hradišťko**			**Úžín**		
Comment		**Core Fo_{min}**	**Core Fo_{max}**	**Rim average**	**Core Fo_{min}**	**Core Fo_{max}**	**Rim average**	**Core Fo_{min}**	**Core Fo_{max}**	**Rim average**
n				**2**			**6**			**1**
SiO_2		40.72	40.73	39.64	40.27	41.43	39.52	40.34	40.57	39.25
Al_2O_3		0.03	0.03	0.02	0.06	0.01	0.16	0.06	0.03	0.04
Cr_2O_3		0.01	0.03	0.02	0.01	0.00	0.02	0.05	0.00	0.00
FeO		12.91	8.66	13.64	13.91	8.71	18.65	13.35	12.03	20.37
MnO		0.10	0.14	0.24	0.27	0.15	0.39	0.20	0.33	0.43
MgO		46.78	50.85	45.67	46.08	49.88	41.44	45.73	47.25	40.77
NiO		0.27	0.36	0.33	0.31	0.39	0.15	0.23	0.40	0.17
CaO		0.20	0.05	0.20	0.29	0.06	0.35	0.30	0.06	0.43
Total		101.06	100.88	99.78	101.24	100.66	100.74	100.28	100.67	101.50
Atoms per formula unit	Si	1.002	0.987	0.994	0.996	1.004	1.003	1.003	1.000	0.998
	Al	0.001	0.001	0.000	0.002	0.000	0.005	0.002	0.001	0.001
	Fe	0.266	0.176	0.286	0.288	0.177	0.399	0.278	0.248	0.433
	Mn	0.002	0.003	0.005	0.006	0.003	0.008	0.004	0.007	0.009
	Mg	1.716	1.837	1.707	1.699	1.803	1.565	1.695	1.736	1.545
	Cr	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000
	Ni	0.005	0.007	0.007	0.006	0.008	0.003	0.005	0.008	0.003
	Ca	0.005	0.001	0.005	0.008	0.002	0.010	0.008	0.001	0.012
Fo		**86.08**	**92.22**	**85.72**	**85.24**	**90.51**	**78.43**	**85.04**	**87.18**	**77.44**

Oxides in %; atoms per formula unit Σ=3; content of forsterite component in mol %.

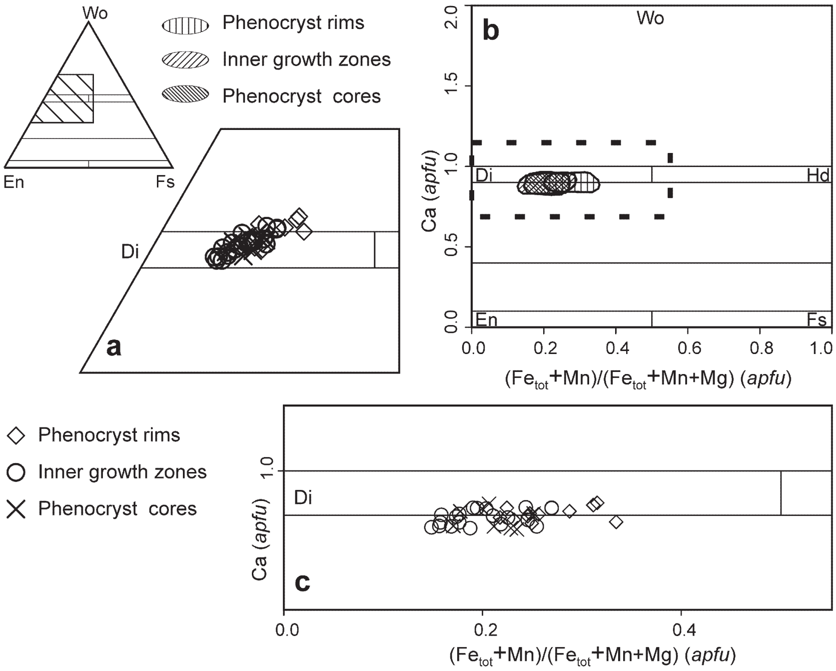

Fig. 11. Composition of clinopyroxenes: (**a**) Quadrilateral diagram (Morimoto 1988), (**b**) Ca-Fe diagram (Rapprich 2005), (**c**) detail of (b).

contents, classify the clinopyroxenes as aluminian augites (their Ca-rich edge) or diopsides. Classification En-Fs-Wo diagram was constructed on basis of normalized Fe, Mg and Ca atomic proportions according to IMA recommendations (Morimoto, 1988; used e.g. by Brady). Calculation of extended end-member set has followed procedure published by Rapprich (2005). Cores of some larger diopside phenocrysts in the coherent feeder of Ostrý Hill consist of augite ($Na_{0.07}Ca_{0.84}Fe^{2+}_{0.25}Fe^{3+}_{0.04}Mn_{0.01}Mg_{0.66}Ti_{0.03}Al_{0.23}Si_{1.87}O_6$) with exsolution orthopyroxene ($Ca_{0.07}Fe^{2+}_{0.7}Fe^{3+}_{0.02}Mn_{0.02}Mg_{1.13}Ti_{0.01}Al_{0.13}Si_{1.92}O_6$) lamellae (Fig. 12). The lamellae form ca 10% of the mineral. The known composition of both phases and their ratio allow us to calculate the original composition. The original augite ($Na_{0.06}Ca_{0.77}Fe^{2+}_{0.29}Fe^{3+}_{0.04}Mn_{0.01}Mg_{0.71}Ti_{0.03}Al_{0.22}Si_{1.87}O_6$) could have been entrained by the ascending magma from underlying magmatic rocks.

Table 2: Average clinopyroxene compositions of the studied rocks.

Sampling site		**Ostrý**			**Hradišťko**		**Úžín**		
Comment		**core**	**zone**	**rim**	**core**	**rim**	**core**	**zone**	**rim**
n		**3**	**4**	**4**	**4**	**3**	**4**	**12**	**5**
SiO_2		48.17	48.06	42.88	48.64	43.26	48.27	49.20	46.79
TiO_2		1.76	1.84	3.55	2.00	3.87	2.03	1.76	2.79
Al_2O_3		6.20	6.37	10.22	4.87	8.99	6.14	5.16	6.34
Cr_2O_3		0.36	0.47	0.11	0.05	0.20	0.20	0.34	0.05
FeO		5.96	5.70	8.06	6.49	7.69	6.32	5.90	7.21
MnO		0.11	0.09	0.10	0.12	0.09	0.15	0.12	0.13
MgO		13.65	13.81	10.90	13.85	11.51	13.67	14.25	12.65
CaO		22.92	22.99	22.59	22.85	22.52	21.88	22.24	22.16
Na_2O		0.46	0.47	0.53	0.37	0.43	0.53	0.47	0.47
Total		99.62	99.85	98.98	99.30	98.58	99.28	99.50	98.65
T	Si	1.785	1.775	1.618	1.813	1.640	1.797	1.824	1.765
	Al	0.215	0.225	0.382	0.187	0.360	0.203	0.176	0.235
M1	Al	0.055	0.052	0.073	0.027	0.041	0.067	0.050	0.047
	Fe^{3+}	0.084	0.091	0.143	0.073	0.124	0.055	0.052	0.063
	Ti	0.049	0.051	0.101	0.056	0.110	0.057	0.049	0.079
	Cr	0.010	0.014	0.003	0.002	0.006	0.006	0.010	0.002
	Mg	0.754	0.760	0.613	0.770	0.650	0.758	0.787	0.711
	Fe^{2+}	0.047	0.032	0.067	0.073	0.068	0.057	0.052	0.098
M2	Fe^{2+}	0.054	0.053	0.044	0.057	0.051	0.084	0.079	0.066
	Mn	0.004	0.003	0.003	0.004	0.003	0.005	0.004	0.004
	Ca	0.910	0.910	0.913	0.913	0.914	0.873	0.883	0.895
	Na	0.033	0.034	0.039	0.027	0.032	0.038	0.034	0.034
Calculated end-members	Kch	1.05	1.37	0.33	0.15	0.59	0.58	0.98	0.16
	Ae	2.24	2.03	3.57	2.53	2.57	3.23	2.40	3.29
	Ka	0.35	0.29	0.33	0.37	0.28	0.48	0.38	0.41
	CAT	5.54	5.24	7.28	2.73	4.10	6.67	4.97	4.67
	CTT	4.92	5.11	10.08	5.61	11.04	5.69	4.91	7.92
	Ess	6.13	7.06	10.74	4.74	9.85	2.27	2.84	3.03
	Fs	5.05	4.27	5.57	6.48	5.98	7.10	6.54	8.21
	En	37.52	37.85	30.48	38.30	32.37	37.67	39.17	35.36
	Wo	37.20	36.78	31.62	39.09	33.22	36.32	37.81	36.96

Oxides in %; atoms per formula unit Σ = 4; calculated end-members Σ = 100 %. **Kch** — Kosmochlor, **Ae** — Aegirine, **Ka** — Kanoite, **CAT** — Ca-Tschermak's molecule, **CTT** — Ca-Ti-Tschermak's molecule, **Ess** — Esseneite, **Fs** — Ferrosilite, **En** — Enstatite, **Wo** — Wollastonite.

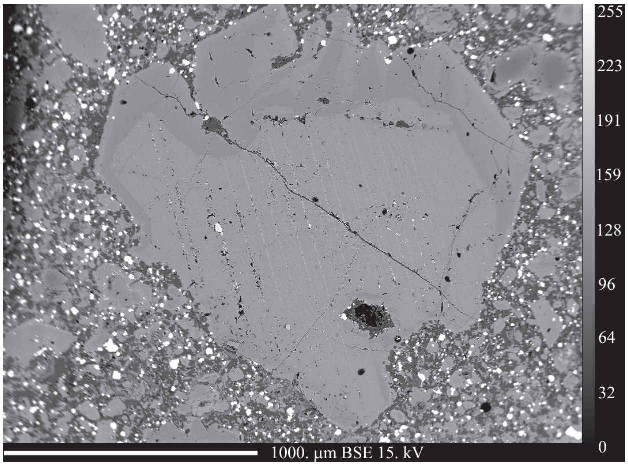

Fig. 12. Back-scattered electron image of a clinopyroxene core with orthopyroxene exsolution lamellae (Ostrý Hill).

Plagioclase has the form of laths, usually too small to be analysed. Plagioclase laths from the Úžín lava correspond to basic labradorite (An_{63-65} Ab_{33-36} Or_1). The analyses of nepheline were affected by sodium loss during electron beaming. Nevertheless, the results are sufficient to document maximum 0.15 *apfu* K and maximum 0.6 *apfu* Ca.

The studied basanites, and particularly the rock of the Ostrý Hill feeder, are relatively rich in xenocrysts. Minerals of these xenocrysts, such as orthopyroxene, K-feldspar and quartz, reflect multifarious country rocks entrained during magma ascent. We already described extremely magnesian cores of olivine phenocrysts which represent relics of mantle-derived xenocrysts. The presence of exsolution lamellae of two slightly different enstatites (one is slightly enriched in Al, Fe and Cr) characterize orthopyroxene xenocryst in the basanite of Ostrý Hill. Both enstatite phases are extremely poor in Ca (0.01 *apfu*) and are equal in their volume. The orthopyroxene was corroded by magma and is overgrown first by common magmatic olivine and then by magmatic diopside.

The sample from the Hradišťko conduit revealed a pseudomorph formed by glass and diopside. Glass composition

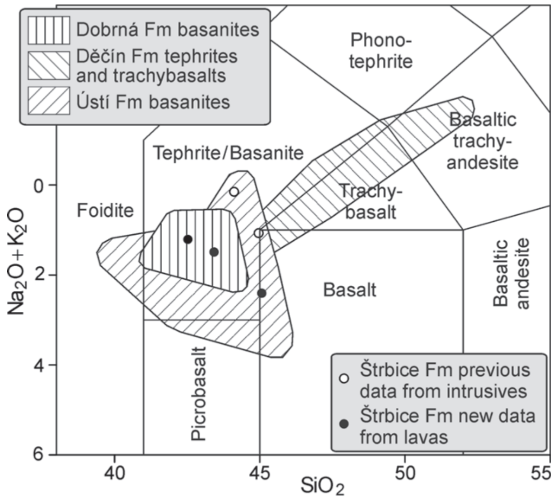

Fig. 13. Composition of the studied rocks compared with the older formations in the TAS diagram (Le Bas et al. 1986).

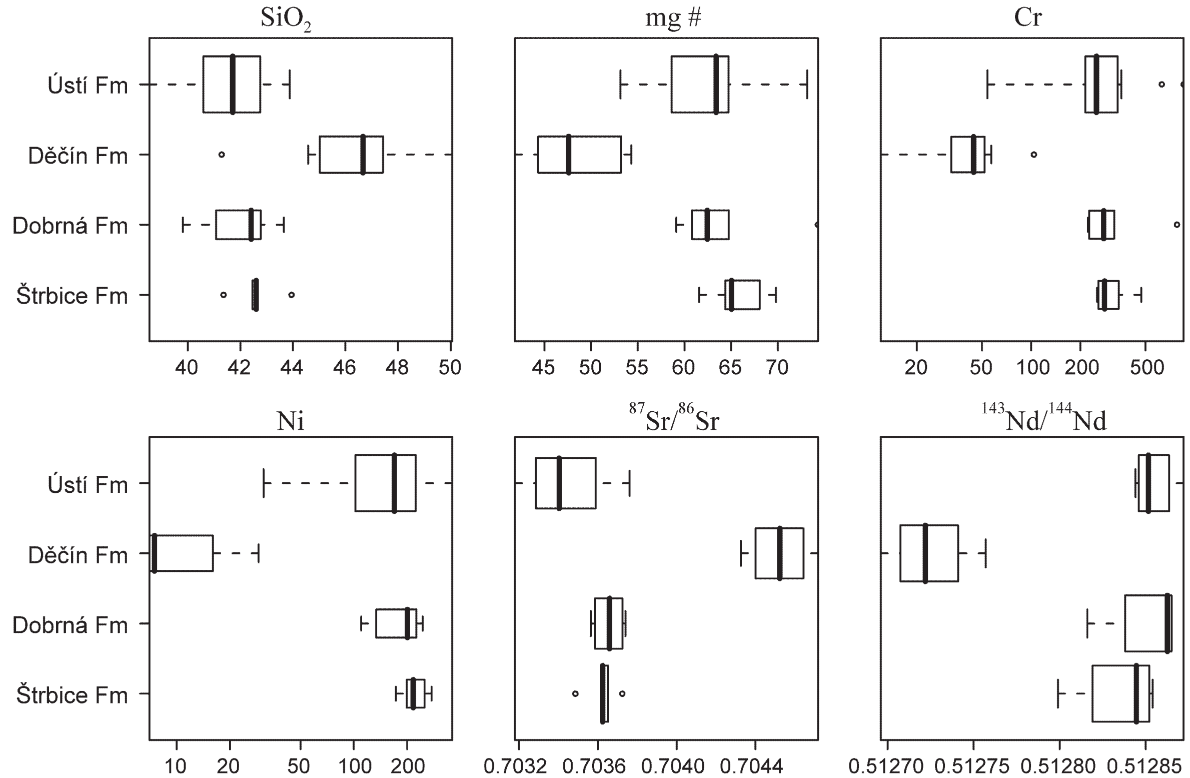

Fig. 14. Box-and-whisker plots showing geochemical differences among lithostratigraphic units of the CSVC. Note that Cr and Ni are in logarithmic scale.

(60–64 wt. % SiO_2, 3.5–4 wt. % K_2O and only 1.5–1.9 wt. % Na_2O) and pseudomorph shape suggest replacement of former K-feldspar. An anomalous composition is also displayed in diopsides enclosed in, and flanking, the pseudomorph. These are poor diopsides with unusually low concentrations of Al_2O_3 and TiO_2.

Bulk-rock chemistry

The studied basaltic products from Hradišťko, Ostrý and Úžín are rather primitive ultrabasic alkaline rocks (Table 3). The petrographic character of the basanites is confirmed by their chemical composition (Le Bas 1986 — Fig. 13), with normative olivine contents above 10 % (11–20 %). The sample from Úžín falls in the basalt field, however, the SiO_2 content is only slightly above 45 % when recalculated on a water-free basis, with rather high water content (3 %). The samples rank between the most primitive basaltic rocks in the CSVC, having 11–13.1 % MgO, 258–473 ppm Cr and 173–275 ppm Ni (Fig. 14). The unfractionated character of the studied samples is further underlined by low Al_2O_3 contents. A similar picture is given by the trace element chemistry (Fig. 15). In addition to the above mentioned high Cr and Ni contents, the samples rank in the lower part of the HFSE (high field strength element) concentration range of the CSVC basanitic rocks, whereas LILE contents are moderate. REE contents are low compared to other CSVC samples however, the LREE/HREE ratio is high for the Hradišťko and Ostrý samples, and only moderate for the Úžín sample. The isotopic signature is in good agreement with the data previously published for the Ústí and Dobrná Formations (LF and UMF in Cajz et al. 1999), with $(^{87}Sr/^{86}Sr)_i$ between 0.70347 and 0.70361, and $(^{143}Nd/^{144}Nd)_i$ between 0.51279–0.51284 (Table 4 and Fig. 16).

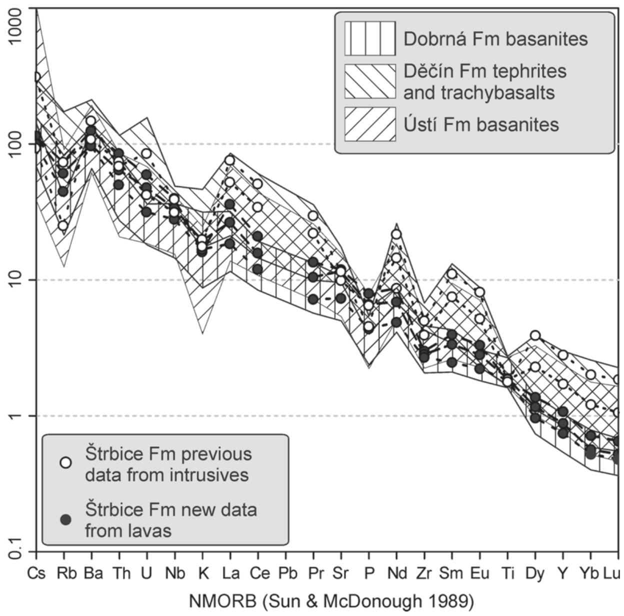

Fig. 15. A spidergram of the studied rocks normalized to NMORB (Sun & McDonough 1989).

Table 3: Chemical composition of basaltic rocks of the Štrbice Formation compared to the lower lithostratigraphic units of the CSVC. *Continued on next page.*

Formation	**Ústí**			**Děčín**			**Dobrná**			**Štrbice**				
Sample	**representative (n = 20)**			**representative (n = 8)**			**representative (n = 4)**			**CS33**	**CS34**	**CS35**	**1353**	**1372**
Location	**aver**	**min**	**max**	**aver**	**min**	**max**	**aver**	**min**	**max**	**Ostrý**	**Hrad.**	**Úžín**	**PH**	**KV**
SiO_2	41.59	38.54	43.88	46.20	41.29	50.06	41.52	39.82	42.77	41.36	42.46	43.06	43.95	42.61
TiO_2	2.86	2.10	3.41	2.85	2.14	3.48	2.99	2.62	3.39	2.32	2.38	2.17	2.34	2.25
Al_2O_3	13.11	8.26	15.56	15.75	14.22	16.82	12.97	12.26	13.83	12.69	11.56	12.25	13.13	13.21
Fe_2O_3	5.27	3.04	7.50	4.59	3.53	5.44	5.16	4.27	6.37	5.51	3.67	3.58	3.10	4.98
FeO	6.37	4.03	7.53	4.70	3.58	5.30	6.83	5.60	7.35	5.98	7.69	6.67	8.68	5.85
MnO	0.19	0.16	0.22	0.19	0.17	0.25	0.19	0.18	0.21	0.23	0.21	0.18	0.21	0.21
MgO	10.28	7.26	13.78	4.76	3.00	6.73	10.48	9.02	12.34	11.08	13.13	12.95	10.31	10.78
CaO	12.22	10.44	15.63	10.25	8.59	13.32	11.70	11.44	12.07	12.51	11.50	10.53	10.46	10.52
SrO	0.10	0.05	0.15	0.12	0.09	0.17	0.09	0.08	0.11	0.12	0.12	0.08	0.10	0.11
BaO	0.07	0.04	0.10	0.10	0.07	0.17	0.08	0.05	0.12	0.08	0.07	0.06	0.19	0.07
Na_2O	3.06	1.84	4.45	3.74	2.66	4.48	3.06	2.83	3.20	3.50	3.01	2.23	3.39	4.38
K_2O	1.01	0.29	1.78	2.37	1.25	3.35	1.47	0.63	2.28	1.16	1.40	1.22	1.43	1.27
P_2O_5	0.64	0.26	0.91	0.54	0.47	0.63	0.61	0.44	0.74	0.93	0.77	0.46	0.76	0.53
H_2O+	1.99	0.77	4.21	2.14	1.23	3.05	2.15	1.24	3.10	1.67	1.31	3.03	1.09	0.78
H_2O-	1.14	0.44	3.24	1.61	0.38	3.47	0.56	0.33	1.01	0.35	0.31	0.81	0.32	2.08
F	0.03	0.01	0.06	0.05	0.04	0.07	0.03	0.02	0.04	0.11	0.10	0.09	0.02	0.02
CO_2	0.30	0.02	2.51	0.20	0.03	0.68	0.16	0.04	0.34	0.08	0.06	0.37	0.61	0.77
TOTAL	100.22	99.12	100.96	100.16	99.49	100.82	100.04	99.71	100.33	99.66	99.75	99.74	100.07	100.43
mg#	61.80	53.15	73.11	48.30	41.85	54.31	61.77	59.14	64.74	64.36	68.05	70.01	61.58	65.04

Table 3: *Continued.*

Formation	Ústí			Děčín			Dobrná			Štrbice				
Sample	**representative (n = 20)**			**representative (n = 8)**			**representative (n = 4)**			**CS33**	**CS34**	**CS35**	**1353**	**1372**
Location	**aver**	**min**	**max**	**aver**	**min**	**max**	**aver**	**min**	**max**	**Ostrý**	**Hrad.**	**Úžín**	**PH**	**KV**
Ba	767	387	1214	1030	820	1336	764	649	855	783	616	609	680	929
Co	54	44	62	31	19	42	55	48	62	52	56	56	53	52
Cr	290	54	857	47	12	104	262	222	322	258	344	473	281	253
Cs	1.03	0.27	7.28	1.55	1.00	2.12	0.64	0.48	0.80	0.80	0.80	0.70	2.18	0.65
Cu	106	42	389	55	31	114	64	53	69	61	62	63	61	55
Hf	6	4	8	9	8	10	7	6	8	5	5	5	6	7
Nb	76	36	97	91	73	114	78	72	85	93	78	65	73	91
Ni	167	31	360	12	7	29	168	110	226	173	275	251	199	217
Rb	27	7	51	63	23	97	31	12	46	41	34	25	41	14
Sc	33	25	55	24	14	36	30	28	35	*	*	23	24	23
Sr	978	484	1408	1126	862	1568	872	773	960	1070	1040	657	889	1032
Ta	4.9	2.3	6.5	5.7	4.6	6.9	5.3	4.7	6.3	6.2	5.6	4.9	4.4	5.6
Y	32.3	21.2	66.7	41.6	23.6	83.8	27.0	25.7	28.8	30.0	24.6	20.8	48.0	78.3
Zn	75	44	100	77	64	93	77	59	87	95	97	75	106	90
Zr	281	166	393	405	315	500	304	270	340	221	209	199	290	369
U	1.74	0.87	3.20	3.27	2.05	7.35	1.56	1.48	1.70	2.79	2.24	1.48	1.98	3.99
Th	6.65	2.49	10.25	11.60	9.49	13.89	6.67	5.85	7.97	10.20	7.71	5.99	8.91	8.22
La	77.7	34.5	171.7	106.8	52.9	214.2	68.4	59.6	79.6	89.9	66.1	46.0	130.5	189.0
Ce	154.1	80.8	329.6	218.6	108.6	454.6	133.9	114.9	144.3	157.0	118.0	89.7	256.5	380.7
Pr	17.2	9.4	34.1	24.2	13.1	47.2	15.8	14.3	17.6	17.8	13.8	9.5	29.0	39.1
Nd	67.1	37.3	134.7	91.2	49.7	190.3	59.0	51.6	63.8	63.1	50.2	35.5	105.8	157.7
Sm	11.98	6.87	24.89	16.07	9.00	34.57	10.75	9.60	11.31	10.40	8.82	6.49	19.72	29.03
Eu	3.46	2.31	7.24	4.16	2.33	8.98	3.00	2.86	3.12	3.37	2.86	2.26	5.27	8.27
Gd	10.54	6.41	20.49	13.31	7.75	29.76	9.01	8.56	9.57	9.11	7.78	5.45	17.64	23.89
Tb	2.09	0.89	4.76	2.18	1.11	3.71	1.43	0.91	1.73	1.22	1.06	0.83	1.80	9.01
Dy	7.19	4.58	14.94	8.72	5.07	17.74	6.06	5.81	6.37	6.22	5.28	4.38	10.40	17.71
Ho	1.22	0.72	2.67	1.59	0.86	3.43	1.01	0.90	1.07	1.08	0.92	0.75	1.92	2.89
Er	2.89	1.78	5.54	3.67	2.09	7.40	2.33	2.03	2.57	2.82	2.33	1.98	4.16	6.53
Tm	0.65	0.28	0.82	0.70	0.41	1.13	*	*	*	0.38	0.30	0.26	0.46	0.89
Yb	2.48	1.58	5.40	3.64	1.79	7.85	2.03	1.62	2.40	2.18	1.72	1.59	3.68	6.11
Lu	0.33	0.21	0.75	0.50	0.25	1.03	0.27	0.21	0.31	0.30	0.24	0.22	0.48	0.84
Age (Ma)	29–36 (n = 6)			25–27 (n = 5)			20–25 (n = 4)			9	9	11	13	13.4
$^{87}Sr/^{86}Sr$	0.70344	0.70318 (n = 4)	0.70376	0.70452	0.70433 (n = 5)	0.70472	0.70366	0.70356 (n = 4)	0.70374	See Table 4. for isotopic data				
$^{143}Nd/^{144}Nd$	0.51285	0.51284 (n = 4)	0.51287	0.51272	0.51270 (n = 5)	0.51276	0.51285	0.51282 (n = 4)	0.51286					

Oxides in %; trace elements including REE in ppm. **Hrad.** — Hradišťko feeder of the Upper Miocene scoria; **PH** — Pohradická hora Hill; **KV** — Keřový vrch Hill. * — not detected or not analysed. CS33–CS35 new data, other analyses from Ulrych et al. (2001). K-Ar age extent and isotopic data of lithostratigraphic units reassessed, compared to previous papers (see text).

Table 4: New data on radiometric ages and Sr-Nd isotopes obtained on superficial products, and complementary analyses of $^{143}Nd/^{144}Nd$ ratio of Ústí Formation samples.

Sample	**CS33**	**CS34**	**CS35**	**CS36**	**1297**	**1374**	**1363**
Formation	**Štrbice**	**Štrbice**	**Štrbice**	**Dobrná**	**Ústí**	**Ústí**	**Ústí**
Location and rock type	**Ostrý, basanite**	**Hradišťko, basanite**	**Úžín, basanite**	**Hradišťko, olivine basalt**	**Kam. Šenov, basanite**	**Taneček, basanite**	**Hlinná, basanite**
K(%) / K_2O(%)	0.96 / 1.16	1.13 / 1.40	1.00 / 0.84	0.97 / 1.26	*	*	*
$^{40}Ar_{rad}$ (ccSTP/g)	3.595×10^{-7}	4.224×10^{-7}	4.431×10^{-7}	7.859×10^{-7}	*	*	*
$^{40}Ar_{rad}$ (%)	27.0	47.2	46.6	33.5	*	*	*
K/Ar age (Ma)	9.61 ± 0.51	9.59 ± 0.36	11.36 ± 0.42	20.72 ± 0.94	*	*	*
$^{87}Sr/^{86}Sr$	0.703624	0.703486	0.703615	*	*	*	*
2SE(M)	0.000013	0.000011	0.000013	*	*	*	*
$(^{87}Sr/^{86}Sr)_i$	0.703609	0.703473	0.703597	*	*	*	*
$^{143}Nd/^{144}Nd$	0.512799	0.512839	0.512850	*	0.512872	0.512844	0.512848
2SE(M)	0.000007	0.000009	0.000011	*	0.000013	0.000014	0.000016
$(^{143}Nd/^{144}Nd)_i$	0.512793	0.512832	0.512842	*	*	*	*

Analytical errors for isotopic data expressed as 2 standard errors of the mean (2SE(M)). Initial ratios calculated using element concentrations reported in Table 3 and decay constants suggested by Steiger & Jäger (1977). In addition to data for the three localities discussed in text, three $^{143}Nd/^{144}Nd$ values extending the dataset (Ulrych et al. 2001) of Ústí Formation are given. * — not analysed for this paper.

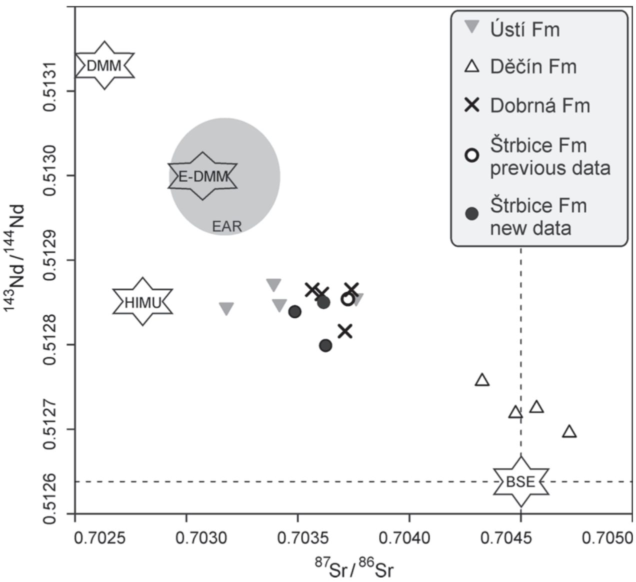

Fig. 16. Initial Sr-Nd isotopic ratios of the Štrbice Formation compared with Ústí, Děčín and Dobrná Formations (Ulrych et al. 2001, 2002b, new data). The initial ratios were calculated from the age of individual samples or formations. Mantle reservoirs after Zindler & Hart (1986) and Cebria & Wilson (1995): **DMM** = depleted mantle MORB, **E-DMM** = enriched-depleted mantle MORB, **BSE** = bulk silicate Earth, **HIMU** = high μ unit, **EAR** = European asthenospheric reservoir.

Discussion

Our research has shown that the scoria cones of the Štrbice Formation SE of Bílina overlie older volcanoes of similar composition and eruptive style or Miocene sediments developed during a prolonged recess in volcanic activity. Eruptions of the Štrbice Formation were dominated by Strombolian style, and no welded accumulations suggesting the presence of Hawaiian eruptions (*sensu* Sumner et al. 2005) were observed. A unique cow-dung bomb found on Ostrý Hill should document only the presence of a crater facies of a Strombolian scoria cone, where plastic bombs may also be present (e.g. Rapprich et al. 2007 and references therein). As we did not find any deposits enriched in xenolithic material or characterized by a high fragmentation index, we suggest that no initial phreatomagmatic phase (Schmincke 1977; Risso et al. 2008) took place and the activity started directly in Strombolian style.

All previously discovered Upper Miocene volcanic bodies of the CSVC are located in its western part, and so are all the newly described apparatuses. Only the Úžín lava is situated some 10–15 km to the NE. The 9–13.5 Ma time span of volcanic activity of the Štrbice Formation within the CSVC is characterized by olivine foidite-tephrite-trachybasalt-trachyte suite on the western margins of the Bohemian Massif (Teplá Highland and Cheb-Domažlice Graben — Ulrych et al. 1999; Ulrych et al. 2002a; Lustrino & Wilson 2007), too. This is the interval which coincides with the K-Ar ages of three basaltic bodies in Saxony (Pfeiffer et al. 1984; Kaiser & Pilot 1986). Two other locations with ultramafic dykes of the same age are known from the Bohemian Cretaceous Basin near the intersection of the Stráž Fault and Lusatian Fault (Ulrych & Pivec 1997). Their ascent is most probably linked to these fault zones. The rest of the Bohemian Massif appeared to be calm at that time, even including areas previously associated with ample volcanism (and situated inside the OG). Unlike in western Bohemia, no differentiated volcanic rocks of Late Miocene activity were found in the CSVC. This suggests that the last volcanic activity in this region resulted from tectonic remobilization, allowing ascent of primitive magmas. This remobilization has only partly influenced the structure of the OG, much like that of other parts of the Bohemian Massif. Late Miocene volcanic activity appears to be independent of the structure of the OG.

The results of this study allow us to redefine the Štrbice Formation of the CSVC (*sensu* Cajz 2000). Its former definition based on intrusive members only is renewed now by description of corresponding conduits, effusive members and pyroclastic deposits including their superpositional characteristics, and newly available K-Ar and other geochemical data. Thus, the recent definition of the Štrbice Formation is fully comparable to the other formations of the CSVC.

Other supposed superficial products of Miocene synsedimentary volcanism were reported from Mradice near Louny by Váně (1981) and later interpreted by Kopecký (1987–1988) as horizontally propagating clastic dykes. These outcrops were completely destroyed in the 1980s. A support for any of the hypotheses is therefore very complicated. Nevertheless, we can point to the following facts: i) no responsible vent has been found yet, ii) the reported thickness reaches 30 m and significantly exceeds the thickness of sedimentary cover (Váně 1981), and iii) hydroclastic intrusion in a shallow depth in unconsolidated wet sediments would rather propagate vertically. We therefore believe that the local volcaniclastic (epiclastic) material most probably represents deposits of polymict gravity flows generated from older volcanic formations and basement of the CSVC, deposited into tectonic "micro grabens" along the Ohře/Eger Fault Zone (Hradecký 1977). A similar feature is well known from the central part of the CSVC (Cajz 1992).

A general geochemical description of the CSVC superficial products was given by Cajz et al. (1999). New field and analytical data are available since than, slightly changing our understanding of volcanic complex development. Accordingly, we have refined the original dataset to comply with new observations (Table 3). Three samples formerly assigned to the Ústí Formation were rearranged into the Dobrná Formation as follows: i) 1373 (Měrunice) with respect to radiometric data of Lustrino & Wilson (2007); ii) 1378 (Prackovice) was assigned to the Dobrná Formation already by Cajz (2000); iii) 1380 (Žďárek) was reinterpreted as a younger intrusion into the Ústí Formation lavas. For two samples lacking Nd-isotopic ratios in the original dataset we have added these data (1297 Kamenický Šenov and 1374 Taneček — Table 4). The Nd-isotopic ratio of the sample 1363 (Hlinná), the sample with most pronounced HIMU-like component influence documented by Ulrych et al. (2002b), was re-analysed (see Table 4). The newly obtained $^{143}Nd/^{144}Nd$ value is significantly higher and the sample plots into the mantle array, in line with the rest of the CSVC samples. Therefore, the presence of HIMU (high-μ unit) component in the České středohoří Mts lavas remains questionable. If compared with the reference dataset (Table 3, Fig. 14), the composition of the presented Štrbice Formation products is virtually undistinguishable from the Ústí and Dobrná Formations products. Nevertheless, the Štrbice Formation lavas with their high mg-values and Cr and Nd contents rank among the most primitive CSVC rocks. Although scarce, partly resorbed crust-derived mineral grains were observed in thin section, bulk-rock geochemistry of the basanites shows no signs of a significant crustal contamination.

The source of the Cenozoic basaltic magmas in anorogenic settings in Europe was widely discussed and reviewed recently (e.g. Wilson & Downes 2006; Lustrino & Wilson 2007). Based on trace element and isotopic indications, the most probable common source is plume-related asthenospheric mantle, termed EAR (European Astenospheric Reservoir — Cebria & Wilson 1995; Wilson 1997), or LVC (Low Velocity Component — Hoernle et al. 1995), with a number of smaller domains with variable degree of enrichment. The resulting image in the Sr-Nd isotopic space is a linear array between EAR and Bulk Silicate Earth composition. All the analysed samples of the Štrbice Formation, together with other isotopic data for the CSVC basalts (see Lustrino & Wilson 2007) fit well within this model. There is no significant offset in the Sr-Nd isotopic data from the mantle array towards the HIMU component, suggesting no or negligible influence of this component during generation of the Štrbice Formation lavas (see Fig. 16). However, its presence cannot be definitely ruled out without Pb isotopic data.

Moderate to low Y and HREE contents, together with low Zr/Nb ratio and moderate to high LREE/HREE ratio, indicate mixing of low degree partial melts of both spinel and garnet lherzolite (model of Harangi 2001).

The extreme magnesian composition of olivine cores suggests the presence of relics of xenocrysts derived from the upper mantle. Presence of such xenocrysts may support an idea of rapid ascent not allowing mantle-derived olivines to lag and to fall through the melt to deeper positions. Some xenocrysts, such as augites, were most probably derived from older magmatic bodies (Cenozoic or even older) forming part of the crustal basement. Finally, one group of xenocrysts (K-feldspar, orthopyroxene and quartz) could have been entrained from granulites or charnockites described among xenoliths from the central part of the České středohoří Mts (e.g. Opletal & Vrána 1989).

Conclusions

• The Late Miocene volcanic activity in the western part of the České středohoří Volcanic Complex is characterized by scattered Strombolian eruptions forming monogenic cinder cones with basanitic lava flows. No conjunction with either the course, or the tectonic activity of the entire structure of the Ohře (Eger) Graben can be observed. This is most probably caused by low or no tectonic remobilization of the formerly active graben(s) — the differentiated volcanics in western Bohemia are situated outside the grabens (Ohře/Eger and Cheb-Domažlice ones), as well as other volcanic bodies of this age (in Saxony and in the Bohemian Cretaceous Basin).

• The Late Miocene volcanic activity took place upon older volcanic edifices of equal composition and similar eruptive style (especially the Dobrná Formation).

• The primitive basanitic lavas of the youngest volcanism (the Štrbice Formation) geochemically resemble the lavas of the preceding volcanism (the Ústí and Dobrná Formations) and document a rapid magma ascent.

• Similarly to other intra-plate lavas in continental Europe, the Upper Miocene products of the CSVC are derived from a slightly enriched asthenospheric source.

• Rapidly ascending magma entrained mineral grains from crustal rocks, but did not assimilate enough material to modify the bulk-rock composition significantly.

• Volcanic bodies of the Štrbice Formation (9–13.5 Ma) represent superficial products with explicit relations to the underlying Miocene sediments. Superposition of the youngest basalts overlying the Miocene sediments allows us to complete the definition of the Štrbice Formation, which now fulfils the same criteria as the other lithostratigraphic units of the CSVC.

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