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Geochemical variations within the Upper Oligocene–Lower Miocene lava succession of Úhošt' Hill (NE margin of Doupovské hory Mts., Czech Republic)

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Purely effusive activity built up a sequence of nine lavas on Úhošť Hill. The oldest erupted lavas are tephrites/basanites (28.66 ±1.06 Ma) and are of slightly evolved character. These are overlain by more differentiated alkali basalt. The succession continues with picrobasaltic lavas rich in phenocrysts (ankaramites 26.38 ±1.04 Ma). The entire succession is crowned by alkali basalt lavas (22.09 ±0.73 Ma). All lavas appear to be emitted from a common conduit. With respect to geochemical and isotopic data, however, the studied sequence could not be interpreted in terms of the exhausting of a simple magma chamber. We propose the role of a more complex reservoir or, of two independent reservoirs attached to a single conduit system. The tephrites/basanites and picrobasalts (ankaramites) are closely related, the latter being derived by accumulation of mafic phenocrysts, namely clinopyroxene. The basalts form another group differing from the tephrites/basanites and picrobasalts in more evolved isotopic compositions of Sr and Nd as well as in incompatible-element ratios. The isotopic composition of the lavas seems to reflect mixed mantle sources derived from the European Asthenospheric Reservoir through the addition of components similar to Enriched Mantle (EM 1 and EM 2). The basalts originated by fractionation of different magma batches that contained a higher proportion of the enriched mantle component(s) or that were more contaminated with crustal material.

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INTRODUCTION

The Cenozoic anorogenic magmatism of the Bohemian Massif is an integral part of the Circum-Mediterranean Anorogenic Cenozoic Igneous Province (CiMACI, Lustrino and Wilson, 2007). The magma ascent was enabled by tectonic reactivation of the Bohemian Massif in its Peri-Alpine setting leading to formation of the European Cenozoic Rift System (ECRIS, Dèzes *et al.*, 2004) over Western and Central Europe. The easternmost branch of the ECRIS is represented by the NE–SW trending Eger Graben that transects the Bohemian Massif along the Saxothuringian/Teplá–Barrandian boundary (Rajchl, 2006) from Eastern Bavaria to southwestern Poland. The northwestern marginal fault of this graben structure is known as the Krušné hory (Erzgebirge) Fault. Two Oligocene volcanic complexes (České středohoří Mts. and Doupovské hory Mts.) and Miocene sedimentary basins are set within the Eger Graben (also known as the Ohře Rift, Fig. 1). The České středohoří Volcanic Complex has been a focus of intensive volcanological and petrological studies for over a century (e.g., Cajz *et al.*, 1999). By contrast, the volcanic complex of the Doupovské hory Mts. has been poorly studied, at least partly because the area is covered by a military training space.

The Doupovské hory Volcanic Complex (DHVC) was formerly interpreted as an erosional relic of a huge stratovolcano with a central caldera situated in the vicinity of the former town of Doupov (Duppau in German). The caldera was believed to be accompanied by scarce parasitic vents (Kopecký, 1987–1988). Recently, a more complex setting of the DHVC has been recognized. The volcanic activity started in the latest Eocene (Shrbený and Vokurka, 1985; Fejfar, 1987) with eruptions of Strombolian up to Plinian style. This activity locally deposited up to 100 m of pyroclastic and epiclastic deposits (Hradecký, 1997; Mikuláš *et al.*, 2003). Later, the activity became dominantly effusive with Hawaiian to weak Strombolian eruptions accompanying lava emissions (Hradecký, 1997; Rapprich, 2003*b*). The lavas are often associated with

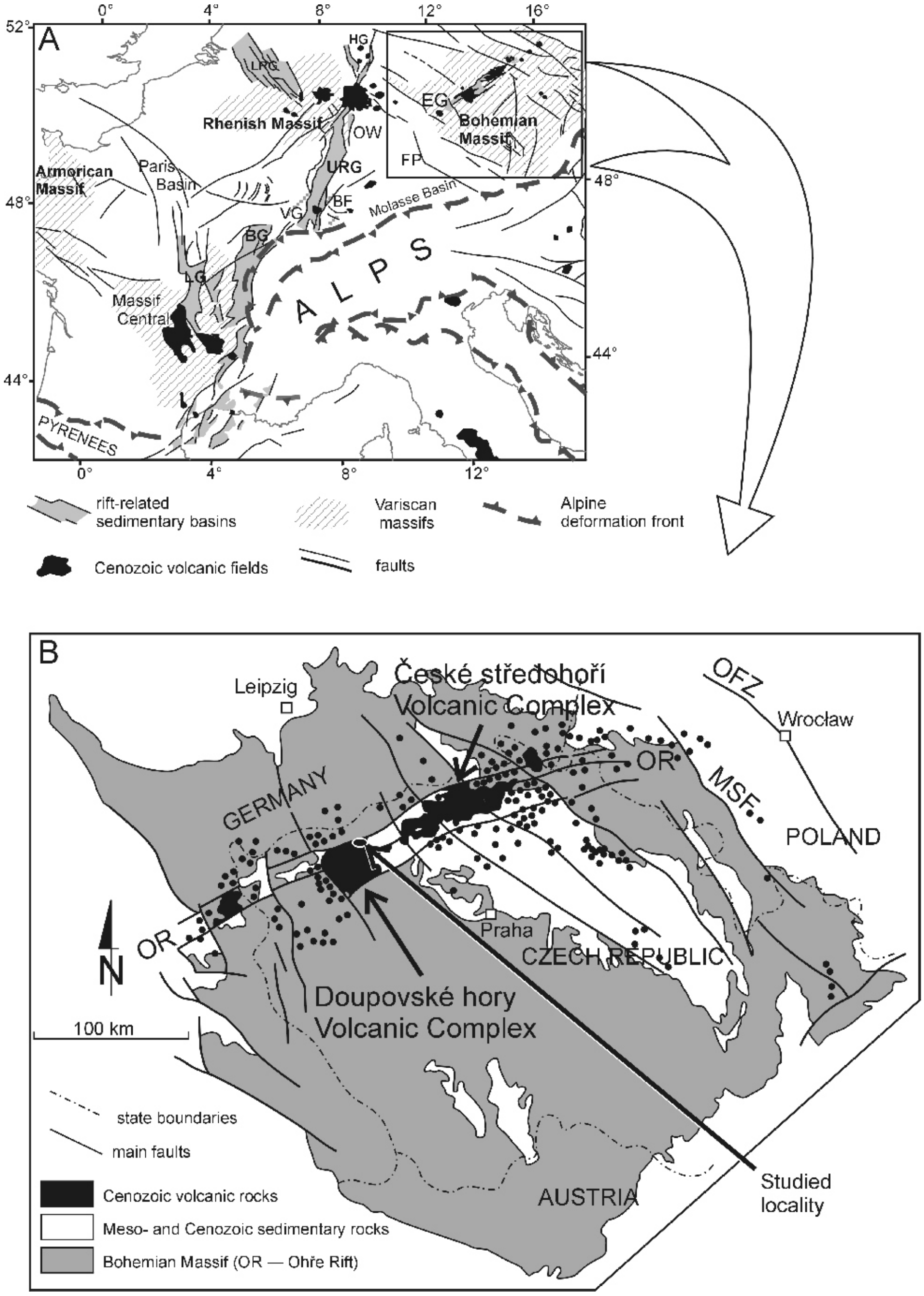

Fig. 1A — localization of the Eger Graben (= Ohře Rift) within the ECRIS (after Dèzes *et al*., 2004); B — tectonic position of the DHVC within the Eger Graben (map adapted after Ulrych *et al*., 1999)

A: BF — Black Forest, BG — Bresse Graben, EG — Eger (Ohře) Graben, FP — Franconian Platform, HG — Hessian grabens, LG — Limagne Graben, LRG — Lower Rhine (Roer Valley) Graben, URG — Upper Rhine Graben, OW — Odenwald, VG — Vosges; **B**: MSF — Marginal Sudetic Fault, OR — Ohře Rift, OFZ — Odra Fault Zone

autoclastic, or rarely also hyaloclastic breccias. Magmas were emitted from numerous vents and the volcanic activity of the DHVC lasted until the Early Miocene (this paper).

After a *ca*. hundred-year dominance of the stratovolcano hypothesis, when the profiles on Úhošť Hill were presented as a type locality for demonstration of the stratovolcanic style of the entire DHVC, Rapprich (2003*a*) made a detailed volcanological, petrographical and geochemical study of this locality for his diploma thesis. This article is mainly based on the data from this thesis (some of these data and brief conclusions were published as an abstract — Rapprich, 2003*b* and in a local journal — Rapprich, 2004). Some analyses were later completed in the laboratories of the Czech Geological Survey and Activation Laboratories to extend and improve the dataset.

ANALYTICAL METHODS

Major and trace element analyses were performed in the Chemical Laboratory of the Geological Institute, Faculty of Science, Charles University in Prague (AAS used for trace elements), and in the laboratories of the Czech Geological Survey (CGS), Prague (XRF used for trace elements). Selected samples were analysed for a large number of trace elements including REEs at Activation Laboratories Ltd. (Ancaster, Ontario) using inductively coupled plasma-mass spectrometry (ICP MS).

Strontium and neodymium isotope compositions were analysed in the CGS laboratories as follows: samples were dissolved using a combined HF-HCl-HNO_3 attack. Sr and Nd were separated by exchange chromatography techniques on polypropylene columns with Sr.spec, TRU.spec and Ln.spec resins (Pin *et al*., 1994; Pin and Zalduegui, 1997). Isotope analyses were made on a Finnigan *MAT 262* thermal ionization mass spectrometer in dynamic mode using a double Re filament assembly. The $^{87}Sr/^{86}Sr$ ratios were corrected for mass fractionation to $^{86}Sr/^{88}Sr = 0.1194$, $^{143}Nd/^{144}Nd$ ratios assuming $^{146}Nd/^{144}Nd = 0.7219$. External reproducibility is given by results of repeat analyses of the NBS 987 reference material [$^{87}Sr/^{86}Sr = 0.710245 \pm 26$ (2σ; n = 28)] and La Jolla reference material [$^{143}Nd/^{144}Nd = 0.511852 \pm 14$ (2σ; n = 27)]. Initial ratios were calculated using the reference age of 29 Ma corresponding to the oldest lava unit of the studied lava sequence. However, the age correction is rather insignificant. Figure 11 was constructed from raw data without any recalculation to get better comparability with present day mantle components (Zindler and Hart, 1986) and published data from Bohemian Volcanic Complexes.

Three selected lavas of the sequence were also dated using the potassium-argon method. The geochronological analyses were carried out in the ATOMKI Laboratories, Debrecen, Hungary. After acid digestion and 0.2M HCl dissolution of samples, the potassium content was determined by flame photometry with a Na buffer and Li internal standard. Measurements were checked by inter-laboratory standards (Asia 1/65, LP-6, HD-B1 and GL-O). Argon was extracted from samples by RF fusion in Mo crucibles under vacuum conditions. An ^{38}Ar-spike was added to samples prior to gas-cleaning in Ti and SAES getters and liquid nitrogen traps, respectively. Isotope ratios of argon were measured in the static mode using a 15 cm radius magnetic sector-type mass spectrometer in Debrecen. Balogh (1985) and Odin (1982) described the methods applied in detail. Age calculations were based on atomic constants proposed by Steiger and Jäger (1977).

Clinopyroxenes from the locality studied were analyzed in the micro-analytical laboratory (LAREM) of the Czech Geological Survey, Prague, in two sets. Analyses of clinopyroxenes from picrobasalts and upper basalts were analysed in 2002 on a *CamScan S4* at operation current 2.5–3 nA, voltage of 15 kV and counting time of 100 s and these data have been already published by Rapprich (2005). Clinopyroxenes from tephrites/basanites and lower basalt were analysed later (in 2006) on a *CamScan 3400* under the same operation conditions. An Energy Dispersion System (EDS — Link ISIS 300) was applied to acquire quantitative analyses. Formulas of clinopyroxenes were calculated based on four cations. The method of Vieten and Hamm (1978) was applied for calculation of ferric iron. Clinopyroxenes were classified and plotted on a quadrilateral diagram (Morimoto, 1988) after subtraction of all additional molecules (such as kosmochlor, aegirine, Ca-Tschermak`s molecules, esseneite, *etc*. — Rapprich, 2005). The purified system wolastonite + enstatite + ferrosilite still represents *ca.* 75% of the total formula. Geochemical calculations and diagrams were made using *GCDkit* software (Janoušek *et al*., 2006).

GEOLOGY OF ÚHOŠŤ HILL

The studied locality is situated at the northeastern margin of the DHVC (Fig. 2). Úhošť Hill is a table rock (593 m a.s.l.) that rises some 150 m above the surrounding landscape and has an apical plateau some 1200 m in length (longitude) and 800 m in width (latitude). A sequence of several lava flows is well exposed on the eastern and western slopes of this hill and belongs to the effusive (younger) evolutional stage of the DHVC. The

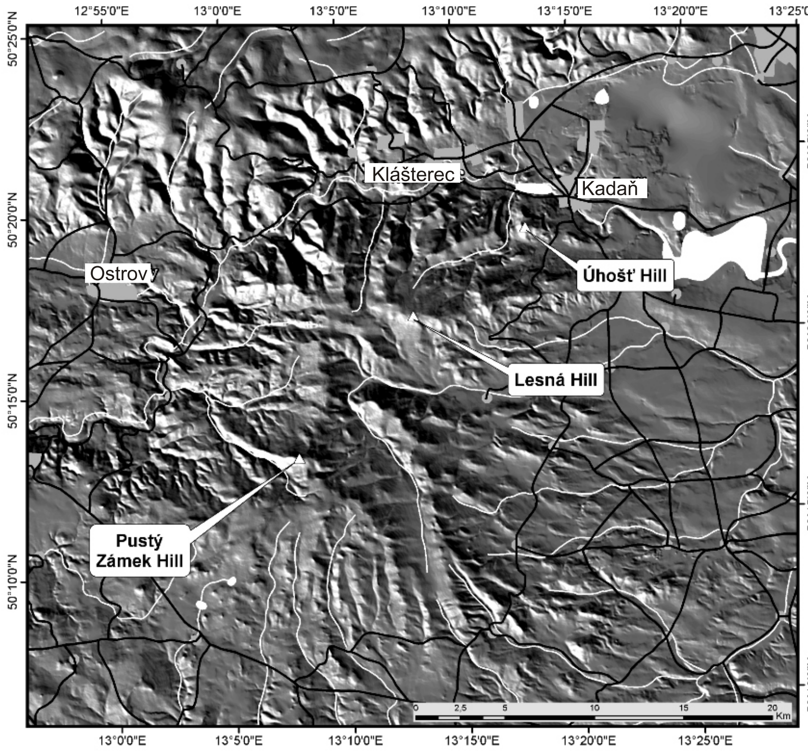

Fig. 2. Digital elevation model of the DHVC and location of structures mentione in the text

lavas overlie poorly exposed pyroclastic and epiclastic deposits of previous volcanic activity.

Both the eastern and western slopes of the hill were documented in detail and all observed lavas were sampled. The general flow direction of the lava is supposed to be from the W or SW to E or NE.

On the eastern slope seven successive lava bodies were observed. On the western slope only five lava units were documented because a lava sequence with clear relations is well exposed and accessible only at the southern edge of the slope. Some lavas probably owed over the northern part of the present hill and therefore these are missing on the southern edge of the western slope.

Field study and petrographic correlation of the two profiles indicate that the lavas on the eastern side represent the lower part of the succession, whereas the upper part crops out on the western side. As there is an overlap between the profiles the total number of outcropping lavas is nine. A schematic section through the hill with location of sampling sites is shown in Figure 3.

From the field study it is clear that Úhošť Hill represents only an erosional relic of a lava succession fed from a more distant source. However, the exact position of the feeder conduit for the Úhošť lavas has not yet been definitely identified. On the other hand, there is only one candidate for the vent for these lavas — Lesná Hill, some 8 km SW from Úhošť Hill (Fig. 2). Morphological ridges extend almost continuously from Lesná Hill towards Úhošť Hill. Structural plateaus of individual lavas are inclined in the same direction. Aerial geophysical survey supports this interpretation showing a positive magnetic anomaly associated with Lesná Hill (Šalanský, 2004). Several occurrences of basaltic rocks in close proximity to Kadaň town were actually interpreted as erosional remnants of a set of lavas. The petrography and succession of these lavas correspond to the lower part of the sequence exposed on Úhošť Hill (Rapprich, 2007). The number of individual lavas decreases towards the north-east (with increasing distance from the source). On the other side, few scoria cone remnants found around Kadaň (NE of Úhošť Hill) are not suitable candidates for conduits of the studied lavas because of their lower attitude, different petrology, and age.

PETROGRAPHY OF THE LAVAS

These nine lavas were divided into four magmatic units according to their position in the succession, petrographical and geochemical characteristics. The lowermost three lavas belonging to the tephrite/basanite unit (TBU) are overlain by the lower basaltic (LB) lava unit no 4. The succeeding lava units (no. 5 and 6) are of picrobasaltic (PU) composition and the succession is crowned by the youngest upper basalt unit (UBU, lavas no. 7–9).

As mentioned above, there are clastic layers interbedded with the lava bodies of Úhošť Hill. The individual lavas are separated by layers up to 2 m thick of argillized volcaniclastic material, in the past erroneously interpreted as coarse-grained fall-out tuffs (with blocks up to 1 m across — e.g. Zartner, 1929, 1938; Kopecký, 1987–1988). Detailed study of the depositional structures shows an absence of any bomb-sags beneath large fragments. Individual fragments consist of coherent basaltic rock without any signs of vesicle-growth fragmentation. The sharp and straight fragment shapes suggest an origin by fragmentation of already solidified crust of lava during its continuing flow. Thin-section studies support such observa-

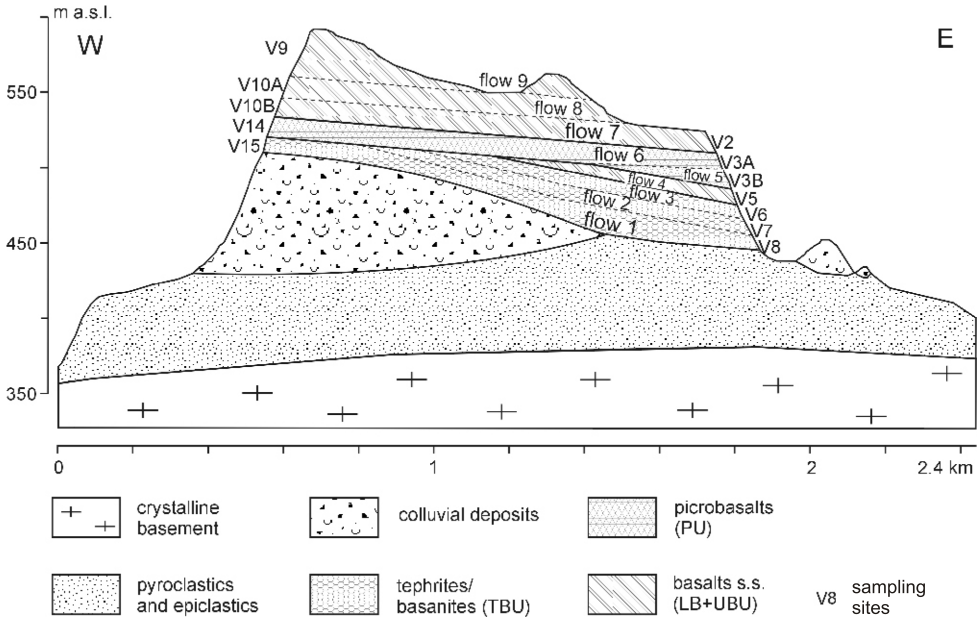

Fig. 3. Schematic profile showing the lava succession of Úhošť' Hill and position of the sampled rocks

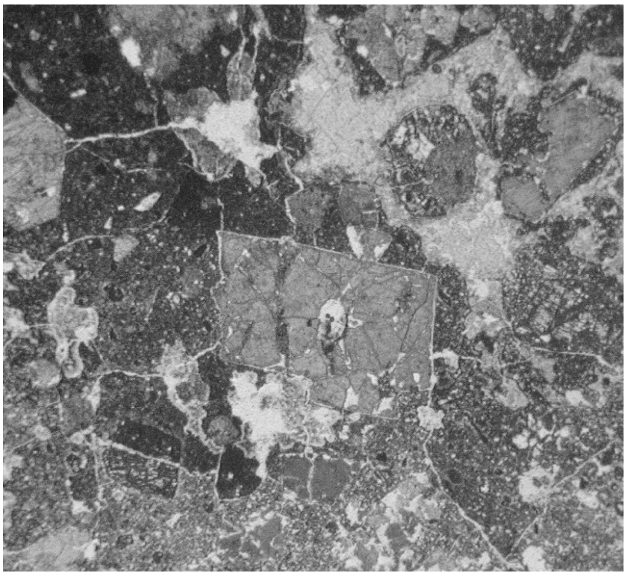

Fig. 4. Microphotograph of the argillized autoclastic facies of a lava from Úhošt' Hill

Brittle fragmentation of cool and solidified basaltic lava is apparent; real width of the image is 3.2 mm

tions, showing a texture of brittle-fragmented basaltic clasts (Fig. 4) that are petrographically uniform and correspond to the related coherent lava body. The typical size of diopside phenocrysts is the same as in the compact lava and the matrix shows a partly argillized mixture of diopside, Fe-Ti oxides and plagioclase similar to the matrix of the compact lava. No pyroclastic texture is visible and therefore these layers were re-interpreted as autoclastic breccias of lava flows. Thus, the Úhošť locality does not indicate a stratovolcanic style for the DHVC; to the contrary, it may serve as evidence of prevailing effusive activity.

TEPHRITE/BASANITE UNIT (TBU)

A low content of diopside phenocrysts, scarce olivine and very fine-grained matrix characterize lavas of this lowermost unit. The content of modal olivine increases up to *ca*. 10 vol.% in the third lava body (the last lava of this unit). The value of normative olivine (CIPW norm) varies around 10 wt.% and precludes exact distinction between tephrite and basanite. The association of felsic minerals changes from nepheline + analcite to plagioclase + nepheline and/or analcite (Table 1). Thus a transition from foidite to tephrite/basanite has been observed.

The oldest lava of this unit (and of the entire sequence) crops out solely on the eastern slope. It was classified as nepheline analcitite according to modal composition, but the TAS (total alkalies-silica) diagram places this rock within tephrites. Diopside phenocrysts (up to 1.5 cm) occur scarcely and pseudomorphs after amphibole and olivine are rare (Fig. 5A, B). The presence of frequent joints filled by late/post-magmatic phases led us to carry out radiometric dating on the overlaying lava that has a much fresher appearance.

The second lava is similar to the previous one. Scarce phenocrysts of diopside (up to 1 cm) enclosed in a fine-grained matrix build up this rock. Small pseudomorphs after phlogopite (comprising diopside + Fe-Ti oxides), amphibole (diopside + Fe-Ti oxides + rhönite) and olivine (carbonate) occur scarcely. The rock was classified as tephrite, which corresponds to its chemical composition. The age of this second lava flow corresponds to late Rupelian (28.66 ±1.06 Ma) according to the K-Ar method.

Table 1

Semi-quantitative modal analyses of Úhošť' lavas [total = 100%]

Unit	TBU	LB	PU	UBU			
Flow no.	**2**	**3**	**4**	**6**	**6**	**7**	**9**
Sample	**V7**	**V6**	**V5**	**V3A**	**V14**	**V10A**	**V9**
Phenocrysts [vol.%]	**15**	**20**	**10**	**55**	**55**	**30**	**20**
Clinopyroxene	++	++	+	+++++	+++++	+++	+++
Olivine (fresh and pseudomorphs)	+	+	+	+++	+++	++	+
Phlogopite (pseudomorphs)	+		+				+
Amphibole (pseudomorphs)	+	+				+	++
Matrix [vol.%]	**85**	**80**	**90**	**45**	**45**	**70**	**80**
Clinopyroxene	++++	++++	++++	+++	+++	++++	++++
Fe–Ti oxides	+++	++	++	++	+++	++	+++
Olivine (pseudomorphs)			++			+	
Plagioclase	++	++++	+++	++		+++	+++
Nepheline/analcite	++	++	+	+	+	+	
Glass and un-recognized aphanitic matrix	+++	++	++	++	++	++	++

TBU — tephrite/basanite unit, LB — lower basalt, PU — picrobasalt unit, UBU — upper basalt unit

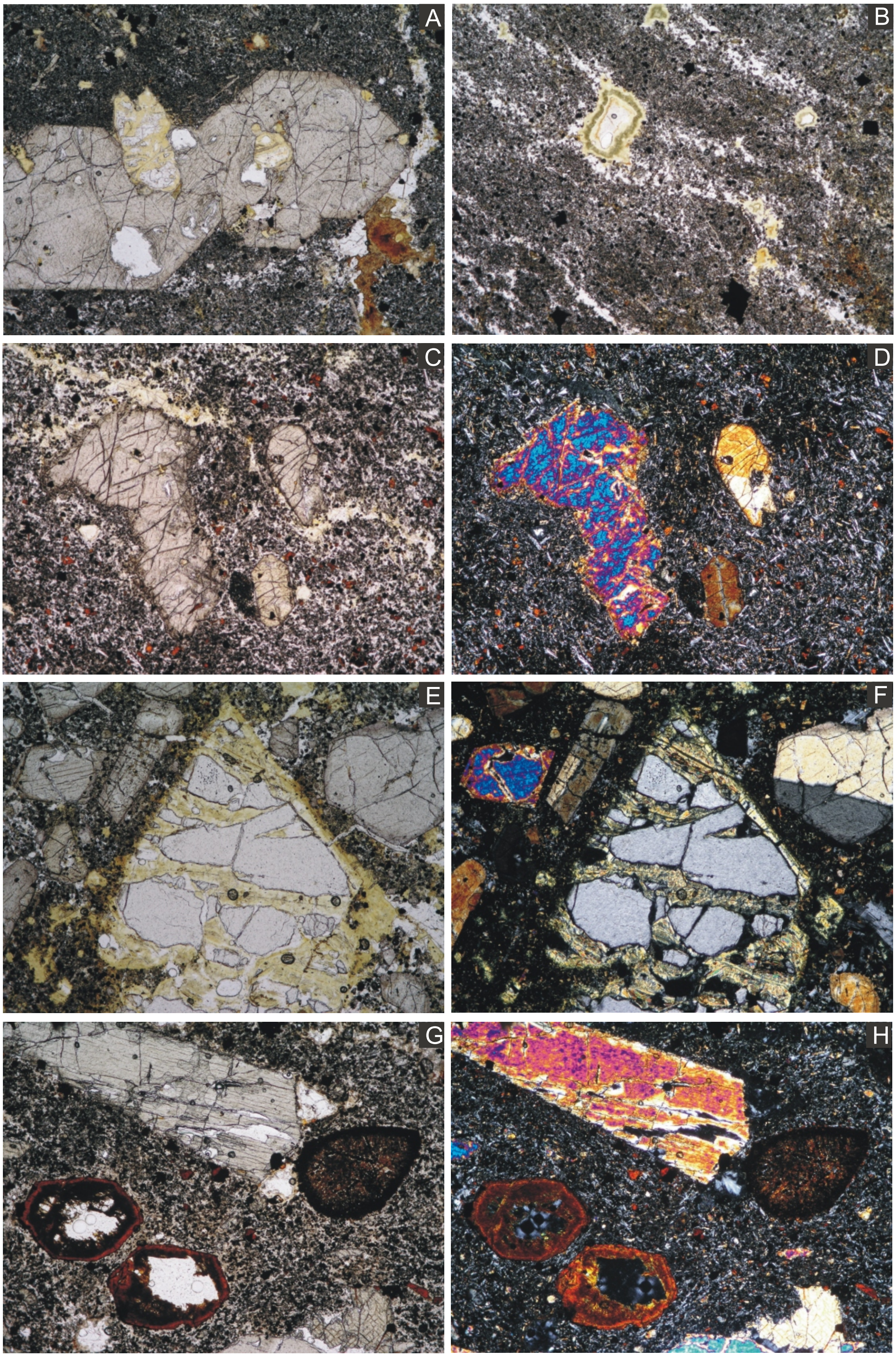

Fig. 5. Microphotographs of representative rock samples

A — scarce clinopyroxene phenocryst with olivine inclusion in tephrite of the first lava (sample V8); **B** — fine-grained matrix of the first lava on the western side (V15); **C**, **D** — clinopyroxene phenocrysts in matrix containing small pseudomorphs after olivine — lava of lower basalt (V5, single and crossed polars respectively); **E**, **F** — large olivine phenocryst surrounded by clinopyroxene phenocrysts in picrobasalt (V14, single and crossed polars respectively); **G**, **H** — upper basalt of the eighth lava: pseudomorphs after amphibole and olivine and diopside phenocrysts (V9, single and crossed polars); real width of all pictures is 3.2 mm

Compared to the previous ones, the third lava is richer in olivine phenocrysts (up to 1.2 cm) that are completely iddingsitized. Pseudomorphs after amphibole (up to 1 cm) consist of a mixture of diopside, Fe-Ti oxides and rhönite. This sample petrographically represents a transitional rock between tephrite and basanite, consistent with petrological data from the TBU (normative olivine).

LOWER BASALT (LB)

The fourth lava is exposed on the eastern slope solely of the studied locality. This basaltic rock differs significantly from the underlying TBU as well as from the overlying picrobasalts. Diopside phenocrysts are enclosed in a fine-grained matrix (Fig. 5C, D). Cavities filled by carbonates and zeolites are abundant. The geochemical characteristics and appearance of this rock are similar to those of basalts from the top of the entire sequence (UBU).

PICROBASALT UNIT (PU)

This unit consists of two lavas, but only the upper one crops out on both sides of the studied locality. The lower one (lava no. 5) is exposed only on the eastern slope. An abundance of vesicles, a high content (about 55 vol.%) of large olivine and namely diopside phenocrysts, and very low contents of feldspar and feldspathoids are the main characteristics of the entire unit (Fig. 5E, F). The olivine is partly iddingsitized, but fresh cores are still preserved. The rock petrographically corresponds to ankaramite, i.e. basaltic rock unusually rich in phenocrysts of clinopyroxene. The thickness of the picrobasaltic lavas reaches at least 5 m, perhaps due to their high crystallinity and therefore increased effective viscosity.

UPPER BASALT UNIT (UBU)

The youngest lavas preserved at Úhošť Hill belong to the UBU. This unit consists of three lavas (lavas 7, 8 and 9), but only the lowest one reaches the eastern side of the hill. Lavas no. 8 and 9 can be currently seen only on the top of the western slope (closer to the original volcanic centre). At present it is hard to say whether this is due to a smaller magma supply, which produced shorter lava flows, or to later erosion. The fine-grained basalt of lava no. 7 is relatively poor in diopside phenocrysts, especially on the eastern slope. The occurrence on the western slope differs from that of the same lava on the eastern slope in a slightly higher content of phenocrysts. Similarly, granulitic xenoliths occur on the western side solely, whereas on the eastern side none have been found. The overlying lava (no. 8) displays a well-developed autoclastic facies at the base, a prevailing compact facies, and a strongly vesiculated top. Diopside phenocrysts (1 cm) build up to 20% of the rock. Relics of amphibole (not exceeding 2 mm) and altered olivine (up to 8 mm) were also distinguished among the phenocrysts (Fig. 5G, H). The youngest preserved lava sheet (no. 9) is coarsely porphyritic (diopside up to 1.5 cm, pseudomorphs after amphibole up to 2.5 cm) basalt. This youngest lava has been dated using the K-Ar method as Aquitanian (22.09 ±0.73 Ma; Table 5).

MINERAL CHEMISTRY

Most of the minerals present in the lavas of Úhošť Hill are generally uniform in composition and give little additional information on magmatic evolution. The olivines studied were mostly so strongly iddingsitized that only in one lava sheet (samples V3A and V14) fresh cores of olivine phenocrysts Fo_{81-86} were preserved. The composition of Ti-magnetite (content of Ti and admixtures of Al, Mg, Mn) is variable within each individual sample and shows no dependence on petrography.

Plagioclase is commonly restricted to the matrix and its laths are frequently too small even for analysis. Those few analysed from the UBU (sample V2) have the composition $An_{50-60}Ab_{39-48}Or_{1-2}$. Feldspathoids are represented by automorphic (or hypautomorphic) nepheline and xenomorphic analcite. The analcite most probably replaces the original glass. No analcite pseudomorphs after leucite (common in many localities within the entire DHVC) were observed in lavas of Úhošť Hill.

The best information on magma evolution is carried by compositional variations of the clinopyroxenes, because of their long crystallization interval. Compositional variations of clinopyroxenes from the entire DHVC were described by Rapprich (2005). Depletion in Si and Mg and enrichment in Ti, Al and Fe towards the rims reflect a common compositional evolution of clinopyroxenes during crystallization of the basaltic melt. Clinopyroxene corresponds to aluminian diopside with a Ca content (always over 90% of the M 2 site — Table 2) too high to be classified as augite. Only weak differences were found in clinopyroxene compositions from different rocks (Fig. 6). The most primitive (Mg-rich) pyroxene occurs in picrobasaltic lavas suggesting early crystallization with high Mg/Fe ratios. Clinopyroxene from other lavas is more evolved, including the very inner cores.

CHEMICAL COMPOSITION OF THE ERUPTED MAGMAS

The DHVC is characterized by dominance of basaltic lavas clustering around the foidite–tephrite/basanite–picrobasalt–basalt *s.s.* field boundaries within the total alkali–silica classification diagram (Fig. 7). The range of chemical composition of lavas of Úhošť Hill (Table 3) fits within the compositional range of common DHVC lavas.

The chemical classification (Le Bas *et al*., 1986; Fig. 7) is in good agreement with the mineralogical classification described above. The only exception is the V8 sample (nepheline analcitite according to its modal composition but tephrite as regards chemical classification). The lavas of the TBU plot in the field of tephrites/basanites, the PU is placed at the boundary between picrobasalts and basalts. A basaltic *s.s.* composition of the LB and UBU was also proved.

The succession starts with TBU lavas poor in phenocrysts. These lavas are weakly evolved according to their differentiation indices (17.4–25.3) and generally low mg# values (49.7–55.7), MgO (6.5–8.3 wt.%), Cr (72–109 ppm) and Ni (26–55 ppm) contents. The younger lava of this unit displays a more evolved composition compared to the older one. The first lava displays increased contents of both MgO and CaO.

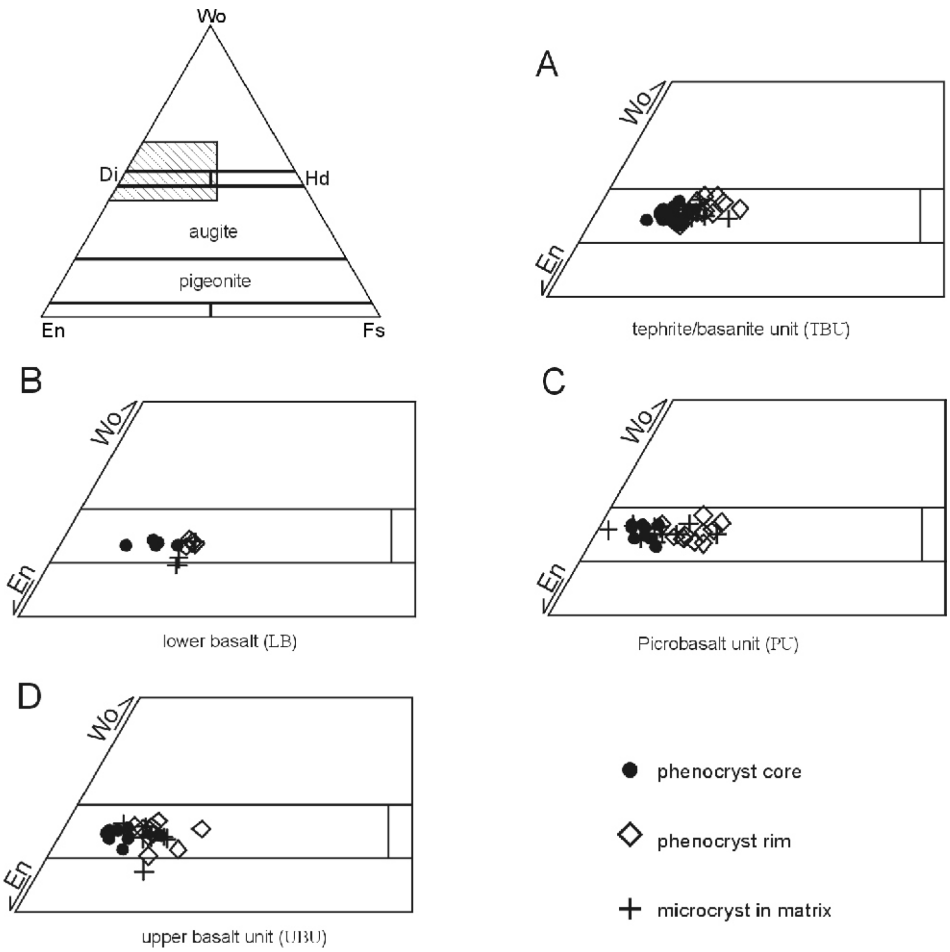

Fig. 6. Classification of clinopyroxenes from lavas of Úhošť' Hill in a quadrilateral diagram (Morimoto, 1988)

Clinopyroxenes are plotted after purification from additional molecules (Rapprich, 2005); **A** — tephrite/basanite unit; **B** — lower basalt; **C** — picrobasalt unit; **D** — upper basalt unit (data: A and B this paper; C and D from Rapprich, 2005); Di — diopside, En — enstatite, Fs — ferrosilite, Wo — wollastonite, Hd — hedenbergite

The following LB lava is characterized by significantly lower mg# (45.3–47.4) and higher DI (34.2–35.4) values as compared to the previous unit. Of incompatible elements, there is an increased content of Rb and also the ratios Rb/Nb and Ba/Nb are significantly higher with respect to the TBU lavas. This basalt is geochemically similar to the youngest lavas (UBU).

Lavas of the PU unit are high in MgO (9.35–12.5 wt.%) and CaO (14.4–15.1 wt.%) and have low total alkali contents (2.6 wt.% for the first lava and 2.0 to 2.2 wt.% for the second one) and low DI values (11.4–16.6) accompanied by high mg# (60.5–68.1), high Cr (424–613 ppm) and Ni (112–151 ppm) contents. Analysis of the V14 sample also shows significantly increased concentrations of Sc in the PU. Contents of incompatible elements are lower than in the TBU lavas.

The uppermost UBU unit consists of basalts *s.s.* with increased DI values (27.8–31.3) and Al_2O_3 contents (13.4–14.6 wt.%). These basaltic lavas again have low mg# values (44.5–54.5) and low contents of Cr (24–123 ppm) and Ni (13–37 ppm). In average, these upper basalts are on average slightly less evolved than the LB.

Geochemical variations as a function of lithostratigraphic position within the sequence are shown in Figure 8. Repeating changes from less evolved to more evolved magmas and *vice versa* are obvious.

The chondrite-normalized REE patterns (Fig. 9) and spidergram for trace elements normalized to primitive mantle (Fig. 10) show very similar geochemical features in all the lavas. The chondrite-normalized REE patterns (Fig. 9) for individual samples are mutually parallel and almost linear with high degrees of LREE enrichment (La_n/Yb_n from 18.9 to 23.5). The ankaramitic lava of the PU has significantly lower contents of all REEs and the lowest La_n/Yb_n ratio.

Also the spidergram of trace element contents normalized to primitive mantle (Sun and McDonough, 1989; Fig. 10) displays very similar patterns for all samples with strong negative anomalies for K and less pronounced ones for Rb and P.

By contrast, higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ values (Table 4) separate basalts (LB and UBU) from tephrites and picrobasalts (TBU and PU). The same is true for some ratios of strongly incompatible elements such as Rb/Nb, Ba/Nb, Th/Ta or Th/Nb (Table 3).

Table 2

Average compositions of clinopyroxenes from Úhošt' Hill

Unit		TBU			LB			PU			UBU		
Zone		core	rim	matrix	core	rim	matrix	core	rim	matrix	core	rim	matrix
n		12	19	6	3	6	3	8	10	10	7	10	8
SiO_2		49.66	45.46	46.03	50.57	46.70	46.75	52.11	47.26	51.01	50.73	47.69	48.85
TiO_2		1.64	3.44	3.32	1.33	2.89	3.11	0.82	2.62	1.31	1.27	2.30	1.85
Al_2O_3		4.40	7.27	6.36	3.95	6.17	5.47	2.90	6.70	3.62	4.39	5.92	5.14
Cr_2O_3		0.25	0.02	0.00	0.22	0.03	0.05	0.41	0.03	0.31	0.33	0.09	0.12
FeO		5.92	7.75	8.12	5.73	8.30	8.78	4.19	7.53	4.87	5.33	7.62	7.49
MnO		0.03	0.07	0.10	0.06	0.07	0.11	0.08	0.14	0.12	0.10	0.15	0.12
MgO		14.26	12.10	12.32	14.68	12.36	12.74	15.68	12.36	14.94	14.72	12.72	13.40
CaO		23.40	23.25	23.21	23.13	22.65	22.22	23.17	22.71	23.19	22.92	22.54	22.55
Na_2O		0.44	0.48	0.45	0.42	0.52	0.45	0.66	0.81	0.65	0.69	0.77	0.74
Total		99.99	99.84	99.90	100.10	99.69	99.68	100.02	100.17	100.04	100.52	99.82	100.27
T	Si	1.832	1.698	1.721	1.860	1.747	1.752	1.903	1.752	1.870	1.853	1.773	1.804
	Al	0.168	0.302	0.268	0.140	0.253	0.241	0.097	0.248	0.130	0.147	0.227	0.196
	Fe^{3+}			0.011			0.007						
M1	Al	0.023	0.019	0.013	0.032	0.020	0.002	0.028	0.045	0.028	0.042	0.033	0.027
	Fe^{3+}	0.078	0.123	0.112	0.058	0.106	0.101	0.059	0.114	0.066	0.074	0.118	0.116
	Ti	0.046	0.097	0.093	0.037	0.082	0.088	0.022	0.073	0.037	0.035	0.064	0.051
	Cr	0.007	0.001		0.007	0.001	0.001	0.012	0.001	0.009	0.009	0.003	0.003
	Mg	0.784	0.674	0.686	0.805	0.689	0.712	0.853	0.683	0.814	0.801	0.705	0.738
	Fe^{2+}	0.062	0.087	0.095	0.062	0.103	0.096	0.025	0.084	0.047	0.038	0.077	0.064
M2	Mg									0.002			
	Fe^{2+}	0.043	0.033	0.035	0.056	0.052	0.071	0.044	0.035	0.037	0.051	0.042	0.051
	Mn	0.001	0.002	0.003	0.002	0.002	0.003	0.002	0.005	0.004	0.003	0.005	0.004
	Ca	0.925	0.931	0.930	0.912	0.908	0.893	0.907	0.902	0.911	0.897	0.898	0.892
	Na	0.031	0.034	0.032	0.030	0.037	0.033	0.047	0.058	0.046	0.049	0.055	0.053
Kch		0.68	0.07		0.65	0.10	0.14	1.18	0.09	0.89	0.94	0.26	0.34
Aeg		2.45	3.38	3.24	2.36	3.65	3.14	3.43	5.73	3.39	3.85	5.26	4.96
Jd								0.07		0.31	0.10		
Kan		0.09	0.23	0.31	0.19	0.23	0.34	0.24	0.45	0.38	0.32	0.48	0.37
CFT			0.02	1.12			0.70					0.01	
CAT		2.31	1.89	1.27	3.17	2.01	0.17	2.75	4.49	2.47	4.13	3.29	2.75
CTT		4.55	9.70	9.33	3.68	8.17	8.80	2.25	7.31	3.66	3.50	6.43	5.13
Ess		5.38	8.91	6.87	3.45	6.91	6.31	2.45	5.69	3.20	3.55	6.50	6.62
Fs		5.23	5.96	6.52	5.92	7.72	8.35	3.46	5.96	4.20	4.45	5.96	5.79
En		39.16	33.57	34.16	40.14	34.34	35.41	42.55	33.92	40.60	39.90	35.03	36.70
Wo		40.12	36.27	37.19	40.43	36.87	36.66	41.6	36.36	40.91	39.25	36.79	37.35

Average analyses (oxides in wt.%, n — number of analyses) recalculated to formulae based on 4 cations and 6 oxygens (T — tetrahedral position, M 1 and M 2 — octahedral positions), and average molar percentages of end-members (Kch — kosmochlor, Aeg — aegerine, Kan — kanoite, CFT — Ca-ferri-Tschermak´s molecule, CAT — Ca-Al-Tschermak´s molecule, CTT — Ca-Ti-Tschermak´s molecule, Ess — esseneite, En — enstatite, Fs — ferrosilite, Wo — wollastonite); "Area" indicates whether core (c) or rim (r) of phenocrysts or microcryst in a matrix (m) was analyzed; (TBU and LB — new data, PU and UBU from Rapprich, 2005); for recalculation method see text

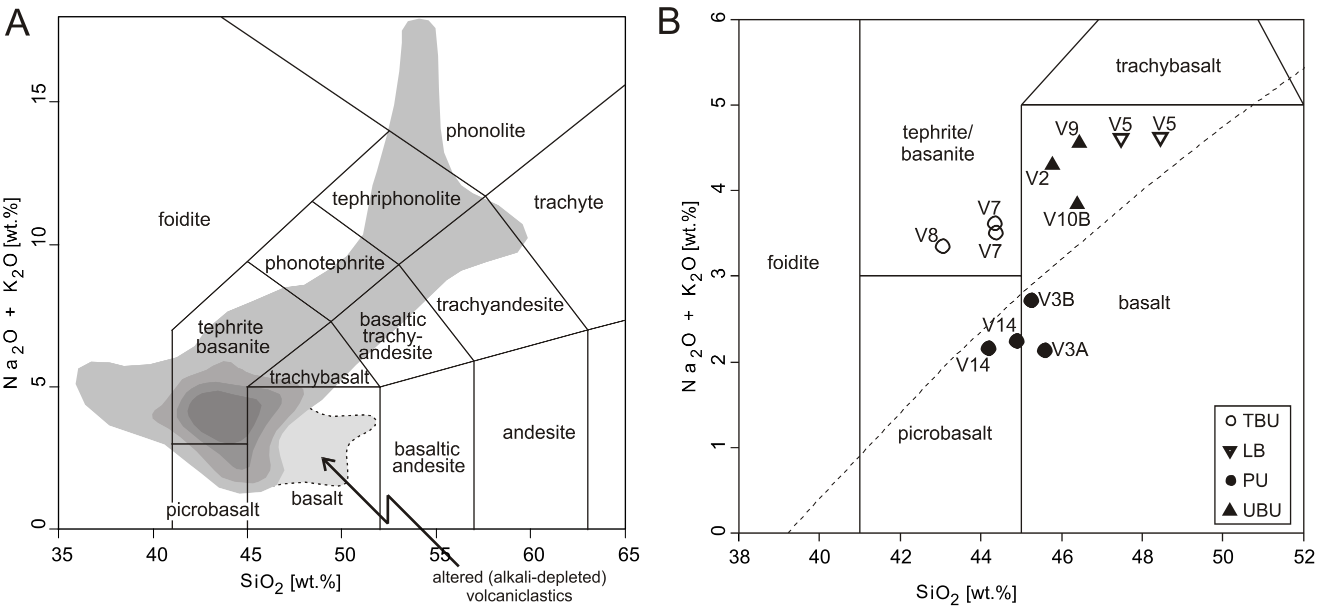

Fig. 7A — range of compositional variation of magmas erupted within the DHVC (*n* = 164, data from: Shrbený, 1982; unpublished data of Adamová for DHVC mapping projects of the Czech Geological Survey; unpublished data of authors). Shading displays relative increase in frequency of the samples analysed; B — detail of the TAS diagram (Le Bas *et al.*, 1986) with samples from Úhošť' Hill; double symbols for samples V5, V7 and V14 represent analyses provided by two independent methods (see Table 3)

Table 3

Major component analyses of lavas from Úhošť' Hill near Kadaň [wt.%]

Unit	Tephrite-basanite unit (TBU)			Lower basalt (LB)		Picrobasalt unit (PU)				Upper basalt unit (UBU)		
Flow	1	2	2	4	4	5	6	6	6	7	7	9
Sample	V8	V7	V7	V5	V5	V3B	V3A	V14	V14	V2	V10B	V9
Lab.	CGS	CGS	AL	CGS	AL	CU	CU	CU	AL	CU	CU	AL
SiO_2	40.87	42.38	42.03	44.84	45.96	43.42	42.78	42.62	43.89	43.88	44.36	45.30
TiO_2	3.06	3.52	3.75	2.89	3.21	2.64	2.40	2.66	2.73	3.56	3.00	3.14
Al_2O_3	11.94	13.30	13.26	13.81	13.47	11.02	9.22	9.96	9.28	14.60	13.43	14.19
Fe_2O_3	8.12	12.95*	13.07*	9.14	12.36*	7.87	8.96	5.65	11.61*	6.68	6.63	12.00*
FeO	4.49	–	–	2.95	–	3.78	2.63	5.62	–	5.78	4.83	–
MnO	0.22	0.21	0.20	0.16	0.16	0.17	0.16	0.16	0.17	0.21	0.19	0.18
MgO	8.31	6.98	6.53	5.64	5.16	9.35	10.85	12.17	12.49	5.31	7.26	6.35
CaO	14.06	12.14	11.68	9.91	9.35	14.63	14.41	15.08	15.04	10.99	11.49	11.29
Na_2O	2.18	2.41	2.52	2.82	2.87	2.07	1.15	1.71	1.79	3.10	2.72	3.21
K_2O	1.00	0.94	0.91	1.53	1.51	0.54	0.85	0.37	0.40	1.03	0.96	1.24
P_2O_5	0.65	0.69	0.79	0.74	0.80	0.47	0.43	0.40	0.35	0.74	0.75	0.61
H_2O^-	0.71	1.30	–	1.10	–	0.66	0.90	0.38	–	0.54	0.62	–
H_2O^+	3.30	3.04	–	3.61	–	3.13	4.58	2.80	–	2.84	3.03	–
CO_2	0.37	–	–	0.10	–	0.15	0.24	0.07	–	0.46	0.19	–
F	0.18	–	–	0.17	–	–	–	–	–	–	–	–
LOI	–	–	4.16	–	4.26	–	–	–	2.45	–	–	2.60
Total	99.67	99.86	98.91	99.64	99.10	99.90	99.56	99.65	100.19	99.72	99.46	100.10
DI	17.4	23.8	25.3	34.2	35.4	16.6	13.7	11.4	13.0	30.5	27.8	31.25
mg#	55.7	51.6	49.7	47.4	45.3	60.6	64.4	67.0	68.1	44.5	54.5	51.2

CGS — Laboratory of the Czech Geological Survey, Prague; CU — Laboratory of Geological Departments, Faculty of Science, Charles University in Prague; AL — Activation Laboratories, Ltd., Ancaster, Ontario (major elements by ICP); * — total Fe as Fe_2O_3; LOI — loss on ignition (uncorrected to oxidation of Fe); DI — differentiation index based on the CIPW norm (sum of normative salic minerals except for anorthite, wt.%); mg# — atomic ratio $100Mg/(Mg+Fe_{tot})$

Table 4

Trace element analyses of lavas from Úhošt' Hill near Kadaň (in parts per million)

Unit	Tephrite-basanite unit (TBU)			Lower basalt (LB)		Picrobasalt unit (PU)				Upper basalt unit (UBU)		
Flow	1	2	2	4	4	5	6	6	6	7	7	9
Sample	V8	V7	V7	V5	V5	V3B	V3A	V14	V14	V2	V10B	V9
Lab.	CGS	CGS	AL	CGS	AL	CU	CU	CU	AL	CU	CU	AL
Ba	690	–	836	985	1102	845	608	699	454	948	1157	849
Cs	–	–	1.2	–	1.6	–	–	–	0.4	–	–	0.9
Co	51	–	40	38	36	53	52	56	52	38	44	35
Cr	109	72	90	41	60	424	487	518	613	24	123	97
Nb	74	84	84	73	76	–	–	–	47	–	–	55
Ni	55	26	50	13	40	112	125	151	138	13	37	32
Rb	50	42	46	83	92	19	83	12	18	24	33	54
Sc	–	–	23	–	22	–	–	–	47	–	–	24
Sr	767	901	1046	784	873	792	438	553	526	910	1050	787
V	425	–	454	346	370	–	–	–	337	–	–	365
Y	28	29	26.6	31	30.6	–	–	–	16	–	–	23
Zn	81	92	110	103	120	–	–	–	88	–	–	116
Zr	290	342	323	384	365	–	–	–	168	–	–	241
Hf	–	–	8.20	–	8.80	–	–	–	5.20	–	–	6.50
Ta	–	–	6.69	–	5.31	–	–	–	3.73	–	–	4.52
Th	–	–	7.05	–	7.72	–	–	–	3.86	–	–	7.06
U	–	–	1.65	–	1.20	–	–	–	0.99	–	–	1.65
Sc/Co	–	–	0.575	–	0.61	–	–	–	0.90	–	–	0.69
Cr/Co	–	–	2.25	–	1.67	8.0	9.4	9.2	11.8	0.63	2.8	2.77
Rb/Nb	0.68	0.51	0.55	1.14	1.21	–	–	–	0.38	–	–	0.98
Ba/Nb	9.32	–	9.95	13.49	14.50	–	–	–	9.66	–	–	15.44
Zr/Nb	3.92	4.07	3.85	5.26	4.80	–	–	–	3.57	–	–	4.38
Nb/U	–	–	50.9	–	63.3	–	–	–	47.5	–	–	33.3
Th/Ta	–	–	1.05	–	1.45	–	–	–	1.03	–	–	1.56
Th/Nb	–	–	0.084	–	0.102	–	–	–	0.082	–	–	0.128

For explanations see Table 3

DISCUSSION

The lava succession of Úhošť Hill starts with tephritoids poor in phenocrysts, with low MgO, Cr and Ni contents and with moderate values of the differentiation index. This initial lava group is buried by more differentiated basalt, which is precedent to two picrobasaltic lavas rich in large phenocrysts of olivine and diopside and with characteristically higher contents of Ni, Cr, and low DI values. The sequence is completed by a set of evolved basaltic lavas displaying the highest DI values, increased contents of silica, alkalis and Al_2O_3. Such a succession could hardly be explained by successive exhaustion of a single magma reservoir filled with magma continuously evolving by fractional crystallization.

Petrographical as well as geochemical data, including the isotopic compositions of Sr and Nd, suggest that all the lavas can be subdivided into two groups. The first group comprises the TBU and PU, the second group covers both the lower and upper basalts (LB and UBU). Each of the two groups displays almost identical (within analytical uncertainty) isotopic compositions and very similar ratios of incompatible elements that are different to those in the other group.

An interesting problem is the origin of ankaramite lavas forming the picrobasalt unit (PU). Geochemical data (see the incompatible-element ratios, e.g., Th/Ta or Ba/Nb) including the isotopic compositions demonstrate their close relationship to the TBU, but both units differ in the content of phenocrysts and their proportions. The TBU represents magma apparently depleted in phenocrysts, whereas the PU contains about 55 vol.% of large phenocrysts dominated by clinopyroxene. Although the picrobasalts display some compositional features aproaching those of near-primary mantle melts (e.g., the high contents of MgO and Cr), they are relatively low in Ni. Con-

Table 5

Rare earth element (REE) contents (parts per million, ppm), Sr- and Nd-isotopic ratios (measured and initial), and K-Ar ages for rocks representing individual units of the Úhošť' Hill lava succession

Unit	TBU	LB	PU	UBU
Flow	2	4	6	9
Sample	V7	V5	V14	V9
La	71.6	81.1	41.5	58.0
Ce	148.0	169.0	83.7	122.0
Pr	16.8	19.2	9.23	14.1
Nd	65.3	72.2	36.8	48.3
Sm	10.9	11.6	7.7	9.35
Eu	3.46	3.58	2.29	2.96
Gd	8.14	8.51	5.20	7.90
Tb	1.21	1.24	0.77	0.98
Dy	6.04	6.28	4.26	5.25
Ho	1.04	1.12	0.70	1.04
Er	2.73	2.93	1.66	2.57
Tm	0.37	0.40	0.21	0.29
Yb	2.14	2.33	1.48	1.96
Lu	0.30	0.33	0.20	0.31
La_n/Yb_n	22.56	23.47	18.90	19.95
La/Nb	0.85	1.07	0.88	1.05
Ba/La	11.7	13.6	10.9	14.6
$^{87}Sr/^{86}Sr$	0.70423	0.70465	0.70413	0.70467
$^{143}Nd/^{144}Nd$	0.512731	0.512683	0.512727	0.512683
$^{87}Sr/^{86}Sr_i$	0.70418	0.70452	0.70409	0.70459
$^{143}Nd/^{144}Nd_i$	0.512712	0.512665	0.512703	0.512661
Age [Ma]	28.66 ±1.06	–	26.38 ±1.04	22.09 ±0.73

tents of CaO and Sc are significantly higher than expected for primitive basanitic to picrobasaltic melts and together with the abundance of phenocrysts suggest that these lavas may represent magma portions containing crystals that were accumulated from a larger magma volume. Although the real situation may be significantly more complicated and we do not know the exact composition of the magma to which the "cumulate" has been added, our very rough calculation based on major oxides seems to support this hypothesis (see Table 6). Assuming that the cumulitic assemblage contained 0% of P_2O_5, the composition of the most mafic ankaramite V14 can be explained as a mixture of 42.5 wt.% of tephritic magma similar to V7 and 57.5 wt.% of a hypothetical ultramafic cumulate consisting of about 14 wt.% of olivine and about 86 wt.% of "clinopyroxene". The composition of this hypothetical "clinopyroxene" seems to be slightly out side of the compositional range of analyzed clinopyroxenes from sample V14 with respect to Al_2O_3, TiO_2 and Na_2O. Therefore, we suppose that some subordinate amount of hornblende could have been originally present in the assemblage. The dominance of clinopyroxene in the cumulitic assemblage combined with the high mineral/melt partition coefficients of Sc and Cr for clinopyroxene in basaltic melts account for the high Cr and Sc concentrations in the ankaramite. Also the strong depletion of sample V14 in Cs, Rb, and slightly smaller depletion in Ba, Nb, Zr, Hf and so on, supports the accumulation of clinopyroxene accompanied by some amphibole.

The accumulation hypothesis corresponds well to the relative position of both units within the succession. The phenocryst-poor tephritoids were erupted earlier than the picrobasalts and probably represent magma portions originally stored in the upper part of the magma reservoir. Picrobasalts (PU) loaded with large crystals of mafic minerals are later and may represent mobilized semi-cumulitic magma from the origi-

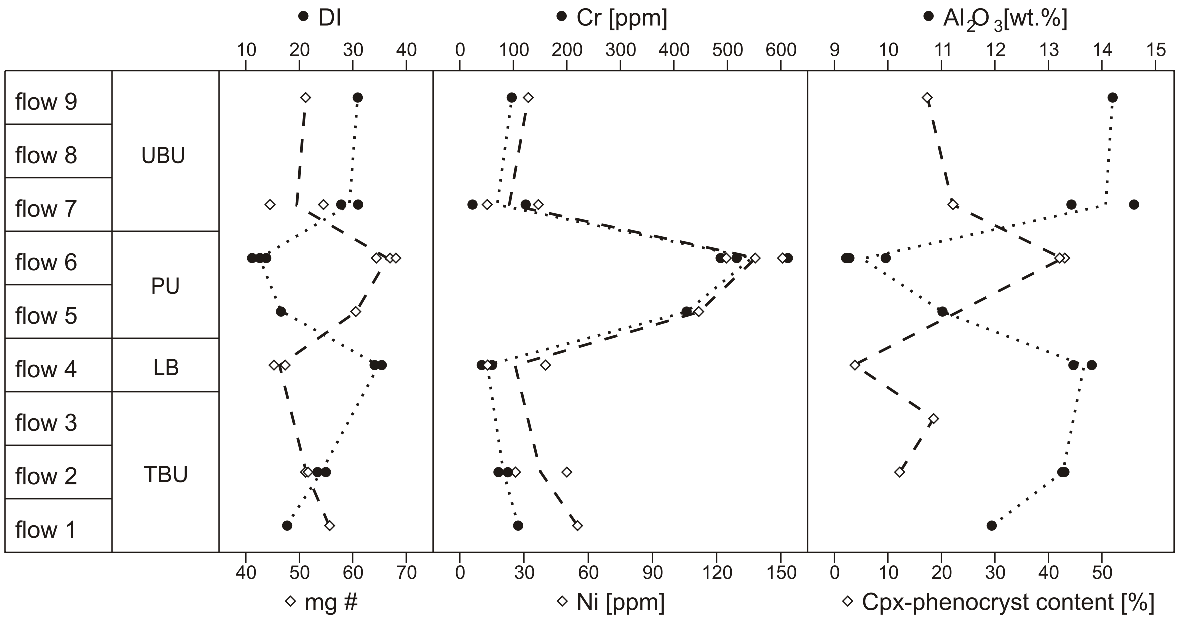

Fig. 8. Variation of differentiation index (DI — based on CIPW norm), mg#, Ni, Cr, Al_2O_3 and Cpx-phenocryst content related to the stratigraphic position of individual lavas in the succession

nal bottom part of the chamber. Eruption of crystal-rich picrobasaltic magma with an increased effective viscosity could have been triggered by repeated invasion of other magma batches coming from another reservoir (situated at greater depth) into the tephritoid/picrobasalt magma reservoir. We speculate that the magma responsible was the basalt though as yet no evidence has been found for mixing between the picrobasalts and the basalts *sensu stricto*.

Despite the rather subtle geochemical differences between the two magma groups, all the erupted magma portions are of roughly similar geochemical character expressed, for instance, in the REE and trace-element normalization spidergrams (Figs. 9 and 10). Their overall chemical composition fits the compositional range of alkaline basaltic rocks from the DHVC.

In the trace element spidergram (Fig. 10) there are negative peaks in Rb, K, and P. Light REEs are apparently more enriched compared with those elements that should display similar degrees of incompatibility. The pronounced negative potassium anomaly is a common feature of magmas from nearly all the CiMACI Province (e.g., Wedepohl and

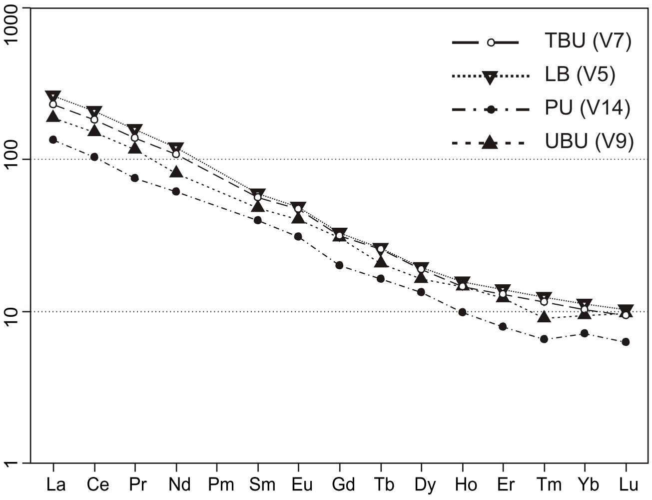

Fig. 9. Spidergram for REEs (rare earth elements) normalized to average chondrite composition (normalizing values from Boynton, 1984)

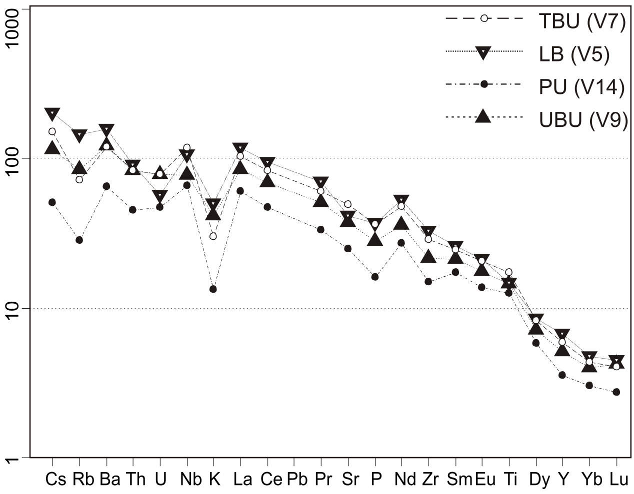

Fig. 10. Spidergram for incompatible elements contents normalized to primitive mantle (normalizing values from Sun and McDonough, 1989)

Table 6

Calculation test of the "cumulitic hypothesis" for the origin of the ankaramite lava V14

	V7	V14	Cumulus	0.575 × Cumulus+ + 0.425 × V7	"Cpx"	Ol	0.86 "Cpx" + 0.14 Ol
SiO_2	44.36	44.90	45.30	44.90	47.00	38.10	45.31
TiO_2	3.96	2.79	1.92	2.79	2.25	0	1.92
Al_2O_3	14.00	9.49	6.13	9.47	7.20	0	6.13
Fe_2O_3*	13.80	11.88	10.45	11.87	–	–	10.43
FeO*	–	–	–	–	7.96	18.67	–
MnO	0.21	0.17	0.15	0.17	0.17	0.30	0.15
MgO	6.89	12.78	17.17	12.80	13.17	42.93	17.17
CaO	12.33	15.39	17.67	15.40	20.75	0	17.67
Na_2O	2.66	1.83	1.21	1.83	1.43	0	1.22
K_2O	0.96	0.41	0.00	0.41	0	0	0
P2O5	0.83	0.36	0.00	0.36	0	0	0
Total	100.00	100.00	100.00	100.00	100	100	100

Cumulus — the hypothetical bulk composition of accumulated mafic phenocrysts added to tephrite V7 to shift the composition towards ankaramite V14; "Cpx" — hypothetical composition of accumulated clinopyroxene including some small amount of amphibole; Ol — composition of olivine Fo_{84}; * — total Fe as Fe_2O_3 or FeO

Baumann, 1999) and commonly is explained by the presence of some residual amphibole in the mantle source region (e.g., Wilson and Downes, 1991, 2006). However, this geochemical feature may simply reflect the source depletion in K relative to the HFSE and REE (Lustrino and Wilson, 2007). Such a relative depletion in K and some other LIL elements, contrasting with the strong enrichment in HFS elements, may be caused by the significant decoupling of those two groups of incompatible elements during older subduction-related processes. The relative depletion in P may be one of the source characteristics. Moreover, the most pronounced negative phosphorus anomaly in the ankaramitic lavas of the PU is apparently enhanced by the accumulation of clinopyroxene containing some Sr and Nd but virtually no P.

Many rocks of the DHVC could have lost part of the original content of K due to alteration and analcimization of leucite. As the Úhošť Hill lavas do not display any evidence for the former presence of leucite, any significant post-magmatic changes in alkali abundances cannot be deduced except in the case of the more altered autoclastic breccias.

In terms of Sr and Nd isotopic compositions, the lavas under study plot within the range of the CiMACI Province volcanic rocks. They are, however, among samples plotting at the greatest distance from the "European Asthenospheric Reservoir" (EAR) as defined by Cebrià and Wilson (1995), i.e. on the trend towards enriched mantle components EM 1 and EM 2 (*cf.* Lustrino and Wilson, 2007) in close proximity to the Bulk Silicate Earth (BSE, see Fig. 11).

Volcanic rocks from the České středohoří Volcanic Complex with isotopic compositions less shifted towards the "enriched mantle" (Fig. 11) have been interpreted as affected by crustal contamination (Cajz *et al*., 1999; Ulrych *et al*., 2002). However, contamination could hardly be the dominant process in magmas from our locality where the pronounced shift is typical for all lavas ranging in composition from picrobasalt through tephrite/basanite to basalt. The Nb/U ratio that does not vary with melt fraction during partial melting but is highly sensitive to contamination by continental crust corresponds well with values from oceanic basalts including MORBs (e.g., Hofmann, 2002). Therefore we interpret the trace element pattern as well as the isotopic composition of the Úhošť lavas primarily as a source signature with possible but hardly demonstrable modification by processes of direct crustal contamination.

Compared with the TBU and PU rocks, the basalts (LB and UBU) display a less pronounced negative K-anomaly in the spidergram (Fig. 10), higher La/Nb, Ba/Nb Th/Ta (1.45–156) and higher ^{87}Sr/^{86}Sr as well as lower ^{143}Nd/^{144}Nd (Tables 4 and 5). These subtle differences, suggesting that the basanitic and basaltic magmas evolved separately, may be caused by more significant addition of geochemically evolved material into basalts, either by enhanced involvement of enriched mantle components during melting (including the older enriched subcontinental lithosphere) or by more significant contamination with continental crust.

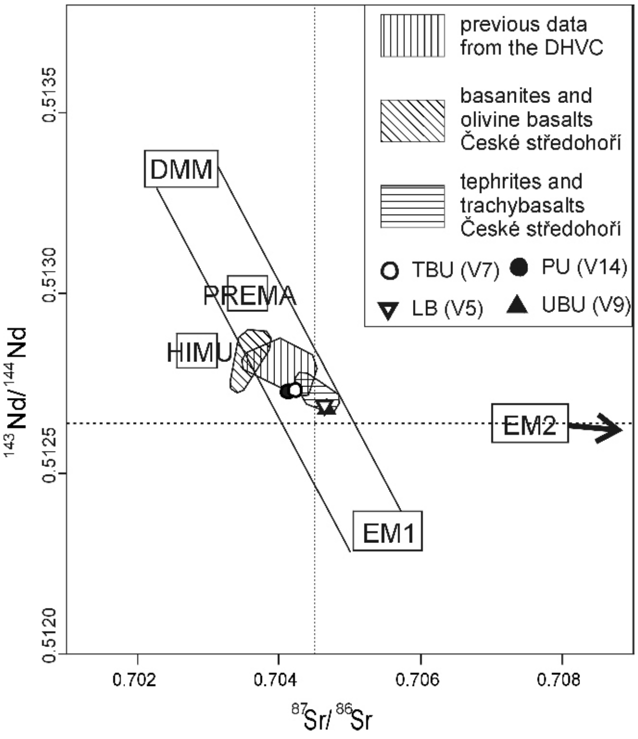

Fig. 11. Sr and Nd isotopic ratios of the lavas studied plotted onto a diagram of mantle components (Zindler and Hart, 1986)

Extent of the limited data available from the DHVC (Vokurka, 1997) and the main petrographic suites from the neighbouring České středohoří Volcanic Complex (Ulrych *et al*., 2002) are plotted for comparison; DMM — depleted MORB mantle component, EM 1 — enriched mantle type 1, EM 2 — enriched mantle type 2, HIMU — high-μ mantle component, PREMA — prevalent mantle

CONCLUSIONS

1. The lava sequence cropping out on Úhošť Hill shows complex compositional changes through time from the lowermost tephrites via basalt and picrobasalts to the uppermost basalts.

2. Such a succession may reflect exhaustion of a complex magma reservoir or, more probably, of two independent reservoirs attached to a single conduit system.

3. Picrobasalts (ankaramites) unusually high in CaO and Sc probably represent magma portions affected by partial accumulation of clinopyroxene and olivine (+ some amphibole?) phenocrysts (i.e., they originated as a semi-cumulate) and not the near-primary melt.

4. The isotopic composition of the lava sequence is close to the Bulk Silicate Earth. This may be due to the mixed nature of the mantle source derived from the European Asthenospheric Reservoir through addition of significant amounts of components similar to Enriched Mantle (EM 1 and EM 2).

5. There was either some difference in the source composition for basalts (LB+UBU) compared to tephrites/basanites (TBU) and picrobasalts (PU), or the basalts are more modified by involvement of subcontinental lithosphere or contamination with crustal material.

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