Rock-forming minerals of lamprophyres and associated mafic dykes from the Krušné hory/Erzgebirge (Czech Republic)

Horninotvorné minerály lamprofyrů a příbuzných mafických žilných hornin z Krušných hor (Česká republika)

(4 figs, 5 tabs)

EDVÍN PIVEC[1] – FRANTIŠEK V. HOLUB[2] – MILOŠ LANG[1] – JIŘÍ K. NOVÁK[1] – MIROSLAV ŠTEMPROK[2]

[1] *Geological Institute, Academy of Sciences of the Czech Republic, Rozvojová 135, CZ 16502 Praha 6, Czech Republic*
[2] *Charles University, Faculty of Science, Albertov 6, CZ 12843 Praha 2, Czech Republic; e-mail: frholub@natur.cuni.cz, stemprok@natur.cuni.cz*

Electron microprobe analyses were made on micas, amphiboles, feldspars, chlorites and accessory minerals in lamprophyric dykes (kersantites, minettes, spessartites), and in associated mafic diorite to tonalite porphyries (porphyrites) of the Krušné hory (Erzgebirge) area and Mariánské Lázně region in Western Bohemia (Czech Republic). All studied rocks are altered to various degrees during deuteric and/or postmagmatic stages of evolution. The only primary mafic mineral preserved in all rock types is Mg-biotite to phlogopite, in spessartites and some diorite porphyries also Ti-rich hornblende corresponding to titanian magnesiohastingsite to kaersutite. Magmatic biotites are relatively rich in Ti with limited variations in their Mg/Fe ratios, evidently re-equilibrated during cooling or re-heating. Olivine is totally replaced by pilitic pseudomorphs and by biotite-actinolite clots. Phenocrystic clinopyroxene is completely uralitized, often in well-preserved original shapes. The secondary amphiboles correspond to Si-rich magnesiohornblende to actinolite. Chlorite and epidote are rather scarce and their important occurrences are restricted to limited number of samples. Instead of chloritization typical of lamprophyres in other parts of the Bohemian Massif, most samples are affected by secondary biotitization. Effects of greisenization *sensu stricto* were observed in some lamprophyres from Krupka where Li-bearing dark micas rich in Si and Mg originated.

Key words: Krušné hory/Erzgebirge, lamprophyres, kersantite, minette, spessartite, mica, amphibole, spinel, biotitization, greisenization

Introduction

Earlier studies of lamprophyres in the Krušné hory (Czech Republic) focused on petrography and whole-rock chemical composition in the main ore districts of Krupka (Fiala 1960, Štemprok *et al.* 1994), Jáchymov (Sattran 1965) and adjacent regions. Some results were published by Škvor (1974) in the geological study of the Krušné hory. Unlike in the German Erzgebirge and surrounding area (Kramer 1976, Kramer – Seifert 1994 a,b, Seifert – Kempe 1994, Seifert 1996, etc.), until recently no systematic work has been dedicated to lamprophyres in the Czech Krušné hory. This vacancy was filled by the project “Petrogenetic position of lamprophyres associated with the Krušné hory batholith and their relationship to metallogeny” of the Grant Agency of Charles University. The paper summarizes briefly the main results of the study of rock-forming minerals from unpublished final report (Štemprok *et al.* 2001).

Geological situation

The Krušné hory/Erzgebirge at the NW margin of the Bohemian Massif (Czech Republic and Germany) is a NE-SW-plunging anticline of metamorphosed rocks. In its eastern part it is formed by monotonous gneisses (metagreywackes) and migmatites of supposed Precambrian age. The overlying formation is more variegated (with additional calcareous, mafic, pelitic and quartzitic lenses) and presumably also Precambrian. Surrounding these two is the Lower Palaeozoic series again of variegated lithology (O’Brien – Carlswell, 1993). The crystalline basement represents a tectonic stack of units of different metamorphic grades. Post-orogenic granites of the Late Variscan age (340–290 Ma) constitute two major intrusive suites (OIC and YIC) and are located in three plutons (Western, Middle and Eastern, Fig. 1). Geophysical data show no evidence for any large mafic intrusions beneath the granitic upper crust (Bankwitz – Bankwitz, 1994).

Most lamprophyre dykes under study occur within two formerly important ore districts. The first is the Jáchymov (Joachimstal) district in the W Krušné hory with complex Ag-Bi-Co-Ni-U mineralization. The second one is the Krupka (Preisselberg) ore district in the Eastern Krušné hory with Sn and W ores related to granites of the Younger Intrusive Complex (YIC). Table 1 gives a list of localities from which the minerals have been studied.

Lamprophyre dykes and dyke swarms occur in the whole Krušné hory/Erzgebirge and are controlled by NW-SE to N-S trending deep fault zones (Kramer 1976). The thickness of generally steep-dipping dykes varies from several tens of cm to 10 m attaining rarely 25 m as shown by underground workings in the Jáchymov ore district (Sattran, 1965). The studied lamprophyres are calc-alkaline in character according to Rock (1984) and include kersantites, minettes, spessartites and diorite porphyries (porphyrites) (Table 1).

Lamprophyre dykes in area of the Western Krušné hory pluton and its country rocks (Fig. 1) belong to at least three intrusive phases: (1) lamprophyres pre-dating the granites of the older intrusive complex (OIC), (2) dykes emplaced in the time between older (OIC) and younger

Table 1 List of localities with analyzed samples

Locality	Area	Rock type	Samples studied
Jáchymov, old quarry near the Tomáš shaft	W	kersantite	La 107, 108, 109/2
		diorite porphyry	La 109/1
Jáchymov, Barbora Shaft (dumps)	W	kersantite	La 117*
		spessartite	La 113*, 119*
		diorite porphyry	La 122*
Jáchymov, Panorama Shaft (dumps)	W	kersantite	La 135
		diorite porphyry	La 133
Jáchymov, Eva Shaft (dumps)	W	kersantite	La140
		quartz diorite porphyry	La 139
Jáchymov, Adam Shaft (dumps)	W	kersantite	La 148
		diorite porphyry	La 145
Hluboký, blocks 2 km N	W	minette	La 130, 131
Mariánské Lázně, Hamelika hill	W	diorite porphyry	La 127, 128
Janov, borehole MV-10	W	diorite porphyry	La 129
Vrchoslav, Gallery of the 5th May (dumps)	E	minette	P-626
		biotite greisen	La 154
Krupka, Večerní Hvězda (dumps)	E	kersantite	La 161
		pilitic biotite spessartite	La 162, 163
		biotite greisen	La 165
Krupka, Martin Gallery (dumps)	E	minette	La 167
Krupka, Preisselberg, Gallery No. 2 (dumps)	E	kersantite	LA 170

W = area of the Western Pluton; E – area of the Eastern Pluton
* – samples strongly affected by secondary biotitization

intrusive complexes (YIC), and (3) postgranitic dykes (Seifert – Baumann 1994). According to Štemprok *et al.* (1994) at least three generations of lamprophyres can be recognized also in the Eastern Krušné hory pluton.

As to the absolute age of lamprophyric intrusions, Seifert (1994) reports from the German Erzgebirge pre-granitic lamprophyres, with the age of about 300 Ma and postgranitic lamprophyres 290–260 Ma old. However, recent dating of granites doubts the age of the earliest intrusions and postulates older age of these lamprophyres (Förster *et al.* 1999). Kersantites intersected by S-type granites (type Ehrenfriedersdorf and Rabenberg) should have a minimum age of 320 Ma.

The samples of lamprophyres and associated mafic dykes for the present study were collected on abandoned dumps of uranium mines in the Jáchymov ore district and dumps from exploration in the Krupka region, to a lesser extent from the outcrops or drill cores (Fig. 1). Due to the scarcity of outcrops and absence of geochronological data on lamprophyres from the Czech part of the Krušné hory area we are unable to assess the actual position of many lamprophyre dykes in the whole magmatic succession.

Rock types

The lamprophyric and related rocks studied can be divided into four types but some transitional varieties are not uncommon.

(1) Minettes are rich in biotite and K-feldspar. Phenocrysts are represented by abundant biotite and uralitized pseudomorphs after clinopyroxene. Only the sample La 167 contains recrystallized pilitic pseudomorphs after olivine. The groundmass is trachytic, composed of K-feldspar predominating over plagioclase and some interstitial quartz, biotite and accessory minerals. The K-feldspar in La 167 forms also spherulitic aggregates. Acicular and rarely stubby apatite is the most abundant accessory mineral.

(2) Kersantites are most frequent but variable in petrographic character. In the close vicinity of Jáchymov, there are mafic kersantites rich in pilitic pseudomorphs after olivine (dominated by acicular actinolitic amphibole), uralitic pseudomorphs after clinopyroxene, fresh biotite or phlogopite, and with ophitic biotite + plagioclase groundmass. Other kersantite varieties may be less mafic and almost lacking pilitic pseudomorphs. Several samples contain also pseudomorphs after prismatic hornblende formed by biotite rich in Ti-oxidic pigment. Relics of brown hornblende are rare. Kersantites from the Krupka area are devoid of ophitic textures and relics of primary hornblende.

(3) Spessartites contain abundant brown amphibole in the form of needles and long prisms. However, the major phenocrystic phase was euhedral clinopyroxene that is totally uralitized with well-preserved original shapes. Subordinate phenocrystic biotite is usually also present. Sample La 162 contains abundant biotite and is rich in pilitic pseudomorphs after euhedral olivine phenocrysts with minute chromite inclusions. Some spessartite samples contain abundant small shreds and fine-grained aggregates of biotite replacing hornblende and locally impregnating the groundmass.

(4) Diorite porphyries are variable in modal compositions and textures. Some mafic varieties from the Jáchymov area resemble kersantites or biotite spessartites except for the presence of some plagioclase phenocrysts. Other, commonly less mafic quartz diorite porphyries, are rich in phenocrysts of plagioclase and poor in phenocrysts of mafic minerals (La 109/1). Some samples even

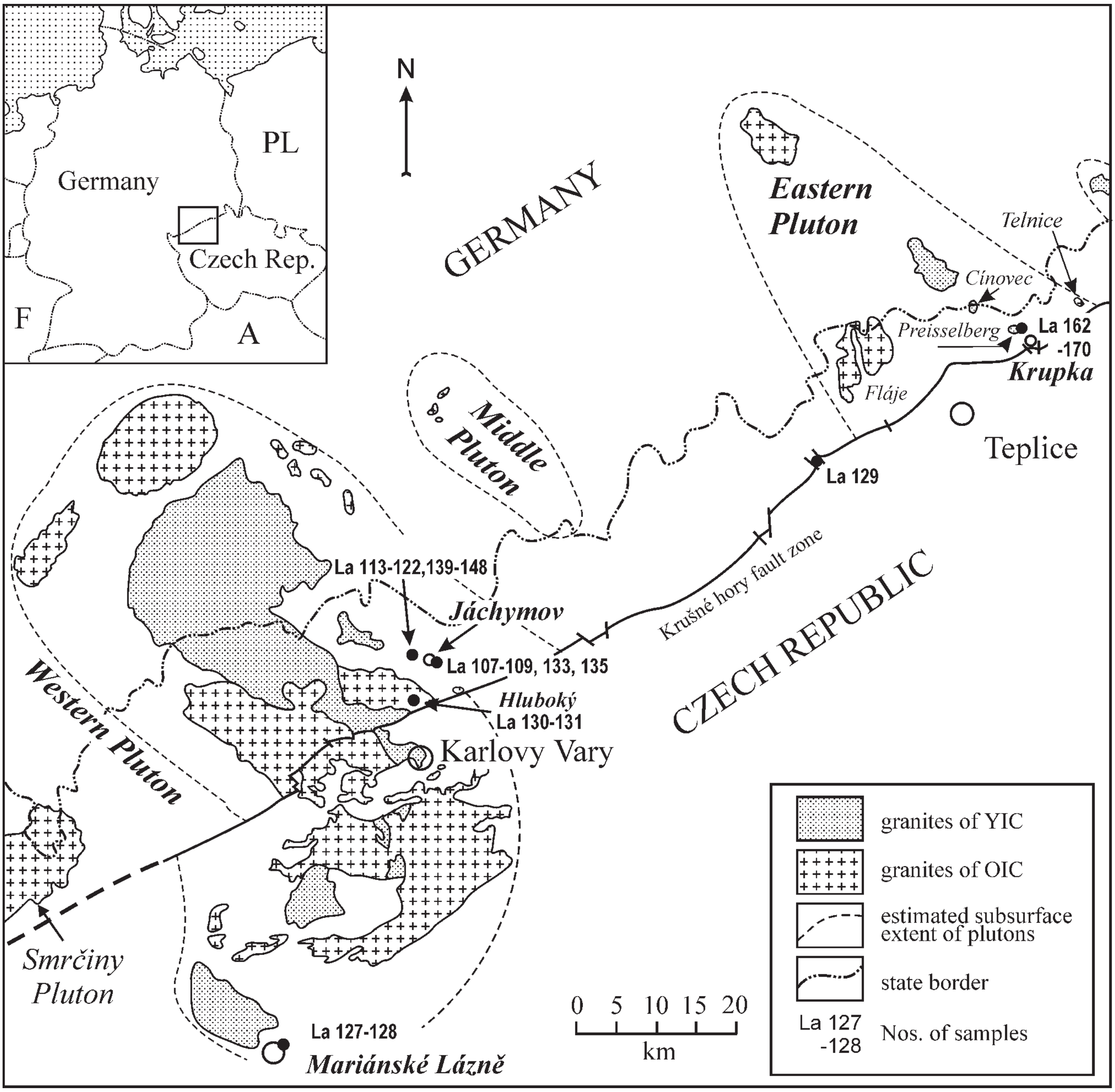

Fig. 1 Simplified geological map of the Krušné hory/Erzgebirge batholith with the main sampling sites of studied lamprophyres and associated diorite porphyries.

lack the actinolite pseudomorphs and biotite may be the only ferromagnesian mineral (La 139).

Partial secondary biotitization is common in many samples of kersantites, spessartites and diorite porphyries from the Jáchymov area. In the area of the Eastern pluton, however, there occur some dark biotite-rich dyke rocks whose original petrographic character can be hardly recognized. These rocks are referred to as altered mafic dyke rocks.

Analytical techniques

All analyses were made on the JEOL JXA 50A electron microprobe with Energy-disperse spectrometer (EDAX DV 9400) at the Geological Institute, Academy of Sciences of the Czech Republic. Both the energy-disperse (EDS) and wavelength-disperse (WDS) techniques were used and routine ZAF corrections were made. Instrumental conditions were: acceleration voltages 20 kV, beam diameter 2–3 mm, counting time 100 s. Typical standards were natural and synthetic minerals. Secondary electron image (SEI) and X-ray maps were used.

Rock-forming minerals

Micas

Dark micas are the main ferromagnesian minerals in kersantites, minettes and diorite porphyries. In spessartites they are subordinate. They form both the phenocrysts and important constituents of the groundmass.

Selected representative analyses are in Table 2. The common variations of biotite compositions are plotted on diagrams Fe/(Mg+Fe) versus tetrahedral aluminium Al(IV) for each rock group (Fig. 2).

These diagrams display relatively narrow ranges of Fe/(Fe+Mg) ratios in biotites from all types of lamprophyric rocks studied. Most samples have magnesian biotite approaching and sometimes straddling the biotite versus phlogopite boundary at Fe/(Fe+Mg) = 0.33. Micas in the most mafic varieties of kersantites from the Jáchymov area (La 107, 109/2) plot within the phlogopite field.

Differences in mica compositions between phenocrysts and the groundmass are mostly weak or even absent (Table 2). There are only two significant exceptions represented by the minette from Hluboký (La 130, 131) and the pilite-biotite spessartite from Krupka (La 162) with phlogopite cores of large phenocrysts and magnesian biotite in their rims and smaller crystals. Both these lamprophyres display very well preserved lamprophyric textures.

Dark micas from minettes differ significantly in Al(IV) between samples from Hluboký in the Jáchymov area (La 130, 131) and those from the Krupka area (La 167, P-626) (Fig. 2a).

The range of biotites from diorite and quartz-diorite porphyries is moderately shifted to higher Fe contents but most compositions overlap with magnesian biotites of lamprophyres (Figs 2, 3). The less magnesian compositions with Fe/(Fe+Mg) of about 0.5 are typical for those porphyry varieties that have relatively lower colour indices and higher contents of quartz.

Many samples contain dark micas of presumably secondary origin, commonly as fine-grained aggregates. Most of these micas still plot into the magnesian biotite field, even those from highly altered (biotitized) mafic dykes (Fig. 2e). In the Fe versus Mg diagram (Fig. 3) they cannot be differentiated from common "magmatic" biotites but compared to them they usually have lower contents of TiO_2 (typically less then 2 wt %) and are systematically lower in Al(IV) due to increased Si (Figs 2b, 2c, 2e).

Some special case is the sample La 163 representing breccia of biotitized lamprophyre (originally spessartite?) fragments cemented by a microgranite. The breccia is partially greisenized and contains secondary Li-bearing micas of two different compositions. As they have too high Si and low Al(IV) they plot off the common biotite field and therefore they cannot be shown in Fig. 2. The Fig. 3 shows that these dark micas in the lamprophyre fragments are lower in Mg and Fe compared to other dark micas from lamprophyres because of appreciably higher Al(VI). Nevertheless, their Mg/Fe ratio remains surprisingly the same as in the primary Mg-biotites and even phlogopites from other lamprophyre samples. Their composition contrasts with that of the secondary Li-mica (protolithionite to zinnwaldite) of the surrounding greisenized microgranite. It is evident that greisenization did not af-

Table 2 Representative microprobe analyses of dark micas

Sample	La 170		La107		P-626		La 130		La 139		La 117
Rock	kersantites				minetes				diorite porphyries		
	ph	gr	ph	gr	ph	gr	ph	gr	ph	gr	ph
SiO_2	35.55	37.40	35.97	38.91	37.34	38.39	35.97	34.63	38.22	36.81	37.50
TiO_2	2.57	2.14	3.62	2.29	3.04	1.92	5.24	4.56	1.63	2.30	2.06
Al_2O_3	16.28	15.81	16.97	14.41	13.82	13.99	14.65	14.94	17.98	18.41	16.03
Cr_2O_3	0.20	0.16	0.15	0.58	0.69	0.31	n.d.	n.d.	n.d.	n.d.	n.d.
FeO*	15.81	15.15	11.51	10.76	14.66	13.88	11.23	14.48	15.84	16.53	15.63
MnO	0.21	0.25	0.33	0.31	0.38	0.30	0.24	0.29	0.28	0.44	0.19
MgO	14.26	15.17	15.99	18.21	14.73	15.38	17.22	14.40	12.00	11.24	13.28
BaO	0.41	0.09	0.97	n.d.	0.52	1.01	n.d.	2.62	0.18	n.d.	n.d.
CaO	0.05	n.d.	0.05	0.19	n.d.	0.17	0.10	0.20	0.09	0.21	0.34
Na_2O	0.46	0.65	0.45	0.56	0.73	0.73	0.30	n.d.	0.20	0.27	0.55
K_2O	9.58	9.84	9.66	9.80	9.49	9.57	10.17	9.36	9.67	9.23	9.51
H_2O**	3.41	3.95	3.78	2.96	3.35	3.65	3.55	3.38	3.58	4.01	3.73
F	1.08	n.d.	0.43	2.34	1.18	0.60	0.97	1.03	0.89	n.d.	0.57
Cl	0.17	0.24	0.20	n.d.	0.23	0.24	0.11	0.15	n.d.	n.d.	n.d.
–O=2F	–0.45	–	–0.18	–0.98	–0.50	–0.25	–0.41	–0.43	–0.37	–	–0.24
–O=2Cl	–0.04	–0.05	–0.04	–	–0.05	–0.05	–0.02	–0.03	–	–	–
Total	99.54	100.80	99.86	100.34	99.61	99.84	99.32	99.58	100.19	99.45	99.15
Mg	0.62	0.64	0.71	0.75	0.64	0.66	0.73	0.64	0.58	0.55	0.60

* – total Fe as FeO; ** – H_2O calculated; ph = phenocryst; gr = groundmass; n.d. = not detected (below the detection limit)

fects the original Mg/Fe ratios significantly in substrates of contrasting compositions (Novák *et al.* 2001).

Fine-grained muscovite is rare in lamprophyres and represents a product of hydrothermal alterations. The $2M_1$ polymorph has been identified by X-ray data in the sample La 113 that is also unusually rich in secondary biotite.

Amphiboles

Two distinct types of amphiboles can be recognised in the studied dyke rocks (Table 3). The first type of presumably primary magmatic origin is brown (X: pale brownish, Y: pale brown, Z: yellowish- to reddish-brown) and forms nearly euhedral small prisms to needles that

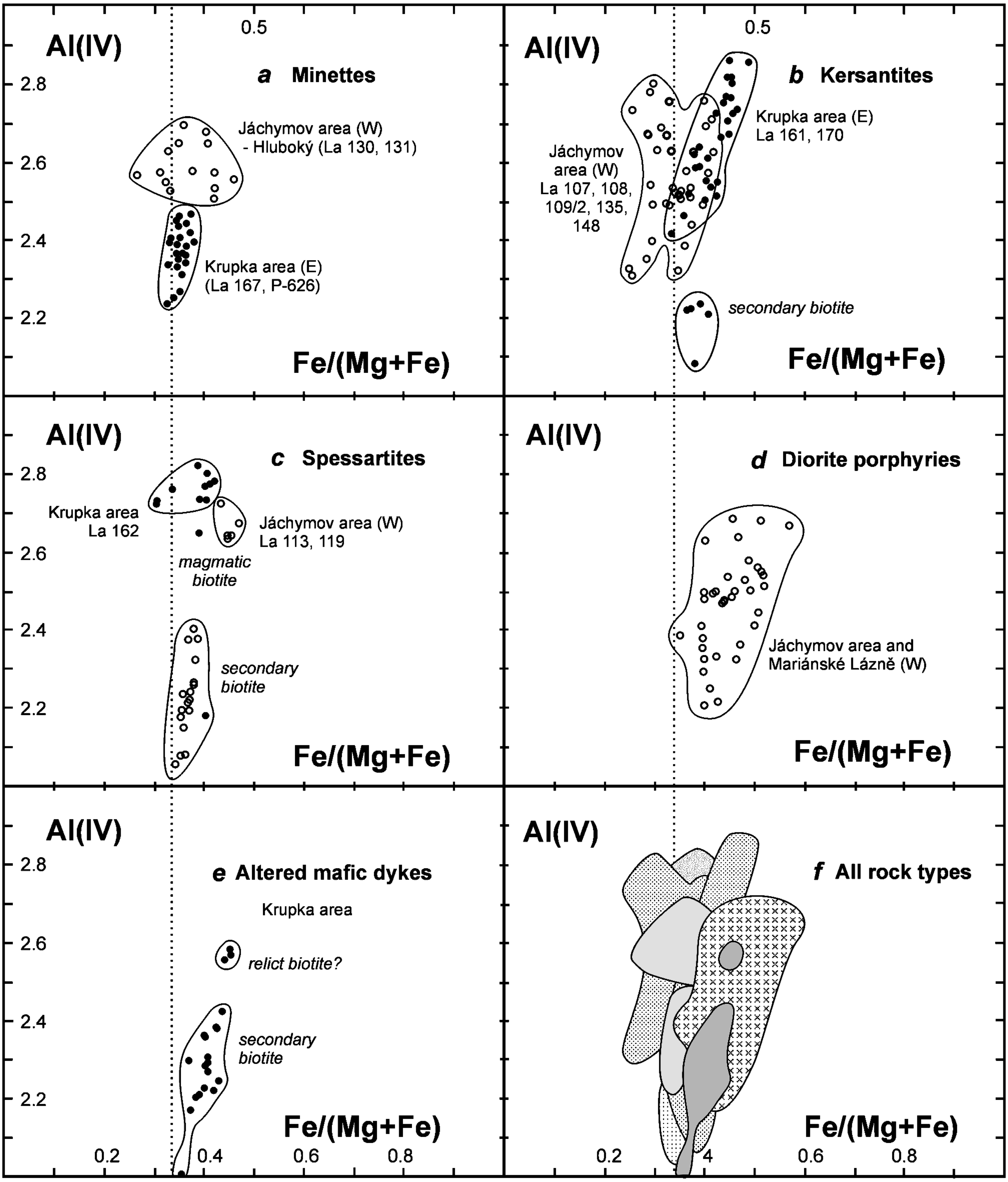

Fig. 2 Variation in composition of dark micas from the lamprophyres in the Western Krušné hory (Jáchymov ore district) and the Eastern Krušné hory (Krupka ore district). The Al(IV) values are from recalculation of formulae to 22 atoms of oxygen.

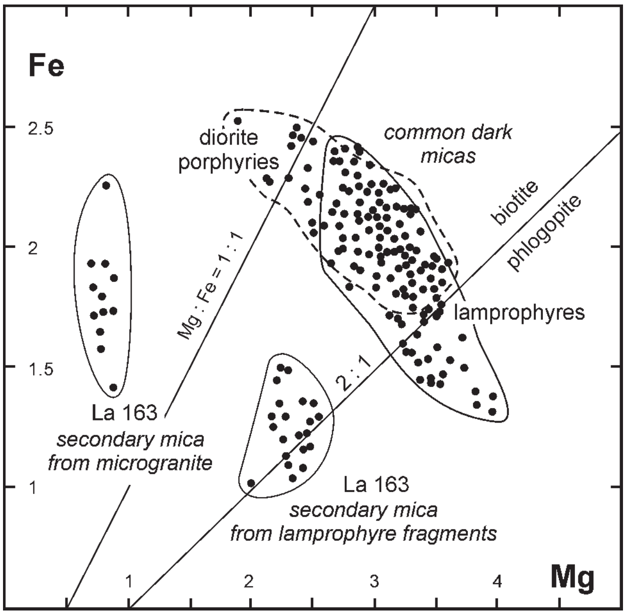

Fig. 3 Compositional variations of dark micas from lamprophyres and other mafic dyke rocks in the Fe versus Mg (in atoms per formula unit) diagram. These values are from recalculation of formulae to 22 atoms of oxygen without any estimation of Fe^{3+}.

are abundant in spessartites (La 119, 162). Their relics have been found also in some kersantites from the Jáchymov area and sporadically even in some samples of dark diorite porphyries (e.g., La 129). These hornblendes are Si-poor and Ti-rich (Figs 4a, 4b). Their composition recalculated using maximum Fe^{3+} estimation (commonly with the sum of Si+Al+Ti+Mg+Fe+Mn = 13) corresponds to titanian magnesiohastingsite up to kaersutite with more than 0.5 atom of Ti per formula unit (classification according to Leake *et al.* 1997). All these hornblende varieties can be classified as potassian (K > 0.25 atom per formula unit). Ti-rich, Si-poor magnesiohornblende occurs sporadically (La 165).

The second group comprises amphiboles that are conspicuously light in colour, greenish to light green along the Z-direction. Their compositions correspond to Al-poor, Si-rich magnesiohornblende and actinolite. Contents of K and Na as well as of Ti are very low in these silica-rich varieties (Fig. 4a, Table 3) as is common in amphiboles of postmagmatic or secondary origin. In compliance with its composition this amphibole forms not only small crystals in the groundmass of many lamprophyres but also fine-grained acicular aggregates and typical pilitic pseudomorphs after olivine as well as uralitic pseudomorphs with well-preserved shapes of former clinopyroxene phenocrysts. In respect to the primary Ti-rich hornblendes, these secondary amphiboles are on average more magnesian and richer in Cr thus reflecting chemistry of the primary phenocrystic phases (olivine, clinopyroxene).

Some actinolitic pseudomorphs after clinopyroxene show occasionally a weak zonality with margins of magnesiohornblende and decreasing Al contents towards central parts of Mg-rich actinolite compositions. This feature probably reflects decreasing temperatures during progressive replacement of clinopyroxene phenocrysts that started at margins and proceeded towards the centres.

Feldspars

Chemical composition of feldspars varies widely. Most samples of kersantites contain only plagioclase whereas potassium feldspars prevail in minettes. Kersantites in the Western Krušné hory area yield a wide range of plagioclase compositions from labradorite to albite. Plagioclase phenocrysts are commonly strongly zoned with calcic cores (An_{70} – An_{50}) and more sodic rims (An_{35} – An_{10}). For instance in the sample La 109, labradorite (An_{60}–An_{50}) prevails and andesine is subordinate whilst in the sample La 133, the cores of labradorite are surrounded by rims of andesine (An_{40} – An_{47}) ranging to oligoclase

T a b l e 3 Representative microprobe analyses of amphiboles

Group	*magmatic amphiboles*				*post-magmatic amphiboles*					
	1	2	3	4	5	6	7	8	9	10
Sample	La-119	La-162	La-119	La-119	La-162	La-107	La-135	La-135	P-626	La-107
Rock	spes	spes	spes	spes	spes	ker	ker	ker	min	ker
SiO_2	40.27	39.53	41.60	46.44	50.02	52.87	51.98	52.41	51.77	53.57
TiO_2	4.53	4.01	3.68	2.30	0.47	0.10	0.00	0.27	0.30	n.d.
Al_2O_3	12.74	13.12	11.94	8.73	4.25	4.18	3.54	3.41	3.09	2.10
Cr_2O_3	n.d.	–	n.d.	n.d.	0.34	0.49	0.51	0.52	0.33	0.24
FeO	10.39	11.97	11.37	11.66	12.14	7.93	9.13	8.66	10.27	9.56
MnO	0.43	0.16	0.20	0.14	0.30	0.38	0.41	0.53	0.30	0.35
MgO	13.91	13.30	13.59	14.63	15.79	18.32	17.54	17.80	17.07	17.43
CaO	11.39	12.20	11.64	11.10	13.05	12.71	12.42	11.96	12.66	12.84
Na_2O	2.28	1.70	1.56	0.82	0.74	0.82	0.89	0.85	0.76	0.85
K_2O	1.56	1.52	1.47	1.68	0.32	0.07	0.01	0.02	n.d.	0.08
Total	97.50	97.05	97.05	97.50	97.42	96.43	97.45	97.42	96.55	96.43
mg=	0.70	0.66	0.68	0.69	0.70	0.80	0.77	0.78	0.75	0.76

min = minette; kers = kersantite; spes = spessartite; n.d. = not detected (below the detection limit)

(An_{15} – An_{20}). Partial albitization is common and the calcic cores may be sericitized to various degrees.

Increased contents of Ba in feldspars are common. The K-feldspar from minettes usually contains from 0.4 to 1.6 wt % Ba. The highest barium content (7.48 wt % BaO) was detected in K-feldspar from spessartite La 119 identified as barium adularia ($Or_{91}Ab_1An_0Cn_8$) of hydrothermal origin.

Chlorites

A specific feature of lamprophyres and associated mafic dyke rocks from the studied area is a lack in minerals of chlorite group, which are much more common in compositionally similar rocks from other parts of the Bohemian Massif (e.g., the Central Bohemian Plutonic Complex). As biotites in minettes and kersantites show minimum compositional differences, the composition of chlorites replacing them is almost identical. Most common are chlorites corresponding to ripidolite (in classification after Hey, 1954). Their iron content varies from 17 to 20 wt % FeO depending on the amount of iron in replaced minerals (mostly in mafic types as minettes and kersantites). Relatively rare are chlorites on fissures where they may be accompanied by quartz or carbonates. Such chlorites are lower in iron (>12 wt % FeO) and correspond usually to sheridanite.

Accessory and ore minerals

Minerals of the spinel group are present sporadically but their compositions are highly variable (Table 4). Magnetites rich in Mn or Cr plus Ni occur in kersantites from Jáchymov (La-108, La-140). Chromite in pilites of spessartite La-162 is relatively rich in Al and has an increased content of Zn. Chromite inclusions in pseudomorphs after olivine were optically identified also in several other samples but usually they are too minute for quantitative analysis.

Sphene belongs to common accessory minerals in a great majority of the studied rocks. Increased Al_2O_3 contents in sphene from minette La 131 (up to 4.6 wt %) suggest its relatively high-temperature origin.

Fluorapatite is the most common accessory in all lamprophyre samples. Apatite in minettes from Hluboký (La 130, 131) and Vrchoslav (P-626) displays elevated contents of Sr (SrO > 1 wt %). Rutile with increased content of Nb (0.93 wt % of Nb_2O_3) was identified in kersantite from Krupka (La 161). Allanite is present in some kersantites (La 109/2, La 161).

The highest amounts of sulphidic ore minerals were found in dyke rocks of the Jáchymov area, especially in kersantites from the quarry near the Tomáš shaft, in kersantites from the Eva shaft and in diorite porphyries from the Panorama shaft. Both pyrite and pyrrhotite are present at those localities whereas dyke rocks from the eastern area practically lack the latter. Measurable Ni contents in pyrites were found only in dykes from the Jáchymov area (Table 5).

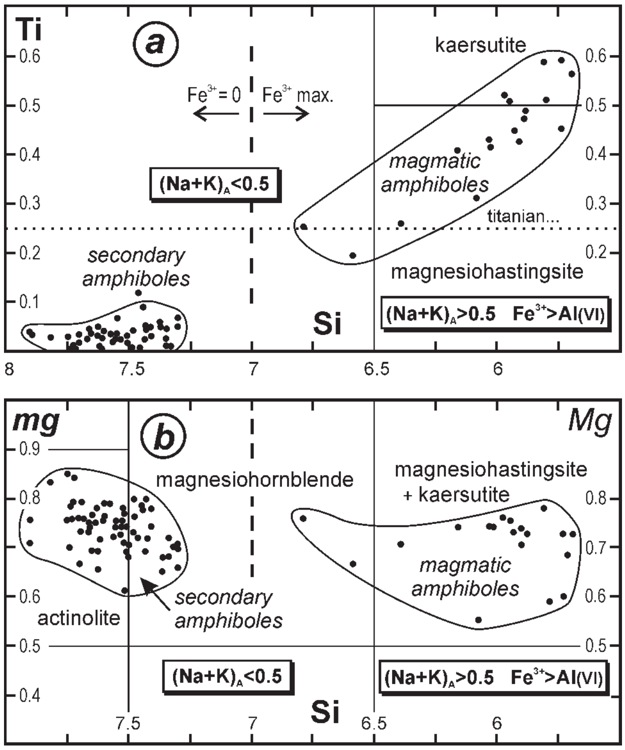

Fig. 4 Compositions of primary (magmatic) amphiboles from spessartites and of secondary amphiboles from various lamprophyres in (a) the plot of Ti versus Si (atoms per formula unit), and (b) the classification diagram *mg* versus Si (atoms per formula unit) after Leake *et al.* (1997). The values for secondary amphiboles are from formulae calculated with 23 atoms of oxygen without calculation of Fe^{3+} that is estimated to be low and insignificant for the classification. Primary hornblendes were recalculated with estimation of the maximum Fe^{3+} (commonly Si+Al+Ti+Fe+Mg+Mn = 13).

Ferrocobaltite was identified in pilitic pseudomorphs and actinolite aggregates from the kersantite dyke near the Tomáš shaft in Jáchymov. Occurrences of ore minerals containing Ni and Co mainly in the Jáchymov ore district (such as Ni-bearing pyrite, Co-bearing arsenopyrite, löllingite and ferrocobaltite) are often accompanied by minute carbonate veinlets (calcite poor in Mn, generally <1 wt % MnO). This fact suggests that at least some lamprophyres could serve as channelways for hydrothermal ore fluids. However, uranium minerals typical for ore veins in the Jáchymov district were not found in the studied lamprophyre samples.

Many accessory minerals namely in the Eastern Krušné hory are products of post-magmatic greisenization. These include scheelite (with 1 wt % MoO_3 in spessartite La-163), fluorite, topaz and Li-mica. Greisenized kersantite from the Krupka ore district was described by Novák *et al.* (2001).

Xenocrystic minerals

Almost all the studied dykes contain xenocrysts derived from the wall rocks and/or rock complexes below the present exposure level. Most common are xenocrysts of

Table 4 Representative analyses of accesory minerals of the spinel group

Mineral	magnetite					chromite	
Rock	kers	kers	kers	kers	kers	spess	spess
Sample	LA-108	LA-108	LA-108	La-140	La-140	LA-162	LA-162
SiO_2	0.08	–	0.15	0.07	–	–	–
TiO_2	–	–	–	–	–	1.76	1.21
Al_2O_3	–	–	–	–	–	13.76	13.99
Cr_2O_3	2.02	–	3.30	18.94	–	38.55	40.67
Fe_2O_3	66.46	68.69	65.10	49.03	68.70	10.45	9.02
FeO	23.11	22.01	17.54	17.20	21.98	29.10	29.18
MnO	7.84	8.78	13.49	1.91	8.81	2.08	1.91
NiO	–	–	–	12.52	–	–	–
ZnO	–	–	–	–	–	5.19	1.91
Total	99.51	99.48	99.58	99.67	99.49	100.89	100.73

kers = kersantite; spes = spessartite

quartz occurring in a great majority of samples as anhedral to amoeboid grains 1 to 5 mm in size. Typical are reaction rims of actinolite that probably replaces the original clinopyroxene.

Garnet (almandine with 7 to 25 mol % of pyrope component), clinopyroxene, kyanite and hercynite occur in enclaves of mafic diorite porphyry (La 127) enclosed in granodiorite porphyry (La 128) from Hamelika at the NE margin of Mariánské Lázně. Composition of xenocrystic pyroxene fits well into the compositional range of pyroxenes from metabasites of the Mariánské Lázně complex (cf. Svobodová 1994).

Discussion

Although there are some differences in frequency of individual types of dyke rocks between the areas of Western and Eastern plutons of the Krušné hory/Erzgebirge batholith, mineral compositions in prevailing samples are very similar. However, compositions of Mg-biotite to phlogopite in minette samples from the western and eastern area display significant differences.

All the samples studied were affected by postmagmatic alterations, namely the pilitization of olivine, uralitization of clinopyroxene, biotitization, chloritization and sometimes also carbonatization. Complete pilitization of olivine is common in lamprophyres almost as a rule. However, absence of fresh clinopyroxene and its complete replacement by magnesiohornblende to actinolite in the whole set of samples from a large area is rather surprising. The only preserved ferromagnesian minerals of magmatic origin are dark micas that are most widespread and Ti-rich hornblendes that are restricted to spessartites and some diorite porphyries.

Biotite is mostly unzoned with rare exceptions. Even the differences between compositions of mica occurring as phenocrysts and groundmass are commonly negligible and this indicates a significant late-magmatic or high-temperature post-magmatic re-equilibration. This may be due to relatively slow cooling rates or even re-heating of dykes by voluminous granite intrusions.

The specific feature of lamprophyres and dark diorite porphyries from the studied area is the widespread regional biotitization with unknown sources and relation to greisenization. This biotitization seems to be a major reason for scarcity of chlorite minerals in our rocks and therefore we suggest its relatively late, secondary origin. In contrast with most other dykes, minette from Hluboký (intruding biotite granite of the OIC) contains abundant chlorite replacing primary biotite with phlogopite cores. Any secondary biotite is absent. This rock, however, belongs to the relatively rare cases of lamprophyres altered in the way common in other areas of lamprophyre occurrences in the Bohemian Massif, e.g., the Central Bohemian Plutonic Complex. The minette could be younger compared to dykes affected by biotitization.

Greisenization *sensu stricto* as a local process affected some lamprophyres in the Krupka area of the Eastern Krušné hory pluton. In this case the ultimate sources of fluids were, without any doubts, granites of the younger group (YIC).

Ore minerals often form impregnations in actinolite aggregates. This fact documents that they are

Table 5 Representative analyses of ore minerals

Mineral	cobaltite	löllingite	pyrrhotite	pyrite	Ni-pyrite
Rock type	kersantite	kersantite	kersantite	kersantite	kersantite
Sample	LA 108	LA 108	LA 140	LA 140	LA 140
Fe	6.13	27.78	64.18	49.54	44.19
Ni	–	3.16	–	1.20	6.43
Co	26.70	3.25	–	–	–
As	47.45	51.61	–	–	–
S	19.72	14.20	35.82	49.26	49.38
Total	100.00	100.00	100.00	100.00	100.00

younger than post-magmatic uralitization. However, the pseudomorphs after olivine locally provided a source of Ni and Co for sulphidic and arsenidic minerals.

Conclusions

Lamprophyres are volumetrically subordinate Variscan dyke rocks in the Czech part of the Krušné hory/Erzgebirge granite batholith. Kersantites prevail over minettes while spessartites are rare. In association with them, mafic diorite porphyries also occur and grade in places into lamprophyres. The samples studied showed similar compositions of the main rock-forming minerals from individual rock types within the whole area with only weak regional differences.

All the studied rocks were altered during deuteric and postmagmatic stages of their evolution. Some dark mica close to phlogopite composition, brown hornblendes rich in Ti, basic to intermediate plagioclase and some accessory minerals (apatite, some varieties of spinel) are considered to be primary. Light green amphiboles of Si-rich magnesiohornblende to actinolite compositions are products of post-magmatic processes. They are replacing both the original olivine phenocrysts in the form of pilite pseudomorphs and former clinopyroxene. Fresh clinopyroxene is absent in all samples studied.

Small and insignificant differences in dark mica compositions between phenocrysts and the groundmass in most of samples suggest that the minerals were re-equilibrated during cooling or re-heating of dykes. Minette from Hluboký near Jáchymov and pilite-biotite spessartite from the Krupka area seem to be rather rare exceptions.

Secondary biotitization is widespread in most lamprophyres and diorite porphyries in the whole area except for minettes. Secondary biotites have their Mg/Fe ratios similar to those of "primary" (but commonly re-equilibrated) Mg-biotites to phlogopites but their Al(IV) and Ti are lower. Effects of greisenization *sensu stricto* were observed in some lamprophyres from the Krupka area leading to origin of Li-bearing, Si- and Mg-rich dark micas.

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Horninotvorné minerály lamprofyrů a příbuzných mafických žilných hornin z Krušných hor (Česká republika)

Lamprofyry variského stáří jsou objemově sice podružné ale zajímavé žilné horniny rozšířené v oblasti krušnohorského batolitu. Převažují kersantity nad minetami a ojedinělými výskyty spessartitů. V asociaci s nimi se vyskytují tmavé dioritové porfyry (porfyrity), které mohou do lamprofyrů (kromě minet) přecházet. Studované vzorky pocházely zejména z okolí Jáchymova, Krupky, dioritový porfyr i z Mariánských Lázní.

Variabilita složení primárních minerálů je mezi jednotlivými lokalitami malá. Všechny studované horniny jsou postiženy deuterickými a postmagmatickými přeměnami. Z původních tmavých minerálů se zachovaly tmavé slídy o složení Mg-biotitu až flogopitu, ve spessartitech a některých dioritových porfyrech hnědé amfiboly bohaté Ti (převážně magneziohastingsit až kaersutit). Primární jsou také bazické až střední plagioklasy, v minetách K-živce, v celé šíři petrografických typů některé akcesorie (hlavně apatit, některé typy spinelidů včetně chromitu). Běžně přítomné světle zelenavé amfiboly o složení Si-bohatého magneziohornblendu až aktinolitu představují produkty postmagmatických procesů. Nahrazují jednak původní fenokrysty olivínu ve formě pilitových pseudomorfoz, jednak tvoří uralitové pseudomorfozy po původním klinopyroxenu. Klinopyroxen se v žádném vzorku nezachoval.

Tmavé slídy ve většině vzorků mají nápadně vyrovnané složení mezi fenokrysty a šupinkami v základní hmotě. Svědčí to o reekvilibraci během pomalého chladnutí nebo opětovného prohřátí hornin. Výjimkou jsou mineta od Hlubokého na Jáchymovsku a pilitický spessartit z Krupky.

Ve většině lamprofyrů i dioritových porfyrů celé studované oblasti je rozšířena sekundární biotitizace, která však nebyla zjištěna v minetách. Naproti tomu ve většině vzorků chybí nebo je nevýznamná chloritizace tmavých minerálů, která je charakteristická pro minetu z Hlubokého a je běžná v lamprofyrech z jiných oblastí. Sekundární biotit se poměrem Mg/Fe podobá primárnímu (často však reekvilibrovanému) Mg-biotitu až flogopitu, ale mívá snížený Al(IV) a obsah titanu. Greisenizace v užším smyslu byla pozorována v některých lamprofyrech z okolí Krupky. Vznikly při ní tmavé slídy s obsahem Li, které jsou bohaté Si ale zároveň i Mg.