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Multiple magmatic pulses of the Eastern Volcano-Plutonic Complex, Krušné hory/Erzgebirge batholith, and their phosphorus contents

Miroslav Štemprok [1] – František V. Holub [1] – Jiří K. Novák [2]

[1] Charles University, Faculty of Science, Department of Petrology and Structural Geology, Albertov 6, 128 43 Praha 2, Czech Republic
E-mail: stemprok@natur.cuni.cz, frholub@natur.cuni.cz
[2] Institute of Geology, Academy of Sciences of the Czech Republic, Rozvojová 135, 165 02 Praha 6, Czech Republic. E-mail: novak@gli.cas.cz

Abstract. Granites of the eastern part of the Krušné hory/Erzgebirge (Czech Republic/Germany) outcrop in separate minor stocks formed by Late Palaeozoic CaO-rich biotite monzogranites of the Older Intrusive Complex (OIC) and syenogranites or alkali feldspar granites of the Younger Intrusive Complex (YIC). These, along with abundant rhyolites and granite porphyry dykes, constitute the Eastern Volcano-Plutonic Complex (EVPC). Using new analyses as well as older unpublished and literature data, we evidenced that these rocks display a wide spectrum of phosphorus contents ranging from very low (well below 0.1 wt% P_2O_5) to intermediate contents (from 0.1 to 0.4 wt% P_2O_5). No equivalent of the high-phosphorus fractionated granites with $P_2O_5 > 0.4$ wt% known from the western Krušné hory/Erzgebirge is present in the EVPC.

We have demonstrated that the OIC granite bodies comprise a number of petrographic varieties and some of them represent individual magmatic pulses. Relatively elevated phosphorus contents in the evolved members of the Fláje granite massif may reflect their origin as individual magma batches from heterogeneous crustal sources. We observed the marginal Preisselberg granite enriched in P among the predominant P-poor YIC granites; this granite probably originated also as a separate magma batch.

On the contrary, the rhyolitic ignimbrites, granite porphyries and YIC granites were derived from a younger, huge and long-standing magmatic system which presumably was formed and maintained as a consequence of significant thermal input from mantle-derived mafic magmas. These mafic magmas homogenized granitic partial melts from lower crustal sources and produced large volumes of highly evolved magma portions via fractional crystallization. The granite magmas with I-type or transitional I/S-type characteristics evolved towards the low-P_2O_5 compositions. This process was disturbed by episodic hybridization of the granite magmas with the mantle-derived melts or products of their fractionation at depth.

The YIC granites probably represent residual, late-stage melts rich in volatiles, with strongly increased incompatible element abundances due to prolonged crystal fractionation. Their composition was strongly affected by interaction with an aqueous fluid phase that changed the phosphorus distribution in only a minor way. Late magmatic and post-magmatic processes obscured the primary chemical characteristics namely in the Li-rich granites. This fact could be the reason for the absence of any correlation between the generally low P_2O_5 and highly variable alumina-saturation indices.

The phosphorus contents thus reflect various aspects of rather complex genetic histories of Late Variscan igneous rocks in the EVPC, particularly within the lower and middle crust. In contrast with the role of phosphorus, the contents of lithium and fluorine are more dependent on subsolidus alterations of granites induced by hydrothermal fluids in late magmatic and post-magmatic stages at shallow crustal levels.

Key words: granite, ignimbrite, mafic magmas, volcano-plutonic complex, Variscan igneous activity, magma pulses, whole rock geochemistry, phosphorus, petrogenesis, Krušné hory/Erzgebirge, Bohemian Massif

Introduction

The distribution of phosphorus in acid igneous rocks attracted the interest of geologists especially during the last decade. Phosphorus contents have been used as indicators of genetic conditions (Raimbault et al. 1991, Bea et al. 1992, Förster et al. 1999). Taylor and Fallick (1997) used the amounts of P for a subdivision of topaz-bearing granites into the „low- P_2O_5“ subtype (< 0.1 wt% P_2O_5) and the „high-P_2O_5 subtype„ (> 0.4 wt% P_2O_5). Bea et al. (1992) suggested the existence of two evolutionary trends of peraluminous granitic magmas differing in the behaviour of phosphorus. The first trend of decreasing P with increasing SiO_2 is typical for the high-Ca granites where the P_2O_5 amounts are controlled by apatite solubility as measured by Harrison and Watson (1984). The second trend of increasing P with raising SiO_2 occurs in low-Ca granitic melts, where the P_2O_5 content is not correlated with apatite solubility because P is incorporated in feldspars. P_2O_5 influences the properties of silicate melts (London 1997, Dingwell et al. 1993). Kosinski et al. (1988) evidenced the existence of $AlPO_4$ units in silicate melts and suggested that phosphorus can be bridged to oxygen variously in dependence on the Si/Al ratio. Thus the alumina-saturation index (A/CNK or ASI) is interpreted to be among the main factors controlling the apatite dissolution in anatectic melts (London 1997, 1998).

We have studied phosphorus distribution in Late Variscan igneous rocks related to the eastern part of the Krušné hory/Erzgebirge granite batholith (KHEB). This area, situated in the NW part of the Bohemian Massif, is well known among economic geologists for its tin-tungsten mineralization of greisen style associated with highly evolved, volatile-rich granites forming granite cupolas.

The treatment of published and archived bulk analyses of Late Variscan granites from the Czech part of the Krušné hory/Erzgebirge batholith (Štemprok et al. 1995) showed that the phosphorus abundances in the younger group of granite intrusions differ between the western and the eastern plutonic regions. The younger suite granites (YIC granites) of the western plutonic part have distinctly higher average P content (ca. 0.30 wt% P_2O_5, n = 299) than petrologically and geochemically similar granites in the eastern region (ca. 0.008 wt% P_2O_5, n=120; this value is, however, lowered by contents below the detection limit).

We examined major and trace element compositions of newly collected granite samples from the Fláje, Preisselberg

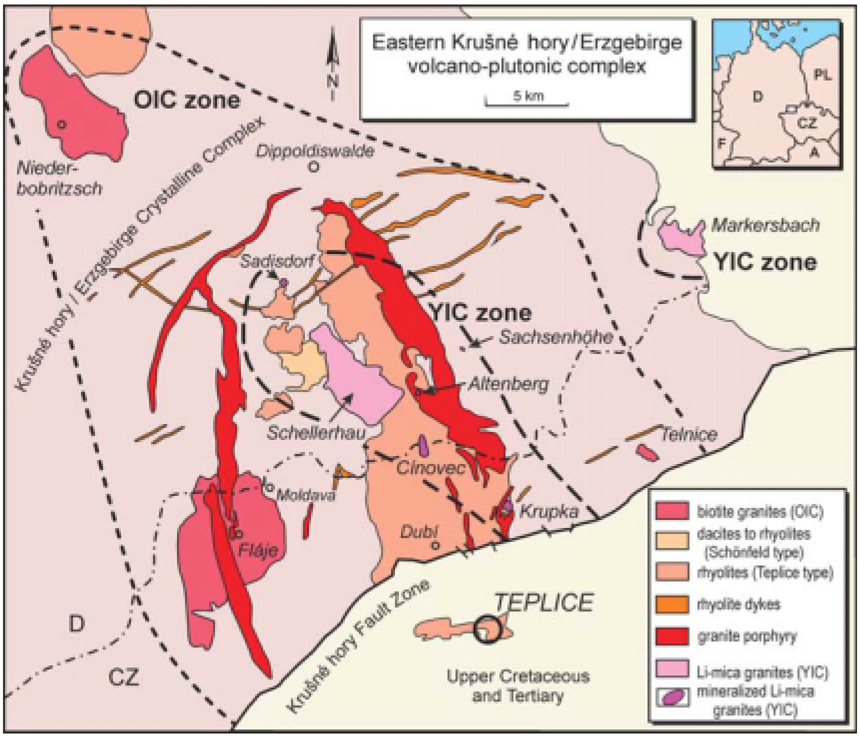

Fig. 1. Simplified geological map of the Eastern Volcano-Plutonic Complex of the Krušné hory/Erzgebirge batholith (simplified from geological maps 1 : 200,000 and 1 : 50,000, Czech Geological Survey, Prague).

and Telnice granite bodies and of granite porphyries and lamprophyres from the Krupka and Telnice ore districts. Then, we compared the results with literature data (e.g., Fiala 1960, Fiala and Pácal 1965, Sattran 1968, 1982, Novák 1980, Novák et al. 1981, Štemprok et al. 1994, Breiter 1998b, Breiter and Frýda 1995) and with data published from the German part of the Eastern Erzgebirge (Fritzsche 1928, Förster et al. 1999, Förster 2001, Müller et al. 2000, Müller and Seltmann 2002) and with the chemical analyses kindly provided by Dr. K. Breiter to the third author.

Major elements in selected granitic rocks were determined by wet chemical methods in the laboratories of the Czech Geological Survey in Prague, former Geoindustria in Černošice, the Institute of Geology of the Academy of Science in Prague, and in the Laboratories of Geological institutes at the Faculty of Science, Charles University in Prague. Trace elements were analysed in the Czech Geological Survey (AAS, RFA, OES, and ICP), at the Faculty of Science (AAS and ICP-MS), and in Analytika, Prague (ICP-MS). Selected samples were analysed by electron microprobe for P-contents in feldspars and composition of accessory phosphates in the Institute of Geology, Academy of Sciences of the Czech Republic (JEOL JXA 50A) with energy-dispersive analyser (EDAX DV 9400) and at the Faculty of Science, Charles University (CAMECA).

Regional setting

The area under study is located in the NW part of the Bohemian Massif in the Eastern Krušné hory (Czech part) or the Erzgebirge (German part). It belongs to the Saxothuringian Zone of the Variscan orogenic belt that comprises largely crystalline complexes intruded by a sequence of Variscan granitic rocks (Fig. 1).

The crystalline basement of the area, referred to as the Krušné hory/Erzgebirge Crystalline Complex, comprises various tectonic units of different metamorphic grades that received their last metamorphic and deformation imprint during the Lower Carboniferous. Monotonous "Grey Gneisses" and migmatites of presumably Neoproterozoic age record a low-pressure metamorphism up to the sillimanite grade (O'Brien and Carswell 1993). The "Red Orthogneisses" (550 Ma) with less deformed parts of metagranite character are exposed in some places in the Central Erzgebirge/ Krušné hory.

During the Carboniferous, voluminous granite bodies intruded the upper crust in the whole area and at least in some places they were associated with acid volcanism. Watznauer (1954) postulated that the whole Erzgebirge/Krušné hory region is underlain by a coherent granitic body. However, relative autonomy of individual plutons was recognized later (e.g., Trumbull et al. 1994). These individual plutonic bodies have been classified as volcano-plutonic centres (Tischendorf and Förster 1990), partial plutons (Štemprok 1993), Western, Middle and Eastern plutons (Förster and Tischendorf 1994) or plutonic regions (Schust and Wasternack 2002).

In contrast with the western parts of the Krušné hory/Erzgebirge batholith, its eastern part is characterized by relative shallow erosion levels. Consequently, many granite intrusions are hidden and we may observe their apical parts only. According to geophysical and geological pieces of evidence (e.g., Tischendorf et al. 1965), a large subsurface accumulation of granitic rocks strikes NW-SE. Acid volcanic rocks and subvolcanic intrusions are preserved together with numerous rock dykes. This is the reason for which we call this part of the KHEB the Eastern Volcano-Plutonic Complex (EVPC).

The principal structure of the area is the deeply eroded Altenberg–Teplice Caldera (ATC) that is younger with respect to some granite bodies. This huge volcano-tectonic structure rimmed by massive dykes of granite porphyries is partly filled with acid volcanic products forming the Schönfeld and especially the voluminous Teplice rhyolite complex. Much like the surrounding crystalline rocks, the volcanic pile of the ATC accompanied with subordinate sedimentary strata have been intruded by the late, post-caldera granites.

Intrusive suites and their temporal relations

Granites in the whole Krušné hory/Erzgebirge area have been traditionally divided into two major granite suites: (1) the Gebirgsgranite and (2) the "Zinngranite" or Erzgebirgsgranite (Laube 1876). More recently, the same two groups were designated as the older and younger igneous complexes (Lange et al. 1972). The Older Intrusive Complex (OIC) comprises granites of predominantly monzogranite composition, whereas the Younger Intrusive Complex (YIC) covers generally more felsic granitic varieties, corresponding to syenogranite or alkali-feldspar granite (Štemprok 1986, 1993). Another group of "transitional granites", of subordinate volume, was recognized by Fiala (1968) and Lange et al. (1972). However, each of the major granite suites is composed of numerous intrusive types of variable volumes. These types, as the smallest units within a granite body, represent the solidification products of individual intrusion pulses (Schust and Wasternack 2002). According to Trumbull et al. (1994), the older granites may achieve levels of fractionation typical of some YIC granites while the earliest phases of younger granites may be as primitive as the older series granites. Förster et al. (1999) distinguished between late-collisional and post-collisional granites on the basis of geochemical and mineralogical criteria.

The traditional concept of two principal granite groups (OIC and YIC) appears to be oversimplified in the light of modern studies of their geochemical variability and their dating in the whole Krušné hory/Erzgebirge region (Förster et al. 1996, 1999, Breiter et al. 1999). However, we maintain this division for the EVPC because it is justified by geological observations and facilitates correlation of earlier data.

In the area of the EVPC, the two groups of granite intrusions are clearly defined by their temporal relations to the origin of the ATC. The OIC granites (like those of the Fláje and Niederbobritzsch massifs) can be termed the pre-caldera or pre-Westphalian intrusions as they were emplaced prior to the Schönfeld volcano-sedimentary unit with fossiliferous tuffite strata (Westphalian B/C – 311 Ma after Lobin 1986) and before the origin of the Teplice Rhyolite Complex. The Fláje OIC granite is intruded by the granite porphyry bordering the caldera. The YIC granites intrude both the rhyolites and granite porphyries and then they represent post-caldera, post-Westphalian intrusions.

The age of the granite porphyry dyke system bordering the ATC has been determined at 308 Ma (K-Ar method on whole rock, Gottstein in Bartošek et al. 1969) for the Loučná–Fláje dyke emplaced in the Fláje massif in the SW as well as for the Altenberg granite porphyry in the NE (308 ± 1 Ma, Ar/Ar method, Seltmann and Schilka 1995). The fact that the intrusions of granite porphyries postdate the emplacement of the OIC but predate the YIC granites is of primary geological importance.

The existing geochronological data for the Eastern Erzgebirge granites are still scarce (cf. Tab. 1). Taking into account data from the Krušné hory/Erzgebirge batholith as a whole, the bulk of reliable ages of granitic igneous activity in the area spans between 330 and 290 Ma. Vigneresse (2001) considers ages of about 325–315 Ma for the OIC granites and 305–285 Ma for the YIC. Age determinations are problematic especially for the YIC granites due to the strong hydrothermal overprint (Gerstenberger 1989). The span of the older granites may correspond to Phase Ib to II of the granite intrusions in the NW Bohemian Massif (Siebel et al. 1997). The YIC granites may be typically assigned to Phase III.

Förster et al. (1999), stressing the petrogenetic significance of variations in P, F and Li contents in granites and the nature of their micas, defined five groups of granites in the KHEB. Three of them are considered late-collisional: (1) low-F biotite granites, (2) low-F two-mica granites, and (3) high-F, high-P_2O_5 Li-mica granites. Other types are denoted as post-collisional granites comprising (4) the geochemically evolved, high-F, low-P_2O_5, Li-mica granites (Förster et al. 1999), and (5) moderate-F, low-P biotite granites (Förster 2001). These two post-collisional groups were interpreted as corresponding to highly fractionated I-types or to A-type granites (Breiter et al. 1991, 1999, Förster et al. 1996).

However, the alphabetic classification of granites (the I-, S-, and A-types) is rather problematic and cannot clearly separate granite bodies or the granite types within the individual bodies. The major type characteristics overlap mainly in the OIC granites (Štemprok 1986), which have been assigned as ordinary S-I transitional granites (Trumbull et al. 1994, Förster et al. 1999) and cannot be reliably distinguished with respect to the source lithologies.

OIC granite bodies

Granites of the OIC crop out within a broad NW-striking zone (Fig. 1). The OIC comprises the Niederbobritzsch massif near Freiberg (Tab. 1), the Fláje massif (SW margin of the ATC), and a small stock at Telnice (E of the ATC).

Fláje granite massif

The Fláje massif consists of predominating medium- to coarse-grained biotite monzogranites with local occurrences of subordinate two-mica granites. Amphibole is totally missing (Beck 1887, Fritzsche 1928, Sattran 1960, 1968, 1982). Typical accessory mineral is apatite. Beck (1887) noted the presence in the main granite of irregular fist- to head-sized portions without sharp contacts composed of biotite and plagioclase with numerous apatite crystals. Beck (1887) and Fritzsche (1928) pointed to a similarity between the Fláje and Niederbobritzsch granites.

However, the Fláje massif is far from being a simple homogeneous intrusion. According to 40 partial whole-rock analyses published by Sattran (1982), the MgO contents range from 0.10 to 1.64 wt%, covering both the primitive and highly evolved granite varieties. Novák et al. (1981) and Chrt and Jurák (1993) reported the so-called

Tab.1. Granite bodies of the Eastern Volcano-Plutonic Complex

Massif name	Outcrop size, km^2	Age Ma (method)	Country rocks	Granite types (textures)	Micas etc.	Stock--scheider	Rare-metal mineralization	References
Nieder-bobritzsch	25	315 ± 6[1] 320 ± 6 (Pb-Pb)[2]	gneiss	NBZ1, C M P NBZ2 M (P) NBZ3 F M (P)	biotite (+hb) biotite biotite	–	none	Fritzsche 1928, Gerstenberger 1989[1], Rösler and Budzinski 1994, Seltmann and Štemprok 1995 Tichomirowa 1997[2], Förster et al. 1999
Fláje	38		gneiss	BG1 P BG2 M E MBG3	biotite biotite biotite-muscovite	–	greisen indices	Beck 1887 Fritzsche 1928 Sattran 1960, 1982
Moldava	hidden		gneiss	E (P)	biotite	–	greisen indices	Novák et al. 1981
Sadisdorf	~ 0.04		gneiss, rhyolite	G1 FP G2 F G3 FE G4 F-M E (afg)	biotite* biotite biotite Li-mica?	+	Sn-Cu greisen	Fritzsche 1928, Seltmann 1994, Breiter et al. 1999
Schellerhau	13		gneiss, mica schist, rhyolite, granite porphyry	SG1 (Gp)F P SG2 (Gm)M E SG3 (F-M, P-E) (afg)	biotite* biotite Li-mica	+	Sn greisen	Seim et al. 1982, Müller et al. 2000
Altenberg	0.1	293 Ma (Rb-Sr)[3] (corrected)	granite porphyry, rhyolite	G1 F P G2 F G3 M-F (afg)	biotite biotite Li-mica	+	Sn greisen	Fritzsche 1928, Just et al. 1987, 1992, Haack 1990[3], Seltmann and Schilka 1995
Cínovec	0.4	281–286 (K/Ar)[4] 306-312 (K/Ar, mica, corrected)[4]	rhyolite	F (afg) M, F P (afg) M-C, P F-M, P	lepidolite zinnwaldite, protolithionite protolithionite	+	Sn-W greisen, veins	Rub et al. 1998, Dolejš and Štemprok 2001[4]
Saschsenhöhe	~ 0.1		gneiss	M-F M	biotite Li-mica?	?	Sn-W greisen	Beck 1889
Preisselberg	0.5		gneiss, rhyolite, granite porphyry	F P (marginal) F P M P F M P (afg)	biotite* biotite biotite Li-mica	+	Sn greisen	Janečka and Štemprok 1967
Knötel	hidden		gneiss	pegmatite F P	biotite biotite		Mo greisen, veins	Žák 1967
Telnice	0.7	338 (K/Ar) Balogh**	gneiss, migmatite	M (P) F	biotite biotite-muscovite	+	molybdenite -quartz	Braun 1941, Chrt 1996
Markersbach	27		gneiss	C M E (P) F	biotite biotite biotite		Sn greisen	Beck (1889), Fritzsche 1928, Förster 2001

* Fe-Mg micas in some YIC granites are zoned and include also Li-enriched varieties classified as protolithionite. Li-mica denotes zinnwaldite- and lepidolite-bearing types

** quarry at Prostřední Telnice, age determination by K. Balogh, Inst. of Nuclear Research of the Hungarian Academy of Science, Debrecen (Dr. E. Pivec, personal communication)

Explanations of textural classification: C = coarse-grained, M = medium-grained, F = fine grained, P = porphyritic, (P) = slightly porphyritic, E = equigranular (seriate). Other abbreviations: afg = alkali-feldspar granite, hb = hornblende

Tab. 2. Chemical analyses (wt%) of granites from the Fláje massif

	Fláje porphyritic monzogranite					Evolved varieties			
	1	2	3	4	5	6	7	8	9
Sample No.	Fl-2	–	Fl-1	–	–	Fl-4	Fl-5	Fl-6	–
SiO_2	66.54	67.07	68.34	70.64	70.90	73.85	73.54	72.78	71.94
TiO_2	0.54	0.58	0.47	0.38	0.32	0.20	0.18	0.19	0.23
Al_2O_3	15.10	16.45	14.94	14.05	14.42	12.82	14.10	13.92	14.49
Fe_2O_3	1.11	0.78	1.32	0.48	0.64	0.13	0.66	0.64	0.46
FeO	1.96	2.02	1.39	1.52	1.06	0.55	0.48	0.18	0.72
MnO	0.042	0.05	0.045	0.04	0.04	0.018	0.023	0.03	0.04
MgO	1.82	1.41	1.49	0.98	0.49	0.27	0.45	0.30	0.37
CaO	2.22	2.50	2.49	1.47	1.10	0.94	0.74	0.57	0.48
Li_2O	0.005	trace	0.007	trace	trace	0.002	0.009	0.005	0.006
Na_2O	3.39	3.52	3.60	3.30	3.36	3.08	3.59	2.39	2.92
K_2O	3.95	3.70	3.96	4.37	4.55	5.12	4.52	6.24	5.59
P_2O_5	0.25	0.24	0.21	0.18	0.26	0.22	0.10	0.39	0.26
CO_2	–	0.20	–	0.30	0.13	–	–	0.12	0.10
H_2O^+	1.49	2.02	0.75	1.17	2.04	0.69	0.61	1.58	1.86
F	0.16	–	0.06	–	–	0.38	0.04	0.14	0.03
Cl	0.02	–	0.01	–	–	0.027	0.01	–	–
S	–	trace	–	0.06	trace	–	–	0.45*	–
H_2O^-	0.26	0.08	0.25	0.04	0.04	0.23	0.32	0.41	0.19
F,Cl,S =O	–0.07	–	–0.03	–0.03	–	–0.17	–0.02	–0.06	–
Total	98.79	100.62	99.30	98.95	99.35	98.36	99.35	100.27	99.69
A/CNK	1.09	1.15	1.01	1.01	1.16	1.04	1.16	1.188	1.24

* SO_3

Fláje porphyritic monzogranite: 1,3 – mine of Moldava II, dumpsite; 2 – Fláje, drill hole F 1, 10.7 m (Sattran 1968); 4 – Šumný důl, S of Fláje (Sattran 1960); 5 – former Pastviny village, drill hole P-2, 23.5 m (Sattran 1968).

Evolved varieties: 6 – Moldava leucogranite, mine of Moldava II, dumpsite; 7 – two-mica granite, former Mackov 2 km NE of Fláje, boulders; 8 – Moldava leucogranite, mine of Moldava II, dumpsite (Novák and Šreinová 1987); 9 – porphyritic microgranite, former Moldava II mine, underground drill hole Mp-2, 256.2 m (Novák et al. 1981)

Moldava leucogranite that occurs in the eastern subsurface continuation of the Fláje massif and individual dykes of porphyritic microgranite that were found in exploration drill holes and in the abandoned fluorite mine at Moldava.

Selected chemical analyses of granites from the Fláje body are given in Tab. 2. The Fláje monzogranite is rather primitive, moderately peraluminous and relatively rich in CaO (up to 2.5 wt%) that decreases with rising silica contents. This major granite type corresponds to the group of low-F biotite granites according to Förster et al. (1999). Low fluorine (0.045 % F on average) and lithium contents (10–100 ppm, average 62 ppm) have been confirmed by Sattran (1982) who published partial analyses of 40 systematically collected samples. The P_2O_5 contents in the whole body range from 0.10 to 0.39 wt% with the average content of 0.25 wt% (Tab. 2 and Sattran 1982) without any systematic co-variation with silica or MgO. The existence of unusually high P_2O_5 contents (0.72 to 1.33 wt%) reported by Fritzsche (1928) has not been confirmed by more recent analyses.

Granite rocks that are significantly higher in silica and lower in TiO_2 compared to the common Fláje monzogranite are herein called the evolved varieties. Such rocks are represented by analyses Nos. 6–9 in Tab. 2.

The Moldava leucogranite is noteworthy by its increased fluorine content that can be linked with mineralization of the nearby fluorite vein deposit. This granite has a relatively high P_2O_5 content, which may connect it with the OIC granite members of the Fláje massif. The porphyritic microgranite has 0.26 wt% P_2O_5 (Novák et al. 1981), which is much higher than phosphorus contents in the YIC granites of the EVPC (see below).

Telnice granite stock

The Telnice stock is exposed close to the village of Zadní Telnice, about 13 km NE of Teplice (Fig. 1). The predominant rock type corresponds to a coarsely porphyritic biotite granite (Braun 1941, Chrt 1996) of monzogranite composition, formerly reported as granodiorite (Chrt and Klomínský 1964). Chrt (1996) noted an alternation of subhorizontally oriented “granodiorite” and granite bodies observed in a drill hole. Similarly, Novák (1987) described an alternation of the main monzogranite with fine-grained biotite granite at the eastern margin of the stock (in the drill holes VN1, VN2 and VN5). Other varieties of compositionally more evolved granites are known from the drill hole VN1

Tab. 3. Chemical analyses (wt%) of granites from the Telnice body

	Porph. biotite monzogranite			Fine-gr.	Porphyritic microgranite		
No.	1	2	3	4	5	6	7
Sample No.	–	Te-1	Te-2	12/506	Te-3	Te-4	Te-5
SiO_2	69.93	71.54	71.49	72.76	72.90	72.92	73.86
TiO_2	0.37	0.32	0.37	0.36	0.20	0.20	0.17
Al_2O_3	14.26	13.49	13.53	13.18	13.50	13.74	13.76
Fe_2O_3	0.77	1.21	0.59	0.39	1.07	0.84	0.54
FeO	1.94	0.77	1.26	0.66	0.38	0.51	0.43
MnO	0.04	0.03	0.04	0.06	0.022	0.017	0.02
MgO	1.26	0.85	0.71	0.87	0.51	0.51	0.38
CaO	1.91	1.64	1.59	1.03	0.99	0.94	0.71
Li_2O	–	trace	0.010	0.011	0.003	trace	0.006
Na_2O	3.60	3.32	3.78	2.51	3.78	3.79	3.28
K_2O	4.22	4.63	4.38	5.87	4.37	4.58	5.03
P_2O_5	0.15	0.14	0.15	0.17	0.09	0.10	0.04
CO_2	trace	–	–	0.79	–	–	–
H_2O+	1.07	0.78	1.02	0.56	0.86	0.79	1.06
F	–	0.12	0.04	1.23	0.18	0.05	0.02
Cl	–	0.05	–		0.007	–	–
S	0.14	–	0.03	0.39	–	–	–
$H_2O–$	0.13	0.25	0.17	0.24	0.32	0.28	0.04
F, Cl, S = O	–0.07	–0.06	–0.03	–0.71	–0.08	–0.02	–0.01
Total	99.72	99.08	99.13	100.37	99.10	99.25	99.34
A/CNK	1.021	1.003	0.947	1.067	1.058	1.065	1.134

Porphyritic biotite monzogranite: 1 – old quarry in the SE part of the stock, Prostřední Telnice (Chrt and Klomínský 1964); 2 – drill hole VN-1 (Nakléřov, Rožný Hill), 3 – drill hole VN-2, 232 m (Zadní Telnice - SW slope of the Rožný Hill). 4 – fine-grained granite, VN-1, 130.2–6 m (see Table 8, No 1 for trace element contents).
Porphyritic microgranite: 5 – drill hole VN-1, 163-163.8 m (Nakléřov–Rožný Hill), 6 – VN-1, 162–162.8 m; 7 - VN-1, 177.6 m.

and from MT1 and MT2 located in the western contact zone. They correspond to fine-grained granite and porphyritic fine-grained granite resembling some microgranitic varieties of the Preisselberg granite stock (YIC). Such rocks are interpreted as younger intrusions.

Their chemical composition (analyses Nos. 5–7 in Tab. 3) shows lower CaO, TiO_2 and also P_2O_5 contents compared to the typical OIC granites. The presence of disseminated molybdenite–pyrite mineralization associated with the Telnice granite stock may be linked to these younger intrusions. Sporadically distributed dykes of granite and granodiorite porphyries, lamprophyres and felsic rhyolites crosscut the monzogranites. Their intrusions into the younger fine-grained porphyritic granite have not been found.

YIC granite bodies

The YIC granite occurrences are concentrated within a NW–SE-trending zone in the central parts of the EVPC, and similar rocks constitute also a separated pluton at Markersbach (Fig. 1). These rocks are poorly exposed and their major parts are hidden beneath the Teplice rhyolite and metamorphic rocks. Small granite outcrops are located, e.g., in the vicinity of Krupka (Preisselberg and Knötel) in the Czech territory, Cínovec/Zinnwald at the border, and Schellerhau, Sadisdorf, Altenberg and Sachsenhöhe in the German territory (Fig.1). In the Czech part of the batholith area, Chrt and Malásek (1984) and Štemprok et al. (1994) distinguished the Cínovec pluton (between the Cínovec granite outcrop and the depression in the granite surface found by the drill holes E-10, E–7, and E–16, see Fig. 2) and the Krupka pluton extending from this depression eastwards to the town of Bohosudov near Krupka. We suggest to combine these two bodies into a single pluton named the Cínovec–Krupka pluton. This is composed of two distinct YIC sequences: (1) the Li-poor, essentially biotite granites (Schellerhau SG1 and SG2, Preisselberg main granite), (2) Li-rich, mainly zinnwaldite granites (upper Cínovec – Zinnwald, Knötel).

Cínovec–Krupka pluton

This pluton is a predominantly hidden granite body in the SE continuation of the Schellerhau massif. Individual small stocks forming apical parts of the Cínovec–Krupka pluton at Cínovec and Preisselberg have relatively steep contacts and are characterized by shallow intrusion levels as testified by magmatic breccias at Preisselberg and Knötel (with depths of upper contacts not exceeding 2 km from the paleosurface). As the erosion has been limited, the greisen-style tin deposits associated with granite cupolas are preserved along the inclined contacts.

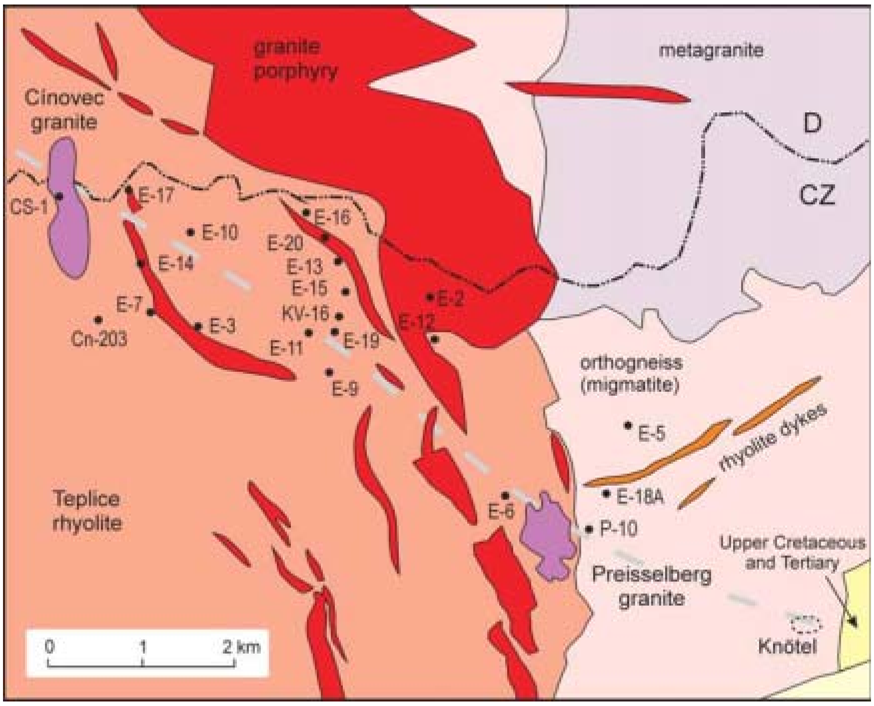

Fig. 2. Geological map of the Cínovec – Krupka area within the Eastern Volcano-Plutonic Complex with locations of exploration drill holes. Subsurface trend of the granite (YIC) elevations is schematically shown as a dashed NW–SE line (from Štemprok et al. 1994 and Breiter 1997).

The vertical compositional variability of the Cínovec stock is known from the deep drill hole CS-1 that was located in the centre of the cupola and reached the depth of 1,596 m below the surface (Štemprok and Šulcek 1969). Upper parts of the intrusion consist of lithium-rich albite granites that gradually pass into syenogranites moderately enriched in Li at a depth of about 730 m. The lower zone (to the bottom of the drill hole) consists of porphyritic medium-grained protolithionite granites with zones of fine-grained porphyritic granites (Štemprok and Šulcek 1969, Rub et al. 1998). The present compositional variability reflects not only the origin by multiple intrusions but also a strong post-magmatic overprint. All the granite varieties are low in P_2O_5 (about 0.02 wt%; Seltmann et al. 1998, Dolejš and Štemprok 2001).

Subsurface continuation of the YIC granites between Cínovec and Krupka was determined in numerous drill holes carried out for tin exploration (Fig. 2; Chrt and Malásek 1984, Novák et al. 1991, Štemprok et al. 1994). Granites found in the drill holes E-10, E-11, and E-15 situated SE of Cínovec (Fig. 2) can be texturally differentiated into equigranular fine-grained and medium-grained biotite syenogranites and the porphyritic syenogranite of the Preisselberg type. The latter typically constitutes the uppermost portions of the hidden parts of the Krupka pluton and prevails also in upper parts of the Presisselberg stock. The Li-mica albite granites form especially the lower levels of the known profile (Štemprok et al. 1994) but rise in the form of the Cínovec stock in the NW and the hidden Knötel cupola in the SE (Fig. 2).

The Knötel stock (about 100 m in diameter at the altitude of 400 m above sea level) occurs in the Eastern Krupka district (Fig. 2). It is composed of Li-mica albite granites (Štemprok et al. 1994) that are accompanied by the overlying K-feldspar-rich pegmatite (Eisenreich and Breiter 1993) and brecciated gneiss material. The greisen and quartz mineralizations are dominated by molybdenite (Žák 1967).

Representative analyses of the YIC granites from the Cínovec–Krupka pluton including the Preisselberg stock are given in Tabs 4 and 5. Analyses of the Cínovec granites were presented, e.g., in Dolejš and Štemprok (2001). All these granites are highly evolved syenogranites and alkali-feldspar granites. They correspond to the high-F, low-P_2O_5 Li-mica granites in the sense of Förster et al. (1999) and Förster (2001).

The YIC granites are mostly peraluminous with minor exceptions of metaluminous compositions. We subdivide them into a) Li-poor (with low to medium Li contents), i.e., biotite to protolithionite granites (lower Cínovec and Preisselberg biotite granites), and b) Li-rich, i.e., lepidolite and zinnwaldite granites (upper Cínovec, Preisselberg Li-mica albite granite). This subdivision corresponds with the classification by Štemprok et al. (1994) of the low-Li granites equivalent to the first sequence YIC granites and the high-Li granites of the second sequence of the YIC granite intrusions.

The Li-rich alkali-feldspar granites are enriched in Na_2O and carry evidence of pervasive post-magmatic albitization (they are classified as albite or albitized granites). They have been also classified as topaz-Li-mica granites and alkaline Li-albite granites (Trumbull et al. 1994) or topaz granites (Taylor and Fallick 1997).

Preisselberg granite stock

The Preisselberg granite stock (Fig. 3) was studied extensively in 1970s by geological mapping and exploration drill holes (Fiala and Pácal 1965, Janečka and Štemprok 1967, Eisenreich in Janečka et al. 1969, Štemprok and Lomozová 1983, Eisenreich and Breiter 1993, Novák 1994), and also in exploration mine workings (crosscuts Nos. 1, 2, 3 in Fig. 3). It was found that biotite syenogranite is intrusive into the Teplice rhyolite, granite porphyry, orthogneiss or migmatite with local formation of intrusive breccias. The syenogranite

Tab. 4. Chemical analyses (wt%) of selected YIC granites from the Cínovec–Krupka pluton

	Preisselberg syenogranite				Preisselberg Li-mica albite granite				
	1	2	3	4	5	6	7	8	9
CGS No.*	–	2024	2023	–	1016	1017	2021	2022	2129
SiO_2	75.11	76.54	74.89	74.73	74.68	74.45	76.53	75.80	72.54
TiO_2	0.13	0.09	0.13	0.11	0.02	0.01	0.04	0.07	0.005
Al_2O_3	12.27	12.26	12.59	12.80	13.05	13.18	12.23	12.36	15.09
Fe_2O_3	0.74	0.47	0.81	0.77	0.58	0.24	0.43	0.35	0.44
FeO	0.68	0.42	0.65	0.57	0.88	0.99	0.73	0.74	0.41
MnO	0.032	0.013	0.024	0.020	0.038	0.061	0.033	0.027	0.045
MgO	0.16	0.07	0.20	0.15	0.10	0.08	0.07	0.07	0.03
CaO	0.68	0.56	0.59	0.66	0.39	0.57	0.52	0.54	0.24
Li_2O	0.031	0.012	0.029	0.010	0.17	0.21	0.061	0.06	0.12
Na_2O	3.01	3.13	3.06	3.23	2.88	2.98	3.51	3.49	5.24
K_2O	5.33	5.12	5.09	5.26	5.16	4.46	4.51	4.83	3.95
P_2O_5	0.06	0.03	0.05	0.12	0.01	0.01	0.02	0.02	0.067
CO_2	–	0.01	0.01	0.05	0.01	0.01	0.01	–	–
H_2O+	0.85	0.68	0.83	1.02	1.13	1.25	0.51	0.65	0.50
F	0.47	0.35	0.44	0.43	0.54	0.93	0.51	0.54	0.73
S	–	0.03	0.02	< 0.01	0.02	0.02	0.02	0.03	–
$H_2O–$	0.20	0.10	0.12	–	0.36	0.25	0.04	0.03	0.07
F, S = O	–0.20	–0.16	–0.19	–0.18	–0.24	–0.40	–0.22	–0.24	–0.31
Total	99.55	99.72	99.34	99.75	99.78	99.30	99.55	99.37	99.17
A/CNK	1.03	1.05	1.08	1.05	1.18	1.22	1.05	1.03	1.13

* sample numbers of the Czech Geological Survey, Prague

Preisselberg syenogranite (biotite granite of the first sequence): 1 – Vrchoslav, dumpsite of the 5th May Gallery; 2 – Horní Krupka, Preisselberg Hill, drill hole E-6, 242 m; 3 – drill hole E-6, 247 m; 4 – drill hole E-6, 139.6 m.

Li-mica albite granite (alkali-feldspar granite of the second sequence): 5 – drill hole E-6, 488 m; 6 – drill hole E-6, 492 m; 7 – drill hole E-6, 703 m; 8 – drill hole E-6, 708 m; 9 – Bohosudov-Knötel, drill hole KV-20.

Analyses 2, 6, 8, 9 were published in Breiter and Frýda (1995) or Breiter (1998a); 3,5,7 – unpublished data provided by K. Breiter

body itself is intruded by aplite, kersantite, and intersected by a younger Li-mica alkali-feldspar granite. The latter corresponds to the second sequence of the YIC granites.

The main type of the Preisselberg porphyritic syenogranite forms the central parts of the intrusion (Fiala and Pácal 1965, Štemprok and Lomozová 1983). It consists of perthitic K-feldspar (40–52 vol%), quartz (33–38 vol%), albite or Na-rich plagioclase (5–15 vol%), biotite (2–4 vol%), scarce muscovite (< 0.7 vol%), fluorite and topaz. Accessory minerals are zircon, sphene, magnetite, xenotime and monazite. Apatite was not observed. Secondary minerals are protolithionite replacing mainly biotite, and sericite, hematite, and kaolinite in feldspars or intergranular spaces.

Granite varieties forming the marginal parts of the body (especially along its W, S and E sides, see Fig. 3) differ from the inner (common) Preisselberg granite both in their texture and composition. We have re-examined samples from the drill hole P-10 (Fig. 4), which explored the eastern contact zone of the Preisselberg granite with the Teplice rhyolite and sampled also its deeper internal parts of the lithium-bearing albite granite.

A fine-grained marginal granite was described by Štemprok and mapped by Eisenreich in Janečka et al. (1969). Chemical analysis was published by Breiter and Frýda (1995). We re-examined this special rock type that we designate as the "marginal microgranite". It is fine-grained and dark grey in colour (Fig. 5a). K-feldspar prevails over quartz, minor albite to albite-oligoclase and subordinate biotite forming relative larger and often partly recrystallized flakes (Fig. 5b). Biotite is more abundant and its composition is more magnesian compared to that in the common variety of the Preisselberg biotite granite. Sparsely distributed are phenocrysts of K-feldspar, quartz (3–5 mm) and some biotite. A typical accessory mineral is apatite. Comparison of this marginal microgranite with the adjacent medium-grained biotite granite is given in Tab. 6.

The Li-mica alkali-feldspar granite constitutes deeper parts of the Preisselberg stock (Fig. 4) and raises to an independent granite cupola (Preisselberg II) that is asymmetrically located with respect to the main Preisselberg intrusion (Štemprok et al. 1994). Except for zones affected by the pervasive Li-bearing greisenization, this granite is equigranular or slightly porphyritic in texture. Zoned lithium micas (protolithionite to zinnwaldite) are irregularly scattered as single skeletal flakes or aggregates (0.5 to 1 mm). The amounts of the zinnwaldite component increase gradually from cores to margins of the mica flakes.

Tab. 5. Major element analyses (wt%) of granites from the drill holes (Fig. 3) and the Nový Martin gallery in the Cínocec–Krupka pluton

	Preisselberg marginal microgranite			Porphyritic biotite granite			Li-rich albite granite		
	1	2	3	4	5	6	7	8	9
Drill hole/mine Depth (m)	P-10 187.6–188.0	P-10 201.9	Nový Martin Gallery	P-10 253.3–6	P-14 50.0–430.0*	E-11 899.5–9	P-10 350.0–2	P-14 466–600*	E-15 653.0–5
Sample	2167	4/563	2151	2168	1285	10/515	2169	1287	11/507
SiO_2	71.21	71.30	71.08	73.72	74.96	76.42	71.26	72.86	73.52
TiO_2	0.20	0.24	0.19	0.12	0.08	0.11	0.07	trace	0.06
Al_2O_3	13.74	13.56	13.48	12.83	12.48	12.16	14.91	14.29	13.21
Fe_2O_3	0.09	1.00	0.66	0.08	0.92	0.50	0.23	0.53	0.88
FeO	3.29	0.98	1.45	2.75	0.79	0.42	2.54	1.00	1.14
MnO	0.03	0.05	0.053	0.03	0.04	0.10	0.10	0.09	0.11
MgO	0.41	0.48	0.25	0.20	0.30	0.26	0.13	0.28	0.11
CaO	0.52	1.12	0.82	0.50	0.42	0.30	0.97	0.72	1.01
Li_2O	trace	0.15	0.10	trace	trace	0.054	0.35	0.27	0.31
Na_2O	2.74	2.00	3.07	2.79	2.76	2.78	2.96	2.52	2.23
K_2O	6.12	6.45	6.42	5.12	5.23	5.35	3.76	3.80	4.60
P_2O_5	0.33	0.32	0.26	0.09	0.06	0.03	0.01	trace	0.03
CO_2	trace	0.22	–	trace	0.09	0.39	trace	0.16	0.32
H_2O+	1.26	0.98	0.66	1.18	1.03	0.53	1.72	2.10	1.23
F	–	0.79	0.583	–	–	0.31	–	1.00	2.82
S	0.08	< 0.01	–	0.06	trace	< 0.01	0.02	trace	< 0.01
$H_2O–$	0.29	0.44	0.11	0.13	0.14	0.34	0.30	0.36	0.24
F, S = O	–	–0.33	–0.24	–	–	–0.13	–	–0.42	–1.19
Total	100.31	99.75	98.95	99.60	99.30	99.82	99.33	99.56	100.96
A/CNK	1.19	1.10	1.00	1.24	1.14	1.12	1.39	1.49	1.26

* average analyses (core samples taken in about 20 m intervals and averaged by crushing and grinding)
Analysis 3 (2151) is from Breiter and Frýda (1995)

Minor fluorite, topaz, hematite and secondary quartz often occur as overgrowths on micas.

Aplitic granite cutting the main syenogranite is small-grained (0.3–0.1 mm in size) and mostly equigranular, scarcely porphyritic, with quartz and plagioclase (albite) phenocrysts. Its P_2O_5 content given by Fiala and Pácal (1965) is very low (in traces).

Representative chemical analyses of granitic rocks from the Preisselberg stock are given in Tabs 4 and 5. P_2O_5 contents are generally low in both the main Preisselberg syenogranite and Li-rich albite granite but strongly increased in the marginal microgranite (Nos 1, 2 and 3 in Tab. 5). Noteworthy are the elevated Li and Rb contents in the marginal microgranite (Tab. 8). They can be attributed to local greisenization that is related to the adjacent medium-grained granite and is apparent from the presence of accessory topaz and a weak lithionitization of biotite.

Schellerhau granite massif

The Schellerhau massif represents the largest outcrop of YIC granites in the EVPC (Tab. 1). It is situated within the ATC between Altenberg and Kipsdorf (Fig. 1). It consists of three main sequences termed as SG1 (G1), SG2, and SG3. The Li- and F-rich leucogranite with a distinct A-type tendency (SG3), enriched in Rb, Li, F, and Sn, was described from the massif by Müller et al. (2000). Schilka and Baumann (1996) noted some greisenization within the G1 granites. According to gravity data and geochemical studies of the drill cores, granites of the Schellerhau type form a predominant part of the mostly hidden YIC part of the Eastern pluton. The G1 porphyritic syenogranite is possibly equivalent to some lower Cínovec granites intersected by the deep drill hole from 730 m downwards (Dolejš and Štemprok 2001). The P_2O_5 contents range from 0.02 to 0.04 wt% (Müller et al. 2000). Micas vary in composition between zinnwaldite and protolithionite, similarly to granites from the Cínovec (Zinnwald) stock.

Markersbach granite stock

The Markersbach pluton (Fig.1, Tab. 1) is located in the vicinity of Berggieshübel (Beck 1889; Förster 2001) in the easternmost Erzgebirge. Only a small part of the texturally variable body (Fritzsche 1928) is exposed to the present surface. Its highly evolved nature is evidenced by very low contents of CaO, MgO (0.01–0.04 wt%), Sr (0.8–5.7 ppm) and Ba (8–20 ppm) according to Förster (2001). The contents of P_2O_5 are low, ranging 0.007–0.02 wt%.

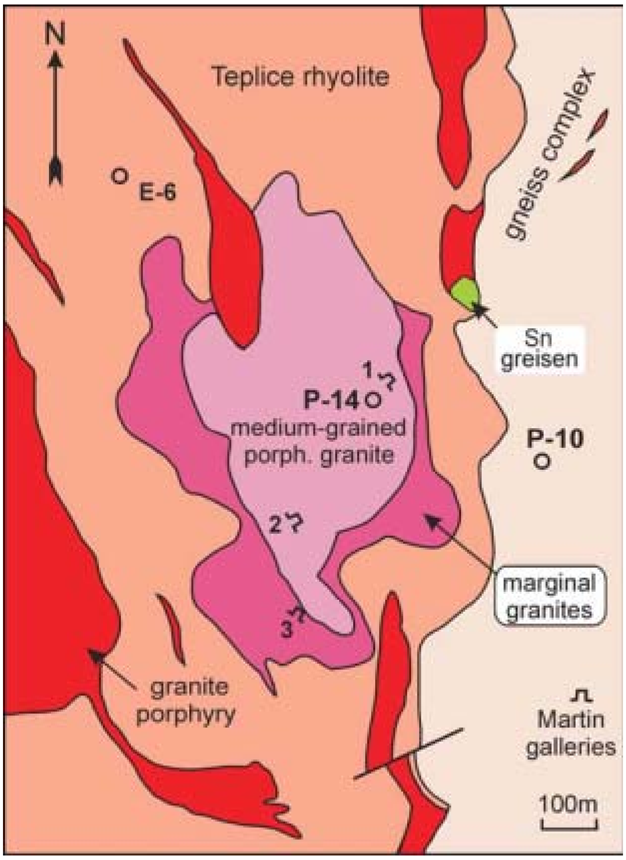

Fig. 3. Geological map of the Preisselberg granite stock and its surroundings near Krupka in the Eastern Krušné hory/Erzgebirge according to unpublished map by M. Eisenreich (in Janečka et al. 1969). Entrances of exploration crosscuts (marked with numbers) and sites of drill holes P-10 and P-14 are shown.

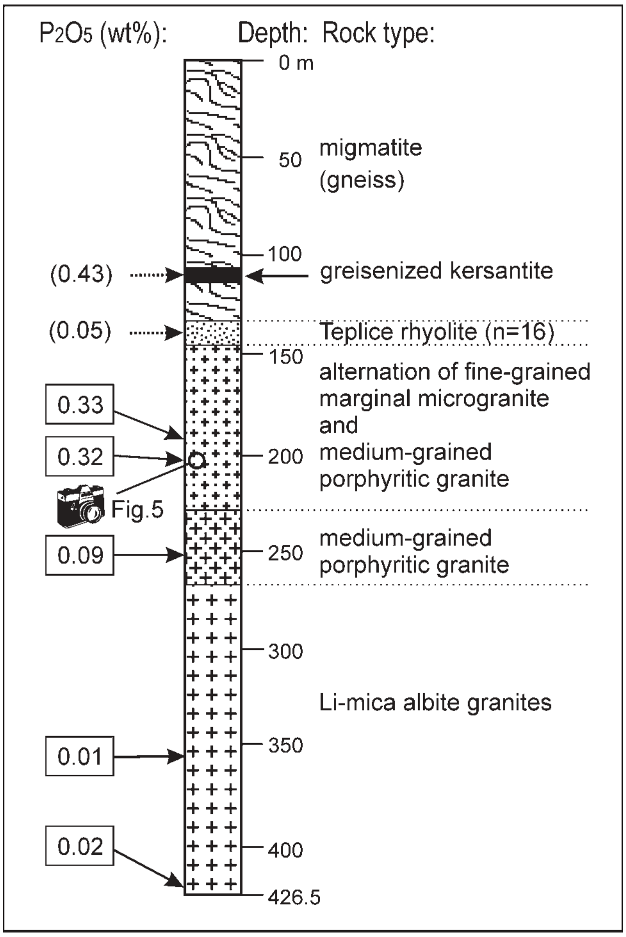

Fig. 4. Schematic geological profile of the exploration drill hole P-10 Krupka across the NE contact zone of the Preisselberg granite stock (from Janečka et al. 1969). Contents of P_2O_5 in samples from this drill hole are in boxes, averaged data for some rock types from other drill holes in a close vicinity are given in parentheses.

Tab. 6. Comparison of the Preisselberg biotite granite and the "marginal microgranite"

		Biotite granite	"Marginal microgranite"
Modal composition (vol%)	K-feldspar	40–52 perthitic	38–40 poor in Na
	Na-feldspar*	5–15	18
	Quartz	33–38	32
	Biotite	2–4	9–10
	Muscovite	0.7	+
Accessory minerals		xenotime, monazite, ilmenorutile	apatite
Biotite composition (wt%)	TiO_2	1.70 (1.55–1.88)	2.30
	Al_2O_3	19.08	21.82
	MgO	1.90 (1.78–2.15)	4.39 (3.98–4.76)
	mg	0.129 (0.120–0.147)	0.256 (0.229–0.276)
Whole-rock (wt%)	SiO_2	> 73	71.1–3
	P_2O_5	< 0.1	0.3

* albite to albite-oligoclase

Rhyolites and associated volcanic products

The Altenberg–Teplice Caldera is filled with a complex sequence of acid volcanic products. The lowermost parts, equivalent to the Schönfeld Unit in Germany, are represented in the Czech part of the area by the basal rhyolite and overlying dacite lavas with some tuffs. These rocks are known from deeper parts of the drill hole Mi4 near Mikulov, SW of Cínovec (Breiter 1997, Breiter et al. 2001).

The Teplice rhyolite complex forms the prevailing part of the nearly 2 km thick volcanic edifice. The present area modified by denudation is elongated in the NNW–SSE direction between Dippoldiswalde (Germany) and Teplice (Czech Republic).

The body of the Teplice rhyolite (formerly known as the "Teplice quartz porphyry") is dominated by crystal-rich ignimbrites (Holub 1980, Jiránek et al. 1987). The rocks were petrographically subdivided into several local petrographic types by Fiala (1960) and by Štemprok and Lomozová (1983). Holub (1980) and Breiter (1997) have shown vertical compositional zoning of the sequence.

Dacite lava flow and tuffs (267.1 m thick) from the drill hole Mi-4, counted to the Schönfeld Unit (i.e., the earlier volcanic sequence) are relatively high in P_2O_5 (average

0.26 wt%, n = 6; Breiter 1997) with respect to the basal rhyolite tuffs and the prevailing parts of the younger, more acid Teplice rhyolite.

The literature data and our data from the exposed Czech part of the Teplice rhyolite give a wide range of silica contents (between 71 to 78 wt%) at the mean value of 5.4 wt% K_2O (4.8–6.2 wt%) and 2.51 wt% Na_2O (1.5–3.2 wt%). The contents of P_2O_5 vary from 0.02 to 0.08 wt% with the average of 0.05 wt% (n = 12). The vertical section of the Teplice rhyolite complex studied by Breiter (1997) displays generally low P_2O_5 contents increasing from the base to the top in each unit (averages for several individual units range between 0.01–0.09 wt%) with decreasing silica contents, i.e., possibly as a consequence of gradational exhausting of the vertically zoned magma chamber. However, Holub (1980) has recognized also much less acid varieties (about 67 wt% SiO_2) of ignimbrites within the Teplice rhyolite body. These varieties contain up to 0.22 wt% P_2O_5 in the deep drill hole Le 127 (about 10 km SW of Teplice, i.e., below the Tertiary sediments). Selected representative analyses of the Teplice rhyolite are given in Tab. 7.

Granite porphyries

Thick granite porphyry bodies form especially the marginal dyke system rimming the Altenberg–Teplice Caldera. The rocks show considerable textural and compositional variations. They usually correspond in chemistry to biotite granite but some portions, e.g., in the Loučná–Fláje dyke, approach granodiorite and may contain subordinate hornblende (Sattran 1960). Granite porphyries ("porphyritic microgranites") of the Altenberg–Frauenstein dyke on the NE margin of the ATC have been classified as G1 (silicic), G2 (mafic) and G3 (most felsic) members by Seltmann et al. (2001) and Müller and Seltmann (2002). According to those authors, the G2 member displays metaluminous composition indicated also by the presence of accessory hornblende. The compositional variability as well as the presence of plagioclase-mantled K-feldspar phenocrysts are explained in terms of hybridization of felsic magma with a mafic one. The P_2O_5 contents vary from 0.14 to 0.38 wt% with increasing colour index; the mean value is 0.24 wt%.

Granite porphyries and rhyolites form also numerous thinner dykes in the whole area of the EVPC. Their petrography is variable and chemical composition remains poorly known. Porphyry dykes with microgranitic textures were observed, e.g., in the crystalline envelope within the Krupka district and in the exocontact of the Telnice stock (Novák 1987). Their P_2O_5 contents range widely about 0.5 wt%.

Representative analyses of granite porphyries from the Czech territory of the EVPC are given in Tab. 7. These rocks are typically lower in silica compared to granites and predominating parts of the Teplice rhyolite complex. The high alumina-saturation indices contradict chemical characteristics of the Altenberg–Frauenstein dyke and may be due to secondary alteration.

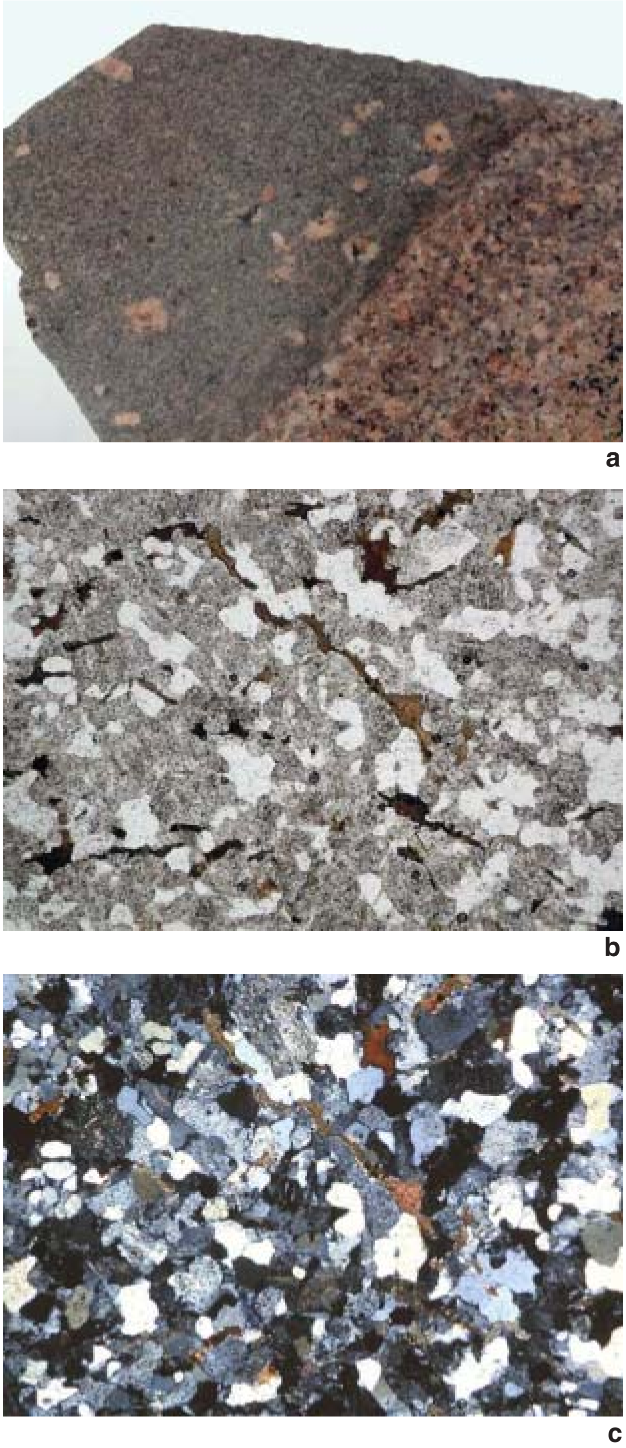

Fig. 5. a – Contact of the marginal microgranite (dark, fine-grained) and the medium-grained Preisselberg granite. Drill hole P-10, depth 201.9 m. Figure width is 15 cm. b – A photomicrograph of the marginal microgranite, plane polarized light, x20. c – As above, crossed nicols.

Lamprophyres

Lamprophyres occur as thin dykes in the crystalline envelope of the EVPC. Those known from the Krupka and Telnice districts are represented by kersantite, subordinate minette and rare spessartite. Almost all lamprophyres are deuterically altered to various degrees and some of them are locally

Tab. 7. Representative chemical analyses (wt%) of various members of the Teplice rhyolite, granite porphyries and lamprophyres

	Teplice rhyolite				Granite porphyry			Lamprophyres	
	1	2	3	4	5	6	7	8	9
SiO_2	72.51	69.68	65.96	72.22	66.96	66.93	70.94	52.46	49.84
TiO_2	0.26	0.38	0.65	0.29	0.68	0.51	0.32	1.30	0.84
Al_2O_3	13.11	13.75	15.27	12.93	14.45	14.91	13.82	13.95	13.87
Fe_2O_3	0.88	0.74	2.40	0.67	2.17	1.80	1.95	1.63	1.91
FeO	1.15	2.57	1.29	1.26	2.15	1.50	0.97	6.41	6.30
MnO	0.033	0.08	0.05	0.03	0.09	0.04	0.02	0.124	0.131
MgO	0.34	0.38	0.61	0.41	0.87	0.28	0.27	7.70	9.02
CaO	0.58	1.36	1.77	0.55	0.98	0.77	0.33	7.89	7.45
Na_2O	3.64	3.67	3.59	2.87	2.17	1.86	0.80	2.37	1.88
K_2O	6.02	5.85	6.31	6.59	6.13	6.76	7.64	3.36	4.20
P_2O_5	0.088	0.09	0.18	0.08	0.28	0.15	0.09	0.68	0.52
H_2O+	0.82	0.66	0.84	0.59	1.58	1.88	1.73	1.23	1.48
CO_2	0.01	0.13	0.51	0.74	0.43	1.26	0.79	0.39	1.95
F	0.05	–	–	–	0.13	0.067	–	–	–
S	0.002	trace	–	–	< 0.01	0.022	–	–	–
$H_2O–$	0.11	0.36	–	0.67	0.44	0.45	0.02	0.18	0.35
F, S = O	–0.02	–	–	–	–0.05	–0.04	–	–	–
Total	99.58	99.70	99.43	99.90	99.46	99.34	99.69	99.67	99.74
A/CNK	0.967	0.926	0.957	1.01	1.21	1.27	1.35	0.633	0.655

1 – Teplice rhyolite (Přední Cínovec type), 2 km NW of Dubí (Schovánek et al. 2001); 2 – Teplice rhyolite, Teplice, Písečný vrch (Sattran 1963) 3 – Teplice rhyolite (ignimbrite), drill hole Le-127, 620.2 m (Holub 1980); 4 – Teplice rhyolite (ignimbrite), drill hole Le-127, 988 m (Holub 1980); 5 – granite porphyry; Horní Krupka, former village of Přední Cínovec, drill hole E-10, 339.5-9 m; 6 – granite porphyry, drill hole Je-97, 122.8 m (including SrO 0.013, BaO 0.17 wt%); 7 – granite porphyry, drill hole Le-127, 379.7 m (Holub 1980), 8 – spessartite, Horní Krupka, Večerní Hvězda gallery dump, 9 – kersantite, Preisselberg, Gallery No. 2 dump

greisenized with the origin of mica-rich greisens. The sequential position of lamprophyre dykes (e.g., in drill hole E-2) is uncertain as they occur mostly in gneisses without any visible relationship to felsic dykes and granite bodies.

Phosphorus contents are relatively high, ranging from 0.49 to 0.65 wt% P_2O_5 in kersantites (average 0.55 wt%, n = 7) and from 0.51 to 0.85 wt% P_2O_5 in minettes (average 0.60 wt%, n = 4). These values are similar to those in lamprophyres of the whole Fichtelgebirge–Erzgebirge anticlinal zone as reported by Kramer (1976). Apatite is obviously very fine-grained; however, greisenized kersantite at Preisselberg contains much larger, presumably recrystallized apatite crystals (Novák et al. 2001). In spite of the recrystallization of apatite, the whole-rock content of P_2O_5 seems to be unaffected by greisenization.

Comparison of chemical parameters

Granites of the Fláje and Telnice stocks are compositionally differentiated into primitive OIC members (with relatively lower SiO_2 contents and high CaO) forming the bulk of the stocks and silica-enriched (more evolved) members (in places found as typically younger intrusions). In the amounts of K_2O (about 4.5 wt%) and Na_2O (3.3–3.6 wt%) they are not significantly different from the YIC granites (Tabs 2–5) except for the increased K_2O in some of the more evolved varieties. Significant differences exist, however, in the contents of TiO_2, MgO and other major components that typically decrease during the magma evolution.

The YIC granites are mostly peraluminous with minor exceptions of metaluminous compositions. The silica contents in the YIC granites range commonly from 73 to 76 wt% SiO_2 with the highest values in some Preisselberg and Cínovec granites (75 to 77 wt% SiO_2, literature data and Tab. 5) that are close to acid members of the Teplice rhyolite. TiO_2 contents are very low (about 0.1 wt%) and similar to the average values from the exposed Teplice rhyolite (average 0.14 wt% TiO_2). Lower contents of FeO and MgO (about 0.1–0.3 wt%) are important characteristics distinguishing these rocks from the OIC granites. CaO contents of the YIC granites are mostly around 0.5–0.6 wt%, similar to the values from the Teplice rhyolite (average 0.67 wt%). All the YIC granites, defined by geological criteria, are low-P except for the Preisselberg marginal microgranite.

Variations in the P_2O_5 vs. SiO_2 contents for the OIC granites are shown in Fig. 6a. The Fláje monzogranites, i.e., the primitive members, display moderate amounts of P_2O_5. The more evolved members are highly variable with markedly elevated P_2O_5 contents in some of them. The Telnice granites have P_2O_5 contents generally lower than the Fláje granites. The Preisselberg marginal microgranite corresponds in its P_2O_5 content to the “evolved” Fláje granites with increased phosphorus, but its silica content is lower.

Tab. 8. Trace element contents (ppm) in representative samples of various granitic rocks from the Eastern Vocano-Plutonic Complex

	1	2	3	4	5	6
Table/No	3/4*	7/5*	5/2*	5/3*	5/6*	5/9*
Sample	12/506	1/503	4/563	2151	10/515	11/507
SiO_2 wt%	72.76	66.96	71.30	71.08	76.42	73.52
Cr	21	9	13	–	7	6
Co	8	5	1	–	1	3
Sc	5.1	9.2	6	–	3.5	8.6
Cu	77	13	8	1	10	13
Pb	131	61	37	37	82	141
Zn	15	155	118	42	13	40
Bi	3.05	0.53	12.1	< 2	1.27	3.77
Sn	7.6	6.8	17.8	16	16.8	30.8
Rb	277	396	1094	1092	830	1578
Cs	12.4	29.8	27.3	–	35	39
Ba	602	925	238	–	64	100
Sr	65	45	29	34	30	25
Ga	18	25	23	–	27	37
Li	51	51	702	460	249	1458
Ta	2.1	1.99	2.17	–	11.1	24.6
Nb	< 7	16	17.1	38	51	88
Hf	4.0	5.2	2.6	–	8.8	5.3
Zr	108	221	86	99	174	160
Y	15	30	22	40	116	47
Th	16.8	25.5	9.4	–	56	24.8
U	< 15	< 15	< 15	19	26	36
La	30.0	65.3	17.5	18.6	29.1	26.9
Ce	58.23	134	36.2	50.5	79.2	80.18
Pr	5.53	14.4	3.82	5.77	11.5	9.54
Nd	22.52	52.5	15.16	27	37.1	26.9
Sm	3.69	9.1	4.00	8.3	9.95	7.44
Eu	0.65	1.29	0.68	0.14	< 0.13	< 0.13
Gd	3.04	8.5	3.92	9.2	11.8	6.69
Tb	< 1	< 1	0.73	< 1	2.13	1.59
Dy	2.67	5.8	4.38	8.2	15.9	11.60
Ho	0.31	1.08	0.83	1.44	3.23	2.11
Er	1.22	2.82	2.43	3.72	11.8	8.65
Tm	< 0.30	0.50	0.31	0.49	1.96	1.93
Yb	1.47	2.87	2.09	3.49	13.4	15.84
Lu	0.23	0.48	0.29	0.48	2.03	2.36

* No of Table / No of column where major element analysis of the sample is given
1 – Telnice body, fine-grained granite Nakléřov - Rožný Hill (drill hole VN-1, 130.2–6 m) 2 – granite porphyry, Horní Krupka, former village of Přední Cínovec (drill hole E-10, 339.5–9 m); 3 – Preisselberg stock, marginal microgranite, (drill hole P-10, 201.9 m); 4 – Preisselberg stock, marginal microgranite, Nový Martin Gallery, Horní Krupka (Breiter and Frýda 1995); 5 – Preisselberg stock, porphyritic microgranite (Sedmihůrky, drill hole E–11, 899.5–9 m); 6 – Loupežný , Li-rich albite granite (former village of Přední Cínovec, drill hole E-15, 653.0–5 m)

Granites of the Fláje massif and the marginal microgranite of the Preisselberg stock have the highest contents of P_2O_5 in the Czech part of the EVPC.

The SiO_2/P_2O_5 plot for YIC granites (Fig. 6 b) shows no clear distinction between the low-Li (biotite and protolithionite) and high-Li (lepidolite or zinnwaldite) albite granites. Average composition of the Teplice rhyolite plots within the field of the YIC granites.

The diagram of A/CNK versus P_2O_5 (Fig. 7a) shows a slight increase in P_2O_5 contents with increasing A/CNK values in the OIC granites. The Preisselberg marginal microgranite plots close to the more evolved members of

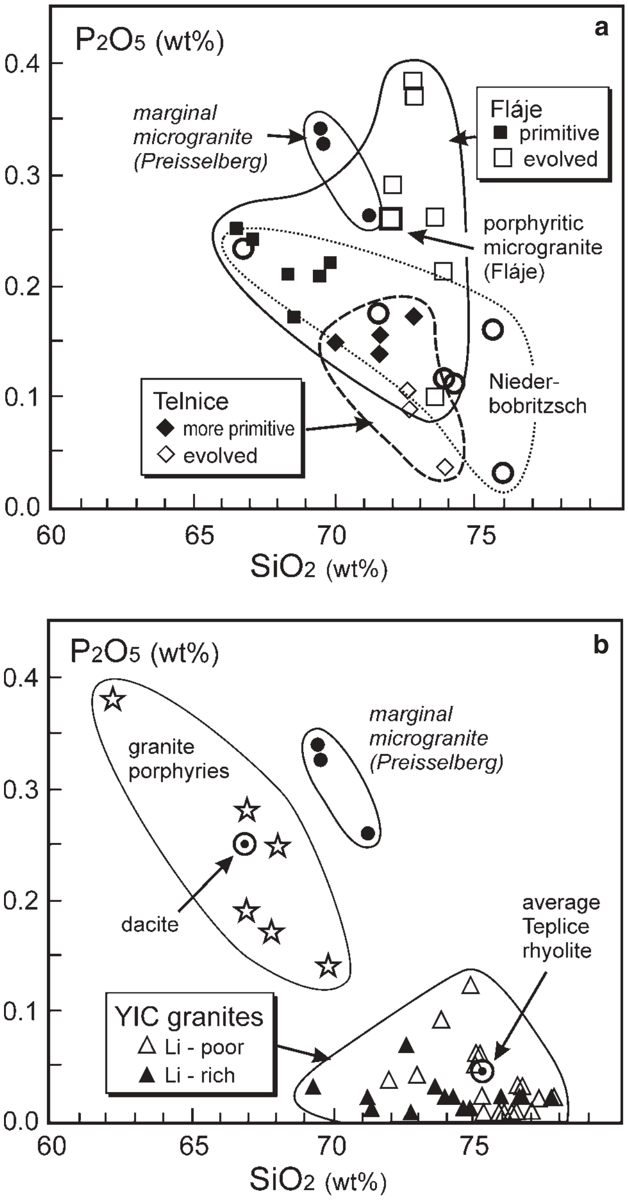

Fig. 6. Variations in P_2O_5 and SiO_2 contents of felsic igneous rocks from the Eastern Volcano-Plutonic Complex.

the Fláje massif. The Telnice granites show relatively low A/CNK values, mainly in their primitive members. The P_2O_5 contents are apparently independent of the A/CNK value, and the regression line for all the data is horizontal with the A/CNK value at about 1.1. The Li-rich albite granites (Fig. 7b) show a broad scatter of the A/CNK values that are apparently caused by subsolidus alterations (albitization, greisenization).

The chondrite-normalised REE pattern of the marginal microgranite is shown in Fig. 8 where it is compared with some other EVPC granites and granite porphyry. It has the lowest amounts of REE and a general course similar to that of the granite porphyry. It is closer to the OIC granites (Telnice) than to the common Preisselberg YIC granites. However, it shows a slight enrichment in HREE, typical for the evolution within the group of the YIC granites (Just et al. 1992, Förster et al. 1995).

Discussion

As we have shown in the preceding chapters, the magmatic evolution of the EVPC was very complex and caused highly variable P_2O_5 contents. The basic statistical parameters of the P_2O_5 contents (their averages and ±1sigma ranges for individual rock types and groups) are summarized in Fig. 9. Variations in P_2O_5 and CaO contents that can highlight some petrogenetic relations are shown in Figs 10 and 11.

Felsic rocks from the area under study can be differentiated into those with low contents of P_2O_5 (< 0.1 wt%) and those with medium P_2O_5 (> 0.1 wt%). Acid rocks with P_2O_5 > 0.4 wt% are absent from the whole area of the EVPC.

The low-P_2O_5 group comprises the prevailing acid varieties of the Teplice rhyolite and both the low-Li and high-Li granites of the YIC (the first and second sequence granites).

The group with medium P_2O_5 contents (> 0.1 wt%) includes the Fláje OIC granites, evolved intrusions at Fláje (the Moldava leucogranite and the porphyritic microgranite), some granite varieties of the Niederbobritzsch massif as well as the prevailing varieties of granite porphyries. Dacite flows from the earlier volcanic sequence of the ATC and the subordinate less acid varieties of ignimbrites within the Teplice rhyolite complex have also relatively increased P_2O_5 contents. The Telnice OIC granites and their evolved types range as transitional between the medium- and low--phosphorus types.

Any equivalent of the high-P YIC granites from the Western pluton (like the Podlesí stock, see Breiter et al. 1997, Breiter and Frýda 2001) is missing in the EVPC. The only acid rocks with significantly elevated P_2O_5 contents in the Eastern pluton are some individual samples from the Fláje massif including the Moldava type (Tab. 2 and Sattran 1982) and the "marginal microgranite" from the Preisselberg stock.

The variations in phosphorus contents in granitic melts can be explained (London 1997, 1998, Zaraisky et al. 1998, Müller and Seltmann 2002) by one or more of the following mechanisms: a) P-enriched granitic protolith or assimilated P-rich material, b) degree of melting of a P-containing protolith, c) the differences in the composition of granitic melts (expressed as the degree of peraluminosity or peralkalinity), d) contamination of P-poor felsic by P-rich mafic magma, e) variable behaviour of P in different stages of magmatic evolution, mainly affected by crystal fractionation, e) post-solidus mobilization of P during decomposition of feldspars. Förster et al. (1999) explained the contrasting behaviour of phosphorus among the three groups of granites distinguished in the German part of the Krušné hory/Erzgebirge batholith in terms of the strong control of melt peraluminosity (A/CNK) on apatite solubility as suggested in the literature.

Our further discussion will be focussed on the following points: (1) the origin of the P_2O_5 variations in rocks forming the OIC granite bodies, (2) the origin of the "marginal granite" relatively high in P, (3) the origin of the low P_2O_5 contents typical for the YIC granites in the EVPC, and (4) the magma evolution and petrogenetic links between various rocks.

Variations in P_2O_5 in the OIC granite bodies

The existence of significant differences in the bulk P_2O_5 contents among some of the OIC and YIC granites in the Eastern pluton can be explained by different lithologies of their source rocks as, e.g., applied by Taylor and Fallick (1997) to topaz granites. However, some important variations in the of P_2O_5 contents exist also among individual granite types within a single granite massif (Fig 9, 10a, b). This has been observed in the Fláje massif and the Telnice stock where some younger, more evolved granite types intrude the main biotite granites.

According to geological evidence, each of the granite bodies of the low-F biotite granites of the OIC (Fláje and Telnice) has a number of separate minor, silica-enriched, mostly distinctly younger phases of intrusions in addition to the prevailing more primitive granite types. Petrological characteristics of the Niederbobritzsch granite (Fritzsche 1928, Rösler and Budzinski 1994) and its wide range of SiO_2 contents (Förster et al. 1999) imply the idea that the situation may be similar in this OIC granite massif.

We emphasize the importance of these later, more evolved intrusive pulses as they enlarge considerably the compositional interval of granitoids in each of the minor OIC massifs and point out to a certain autonomy in their evolution. The P_2O_5 contents thus have a wide scatter but some average levels may be typical for separate intrusions.

The Ca contents of the OIC granites were apparently sufficient for the origin of accessory apatite (as at Fláje) in the earlier stages of crystallization as predicted by the model of Harrison and Watson (1984) and evidenced by the presence of apatite-rich cumulates reported in the literature. The more evolved intrusive members in the Fláje massif (Fig. 10a) are, however, not impoverished in P (with rare exceptions) as could be predicted by the model. They are at the same level or even higher in phosphorus than the main, earlier and more primitive granites. Thus the changes in P contents have possibly more complex causes, and detailed systematic studies would be needed to reveal the path of each of them. One plausible explanation is that the granitic types within individual granite massifs do not represent different stages of evolution of the same parent magma but rather individual magma batches (and their fractionation products) with various levels of phosphorus contents due to the significant heterogeneity of the source area in the lower crust.

We regard the variability of the source lithologies as the most important cause for the derivation of granite magmas with different levels of phosphorus contents. This holds possibly also for the difference between the YIC in the Western and Central plutonic regions of the KHEB and the EVPC.

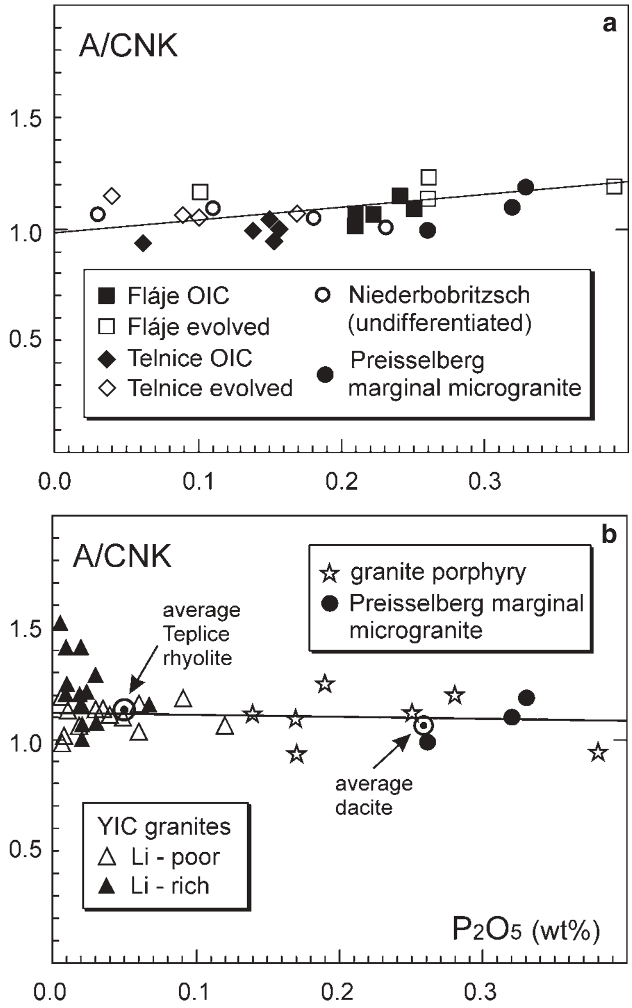

Fig. 7. Plots of the P_2O_5 contents against the alumina saturation index A/CNK, i.e., molar $Al_2O_3/(CaO+Na_2O+K_2O)$, in felsic igneous rocks from the Eastern Volcano-Plutonic Complex.

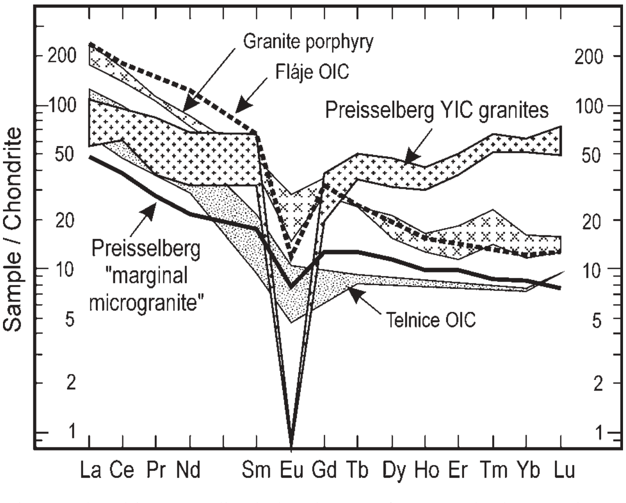

Fig. 8. Chondrite-normalized abundances of rare earth elements in selected rocks of the Eastern Volcano-Plutonic Complex. Data are from Table 8 and Just et al. (1987).

Origin of the "marginal microgranite"

Recognition of the marginal microgranite, differing significantly in the phosphorus content from the enclosing YIC granite of the Preisselberg stock (Tab. 6), brings up some new problems. Its major-element composition (including P_2O_5) and some petrographic features are comparable to some older (pre-YIC) intrusions, such as the relatively

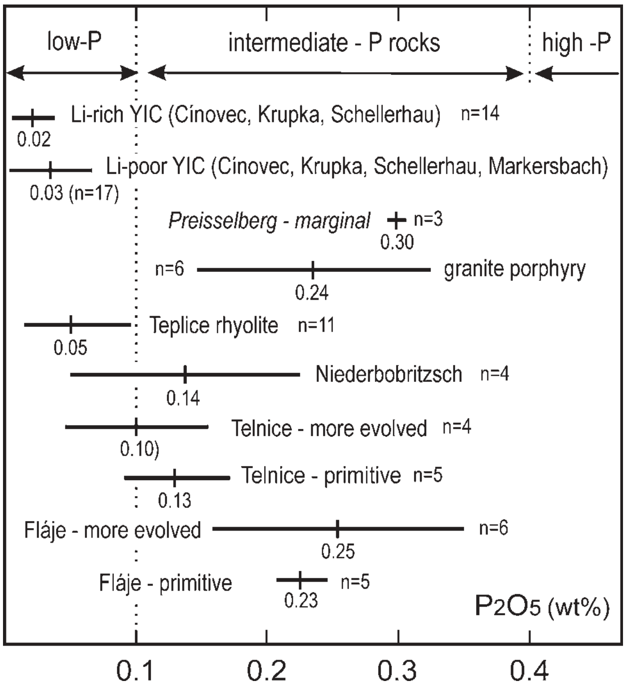

Fig. 9. Ranges (±1 sigma) and average contents of P_2O_5 in felsic igneous rocks from the Eastern Volcano-Plutonic Complex.

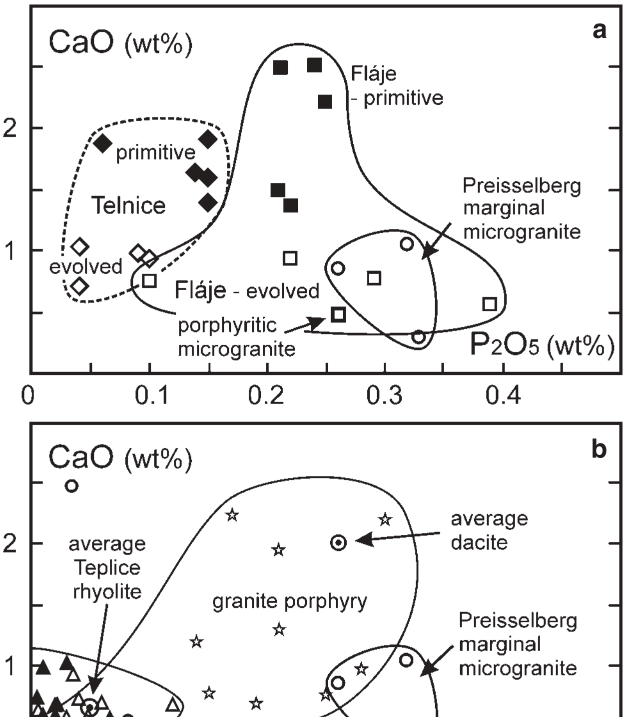

Fig. 10. Plot of CaO vs. P_2O_5 contents in various felsic igneous rocks from the area of the Eastern Volcano-Plutonic Complex.

evolved varieties from the Fláje massif. The granite occurs, however, in marginal parts of the Preisselberg stock emplaced into the Teplice rhyolite. Therefore, the marginal microgranite may represent a rather independent intrusion (pre-first sequence) within the YIC suite; this early magma portion was much more primitive in composition compared to the generally highly evolved, typical YIC granites. Such an explanation is in concert with the opinions proposed by Trumbull et al. (1994). However, solving of these problems requires additional data.

Low-P_2O_5 YIC granites of the EVPC

The low to very low phosphorus contents, characteristic for the YIC granites from the EVPC area and contrasting with those from the western part of the Krušné hory/Erzgebirge batholith, require more complex explanation.

The low Ca contents of the YIC granites were apparently not sufficient for apatite formation at these late stages of crystallization as shown by the lack of accessory apatite. In strongly peraluminous granite magmas this could lead to the accumulation of P_2O_5 in residual melts as is common in highly fractionated S-types (e.g., Chappell 1999) and, consequently, to the incorporation of phosphorus into feldspars (Breiter 1998a). However, the YIC granites of the EVPC are not S-types and, similarly to the acid rocks of the Teplice rhyolite, their magmas perhaps have never been strongly peraluminous. During the rock–fluid interactions, the alumina-saturation indices in various parts of the YIC granite bodies were changed due to the migrations of alkalis, Ca, etc. These phenomena are most pronounced in the YIC granites that were designed as "autometamorphic" by Zoubek (1978). Such processes operated at shallow crustal levels, often in rather subvolcanic conditions, and could have been linked to juvenile as well as meteoric waters (Dolejš and Štemprok 2001). The strongly albitized and/or greisenized rocks frequently display the highest variations in the A/CNK values that may be quite different from those in the original granite magma. On the other side, the whole-rock contents of phosphorus were nearly unaffected by post-solidus redistribution (Štemprok et al. 1998). This is in contrast to the distribution of lithium and fluorine, which are strongly affected by subsolidus alterations accompanying the participation of an aqueous fluid phase (mainly greisenization). In summary, classification based on the phosphorus contents and classification based on F and/or Li may reflect quite different processes and conditions.

The fact that the low amounts of P in the YIC granites are accommodated primarily in the Y and REE accessory minerals instead of apatite can be explained by the low solubilities of monazite and xenotime in granite melts as found experimentally by Wolf and London (1995). Thus these minerals crystallized before apatite at low P and CaO contents in the magma. During the earlier stages of fractionation, however, apatite crystallization was playing also a role. This fact is evidenced, e.g., by the typical presence of accessory apatite in ignimbrites of the Teplice rhyolite regardless of their variable and mostly high acidity (Holub 1980).

Magmatic evolution of the EVPC

The presence of huge amounts of acid volcanic rocks accompanied by subvolcanic intrusions in the EVPC requires operating of a large magma system with temperatures well above those typical for crustal granite magmatism induced by radioactive decay in thickened crust.

We emphasize the role of mantle-originated mafic magmas and their fractionation products as important sources of the extra heat necessary for extensive melting, fractionation and ascent of magmas to very shallow levels or to the surface. Large volumes of magmas are evident from the extent of denudation relics of the volcanic edifice and from areal extent of the Altenberg–Teplice Caldera.

Possible role of mafic magma has been proposed by Seltmann et al. (2001) and Müller and Seltmann (2002) for the origin of plagioclase-mantled K-feldspar phenocrysts in the Altenberg–Frauenstein granite porphyry (porphyritic microgranite according to the cited authors) and for the derivation of the hornblende-bearing, relatively low-silica variety (GPII) of the rock. We draw attention to the fact that compositionally similar varieties relatively low in silica exist also among the ignimbrites at the margin of the Teplice rhyolite body.

In the Western Pluton of the KHEB, the mafic magmas contemporaneous with acid ones are poorly evidenced. However, mafic precursors are described as redwitzites, gabbrodiorites and diorites in the vicinity of the OIC granites. These may suggest the possible role of mafic magmas also during the origin of the YIC granites.

Lamprophyres (Fig. 11), that are of primitive, MgO and CaO-rich compositions with high phosphorus contents, represent clearly multi-generation, low-volume intrusions scattered over the whole area of the Krušné hory/Erzgebirge batholith. Their genesis is apparently unrelated to the crustal sources of granitic melts as the nature of the magmas requires mantle sources. Possibility of some interactions of these mantle-derived magmas rich in phosphorus with some portions of granitic magmas cannot be excluded. However, temporal relations between the lamprophyres and different stages of felsic igneous activity in the area of the EVPC are poorly known.

Our hypothesis is summarized in Fig. 12 where all the rock types and groups of the EVPC are linked to various stages and processes operating at various depths of the large magma system. The YIC granites in this model represent late-stage, volatile-rich residual melts highly enriched in elements incompatible with respect to major minerals. These residual melts were derived from the same magma chamber that produced the large volumes of volcanic rocks. The OIC granites seem to have more independent origins, perhaps due to melting in separate domains of the heterogeneous continental crust. This was possible during the early stages of crustal melting when the individual magma batches were not homogenized by operation of a large magma system.

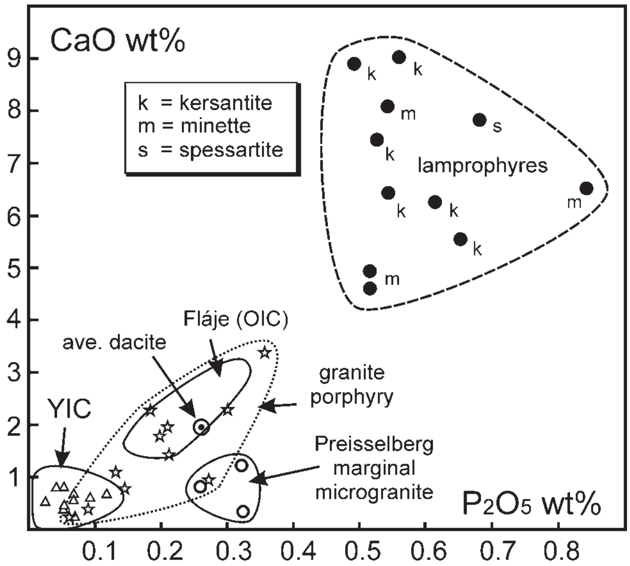

Fig. 11. Plot of CaO vs. P_2O_5 contents in lamprophyres and selected felsic igneous rocks from the area of the Eastern Volcano-Plutonic Complex.

Conclusions

Felsic igneous rocks of Late Variscan ages in the Eastern Volcano-Plutonic Complex of the Krušné hory/Erzgebirge batholith display a wide spectrum of phosphorus contents. Some granitic rocks, such as the Older Intrusive Complex and the granite porphyries, have intermediate P_2O_5 contents (0.1 to 0.4 wt% P_2O_5). Others, such as the granites of the Younger Intrusive Complex and also the prevailing part of the Teplice rhyolite, are low in P_2O_5 (commonly well below 0.1 wt%). The high-P_2O_5 fractionated granites ranging to about 1 % P_2O_5, known from the western parts of the Krušné hory batholith, are missing in the area of the EVPC.

We have demonstrated that the OIC granite bodies comprise a number of petrographic varieties and that at least some of them represent individual magma pulses. The lack of simple co-variation of phosphorus with the SiO_2 contents and other parameters reflecting the degree of magma evolution cast doubt on simple magma fractionation as the major process controlling the composition of rocks. We suggest that relatively high phosphorus contents even in the "evolved" members of the Fláje granite massif may reflect their origin as individual magma batches from heterogeneous crustal sources. The "marginal microgranite" (about 0.3 wt% P_2O_5) from the Preisselberg stock, dominated by the low-phosphorus YIC granites, could have formed in a similar way (i.e., as a separate magma batch).

A different story can be presumed for acid rocks derived from the younger, huge, long-lasting magma system to which the rhyolite ignimbrites, granite porphyries, and granites of the YIC are related. This predominantly acid magma system presumably originated and maintained as a consequence of significant thermal input from mantle-derived mafic magmas, was able to homogenize granitic partial melts from lower crustal sources, and produced large volumes of highly evolved melts via fractional crystallization.

Granite magmas of the I-type or transitional I/S-type characteristics (with relatively low A/CNK) and of highly potassic nature evolved towards the low-P_2O_5 compositions. This process was disturbed by episodic hybridization and mixing of the granite magma with mantle-derived melts or products of their fractionation at depth. As these more mafic magma portions were richer in phosphorus, the partial hybridization resulted in increased P contents in some granitic magma portions. The acid magma system served, however, as a huge trap for mafic magmas disabling them to pass through the continental crust upwards.

The YIC granites probably represent residual, late-stage melts rich in volatile components and with strongly increased incompatible element abundances due to prolonged crystal fractionation. Their composition was, however, strongly affected by the interaction with a fluid phase. Late magmatic and post-magmatic processes obscured some primary chemical characteristics, especially in the Li-rich albite granites. This fact could be the reason for the absence of any correlation between the generally low-P_2O_5 and highly variable alumina-saturation indices.

Thus, the phosphorus contents reflect various aspects of rather complex genetic histories of igneous rocks in the lower and middle crust. In contrast with the role of phosphorus, lithium and fluorine contents are more dependent on post-solidus alterations of granites induced by hydrothermal fluids in late magmatic and post-magmatic stages within the upper crust.

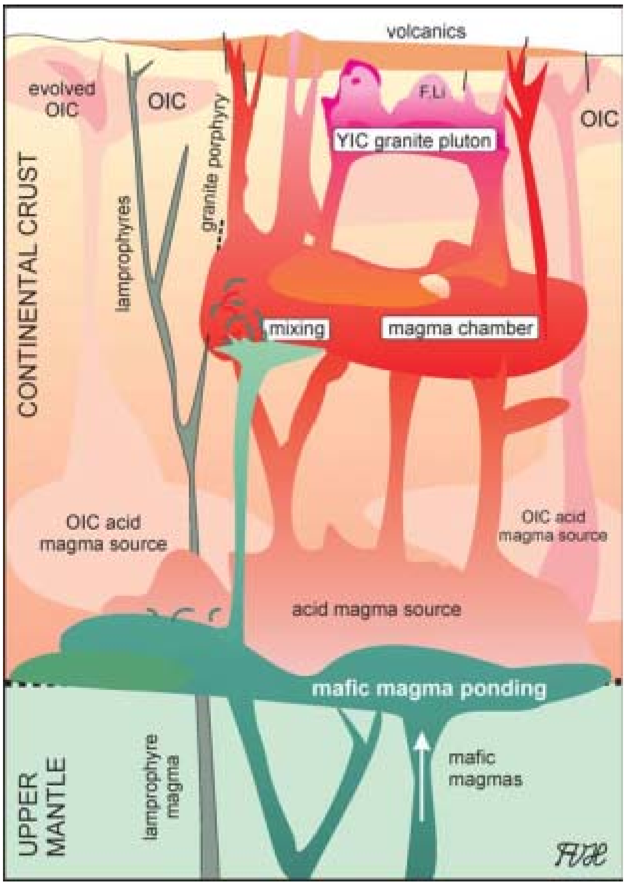

Fig. 12. Schematic model for the origin of the Eastern Volcano-Plutonic complex. The OIC granites originated from a different crustal source than YIC granites. The latter source is parental also for the associated felsic extrusives and granite porphyry dykes. Evolution of the magma chamber of the YIC granites was affected by mantle-derived mafic magmas.

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