Petrology, geochemistry and zircon age for redwitzite at Abertamy, NW Bohemian Massif (Czech Republic): tracing the mantle component in Late Variscan intrusions

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Abstract

A small body of mafic texturally and compositionally varied igneous intrusive rocks corresponding to redwitzites occurs at Abertamy in the Western pluton of the Krušné hory/Erzgebirge granite batholith (Czech Republic). It is enclosed by porphyritic biotite granite of the older intrusive suite in the southern contact zone of the Nejdek-Eibenstock granite massif. We examined the petrology and geochemistry of the rocks and compared the data with those on redwitzites described from NE Bavaria and Western Bohemia.

The redwitzites from Abertamy are coarse- to medium-grained rocks with massive textures and abundant up to 2 cm large randomly oriented biotite phenocrysts overgrowing the groundmass. They are high in MgO, Cr and Ni but have lower Rb and Li contents than the redwitzites in NE Bavaria. Compositional linear trends from redwitzites to granites at Abertamy indicate crystal fractionation and magma mixing in a magma chamber as possible mechanisms of magma differentiation. Plots of MgO versus SiO_2, TiO_2, Al_2O_3, FeO, CaO, Na_2O, and K_2O indicate mainly plagioclase and orthopyroxene fractionation as viable mechanisms for *in situ* differentiation of the redwitzites.

The porphyritic biotite monzogranite enclosing the redwitzite is the typical member of the early granitic suite (Older Intrusive Complex, OIC) with strongly developed transitional I/S-type features. The ages of zircons obtained by the single zircon Pb-evaporation method suggest that the redwitzites and granites at Abertamy originated during the same magmatic period of the Variscan plutonism at about 322 Ma.

The granitic melts have been so far mainly interpreted to be formed by heat supply from a thickened crust or decompression melting accompanying exhumation and uplift of overthickened crust in the Krušné hory/Erzgebirge due to a previous collisional event at ca. 340 Ma. The presence of mafic bodies in the Western pluton of the Krušné hory/Erzgebirge batholith confirms a more significant role of mantle-derived mafic magmas in heating of the sources of granitic melts than previously considered.

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1. Introduction

The goal of the present study is to elucidate the role of mafic magmas in the origin of the Variscan Krušné hory/Erzgebirge granite batholith in the Bohemian massif. The presence of mafic magmas during the formation of the batholith is indicated by the rare occurrences of redwitzites associated with the granites of the earlier suite in the Western pluton. The present paper contributes to the petrology and geochemistry of these rocks using modern laboratory methods and new genetical interpretations.

Redwitzites were originally defined in NE Bavaria at the NW margin of the Bohemian massif by Willmann (1920). They comprise coarse- to fine-grained, porphyritic to equigranular igneous rocks of mafic to intermediate chemical compositions ranging from quartz gabbro to quartz monzonites. Their structures are highly variable, ranging from massive undeformed randomly oriented structures up to varieties with well developed planar structures marked by preferred orientation of biotite flakes.

Their geochemistry and isotopic composition has been studied by Troll (1968), Miessler and Propach (1987), Spiegel and Propach (1991), Holl et al. (1989), Siebel (1994), Siebel et al. (1995, 2003) and René (2000).

Typical dark minerals are amphibole (mostly secondary uralite replacing pyroxene) and biotite (both rich in Mg but markedly poor in Al). Plagioclase (An_{70}–An_{30}) is the predominant feldspar. Less common are quartz, K-feldspar, pyroxene, titanite and apatite as well as postmagmatic Ca–Al minerals like uralite and chlorite (Freiberger et al., 2001). In comparison with the associated granites they have lower SiO_2 (53–63 wt%), lower A/CNK (<1.05), high TiO_2 (0.8–1.7 wt%) and low Rb/Ba (<0.18; Siebel et al., 2003). Their isotopic ratios indicate heterogenous enriched mantle as possible source material ($\varepsilon Nd_{325\ Ma}$ = +1 to −4 and $^{87}Sr/^{86}Sr_{325\ Ma}$ = 0.706–0.780; Siebel et al., 2003) modified by a various degree of AFC processes and mixing with crustal derived magmas.

Redwidzites occur as small, sometimes zonal intrusions, hundreds of square meters to several square kilometers of outcrop size, several square meters up to several tens of meter thick dikes and tabular bodies intruding into Moldanubian gneisses, Saxothuringian metasediments, metabasites of the Mariánské Lázně Complex and Kladská unit or larger irregular bodies enclosed in host biotite porphyritic granites (Leuchtenberg, Western Krušné hory/Erzgebirge and Bor plutons).

The formation of redwidzites of NW Bohemia, Oberphalz and Fichtelgebirte represents specific pulse (340–320 Ma, Dörr et al., 1998; Siebel et al., 2003; Kováříková et al., 2005) of mantle derived magmas in the Variscan Bohemian massif, after the intrusion of early syntectonic Variscan gabbros and associated quartz diorites of the Central Bohemian Plutonic complex (370–350 Ma, Košler et al., 1993; Janoušek et al., 2000) and with exhumation related ultra-potassic and high K-rocks of durbachitic series of the Moldanubicum (340–330 Ma, Holub, 1997; Gerdes et al., 2000).

Various geochronological methods have been used to determine their age. Troll (1968) interpreted them as basic precursors of the Fichtelgebirge granites G1–G4 on the basis of geological criteria. Taubald (2000) considered redwitzites as Upper Carboniferous in age and regarded them to be younger than the early Variscan subduction-related processes at 380 Ma. The Pb single grain evaporation method on zircons brought new data (Siebel et al., 2003) which showed an age interval between 324 and 322 Ma for the redwitzite formation. This interval is comparable with the ages derived by U–Pb titanite geochronology (325–322 Ma; Siebel et al., 2003). The zircons proved to be primary minerals crystallizing from the magma not containing lead from older cores as was also shown by cathodo-luminescence investigation (Siebel et al., 2003).

The granitoids of the so-called "basic zone" of the Bor massif between Tachov and Planá by Mar. Lázně (Vejnar et al., 1969) in the Western Bohemia were studied by Siebel et al. (1997) and René (2000). These rocks bear typical features identical with the redwitzites from NE Bavaria in terms of composition and textures (Siebel et al., 1997).

Mafic igneous rocks in the Late Variscan Krušné hory/Erzgebirge granite batholith are rare. Their occurrences have been reported from the southern part (Fig. 1) on the eroded slope of the Krušné hory/Erzgebirge mountain range (Zoubek, 1948, 1951), and namely in the Czech part of the Nejdek-Eibenstock massif at Abertamy (Sattran, 1961; Štemprok, 1986). They also occur in the Slavkovský les area near Lobzy (Fiala, 1961, 1968) south of the Krušné hory/Erzgebirge fault zone. The mafic rocks were grouped together with the earlier group of granitoids (OIC group) as Late Variscan granitoids. Fiala (1968) used the name redwitzite only for a group of plutonic rocks with planar texture and identified other mafic rocks as biotite-amphibole pyroxene gabbrodiorite, biotite-amphibole diorite and quartz diorite to granodiorite and proposed three possible explanations of their genesis: (a) hybrid, strongly metasomatic altered rocks of the Precambrian spilitic magmatism, (b) earlier mafic intrusions of the Assynthian cycle reworked by later granites, (c) earlier magmatic intrusions of the Variscan orogenic cycle. At the present time the third explanation is accepted (Jelínek et al., 2003, 2004) also for the Slavkovský les redwitzite rock group on the basis of detailed geochemical work.
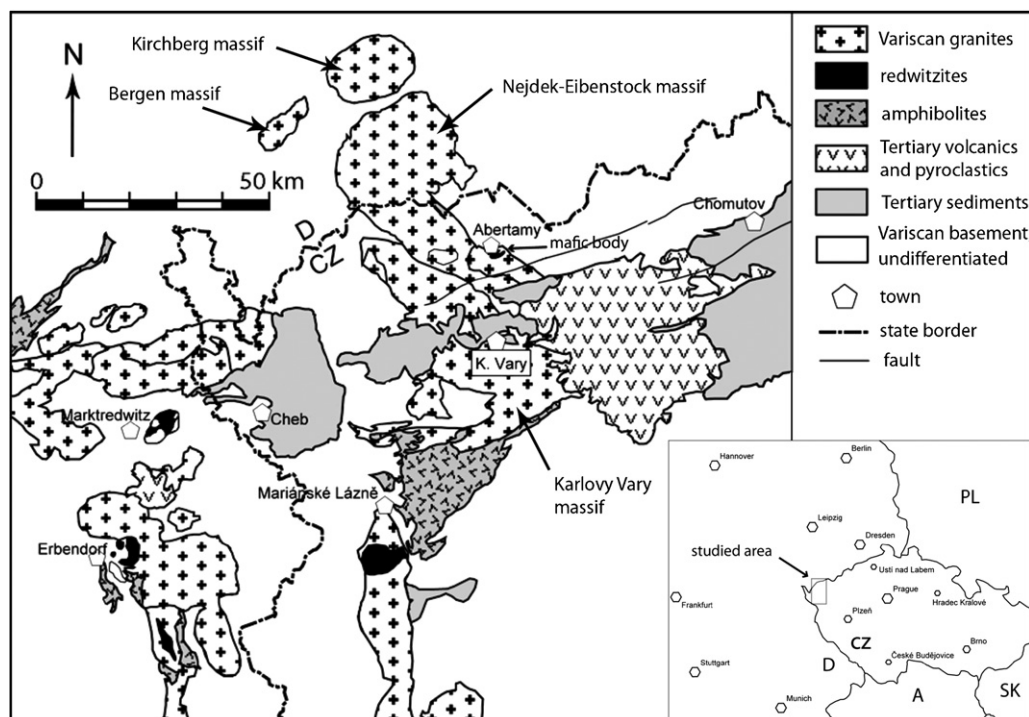
Fig. 1. Simplified geological map of NE Bavaria, southern Saxonia and NW Bohemia showing Variscan granitoid distribution. Redrawn using the geological map 1:500,000 (Czech Geol. Survey) and the data from Siebel (1993) and René (2000).

2. Geological setting

The studied redwitzites occur in the Krušné hory/ Erzgebirge granite batholith area located in the Saxothuringian zone of the Bohemian massif (O'Brien and Carswell, 1993). It is considered as one of the peri-Gondwana derived terranes, which formed the Armorican Terrane Assemblage (ATA; Matte, 2001; Linnemann et al., 2004). The Saxothuringian zone is interpreted as a Cadomian crustal fragment which underwent Cambro-Ordovician rifting and was affected by essentially south-eastward subduction and dextral transpression (Franke, 1989, 1993) during the (?) Silurian, Devonian and Early Carboniferous time. The south-eastern part of the Saxothuringian belt forms an antiform which exposes in its core (?) Proterozoic and Cambro-Ordovician rocks of higher metamorphic grades and in the flanks in the Northern and Western Erzgebirge/Krušné hory Lower Palaezoic sedimentary and magmatic rocks.

The geographic location of the batholith coincides with parts of the Krušné hory/Erzgebirge, Vogtland and Slavkovský les. The batholith intruded as a late- to post-tectonic body into various units differing in protolith ages and metamorphic evolution which were stacked together during the Variscan collision of the Teplá-Barrandian and Saxothurigian microplates (Franke, 1989; Franke et al., 2001; Kachlík, 1993, 1997; Rötzler et al., 1998; Mingram et al., 2004) and modified during

the following processes of crustal relaxations. This is why the host rocks include a large variety of lithologies. The batholith emplacement is associated with the late Variscan collisional magmatism (330–280 Ma, Förster et al., 1999; Schust and Wasternack, 2002). The granites are calc-alkaline and peraluminous, evolving from early I/S- to late S-types (Štemprok, 1986; Förster et al., 1999; Breiter et al., 1999) and form two subsequent intrusive complexes (older – OIC and younger – YIC, respectively, Štemprok, 1986; Tischendorf et al., 1987; Tischendorf and Förster, 1990).

The batholith is spatially divided into three plutons (Western, Central and Eastern) of which the Western pluton forms the largest outcropping body. Within this pluton the biggest intrusion is the Nejdek-Eibenstock massif (Dalmer, 1900) which is divided into Eibenstock, NW of the state boundary between Czech Republic and Germany, and Nejdek which extends south from the state boundary to the Sokolov basin. The granite bodies in the Slavkovský les are located southeast of the Sokolov basin (Hejtman, 1984). The Czech authors so far have preferred to use the name Karlovy Vary pluton for all parts of this body (Zoubek, 1951; Sattran, 1961; Absolonová and Matoulek, 1972, 1975; Jiránek, 1982). In this paper we term the northern part of the pluton as the Nejdek-Eibenstock massif and the southern part as the Karlovy Vary massif (pluton, Fig. 1).

Geological and geophysical evidence suggests that shallowly emplaced granites can be traced from the

eastern contact to a distance of approximately 15 km eastwards from the surface exposures (Tischendorf et al., 1965). Intrusions of mafic rocks are known only from the southern part of the batholith in the area NW of Karlovy Vary and in the Slavkovský les (Karlovy Vary massif). However, numerous mafic rocks are a component of the bimodal dyke assemblage (Škvor, 1975) that includes gabbros, diorites, granodiorites and lamprophyres.

Recent dating of the Eibenstock part of the Nejdek-Eibenstock massif gave a $^{207}Pb/^{206}Pb$ age of 320 ± 8 Ma for the megacrystic Eibenstock granite and of 290 ± 5 Ma for a rhyolitic dyke suggesting a significant time gap between the main granite intrusion and anorogenic rhyolite dykes, which intruded breccia bodies of tin-hosting greisens (Kempe et al., 2004). For the Kirchberg granite an age of 290 ± 5 Ma was defined by U–Pb uraninite geochronology (Kempe, 2003).

3. Redwitzite body at Abertamy

The redwitzite body at Abertamy is located in the Western Krušné hory/Erzgebirge about 7 km NW of Jáchymov. The northern contact zone of the granitoid massif is bordered by mica schists (Fig. 2) and two-mica gneisses and intersected by abundant dykes of granite porphyries. The south-eastern part of the area is occupied by a Tertiary nephelinite which intersects the granite.

Mafic intrusions are confined to the endocontact of the massif which is formed by coarse-grained and medium-grained OIC granite. The earlier geological map distinguished between these two granite varieties. However, owing to the lack of outcrops, their cartographic representation is difficult and not possible to identify reliably as separate bodies without a new trenching.

The earlier mapping (Zoubek, 1947; Škvor and Sattran, 1974) revealed a very irregular shape of this particular outcrop. The new mapping in scale 1:10,000 of the first author (using shallow cartographic drilling) showed that the two redwitzite outcrops can be mutually interconnected below the Quaternary cover sediments and interpreted as a single outcropping lensoid body of about 0.6–1.4 km size of NE–SW strike (Fig. 2). The geophysical data (see below) point to a shallow extension of the redwitzite body.

The redwitzite body at Abertamy was studied by Zoubek (1948) who interpreted the rock, which he referred to as gabbrodiorite, to be younger than the OIC granites based on the surface shape resembling a lobate dyke. In general schemes, Zoubek (1951) and Štemprok (1986, 1992) considered, however, the redwitzites as the earliest members of Variscan granitoid magmatism.

In the south-western part of the redwitzite body we identified a thin dyke of biotite granite with a sharp contact against the redwitzite. This suggests that at least some contacts between the redwitzite and the granite are intrusive and the OIC granite intruded later than the redwitzite.

A complete silicate analysis for the Abertamy gabbrodiorite is given by Sattran (1963) compared with some other igneous and metamorphic rocks of the Krušné hory/Erzgebirge. A more detailed petrological and petrochemical description of gabbrodiorites from the western part of the Krušné hory/Erzgebirge pluton is published in Štemprok (1986) and of the Abertamy gabbrodiorite in Štemprok (1992). The results of a new study of redwitzites are reported in Jelínek et al. (2003, 2004).

4. Sampling

Samples (5–15 kg) for petrological and geochemical studies were taken from large boulders, from a section in the valley of Brook Bystřice and from boulders in the
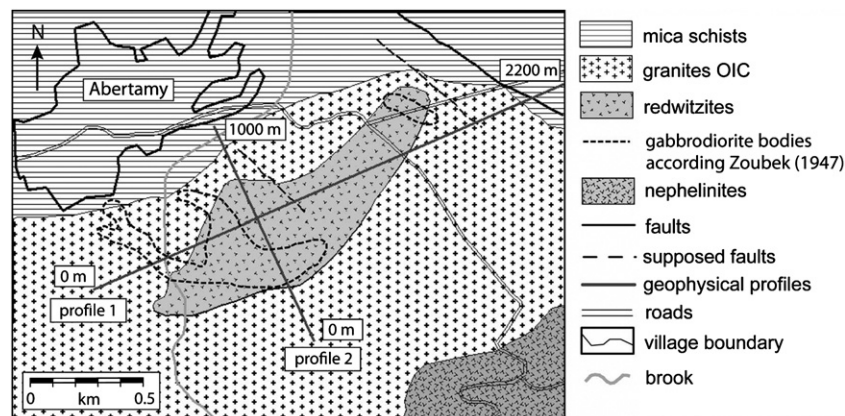

Fig. 2. Geological map of the Abertamy mafic intrusion with the profiles of geophysical measurements.

river base. The samples were collected in two campaigns: one in 1991–1992 (Štemprok, 1992, samples labelled as PLE) and the second in 2002 (Kovaříková, 2004, samples labelled as AB). The list of samples is given in Jelínek et al. (2003).

5. Analytical techniques

A Scintrex CG-3M gravimeter was used for gravity survey and a proton magnetometer PM-2 was used for measurement of total component of magnetic field. The mean square error calculated from repeated measurements is ± 0.004 mGal for gravity and ± 2 nT for magnetic values. Gravity measurements were processed to the form of relative Bouguer anomalies Δg with complete topographical corrections (radius 166.735 km from measured stations). ΔT values were calculated from total field magnetic measurements. The normal magnetic field was set as a median of the measured values at each locality.

Major and trace element analyses on selected whole-rock samples have been conducted in the Chemical laboratory of the Czech Geological Survey in Prague by conventional wet methods (silicate analyses, major elements), by optical emission spectrometry (OES) (B, Be, Bi, Co, Cr, Cu, Ga, Mo, Pb, Zn), by X-ray fluorescence analyses (XRF) (Nb, Y, Zr, U), inductively coupled plasma mass spectrometry (ICP-MS) (REE and Y, Sc, Th, Ta, W) and atomic absorbtion spectrometry (AAS) (Sr, Ba, Cs, Rb, Zn, V and Ni) methods. Additional analyses have been performed in the chemical laboratory of the Faculty of Science, Charles University, Prague (wet silicate analyses and AAS for Li, Rb, Cu, Co, Cr, Ni, Zn, Sr, Pb and ICP-MS for REE and Ba, Hf, Sc, Nb, Ta, Th, U).

The minerals were analyzed by electron microprobe in the Chemical laboratory of the Czech Geological Survey in Prague (CamScan S-4 Link ISIS 300), at the Faculty of Science, Charles University, Prague (CamScan S-4 Link ISIS EDX) and at the Laboratory of the Institute of Geology of the Academy of Science (CAMECA SX-100 electron microprobe in the wavelength dispersive mode). The CamScan microprobe was used for the backscattered electron images of zircons.

Heavy mineral fractions were prepared in the Laboratories of the Czech Geological Survey in Barrandov, Prague. The crushed samples were separated in heavy liquids and zircons were handpicked from the heavy mineral assemblage after magnetic separation.

For single-zircon Pb-evaporation (Kober, 1986, 1987) chemically untreated zircon grains were analyzed with a Finnigan MAT 262 mass spectrometer equipped with a secondary electron multiplier (SEV) at the University of Tübingen. Principles of the evaporation method used in

this study are described in Siebel et al. (2003). With the exception of four grains from sample AB4, only data with high radiogenic Pb component ($^{204}Pb/^{206}Pb < 1 \times 10^{-4}$) were used for evaluation. One grain from sample AB7 yielded very high Pb intensities and masses 206, 207 and 208 were also detected simultaneously in Faraday cups. All $^{207}Pb/^{206}Pb$ ratios were corrected for common Pb according to the formula given in Cocherie et al. (1992) following the two stage growth model for the evolution of Pb isotopic ratios of Stacey and Kramers (1975). No correction was made for mass fractionation.

The common Pb corrected $^{207}Pb/^{206}Pb$ ratios normally define a Gaussian distribution and the mean of the $^{207}Pb/^{206}Pb$ ratios was derived from this distribution. The error for a single zircon age was calculated according to the formula

$$\Delta_{age} = \sqrt{\left(\frac{2\sigma}{\sqrt{n}}\right)^2 + \Delta f^2},$$

where n is the number of $^{207}Pb/^{206}Pb$ isotope ratio scans, 2σ is the 2sigma standard error of the Gaussian distribution function and Δf an assumed error for the measured $^{207}Pb/^{206}Pb$ ratios of 0.1% which includes potential bias caused by mass fractionation of Pb isotopes and uncertainty in linearity of the multiplier signal. The mean age for one zircon from sample AB7 is given as weighted average and the error refers to the 95% confidence level (ISOPLOT, Ludwig, 1999). Repeated measurements on two internal standard zircons of similar age show that most of the investigated samples were performed for geologically realistic age and error treatment.

6. Petrography

6.1. Granites

The biotite granite in the surrounding of Abertamy is medium- to coarse-grained, and has a porphyritic to hypidiomorphic texture and is mostly classified with monzogranite. Near the contact to the redwitzites the amount of biotite increases and forms conspicious accumulations with rare muscovite flakes. Phenocrysts of K-feldspar show no apparent preferred orientation. The matrix is composed of quartz, K-feldspar and biotite, less abundant are plagioclase and muscovite. The main accessories are zircon, apatite, monazite and xenotime. K-feldspar is often perthitic. Myrmekite occurs near some margins of K-feldspars. Quartz forms isometric grains, usually with undulatory extinction. Biotite composes dark brown flakes with light brown to dark brown pleochroism. Most biotites are altered by chloritization. Minute grains of radioactive accessory minerals occur within the biotite flakes surrounded by

pleochroic haloes. They often intergrow with feldspars. Plagioclase (An_{26} to An_{11}; Table 1) constitutes small, hypidiomorphic tabular crystals, which are markedly zoned (Fig. 3a). Zircons show relicts of inherited cores (Fig. 3e) preserved from other cycles of zircon crystallization and this early component affected the age dating (Jelínek et al., 2004). Petrographically the granite is comparable with the most primitive members of the OIC group of granites (Štemprok, 1986; Hejtman, 1984).

Sporadically enclaves of fine-grained mafic rocks of up to 5 cm in size occur in the OIC granites. The boundary between granite and these mafic enclaves is commonly sharp. Around such enclaves a 0.5–1 cm thick zone consists predominantly of plagioclase and quartz. The mineral assemblage of the mafic enclaves is identical to that of the gabbrodiorite.

6.2. Granite porphyry

In the OIC granite near the outcrop of the redwitzite body, a steep granite porphyry dyke, about 0.5 m thick, occurs with a sharp contact to the enclosing granite. It is a fine-grained rock with quartz and feldspar phenocrysts of up to 2 cm in size and with biotite flakes. The matrix consists of quartz, plagioclase, K-feldspar and biotite. Phenocrysts of quartz also form clusters of several quartz grains which show non-uniform undulous extinction. K-feldspar forms hypidiomorphic phenocrysts. Biotite is strongly chloritised. In places small enclaves (up to 15 mm size) of the biotite granite or mafic rocks occur in the dyke. The rock shows a remarkable flow texture and texturally resembles the rhyolites dated recently by the U–Pb method in the northern part of the Nejdek-Eibenstock massif at 290 ± 5 Ma (Kempe et al., 2004).

6.3. Redwitzites

The mafic body near Abertamy is petrographically inhomogeneous and consists of coarse- to medium-grained textural types. These differ also in mineralogy and geochemistry. However, both types have similar textural features, such as randomly-oriented idiomorphic to hypidiomorphic crystals of plagioclase and conspicuous large (from few mm to 2 cm) sheets of biotite, that enclose plagioclase crystals in poikilitic texture (Fig. 3b). The presence of large biotite flakes gives these rocks a very characteristic appearance corresponding to redwitzites described from the classical locality near Marktredwitz. Both rock-types display hypidiomorphic-grained textures.

6.3.1. Quartz gabbrodiorite

The NE part of th mafic body is made up of biotite-amphibole quartz gabbrodiorite. It is a medium-grained

Table 1. Representative analyses of plagioclases (explanation of samples see Table 4)

Sample (wt%)	AB 1 C	AB 1 OC	AB 1 BR	AB 1 R	AB 5 C	AB 5 R	AB 5 H	AB 7 C	AB 7 R	PLE 1 H	PLE 1 H	PLE 3 IH	PLE 3 IH	PLE 3 IH	PLE 3 C	PLE 5 OC	PLE 5 R	PLE 5 R
SiO_2	48.63	51.31	57.38	60.99	49.67	53.80	53.92	55.99	59.06	48.97	59.26	59.43	58.35	49.07	59.99	55.28	61.57	48.91	52.69	55.82	54.86
Al_2O_3	32.04	32.41	25.90	25.86	33.39	30.62	30.08	28.60	26.27	33.19	26.51	25.58	26.56	32.57	25.33	27.87	24.54	33.36	30.20	28.42	28.92
FeO	–	–	–	–	–	–	–	–	–	–	–	0.14	0.13	0.10	–	0.39	0.13	0.09	0.24	0.08	0.22
CaO	14.68	13.93	8.20	6.84	13.93	10.93	10.36	9.95	7.07	15.33	8.01	7.12	8.16	15.31	6.31	9.95	5.41	15.41	11.54	9.99	10.51
Na_2O	3.04	3.02	6.03	7.06	3.05	5.03	5.25	5.88	7.35	2.71	6.91	7.80	6.80	3.16	7.87	6.06	8.13	2.77	5.01	5.71	5.94
K_2O	0.04	–	0.34	0.20	–	–	–	0.09	0.14	–	0.24	0.05	–	0.24	0.23	0.23	0.21	0.15	0.08	0.04	0.11
Total	98.43	100.67	97.85	100.95	100.04	100.38	99.61	100.51	99.89	100.01	100.93	100.12	100.00	100.45	99.73	99.78	99.99	100.69	99.76	100.06	100.56
Ab	27.20	28.20	55.90	64.40	28.40	45.40	47.80	51.40	64.80	24.20	60.10	66.30	60.10	26.80	68.40	51.80	72.20	24.30	43.80	50.70	50.30
An	72.60	71.80	42.00	34.40	71.60	54.60	52.20	48.10	34.40	75.80	38.50	33.40	39.90	71.80	30.30	47.00	26.60	74.80	55.70	49.00	49.10
Or	0.20	0.00	2.10	1.20	0.00	0.00	0.00	0.50	0.80	0.00	1.40	0.30	0.00	1.30	1.30	1.20	1.20	0.90	0.50	0.20	0.60

C = core, OC = outer core, BR = zone between outer core and rim, R = rim, H = homogenous plagioclase, IH = inhomogenous plagioclase, IH = inhomogenous plagioclase with basic and acid portions.
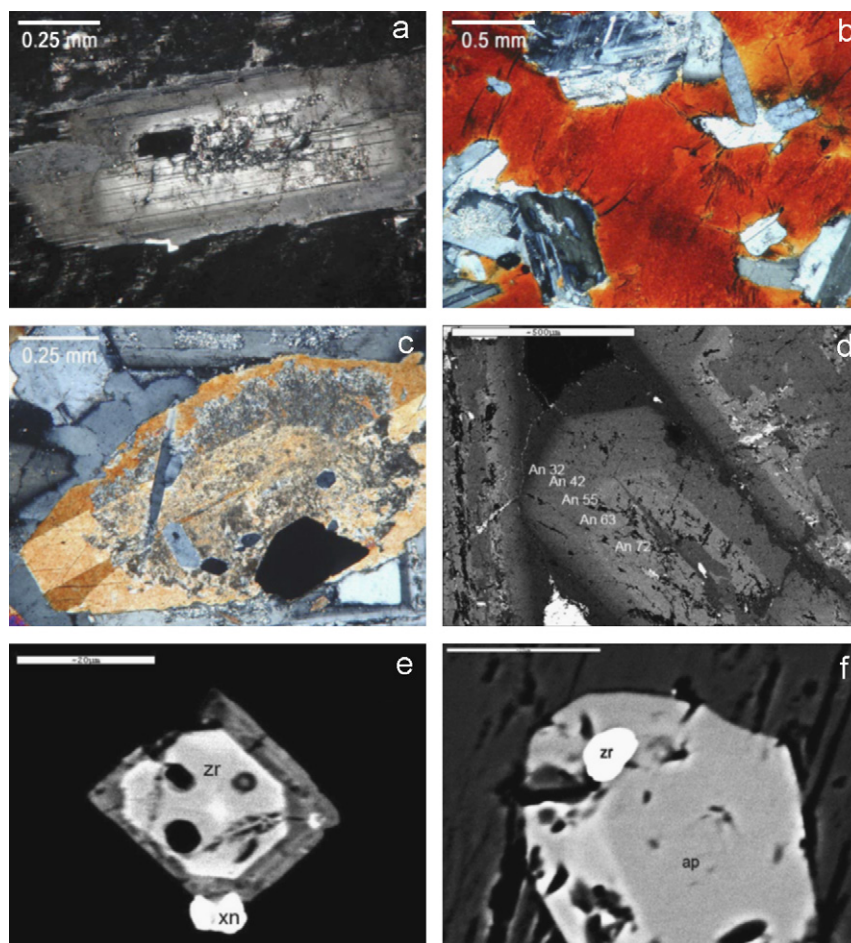
Fig. 3. (a) Zoned plagioclase; OIC granite; (b) Poikilitic overgrowth of biotite with plagioclase; gabbrodiorite; (c) Hornblende in gabbrodiorite; (d) Zoned plagioclase, gabbrodiorite (backscattered electron image, bar 500 μm); (e) Zircon with xenotime, OIC granite (backscattered electron image, bar 20 μm); zr – zircon, xn – xenotime; (f) Apatite with zircon, OIC granite (backscattered electron image, bar 10 μm); ap – apatite.

rock composed of biotite, hornblende (Fig. 3c), and plagioclase, accompanied by smaller amounts of pyroxene, quartz and K-feldspar. Plagioclase crystals (An_{72} to An_{26}; Table 1) are hypidiomorphic to idiomorphic in shape and are markedly zoned (Fig. 3d, sample AB 1 in Table 1). They have noticeable core which is predominantly of labradorite to bytownite in composition. Then two or three broad zones follow, that are often separated by a narrow more acid zone. Marginal parts of plagioclase crystals range from calcic oligoclase to medium andesine. Pyroxenes occur as turbid relicts of diopsidic composition (Table 2). Idiomorphic grains of usually perthitic K-feldspar are present less commonly. Quartz composes oval xenomorphic grains which often show undulatory extinction.

Amphiboles are light green with very weak pleochroism in idiomorphic crystals. They range in composition from actinolite to magnesiohornblende with a low amount of Al (Table 3). The abundant secondary actinolitic amphibole probably originated from an earlier pyroxene generation.

Biotite (annite to phlogopite; Fig. 4) forms hypidiomorphic to xenomorphic, dark brown sheets often poikilitically enclosing plagioclase crystals. Most biotites are altered to chlorite along the margins or cleavage planes whose composition ranges from diabanite to pyknochlorite.

The quartz gabbrodiorites have remarkable high contents of accessories, especially of ilmenite and apatite. Titanite and zircon are common accessories whereas orthite is rare. Opaque minerals are represented mainly by pyrrhotine and pyrite. Idiomorphic grains of apatite, zircon or other accessories are often confined to biotites; around them are noticeable dark pleochroic halos. Zircons studied in backscattered electron images do not show any cores and are weakly zoned suggesting that they crystallized directly from the melt.

Table 2.   Representative analyses of pyroxenes (explanation of samples see Table 4)

Sample (wt%)	AB 5 opx	AB 5 opx	AB 5 opx core	AB 5 opx rim	PLE 3 cpx	PLE 3 cpx
SiO_2	55.33	53.41	54.51	54.02	53.90	53.56
TiO_2	0.09	1.56	0.34	0.45	0.18	0.25
Al_2O_3	0.70	1.65	1.24	1.15	0.32	0.54
Cr_2O_3	0.03	0.24	0.11	0.10	–	–
FeO	16.45	17.09	16.36	17.00	6.29	5.03
MnO	0.33	0.20	0.36	0.30	0.29	0.32
MgO	27.62	25.87	26.57	25.49	14.76	15.77
BaO	0.00	0.01	0.00	0.00	–	–
CaO	0.60	1.51	1.29	1.23	24.64	24.50
Na_2O	0.00	0.03	0.02	0.01	0.45	0.10
K_2O	0.00	0.01	0.00	0.00	–	–
Total	101.15	101.58	100.80	99.75	100.83	100.07

opx = orthopyroxene, cpx = clinopyroxene.

Table 3.   Representative analyses of amphiboles (explanation of samples see Table 4)

Sample (wt%)	AB 5 act	AB 5 act	AB 5 act	AB 7 act	AB 7 act	AB 7 act	PLE 1 acth	PLE 1 acth	PLE 1 acth	PLE 3 acth
SiO_2	55.81	55.01	55.29	52.98	54.52	54.94	52.23	51.63	52.08	51.34
TiO_2	0.27	0.39	0.31	0.58	0.32	0.35	0.61	0.73	0.51	0.77
Al_2O_3	3.54	4.14	4.19	4.41	3.14	2.51	3.52	4.05	4.64	4.00
Cr_2O_3	–	–	–	–	0.18	0.31	–	–	0.33	–
FeO	5.79	6.61	6.08	8.49	8.04	7.87	12.44	12.88	11.18	13.12
MnO	–	–	–	–	–	–	0.39	0.41	0.23	0.22
MgO	20.79	20.63	20.48	18.07	18.76	18.91	15.90	15.56	16.74	14.84
CaO	10.78	10.38	10.33	11.49	11.79	11.95	11.57	11.38	10.34	11.83
Na_2O	0.75	0.97	0.84	1.00	0.81	0.57	1.04	1.04	0.46	1.06
K_2O	0.26	0.29	0.25	0.36	0.27	0.12	0.19	0.45	1.37	0.41
Total	97.99	98.42	97.77	97.38	97.83	97.53	97.89	98.13	97.88	97.59

act – actinolite, acth — actinolitic hornblende.
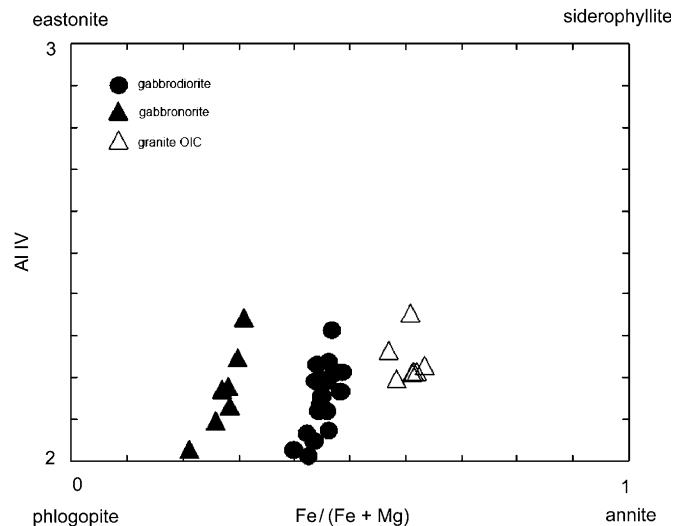
Fig. 4. Biotite composition of redwitzites and granites as based on microprobe data.

6.3.2. Biotite-amphibole gabbronorite

Gabbronorite occurs in the western part of the mafic body. The plagioclase crystals of this rock type (An_{79} to An_{33}) are strongly zoned, in their inner parts the compositions range from bytownite to anorthite (Table 1), the margins correspond to acid labradorite and, very rarely, to andesine (near the contact with quartz). Plagioclase from sample AB7 (Table 1) has the rim more basic than the core because of the strong albitisation of the plagioclase's core. The composition of amphibole (Table 3) ranges from hornblende to actinolite. Quartz and K-feldspar are rare, similarly as in gabbrodiorite. The accessories are identical to those in the gabbrodiorite. In one sample an apatite crystal of black color was observed in mineral separates increased uranium content.

Some portions of the rock show a total uralitisation of primary mafic minerals, but in some samples preserved relicts of pyroxene were observed. In a single sample relicts of orthopyroxene (enstatite; Table 2) were identified. Clinopyroxene crystals form xenomorphic grains which enclose small crystals of plagioclases along their margins. Secondary amphibole (fibrous actinolite) after pyroxene and possibly also after primary hornblende occurs in the samples which shows an advanced stage of uralitisation. However, from the bulk chemical composition it can be deduced that in the primary magmatic mineral association orthopyroxene was abundant among the rock-forming minerals. The presence of orthopyroxene in the primary mineral assemblage of the gabbronorites is the main difference from the quartz gabbrodiorite, where this mineral is absent.

7. Geophysical measurements

Gravity and magnetic methods were used to determine the size and extent of the Abertamy redwitzite body. It was expected that magnetic methods would indicate a near-surface situation of mafic rocks while gravity would show the extent of the intrusion at depth. According to *in situ* kappametry, redwitzites have relative magnetic susceptibilities two orders of magnitude higher than densities of the surrounding granites. Densities of redwitzites are approximately $2850\,kg/m^3$, markedly higher than densities of granites ($2620\,kg/m^3$).

Two perpendicular geophysical profiles were staked out across the outcrops of the mafic rocks (Fig. 2). The distance between the gravity stations was 50 m, the distance between magnetic stations was 10 m. Results of the geophysical measurements are shown in Fig. 5. Steep gradients of gravity values Δg on the SW side of profile 1 and the SE side of profile 2 indicate the boundary between redwitzites and granites. The boundary between redwitzites and metasediments (mica schists) on the

opposite sides of the profiles is less obvious, because the density contrast between these rocks is smaller than the density contrast between redwitzites and granites. The averaged or quiet magnetic field above the granites is by 20 nT lower than the magnetic field above the metasediments. The magnetic field above the redwitzites is slightly higher than above the neighbouring geological units and it is more variable. Sources of local anomalies are boulder fields of mafic rocks on the surface. The magnetic field is most variable at places of terrain depressions carved out by local streams (Fig. 2, profile 1, meters 400–500 and 1200–1700). Sources of fluctuating magnetic field are fluvial deposits bearing magnetic minerals from nearby outcrops of highly magnetic Tertiary volcanic rocks (nephelinite).

Gravity measurements were interpreted quantitatively. Geological models are shown in Fig. 5. Vertical geological sections are not exaggerated and displayed are areas beyond the ends of the measured profiles, to include all modeled geological units and the real shape of the mafic intrusion. The models are 2.75-D which means that geological bodies have a finite length in the direction perpendicular to the profiles and densities over the ends of geological blocks could be different. Constrains of the model are gravity measurements, geological maps and densities of rocks taken from Blížkovský et al. (1981). We conclude that the mafic intrusion is a plate-like body of about 1.5 km thick dipping generally to the north. Geophysical measurements support the fact that the two surface outcrops of redwitzites form a continuous single mafic body which extents shallowly at depth.

8. Geochemistry

Both redwitzite varieties from Abertamy differ in their chemical composition (Fig. 6, Table 4). The gabbronorites have MgO contents between 11 and 18 wt% significantly higher than in the gabbrodiorites (4–5 wt%). The CaO contents are roughly similar in both rock types. Gabbrodiorites and gabbronorites, have low SiO_2 (48–52 wt%) classifying them as basic to marginally intermediate rocks. In contrast to the gabbronorites, the gabbrodiorites have higher contents of TiO_2, Al_2O_3 and alkalies. Fluorine concentrations are generally lower in the gabbronorites than in the gabbrodiorites.

In the AFM diagram (Fig. 7) the gabbrodiorites and the associated OIC granites from Abertamy plot into the calc-alkaline series field (CA) whereas the gabbronorites plot in the tholeiite series field close to the boundary of the CA field.

In comparison with literature data the Abertamy redwitzites are very similar in chemical composition to
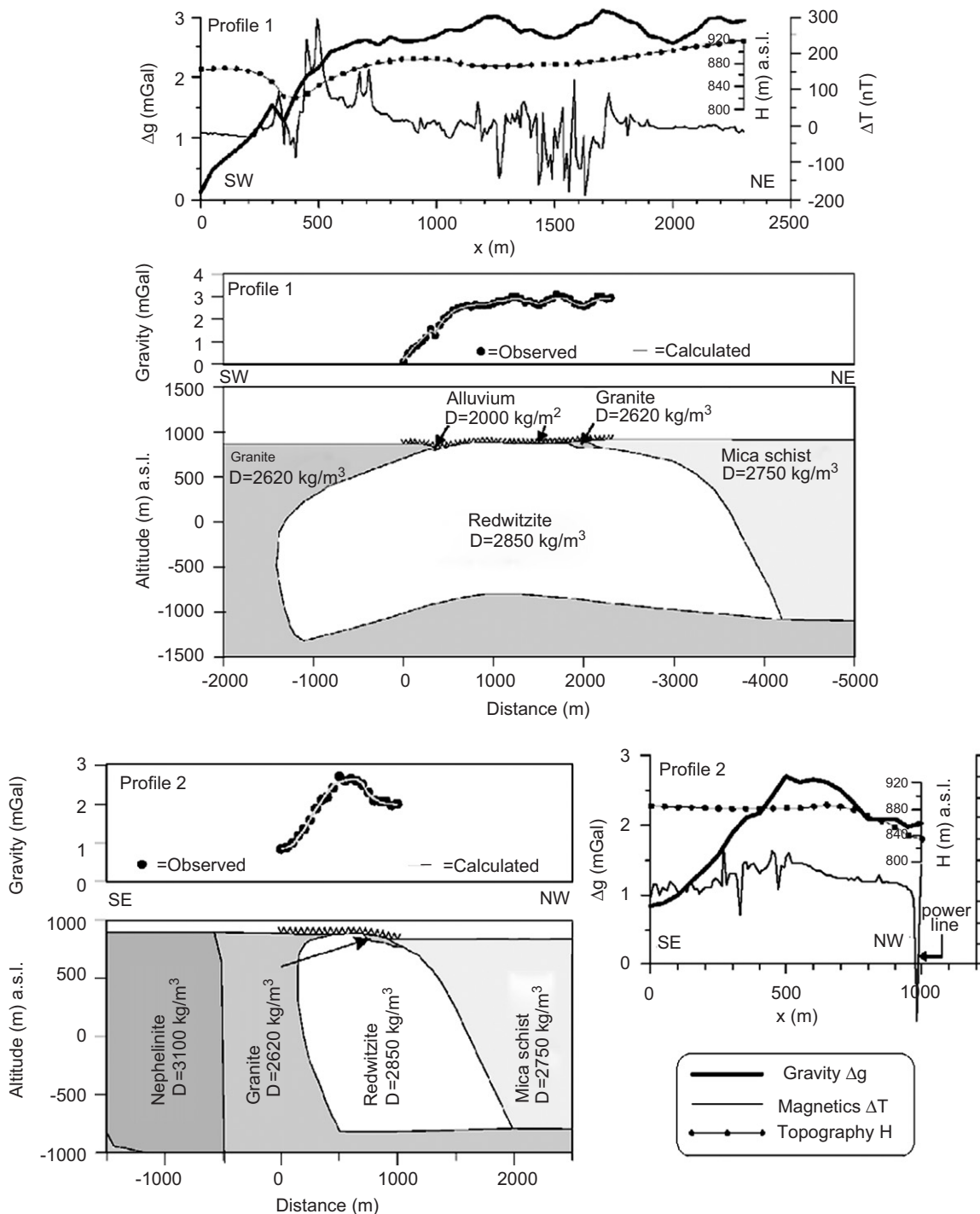
Fig. 5. Geophysical measurements over the mafic body with the gravity, magnetics and topography profiles and geophysical model of the redwitzite body at Abertamy.

basic redwitzite varieties from the Marktredwitz type locality (Troll, 1968) and to the gabbrodiorites from the Slavkovský les (Fiala, 1968). The compositional difference between more primitive gabbronorites and more evolved gabbrodiorites is evident. The former are closer to the basic redwitzites from Marktredwitz (Troll, 1968), but the latter are more similar to redwitzites from the

northern Oberpfalz (Siebel, 1993), the Bor massif (Siebel et al., 1997; René, 2000) and the Fichtelgebirge (Taubald, 2000).

Abertamy redwitzites have lower contents of SiO_2 and alkalies (K_2O and Na_2O) and higher contents of CaO and FeO compared with most other redwitzites described in the literature. Gabbrodiorites at Abertamy have very high
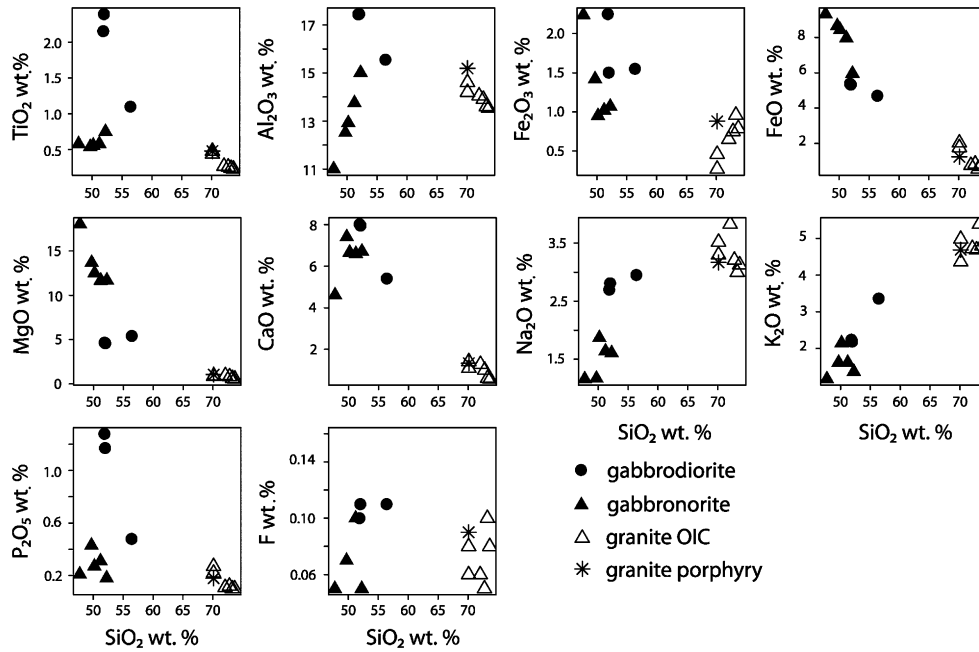
Fig. 6. Harker variation diagrams for redwitzites and associated granitoids from Abertamy.

Table 4. Chemical analyses of main and trace elements of redwitzites, granites OIC and granite porphyry

Sample	AB 1	AB 2	AB 3	AB 4	AB 5	AB 6	AB 7	PLE-1	PLE-2	PLE-3	PLE-4	PLE-5
wt%												
SiO_2	51.84	70.12	72.77	72.06	52.24	47.74	49.70	56.40	73.65	51.98	73.25	51.22
TiO_2	2.15	0.48	0.26	0.27	0.75	0.58	0.54	1.10	0.23	2.39	0.24	0.58
Al_2O_3	17.44	15.19	13.91	14.05	15.01	11.00	12.51	15.55	13.53	17.45	13.59	13.75
Fe_2O_3	2.25	0.88	0.75	0.65	1.07	2.24	1.42	1.55	0.79	1.50	0.96	1.02
FeO	5.38	1.24	0.84	0.76	5.96	9.32	8.65	4.70	0.71	5.32	0.55	7.96
MnO	0.12	0.04	0.03	0.03	0.14	0.15	0.15	0.11	0.02	0.12	0.02	0.13
MgO	4.64	1.05	0.82	0.95	11.69	18.02	13.67	5.41	0.55	4.58	0.62	11.67
CaO	8.02	1.34	1.01	1.29	6.71	4.61	7.40	5.40	0.58	7.94	0.62	6.60
Na_2O	2.70	3.17	3.21	3.83	1.61	1.16	1.17	2.95	3.13	2.81	3.00	1.64
K_2O	2.24	4.69	4.69	4.73	1.37	1.17	1.62	3.36	4.80	2.19	5.39	1.62
P_2O_5	1.28	0.18	0.12	0.11	0.18	0.21	0.43	0.48	0.10	1.17	0.10	0.31
H_2O^-	0.16	0.20	0.12	0.14	0.08	0.06	0.12	1.86	1.20	1.92	1.33	2.41
H_2O^+	1.46	1.03	1.01	0.68	2.08	3.14	1.12	0.18	0.25	0.19	0.22	0.23
CO_2	0.03	0.10	<0.02	0.05	0.24	0.17	0.65	0.00	0.00	0.00	0.00	0.00
F	0.10	0.09	0.05	0.06	0.05	0.05	0.07	0.11	0.08	0.11	0.10	0.10
Total	99.81	99.80	99.54	99.66	99.18	99.62	99.22	99.16	99.62	99.67	100.00	99.23
K_2O/Na_2O	0.83	1.48	1.46	1.23	0.85	1.01	1.38	1.14	1.53	0.78	1.80	0.99
ppm												
Li	91.00	79.50	75.90	71.30	83.20	74.20	58.00	69.00	55.00	78.00	55.00	37.00
Ba	1170.00	834.10	494.00	605.50	522.90	471.70	726.00	1203.00	394.00	1003.00	376.00	681.00
Rb	88.50	232.80	216.70	216.50	65.00	44.40	73.20	113.00	190.00	87.00	222.00	62.00
Sr	804.50	177.60	126.80	173.60	381.10	273.40	423.10	672.00	102.00	791.00	117.00	521.00
Cs	13.20	8.60	11.50	17.40	15.50	13.50	23.20	0.00	0.00	0.00	0.00	0.00
Zr	192.50	289.90	144.70	133.80	111.70	100.60	100.80	241.00	89.00	172.00	102.00	92.00
Y	24.50	27.50	30.60	28.30	14.00	13.40	16.80	25.00	27.00	24.00	23.00	12.00
Th	16.20	37.90	28.80	25.40	7.60	6.00	8.60	–	47.00	–	–	–
U	3.20	8.50	5.90	8.40	1.80	1.60	2.30	–	–	–	–	–
V	252.10	30.70	17.10	19.00	276.40	159.80	231.70	100.00	14.00	174.00	16.00	180.00
Nb	20.70	19.00	16.30	12.50	6.70	6.20	7.50	16.00	18.00	24.00	21.00	12.00

Table 4. (*continued*)

Sample	AB 1	AB 2	AB 3	AB 4	AB 5	AB 6	AB 7	PLE-1	PLE-2	PLE-3	PLE-4	PLE-5
Hf	4.90	8.20	4.90	4.30	2.90	2.50	2.90	–	–	–	–	–
Ta	1.50	1.90	1.80	1.60	0.60	0.60	0.60	–	–	–	–	–
Mo	0.80	0.30	0.50	0.80	1.00	1.00	2.50	1.00	–	–	–	1.00
Cr	46.90	37.80	30.80	19.90	502.30	358.70	736.70	237.00	9.00	52.00	16.00	587.00
Zn	98.60	62.00	66.60	62.10	141.40	116.00	94.60	136.00	–	126.00	41.00	113.00
Cu	22.10	20.00	17.40	25.80	47.20	40.20	75.40	37.00	23.00	21.00	28.00	84.00
Ni	19.90	31.50	27.80	24.90	82.70	118.20	279.70	82.00	–	–	–	178.00
Co	18.50	4.90	2.70	3.20	45.90	79.50	72.50	29.00	3.00	24.00	2.00	54.00
Sn	5.90	4.30	11.60	5.30	6.90	2.30	4.40	21.00	14.00	25.00	62.00	13.00
Pb	14.00	47.40	56.00	51.40	18.30	6.40	8.30	25.00	50.00	16.00	58.00	8.00
Rb/Sr	0.10	1.30	1.70	1.20	0.20	0.20	0.20	0.20	1.90	0.10	1.90	0.10
La	72.60	65.00	47.90	45.30	24.60	22.90	33.20	74.20	24.20	58.10	28.20	29.00
Ce	142.10	121.90	93.80	87.50	45.50	43.20	66.90	137.10	47.80	126.90	72.30	57.80
Pr	18.00	14.40	11.30	10.20	5.70	5.60	8.70	16.90	4.80	15.70	6.70	7.50
Nd	69.40	49.70	39.50	35.70	21.50	21.40	34.40	65.20	20.90	60.90	22.90	26.00
Sm	11.50	8.50	7.60	6.60	3.80	3.90	6.30	10.00	3.60	8.70	4.50	3.60
Eu	2.70	1.00	0.80	0.90	1.40	1.10	1.70	2.20	0.50	2.30	0.60	1.50
Gd	7.00	5.50	5.00	4.20	2.60	2.70	4.10	7.30	3.00	7.90	3.70	3.40
Tb	1.00	0.90	0.90	0.80	0.50	0.40	0.60	1.10	–	–	–	–
Dy	5.30	5.30	5.70	4.90	2.60	2.50	3.50	4.30	3.50	4.80	4.10	2.30
Ho	1.00	1.10	1.20	1.00	0.50	0.50	0.70	0.90	0.60	0.80	0.90	0.40
Er	2.60	2.90	3.30	3.10	1.60	1.40	1.80	1.90	2.40	2.10	2.70	1.30
Tm	0.30	0.40	0.50	0.50	0.20	0.20	0.20	0.30	0.40	0.30	0.40	–
Yb	2.20	2.90	3.40	3.20	1.60	1.40	1.60	2.00	2.30	2.20	2.80	1.40
Lu	0.30	0.40	0.50	0.40	0.20	0.20	0.20	0.30	0.30	0.30	0.40	0.20
nLa/nLu	251.37	168.79	99.51	117.63	127.76	118.93	172.43	256.91	83.79	201.16	73.23	150.61

AB 1, PLE 3 – biotite-amphibole quartz gabbrodiorite, AB 2 – granite porphyry, AB 3, AB 4, PLE 2, PLE 4 – granite OIC.
AB 5–7, PLE 1, PLE 5 – biotitic gabbronorite.
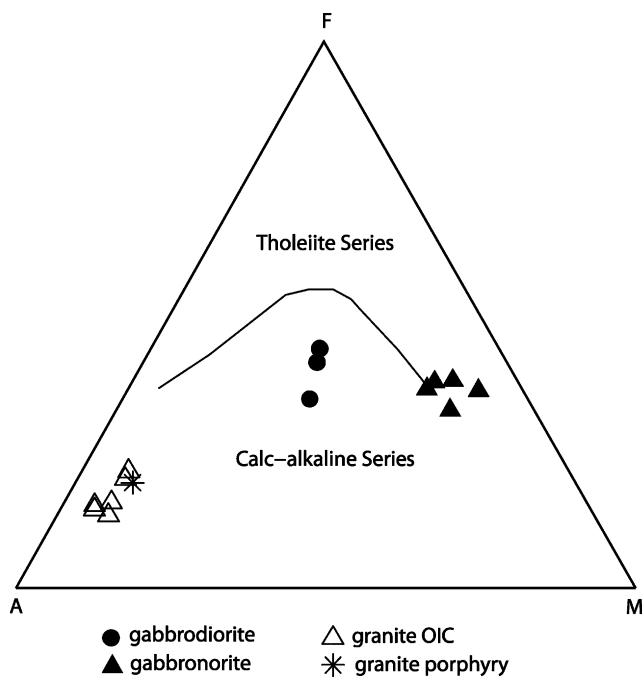nLa, nLu – La, Lu normalized to chondrite.

Fig. 7. AFM diagram for redwitzites and associated granitoids from Abertamy.

contents of TiO_2, higher than all other redwitzites. On the other hand, gabbronorites have very low TiO_2 and P_2O_5 content and have high MgO and thus are comparable with Marktredwitz basic redwitzites.

The adjacent OIC granites and the granite porphyry have higher SiO_2 (>70 wt%) and lower TiO_2, Fe_2O_3, FeO, MnO, MgO and CaO concentrations than the associated redwitzites. Potassium prevails over sodium and the average K_2O/Na_2O ratio is 1.47. The content of aluminum is similar in all rock types (Table 4). All described granites are markedly peraluminous in contrast to the redwitzites which are metaluminous. The typical OIC granites are close to I-type granites (Štemprok, 1986) but the Abertamy granites have more features resembling S-type granites: they have low Na_2O content, A/CNK ratios higher than 1.1, and more than 1% of normative corundum.

8.1. Trace elements

Generally, the gabbrodiorites have higher contents of incompatible elements (Cs, Rb, Ba, Sr) and high

field strength (HFS) elements (U, Ta, Nb, Th, REE), whereas the gabbronorites are relatively enriched in compatible elements like Ni, Cr, Sc, V and Co (Fig. 8, Table 4).

The spidergrams of gabbronorites, gabbrodiorites and granites from Abertamy are shown in Fig. 9. All rock types, normalized to primitive mantle, are characterized by enrichment in large ion lithophile (LIL) elements and P and by negative peaks of Nb. This pattern is typical for rocks from the continental crust. Elevated phosphorus contents are characteristic also for some Variscan granites in the Western part of the Bohemian massif (Siebel et al., 1999).

The trace element composition of the OIC granites is similar to that of the gabbrodiorites with respect to the enrichment in incompatible elements. The granites have high Rb (190–232 ppm), Th (up to 47 ppm) and Pb (47–58 ppm) concentrations and higher Rb/Sr (>1.25) ratio compared to the gabbrodiorites (Rb/Sr = 0.11) and the gabbronorites (Rb/Sr = 0.17). The Abertamy granites are enriched in those trace elements whose content is controlled by the presence of accessory minerals (Y, Zr, Sn, REE, Hf, Pb, Th, and U) as expected from mineralogy. However, some trace element concentrations such as Li, Zr, Nb and Ba are at similar levels as in the redwitzites whereas Co, Ni and V are typically higher only in the redwitzites.

8.2. Rare earth elements

All studied rocks are enriched in LREE compared to HREE (Fig. 10). The total amount of REEs in the gabbrodiorite exceeds that of the gabbronorites. From the most primitive to the most evolved redwitzite samples, normalized La and Ce increases by a factor of three. The normalized La/Lu ratio in the OIC granites at Abertamy is about 100, in gabbrodiorites it is approximately 250 and in gabbronorites around 130. The OIC granites are characterized by a negative Eu anomaly whereas the Eu anomaly is absent in the redwitzites. The REE pattern for the OIC granite and the crosscutting granite porphyry (rhyolite) are almost identical.

8.3. Harker diagrams

Fig. 11 shows the comparision of Abertamy redwitzites with those from the Slavkovský les (Fiala, 1968), northern Oberpfalz (Siebel, 1993), Bor massif (René, 2000) and Marktredwitz (Troll, 1968) in Harker variation diagrams. All plots show a continuous compositional trend from the most mafic members of the redwitzite suite to the OIC granites. Redwitzites from Abertamy as well as redwitzites from the
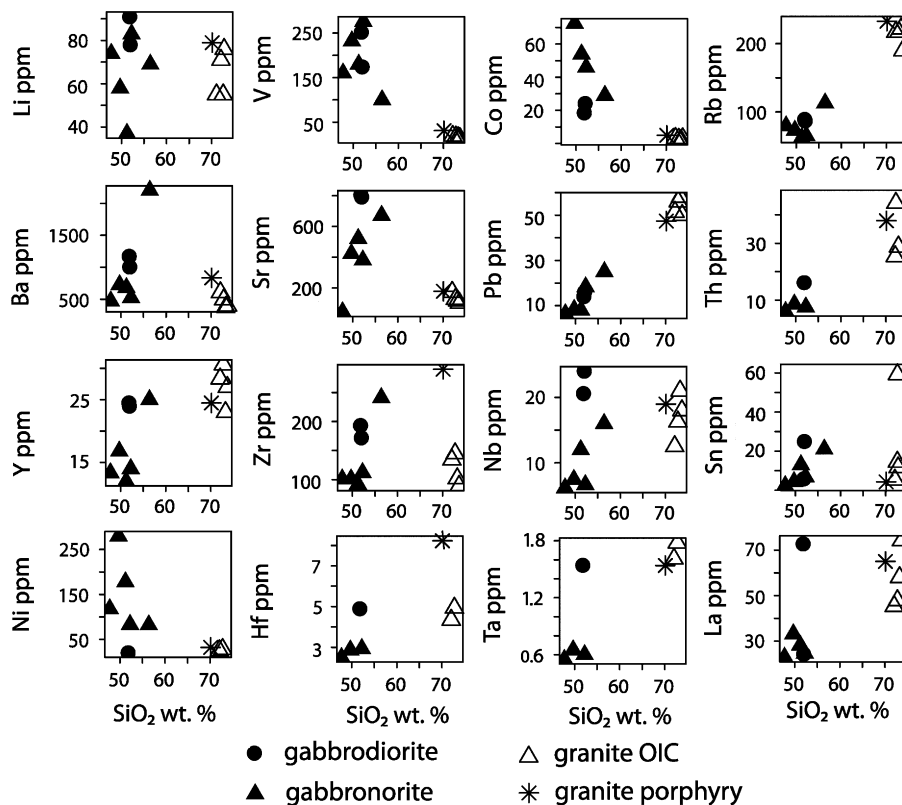

Fig. 8. Trace elements versus silica for redwitzites and associated granitoids from Abertamy.
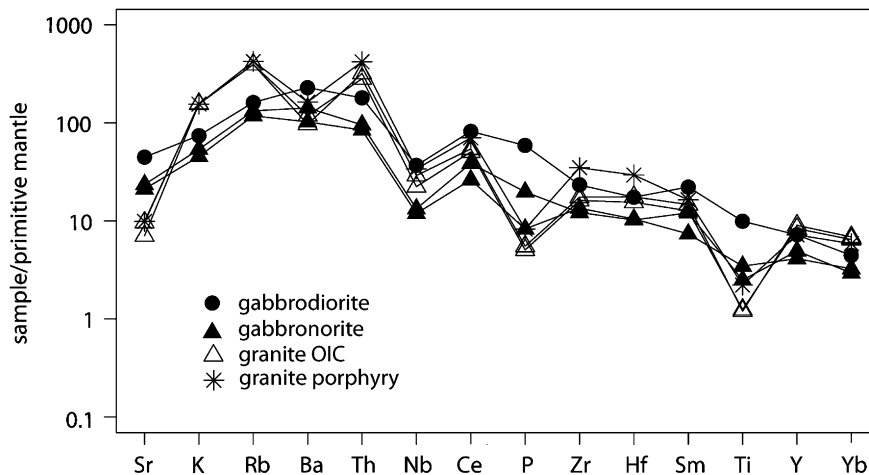
Fig. 9. Spidergrams for redwitzites and associated granitoids from Abertamy (normalized to primitive mantle – Taylor and McLennan, 1986).
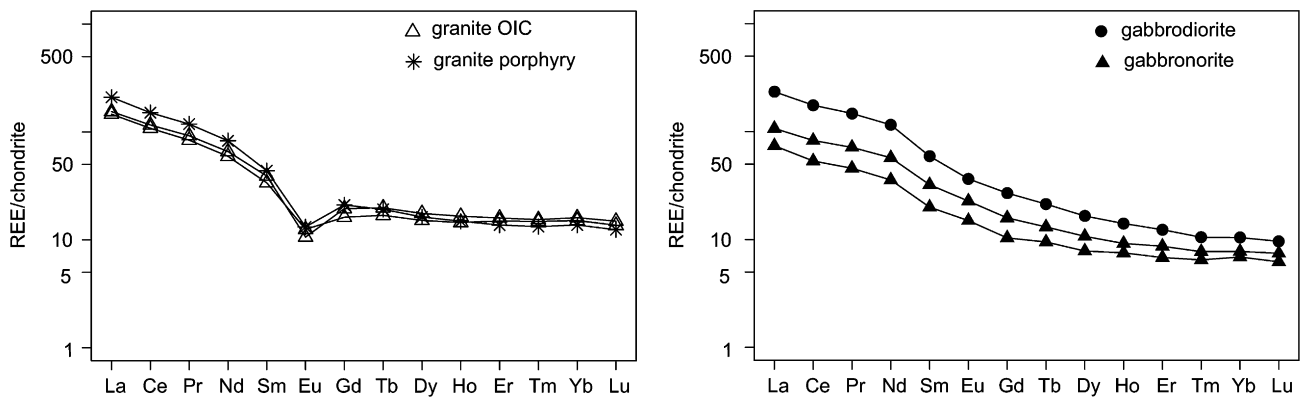

Fig. 10. REE normalized diagram for redwitzites and associated granitoids from Abertamy (normalized to chondrite, Boynton, 1984).

Slavkovský les and the basic varieties from Marktredwitz have SiO_2 contents < 55 wt%. Others have silica contents ranging from 55 to 60 wt%.

The TiO_2 vs. SiO_2 diagram shows a large scatter for samples with $SiO_2 < 55$ wt%. For samples with SiO_2 over 55 wt% TiO_2 correlates negatively with SiO_2. A significantly negative correlation also exists for the FeO contents. This is apparently caused by decreasing amounts of mafic minerals from redwitzite towards granites. A similar relationship with a wider scatter is shown between the CaO and SiO_2 contents which can be explained mainly by the decreasing anorthite component in the plagioclases. The MgO contents in rocks with low SiO_2 show a wide scatter and a steep negative correlation. In rocks with SiO_2 contents over 50 wt% the trend is less scattered and characterized by a moderate decrease of MgO with raising silica. A change of the slope with increasing silica can also be observed for Al_2O_3. K_2O and Na_2O. These show a positive correlation with raising SiO_2 but are characterized by

very large variations which can be explained in addition to primary magmatic processes by secondary alterations (e.g. deuteric albitization in redwitzites and granites, muscovitization in the granites, etc.). The diagram for the P_2O_5 vs. silica contents indicates two populations independent of SiO_2: one with P_2O_5 content over 0.8 wt% and the other one with $P_2O_5 < 0.6$ wt%.

9. Age determination

From the redwitzite sample AB7 two zircon grains gave $^{207}Pb/^{206}Pb$-evaporation ages of 322.9 ± 1.8 Ma (grain 1) and 322.4 ± 1.8 Ma (grain 2) (Fig. 12, Table 5). Grain 1 was also analyzed in static mode by the Faraday detection (instead of ion counting in peak jumping mode) and gave an age of 326.9 ± 2.1 Ma. The small difference in age (i.e. 322.9 vs. 326.9 Ma) might be due to systematic counting error but it is within the
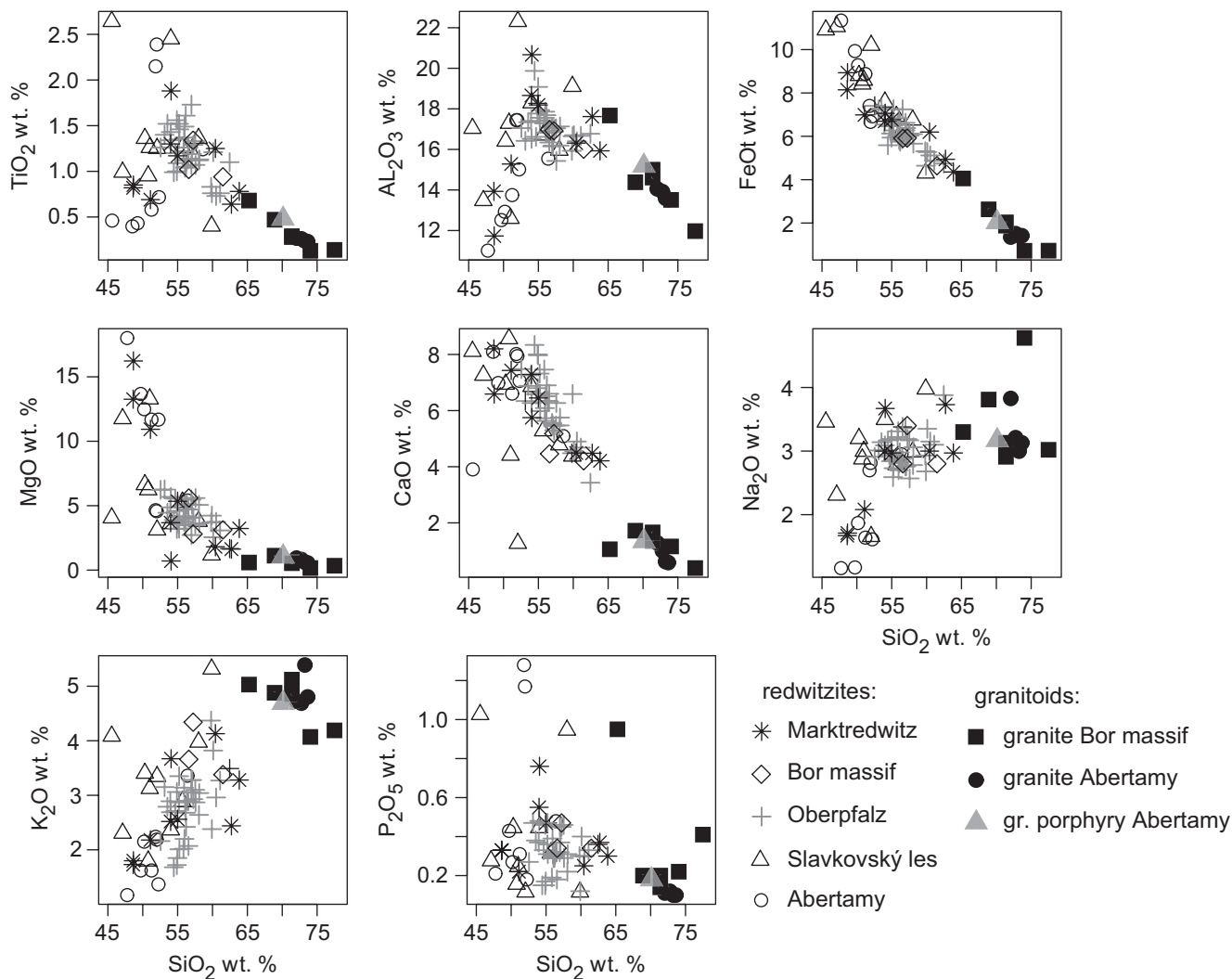
Fig. 11. Harker diagrams for the redwitzites and selected granites from the NW margin of the Bohemian massif.

bounds of the errors. The two zircon grains from sample AB7 can be thus regarded as equal in age.

Granite sample AB4 contains zircons with an inherited component. However, a single grain (grain 6) gave a well defined Pb-evaporation age of 323 Ma. There was no evidence of older core material in this sample and this age, although not reproduced by a second analyses, may constraint on the time of granite crystallization. Most of the analyzed grains from sample AB4 are characterised by a very high common lead component (i.e. low $^{206}Pb/^{204}Pb$ ratios). This component was present even at the high temperature evaporation steps. This was particularly the case for grain 4 and grain 5, but also partly for grain 2 and grain 3. In general, only data with high $^{206}Pb/^{204}Pb$ ratios are considered for evaluation because the exact isotopic composition of the common lead component is not well known and thus increases the uncertainty of the $^{207}Pb/^{206}Pb$ age.

The reason for the high common Pb component remains unclear and most of the data from AB4 mainly serve only as an indication for the presence of older core component present in the zircons. However, the lack of Precambrian ages may be taken as indication that the inherited component (at least for this sample) was Paleozoic in age.

10. Granites and redwitzites derived from sediments and amphibolites

Patiño Douce (1999) produced experimental melts by melting rocks with various mineral associations and suggested that the differences between the amphibolite-derived melts and melts derived from mica-rich sources can be deduced from the differences in the major
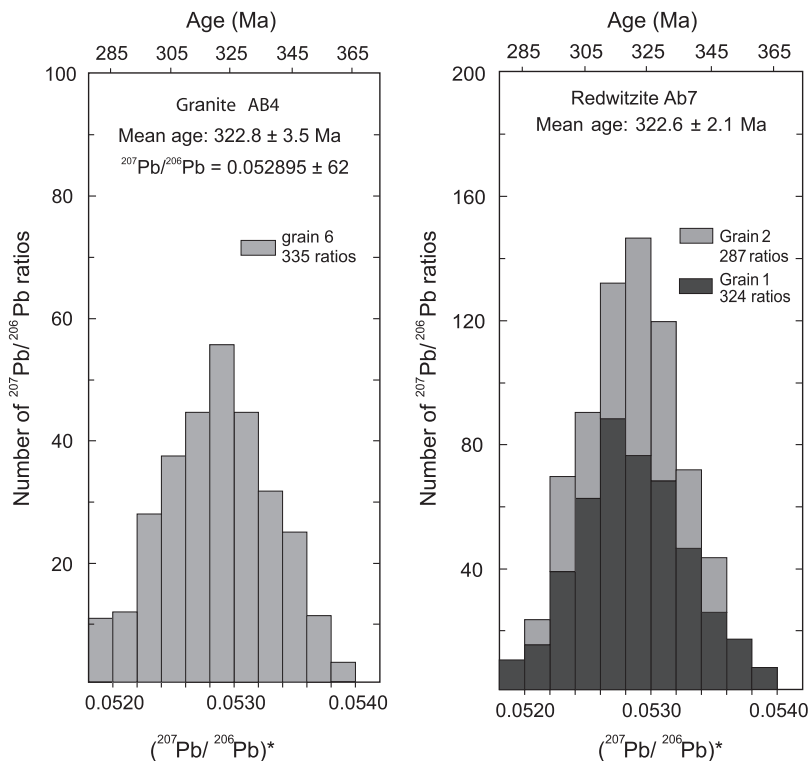
Fig. 12. Histograms showing the distribution of radiogenic $^{207}Pb/^{206}Pb$ ratios obtained from evaporation analyses of one zircon from granite sample AB4 and two zircons from redwitzite sample AB7.

Table 5. Isotope data for single grain $^{207}Pb/^{206}Pb$ evaporation analyses (explanation of samples see Table 1)

	No. of $^{207}Pb/^{206}Pb$ ratios	$^{204}Pb/^{206}Pb$	$^{206}Pb/^{208}Pb$	U/Th	$^{207}Pb/^{206}Pb$	Age (Ma)
AB7/grain1	446	0.000009	3.10	0.98	0.052862 ± 0.000041	322.9 ± 2.9
AB7/grain1[a]	195	0.000008	3.08	0.97	0.052955 ± 0.000049	326.9 ± 3.1
AB7/grain2	281	0.000013	8.03	2.51	0.052850 ± 0.000042	322.4 ± 2.9
Weighted avg. (Faraday measurement not included)						322.6 ± 2.1
AB4/grain1	257	0.000020	11.30	3.53	0.053435 ± 0.000042	347.3 ± 3.1
AB4/grain2	38	0.000440	4.40	1.31	0.057168 ± 0.000371	498 ± 15
AB4/grain3	83	0.000738	5.60	1.54	0.053394 ± 0.000192	346 ± 9
AB4/grain4	105	0.005266	4.17	0.78	0.054984 ± 0.000381	412 ± 16
AB4/grain5	197	0.003415	5.11	1.01	0.053568 ± 0.000197	353 ± 9
AB4/grain6	335	0.000062	5.24	1.63	0.052859 ± 0.000062	322.8 ± 3.5

[a]Measured with Faraday cups instead of ion counter.

element oxides. Melts derived from amphibolites are depleted in total alkalies and are enriched in CaO relative to mica-rich sources. Melts derived from muscovite-rich sources are depleted in $FeO + MgO + TiO_2$ relatively to biotite-rich sources. In Fig. 13 the fields of melt composition derived from different sources (greywackes, mafic pelites, felsic pelites and amphibolites, Patiño Douce, 1999) are marked and the compositions of redwitzites and granites from Abertamy and from other redwitzite localities plotted in this diagram. The Abertamy redwitzites as well as the redwitzites from other localities partially overlap with the fields of

amphibolite-derived melt. However, the plots of most samples are outside of this field. Redwitzites have lower content of alkalies, but they have higher amount of ferromagnesian components ($FeO + MgO + TiO_2$) and Al_2O_3 compared with amphibolite-derived melt. They follow well the trend of the low pressure (LP) mixing curve. The granites from Abertamy coincide with the field of greywackes-derived melt. Förster et al. (1999) postulated for the Krušné hory/Erzgebirge granites more variegated metasedimentary sources like metapelites, metagreywackes and orthogneisses. We can conclude that amphibolites are an improbable lithology for
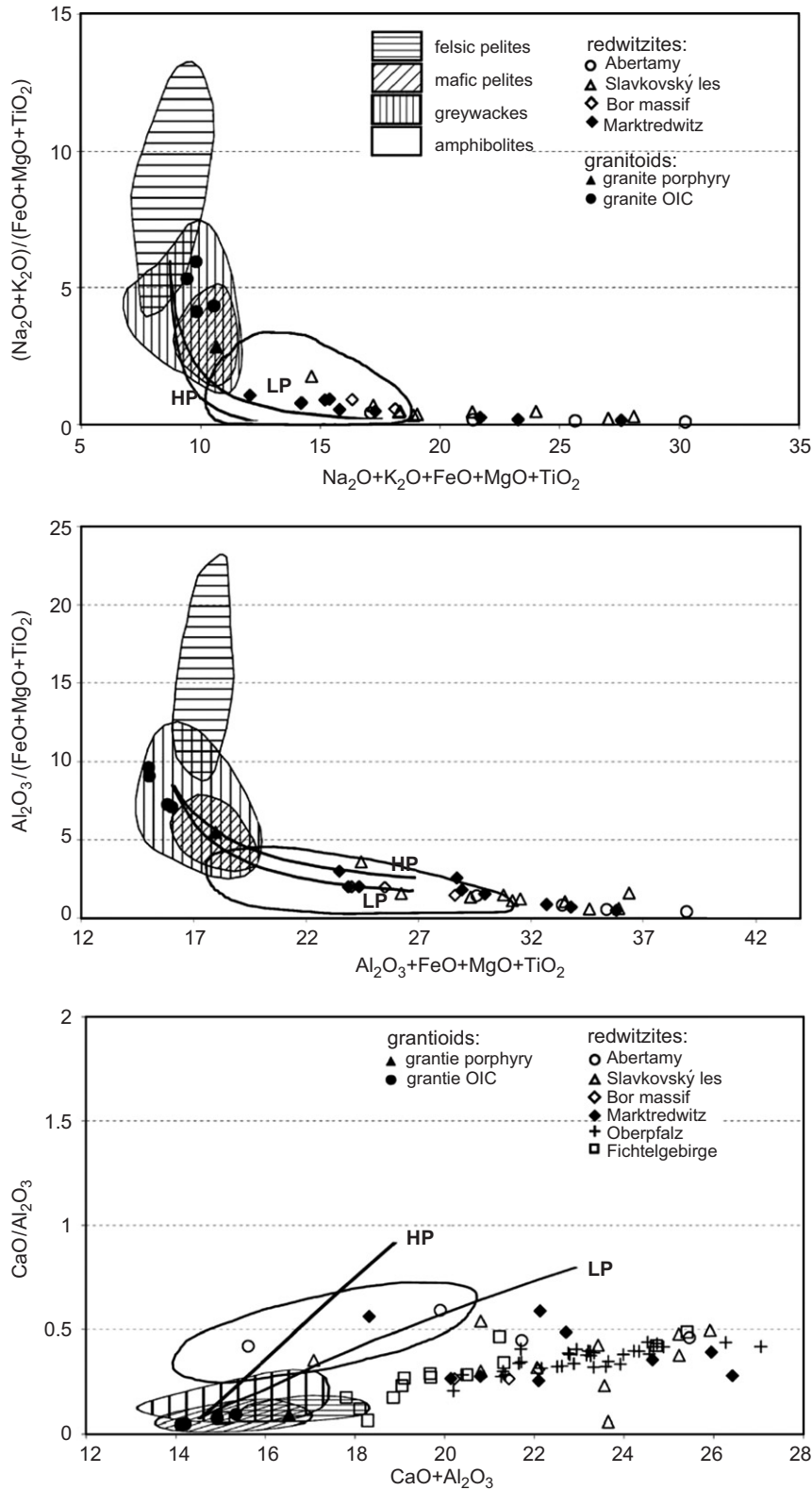
Fig. 13. Composition of redwitzites and selected granites from the NW margin of the Bohemian massif as plotted in the diagram according to Patiño Douce (1999). The thick solid lines are reaction curves that model melt compositions that would be produced by hybridization of high-Al olivine tholeiite with metapelite. LP – low pressure (P< = 5 kbar, reaction produces an assemblage dominated by plagioclase and Al pyroxene), HP – high pressure (P = 12–15 kbar, product of reaction is garnet accompanied by subordinate plagioclase).

the origin of the Abertamy redwitzites but the enclosing granites originated probably from greywacke lithology.

11. Magma mixing

Magma mixing in the genesis of redwitzites (Wurm, 1932; Siebel, 1993; Taubald, 2000) was accepted as one of the possible mechanisms of their origin. Holl et al. (1989) explain on the basis isotopic evidence the origin of redwitzites as isotopic heterogeneous mixing between basic and intermediate magmas.

In general mixing may range from complete and homogenous mixing (where the character of the different magmas is not noticeable) to a magma mingling where original components maintain much of their individual features. Our geological evidence is in favour of homogenous mixing as inhomogeneous transitional textural types were not found on the outcrops studied at Abertamy and we observed intersection of the solid redwitzite enclave by the granite in the southern part of the body.

The linear trend in binary geochemical plots is the result of ideal mixing of mafic and felsic magma and this can be observed in FeOt and CaO Harker diagrams (Fig. 11). The correlation depends on the stage of mixing, homogeneity of both end members, other petrogenetic processes which can occur, and the precision of analytical methods (D'Lemos, 1996).

From two end members – mafic and acid (granitic) magmas – it is possible to calculate the composition of hybrid magmas according to the linear equation (after Langmuir et al., 1978; Fourcade and Allègre, 1981)

$$C_M = X_A \times C_A - (1 - X_A) \times C_B,$$

where C_M is the concentration of the element in hybrid melt, C_A the concentration of the element in acid component, C_B the cocentration of the element in basic component, X_A the amount of acid component participating in mixing (number from 0 to 1) and $X_B = 1 - X_A$ the amount of basic component participating in mixing.

In the case that one of the end members is missing it is possible to carry out inverse calculation for C_M using the composition of a real hybrid (averaged Abertamy redwitzite). With one end member known (averaged OIC granite from Abertamy) we can calculate the theoretical composition of the other end member under

the assumption that we state the amount of the admixture of the acid component. Using the amounts of Ni and Cr as the typical mafic compatible elements we postulated that the admixture of acid component to the magma parental to redwitzite did not exceed 25 wt.% but was probably less (about 15 wt.%).

The theoretical composition of the mafic end member is given in Table 6. This composition corresponds best to mafic gabbros, namely to olivine gabbros or norite according to Soloviev (1970) or Kramer (1988). This strengthens the early concept of Wurm (1932) postulating the genesis of redwitzite in Marktredwitz area by mixing of the granitic magmas with norites at depth.

12. Fractional crystallization

The variation between the composition of gabbronorites and gabbrodiorites are expected to be caused by *in situ* fractionation of predominant rock-forming minerals which is the typical process in mafic igneous rocks. This is also supported by the geological situation of the rocks at Abertamy. Guo et al. (2004) pictured the trends of chemical changes in a magma during fractionation of rock forming and accessory minerals in MgO vs. major and trace element binary plots based on the study of lamprophyres. The fractionated minerals are similar to those crystallizing from a mafic magma. The result of such modelling is a residual magma composition arising from a fractionated mineral assemblage, which can explain the chemical variation of the rocks.

In Fig. 14 we compare the major element oxide composition of the gabbronorites and gabbrodiorites in MgO versus major oxides plots. Diorites from the Slavkovský les (Fiala, 1968), which have a similar position to the redwitzites from Abertamy, are shown for comparison. The trends of fractionation have been calculated according to the equation

$$c_{PM}^i = c_{min}^i f_{min} + c_{RL}^i (1 - f_{min}),$$

where c^i is the concentration of an element, PM is the original magma, RL refers to the magma after differentiation, min means the mineral that fractionates and f is the amount of fractionated mineral (number from 0 to 1).

The result of such calculation is the composition of magma, which originated by fractional crystallization of

Table 6. The calculation of mafic end member composition for magma mixing

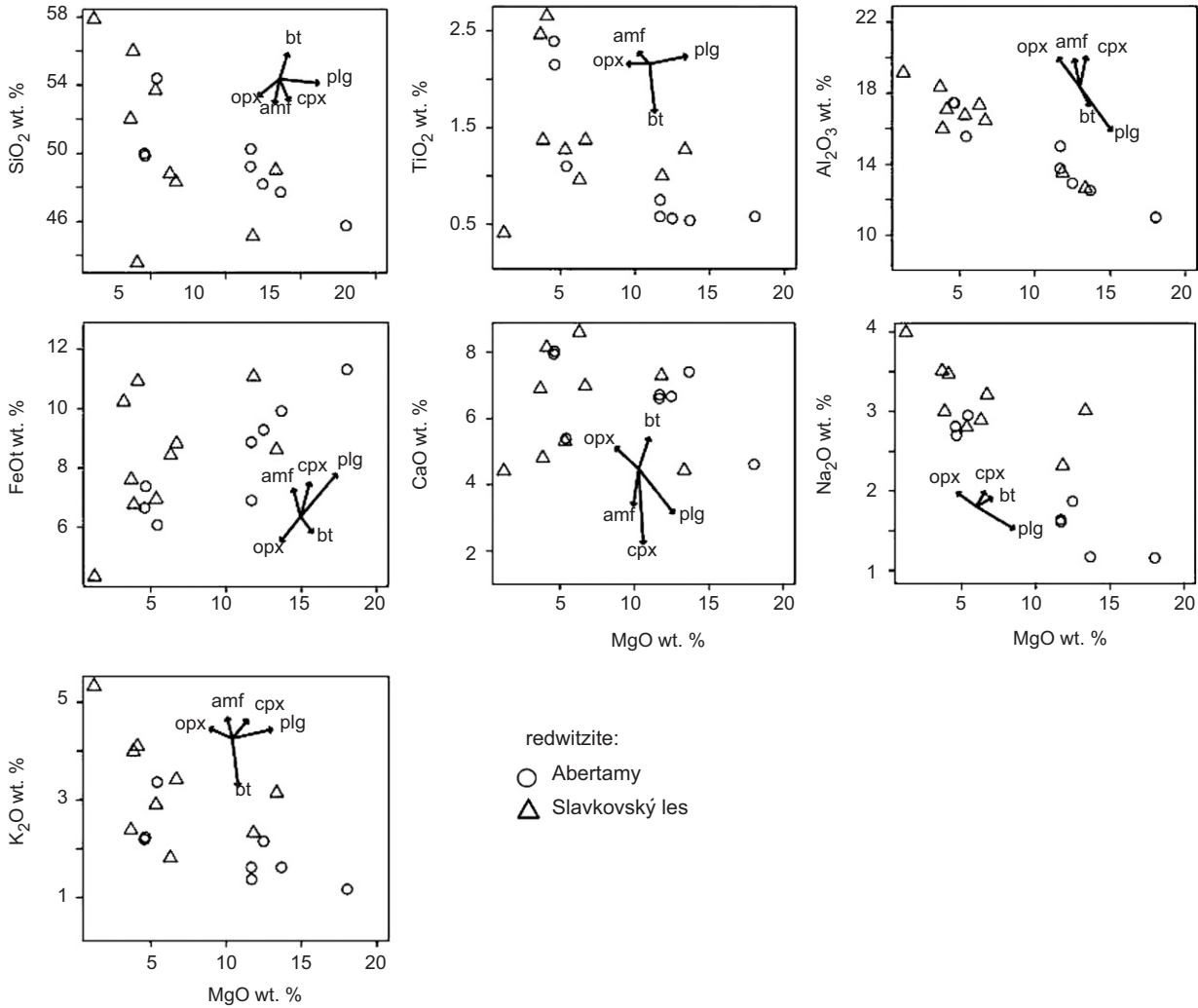| wt%	SiO$_2$	TiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	FeO	FeOt	MnO	MgO	CaO	Na$_2$O	K$_2$O
% of acid member											
15	48.03	1.71	14.60	1.84	7.31	8.95	0.15	9.67	8.11	2.00	1.55
20	46.50	1.80	14.64	1.91	7.72	9.42	0.15	10.22	8.54	1.91	1.35
25	44.78	1.90	14.68	1.99	8.18	9.95	0.16	10.84	9.03	1.80	1.13

Fig. 14. Fractionation trends in Bowen diagrams for redwitzites from the NW margin of the Bohemian massif, amf – amphibole, bt – biotite, cpx – clinopyroxene, plg – plagioclase, opx – orthopyroxene.

a single mineral. Arrows in the MgO binary diagrams show the changes of composition if 10% of plagioclase, biotite, orthopyroxene, clinopyroxene or amphibole fractionate from the magma.

In Fig. 14 there is positive correlation between MgO and FeO values of CaO are very scattered, however weak positive correlation can be deduced. These trends could be explained by the fractionation of plagioclase and orthopyroxene. Most of the plots show negative correlation such as those of SiO_2, TiO_2, Al_2O_3, Na_2O and K_2O. These trends could be correlated with the fractionation of plagioclase, or of orthopyroxene (in the case of Al_2O_3 and Na_2O). The variations of K_2O and TiO_2 can be explained by the fractionation of biotite. We conclude that some chemical variations of the redwitzite bodies can be explained by *in situ* fractionation of the essential redwitzite minerals which may have generated orthopyroxene and clinopyroxene cumulates in the crystallizing magma and have led to the difference

between the composition of the gabbronorite and gabbrodiorite.

13. Zircon thermometry

According to the calibration curves of Watson and Harrison (1983), the Abertamy redwitzites and OIC granites have low zircon saturation temperatures between 750 and 860 °C. These zircon saturation temperatures are also typical for redwitzites and early biotite granites from NE Bavaria (Siebel et al., 2003). Unlike the granites from NE Bavaria, the Abertamy OIC granites have zircon grains with preserved older cores. Even if the temperature of the melt was probably higher than the zircon saturation temperature, a chemical disequilibrium between zircon and the melt may have existed during partial melting causing the older cores of zircon grains in the granitic magmas to be preserved.

14. Discussion

The role of the mafic magmas in the genesis of granitoids is broadly discussed in the literature using the concept of magma mixing and/or mingling or considering additional heat sources for melting or remelting of crustal rocks (Castro et al., 1991; Barbarin and Didier, 1991; Collins, 1998). Collins (1998) supposes that large homogenous granodioritic to granitic intrusions could represent well-mixed hybrids. However, Gerdes et al. (2000) argue that such hybrids should be strongly heterogenous on a large scale because of a high viscosity contrast, slow rates of chemical diffusion, fast cooling rates and limited convection in plutonic systems which imply that homogenous felsic granitoids are unlikely to be hybrids of mantle derived and crustal melts.

The evidences that mixing of mafic and felsic magmas at different scales exist is testified by mafic enclaves (Barbarin and Didier, 1991) in felsic granitoids, linear elemental co-variation between assumed mafic and felsic end members (Wall et al., 1987) and evidence from isotopic investigations and modeling (DePaolo, 1981). An important problem of granite petrology is the identification of heat sources, causing large scale melting of crustal rocks producing granitoid magmas. Henk et al. (2000) envisaged four potential heat sources in the Variscan orogen of Europe: (1) radiogenic production from the decay of U, Th, K in thickened crustal rocks; (2) advection of heat by exhumation of deeply buried hot rocks; (3) advection of heat by intrusion of mantle-derived melts; (4) conduction of heat from a hotter than normal mantle. It is extremely difficult to find out exactly the contribution from the mentioned sources in the case of the Krušné hory/Erzgebirge granitic magmas. Evidence of magma mixing/mingling and geochemical and isotopic criteria showing interaction of mantle derived melts with crustal rocks are described from root domains of the Variscan chain from Central Iberian Zone (Menéndez and Ortega, 1999; Bea et al., 1999), Massif Central (Turpin et al., 1998; Joly et al., 2006) and Bohemian Massif (Janoušek et al., 2000; Gerdes et al., 2000; Holub and Janoušek, 2003).

In the Bohemian Massif Variscan magmatism is concentrated in the Moldanubian root zone, large calc-akaline plutons straddle the Moldanubian/Teplá-Barrrandian and Saxothuringian/Teplá Barrandian boundaries. The mantle derived granitoid magmas intruded in several short-lived pulses divided by longer episode of a weak magmatic activity.

Intrusions of redwidzites follow a relatively narrow belt between the Franconian line and the West Bohemian shear Zone and its continuation to the Saxothuringian belt (Mariánské Lázně fault). The emplacement ages on zircon by U–Pb technique range between 342 and 323 Ma (342 – Mutěnín body on the czech quartz lode, 332 Ma – Drahotín body, Dörr et al.,

1998), Ar–Ar-cooling ages 326 and 323 Ma (Kreuzer et al., 1992). The most recent data from the Oberphalz, the Fichtelgebirge and the Western pluton of the Krušné hory/Erzgebirge batholith cluster between 326 and 323 Ma and overlap with the age of biotite granites of the older intrusive suites (Siebel et al., 2003).

The occurrences of mafic rocks in the Krušné hory/Erzgebirge batholith area have been so far considered as unimportant (Bankwitz and Bankwitz, 1994) for granite genesis and their practical absence was taken as evidence that other processes than mafic magma intrusion or underplating were decisive in melting of the crustal rocks. Förster et al. (1999) point to the lack of redwitzites in the Krušné hory/Erzgebirge compared with the geological situation in NE Bavaria and favored the model of intracrustal origin of the Krušné hory/Erzgebirge granites with heat provided by radioactive decay in a thickened continental crust. However, they did not rule out additional heat from mafic magmas supported by lithosperic thinnig of the thickened orogenic root delaying thermal equilibration.

Our description thus shows that redwitzites are present in the Krušné hory/Erzgebirge batholith area and can be identified within the Western pluton of this batholith and thus offer an indication for the role of mantle input in Variscan time to the granite sources.

The evidence is in favour of the idea that the Late Variscan mantle has triggered melting of the crust. The scenario could be either the delamination of material from the bottom of the crust and/or underplating/replacement of mantle lithosphere. However, the physical involvement of mantle melts in the crust should assume to be rather small. At least there is no firm evidence for this in currently exposed crust documented in different occurrences of Variscan granitoids in NW Bohemian Massif.

The proof for mantle derivation of the basic mixing end member is, however, much more difficult to provide. There is no exact evidence whether the parental melts came directly from the mantle. Instead they could have been added to the crust before and remelted to give rise to the basic precursor of the redwitzites. Sr and Nd isotope ratios measured in Bavarian redwitzites indicate heterogenous enriched mantle as a possible source material modified by a various degree of AFC processes and mixing with crustal derived magmas (Siebel et al., 2003). An argument that one of the mixing end-members was derived from the mantle can be Troll's observation that gabbroic rocks occur in the Marktredwitz area (Troll, 1968) and also our assumption of the gabbroic end member in our studies of the mixing series at Abertamy.

Intrusion of mafic magma is often considered as the source of heat in the origin of many granitic rocks (Bergantz, 1989) in general. This has been proposed also for the Krušné hory/Erzgebirge granite batholith

(Kramer, 1976) also in connection with its ore-bearing potential using the occurrence of coeval lamprophyres as the representatives of mafic rocks. However the small volumes of lamprophyres have led to the rejection of this concept (Förster et al., 1999) by the most recent researcher in the area. Our evidence distinctly proves the existence of the mantle input in the early stages of the Variscan granitoid magmatism in the Krušné hory/ Erzgebirge batholith area but the exact nature of this contribution remains still not fully clear.

The mafic magma in the early stages of Variscan magmatism may have served not only as the heat carrier but it interacted also with the crustal magmas. These chemical interactions are complex and involve assimilation and other processes such as magma mixing, fractional crystallization of mixed magmas and crystal accumulation and can produce hybrid magmas of typical redwitzites. This interaction is evidenced by the intrusions of redwitzite broadly synchronous with the earliest Variscan granites (Siebel et al., 2003) and this is shown also for the Abertamy redwitzite.

It is difficult to make solid estimates of the volumes of mantle melts added to the crust during Late Variscan times based on the exposed volume of redwitzite. The redwitzites are so much modified by mixing/hybridization that the original amount of mantle material which could have been present in these rocks appears to be very small. Gerdes et al. (2000) give the estimate for the case of the large granitoid South Bohemian Batholith that it is unlikely that the enriched mantle melts made up more than 4% of the total melt budget.

15. Conclusions

The Abertamy mafic rocks enclosed in the early biotite granites of the Western pluton of the Krušné hory/Erzgebirge batholith are gabbronorites and gabbrodiorites and correspond to redwitzites defined from the NW margin of the Bohemian massif. They were emplaced in the contact zone of the Nejdek-Eibenstock massif as a tabular body not exceeding the thickness of 1–2 km in which differentiation occurred predominantly by fractional crystallization. The mafic body intruded and crystallized before the intrusion of granites but in the same magmatic period as the most primitive granitoids as testified by numerous zircon age data in NE Bavaria (325 Ma) and the dating on our samples. The mafic precursors are indication of the role of mafic magmas as heat suppliers to the Late Variscan granite magmatism. This mafic magma mixed with granitic magmas in the crust during the initial stage of Variscan granitic magmatism forming compositions from gabbrodiorites/gabbronorite to granodiorites in dependence on the amount of acid component. The most probable composition of the mafic end member as calculated under the assumption of the 15–25% admixture of acid end member (Abertamy granite) are olivine gabbrodiorite or norite. This explanation is alternative to the opinion on the predominant role of thickened crust unaffected by the mantle in the origin of Late Variscan granites in the Krušné hory/Erzgebirge.

Acknowledgement

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