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Original paper

Source compositions and melting temperatures of the main granitic suites from the Moldanubian Batholith

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The granitoids of the Moldanubian Batholith (Moldanubian Zone of the Bohemian Massif) are represented by three main suites: I- to I/S-type Weinsberg biotite granites–granodiorites, S-type Eisgarn two-mica granites and I/S-type Freistadt biotite granites–granodiorites. As shown by major-element data and zircon with monazite saturation thermometry, partial melting of metapelites likely produced most of the Eisgarn suite (Mrákotín/Čímĕř varieties) at *c.* 775–825 ºC. Parental melts of the Weinsberg and Freistadt suites could have been generated by partial melting of a metagreywackes–metabasalts mixture at *c.* 740–940 ºC.

This study confirms that the CaO/Na_2O ratio could be used for source assignment of S-type granite melts, whereas the $CaO/(FeO + MgO + TiO_2)$ ratio is more suitable for I/S-type granites. The observed systematic positive shift of Al_2O_3/TiO_2 temperatures compared with zircon and monazite saturation temperatures in all granitoids of the Moldanubian Batholith (up to 118 ºC) may be explained by accumulation of ilmenite in the S-type Eisgarn suite. In the I- and I/S-granite types of the Weinsberg and Freistadt suites the Al_2O_3/TiO_2 ratio is controlled by the accumulation of ilmenite and/or titanite. Consequently, the Al_2O_3/TiO_2 ratio may be used as a thermometer only with caution.

Keywords: granites, petrology, geochemistry, Moldanubian Zone, Bohemian Massif
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1. Introduction

Low-pressure–high-temperature (LP–HT) metamorphism, crustal anatexis, and generation of granitic magmas are characteristic late-stage features in the development of collisional orogens (Le Fort et al. 1987; Guillot and Le Fort 1995; Williamson et al. 1996; Clemens 2003; Chappell and Hine 2006). One of the classic examples is the Variscan Belt in Europe, produced as a result of the late Palaeozoic convergence of Gondwana and Laurussia. The Moldanubian Batholith (MB) that forms one of the largest plutonic complexes within the European Variscan Belt, covering 10 000 km^2 in the central and western parts of the Moldanubian Zone of Bohemian Massif (an easterly exposure of the European Variscan Belt), provides an excellent insight into the origin and emplacement of such crustally derived magmas (e.g., Liew et al. 1989; Holub et al. 1995; Gerdes et al. 2000; Finger et al. 2009; Verner et al. 2014).

The aim of this paper is to estimate the source composition of the MB from major-element ratios, especially CaO/Na_2O, Al_2O_3/TiO_2 and $CaO/(FeO + MgO + TiO_2)$. Melting temperature estimations are based on Al_2O_3/TiO_2 thermometry (after Jung and Pfänder 2007) and on more conventional zircon and monazite saturation thermometry (Watson 1979; Watson and Harrison 1983; Montel 1993). Partial melting of metapelites produced the majority of the Eisgarn suite at temperatures ranging from 770 to 830 ºC. Melts of the Weinsberg and Freistadt suites were generated by partial melting of a mixture of metagreywackes and metabasalts at temperatures in the range of 740–940 ºC.

2. Geological setting

In map-view, the MB consists of two-nearly perpendicular segments (Fig. 1). The first, ~NNE–SSW trending segment, is formed mainly by a large continuous exposure of plutonic rocks, whereas the ~NW–SE segment is defined by a number of separate smaller plutons, some of which seem to be either roughly parallel to, or are crosscut by, the ~NW–SE trending regional Pfahl and Danube shear zones (Brandmayr et al. 1995, 1999; Mattern 2001; Büttner 2007). Both batholith segments are closely associated with the host migmatites.

In more detail, the MB is built by multiple plutons and stocks, predominantly composed of granitic to granodioritic rocks with either S- or transitional I/S-type character (e.g., Holub et al. 1995; Gerdes et al. 2000; Finger et al. 1997, 2009; Breiter and Koller 1999; René et al. 2008; Breiter 2010). All these granitoids can be classified into several, in part diachronous, main suites. The most important are coarse-grained, porphyritic I- to I/S-type

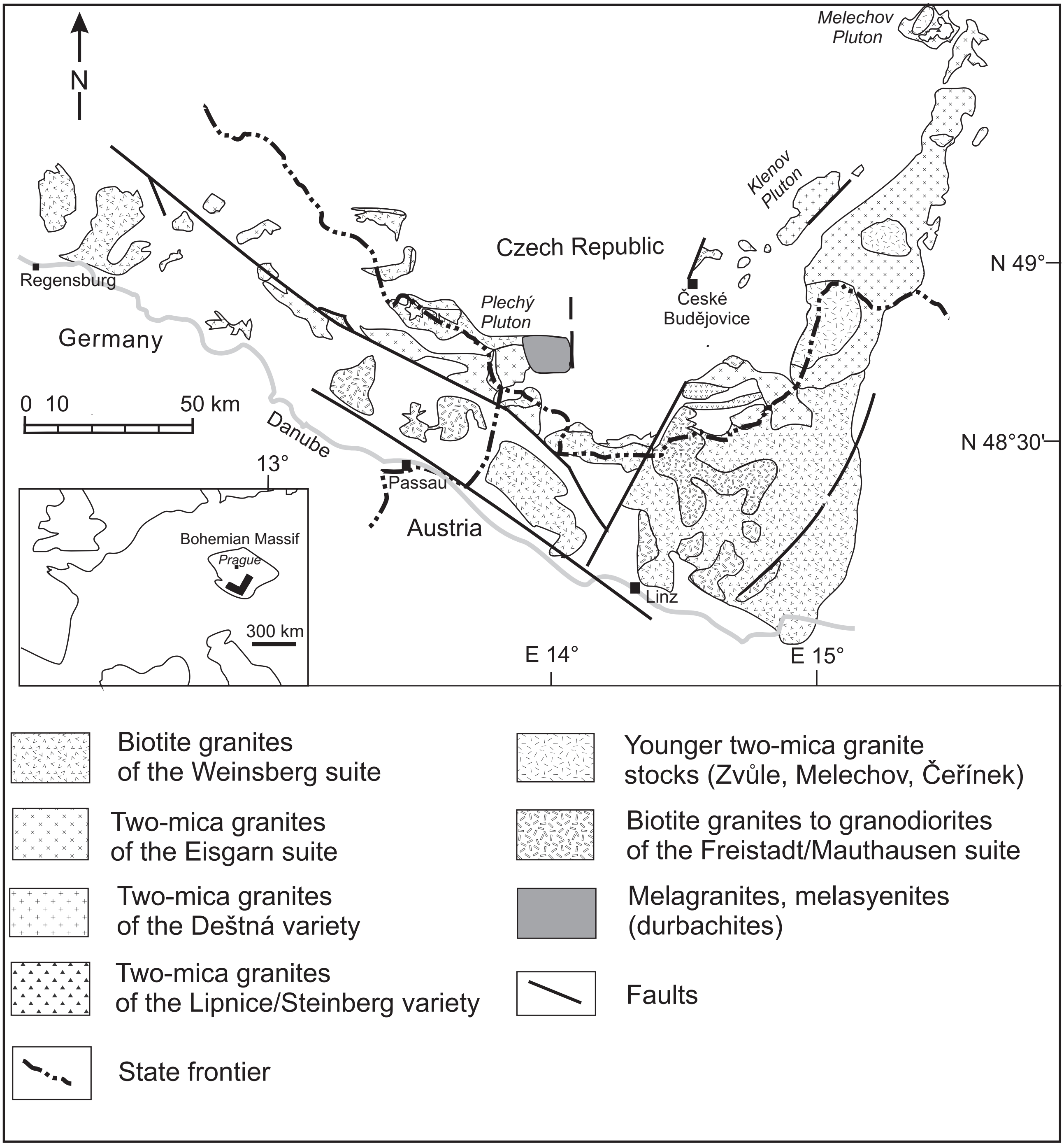

Fig. 1 Simplified geological map of the Moldanubian Batholith showing distribution of main granite suites (after Verner et al. 2015, modified).

biotite granites–granodiorites of the Weinsberg suite (331–323 Ma), S-type two-mica granites of the Eisgarn suite (329–324 Ma), and fine- to medium-grained I/S-type biotite granites–granodiorites of the Freistadt/Mauthausen suite (320–310 Ma). The Rastenberg and Knížecí Stolec plutons (337–340 Ma) are part of the durbachitic granites belt; also different diorites form small isolated bodies (323–327 Ma) within the Moldanubian Batholith (e.g., Gebharts diorites) (Frasl and Finger 1988; Liew et al. 1989; Vellmer and Wedepohl 1994; Klötzli and Parrish 1996; Finger et al. 1997, 2009; Gerdes et al. 2000, 2003; Siebel et al. 2008; Žák et al. 2011; Verner et al. 2008, 2014).

The *Weinsberg suite* (WbG) represents coarse-grained biotite granites to granodiorites. Previous systematic studies of zircon morphology (Stöbich 1992) identified two main WbG varieties: coarse-grained, porphyritic biotite granites to granodiorites (Weinsberg I) and very coarse-grained, porphyritic biotite to muscovite–biotite granites (Weinsberg II) (Frasl and Finger 1988; Liew et al. 1989; Gerdes 2001).

The two-mica granites of the MB are commonly referred to as the *Eisgarn suite*, first defined near the village of Eisgarn in Austria (Köhler 1931) and later described as the Čímĕř variety in the Czech part of the MB (Zoubek 1949). Both granite varieties are represented by porphyritic monzogranite with predominance of biotite over muscovite. Several equigranular varieties were also identified (Mrákotín – Koutek 1925; Sulzberg – Fuchs 1964; Haidmühle, Theresienreut – Ott 1988). In the Klenov Pluton, the leucocratic Deštná granite occurs (Klečka et al. 1991; René et al. 2008). In the Eisgarn granite suite are intruded dykes of microdiorites – microgranodiorites, granite porphyries, dyke rhyolites and small stocks of highly fractionated muscovite granites (e.g., Homolka stock) (René 2003, Breiter 2010 and references therein).

Two significant petrographic varieties were previously identified in the main body of the *Freistadt suite* in the Austrian Mühlviertel, the coarse-grained, biotite granodiorites of the "marginal variety" and medium-grained, biotite granodiorites of the "central variety" (Klob 1971). Later, in the area of Freistadt, the muscovite-bearing biotite granites were recognised by Friedl (1990) and described as the Grabengranite variety.

3. Analytical methods

Rock samples of 2–5 kg in weight were crushed in a jaw crusher and a representative split of this material was ground in an agate ball mill. Major elements and some trace elements (Ba, Rb, Sr, Zr, Nb, Y, U, Th) were determined using a Bruker AXS S4 Pioneer X-ray fluorescence (XRF) spectrometer at the University of Salzburg, Austria on fused glass discs and pressed rock powder pellets, respectively. The FeO was determined by titration and H_2O^+ and H_2O^- were analysed gravimetrically in the chemical laboratory of the Institute of Rock Structure and Mechanics, Czech Academy of Sciences in Prague. Rare earth elements (REE) were quantified by inductive coupled plasma mass spectrometry (ICP-MS) techniques at Activation Laboratories Ltd., Ancaster, Canada, using a Perkin Elmer Sciex ELAN 6100 ICP mass spectrometer, following standard lithium metaborate/tetraborate fusion and acid decomposition sample preparation procedures (4B2–Research, *http://www.actlabs.com*). Zircon and monazite saturation temperatures were calculated using the GCDkit 4.1 software (Janoušek et al. 2016).

Microprobe analyses of selected minerals (feldspars, biotite) were performed in polished thin sections

Tab. 1 Modal composition and mineralogy of the Moldanubian Batholith granitic rocks

Suite	Variety	Modal composition (vol. %)	Accessories	Plagioclase	Biotite
Weinsberg	Weinsberg I	Qtz 16–35,Kfs 12–54, Pl 9–44, Bt 6–27	apatite, zircon, ilmenite, titanite, monazite, allanite	An_{15-42}	siderophyllite–annite, Fe/(Fe + Mg) 0.60–0.67, ^{IV}Al 2.05–2.39, Ti 0.23–0.45 apfu
	Weinsberg II	Qtz 25–30, Kfs 3–30, Pl 23–33, Bt 7–15, Grt 0–3	apatite, zircon, ilmenite, monazite	An_{24-31}	siderophyllite, Fe/(Fe + Mg) 0.79–0.81, ^{IV}Al 2.43–2.47, Ti 0.34–0.42
Eisgarn	Deštná	Qtz 28–42, Kfs 21–41, Pl 15–50, Ms 1–8, Bt 1–5	apatite, ilmenite, monazite, zircon, xenotime	An_{12-25}	siderophyllite, Fe/(Fe + Mg) 0.62–0.74, ^{IV}Al 1.64–2.67, Ti 0.17–0.53 apfu
	Mrákotín	Qtz 23–46, Kfs 14–42, Pl 10–37, Ms 3–17, Bt 3–11	apatite, andalusite, ilmenite, zircon, monazite	An_{9-25}	siderophyllite, Fe/(Fe + Mg) 0.61–0.72, ^{IV}Al 2.23–2.50, Ti 0.15–0.40 apfu
	Čímĕř	Kfs 14–50, Qtz 22–41, Pl 8–38, Bt 3–16, Ms 1–8	andalusite, apatite, ilmenite, zircon, monazite, cordierite	An_{9-23}	siderophyllite, Fe/(Fe + Mg) 0.64–0.72, ^{IV}Al 2.20–2.41, Ti 0.25–0.39 apfu
	Lipnice	Qtz 26–33, Kfs 23–25, Pl 29–37, Bt 6–9, Ms 6–7	apatite, ilmenite, monazite, zircon, rutile, sillimanite	An_{13-20}	siderophyllite, Fe/(Fe + Mg) 0.59–0.62, ^{IV}Al 2.27–2.40, Ti 0.30–0.35 apfu
	Steinberg	Kfs 23–40, Qtz 25–37, Pl 19–25,Bt 7–10, Ms 2–7	apatite, ilmenite, monazite, zircon	An_{1-13}	siderophyllite, Fe/(Fe + Mg) 0.67–0.75, ^{IV}Al 2.10–2,42,Ti 0.22–0.30 apfu
Freistadt	Freistadt central	Qtz 23–29, Pl 33–49, Kfs 13–25, Bt 9–14, Ms 0–2	apatite, zircon, ilmenite, monazite, titanite, xenotime	An_{20-22}	siderophyllite, Fe(Fe + Mg) 0.58–0.59, ^{IV}Al 2.20–2.24, Ti 0.58–0.59
	Freistadt marginal	Qtz 12–32, Pl 32–68, Kfs 3–27, Bt 6–17, Ms 0–1	apatite, zircon, ilmenite, titanite, monazite, allanite	An_{25-37}	siderophyllite–eastonite, Fe/(Fe + Mg) = 0.44–0.62, ^{IV}Al 2.09–2.63, Ti 0.30–0.50 apfu
	Grabengranite	Qtz 29–31, Pl 33–40, Kfs 19–25, Bt 5–9, Ms 2-6	apatite, zircon, ilmenite, monazite	An_{23-26}	siderophyllite, Fe/(Fe + Mg) 0.66–0.69, ^{IV}Al 2.33–2.41, Ti 0.38–0.41

Qtz – quartz, Kfs – K-feldspar, Pl – plagioclase, Bt – biotite, Ms – muscovite, Grt – garnet

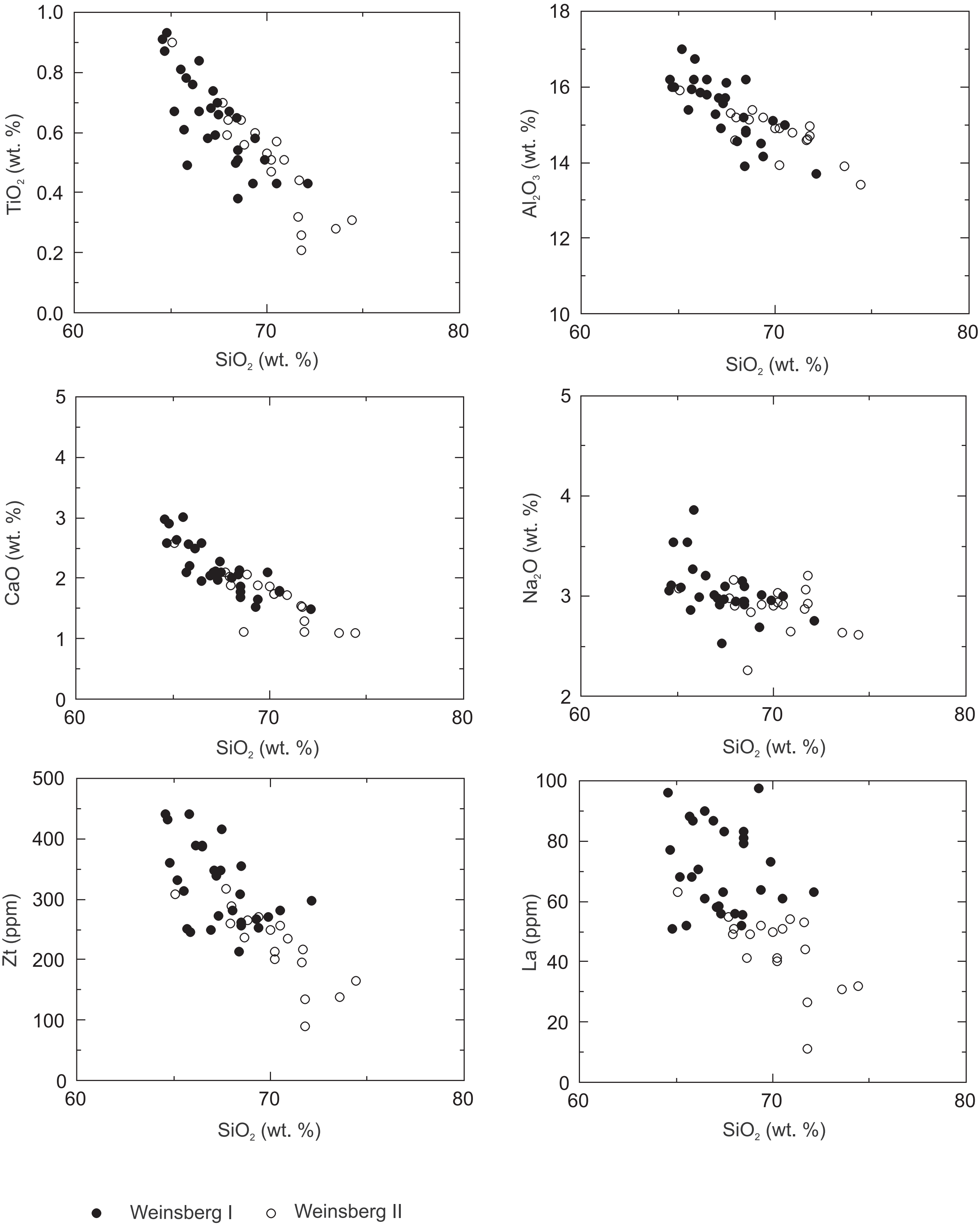

Fig. 2 Binary plots of TiO_2, Al_2O_3, CaO, Na_2O, Zr and La vs. SiO_2 for granitic rocks of the Weinsberg suite.

using a CAMECA SX-100 microprobe operated in wavelength-dispersive mode at the Institute of Geology, Czech Academy of Sciences, Prague. The raw analytical data were corrected using the PAP procedure

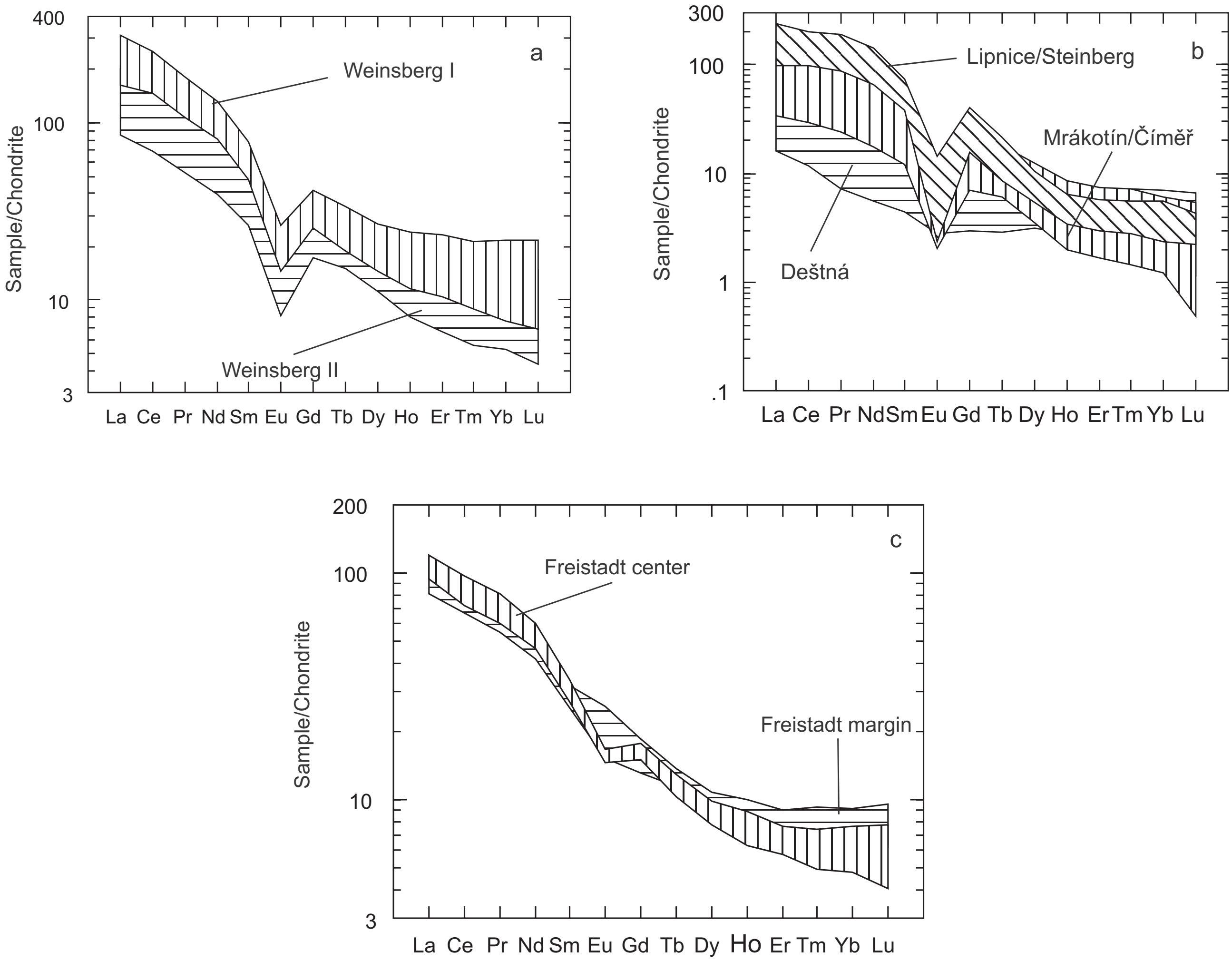

Fig. 3 Chondrite-normalized REE patterns for granitic rocks of the Weinsberg suite (**a**), Eisgarn suite (**b**) and Freistadt suite (**c**). Normalizing values are from Boynton (1984).

(Pouchou and Pichoir 1985). Operation conditions were: accelerating potential 15–20 kV, beam current 10–70 nA (measured on a Faraday cup) and a beam diameter of 2 µm. Both synthetic and natural minerals were used as reference materials. Mineral formulae were recalculated using the MinPet 2.02 software (Richard 1995).

4. Results

4.1. Petrography

The *Weinsberg suite* represents coarse-grained, biotite granites to granodiorites with megacrystic K-feldspar. Major components of the Weinsberg granite are quartz,

Tab. 2 Chemical composition of Moldanubian Batholith granitic rocks

Suite	Variety	A/CNK	SiO_2 wt.%	TiO_2 wt.%	Al_2O_3 wt.%	CaO wt.%	Zr ppm	Th ppm	Rb ppm	La_N/Yb_N	Eu/Eu*
Weinsberg	Weinsberg I	1.0–1.1	64.6–72.1	0.4–0.9	13.7–17.0	1.5–3.0	214–441	19–45	157–279	10.0–33.4	0.30–0.60
	Weinsberg II	1.1–1.4	65.1–74.0	0.2–0.9	13.4–15.9	1.1–2.6	89–389	4–69	172–304	9.7–19.0	0.28–0.53
Eisgarn	Deštná	1.0–1.2	72.0–74.4	0.1–0.2	13.7–15.4	0.5–1.2	15–94	2–7	154–265	3.2–15.6	0.96–1.18
	Mrákotín	1.1–1.3	70.6–74.3	0.1–0.4	13.6–15.3	0.4–1.1	75–175	8–37	181–393	7.1–47.9	0.15–0.59
	Číměř	1.1–1.3	70.8–74.7	0.2–0.4	13.5–16.0	0.5–1.1	84–175	23–54	236–450	13.5–43.3	0.16–0.37
	Lipnice	1.1–1.3	69.5–71.4	0.4–0.5	14.5–15.7	0.9–1.1	182–291	39–54	321–363	29.4–39.0	0.24–0.31
	Steinberg	1.2–1.4	70.3–75.5	0.3–0.5	13.0–15.0	0.3–0.9	143–251	55–110	380–521	20.0–64.5	0.09–0.17
Freistadt	Freistadt central	1.0–1.1	68.1–69.1	0.4–0.5	16.0–16.3	2.4–3.4	102–164	8–13	74–90	12.2–20.9	0.68–0.81
	Freistadt marginal	1.0–1.1	65.2–71.3	0.3–0.7	14.9–17.0	2.0–4.1	99–214	7–18	59–219	9.9–16.6	0.56–0.84
	Grabengranite	1.1–1.1	69.9–72.9	0.3–0.4	14.8–15.8	1.8–2.3	98–171	10–15	85–112	19.7–30.7	0.58

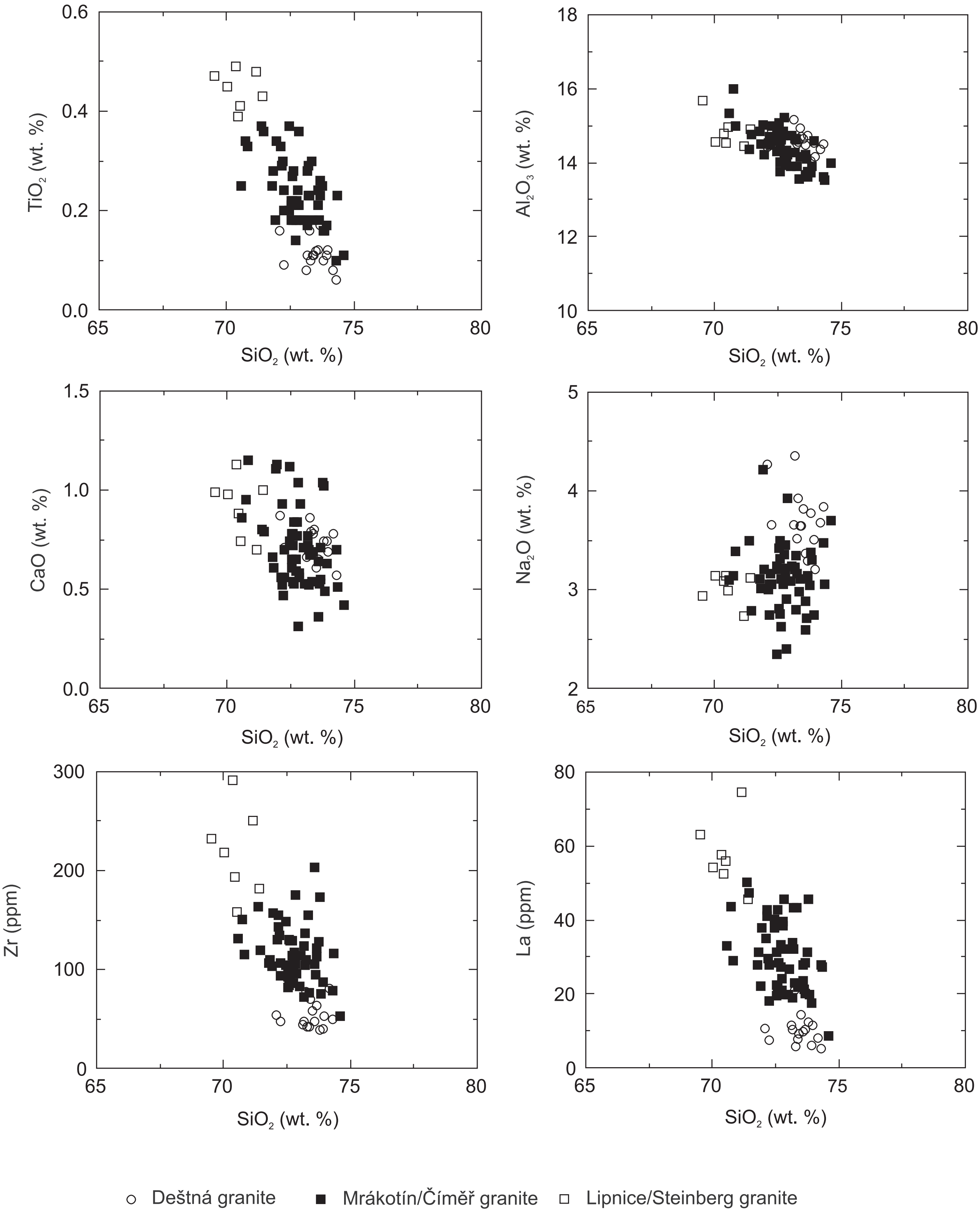

Fig. 4 Binary plots of TiO_2, Al_2O_3, CaO, Na_2O, Zr and La vs. SiO_2 for granitic rocks of the Eisgarn suite.

K-feldspar, plagioclase and biotite. The accessories include apatite, zircon, ilmenite, titanite, allanite, monazite and very rare xenotime. For some samples of the Weinsberg II granite, the presence of garnet was observed (Tab. 1).

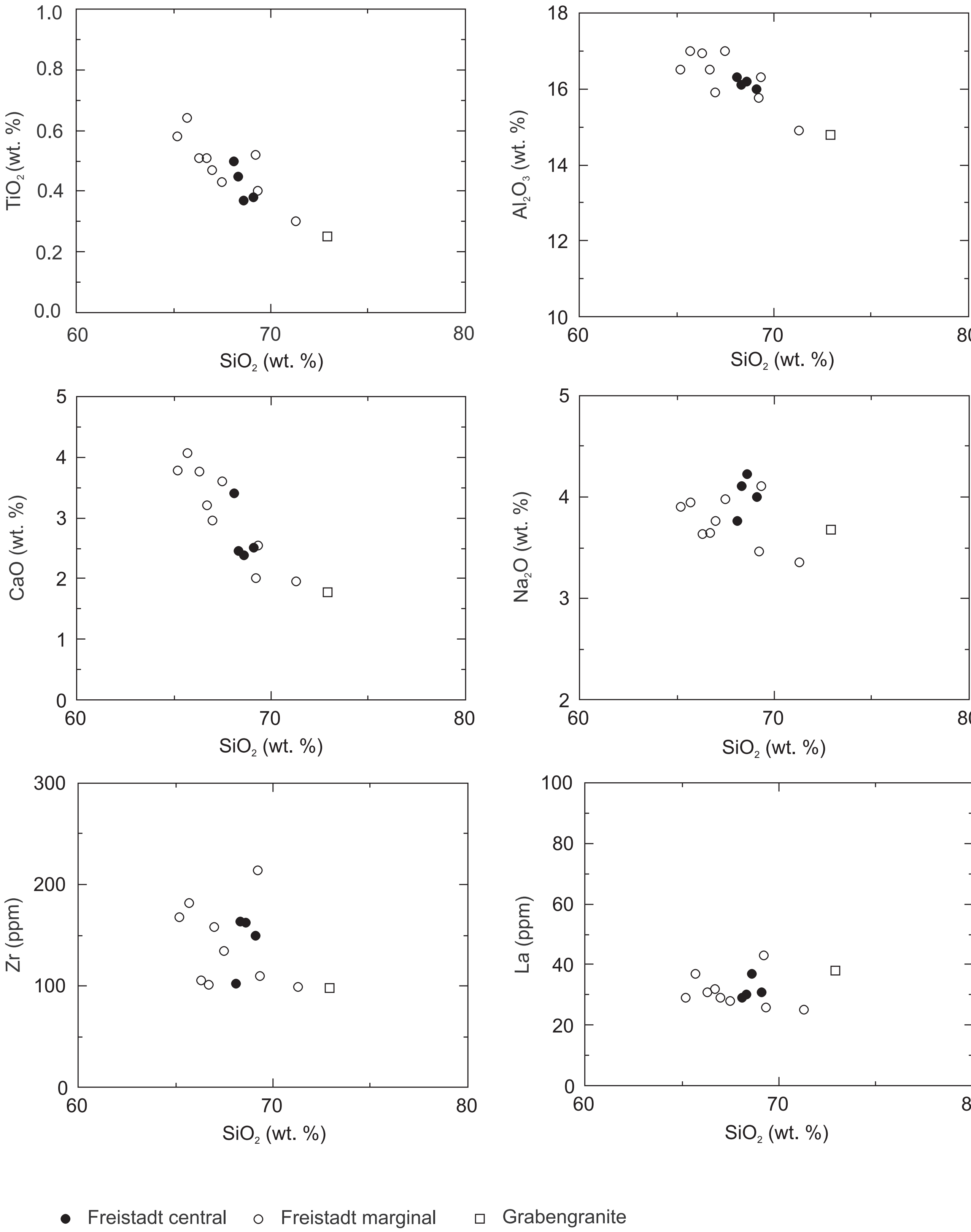

Fig. 5 Binary plots of TiO_2, Al_2O_3, CaO, Na_2O, Zr and La vs. SiO_2, for granitic rocks of the Freistadt suite.

The two-mica granites of the *Eisgarn suite* are the most abundant granitic rocks in the MB. Several petrographic varieties were identified, with variable texture and biotite to muscovite proportions. Monzogranites

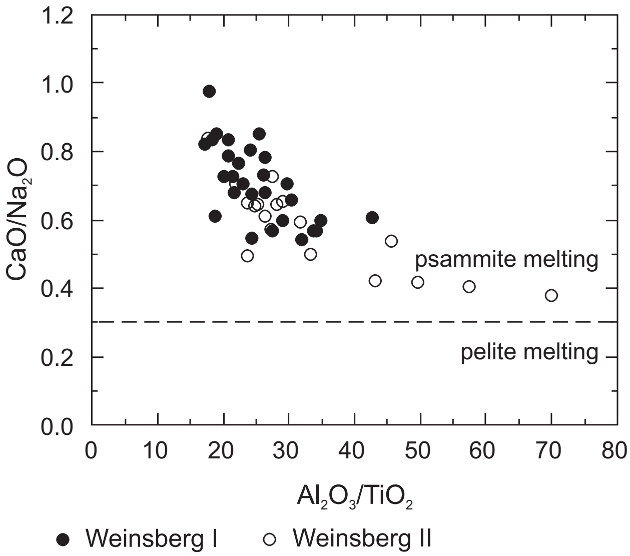

Fig. 6 Plot of CaO/Na_2O vs. Al_2O_3 for granitic rocks of the Weinsberg suite with boundary between experimental melts derived from metapelitic and metapsammitic sources (Jung and Pfänder 2007).

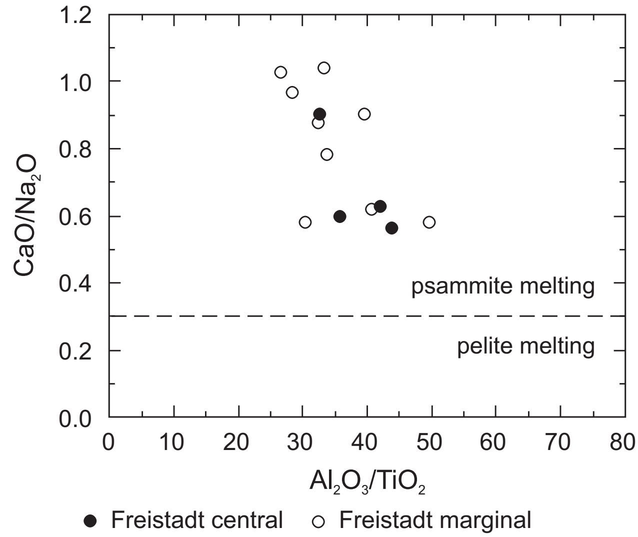

Fig. 8 Plot of CaO/Na_2O vs. Al_2O_3 for granitic rocks of the Freistadt suite with boundary between experimental melts derived from metapelitic and metapsammitic sources (Jung and Pfänder 2007).

dominate over alkali feldspar granites and granodiorites. The Eisgarn suite is generally represented by a porphyritic variety with biotite > muscovite (Číměř/Eisgarn). In the Czech part of the MB, the equigranular granite of the Mrákotín variety predominates. Similar equigranular two-mica granites occur in NW Austria (Sulzberg variety in the Aigen Pluton) and Bavaria (Haidmühle, Theresienreut). In the Klenov Pluton, the equigranular two-mica leucogranites are known as the Deštná granite. In the following section, all the equigranular granites are referred to as the Mrákotín variety (Tab. 1). Accessory minerals in the porphyritic and equigranular varieties of two-mica granites are apatite, ilmenite, zircon and monazite. The accessory mineral assemblage in the Deštná granite contains xenotime in addition.

Major rock-forming minerals of both varieties of the *Freistadt biotite granodiorites* are quartz, plagioclase, K-feldspar and biotite. The Grabengranite contains 3–6 vol. % of muscovite and a slightly lower amount of biotite. The accessories in the Freistadt granodiorite in-

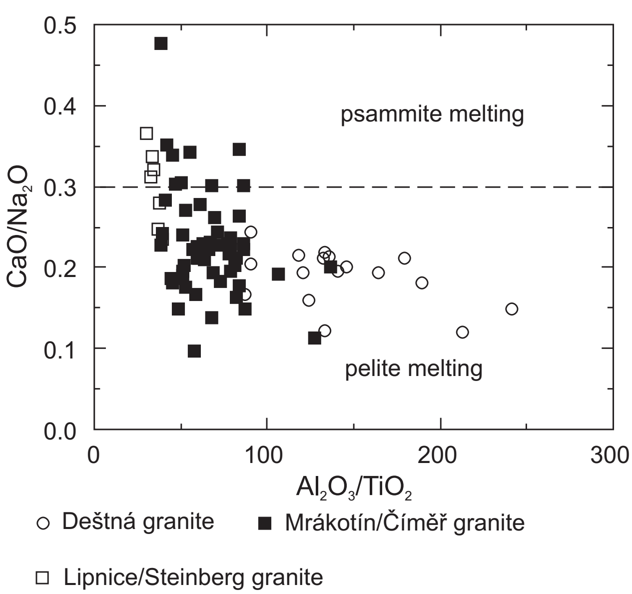

Fig. 7 Plot of CaO/Na_2O vs. Al_2O_3 for granitic rocks of the Eisgarn suite with boundary between experimental melts derived from metapelitic and metapsammitic sources (Jung and Pfänder 2007).

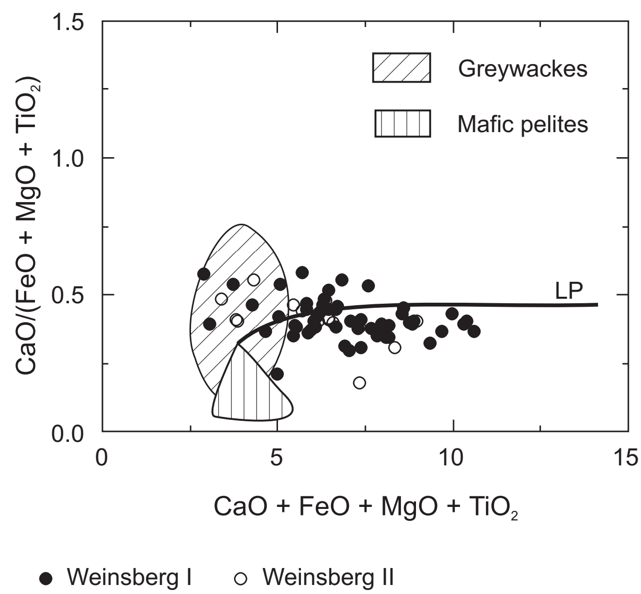

Fig. 9 Composition of the Weinsberg suite compared to melts produced by experimental dehydration melting of various types of metasediments summarized by Patiño Douce (1999). The thick solid line 'LP' is reaction curve that would be produced by hybridization of high-Al tholeiite with metapelite at low pressure (< 5 kbar) (Patiño Douce 1995, 1999).

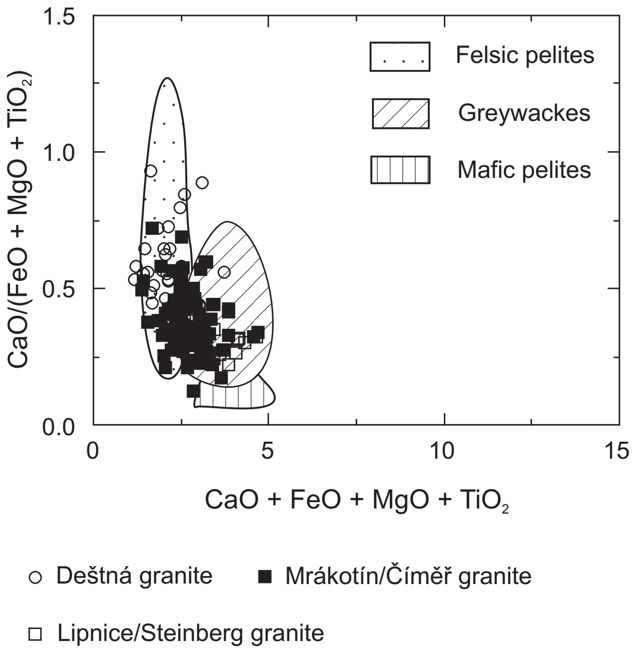

Fig. 10 Composition of the Eisgarn suite compared to melts produced by experimental dehydration melting of various types of metasediments (after Patiño Douce 1999).

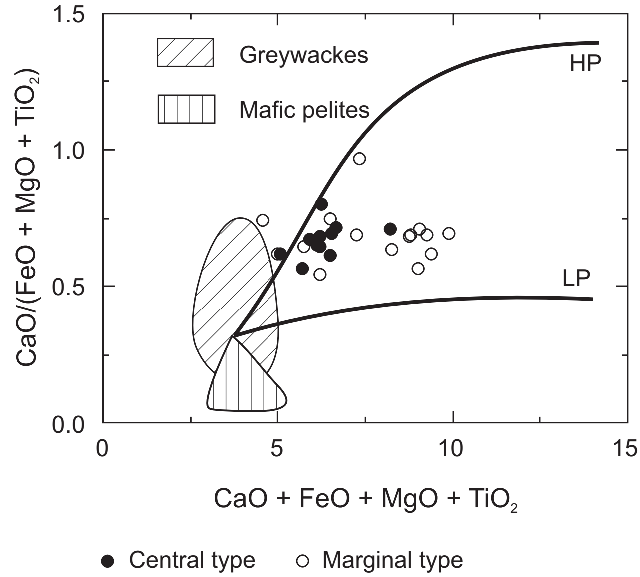

Fig. 11 Composition of the Freistadt suite compared to melts produced by experimental dehydration melting of various types of metasediments (Patiño Douce 1999). The thick solid lines are reaction curves that would be produced by hybridization of high-Al tholeiite with metapelite at low pressure (LP, < 5 kbar) and high pressure (HP, 12–15 kbar) (Patiño Douce 1995, 1999).

clude apatite, ilmenite, zircon, titanite, allanite and rare xenotime (Tab. 1).

4.2. Geochemistry

Discussion of the whole-rock composition of selected granitoids is based on the analyses of 66 samples, both new and published previously (René 2012, 2013; René and Hájek 2010, 2011; René et al. 2008). Their list and analyses are given in the electronic supplement. For the geochemical study of the Weinsberg and Freistadt suite, published analyses of Gerdes (1997) were also used.

The WbG I, II are subaluminous to weakly peraluminous granites with A/CNK [mol. Al_2O_3/(CaO + Na_2O + K_2O)] of 0.9–1.2, SiO_2 65–74 wt. %, Na_2O 2.3–3.9 wt. %, K_2O 3.4–6.2 (Fig. 2) and fractionated REE patterns (La_N/Yb_N = 9.7–33.4; Fig. 3a). Of both varieties of the Weinsberg suite are characteristic high Ba (291–1038 ppm), Sr (75–251 ppm), Zr (89–441 ppm) and ΣREE (133–491 ppm). The WbG II differs from the WbG I by lower Sr (75–206 ppm) and lower La_N/Yb_N ratios (9.7–19.0) (Fig. 3a, Tab. 2).

Three main geochemical varieties of two-mica granites could be distinguished: the low-Th (2–7 ppm) Deštná granites, the intermediate-Th Mrákotín/Číměř granites (8–54 ppm) and the high-Th Lipnice/Steinberg granites (39–110 ppm) (Tab. 2). All these granites are subaluminous to strongly peraluminous (A/CNK 1.0–1.3) with low CaO concentrations (0.3–1.2 wt. %) (Fig. 4, Tab. 2). In the most peraluminous ones, magmatic andalusite, sillimanite and rarely cordierite are present. In Mrákotín granites, peraluminosity is also expressed by widespread dominance of muscovite over biotite. The highest ΣREE was found in the Lipnice and Steinberg granites (207–242 ppm), whereas the lowest ΣREE was observed in the Deštná granites (33–69 ppm). For granites of the Mrákotín/Číměř variety, higher LREE/HREE ratios (La_N/Yb_N = 7–48) and, remarkably deep negative Eu anomalies (Eu/Eu* = 0.15–0.59) were found. The decrease in LREE, Th and Zr with increasing Rb and Cs concentrations can be observed in more fractioned samples of these granites. The LREE/HREE ratio of the Lipnice/Steinberg varieties is higher (La_N/Yb_N = 20–65) than in the Deštná granites (La_N/Yb_N = 3–16). The Deštná granites display none or slightly positive Eu anomaly (Eu/Eu* = 0.96–1.18) (Fig. 3b, Tab. 2).

All varieties of the Freistadt suite are subaluminous (A/CNK = 1.0–1.1) with elevated CaO concentrations (marginal granodiorites: 2.0–4.1 wt. %, central granodiorites 2.4–3.4 wt. %, Grabengranite: 1.8–2.3 wt. %) (Fig. 5). Granodiorites of the central and marginal facies are rich in Ba (687–1017 ppm, 469–875 ppm) and Sr (316–334 ppm, 253–471 ppm) respectively; their ΣREE are 129–279 ppm. These granodiorites display relatively low La_N/Yb_N of 10–17 with moderate to low negative Eu anomaly (Eu/Eu* = 0.56–0.84) and low Th (7–18 ppm). The Grabengranite is more fractioned with La_N/Yb_N = 20–31 and Eu/Eu* = 0.58 (Fig. 3c, Tab. 2).

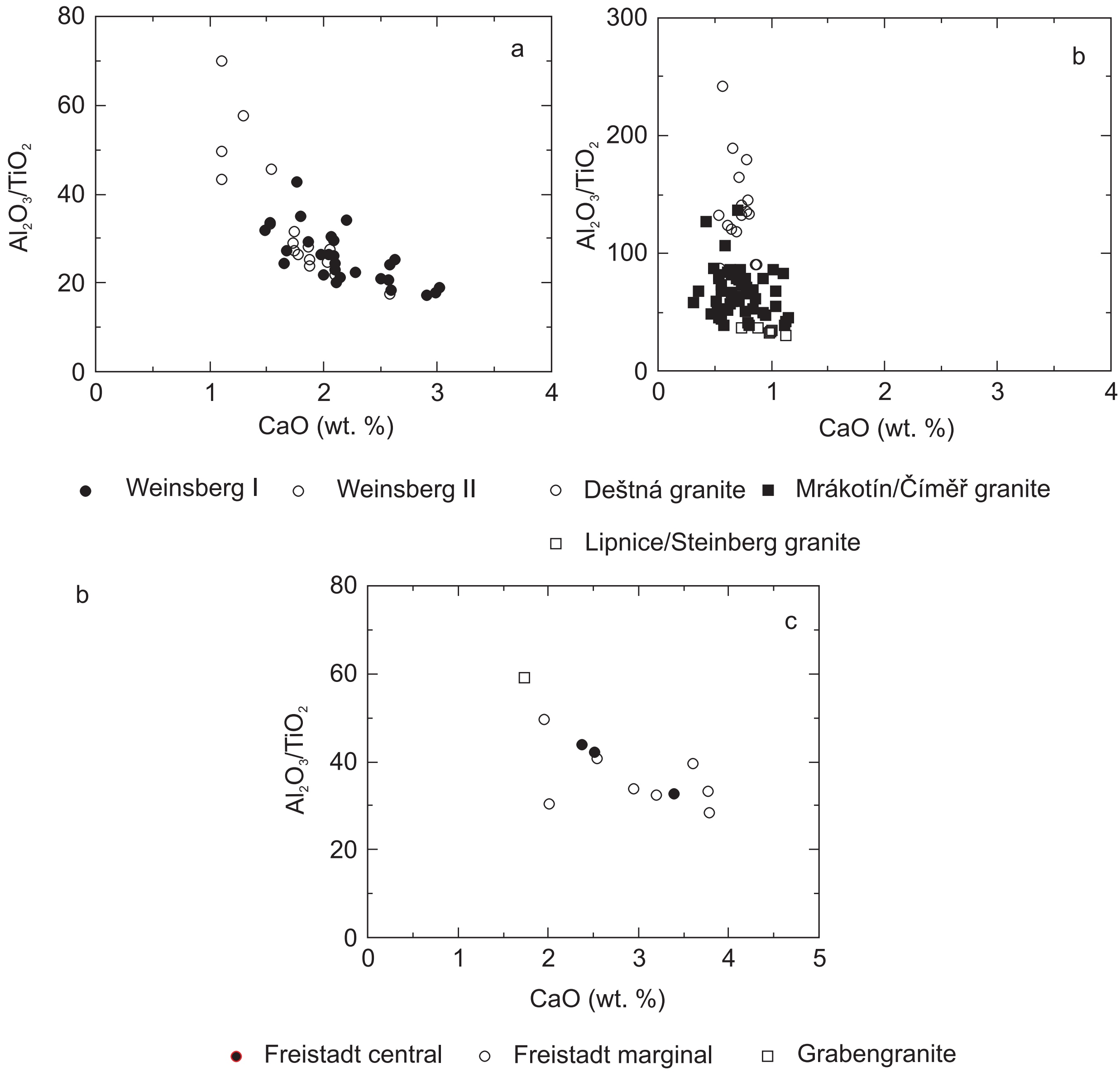

Fig. 12 Plot of Al_2O_3/TiO_2 vs. CaO for granitic rocks of the Weinsberg suite (**a**), Eisgarn suite (**b**) and Freistadt suite (**c**).

4.3. CaO/Na_2O as an index of source composition

As shown by Sylvester (1998) and Jung and Pfänder (2007), the CaO/Na_2O ratio can be used to highlight the effect of source composition on granitic melts. For highly peraluminous granites with clay-rich sources, the CaO/Na_2O ratio is a valuable index of source composition. However, it is less useful for intermediate I/S type rocks, as their CaO/Na_2O ratios are similar to those of metagreywackes (e.g., Condie 1993; Sylvester 1998). Partial melts of metapelites have $CaO/Na_2O < 0.3$, whereas those of metagreywackes have this ratio mostly higher. Melts with variable, and often high CaO/Na_2O ratios of 0.1 to 9.9 may be derived from metabasaltic sources, as shown by laboratory experiments (Jung and Pfänder 2007 and references therein).

Granitoids of the Weinsberg suite display the highest CaO/Na_2O ratios, especially the Wbg I facies (0.48–0.98) (Fig. 6). All these granitoids were probably derived from metagreywackes, metagranites and/or melt of a metagreywackes–metabasites mixture. Two-mica granites of the Eisgarn suite display distinctly lower CaO/Na_2O ratios (0.10–0.48); most of them (Mrákotín and Deštná varieties) display $CaO/Na_2O < 0.3$ (Fig. 7). Therefore, potential protolith of two-mica granites had very probably metapelitic composition. Melting of metagreywackes could have produced granites and granodiorites of the Freistadt suite with CaO/Na_2O ratios of 0.47 to 1.04 (Fig. 8).

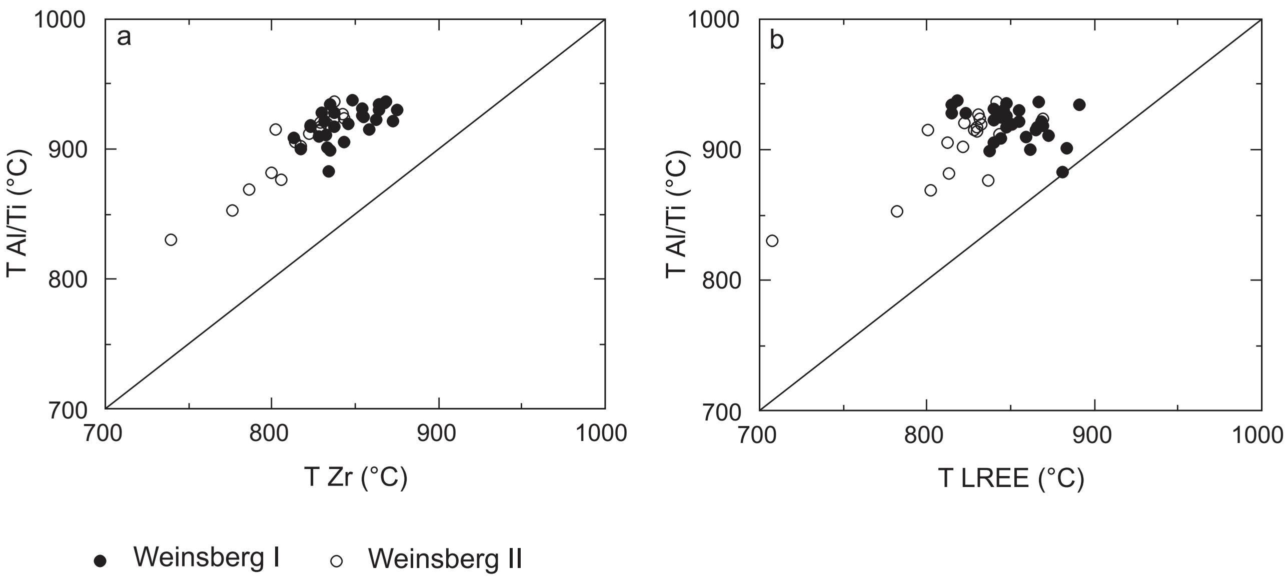

Fig. 13a – Plot of Al_2O_3/TiO_2 temperature estimates vs. zircon saturation temperatures for the Weinsberg suite; **b** – Plot of Al_2O_3/TiO_2 temperature estimates vs. LREE (monazite) saturation temperature for the Weinsberg suite.

According to this partly elevated ratio granodiorites of the Freistadt suite could be also derived from tonalitic and/or metabasaltic sources.

4.4. CaO/(FeO + MgO + TiO_2) as an index of source composition

For subaluminous to weakly peraluminous granites and granodiorites some other major elements ratios, such as (Na_2O + K_2O)/(FeO + MgO + TiO_2) or CaO/(FeO + MgO + TiO_2), are useful indices for source composition (Patiño Douce 1999). Both ratios can help distinguish between felsic or mafic metapelite and metagreywacke sources.

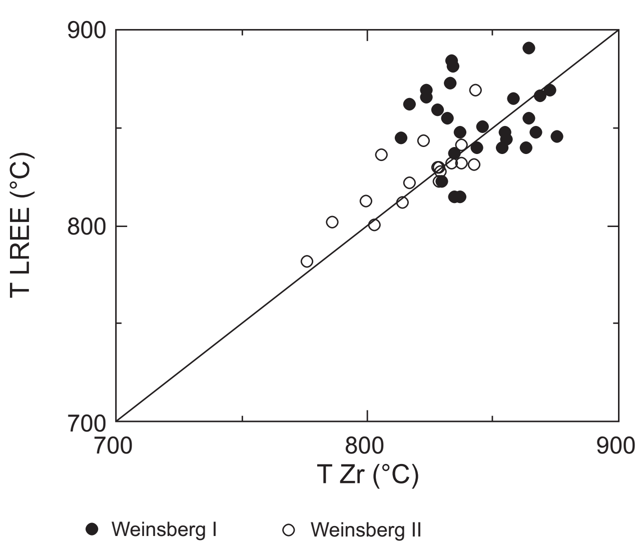

Fig. 14 Plot of LREE saturation temperature vs. zircon saturation temperature for the Weinsberg suite.

According to the CaO/(FeO + MgO + TiO_2) ratio (0.31–0.58) the parental magma of the Weinsberg suite could have been produced by hybridization of high-Al olivine tholeiite melt with metagreywackes and metapelites (Fig. 9). According to this ratio the majority of two-mica granites of the Eisgarn suite were probably derived by melting of metapelites and metagreywackes (Fig. 10). In particular, the CaO/(FeO+ MgO + TiO_2) ratios for the Deštná granites (0.24 to 1.97) require mainly felsic metapelites in the source. The two-mica granites of the Lipnice/Steinberg variety may have been derived by melting of metagreywackes (Fig. 10). The granites and granodiorites of the Freistadt suite (CaO/(FeO + MgO + TiO_2) = 0.49–0.97) could have been again generated by hybridization of tholeiitic melts with metagreywackes (Fig. 11).

4.5. Al_2O_3/TiO_2 ratio as a geothermometer

Experimental results suggest that Al_2O_3/TiO_2 ratios can be used to constrain the melting temperatures of granitoids (Sylvester 1998; Jung and Pfänder 2007). During partial melting of metapelites and metagreywackes, concentrations of Al_2O_3 in the melt remain constant, due to buffering by aluminous minerals (plagioclase, garnet, cordierite or Al_2SiO_5). In contrast, the TiO_2 concentration increases with increasing temperature, probably due to the progressive breakdown of biotite or ilmenite at higher temperatures (Sylvester 1998). As shown in Fig. 12, Al_2O_3/TiO_2 vs. CaO concentrations are controlled by content of plagioclases, whereas concentrations of TiO_2 in S-type granites may be, to a large extent, driven by accumulation of ilmenite. However, in I-type and I/S-type granites Al_2O_3/TiO_2 ratios and TiO_2 concentrations are also controlled by occurrence of titanite.

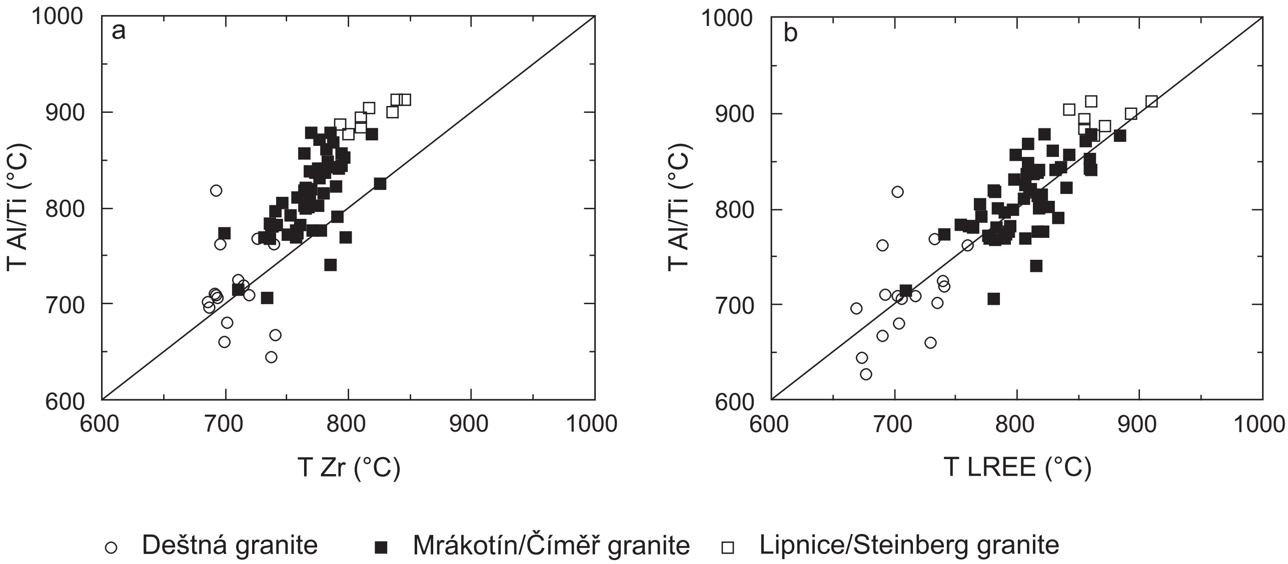

Fig. 15a – Plot of Al_2O_3/TiO_2 temperature estimates vs. zircon saturation temperature for the Eisgarn suite; **b** – Plot of Al_2O_3/TiO_2 temperature estimates vs. LREE saturation temperature for the Eisgarn suite.

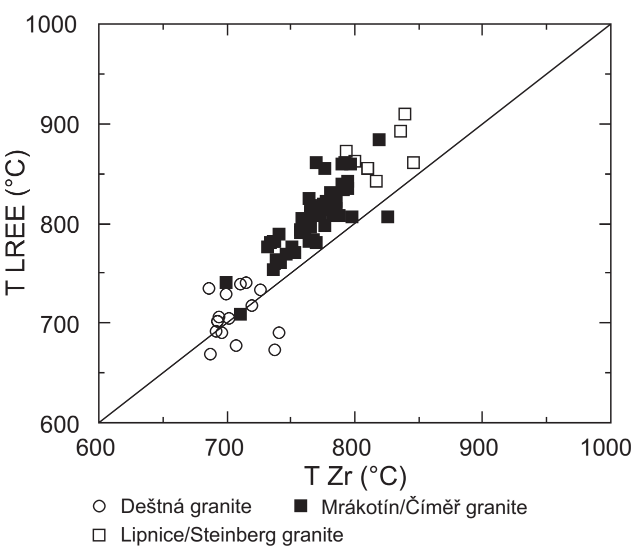

Fig. 16 Plot of LREE saturation temperature vs. zircon saturation temperature for the Eisgarn granite suite.

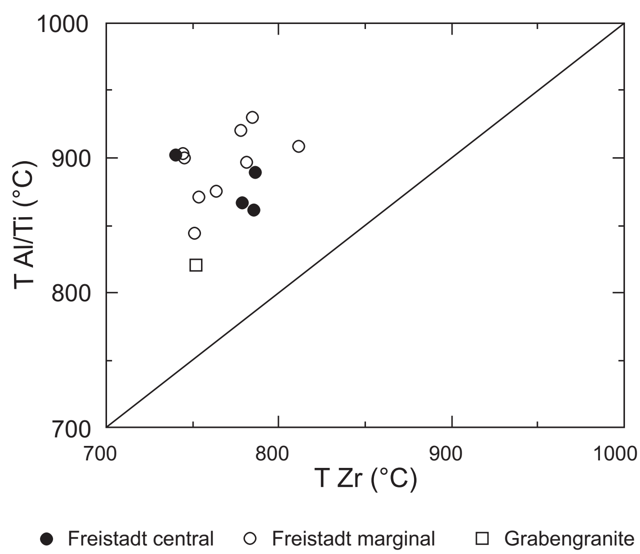

Fig. 17 Plot of Al_2O_3/TiO_2 temperature estimates vs. zircon saturation temperature for the Freistadt suite.

Using the good correlation between Al_2O_3/TiO_2 ratios and temperatures of partial melts derived from different source rocks, 18 quantitative thermometric expressions were calculated by Jung and Pfänder (2007), utilizing different regression methods (power law, exponential law, linear regression) for pelite, psammite, amphibolites and igneous rock melting. All these expressions were tested for all granite varieties of the MB. The best agreement with the temperatures calculated using conventional accessory mineral saturation thermometry (Watson and Harrison 1983; Montel 1993) was obtained by using the exponential regression method for psammite melting (T ºC = [ln (23400) – ln (Al_2O_3/TiO_2)]/0.00729).

In regard of potential metapelitic protolith of two-mica granites of the Eisgarn suite were also tested Al_2O_3/TiO_2 temperature equations for pelite melting. However, these equations display distinctly higher, very probably unrealistic melting temperatures.

For the Weinsberg suite, the temperatures calculated from Al_2O_3/TiO_2 ratios are 830–938 ºC, and thus *c.* 20–100 ºC higher than both saturation temperatures (Fig. 13). The saturation temperatures are mutually comparable; however, some differences are observed that may be explained by the presence of inherited zircon or monazite grains (Fig. 14).

Comparison of temperatures calculated from Al_2O_3/TiO_2 ratios and saturation models for granitoids of the

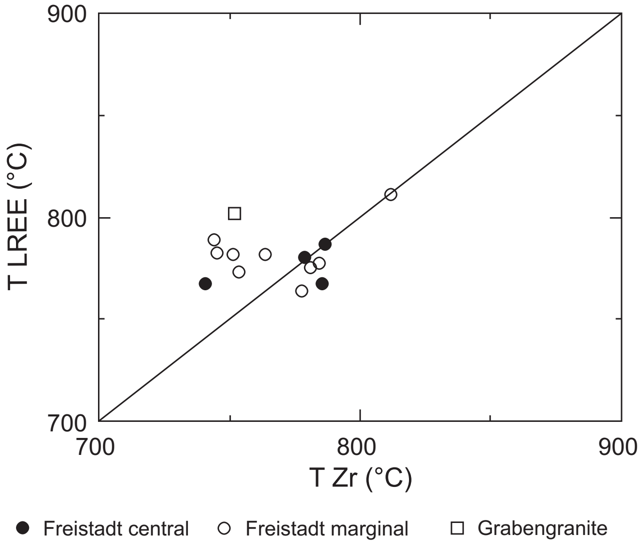

Fig. 18 Plot of LREE saturation temperature vs. zircon saturation temperature for the Freistadt suite.

Eisgarn suite paints another picture. The lowest melting temperatures were found for the Deštná granites (627–763 ºC), and the highest for the Lipnice/Steinberg granites–granodiorites (884–913 ºC). They are thus 4 to 67 ºC higher than the zircon saturation temperatures (Fig. 15). The highest difference is seen in the Lipnice/Steinberg granites, which display the lowest Al_2O_3/TiO_2 ratios but the highest TiO_2 concentrations (up to 0.5 wt. %). Saturation temperatures for zircon are usually 3 to 64 ºC lower than the LREE saturation temperatures (Fig. 16).

The temperature range for Freistadt biotite granodiorite calculated from the Al_2O_3/TiO_2 ratios is 820–930 ºC, and thus 59–118 ºC higher than the zircon saturation temperatures (Fig. 17). The LREE saturation temperatures are partly higher than the zircon-based ones (Fig. 18).

5. Discussion

In the past, the origin of granitoids from the Moldanubian Batholith was discussed using source modelling based on trace-element distribution (Vellmer and Wedepohl 1994; Siebel et al. 2008), Sr–Nd isotope compositions (Liew et al. 1989; Vellmer and Wedepohl 1994; Finger and Clemens 1995; Matějka and Janoušek 1998; Gerdes 2001) and experimental stability of biotite (René et al. 2008). All these studies concluded that granitoids of Moldanubian Batholith were generated by LP–HT partial melting of metasedimentary sources (especially granites of the Eisgarn suite; Vellmer and Wedepohl 1994; René et al. 2008) and/or by melting of a mixture of metasediments and amphibolites (e.g., Weinsberg suite; Gerdes 2001). The majority of these studies presumed that the granitic magmas further evolved by often significant fractional crystallization, (e.g., Matějka and Janoušek 1998; Breiter 2010; Žák et al. 2011).

The use of major-element data, especially CaO/Na_2O and/or $CaO/(FeO + MgO + TiO_2)$ ratios, for distinguishing source rocks of granitic melts was largely discussed by Patiño Douce (1995, 1999), Sylvester (1998) and Jung and Pfänder (2007). These studies, based on extensive databases of melting experiments (e.g., Patiño Douce 1999), showed that the CaO/Na_2O ratio is suitable for source rock estimation in the case of peraluminous granites (Sylvester 1998), whereas the $CaO/(FeO + MgO + TiO_2)$ ratio can be used for both peraluminous and metaluminous felsic compositions (Patiño Douce 1995, 1999). Melts with high CaO/Na_2O ratios are generally interpreted as being derived from orthogneisses and/or amphibolites, rather than metagreywackes (e.g., Miller 1985; Sylvester 1998; Jung and Pfänder 2007).

The estimation of melting temperatures of granitic melts is often based on conventional saturation thermometers (Watson 1979; Watson and Harrison 1983; Montel 1993). However, especially in granitic rocks with abundant inherited zircon, the zircon saturation temperatures need to be interpreted with caution (Miller et al. 2003). In the case of the MB, these conventional thermometers were used for estimating melting temperatures of the Weinsberg (Gerdes 1997) and Eisgarn (Gerdes 1997; René et al. 2008) suites.

The systematic positive shift of Al_2O_3/TiO_2 temperatures in comparison with conventional saturation thermometers was explained by Jung and Pfänder (2007) through disequilibrium partial melting, during which some zircon and monazite were left in the source region. On the other hand, such differences found in all granite suites of the MB may be better accounted for by accumulation of ilmenite in the S-type granites, joined by titanite in the I- and I/S-type granites. Consequently, use of the Al_2O_3/TiO_2 ratios for determination of granite melting temperatures can be questionable, especially in the fractionated I- and I/S-type granites.

6. Conclusions

This study of CaO/Na_2O and Al_2O_3/TiO_2 ratios in three main magmatic suites of the Moldanubian Batholith (BM; Bohemian Massif) showed that both ratios might be, with some caution, used to constrain possible source rocks and melting temperatures. The melt of the Weinsberg suite was probably generated by partial melting of a metagreywackes–metabasalts mixture at *c.* 740–940 ºC. According to the $CaO/(FeO + MgO + TiO_2)$ ratios, the majority of two-mica granites (Mrákotín/Číměř varieties) were generated by melting of metapelites at 770–825 ºC. Melting of felsic metapelites probably generated Deštná leucogranites, whereas melting of metagreywackes could have produced the Lipnice/Steinberg granites. The systematic positive shift of Al_2O_3/TiO_2 temperatures compared with zircon and monazite saturation temperatures in some S-type granites (Mrákotín/Číměř and Lipnice/Steinberg varieties) of the MB (up to ~+70 ºC) can be explained by ilmenite accumulation. In I- and I/S-type granites of the MB, the distinctly higher difference between both approaches (up to ~+120 ºC) may be explained by ilmenite accumulation and/or by the appearance of titanite.

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Electronic supplementary material. The sample locations and whole-rock geochemical data for the newly analysed samples are available online at the Journal web site (*http://dx.doi.org/10.3190/jgeosci.223*).

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