Petrochemistry of Variscan granitoids of Central Europe: Correlation of Variscan granitoids of the Tisia and Pelsonia Terranes with granitoids of the Moldanubicum, Western Carpathian and Southern Alps. A review: Part I

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Three major groups (A–C) of Central European Variscan granitoids can be distinguished based on petrologic and chemical data:

A. Low-K, high-Na, calc-alkaline, alkali-calcic, met/peraluminous, I- and S-type, trondhjemitic (slightly granodioritic)-suite, mostly magnesium granitoids formed at the early stage of continent-continent collision (353–356 Ma). These types of granitoids occur in the northern part of the Central Bohemian Plutons (CBP) in the Moldanubic Zone or in the Austroalpine Zone of the outer belt of the Western Carpathian Plutons (WCP). The granitoid melt source originated from partially melted oceanic and continental crusts due to compression.

B. High-K, high-Mg, calc-alkaline, metaluminous, I-type, monzonitic-suite granitoids with lamprophyre-derived small, ultrapotassic, Mg-rich intrusions formed in the post-collision zone, where the melts originated from the partially melted, uplifted, LIL-rich mantle and continental crust, due to extension (334–354 Ma) after earlier compression. These intrusions can be found in the southern part of the CBP, the eastern part of Southern Bohemian Plutons (SBP) and northwestern part of the Tisia Terrain. Later on (314–303 Ma), as a result of interaction of melts originated from depleted mantle and partial melted lower crust, low-K, high-Na, calc-alkaline-type granitoids formed during extension, occurring in the inner part of the WCP.

C. Peraluminous, S or S/A-type granodioritic-suite, small intrusions with some K-subalkaline and alkaline characters, formed in post-orogenic or probably rifting settings at the main tectonic zones, e.g. the Periadriatic–Balaton Lineament (Velence Mts, Gemericum) during the Lower Permian (274±1.7 Ma).

The most unstable part of the Variscan orogenic belt was where the high K, Mg-calc-alkaline granitoid and ultrapotassic intrusions occur (Massif Central, Vosges, Black Forest, the southern part of the CBP, the eastern part of the SBP and the northwestern part of the Tisia Terrain). They formed the innermost part of the Variscan Belt; only the Tisia Terrain occurs in allochthonous positions, which originated from the Moldanubian Zone and were completely separated from it since mid-Cretaceous times.

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Introduction

Approximately one thousand high-quality whole rock chemical analyses of granitoids were collected from the Moldanubian Zone of the Variscan collision belt (Central and South Bohemian Plutons), the West Carpathian Plutons, the Tisia and Pelsonia Terranes and the Southern Alps from references (Hovorka 1972; Vejnar 1972; Bargossi et al. 1979; D’Amico 1979; Alberti et al. 1983; Jantsky 1957, 1979; Buda and Dobosi 2004b) and submitted to renewed analysis by atomic absorption and XRF methods. This large number of major element rock analyses was evaluated using petrochemical calculations and statistical methods (see part II). In this paper we deal with only the major chemical components, in spite of the large number of modal, trace element and isotope analyses available, in order to classify and correlate the granitoids. The similarities mean that similar sources of melt produced similar geodynamic events during the evolution of the Variscan orogenesis.

Methods

We used the Debon and Le Fort’s (1983) methods based on De La Roche’s (1964) diagram (Q = Si/3-[K+Na+2Ca/3], P = K-[Na+Ca] expressed in gram-atoms × 10³ for each element in 100 g of rock), which is more or less comparable with Streckeisen’s (1976) Q-Pl-Kf modal diagram, only Debon and Le Fort’s granite includes syenogranite and part of the monzogranite of Streckeisen, and the other part of Streckeisen’s monzogranite corresponds to adamellite. We use the term "granite" instead of granite, adamellite or syenogranite, monzogranite, and "granitoid" in a general sense, including all quartz, plagioclase and alkaline feldspar-bearing plutonic rocks.

Debon et al. (op cit.) used Shand’s (1927) per- and metaluminous indices (peraluminous = K+Na+2Ca<Al, metaluminous = K+Na+2Ca>Al) and the B = (Fe+Mg+Ti) index referring to the dark minerals in granitoids introduced by De La Roche (op cit.). The characteristic leucocratic and melanocratic minerals were counted and plotted on the A (Al – [K+Na+2Ca]) vs. B (Fe+Mg+Ti) diagram. Two domains were distinguished: (i) peraluminous Al-rich and Ca-poor granites (I. muscovite alone or muscovite>biotite by volume, II. biotite> muscovite, III. only biotite = siderophyllite or annite) and (ii) metaluminous Al-poor granites, always Ca-rich and containing Mg-rich biotite, amphibole and/or orthopyroxene, clinopyroxenes, sphene, etc. The A/CNK ratio is very sensitive to alteration; consequently it can only be used with caution. The two domains were divided into three types: cafemic (hybrid source with prevailing mantle component), alumino-cafemic (also hybrid, with prevailing sialic crustal component) and aluminous (originated through anatexis of sialic crust). Cafemic is equivalent.
to I-type, with A/CNK<1.1 at SiO₂ = 70 wt%, and aluminous to S-type granitoids (A/CNK>1.1) of Chappell and White (1974) and White and Chappell (1977). There is a correlation between magnetite-series I-type and ilmenite-series S-type granitoids (Ishihara 1977; Chappell and White 2001). The cafemic (aluminocafemic) includes the tholeitic, alkaline, subalkaline and calc-alkaline granitoids.

Lameyre and Bowden (1982) distinguished three suites within the calc-alkaline series: low-K or trondhjemitic (tonalite), medium-K or granodioritic and high-K or monzonitic suites, based on modal values; later, however, Bowden et al. (1984) proved that the norms give similar results (remark: norm counting from chemical analyses always results in higher plagioclase content compared to modal). Na₂O-K₂O-CaO ratios were plotted in order to distinguish the high-K and the high Na-granitoids. Debon and Le Fort (1983) classified the monzonitic suite into subalkaline (or monzonitic) subtype because of enrichment in potassium. It is intermediate between the calc-alkaline and alkaline series and often called potassic calc-alkaline suites. The AFM diagram (Irvine and Baragar 1971) was useful for the discrimination of the tholeiitic series from the calc-alkaline one. Mg and Fe-enriched granitoids were distinguished within the calc-alkaline series. The A/NK (Al/Na+K) vs. A/CNK plot (Maniar and Piccoli 1989) was used for the discrimination of metaluminous, peraluminous and peralkaline (A/NK<1) granitoids. Barbarin (1990) described three main contrasted granitoid types:

1. The crustal-type, formed in the continent-continent collision zone, divided into three subgroups: (a) intrusive two-mica leucogranites, (b) peraluminous autochthonous granitoids, (c) peraluminous intrusive granitoids.

2. The mixed type (crust+mantle), divided into two subgroups: (a) K-rich hybrid type, originating from the injection of mantle melts into the thick continental crust following collision (compression) during relaxation (extension), and (b) K-poor, intruded in the thin continental crust above the subduction zone.

3. The mantle origin type, formed in island arc or mid-oceanic environments (tholeiitic), or in continental rifting zones (alkaline and peralkaline).

Pearce (1996) distinguished (a) ocean ridge granites (ORG), which predominantly contain Na-rich tonalite and plagiogranite (metaluminous, alkalic and calcic with clinopyroxene and amphibole) fractioned from basalt, (b) volcanic arc granites (VAG) with subduction signatures, containing I-type granodiorite and tonalite (metaluminous, calc-alkaline with pyroxene, amphibole and biotite), (c) within-plate granites (WPG) contain A-type alkali granites of peralkaline composition with Na-pyroxene and amphiboles. The syn-collision granites can be continent-arc collision, producing metaluminous, I-type granites with biotite or continent-continent collision ones with peraluminous, S-type granites with muscovite and biotite. The post-collision granites can range from I- to A-type; the melts originated from mantle above an earlier subduction zone with I-type character or were derived from the lithosphere beneath the passive margin with A-type character. Barbarin (1999) distinguished seven granitoid groups according to their mineral compositions, petrography,
chemistry and tectonic settings: 1. muscovite-bearing peraluminous (MPG), 2. cordierite-bearing (biotite-rich) peraluminous (CPG) of crustal origin, S-type formed in the continent-continent collision zone, 3. K-rich, calc-alkaline with K-feldspar porphyries (KCG) formed in transitional regimes, 4. amphibole-rich, calc-alkaline (ACG) of mixed origin (mantle+crust), I-type, formed in subduction zones, 5. arc tholeiitic (ATG), 6. ridge tholeiitic (RTG), M-type, 7. peralkaline and alkaline mantle origin A-type granitoids (PAG) related to continental rifting. The granitoid can be used correctly as a geodynamic indicator if all geochemical, chronological and structural data are known. Frost et al. (2001) introduced a new geochemical classification based on the aluminum saturation index (ASI), modified alkali-lime index (MALI) and Fe-number. The Fe-number or Fe* = FeO/FeO+MgO is convenient for separation of magnesian (Cordilleran) and ferroan (A-type) granitoids. The magnesian continues into the field of the ferroan-type as a result of differentiation; consequently, these indices are useful if the whole suite is considered between SiO₂ = 50–75 wt% giving information about the differentiation history of the magma. The MALI (Na₂O+K₂O-CaO), related to the source of magma, and the ASI (Al/(Ca-1.67*P)+Na+K), provide information about the nature of micas and accessories. Sixteen granitoid-types were created with the combination of these indices but some of them are not known in nature. The granitoid rock compositions were plotted in the De La Roche et al. (1980) R₁ [4Si-11(Na+K)-2(Fe+Ti)] and R₂ (6Ca+2Mg+Al) diagram, showing six tectonomagmatic divisions postulated by Pitcher (1979, 1982) and applied by Batchelor and Bowden (1985) for different major granitoid associations. In order to predict the most important accessory minerals supporting the previously identified I- (magnetite) and S- (ilmenite) types of granitoids, M = (Na+K+2Ca)/(Al*Si) and D = (Na+K+2Ca)/(Al+Si)*Al) indices were counted. According to Rapp et al. (1987) and Montel (1986, 1993), if M is between 1–1.3, D = 0.9–1.1 and Ca<0.7 wt%, monazite is the only characteristic accessory mineral and the host rock is peraluminous S-type granitoid; if these indices are lower and CaO more then 2.0 wt% only allanite occurs, and the host rock is metaluminous I-type granitoid.

Petrochemistry of granitoids of Central Europe

Moldanubian Zone

In Central Europe two main magmatic complexes occur in the Moldanubian Zone of the Variscan orogenic belt: I. Central Bohemian Plutonic Complex II. South Bohemian Plutonic Complex (Fig. 1).

I. Central Bohemian plutonic complex (CBP)

Two main zones were distinguished according to the major chemical composition of granitoid rocks: 1. the granitoids of the northern zone (Sázava, Červená, Blatná, Benešov rock types) are rich in Na (Na/K=1.0). Major rock types
Fig. 1
Sketch map showing locations of investigated Variscan granitoids
### Characters of Variscan granitoid rocks occurring in Central Bohemian Plutonic Complex, South Bohemian Plutonic Complex

#### CENTRAL BOHEMIAN PLUTONIC COMPLEX (CZECH REPUBLIC)

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<th>Locality</th>
<th>Chemical parameters</th>
<th>Rock nomenclature</th>
<th>Characteristic minerals</th>
<th>Zircon typology</th>
<th>Characteristic accessories</th>
<th>Tectonic environment</th>
<th>Source rock</th>
<th>fO2</th>
<th>ΩDm</th>
<th>ΩSr,ΩSr</th>
<th>K/Ar Ma</th>
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<tr>
<td>Šineva, Červená Bláni Benčetov</td>
<td>metaluminous</td>
<td>(75%) Na/K=0.0</td>
<td>granite; 33% quartz monzonte; 24% granodiorite; 24% calc-alkaline granodiorite-suit</td>
<td>pyroxene hornblende biotite</td>
<td>plagioclase feldspar; biotite</td>
<td>post-collisional uplift</td>
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<td>II. zone</td>
<td>Černový dvůr, Třeboň, Sudíky, Řízany</td>
<td>metaluminous</td>
<td>granite; 35% quartz monzonte; 35% granite; 9% high-K-Mg calc-alkaline monzonte suite</td>
<td>pyroxene hornblende calc-alkaline type Mg-biotite (low oxidized)</td>
<td>plagioclase feldspar; biotite</td>
<td>post-collisional uplift</td>
<td>biotite</td>
<td>-</td>
<td>0.7102</td>
<td>0.7128</td>
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#### SOUTH BOHEMIAN PLUTONIC COMPLEX (AUSTRIA)

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<th>Rock nomenclature</th>
<th>Characteristic minerals</th>
<th>Zircon typology</th>
<th>Characteristic accessories</th>
<th>Tectonic environment</th>
<th>Source rock</th>
<th>fO2</th>
<th>ΩDm</th>
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<th>K/Ar Ma</th>
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<th>U/Pb Ma</th>
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<td>I. Rastenberg</td>
<td>metaluminous</td>
<td>(82%) Na/K=0.8</td>
<td>granite; 35% quartz monzonte + quartz monzonte + quartz monzonte (2-60%) granodiorite 18% granite; 13% High-K-Mg calc-alkaline monzonte suite</td>
<td>pyroxene hornblende calc-alkaline type Mg-biotite (low oxidized)</td>
<td>plagioclase feldspar; biotite</td>
<td>post-collisional uplift</td>
<td>biotite</td>
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<td>322</td>
<td>340</td>
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<td>353-338</td>
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<tr>
<td>II. Schrems Mauthausen, Weingeb, Čeplčí</td>
<td>peraluminous</td>
<td>(100%) Na/K=0.9</td>
<td>granite; 35% granodiorite; 24% calc-alkaline granodiorite suite</td>
<td>muscovite peraluminous Fe-Al biotite</td>
<td>plagioclase feldspar; biotite</td>
<td>magma-magma interaction</td>
<td>biotite</td>
<td>-</td>
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<td>0.7142</td>
<td>293-312</td>
<td>318</td>
<td>331-323</td>
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Isotopic data from: Halloch et al. (unpublished); Huda (1995); Holub (1997); Janousek et al. (1995, 2005); Klötzli et al. (1995); Schärer et al. (1990); Vellmer et al. (1994)
are granite, quartz monzonite and granodiorite (Table 1) with small intrusions of gabbro and monzogabbro. They belong to the calc-alkaline Na-enriched granodioritic (trondhjemitic) suite. 2. The plutonic rocks of the southern zone (Čertovo brümeno+Tábor, Sedlíčany, Říčany rock types; Fig. 1) are rich in K (Na/K = 0.8). The major rock types are quartz syenite and granite (Table 1). In both zones the plutonic rocks are of prevailing metaluminous character (Table 1) with considerable amounts of melanocratic constituents (pyroxenes, hornblende, biotite), sometimes with some muscovite in the strongly differentiated, small peraluminous intrusions (Table 1). The characteristic accessory mineral is allanite (counted from low M and D values and high CaO content) in both zones. This paper concentrates on the so-called southern zone, showing similarities in several respects to the granitoids of the Tisia Terrane (Mecsek Zone). Most ubiquitous mafic constituents are the calc-alkaline-type Mg-biotite (low oxidized; Buda et al. 2004a), hornblende and orthopyroxenes and/or clinopyroxenes. Petrochemically this represents a metaluminous, high K-Mg calc-alkaline monzonitic suite plutonic rock series (Table 1, Fig. 1a, b, c, e). Zircon typology shows the same character. The A/CNK ratio is always below 1.1 (0.84±0.17; Table 4) typical for I-type granitoids (Fig. 2d). Two sub-series can be distinguished: 1. magnesian-alkaline: durbachitic enclaves, dykes etc. (Fig. 5f, g, line 2a), 2. calc-alkaline (host rock) starts with Mg-rich and ends with Fe-enriched rocks (Fig. 5f, g, line 2b). The southern part of the CBP formed in a post-collision uplifted tectonic setting (Fig. 2f). The U/Pb age is 343 Ma (Čertovo brümeno; Holub et al. 1997a) and the Pb-Pb age is 336 Ma (Tábor; Janoušek and Gedes 2003). The K/Ar age is 333–339 Ma from biotite (Balogh K., unpublished; Table 1) younger than the northern part (U-Pb age 354 Ma of the Sázava tonalite; Janoušek et al., op. cit.).

II. South Bohemian plutonic complex (SBP)

The Southern Bohemian Pluton can be divided into two parts according to the petrochemistry. The first part contains mostly quartz syenite, quartz monzonite, quartz monzodiorite (Σ 60%), granodiorite and granite (Table 1). Mafic rock-forming minerals are pyroxenes, hornblende and calc-alkaline-type, low oxidized Mg-biotite (Buda et al. 2004a), occurring mostly in Rastenberg (Fig. 1). They are allanite-type granitoids (Table 1). The zircon-types are mostly K-calc-alkaline. They belong to the high K-calc-alkaline monzonitic suite, I-type granitoid complexes with metaluminous (A/CNK=0.89±0.09; Table 4) character (Fig. 2a, b, c, d, e). FeOtot/(FeOtot+MgO) vs. SiO2 and Na2O+K2O-CaO vs. SiO2 diagrams indicate a magnesian alkaline (durbachitic) plutonic series (Fig. 5f, g, line 2a) formed in the post-collisional uplifted tectonic setting (Fig. 2f). The second part, also enriched in K (Fig. 4a, Table 1), contains (peraluminous) granite and granodiorite (Schrems, Mauthausen, Weinsberg, Eisgar, Karlstäd; Table 1). Characteristic minerals are muscovite and peraluminous Fe-Al biotite (Table 1) beside leucocratic constituents. They are monazite-type; only the Mauthausen granitoid has transitional characters with monazite and allanite. Zircon types are
peraluminous allochthonous and intrusive (Table 1). The A/CNK ratio is 1.19±0.14 (Table 4), characteristic for S-type granitoids (Fig. 4a, b, c, d). The QAP diagram shows a granodioritic suite (Fig. 4e) with calc-alkaline differentiation trend (Fig. 5f, g, line 3), formed from anatectic magma (crustal origin) in the late, post-orogenic tectonic settings (Fig. 4f).

These two parts are different in ages as well. The older is the Rastenberg-type (353–338 Ma with inherited age of 623 Ma; Klötzli et al. 1996) similar to the Tisia Terrane (Klötzli et al. 2004) and younger Weinsberg, Mauthausen and Eisgarn types (331–323 Ma; Gerdes et al. 2003).

Tisia Terrane (South Hungary)

Three granitoid occurrences have been distinguished in the Hungarian part of the Tisia Terrane: 1. Mecsek Mts (Fig. 1) studied in several outcrops as well as in drill cores (more than one hundred samples were analyzed chemically), 2. Danube–Tisza Interfluve (continuation of the Mecsek Zone); the granitoids occur below the surface at more than 1000 m depth, being studied in a very limited amount of cores (number of samples: 15). 3. East of Tisza, also studied in cores (Battony, etc., number of samples: 26). Our conclusions are based mostly on the petrochemistry of granitoids of the Mecsek Mts; the other two occurrences cannot be treated statistically because of the limited number of chemical analyses.

In the Mecsek Mts, beside granite, quartz syenite and quartz monzonite occur and in the other two occurrences only granite and granodiorite are common (Table 2). In the Mecsek Mts the mafic minerals are pyroxene, hornblende, biotite, and some muscovite (Table 2). The characteristic accessory is allanite (76%). Monazite is not very common and occurs only in peraluminous microgranite. Potential enrichment is characteristic (Na/K=0.9). According to the AFM distribution they have calc-alkaline character with an enrichment of Mg. They are mainly metaluminous (Fig. 2a, b, c); the A/CNK ratio is 0.95±0.21 (Table 4), transitional between I and S-type granitoids with the I-type being more common (Fig. 2d). In the QAP diagram the samples show a typical K-calc-alkaline
Two trends can be distinguished: a high magnesian alkaline one (Fig. 5f, line 2a) occurring as small intrusions or enclaves (lamprophyre-derived durbachite; Buda and Dobosi 2004b), and a calc-alkaline one with lower Mg content and a slight enrichment in Fe, forming the host rock of the previous one (microcline megacryst-bearing granitoid) or microgranite crosscutting both (Fig. 5f, line 2b). This plutonic complex formed in the late and mostly in the post-collision uplifted tectonic settings (Fig. 2f). Age of crystallization is 354–339 Ma (U/Pb from zircon; Klötzli et al. 2004).

### Table 2

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<th>Locality</th>
<th>Chemical parameters</th>
<th>Rock nomenclature</th>
<th>Characteristic minerals</th>
<th>Zircon typology</th>
<th>Characteristic accessories</th>
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<th>Source rock</th>
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<td>granite; 49%</td>
<td>quartz monzonite</td>
<td>type</td>
<td>biotite (30%)</td>
<td>post-collision uplift</td>
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<td></td>
<td>calc-alkaline</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>calc-alkaline</td>
<td></td>
<td></td>
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</tbody>
</table>

Isotope data from: Balogh et al. (1983); Buda et al. (1995, 2000; 2004a, b); Klötzli et al. (2004)

In the West Carpathian Plutons, both occurrences have a mostly peraluminous character (outer belt A/CNK = 11.3–11.7), whereas the inner belt is more metaluminous (A/CNK = 10.1–11.3). The outer belt contains less muscovite-biotite and more calc-alkaline Mg-biotite and pyroxene, whereas the inner belt contains more muscovite-biotite and less calc-alkaline Mg-biotite and pyroxene. The inner belt is characterized by its higher Sr/Rb ratio (2.6–3.7) compared to the outer belt (1.6–2.5).
Table 3
Characters of Variscan granitoid rocks occurring in Western Carpathian, Eastern part of Tisia Terrane, Pelsonia Terrane and Southern Alps

### WESTERN CARPATHIAN

<table>
<thead>
<tr>
<th>Locality</th>
<th>Chemical formula</th>
<th>Rock nomenclature</th>
<th>Characteristic minerals</th>
<th>Zircon morphology</th>
<th>Characteristic accessories</th>
<th>Tectonic environment</th>
<th>Source rock</th>
<th>Sr (<em>ppm</em>)</th>
<th>Sr (<em>ppm</em>)</th>
<th>K/Ac</th>
<th>Sr/Rb</th>
<th>Ca/Rb/Ma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Malé Karpaty, Střelčí, Žiar Mielá Faia, Velka Faia</td>
<td>peraluminous (73%) NaK&gt;1,7</td>
<td>granodiorite (70%) granite (35%) tonalite (15%)</td>
<td>pyroxenes (22%) hornblende, peraluminous Fe-biotite (22%) muscovite-biotite (51%)</td>
<td>peraluminous anatectic and intrusive</td>
<td>allanite (~48%) zranzite (~45%)</td>
<td>mantle-destructive plate margin (35%) + anatectic magmatism (35%)</td>
<td>14-type Sr-type</td>
<td>8.9 - 11.7</td>
<td>0.706 - 0.708</td>
<td>-</td>
<td>353-456</td>
<td></td>
</tr>
<tr>
<td>Třebeš, Nižná Tatra Veprečniková</td>
<td>peraluminous (78%) NaK&gt;3-5,4</td>
<td>granodiorite (40%) granite (38%) gneiss (20%) calc-alkaline migmatised gneiss</td>
<td>pyroxenes (22%) hornblende, calc-alkaline Mg-biotite (54%) muscovite-biotite (24%)</td>
<td>peraluminous anatectic and intrusive</td>
<td>allanite (~75%) zranzite (~25%)</td>
<td>destructive active plate margin (51%) + anatectic magmatism (29%)</td>
<td>14-type Sr-type</td>
<td>7.8 - 9.9</td>
<td>0.706 - 0.708</td>
<td>-</td>
<td>303-314</td>
<td></td>
</tr>
</tbody>
</table>

### EASTERN PART OF TISIA TERRANE

<table>
<thead>
<tr>
<th>Outcrop (hills around the city)</th>
<th>Chemical formula</th>
<th>Rock nomenclature</th>
<th>Characteristic minerals</th>
<th>Zircon morphology</th>
<th>Characteristic accessories</th>
<th>Tectonic environment</th>
<th>Source rock</th>
<th>Sr (<em>ppm</em>)</th>
<th>Sr (<em>ppm</em>)</th>
<th>K/Ac</th>
<th>Sr/Rb</th>
<th>Ca/Rb/Ma</th>
</tr>
</thead>
<tbody>
<tr>
<td>East of Tisza river (Báthony Mezőhegyes)</td>
<td>peraluminous (100%) NaK&gt;1,7</td>
<td>granite (56%) granodiorite (53%) quartz diorite</td>
<td>calc-alkaline, peraluminous Mg- and Fe-bioties</td>
<td>-</td>
<td>tranzite (~52%) allanite (~48%)</td>
<td>destructive active plate margin</td>
<td>1/8 type</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>320</td>
<td>-</td>
</tr>
</tbody>
</table>

### PELSONIA TERRANE (VELENCE–BALATON TECTONIC LINE)

<table>
<thead>
<tr>
<th>Velence Mt. (Ságvár, Beszterc)</th>
<th>Chemical formula</th>
<th>Rock nomenclature</th>
<th>Characteristic minerals</th>
<th>Zircon morphology</th>
<th>Characteristic accessories</th>
<th>Tectonic environment</th>
<th>Source rock</th>
<th>Sr (<em>ppm</em>)</th>
<th>Sr (<em>ppm</em>)</th>
<th>K/Ac</th>
<th>Sr/Rb</th>
<th>Ca/Rb/Ma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breccanone (Val Canonico, L. Maggiore)</td>
<td>peraluminous</td>
<td>granodiorite (70%) granodiorite-schist</td>
<td>Fe-rich biotite (fayalite)</td>
<td>-</td>
<td>-</td>
<td>postcollision</td>
<td>1/2-type</td>
<td>0.708</td>
<td>271 - 291</td>
<td>280</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

### SOUTHERN ALPS

<table>
<thead>
<tr>
<th>Breccanone (Val Canonico, L. Maggiore)</th>
<th>Chemical formula</th>
<th>Rock nomenclature</th>
<th>Characteristic minerals</th>
<th>Zircon morphology</th>
<th>Characteristic accessories</th>
<th>Tectonic environment</th>
<th>Source rock</th>
<th>Sr (<em>ppm</em>)</th>
<th>Sr (<em>ppm</em>)</th>
<th>K/Ac</th>
<th>Sr/Rb</th>
<th>Ca/Rb/Ma</th>
</tr>
</thead>
</table>

Isotope data from Burgoa et al. (1979), Broska et al. (1990, 1991); Függet et al. (2003); Kőrösi et al. (unpublished); Petrik and Kolcz (1997), Poller and Todi (2000)
1.07±0.15; Table 4). A slightly higher enrichment of Al can be observed in the outer belt. According to zircon typology both zones are of peraluminous crustal-anatectic origin (Broska and Uher 1991). If we take the whole series into consideration, it begins with metaluminous rocks and goes to peralumionous rocks (Fig. 3c), indicating a mixed I/S-type origin (Fig. 3d). Abundant presence of allanite indicates enrichment of Ca in the inner belt, whereas monazite is more common in the outer one. Both occurrences are enriched in Na (Na/K=1.7 in the outer belt, 3.4 in the inner belt; Fig. 3a, Table 3). The entire series has a calc-alkaline (Fig. 3b) to alkali-calcic character (Fig. 5g, line 1), with a slight enrichment of Mg. It contains a transitional suite between the trondhjemitic (tonalitic) and granodioritic (Fig. 3e) one, according to the A-Q-P norm distributions. The plutonic complex (Fig. 5f, line 1) contains magnesian and ferroan granitoids as well. The whole complex shows pre-plate and post-collision chemical characters (anatectic magmatism; Fig. 3f, Fig. 5h, line 1), but the inner belt intrusions are younger than those of the outer one (inner: 303–314 Ma, outer 353–356 Ma; Broska et al. 1990; Petrik and Kohút 1997; Poller and Todt 2000; Table 3); consequently, the younger, more Na-rich granitoids crystallized from basic melt originated from depleted upper mantle, mixed with partially melted crust in the post-collision setting, and not in the pre-plate period. The petrochemical characters of the eastern part of the Tisia Terrane (east of the Tisza River: Battonya, etc., Fig. 1) show similarities with the WC Plutons (Table 3).

**Pelsonia Terrane (Velence Mts)**

Several granitoid intrusions occur along the so-called Velence-Balaton tectonic line continuation of the Periadriatic Lineament. Large outcrops occur only in the Velence Mts; other samples can be found only in drill cores (Ságvár, Buzsák; Fig. 1); therefore we only have enough petrochemical data for statistical evaluation from the Velence Mts. Three main rock types can be distinguished: biotite granite forming the main intrusion, microgranite occurring as a small intrusion, and granite porphyry dykes crosscut the main granite intrusion. In the main intrusion the most important mafic mineral is Fe-rich peraluminous-alkaline biotite (Table 3); further small amounts of amphibole and rare fayalite can be found. Muscovite (sericite) occurs as a secondary mineral. The prevailing accessory minerals beside K-subalkaline-type zircon, are monazite with a small amount of allanite and apatite (Table 3). All rock types are potassium enriched (Na/K<1) and rich in Al (A/CNK=1.14 ±0.1; Table 4), indicating an S-type origin.

← Fig. 3

Plots of K₂O-Na₂O-CaO (a), AFM (b), A/NK v. A/CNK (c), A/CNK v. SiO₂ (Wt%) (d), AQP (e), R₂ v. R₁ (f) of granitoid rocks occurring in Western Carpathian Plutons (No. of analyses: outer belt: 122, inner belt: 316)

Characters: Na/K=1.7-3.4, calc-alkaline, met-/peraluminous, I/S type, trondhjemitic-suite. Tectonic settings: pre-plate collisional and syn-collisional (subduction-type) according to the rock chemistry.
It is a granodioritic suite (Fig. 4b, e) and was probably formed from continental crust by anatexis after the continent-continent collision (Fig. 4f), but some alkali (A-type) properties of the plutonic rocks suggest the beginning of rifting (Uher and Broska 1994) in the lower Permian (U/Pb age from zircon is 274±1.7).

Southern Alps plutons

Granitoid intrusions occur along the Periadriatic Lineament (Bressanone, Val Bianoino, Lago Maggiore, etc.). They are mostly granite, with smaller amounts of granodiorite, quartz monzodiorite and monzodiorite. Most of these rocks are peraluminous (A/CNK=1.06±0.11; Table 4, Fig. 4c). A slight enrichment in K can be recognized, transitional between I/S-type granitoids (Fig. 4a, d), probably tending toward the A-type granitoids, e.g. presence of fayalite-bearing granitoids. They belong to the calc-alkaline granodioritic suite (Fig. 4b, e) and were formed by partial melting of continental crust after the continent-continent collision (Fig. 4f), with an intrusion age of 273–282 Ma (D’Amico 1979).

Discussion and conclusion

Three major groups can be distinguished, according to the major chemical components of the Variscan granitoids of Central Europe:

A. Low-K, high-Na, calc-alkaline, alkali-calcic met/peraluminous, I- and some S-type, trondhjemitic-suite, mostly magnesian, slightly ferroan granitoids (Fig. 5a, b, c, d, e, f, g, line 1). Beside quartz, feldspars (mainly plagioclases), biotite and muscovite are common; sometimes hornblende and pyroxenes also occur. Accessory minerals are monazite as well as allanite.

Occurrences: Western Carpathian Plutons (the outer zone is richer in Al with muscovite, Fe-Al biotite and more commonly monazite; the inner one is richer in Mg with Mg-biotite, hornblende and more commonly allanite). The melts of the two mica-granitoids contained more crustal components in the outer belt than the melts of the Mg-biotite hornblende-bearing granitoids in the inner belt. The ages of the outer intrusions ranges between 356–353 Ma and in the inner zone 306–314 Ma.

B. High-K calc-alkaline, Mg-rich, metaluminous, I-type monzonitic-suite granitoids (Fig. 5a, b, c, d, e, line 2). Major rock types are granite (syenogranites and monzogranites), quartz syenite, quartz monzonite and sometimes quartz monzodiorite. Major mineral constituents, beside quartz and feldspars are biotite,

Plots of K2O-Na2O-CaO (a), AFM (b), A/NK v. A/CNK (c), A/CNK v. SiO2 (Wt%) (d), AQP (e), R2 v. R1 (f) of granitoid rocks occurring in Southern Bohemian Plutons (West-part, No. of analyses: 94), Pelsonia Terrane (Velence Mts, No. of analyses: 56), Southern Alps (No. of analyses: 82)

Characters: calc-alkaline, peraluminous, S- or S/I-type, granodioritic-suite. Tectonic settings: late-orogenic or post-collisional according to the rock chemistry
Table 4
Average composition of Variscan granitoids of Central Europe

<table>
<thead>
<tr>
<th>Sample</th>
<th>Central Bohemian Pluton (South part)</th>
<th>Southern Bohemian Pluton (East part)</th>
<th>Southern Bohemian Pluton (Western part)</th>
<th>Mecklenburg Tornquist Trough</th>
<th>East of Tisza River</th>
<th>WCP outer</th>
<th>WCP inner</th>
<th>Velence granite</th>
<th>Velence granite porphyry</th>
<th>Southern Alps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (No. 69)</td>
<td>Mean (No. 28)</td>
<td>Mean (No. 91)</td>
<td>Mean (No. 129)</td>
<td>Mean (No. 15)</td>
<td>Mean (No. 26)</td>
<td>Mean (No. 122)</td>
<td>Mean (No. 316)</td>
<td>Mean (No. 56)</td>
<td>Mean (No. 12)</td>
</tr>
<tr>
<td>SiO₂</td>
<td>70.12 ± 2.15</td>
<td>72.34 ± 1.84</td>
<td>70.17 ± 6.09</td>
<td>68.89 ± 4.09</td>
<td>71.19 ± 3.15</td>
<td>71.31 ± 4.82</td>
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<tr>
<td>Al₂O₃</td>
<td>11.72 ± 0.93</td>
<td>10.84 ± 0.71</td>
<td>12.06 ± 0.78</td>
<td>11.87 ± 0.84</td>
<td>11.94 ± 0.71</td>
<td>11.93 ± 0.71</td>
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</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.52 ± 0.12</td>
<td>1.46 ± 0.11</td>
<td>1.64 ± 0.15</td>
<td>1.84 ± 0.15</td>
<td>1.89 ± 0.15</td>
<td>1.86 ± 0.15</td>
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<tr>
<td>MnO</td>
<td>0.09 ± 0.07</td>
<td>0.10 ± 0.02</td>
<td>0.03 ± 0.01</td>
<td>0.15 ± 0.28</td>
<td>0.11 ± 0.06</td>
<td>0.06 ± 0.07</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>MgO</td>
<td>2.41 ± 0.14</td>
<td>2.63 ± 0.17</td>
<td>2.28 ± 0.15</td>
<td>2.50 ± 0.17</td>
<td>2.50 ± 0.17</td>
<td>2.50 ± 0.17</td>
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</tr>
<tr>
<td>CaO</td>
<td>3.27 ± 0.18</td>
<td>4.96 ± 1.03</td>
<td>1.12 ± 0.62</td>
<td>0.44 ± 0.3</td>
<td>1.04 ± 0.71</td>
<td>1.04 ± 0.71</td>
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</tr>
<tr>
<td>TiO₂</td>
<td>0.68 ± 0.26</td>
<td>0.26 ± 0.14</td>
<td>0.73 ± 0.47</td>
<td>0.44 ± 0.22</td>
<td>0.49 ± 0.29</td>
<td>0.30 ± 0.22</td>
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</tr>
<tr>
<td>P₂O₅</td>
<td>0.68 ± 0.26</td>
<td>0.73 ± 0.47</td>
<td>0.44 ± 0.22</td>
<td>0.49 ± 0.29</td>
<td>0.30 ± 0.22</td>
<td>0.34 ± 0.21</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>K₂O</td>
<td>6.05 ± 0.73</td>
<td>7.06 ± 0.79</td>
<td>8.54 ± 0.82</td>
<td>10.54 ± 0.82</td>
<td>10.54 ± 0.82</td>
<td>10.54 ± 0.82</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>99.57 ± 0.59</td>
<td>99.57 ± 0.59</td>
<td>99.57 ± 0.59</td>
<td>99.57 ± 0.59</td>
<td>99.57 ± 0.59</td>
<td>99.57 ± 0.59</td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Average composition of Variscan granitoids of Central Europe:

- **Central Bohemian Pluton (South part)**
- **Southern Bohemian Pluton (East part)**
- **Southern Bohemian Pluton (Western part)**
- **Mecklenburg Tornquist Trough**
- **East of Tisza River**
- **WCP outer**
- **WCP inner**
- **Velence granite**
- **Velence granite porphyry**
- **Southern Alps**

The table includes the mean compositions of various elements such as SiO₂, Al₂O₃, Fe₂O₃, MgO, CaO, TiO₂, P₂O₅, K₂O, and Total, along with standard deviations (Mean ± Std) for each sample category.
biotite+hornblende and pyroxenes. The plutons contain melasyenite, melam-
monzonite, meladiorite (locally called durbachite, vauagnerite) small mafic
intrusions, dykes and enclaves. These rocks are enriched in Mg (Fig. 5f, line 2a)
and K (Fig. 5g, line 2a). The tectonic setting is post-collision uplift (Fig. 5h, line 2).
The crystallization age of these magmatic complexes was about 340 Ma (354–336
Ma determined by single zircon U/Pb, Pb-Pb methods).

Occurrences: In the Moldanubian Zone: southern part of the Central
Bohemian Plutonic Complex, eastern part of the South Bohemian Plutonic
Complex, and the northwestern part of the Tisia Terrane.

C. Medium-K, peraluminous, S (S/I, or S/A)-type, granodioritic-suite plutonic
rocks. They contain Fe-rich peraluminous or alkaline-type biotite (muscovite) and
sometimes fayalite (Velence Mts, Southern Alps). The zircon morphology
indicates a peraluminous allochthonous, intrusive (WSBP) or K-subalkali-type
(Pelso T), and monazite is also characteristic.

Occurrences: Western part of the Southern Bohemian Plutons (WSBP),
Pelsonian Terrane (Velence Mts) and Southern Alps. They formed in late orogenic
and post-orogenic tectonic settings. The ages of the intrusions are between 273–
282 Ma (D’Amico 1979; Klötzli et al., unpublished). Only the granitoids of the
WSBP have an older age (323 Ma); consequently, their tectonic setting is not yet
clear. According to Petrík and Kohút (1997) the Gemicar granitoids in the WC also
have a similar petrochemistry and age (280 Ma) as the granitoids of the Pelso
Terrane.

The intrusion ages of these Central European granitoid plutons are between
the Carboniferous and lower Permian (356–274 Ma, based on single zircon-age
dating; U/Pb or Pb-Pb methods). In some intrusions (Rastenberg, Mecsek Mts,
Weinsberg) Cadomian inherited ages were measured (623–523 Ma). Most of the
granitoids are I-type or mixed I/S-type; only the small Lower Permian intrusions
are peraluminous S-type, but the Fe-rich biotite, rare fayalite and zircon typology
indicates an alkaline A-type affinity.

The early Carboniferous (356–353 Ma) continent-continent collision resulted in
crustal thickening with anatexis of continental and oceanic crusts, leading to an I
or I/S-, monazite (allanite)-type, met/eraluminous Na-enriched trondhjemitic/
granodioritic suite, further mixed intrusions like the northern-part of the Central
Bohemian Plutons in the Moldanubian Zone, or the outer belt of the Western
Carpathian Plutons.

This compression was followed by extension (340 Ma), resulting in the partial
melting of uplifted LIL element-enriched mantle and partial melting of the lower
crust. The plutons crystallized from these melts are I-type, high K-Mg calc-
alkaline monzonitic-suit granitoids, containing small mantle-derived
lamprophyric, durbachitic intrusions (southern part of the Central Bohemian
Plutons, eastern part of the Southern Bohemian Plutons, northwestern part of
the Tisia Terrane). These plutonic complexes were encountered above the roots of
the internal parts of the Variscan orogenic belt, which was unstable because of

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Summary of the petrochemical characters of Variscan granitoids occurring in Central Europe

Legend: 1. Western Carpathian Plutons; 2. South part of CBE East part of SBP Tisia Terrane (Mecsek Zone); 3. West of SBP Pelsonia Terrane (Velence–Balaton tectonic line), Southern Alps

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isostasy, and disappeared within a very short time (Ferré and Leake 2001). These very characteristic intrusions occur in the northern part of Tisia Terrane in an allochthonous position, which used to form the internal part of the orogenic belt (Massif Central, Vosges, Black Forest, Central and Southern Bohemian Plutons, etc.) from where they moved behind the Austroalpine collision zone (Klötzli et al. 2004). The Tisia Terrane separated from the Moldanubian Zone in the Early Bathonian (Haas and Péró 2004).

This magmatism was followed by low-K, high-Na calc-alkaline granitoid intrusions (inner Western Carpathian Plutons; 303–314 Ma) as a result of extension, producing a partial melting of depleted mantle and continental crust.

In the Lower Permian (270–280 Ma) the extensional tectonics culminated and resulted in penetration small hypabyssal granitoid intrusions with S/A-type characters like the Generic granitoids (Broska and Uher 2001), or granitoids occurring along the Balaton–Velence or Periadriatic Lineaments (Southern Alps). The granitoids along the Velence–Balaton tectonic line at the southern rim of the Pelsonian Terrane are in allochthonous position, displaced due to significant dextral strike-slip faulting of the Southern Alps (Buda 1998).

Acknowledgements

The Hungarian Scientific Research Fund (OTKA), No. T 023762, T 037595 and the Ministry of Education Research Fund (FKFP), No. 0181/1999, supported this study.

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