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THE VARISCAN WEST-CARPATHIAN GRANITIC PEGMATITES: MINERALOGY, PETROGENESIS AND RELATIONSHIP TO PEGMATITE POPULATIONS IN THE EASTERN ALPS AND ROMANIAN CARPATHIANS

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Abstract: West-Carpathian granitic pegmatites are spatially and genetically connected with Variscan Carboniferous granitic rocks. Two basic groups are distinguished: 1 - The Moravany type (PMOG) and Prašivá type (PAOG). PMOG are connected with Lower Carboniferous monazite-bearing S>I-type granodiorites-granites and contain accessory minerals of Be and Nb-Ta (Ti-poor). PAOG are connected with Middle-Upper Carboniferous I-type tonalites to granites, and contain a Be, Ti-Nb-Ta bearing assemblage. Pegmatites originated at temperatures and pressures about 650 - 700 to 350 °C and 400 - 300 MPa (PMOG) and 700 - 450 °C and 200 MPa (PAOG). A limited hydrothermal overprint is apparent. The Variscan West-Carpathian pegmatites show general similarity with pre-Alpine pegmatites in adjacent Eastern Alps and Romanian Carpathians. These pegmatites also contain Be, Nb-Ta mineralization but locally with Li-phases (mainly spodumene) and they are commonly remote from potential parental granites.

Key words: Western Carpathians, Eastern Alps, Romanian Carpathians, granitic pegmatites, mineralogy, petrogenesis.

Introduction

Granitic pegmatites have been known in the Western Carpathians at least since the 19th century. The first valuable studies were published by Polish authors, in the Tatra Mts.; e.g. Morozewicz (1914) first emphasized genetic relationships between granites and pegmatites on the basis of geochemical data.

Lately, West-Carpathian pegmatites attracted attention only sporadically due to their small size and poor visible mineralization. Nevertheless, in some regions, especially in the Bratislava Massif, the internal zoning of pegmatite bodies and some minerals (feldspar, garnet, zircon, gahnite) were examined in detail (Valach 1954; Dávidová 1968, 1970, 1971; Gbelský 1979, 1980; Gbelský & Krištín 1985). However, general understanding of these granitic pegmatites remained unsatisfactory; consequently they were classified as barren, without any rare-element minerals (Dávidová 1978; Staněk & Dávidová 1981).

On the other hand, repeated finds of beryl (Fiala 1931; Pitoňák & Janák 1983; Gargulák & Vanek 1989) as well as Nb-Ta oxide minerals (Valach 1954; Határ 1979) have provoked a new systematic research by the author (e.g. Uher 1991, 1992) which results in a new genetic characterization of West-Carpathian pegmatites, as presented here.

Characteristics of two pegmatite types

Two principal genetic groups of granitic pegmatites occur in the West-Carpathian Variscan crystalline complexes, defined by the dichotomy of their parental granitic rocks (Fig. 1):

1 - Pegmatites of the monazite-bearing orogenic granitoids (PMOG), or Moravany type pegmatites

PMOG or Moravany type pegmatites are spatially as well as genetically closely connected with Lower Carboniferous monazite-bearing orogenic granitoids (MOG). Granitoids can be defined as leucocratic two-mica, rarely biotite or muscovite syeno- to monzogranites and granodiorites, rarely leucotonalites (trondhjemites). They exhibit peraluminous, moderately calc-alkaline and S>I-type trends, and they generally have a middle-crustal origin (see Hovorka & Petrík 1992; Petrík et al. 1994 this volume). The pegmatites cut mainly the apical, more fractionated parts of granitic intrusions, and they locally also penetrate neighbouring metamorphic rocks (paragneisses, amphibolites).

True veins or platy lenticular bodies with X - XO m, max. up to 100 - 150 m in length and XO cm to 10 - 15 m in thickness are characteristic for the Moravany type pegmatites. Thicker bodies often exhibit a sharp symmetric to asymmetric zonality from the graphic border to the coarse-grained and blocky core-margin K-feldspar - muscovite - (biotite) to quartz core unit; all these units are locally replaced by late albite-rich assemblages (Fig. 2 - left).

Rare-element Be, Nb-Ta and Ti-poor accessory mineral assemblages have been determined in the most fractionated PMOG in the Bratislava Massif (Malé Karpaty Mts.), the Bojná Massif (Považský Inovec Mts.) and the Žiar Mts. (Uher 1992; Uher & Broska in press) - Fig. 1, Tab. 1. Columnar crystals of beryl (1 - 12 cm long) with up to 0.5 wt. % of alkali oxides occur along the boundaries between coarse-blocky K-feldspar-(albite)-muscovite and quartz core units. The Nb-Ta oxide minerals, mainly columbite - tantalite group (ferrocolumbite to manganotantalite), rarely ferrotapiolite, fersmite and pyrochlore

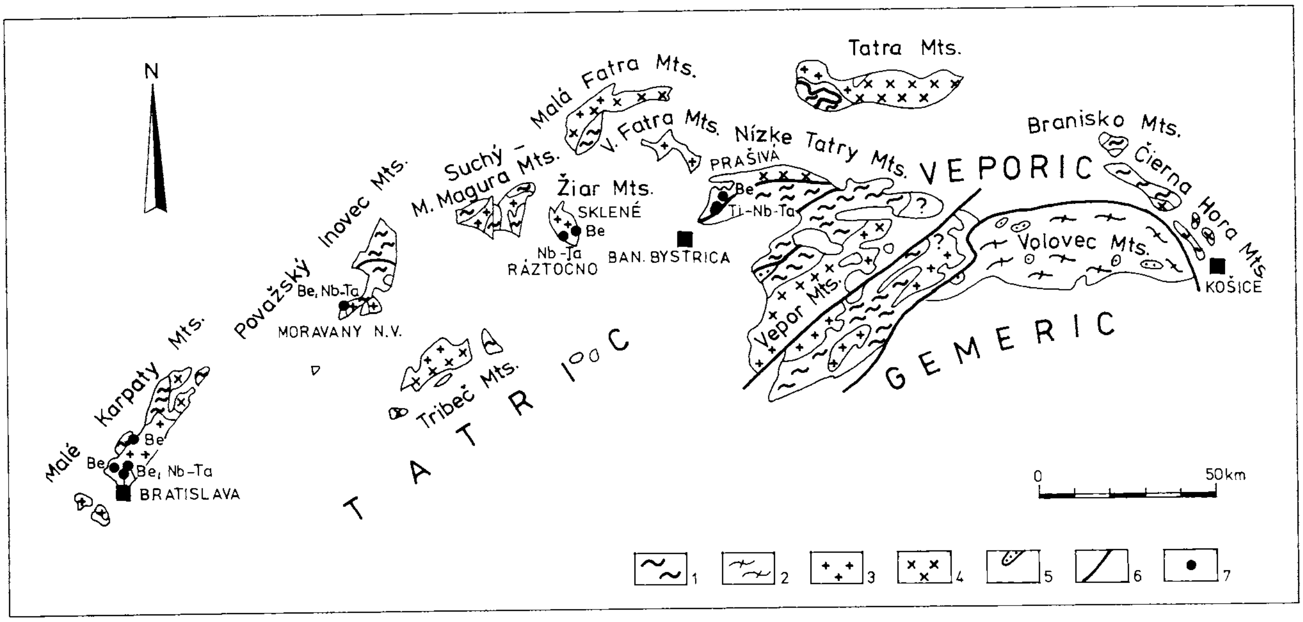

Fig. 1. Schematic map of the West-Carpathian Variscan crystalline basement with occurrences of Be and/or Nb-Ta, Ti-Nb-Ta mineralization in granitic pegmatites. Explanations: **1** - low, medium to high grade metamorphic rocks (Lower Paleozoic), **2** - mainly low grade metamorphic rocks of Gemeric Unit (Lower Paleozoic), **3** - monazite-bearing orogenic granitoids (MOG), **4** - allanite-bearing late-orogenic granitoids (AOG), **5** - post-orogenic Permian granitoids, **6** - faults, **7** - occurrences of rare-element mineralization in pegmatites.

group minerals (mainly microlite) are present especially in the late magmatic to subsolidus albite-rich assemblages: fine-grained saccharoidal albite or in coarse-grained unit of fan-shaped cleavelandite and quartz (Moravany nad Váhom, Ráztočno, Bratislava). Columbite rarely occurs in a coarse-grained K-feldspar + quartz ± muscovite assemblage (Bratislava). The above-mentioned Ta-Nb minerals form small crystals or inclusions (0.2 mm to 2 cm) with a very broad variations in Ta/Nb and Mn/Fe, as well as in some other elements, such as Sn, W, Na. Nevertheless, the Ti contents in all Nb-Ta oxide minerals are very low (up to 2.5 wt. % TiO_2, Uher 1992).

Garnet (almandine-spessartine), metamict zircon, fluorapatite, locally monazite-(Ce), xenotime-(Y), gahnite, pyrite, ilmenite and magnetite also occur as widespread accessory minerals of PMOG.

2 - Pegmatites of the allanite-bearing orogenic granitoids (PAOG) or Prašivá type pegmatites

In contrast to the previous group, PAOG or Prašivá-type pegmatites are connected with the Middle to Late Carboniferous allanite-bearing orogenic granitoids (AOG), especially with their most fractionated members, such as the Prašivá type porphyric biotite monzogranites-granodiorites, rarely also with more basic biotite granodiorites - tonalites of the Sihla s.l. type (see Broska & Petrík 1993). Parental as well as host granitic rocks show metaluminous to slightly peraluminous bulk chemistry, a clearly defined calc-alkaline I-type trend and commonly contain numerous dark magmatic enclaves of tonalitic - dioritic composition which indicate magma mixing/mingling and lower crustal origin of the AOG magma (Hovorka & Petrík 1992; Broska & Petrík 1993; Petrík et al. 1994).

The Prašivá intrusion in the W - NW part of the Nízke Tatry Mts. (Határ 1979; Lukáčik 1981) is the only known area of widespread PAOG occurrences (Fig. 1). Pegmatites lie directly within granitic rocks, without any direct contacts with surrounding metapelitic rocks.

Prašivá type pegmatites occur as narrow true veins (up to 0.5 m) without any zoning, or with only slight symmetric to asymmetric zonal arrangement showing blocky pink K-feldspar and quartz core. A late fine-grained albite-rich assemblage locally replaces other units (Fig. 2 - right).

Table 1: Accessory rare-element minerals in the West-Carpathian granitic pegmatites.

mineral	**pegmatite**	
	PMOG	PAOG
beryl $Al_2Be_3[Si_6O_{18}]$	+	+
columbite-tantalite $(Fe,Mn)(Nb,Ta)_2O_6$	+	-
titanian ixiolite-columbite $(Fe,Mn)(Nb,Ta,Ti)_2O_6$	-	+
ferrotapiolite $FeTa_2O_6$	+	-
fersmite $Ca(Nb,Ta)_2O_6$	+	-
niobian/tantalian rutile $(Ti,Fe,Nb,Ta)O_2$	-	+
microlite $(Ca,Na)_{2-x}(Ta,Nb)_2O_6(O,OH,F)_y$	+	+
betafite $(Ca,U)_{2-x}(Ti,Nb,Ta)_2O_6(O,OH,F)_y$	-	+
uranmicrolite $(U,Ca)_{2-x}(Ta,Nb)_2O_6(O,OH,F)_y$	+	-
pyrochlore $(Ca,Na)_{2-x}(Nb,Ta)_2O_6(O,OH,F)_y$	+	-

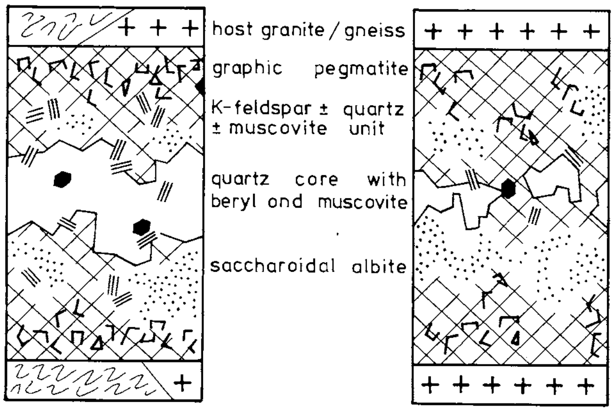

Fig. 2. Idealized cross-sections of the Moravany type (left) and the Prašivá type (right) pegmatites.

Accessory rare-element Be, Ti-Nb-Ta mineralization is locally developed. In contrast to the Moravany type, rare-element minerals in the Prašivá type contain high amounts of mafic elements, mainly Ti, Fe and Mg, due to their relative enrichment in parental AOG magma. For example, alkali-enriched beryl from the Prašivá pegmatites contains over 2 wt. % FeO as well as MgO. Enrichment in Ti is represented by abundant niobian-tantalian rutile, titanian ixiolite - columbite, and subordinate betafite, titanian microlite and niobian titanite (Tab. 1). Spessartine - almandine from PAOG also contains more Mg than that from PMOG (Uher 1992; Uher & Broska in press). Fluorapatite, xenotime, zircon, epidote, magnetite, pyrite and arsenopyrite are the other characteristic accessory minerals in the Prašivá pegmatites studied (Határ 1979).

Petrogenetic conditions

Although both PMOG and PAOG are so far without any economic importance, due to their small size and only slightly developed and scarce rare-element mineralization, their mineralogy as well as host-rock petrology allow to classify West-Carpathian pegmatites into beryl type, beryl-columbite subtype of rare-element class according to the classification of Černý (1991a).

The evolution of the Moravany (PMOG) equally as the Prašivá type pegmatites (PAOG) started after solidification of parental granite bodies and cooling accompanied by contraction fracturing and tectonic displacements.

In the Moravany type pegmatites, the beginning of pegmatite crystallization could be estimated near at a solidus temperature of host-granites, close to 650 - 700 °C and a pressure of at least 300 - 400 MPa (Fig. 3), at depths around 11 - 15 km. These values were determined on the basis of the wet granitic solidus and minimum temperature of hydrous granitic melt (Tuttle & Bowen 1958; Luth et al. 1964; Winkler 1979; Jahns 1982; Johannes 1984) at the pressures indicated from the mineralogy of host-rock metapelites (Korikovsky et al. 1984; Korikovsky & Putiš 1986; Krist et al. 1992). The PMOG evolution progressed from the external graphic K-feldspar-quartz intergrowth, through coarse to blocky K-feldspar-(quartz-mica)-rich units and quartz core (± beryl) to the late magmatic albite-rich assemblages (saccharoidal albite, cleavelandite) which replaced parts of all of the older units. The K-feldspar-rich core-margin assemblage could have crystallized from the pegmatite melt at about 600 - 500 °C, because their subsolidus equilibration exsolution breakdown into pure K- and Na-phase took place at 575 - 370 °C (two-feldspar geothermometry by Dávidová 1971, 1992). On the basis of lower thermal limit of almandine-spessartine (Hsu 1968; Baldwin & von Knorring 1983), zircon typology (Pupin 1980) as well as albite-rich assemblages in pegmatites (e.g. London 1987), the temperature of late albitic units may be estimated at 450 - 350 °C (cf. also Chakoumakos & Lumpkin 1990). The latest hydrothermal events generating adularia (Dávidová, unpubl. data) and alteration of microlite locally took place during the post-solidification uplift of the host granite (Moravany nad Váhom pegmatite). The temperature of this latest stage dropped as low as 240 °C (Dávidová 1992).

On the other hand, the solidification of PAOG or Prašivá type pegmatites began at higher temperatures (about 700 °C) but at a lower pressure (ca. 200 MPa) and depth (around 7.5 km) than that of the Moravany type pegmatites (Fig. 3). The assumed temperature is based on the more basic composition of the host biotite granites to granodiorites and pegmatites, with some enrichment of mafic elements such as Ti, Mg and Fe (Határ 1979; Lukáčik 1981). The pressure of granite solidification was estimated by Lukáčik (l.c.) at 500 MPa, but the distinctly porphyritic texture of the granite (phenocrysts of K-feldspar up to 8 cm in size) and the low-grade metamorphism of the adjacent metapelites (the Klinisko phyllite near Magurka, Prašivá region) both suggest a much shallower level of emplacement. A reasonable estimate for the most fractionated Prašivá type granites would be a 720 - 700 °C solidus at about 200 MPa.

A final stage of PAOG solidification is not clear, but it can be estimated at ca. 500 - 450 °C and around 150 - 200 MPa during crystallization of fine-grained albite-rich assemblages with spessartine-almandine and/or locally Ti-Nb-Ta oxide minerals. The alteration of microlite and the presence of sulphides both indicate a late hydrothermal overprint during uplift of the granite ($t < 400$ °C, $p < 200$ MPa).

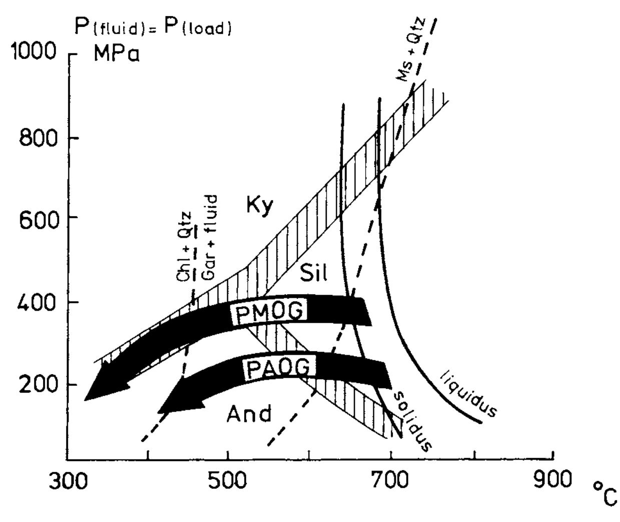

Fig. 3. P-T evolution trends of the Moravany type (PMOG) and the Prašivá type (PAOG) pegmatites. The P-T grid boundaries between sillimanite (Sil) - kyanite (Ky) - Andalusite (And) and solidus-liquidus from Černý (1991a), muscovite (Ms) + quartz (Qtz) breakdown from Kerrick (1972), Fe-Mn-chlorite (Chl) + quartz = Fe-Mn-garnet (Gar) + fluid from Hsu (1968).

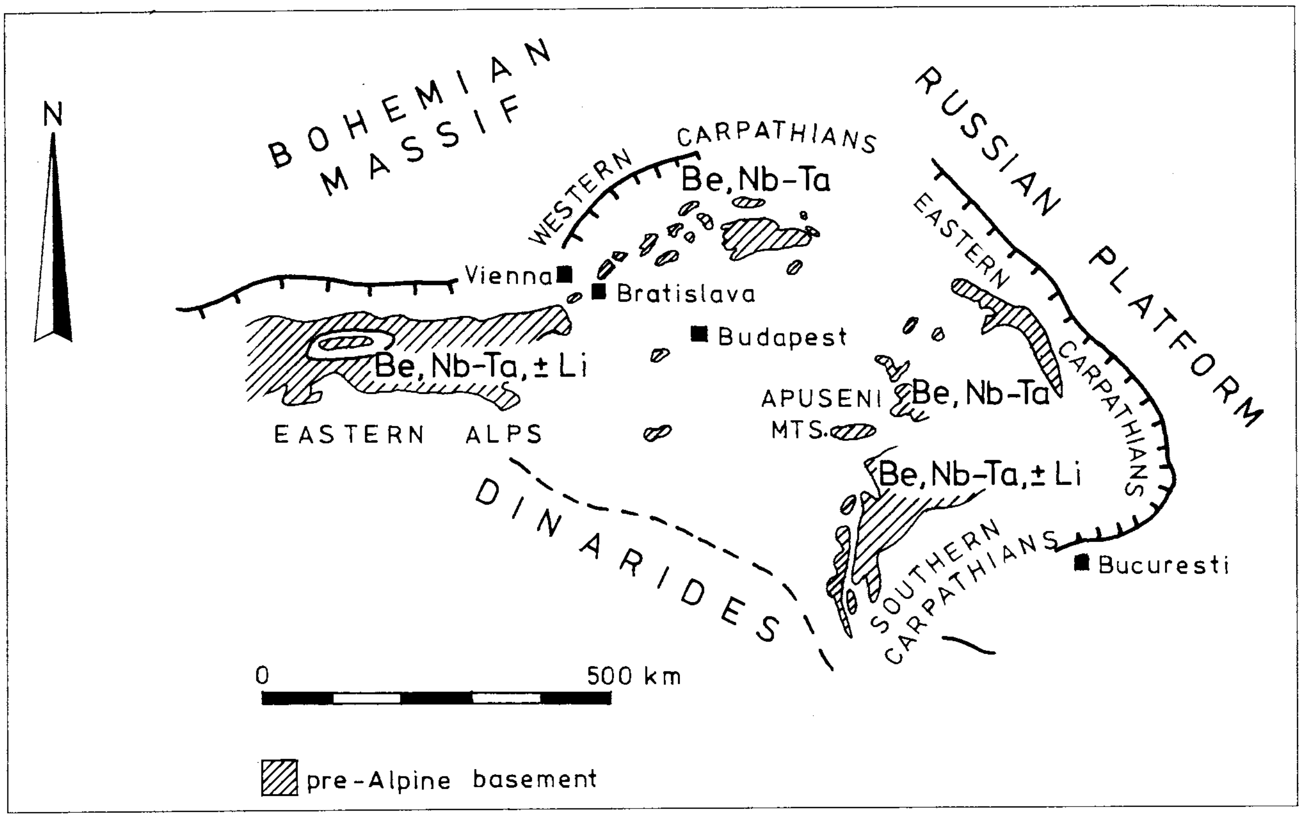

Fig. 4. The area of pre-Alpine basement of the Eastern Alps, Western Carpathians and Romanian Carpathians with characteristic rare-element mineralizations.

Both PMOG and PAOG solidified from a residual, highly fractionated fluid-rich magma with a strong dominance of water over florine, boron and phosphorus. The absence or scarcity of F-rich minerals, tourmaline and phosphates, as well as Mn-poor but and Fe-rich columbite-tantalite (Uher & Broska in press) both support this assumption.

Oxygen fugacity (fO_2) of PMOG magma was probably relatively low (generally below NNO buffer) because of the scarcity of Fe^{3+}-phases, abundance of Fe^{2+}-rich almandine-spessartine and virtually no magnetic susceptibility of the rock. On the contrary, the presence of magnetite and locally high magnetic susceptibility of the Prašivá type pegmatites (κ = 0.0X - 3.8 . 10^{-3} SI units) all indicate a higher fO_2 of the pegmatite magma (between FMQ and HM buffers). Both above-mentioned ranges correspond with fO_2 estimated for the parent monazite-bearing (low fO_2) and allanite-bearing (high fO_2) granitic rocks (Hovorka & Petrík 1992; Petrík et al. 1994).

The age of the Moravany type pegmatites is practically identical with solidification of their parent monazite-bearing granite, ca. 350 ± 10 Ma according to the U/Pb zircon data from the Kohút Massif and Rb/Sr WR data from the Bratislava Massif (Cambel et al. 1990). Similarly, the mean K/Ar muscovite ages from granites as well as pegmatites is close to 340 ± 40 Ma (Bratislava Massif, Cambel et al. l.c.). On the contrary, the 300 ± 40 Ma mean K/Ar biotite ages for the granites of the Bratislava and Bojná Massifs (Kantor 1961; Cambel et al. l.c.) could be indicative of the age of late hydrothermal events in the Moravany type pegmatites continuously with the rock uplift at temperatures of about 300 - 250 °C (cf. Burchart et al. 1987).

Although the U/Pb zircon ages of the basic varietes of allanite-bearing (AOG) or Sihla s.l. tonalites to granodiorites gave Upper Carboniferous values (ca. 305 ± 10 Ma, Bibikova et al. 1990; Broska et al. 1990), the Rb/Sr wall rock isochron and K/Ar cooling ages of the Prašivá type granites and pegmatites in the Nízke Tatry Mts. indicate generally older ages, between ca. 360 to 290 Ma (Kantor 1959; Cambel et al. 1990).

Comparison to granitic pegmatites of the Eastern Alps and Romanian Carpathians

The West-Carpathian Variscan crystalline basement is a part of the Alpine-overprinted European Variscan belt, together with the adjacent Eastern Alps, Romanian Eastern to Southern Carpathians and the Apuseni Mts. However, the crystalline basement of the Romanian Carpathians shows some specific features, such as the dominance of Proterozoic to Baikalian (Cadomian) metasedimentary and granitic rocks (Kräutner 1993). Similarly, the Paleozoic metamorphic and granitic rocks in the Penninic and Austroalpine areas are not direct lithologic, metamorphic or magmatic equivalents of the West-Carpathian pre-Alpine basement (cf. von Raumer & Neubauer 1993; Krist et al. 1992; Petrík et al. this volume).

Despite of the above-mentioned differences, the generally dominant siliciclastic metapelitic-metapsammitic lithology with Variscan and/or Precambrian to Cadomian (Romania) calc-alkaline peraluminous granitic rocks are characteristic of the whole region. The occurrences of granitic pegmatites, and mainly their rare-element mineralization, also show some similarities (Fig. 4).

The granitic pegmatites with rare-element Be-Nb-Ta ± Li mineralization are found in many locations of the Eastern Alps, especially in the southern and western part of the Austroalpine crystalline complexes. Pegmatite bodies are hosted by Lower-Paleozoic metapelites-metapsammites or amphibolites, less commonly in their parent Variscan granites. Rare-element granitic pegmatites can be subdivided into two paragenetic/geochemical types: (1) Be-Nb-Ta pegmatites without Li contain beryl, sometimes columbite-tantalite and ferrotapiolite, e.g. Stubenberg, Zissingsdorf, Markogel, Spittal/Drau (Wieseneder 1968; Khalili 1972; Černý et al. 1989a) and (2) Li-(Be)-Nb-Ta pegmatites with spodumene, Nb-Ta oxide minerals and rarely beryl, e.g. Weinebene, Rieserferne, Wollatratten, Edling, Wolzer Tauern, Packalpe, Gleinalpe, Wildbachgraben, St. Radegund, Anger (Černý et al. 1989b; Göd 1989). Whereas the first group bears the features of the beryl-columbite subtype, the second one belong to complex spodumene subtype or the albite-spodumene type of the rare-element class of granitic pegmatites (after Černý's 1991a classification).

Similarly, the granitic pegmatites of the Apuseny Mts. and of the Southern Carpathians (Romania) locally contain the (1) beryl or (2) complex Li-Be-Nb-Ta ± P rare-element granitic pegmatites. The beryl-bearing group occurs both in the Apuseni Mts., e.g. Razoare and Bondurease (Radulescu & Dimitrescu 1966; Marza et al. 1988), and (mainly) in the Southern Carpathians, e.g. Armensis, Voislova, Pirvova, Pietrele Albe, Hanes, Streaja, Geamana (Radulescu & Dimitrescu l.c.; Hann 1987). These Romanian pegmatites could be correlated with the West-Carpathian Moravany type beryl-bearing pegmatites without or with scarce Nb-Ta minerals, mainly in the Bratislava Massif. However, the beryl pegmatites in the Apuseni and South Carpathian Mts. are emplaced mainly into Precambrian metamorphic rocks without direct contact with parent (?) granites, whereas the West-Carpathian pegmatites of PMOG (and even PAOG) groups are situated in endocontact or near exocontact of parent granitic intrusions, in Lower-Paleozoic metasediments. Thus, some authors suggested a metamorphic origin of the South-Carpathian pegmatites (Hann 1987).

Moreover, the affiliation of complex rare-element pegmatites carrying spodumene, beryl, columbite-tantalite, and locally samarskite, triphylite and montebrasite (e.g. the Teregova and Contu occurrences; Schneiderhöhn 1961; Radulescu & Dimitrescu l.c.; Hahn l.c.) with high-grade rocks resembles the Austroalpine spodumene-bearing pegmatites rather than West-Carpathian lithium-poor bodies.

Conclusions

We can conclude that the Variscan West-Carpathian granitic pegmatites occur as true magmatic differentiates of parent granitic intrusions. The close spatial relationship to granitic rocks (mainly endocontacts or immediate exocontacts) as well as mineralogical and geochemical similarities and sequental trends both support such an origin.

Rare-element Be-Nb-Ta mineralization is developed in the most fractionated West-Carpathian pegmatites; they rank with the beryl type, beryl-columbite subtype.

Two principal pegmatite populations can be distinguished: **1** - pegmatites of monazite-bearing granitoids (PMOG) or Moravany type are genetically connected with Lower Carbonifeous (granodiorites to) leucogranites. These zoned rare-element pegmatites contain a titanium-poor Nb-Ta bearing assemblage with dominant columbite-tantalite, alkali-poor beryl and practically Mg-free garnet (Bratislava Massif, Považský Inovec Mts., Žiar Mts.). On the contrary, **2** - the Prašivá type pegmatites of allanite-bearing granitoids (PAOG) are connected with Middle to Upper Carboniferous (leuco)tonalites - granodiorites, less commonly granites. Their scarce, slightly zoned rare-element pegmatites occur only in more fractionated porphyric granodiorites-granites of the Prašivá Massif (Nízke Tatry Mts.) and contain Ti-rich Nb-Ta bearing assemblages, with dominant titanian ixiolite-columbite and niobian (tantalian) rutile, Fe- and Mg-rich alkali-enriched beryl and Mg-enriched garnet.

The PMOG consolidation started at ca. 650 - 700 °C, 300 - 400 MPa and around 350 ± 10 Ma ago, with a late magmatic - early hydrothermal stage active between 450 - 350 °C, and finally with the low temperature-pressure hydrothermal overprint between 350 - 240 °C and 250 - 300 MPa. The PAOG solidified between ca. 700 to 450 °C, 200 MPa and around 330(?) - 300 Ma ago. The latest hydrothermal stage acted at less than 400 °C and <200 MPa.

Rare-element granitic pegmatites occur in all of the pre-Alpine (Proterozoic - Paleozoic) crystalline basement areas from the Eastern Alps throught the Western Carpathians to the Southern Carpathians. They are situated in the endocontacts (Western Carpathians) or in the exocontacts (Eastern Alps, Romanian Carpathians) of parental Variscan or Precambrian to Cadomian granitic rocks. All pegmatites exhibit a slightly to strongly developed peraluminous and LCT (lithium-cesium-tantalum) affinity rather than a metaluminous NYF (niobium-yttrium-fluorine) signature (cf. Černý 1991b). On the basis of mineralogical and geochemical characteristics, these East-Alpine and Carpathian pegmatites could be subdivided into:

1 - beryl ± columbite pegmatites (Eastern Alps, Western Carpathians, Apuseny Mts., Southern Carpathians). The (1A) Ti-poor Nb-Ta (Moravany type or PMOG) and (2B) Ti-Nb-Ta (Prašivá type or PAOG) populations can be distinguished (Western Carpathians, maybe in other areas).

2 - complex spodumene-bearing pegmatites with Nb-Ta minerals and beryl (Eastern Alps, Southern Carpathians). It is questionable if a subdivision of these complex pegmatites may be suggested on the basis of Ti-poor and Ti-rich Nb-Ta assemblage. However, the majority of the spodumene-bearing Alpine-Carpathian pegmatites seems to be Ti-poor, in contrast to the Ti-Nb-Ta bearing assemblage of the Weinebene pegmatites (Černý et al. 1989b).

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