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EVOLUTION OF THE WESTERN CARPATHIAN GRANITE MAGMATISM: AGE, SOURCE ROCK, GEOTECTONIC SETTING AND RELATION TO THE VARISCAN STRUCTURE

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Abstract: Available mineralogical, petrological and geochronological data suggest that Variscan granitoids forming the hard core of Western Carpathian basement can no more be considered as one genetic group. The most reliable, U/Pb data allow their sub-dividing into three genetic groups which show generally S-, I- and A-type characteristics with decreasing age. Probably oldest, the S-type (monazite-bearing) group is related to thickening of crust and peak metamorphic conditions. The younger I-type (allanite-bearing) tonalites record a thermal event at the end of Carboniferous and coeval occurrence of acidic and mafic magmatism. The youngest, A-type tending group with documented Permian age, may be connected with post-orogenic consolidation and deep faulting. Muscovite dehydration melting of quartz-rich mica-bearing upper crustal rocks and biotite dehydration melting of intermediate biotite- and hornblende-bearing source lithologies is supposed for the S-type and I-type groups, respectively. The S- and I-type granitoids seem to be emplaced in the upper unit of the Variscan nappe structure.

Key words: Western Carpathians, Variscan structure, age, source rock, granitoids.

Introduction

There have been several attempts to interpret Variscan granitoid rocks of the Western Carpathian pre-Mesozoic basement in terms of their age, genesis, source rocks, differentiation etc. Earlier works put forward their crustal features: modal inhomogeneities (Siegl 1976), gneiss - migmatite - granite transitions and lack of intermediate and basic members (Cambel 1980), overall peraluminous character (Hovorka 1980; Hovorka & Fejdi 1983) to emphasize their crustal, anatectic (palingenetic) origin. Such interpretations did not, however, cover several different petrographical and geochemical features: metaluminous nature of some regional granite types (e.g. Modra Massif of the Malé Karpaty Mts., Sihla type of the Veporic Unit) along with the sporadic presence of hornblende in relatively more basic biotite (± hornblende) tonalites (Tribeč Mts., Ďumbier type of the Nízke Tatry Mts.) and relatively low Sr initials: 0.705 - 0.707 (Cambel et al. 1990). Cambel & Petrík (1982), later stated the prevalence of I-type characteristics for the bulk of Western Carpathian granitic rocks (with the exception of Sn-bearing granites from the Gemeric Unit which were ascribed to the S-type, l.c.).

Nevertheless, after the recognition of two mineralogically different granitic groups: allanite (+ magnetite)-bearing on the one hand, and monazite (± ilmenite)-bearing on the other hand (Broska & Uher 1991; Broska & Gregor 1992) it was felt that these interpretation attempts were not satisfactory. Moreover, new U/Pb zircon data (Bibikova et al. 1990; Broska et al. 1990; Kráľ 1992) revealed two granite-forming events at about 350 Ma and 300 Ma ago (l.c.). It became increasingly more obvious that treating Variscan granitic rocks as a single group is no more acceptable. The finding of mafic magmatic enclaves with tonalite to diorite composition in the Tribeč Mts. (Petrík & Broska 1989) in allanite and magnetite-bearing granitoids (and later in the whole area of the Sihla type s. l., Broska & Petrík 1993a, b) added new evidence for a deep formation of the Sihla type tonalite magma as well as for the presence of coeval acid - mafic magmatism in the Upper Carboniferous. The allanite- and monazite-bearing granitoids found in the Tribeč Mts. were correlated with I- and S-type, respectively (Petrík & Broska 1994).

Based on differing mineral assemblages (l.c.) were inferred contrasting P-T-X conditions for parental magmas. Description of a third genetic granite type showing a distinct A-type tendency from the Turčok Granite Body (Uher & Gregor 1992) in the northern Gemeric Unit and from pebbles of the Pieniny Klippen Belt (Upohlav type, Uher & Marschalko 1993; Uher et al. 1994), completed the Variscan granite family. A similar A-type tendency was recently described also for the Velence Granite (Uher & Broska 1994a) and the Hrončok Granite Body of the Veporic Unit (Petrík et al. in prep.) The Upohlav type has a documented Permian age (274 ± 13 Ma, U/Pb zircon upper intercept, Uher & Puškarev 1994). A more detailed characterization of all the genetic types was recently given by Hovorka & Petrík (1992) and Petrík et al. (1993).

The purpose of this paper is to discuss the recognized genetic groups (Fig. 1) in view of their age relations, source rock diversity and relation to the Variscan basement structure.

Age relations

The re-interpretation by Burchart et al. (1987) of the plethora of K/Ar ages available from the pre-Mesozoic basement of the Western Carpathians by isochron checking showed that they yielded cooling ages at best (hornblendes). Therefore, the signi-

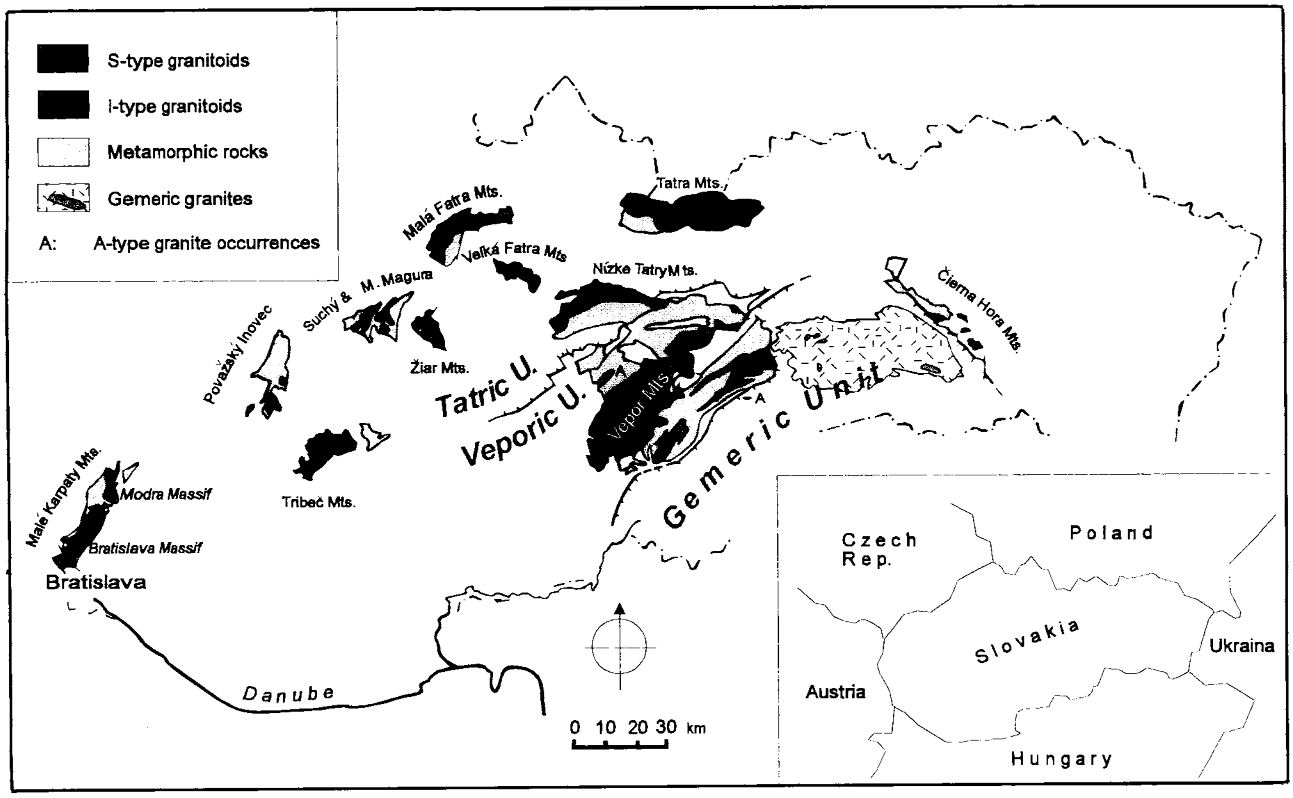

Fig. 1. Sketch map showing the distribution of three main genetic granite groups of S-, I-, A-type in the pre-Mesozoic basement of the Western Carpathians. The I/S boundary shown within the cores of the Malá Fatra, Tatra and Vepor Mts. is tentative and partly schematic.

ficance of Rb/Sr and particularly U/Pb zircon datings, became more than obvious. The Rb/Sr method has been widely used and believed to give results relevant to granite genesis (see Cambel et al. 1990 and references therein). However, three later zircon datings yielding nearly-concordant U/Pb ages lower than Rb/Sr ones (the Rimavica Granite Bibikova et al. 1988; the Tribeč Tonalite Broska et al. 1990; the Sihla Tonalite, Bibikova et al. 1990), questioned the former results and raised a possibility of pseudoisochron. The matter was discussed by Kráľ (1992) and interpreted as a result of a probable initial slope of the isochrons, i.e. in terms of source rock and parental melt isotopic ($^{87}Sr/^{86}Sr$) inhomogeneity. The initial slope would correspond approximately to 50 Ma (l.c.) making possible to re-interpret older Rb/Sr data. For example, a very high "age" of 393 Ma ± 6 Ma (Kráľ et al. 1987) from the Suchý S-type granites would give a more realistic value around 340 Ma.

The discordance between Rb/Sr and U/Pb data is a widespread feature in the mid-European Variscan fold belt. Similar discordance was found in the Southern Bohemian Batholith where a Rb/Sr WR isochron gave 349 ± 6 Ma for Weinsberg type Granite, respectively, whereas a monazite U/Pb concordant age 318 ± 4 was obtained for the same granite (von Quadt & Finger 1991). The initial slope was also invoked by von Quadt (in Finger et al. 1993) for interpretation of some Rb/Sr WR isochron ages from the Tauern Zentralgneise.

We, therefore, prefer U/Pb zircon ages for the discussion of age and genetic relations. From the Tab. 1 it follows that three genetic groups of granites (S-, I- and A-type) show a certain degree of correlation with zircon datings: the S-type group seems to correlate with the highest ages around 350 Ma, the I-type (with the exception of the Malá Fatra Mts. tonalite) records a magmatic event at around 300 Ma B.P. and the A-type granites may be associated with Permian post-orogenic magmatism (around 280 Ma).

Source rocks

The subdivision of granites in terms of S-, I- and A-type terminology presumes their respective sedimentary and igneous source lithologies.

S-type quartz-rich (Fig. 2), monazite (± ilmenite)-bearing peraluminous two-mica granites and granodiorites typically occur in the outer zone of Tatric cores (Hovorka & Petrík 1992): the Bratislava Massif of the Malé Karpaty Mts., Považský Inovec Mts., Suchý and Malá Magura cores, Žiar Mts., northeastern Malá Fatra Mts., Veľká Fatra Mts., Western Tatra Mts. However, they also occur in the southern Veporic Unit represented by the Rimavica Granite (Fig. 1).

All the S-type granites are peraluminous due to the Al-rich character of granitic/migmatitic melt with resulting mineral assemblage:

Al-, Fe-, Ti-rich biotite + muscovite ± alm-spess garnet.

This primary assemblage is often obliterated by the development of post-magmatic muscovite and fibrolitic sillimanite (Korikovsky et al. 1987) and development of grossular-rich garnets. The rock-forming minerals are accompanied by a typical

Table 1: U/Pb zircon data on the three genetic groups of Variscan granitoids.

Core/mountains	age (Ma)	note	source
(1) Group of S-type (monazite-bearing) granitoids			
Rimavica type, Stolické Mts.	350 ± 5	M	Bibikova et al. (1988)
Strážovské Mts.	348, 350	M	Kráľ (1992)
(2) Group of I-type (allanite-bearing) granitoids			
Modra Massif (MK)	<320	M	Shcherbak et al. (1988)
Tribeč Mts.	306 ± 10	C	Broska et al. (1990)
Malá Fatra Mts.	353 +11/-5	UI	Shcherbak et al. (1990)
Sihla type, Vepor Mts.	303 ± 2	C	Bibikova et al.(1990)
(3) Group of A-type granitoids			
Upohlav type, Klippen Belt	274 ± 13	UI	Uher & Pushkarev (1994)
Hrončok type, Vepor Mts.	255	M	Cambel et al. (1990)

Explanations: UI - upper intercept, C - concordant or nearly-concordant age, M - model age $^{206}Pb/^{238}U$

assemblage of accessory minerals: monazite ± ilmenite ± pleochroic apatite.

The assemblage includes low S and L morphological types of zircon (pyramids 211 > 101, prisms 110 > 100). This mineralogy was interpreted as indicative of reduction conditions during crystallization of parental magma (Petrík & Broska 1994). This is confirmed by the absence of magnetite and titanite (Fe^{2+} and Ti entering mainly biotite, Fig. 3) and by the identification of carbonaceous and carbide matter in pleochroic apatite (Broska et al. 1992). Based on biotite chemistry, a lower water content (2.3 wt. %) was inferred for Tribeč monazite-bearing S-type granitoids (Petrík & Broska l.c.). Several tens of new, Mössbauer-based biotite Fe^{3+}/Fe^{2+} ratios (Petrík et al. in prep.) revealed a distinct difference between the bulk of S- and I-types, the former containing reduced biotites with F_{ox} ratio (= 100 x Fe^{3+}/Fe_{total}) 0 - 10 %, typically 4 - 7 %. We, therefore, assume reducing, water-poor conditions to be characteristic of the intrusive S-type granites in the Western Carpathians.

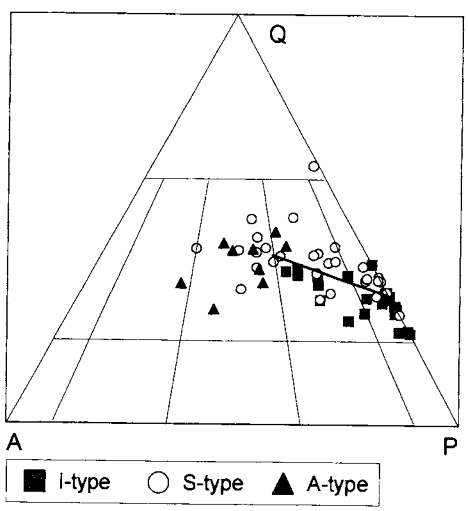

Fig. 2. Modal compositions of main genetic types of granitoids in the QAP diagram. The heavy line divides I-type and S-type dominated fields. S-type granitoids are represented by Suchý, Považský Inovec and Tribeč Mts.; I-type by Tribeč, Vepor, Nízke Tatry and Čierna Hora Mts.; A-type by Hrončok body and Velence Mts.

The above characteristics puts certain limits on source lithologies and melting conditions: peraluminous muscovite- and biotite-bearing metasedimentary rocks might have produced S-type magmas via processes of muscovite and biotite dehydration melting (750 and 850 °C respectively, at pressures 600 - 800 MPa, Le Breton & Thompson 1988; Vielzeuf & Holloway 1988). Carbonaceous, graphitized interlayers may well account for the reducing conditions in magma.

Muscovite dehydration melting was shown to produce limited amounts of water-rich melt (Clemens & Vielzeuf 1987) and may have produced migmatites typically occurring e.g. in the Strážovské Vrchy Mts., Vepor pluton, or Branisko Mts. However, the intrusive two-mica S-type granitoids (Bratislava Massif of the Malé Karpaty Mts.) lack any migmatites, instead they typically contain pegmatite and aplite veins (sometimes with Be-Ta-Nb rare-element mineralization, Uher 1991; Uher & Broska 1994b) indicating increased water contents in late stages of differentiation. A reaction of the type: Ms + Bt + Plg + Qtz = Grt + Kf + L, was suggested by Clemens & Vielzeuf, Le Breton & Thompson l.c. to produce large amounts of peraluminous

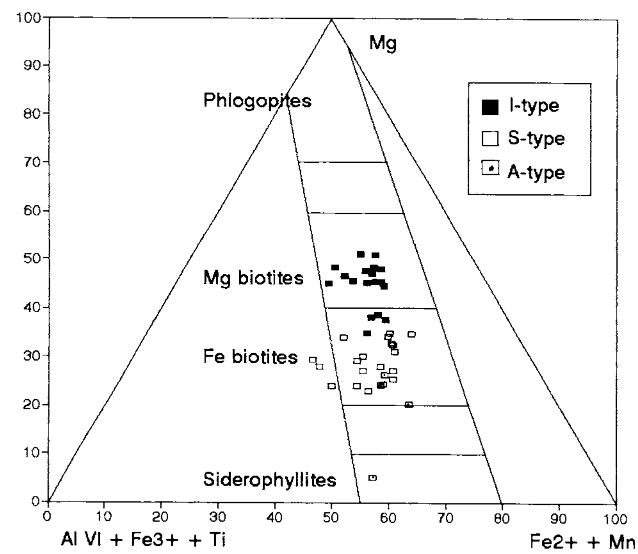

Fig. 3. Composition of granitoid biotite in terms of octahedral cations. Fields after Foster (1960).

melts at great pressures (1000 MPa). Such melting would be possible only in conditions of low geothermal gradient (≈ 20 °C/km) to avoid the low pressure migmatite formation. Alternatively, a protracted fractionation of water-poor mineral assemblage may have been able to rise the water concentration up to the saturation level giving the pegmatite melts. The rare-element mineralization supports the high degree of evolution of some S-type magmas (Uher 1991; LCT family of Černý 1991).

I-type plagioclase-rich granodiorites - tonalites (rarely granites, e.g. Prašivá type) are typically represented by the Sihla type s.l. defined by Broska & Petrík (1993b). They crop out mainly in the inner belt of the Tatric Unit (Tribeč Mts., Nízke Tatry Mts.) and in the Veporic Unit (Sihla type s.s. of the Vepor Mts. and Čierna Hora Mts.), Fig. 1.

Its characteristic mineralogy involves: Mg-biotites ± (rare) hornblende + titanite + allanite + magnetite + apatite and abundant secondary epidote-clinozoisite. The mineralogy includes zircons S_{12} (pyramids 211 > 101, prisms 100 ≥ 110). A relatively lower quartz content and strongly saussuritized plagioclases characterize the rock-forming mineral assemblage. The Mg-biotite (Fig. 3) coexisting with magnetite and titanite was shown to indicate increased both oxygen and water fugacities in Tribeč I-type tonalites (Petrík & Broska 1994). Mössbauer-derived biotite F_{ox} ratios (l.c., Petrík et al. in prep.) strongly support oxidation conditions in parental magma. The ratios ranging between 10 - 20, typically 13 - 17 %, are interpreted as primary, indicating fO_2 buffered approximately by titanite-magnetite-quartz-amphibole buffer (Noyes et al. 1983). The water content derived for Tribeč I-type is about 5 wt. % (Petrík & Broska 1994). Generally similar water contents are presumed also for the other I-type granitoid occurrences (Modra Massif of the Malé Karpaty Mts., Ďumbier and Prašivá type of the Nízke Tatry Mts., Sihla type s.s. of the Vepor pluton). Although the I-type group granitoids are poorer in pegmatites the veins of latter can be found typically cutting the parental tonalites, e.g. in the Tribeč Mts. A pegmatite with Ti-Nb-Ta (± Be) mineralization was identified in the Prašivá Granite (Uher & Broska 1994b).

A characteristic feature of I-type granodiorites - tonalites, the presence of mafic magmatic enclaves, is believed to record a process of magma mingling at depth: hot globules of mafic magma were trapped by and quenched against cooler tonalite magma to give fine-grained textures (Petrík & Broska 1989). Mainly due to its strong interactions with host tonalite magma the mafic dioritic magma is not well constrained geochemically. While the Tribeč enclaves do not show a mantle signature, those of the Malá Fatra, Nízke Tatry and Sihla (s.s.) tonalites reach Cr and Ni values between 100 - 200 and 50 - 70 ppm, respectively (Broska & Petrík 1993a) suggesting a deep crustal or mantle component in source region. Existing isotopic data (Rb/Sr isochron of Tribeč tonalites, Bagdasarjan et al. 1986) indicate a complete re-equilibration of Sr isotopes in both magmas (cf. Holden et al. 1987). Nevertheless, the very existence of the mafic magma in direct interaction with granitoid one allows an assumption of higher temperatures in the source region. The mafic magma is actually thought to have been a main source of heat causing melting of lower crustal lithologies (see Huppert & Sparks 1988; Dewey 1988 amongst others). An intermediate lithology containing biotite and hornblende may have produced considerable amounts of I-type melts through biotite and hornblende dehydration melting (Clemens & Vielzeuf 1987). A biotite-dominated (31 % Bt, 3 % Hbl) intermediate composition of Clemens & Vielzeuf (1987) would yield 20 - 25 % of melt with about 5 % of water, a value consistent with the estimate made for Tribeč tonalites (Petrík & Broska 1994). Biotite- and biotite-hornblende plagiogneisses seem to meet the requirements of rock petrology for the source rock.

Recently, Hovorka et al. (1993) suggested banded amphibolites (the Leptyno-Amphibolite Complex of the Western Carpathians, LAC) as source rocks of "less differentiated" (≈ I-type) Variscan granitoids. Indeed, field observations confirm partial melting of these amphibolitic rocks (Janák et al. 1993b). Nevertheless, there are some reasons which contradict such an assumption:

1 - The melting of amphibolite rocks in vapour-absent conditions typically produces trondhjemitic rather than tonalitic rocks, with restite mineralogy dominated by cpx ± gar ± plg depending on pressure (Rapp et al. 1990; Van der Laan & Wyllie 1992), unless hydrous conditions are supposed. A hornblende (± cpx) dominated restite is more realistic in the case of I-type biotite tonalites, biotite being the main source of water and potassium in the melt. By contrast, biotite is totally absent in the Leptyno-Amphibolite Complex (Hovorka et al. 1993).

2 - Although the precise age of banded amphibolites is not known, existing isotopic data (400 - 450 Ma, $^{40}Ar/^{39}Ar$ total gas age, Janák & Onstott 1993) indicate rather a pre-Variscan age of metamorphism (cf. Spišiak & Pitoňák 1992). This contrasts with the Upper Carboniferous age of I-type granite magmatism documented by U/Pb zircon data (see above).

The *A-type* granite, was identified recently in tectonic slices of the Turčok and Hrončok Granite Bodies (Uher & Gregor 1992; Uher et al. 1994; Petrík et al. in prep.), in pebbles occurring in the Cretaceous-Paleogene flysch conglomerates of the Carpathian Pieniny Klippen Belt (the Upohlav type, Uher & Marschalko 1993) and possibly in the Velence Mts., Hungary (Uher & Broska 1994a). This type, represented by biotite leucogranites rich in pink K-feldspar phenocrysts Fig. 2, is often accompanied by volcanic equivalents (Upohlav type, Velence Mts.). The Upohlav type pebbles show the signs of strong subsolidus alterations (chloritization and oxidation of biotite), the granites of Turčok (Uher & Gregor 1992) and Hrončok bodies (Petrík at el. 1993a) are intensely deformed. All the A-type granite biotites are extremely Fe-rich (Fig. 3) which seems to be typical of the A-type granites. Clemens et al. (1986) report annite in the Watergums A-type granite. The Mössbauer-derived biotite F_{ox} ratio (20 - 30) suggests a strong, probably partly secondary oxidation. The above characteristics is consistent with a low water content of parental magma, moderate to high oxygen fugacity and very late crystallization of biotite. The last feature is confirmed by petrographical observation (Uher & Marschalko 1993) and experimental work (Clemens et al. 1986). The accessory mineral assemblage suggests a wide range of magma P-T-X conditions: from more reducing with monazite + lower I.T. zircon (pyramids 101, prisms 110 > 100) ± xenotime ± garnet (Hrončok) to more oxidizing indicated by mainly P-type zircon (pyramids 101, prisms 110 > 100) + allanite ± magnetite (Turčok, Velence, Upohlav pebbles).

The lithologies suggested for the source of A-type granites are usually deep-seated, relatively dry, granulite facies rocks having already suffered from a melting event. First stage magmas, richer in water, had impoverished the residual rocks in water, increasing the relative influence of other volatiles: fluorine, chlorine (Collins et al. 1982). Indeed, biotite fluorine analyses of the Hrončok Granite revealed the highest content of fluorine amongst all Veporic granitoids (6000 ppm). Even though such content is not as high as those reported e.g. by Nash (1993), it supports a distinct A-type tendency of the Hrončok Granite. We, therefore, suggest that Western Carpathian Permian A-type magmatism arose from the melting of residual lithologies which had already produced a granite magma, possibly of the earlier I-type.

Sn-bearing granites of the Gemeric Unit

Gemeric granites outcrop in small bodies in the Gemeric Unit mostly as apical parts of hidden intrusions of tin-bearing leucogranites and granite porphyries in the Early Paleozoic low grade, volcano-sedimentary Gelnica Group, Fig. 1. They are represented by highly evolved, rare-element enriched, two-mica granites sometimes of greisen and albitite character (Tauson et al. 1974). Total contents of REE are generally very low, chondrite normalized patterns are flat and show pronounced negative Eu anomalies. Both REE patterns and other trace elements behaviour indicate a relatively high fractionation of the granite magma. Their zircon typology indicates an intermediate alkalinity and temperature of the parental magma (Jakabská & Rozložník 1989). The Rb/Sr WR and biotite dating yielded a Lower Permian age of intrusion (Kovách et al. 1986). High Sr initials (often > 0.708) confirm a mature (high Rb/Sr) crustal source. The presence of monazite and ilmenite indicates low oxygen fugacity of the granite melt and a very common presence of tourmalines suggests boron enrichment of the melt which may reflect the source composition. Cassiterite and topaz formed in the greisenized, apical parts of Gemeric granites (Baran et al. 1970). Based on garnet study, Faryad & Dianiška (1989) estimated generation of the melt at least in the depth of 20 km at temperatures 750 - 780 °C.

Above mentioned features as well as late-Variscan, Permian age (Kovách et al., 1986) support both A-type and S-type signature for the Gemeric granites.

Geotectonic setting

Previous discussion showed that Variscan granitoids of the Western Carpathians have formed in different conditions in various source regions and different times. Indeed, the time span of granite plutonism from Upper Devonian to Upper Permian frames our considerations.

It seems reasonable to link the S-type magmatism (dated between 330 - 350 Ma, Tab. 2) with Early Carboniferous tectonometamorphism documented throughout the Variscan orogenic belt. This setting was characterized by crustal thickening and gradual thermal equilibration of the shortened crust accompanied by the increase of geothermal gradient, prograde metamorphism and melting in lower crust (first three orogenic phases of Dewey 1988). More extensive melting induced by the thermal relaxation in great depths and/or following decompression may have produced intrusive S-type plutons (e.g. Bratislava or Rimavica Massifs), besides migmatite fronts.

I-type plutonism may record later, thermal events also documented throughout the Variscan belt. The ages cluster between 290 - 320 Ma, Tab. 3. This plutonism produced more basic granodiorites, tonalites and dioritic rocks often showing interactions of felsic and mafic magmas, enclaves and magma mixing/mingling (e.g. Didier & Barbarin 1991). The occurrence of coeval mafic magmatism evokes a deep-seated source of heat, possibly underplated, high-temperature mantle magmas. Such magmas could have been a product of continuing or a renewed subduction (Finger & Steyrer 1990) or could have resulted from a sudden convective erosion of mantle root (Houseman et al. 1981), or a delamination of subducting slab (Nelson 1990). These processes allowed both rapid uplift and heating of the lower crust by fresh and hot mantle melts followed by more or less extensive melting. Recent discussion (Neubauer 1991; Finger & Steyrer 1991) is relevant to this problem. Subduction, a process introducing large amount of volatiles into the mantle (mantle metasomatism, e.g. Peacock 1993), is attractive accounting for the relatively water- and REE-rich nature of I-type granitoids and diorites. It also explains a more oxidized nature of these deeper magmas through dissociation of water. Such a process, however, could also have operated already during the closure of Paleotethys in Carboniferous. Indeed, the high-precision timing of plutonic and metamorphic events is crucial in this discussion, and it hardly seems possible to make a more rigorous conclusion with these data lacking.

Finally, the origin of post-orogenic Permian acid magmatism may be connected with extensional movements in the just consolidated, nascent late-Variscan Pangea. Anatexis in lower parts of crust containing older granulitic and acid metamorphic lithologies may have produced A-type magmas which ascended along huge strike-slip and rift-related fault systems (Lameyre 1988; Bonin 1990). Such melting producing A-type granite magmas, dated around 280 - 250 Ma, is recorded throughout Europe (Bonin l.c.; Finger et al. 1993; etc.) similarly as the Sn-bearing varieties of Permian granites are known in European Variscides (Krušné Hory Mts., Cornwall, Portugal).

The account of granitoid magmatism evolution in the Western Carpathians given above fits well with that of other areas of European Variscides (e.g. Central zone in Spain Villaseca et al. 1993) or the scenario suggested by Bonin et al. (1993) for the Alpine basement. An exception is represented by the early high-K granitoid type occurring in the Variscan basement of the Hohe Tauern (Finger et al. 1993). This type, has not yet been identified in the Western Carpathians. Neither were found high-K granites associated with later I-type magmatism.

Relation to the Variscan structural edifice

The nappe structure of the Variscan basement in the Western Carpathians is becoming generally accepted. The understanding of the Variscan architecture was largely improved by recognition of Variscan thrusting in the Western Tatra (Kahan 1969; Janák et al. 1988; Fritz et al. 1992). The Variscan thrust tectonics was also recognized in the Veporic Unit (Putiš 1992; Bezák 1993)

Table 2: U/Pb ages of S-type dominated granitoids and collisional metamorphism in European Variscides.

granite/unit	*age (Ma)*	*note*	*source*
Southern Aar syntectonic granite, Central Alps	≈ 350	LI	Schaltegger & Corfu (1992)
Wolfshof syntectonic granite, Gföhl terrane	338 ± 6	UI mo	Friedl et al. (1993)
Gföhl and Drosendorf gneisses	340 ± 4	C mo	Friedl et al. (1993)

Explanations: **UI** - upper intercept, **LI** - lower intercept, **C** - concordant or nearly-concordant age, **mo** - monazite

Table 3: U/Pb ages of I-type dominated granitoids in European Variscides.

granite/unit	age (Ma)	*note*	*source*
Hochalm Tonalite Tauern W.,Eastern Alps	314 ± 7		Cliff (1981)
Mont Blanc Massif Central Alps	304 ± 3	C	Bussy & von Raumer (1993)
Southern Bohemian batholith Weinsberg Granite	318 ± 4	C mo	Friedl et al. (1993)
Rastenberg Granite	323 ± 2	C mo	
Sädelhorn Diorite, Gotthard Massif, Central Alps	293 ± 5	UI	Bossart et al. (1986)
Basic metaigneous granulite xenolith, Massif Central	305	UI	Costa et al. (1993)

Explanations: **UI** - upper intercept, **C** - concordant age, **mo** - monazite

and other Tatric cores (Malé Karpaty Mts., Putiš l.c.). First generalizations were attempted by Putiš l.c., Janák et al. (1993a), Hovorka et al. (1993) and Bezák (1994). A main feature of Variscan tectonics is the mid-crustal thrusting of different lithological units: the lower unit is of flyschoid nature (metapelitic and metapsammitic sequences), the upper one contains characteristic high-grade metamorphics (banded amphibolites, orthogneisses, ultramafites) recording possibly a pre-Variscan HT-HP metamorphism (Hovorka & Méres 1989; Janák et al. 1993a). Bezák (1994) distinguished also a lowest unit composed of greenschist facies metamorphic rocks. Granitoids typically occur in the upper unit where they are thought to be the main cause of LP-HT metamorphism.

As this thrusting seems to represent a main mechanism of the Variscan crustal thickening, the age of piling is crucial for metamorphism and S-type granite genesis. The recent $^{40}Ar/^{39}Ar$ dating by Dallmeyer et al. (1993) of mylonitic orthogneiss muscovite (Nízke Tatry Mts., Bystrá Valley) yielded a plateau age 332.4 ± 1.3 Ma. As the muscovite blocking temperature is 375 ± 25 °C (l.c.), the above age represents a lower limit for the thrusting. The age in excess of 330 Ma corresponds well to metamorphic ages form other Variscan areas (Tab. 2). Thus, while some of the S-type granites seem to have been coeval with the thrusting (Fig. 4a), the I- type granodiorites post-date the nappe tectonics. We interpret it as a response to a thermal event at the end of Carboniferous (Fig. 4b).

The origin of I-type magmas from lower crustal rocks is inferred from the petrological data discussed in previous sections. This not necessarily means a deeper formation place for the I-type magmas because of the higher geothermal gradient, which is probable for the thermal event. The place should have been located more to the north of the thrusting line leaving a place for the formation of S-type magmas more southward and closer to, or even within, the underthrusting accretionary sequences. A lower geothermal gradient may have required a greater depth for melting, in spite of lower dehydration melting temperatures of S-type magmas. They, therefore, may have formed in depths similar to those of I-type magmatism.

Conclusions

The protracted history of the Western Carpathian basement is recorded also by the evolution of Variscan granite family rocks. The collision-related S-type granite magmas may have arisen by the vapour-absent melting of upper crustal quartz-feldspathic mica-bearing rocks as a result of crustal thickening and prograde metamorphism in Lower Carboniferous times. A fundamental feature of these rocks, the low oxidation state, implies the involvement of graphite-bearing interlayers in source lithologies and supports their shallow origin.

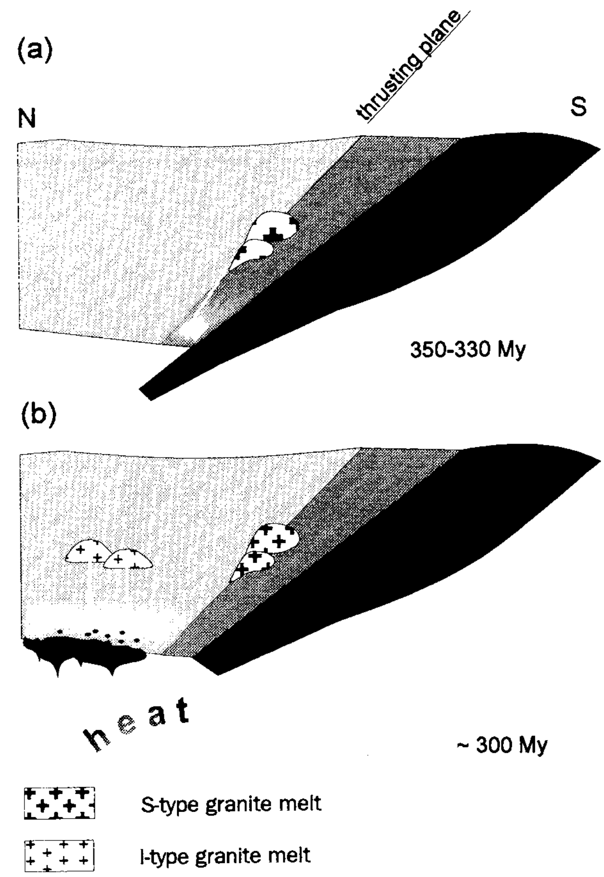

Fig. 4. Simplified cartoon showing first two stages of granitoid magmatism in the Western Carpathian segment of Variscan orogen: **a** - Lower Carboniferous: melting of flyschoid sequences (lower unit) buried in the Variscan accretionary wedge may have occurred due to thermal relaxation and/or decompression and produced S-type granite -granodiorite magmas. The magmas may have used shearing zones for their ascent (Hutton & Reavy 1992). **b** - Upper Carboniferous: the heat of underplated mantle magmas caused a thermal event recorded by crustal rocks and may have produced I-type granodiorite - tonalite magmas by melting of mid-lower crustal lithologies. Mixing/mingling occurred at the interface of mafic and felsic magma.

A thermal event, recorded throughout the Variscan orogen at the end of Carboniferous, caused vapor-absent melting of lower crustal biotite (± hornblende)-bearing intermediate feldspathic rocks and produced I-type dominated granitoid melts. Hot lower crustal and/or mantle magmas, which may have been the ultimate source of heat, were sampled by the granitoid magmas as mafic enclaves. A previous, subduction-related hydration and metasomatism of the mantle-derived magmas may account for the increased water contents, oxidized and REE enriched nature of the I-type granitoids.

The last group of A-type granites formed in extensional environment after the consolidation of Pangea in Permian. This, post-orogenic setting was favourable for strike-slip faulting and formation of small amounts of granitic melts, possibly through melting of restite-enriched source rocks. A-type granites were identified in Veporic and Gemeric Units of central Western Carpathians and in the Cretaceous flysch of the Klippen Belt as pebbles. The tectonic setting of the Gemeric granites is still uncertain. However, specific features of both A- and S-type suggest a different provenance.

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