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The petrogenesis of a wolframite-bearing greisen in the Vykmanov granite stock, Western Krušné hory pluton (Czech Republic)

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Abstract. A wolframite-bearing greisen at Vykmanov, near Ostrov (Czech Republic) occurs at the contact of a small granite stock belonging to the Late Variscan Younger Intrusive Complex (YIC) of the Western Krušné hory/Erzgebirge pluton. The stock emerges as an outcrop of 0.8 × 0.3 km size from a hidden granite body in the eastern continuation of the Nejdek-Eibenstock granite massif. The lens-like greisen body consists mainly of quartz, topaz, protolithionite, and muscovite; it also contains wolframite (ferberite) and native bismuth mineralization. It was formed by replacement of a medium-grained, equigranular, slightly porphyritic Li-F granite of the Karlovy Vary pluton characterized by weak postmagmatic albitization and pervasive muscovitization. The greisen is geologically and compositionally transitional between the Li-rich greisens in albite granites (e.g. with zinnwaldite such as at Krásno) and the Li-poor greisens (e.g. phengite greisens at Gottesberg and Přebuz) associated with weakly albitized granites of the Younger Intrusive Complex.

The Vykmanov greisen formed in a subsolidus stage of granite evolution by progressive alkali loss and fluorine metasomatism, leading to the formation of Li-mica quartz greisen subsequently replaced by topaz-quartz greisen at the granite/crystalline contact. These greisens were affected by late-stage muscovitization and argillitization (sericitization, the formation of clay minerals). The Li-Fe mica composition of the greisens corresponds to protolithionite (lithian siderophyllite) and is similar to the composition of micas in the enclosing granite.

The tungsten-bearing greisenization represents a postmagmatic episode in the development of the Krušné hory/Erzgebirge batholith, and is located at the eastern contact of highly evolved YIC granites of the Western Krušné hory pluton. The greisen formed from CO_2-poor hydrothermal solutions, at about 400 °C, which evolved from highly saline brines as evidenced by fluid inclusion studies. The geological situation suggests that the mineralizing fluids were mostly magmatic and were responsible for the tungsten-bismuth specialization of the greisens, whereas meteoric waters participated in mineralization during later stages.

Key words: Krušné hory/Erzgebirge, ore-bearing granite, Variscan magmatism, greisen, feldspathite, protolithionite, ferberite, wall-rock alteration, tungsten mineralization

Introduction

Greisens associated with late Variscan granites (Tischendorf 1989, Štemprok et al. 1997) are a common host of tin and tungsten ores in the Sn-W metallogenic province of Central Europe (Štemprok and Seltmann 1994). They are metasomatic rocks mostly formed from a granite precursor, and consist of quartz, mica (Li-Fe mica or muscovite), and/or topaz. The greisens are spatially related to the tin and tungsten mineralization of the Younger Intrusive Complex (YIC) granites of the Krušné hory/Erzgebirge granite batholith. Among the ore minerals, the greisens contain cassiterite, wolframite, and/or scheelite in variable combinations and proportions, in addition to a small amount of sulphides. The cassiterite-bearing greisens were studied by Teuscher (1936a, b), Kühne et al. (1972), Štemprok et al. (1997), and Novák and Štemprok (1997). Škvor (1960) described tin-bearing greisens from Přebuz, while Kaemmel (1961) described those from Tannenberg, and Wasternack et al. (1995) from Gottesberg. A tungsten-bearing greisen type was found at Boží Dar in the eastern contact zone of the Nejdek-Eibenstock massif by Absolonová (1978), and at Vykmanov by Štemprok (1984; Fig. 1). The present paper describes the latter greisen, and is based on earlier unpublished reports (Štemprok 1982, 1983) and a short note published in Czech (Štemprok 1984). It extends the application of modern laboratory methods and uses new genetic interpretations of greisen origins.

Geological setting

The Krušné hory/Erzgebirge granite batholith is in the north-western part of the Bohemian Massif. Its emplacement was associated with the Variscan late- to post-collisional magmatism (330–280 Ma, Förster et al. 1999, Schust and Wasternack 2002). The granites are calc-alkaline and peraluminous, evolving from early I/S- to late S-types (Štemprok 1986, Förster et al. 1999, Breiter et al. 1999), and form two subsequent intrusive complexes [older (OIC) and younger (YIC) – Štemprok 1986, Tischendorf 1989, Tischendorf and Förster 1990]. The batholith is spatially divided into three plutons (Western, Central, and Eastern) of which the Western Krušné hory/Erzgebirge pluton includes the largest group of granite outcrops in the Western Krušné hory/Erzgebirge, Vogtland, and the Slavkovský les. The largest granite body is called the Nejdek-Eibenstock massif (N-E). It lies at the border between the Czech Republic and Germany, and the Karlovy Vary massif (pluton, K-V) south and south-west

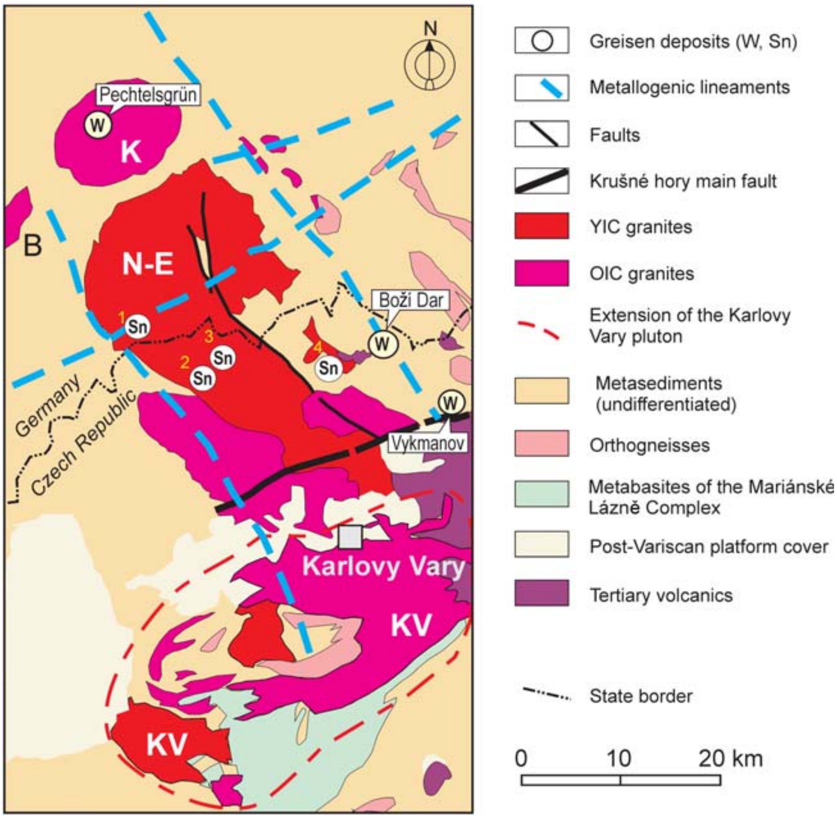

Figure 1. Geological map of the Western Krušné hory/Erzgebirge granite pluton, simplified from the geological map (1 : 500 000) of the Czech Geological Survey, Praha. The greisen localities: 1 – Gottesberg, 2 – Přebuz, 3 – Rolava, 4 – Horní Blatná. Metallogenic lineaments from Wasternack et al. (1995). N-E = Nejdek-Eibenstock massif, KV = Karlovy Vary massif, red stippled line, K = Kirchberg massif, B = Bergen massif.

of Karlovy Vary (Fig. 1). Along its eastern contact several satellite granite bodies occur, to which the Vykmanov granite stock belongs. Geological and geophysical evidence suggests that the shallowly emplaced granites can be traced from the eastern surface exposures to a distance of approximately 15 km (Tischendorf et al. 1965).

Tin and tungsten deposits

The largest greisen deposit in the area was explored at Gottesberg at the western contact (Fig. 1, Wasternack et al. 1995). It is a breccia-type greisen deposit, low in lithium, with predominant cassiterite in muscovite and sericite greisens. Similarly, muscovite greisens with cassiterite occur as fissure-controlled bodies mined and explored at Přebuz (Freels and Štemprok 1996). The tin and tungsten greisens also occur in the Slavkovský les Mts. part of the Western Krušné hory pluton, where lens-like, lithium-rich greisens were mined at Krásno (Jarchovský 1994, Dolejš and Štemprok 2001). Numerous fissure-controlled, tin-bearing greisens occur in the Blatná granite massif, which is the largest YIC granite satellite body of the Nejdek-Eibenstock massif (Fig. 1).

Another tungsten greisen, which is very similar to the Vykmanov greisen described in this paper, occurs as a blind body at Boží Dar (Absolonová 1978, Absolonová and Pokorný 1983). It was found by drilling at depths of 422 to 489 m at the contact of a hidden granite massif with a metamorphic envelope of phyllites and mica schists enclosing quartzite, amphibolite, and skarn intercalations (Fig. 2). The deposits occur in the form of quartz-mica and quartz-topaz greisens with wolframite (ferberite), molybdenite, and bismuth. The greisen was formed by replacement of a coarse-grained, two-mica topaz granite belonging to the YIC granites of the Western Krušné hory pluton. The wolframite mineralization is linked mainly to the quartz-topaz greisen above the quartz-mica greisen and the greisenized granite containing tourmaline and hematite. The ore mineral assemblage includes bismuth, bismuthinite, arsenopyrite, löllingite, stannite, pyrite, sphalerite, chalcopyrite, galena, and hematite. Micas in the greisen are represented by zinnwaldite and muscovite. In addition to tourmaline, the greisen also contains apatite, calcite, siderite, dickite, and accessory amounts of zircon, amphibole, beryl, and triplite (Absolonová 1978).

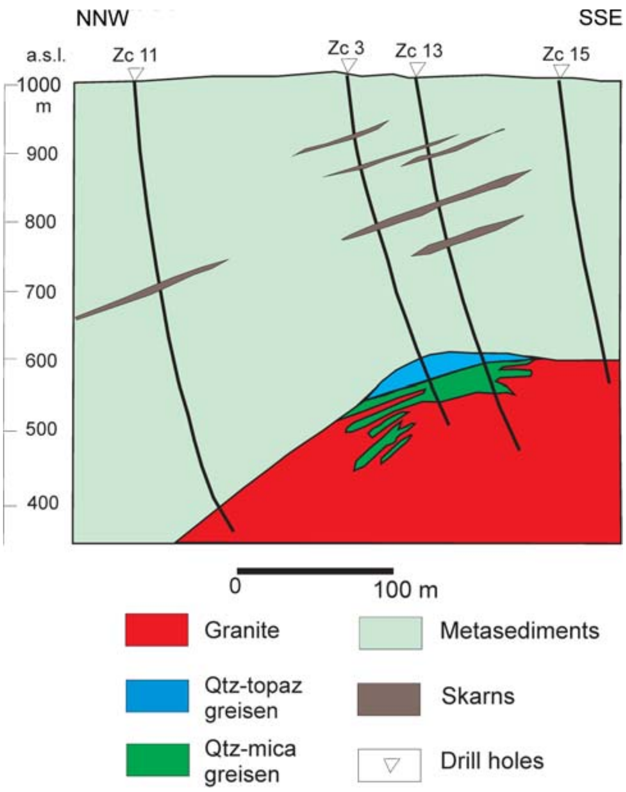

Figure 2. The geological section of the tungsten-bearing greisen at Boží Dar as based on the drill holes, from Absolonová and Pokorný (1983).

The location of the tin- and tungsten-bearing bodies in the Nejdek-Eibenstock massif is apparently controlled by the intersection of major fault zones at Gottesberg

(Wasternack et al. 1995, Fig. 1). The Vykmanov granite massif is in the vicinity of a large Jáchymov-Gera lineament that contains hydrothermal uranium mineralization. The tungsten-bearing greisens and quartz veins are within a large outer tungsten metallogenic zone that encircles the granites of the Western Krušné hory/Erzgebirge pluton (Štemprok and Seltmann 1994), and are characteristic of the western part of the Erzgebirge/Krušné hory ore province.

Geographical and geological position of the Vykmanov greisen

The tungsten-bearing greisen is located at the topographical elevation of 671.5 m (Fig. 3) between Jáchymov and Ostrov in the Karlovy Vary district, about 1.5 km NE of Vykmanov and 750 m SE of the former village of Hanušov in a forested part of an east-west-trending crest.

The Vykmanov greisen was first described by Berwerth (1917), and its wolframite mineralization identified by Štemprok (1982, 1984). It is spatially related to a small granite stock (about 0.8 × 0.3 km in outcrop), see Fig. 3. The broader envelope of this part of the Western Krušné hory pluton is built up by the metamorphic complex of orthogneisses, mica schists with intercalations of quartzites, carbonates, and metabasites (Trvala et al. 1962, Škvor 1975, Škvor and Sattran 1975) belonging to the Jáchymov series (presumably of Upper Cambrian age). The immediate exocontact zone of the Vykmanov granite stock is to the north and east (Fig. 3), and is formed by orthogneisses (migmatites) irregularly intercalated with quartzites, quartz-enriched mica schists, and mica schists. The southern contact is intersected by the major Krušné hory fault, along which the stock is juxtaposed to Tertiary volcanics (lavas and volcanoclastics) and Quaternary sediments of the sub-Krušné hory basin. The granite body is cut in the west by the Plavno fault of NW strike, accompanied on its western side by parallel dykes of granite and syenite porphyries. Rare kersantites, striking approximately NW and NE, were observed in the metamorphic envelope along the western and northern margins of the massif and its subsurface exposures in the Vladimír mine (Trvala et al. 1962).

The detailed morphology of northern hidden granite contact is known from the drill holes and mine workings of a former uranium mine (Fig. 4). The NE granite contact dips at an angle of about 25–30° from the surface (625–650 m a. s. l.) to about 500 m a. s. l., and then more steeply 40–50° towards the NE. The contact with the metamorphic envelope is sharp. In the Vladimír mine xenoliths of the country rock within the granite were observed in the sixth level (Trvala et al. 1962).

The detailed gravity measurements by Polanský (1981) (accuracy of local anomalies 0.5 μm . s^{-2}) showed a negligible effect of the outcropping granite body on the overall gravity picture. The granite was thereby interpreted as a subordinate elevation in the largely hidden upper surface of a concealed granite body underlying the entire metamorphic complex. The outcrop of the greisen body showed an insignificant positive gravity anomaly. Along

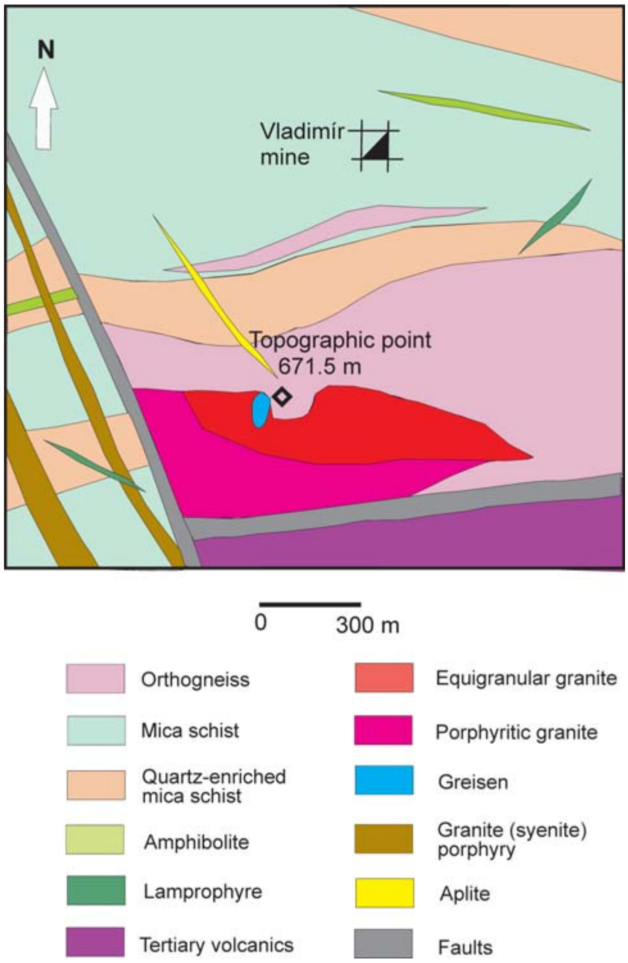

Figure 3. Geological map of the Vykmanov area from Štemprok (1984) based on the geological mapping by Lyubanov (1957).

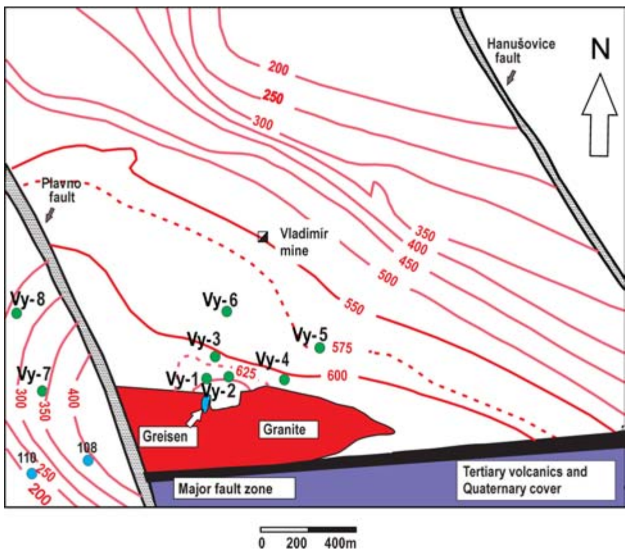

Figure 4. Topography of the hidden granite surface of the Vykmanov area derived from drillings, mine workings, and gravity data (Štemprok 1984). Green circles show drill holes from tungsten exploration, blue circles from the exploration for uranium ore.

the Plavno fault the western continuation of the granite relief sunk to about 200–400 m under the present surface (Štemprok 1983), but no tin or tungsten mineralization was found in the drill holes from within or above the hidden granite.

Exploration and earlier studies

The tungsten deposit was explored by the Czech Geological Survey (Štemprok 1982, 1983, 1984). This exploration, based on recognition of the greisen body on the surface, included soil metallometry over the northern contact zone of the massif, inclined drill holes to depths of 100–150 m (Vy-1–5), and a single vertical drill hole 160.3 m deep (Vy-6). In addition, two vertical drill holes (Vy-7 and 8) traced the western continuation of the massif.

The drilling identified the greisen as a flat lens-like body, lining the northern upper granite contact and passing into ungreisenized granite at depth. The exploration indicated that the deposit is subeconomic with possible reserves of 1,130,000 tons of ore with a grade of 0.12 wt.% W (Štemprok 1982). Fluid inclusions in quartz and topaz in the greisen were studied by Ďurišová (1984), who measured homogenization temperatures and fluid salinity. The homogenization temperatures in topaz were found to range from 409 to 383 °C in vapour-dominated, and from 357 to 328 °C in liquid-dominated inclusions. In quartz the ranges were observed to be 400 to 383 °C in vapour-dominated, and 367 to 316 °C and 280 to 228 °C in liquid-dominated inclusions. Primary vapour-rich inclusions were predominant in topaz. Multiphase inclusions were interpreted to indicate the presence of highly concentrated solutions.

Analytical procedures

The drill cores of the mineralized greisens and of the adjacent granites and metamorphic rocks were cut in half. One of the halves was then crushed, pulverized, and analysed by X-ray fluorescence and optical spectroscopic methods in the analytical laboratory of Geologický průzkum Brno (Geological Exploration, Brno branch). Major element contents of the greisen and granite samples were determined by wet chemical techniques in the laboratories of the Geological Institutes of the Faculty of Science, Charles University in Prague, and the trace elements by AAS method in the same laboratory and by the ICP-MS method by Analytika s. r. o., Prague.

Feldspars were analyzed at the Institute of Geology, Academy of Sciences of the Czech Republic in Prague using a JEOL JXA 50 A electron microprobe, equipped with EDAX 711, operating at 15 kV, with a beam current of 3 nA, beam diameter of 2 μm, and a counting time of 30 s. Analyses of micas, topaz, and ferberite were carried out on a CAMECA SX-100 electron microprobe in the wavelength dispersive mode by the third author of the present paper at the Institute of Geology, Academy of Sciences of the Czech Republic in Prague. The beam diameter was 10 μm with an accelerating voltage of 15 kV, and the beam current was 10 nA measured by a Faraday cup. The counting time was 10 s. The standards employed were synthetic SiO_2, TiO_2, Al_2O_3, Fe_2O_3, RbCl, and natural jadeite, apatite, leucite, diopside, spinel, and halite. The data were reduced using the X-PHI correction procedure.

Analyses of the Li mica separates were carried out by the AAS method in the Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic in Prague; trace element concentrations were measured by INAA method (Nuclear Physics Institute, Academy of Science of the Czech Republic in Řež). Mica separates were also studied by the X-ray diffraction method using a Philips X'Pert automatic powder diffractometer, employing Cu K_{α} radiation and graphite monochromator, with a scanning speed of 1°/min, a generator voltage of 40 kV, and a generator current 40 mA.

The geochemical data were processed by Minpet 2.01 computer programme used in REE and spidergram plots, and for the calculation of statistical data.

Results and interpretations

Petrology of the host granite

The Vykmanov granite stock consists of two textural varieties which may represent two separate intrusive pulses:

a) Two-mica, medium-grained to fine-grained, equigranular (scarcely porphyritic) granite classified as aplite in the early study by Berwerth (1917). It contains quartz, plagioclase An_{10}, K-feldspar (with perthitic inclusions), protolithionite, muscovite, and abundant topaz. Muscovite appears texturally as a secondary phase (Fig. 5). Plagioclase crystals often occur as polycrystalline aggregates (Plate Ia). Quartz occurs in round aggregates (up to 5 mm in size), plagioclase feldspar in tabular crystals (up to 25 mm), and Li-Fe micas (up to 4 mm) as phenocrysts (Fig. 5). This granite forms a zone up to 80 m thick in the upper part of the main granitic body (Fig. 6). Texturally, a similar granite also forms several flat dykes (0.1 to 5 m thick) in the envelope of the granite massif (drill hole Vy-5). Some of these dykes have an upper contact bordered by a several cm thick pegmatitic rim similar to a "stockscheider". The contact between the equigranular medium-grained and coarse-grained porphyritic variety in the drill holes is marked by a rapid change in the texture (involving grain size and the size and proportion of phenocrysts), except for the occurrences of granites forming a transitional zone.

b) Two-mica, coarse- to medium-grained, coarsely porphyritic granite with abundant phenocrysts up to 3 cm in size (quartz, alkali feldspar, plagioclase, micas), and with accessory topaz. This granite corresponds to the main type of YIC granites in the Nejdek-Eibenstock massif (Absolonová and Matoulek 1975), and was observed in an abandoned quarry in the lower part of the Vykmanov

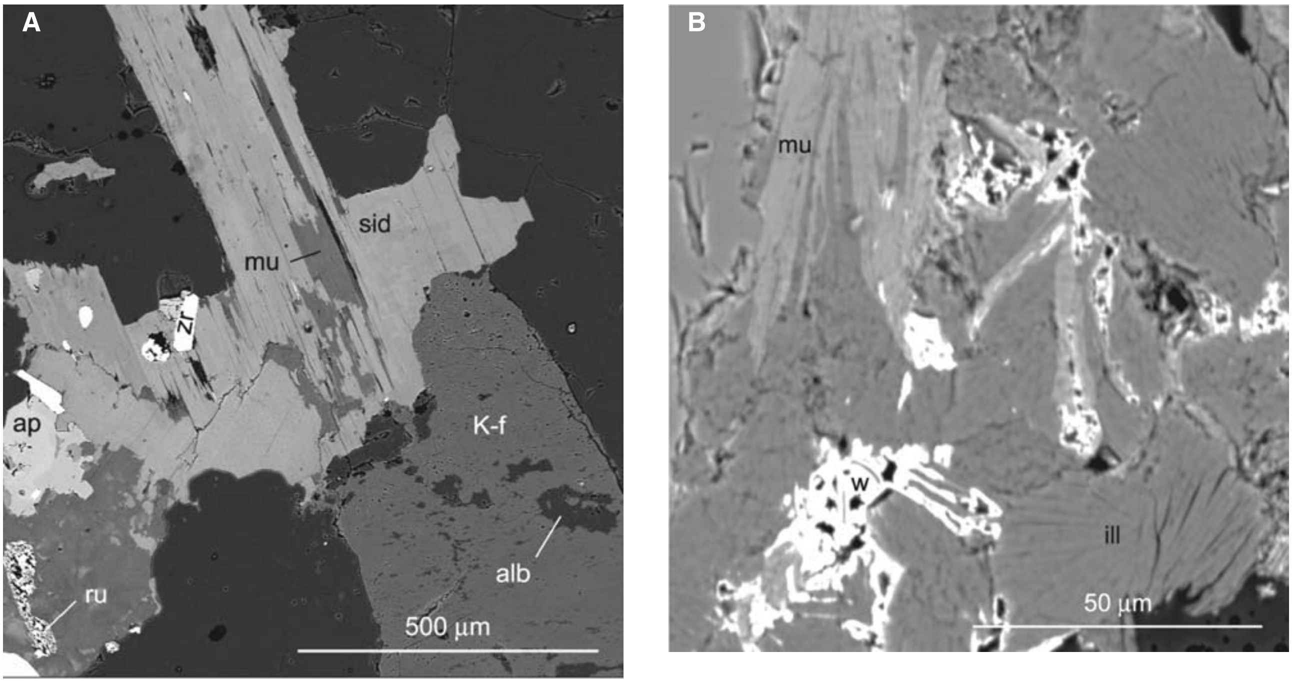

Figure 5. A – back scattered electron image of greisenized granite. Protolithionite (sid) is replaced by muscovite (mu) along cleavage, zr – zircon, ru – rutile, alb – albite, K-f – alkali feldspar, ap – apatite. B – back scattered electron image of quartz-topaz greisen, muscovite (mu) is strongly illitized (ill) and wolframite (w) grains are located along its relics.

massif and in the lower portions of the drill sections. This granite type was also found in the depressed block west of the Plavno fault zone in drill hole Vy-7. It is composed of quartz (30–40 vol%), K-feldspar (30–45 vol%), with a generally low amount of perthite, earlier plagioclase An_{18-21}, and predominant albite (An_{10-2}, see Table 1) at about 15–20 vol%, protolithionite (lithian siderophyllite, X = light brown, Y = brown) at 5–3 vol%, and muscovite at 2 vol%. Accessory minerals are topaz, apatite, rutile, zircon, monazite, and tourmaline. Some accessories are

Table 1. Selected microprobe analyses of feldspars from the porphyritic medium-grained granite of Vykmanov (quarry, entrance to the adit)

Oxide	Perthite		Plagioclase		Albite
	K-phase	Na-phase			
SiO_2 (wt.%)	64.94	67.13	64.23	65.07	67.45*
TiO_2	0.00	0.01	0.06	0.10	0.08
Al_2O_3	18.90	20.66	21.90	21.41	20.19
FeO	0.00	0.00	0.20	0.22	0.20
MgO	0.00	0.00	0.36	0.31	0.37
MnO	0.00	0.00	0.14	0.19	0.14
CaO	0.00	0.46	4.09	3.57	1.25
Na_2O	2.33	11.62	8.36	8.46	9.64
K_2O	14.03	0.26	0.36	0.46	0.48
Rb_2O	0.18	0.01	–	–	–
Total	100.38	100.15	99.70	99.79	99.80
Ab	19.9	96.6	77.0	79.2	90.5
An	–	2.1	20.8	18.5	6.5
Or	80.1	1.3	2.2	2.3	3.0

* analytical data of J. K. Novák

preferentially enclosed in the Li-Fe micas and are surrounded by pleochroic haloes (Plate Ib). Topaz forms aggregates of anhedral grains in the groundmass (Plate Ic). Both the granite types belong to the YIC complex of the Krušné hory/Erzgebirge batholith as shown by their mineralogy (see Teuscher 1936a, b, Zoubek 1951, Lange et al. 1972) and geochemistry (Štemprok 1986, Breiter et al. 1999).

Some plagioclase crystals are replaced by K-feldspars, as also observed by Škvor (1960) at Přebuz. The more calcic cores of plagioclase crystals are often affected by sericitization (Plate Id). Later replacement of Li-Fe micas by muscovite is common (Fig. 5A). Topaz is abundantly altered by sericitization and argillitization (to illite and kaolinite group minerals). All granite types were subjected to strong hematitization forming a pervasive

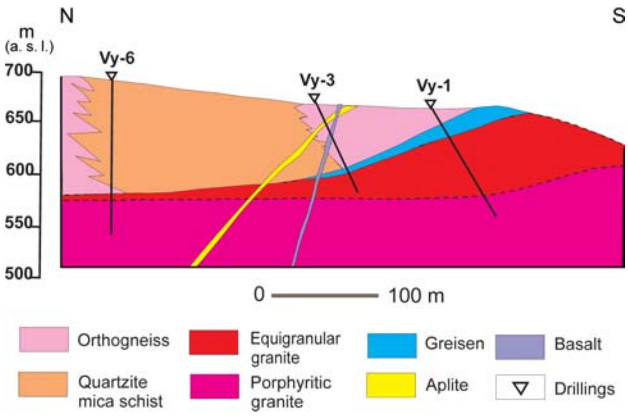

Figure 6. Geological section through the Vykmanov greisen body based on drill holes and surface mapping (Štemprok 1984).

impregnation in the rock-forming minerals, or occurring along the fissure or fault zones intersecting the granite.

Aplite is locally observed in the form of equigranular steeply dipping dykes about 0.5 m thick (see Fig. 3) and also containing pegmatite pods. In drill hole Vy-8, a 5 m thick dyke of aplitic topaz granite with brown Li-Fe micas and very abundant tourmaline was observed. Pegmatite pods contain strongly perthitic alkali feldspar which encloses the minute euhedral crystals of earlier plagioclase. We interpret the aplite as younger than the YIC granites based on the observation of dykes intersecting both granite varieties of the massif (Fig. 6). In drill hole Vy-3, at depths of 14.5 to 20.5 m in the orthogneiss, a zone of quartz fragments in a low recovery drill core was observed which may correspond to the quartz zone of a pegmatitic body. A pegmatitic rim was also found as a 10–20 cm thick upper border of some aplitic dykes in drill hole Vy-5.

Hydrothermal assemblages

Feldspathites (episyenites)
Medium-grained, irregularly developed, metasomatic rock with diffuse contacts about 2 m in thickness was observed in drill hole Vy-2 (41.7–43.7 m) within the equigranular granite. The feldspathite is composed of K-feldspar, Li-Fe mica, muscovite, and small amounts of quartz and accessory apatite. The K-feldspar contains numerous cavities typical of some hydrothermal feldspars and is devoid of perthite exsolutions (Plate Ie).

Cassiterite-quartz veins
Quartz veinlets (0.5–1 cm thick) composed of quartz crystals in two-generations, with cassiterite, protolithionite, and abundant albite were observed in the rock debris in the surroundings of drill hole Vy-6 (Plate If). Cassiterite (0.2–0.5 mm) displays optical zoning with alternating dark-brown and light-brown zones. The microprobe analysis of this mineral showed that the contents of Fe, Nb, Zr, W, and Ta are all below the detection limit of the microprobe (~ 100 ppm).

Tourmalinites
Quartz-tourmaline or monomineral tourmaline (schorl) accumulations occur in the form of impregnations in orthogneiss, or in association with quartz along fissures in mica schist in the weathering products in the vicinity of drill hole Vy-6. Some tourmaline aggregates also contained cassiterite. In addition to these massive tourmaline aggregates, individual larger crystals of schorl occur in pegmatitic pods in metasedimentary rocks between Hanušovice and Jáchymov (Plavno-Holzbach, Suchá-Dürnberg reported by Kratochvíl 1960).

Skarns
Lenses of several tens of meters in thickness, composed of garnet, actinolite, epidote, and chlorite, with minor muscovite, biotite, apatite, rutile, magnetite, hematite, sphalerite, chalcopyrite, arsenopyrite, pyrrhotite, Bi-sulphosalts, and cassiterite were recognized in the mica schists in the mine workings of the Vladimír uranium mine at depths of 100 and 200 m (Exler and Kovačík 1962) below the surface. A small skarn body in the second level of the same mine hosted tin contents between 0.13 to 2.23 % Sn in cassiterite as the main ore mineral, and were accompanied by sphalerite enriched in indium (Hak et al. 1979).

Mica metasomatites
Irregular nests of sericite rock, with relics of quartz with grain sizes of 0.05–0.1 mm and accompanied by hematite, occur irregularly in the metamorphic complex as found by the drill holes (e.g. Vy-1 at 14.6 m). They contained disseminated sphalerite and arsenopyrite, locally accompanied by abundant hydrothermal quartz.

Uraninite-carbonate mineralization
Steep fissures containing uranium mineralization were the subjects of previous mining activity (Vladimír shaft, Jáchymov mines, see Fig. 3). The fissures, striking north-south and east-west, contained pitchblende and carbonates, and belong to the uranium-quartz-carbonate-F (uqk) type of mineralization (Kuschka in Freels and Štemprok 1996). Torbernite impregnation was observed in some fissures in the metamorphic envelope in the vicinity of greisens.

Petrology of the greisens

Granite greisen

The greisen body is a lens-like sheet located along the northern endocontact of the Vykmanov granite. Its greatest thickness is about 18 m at the outcrop, and from there it gradually narrows (see Fig. 6) over a distance of about 200 m. It has a sharp contact with the enclosing orthogneiss, but a relatively sharp textural and mineralogical transition into the underlying unaltered granites. The grain sizes in the greisens range from 0.2 to 2 mm, with the most common grain sizes between 0.5 to 1 mm. The texture of the greisen is subhedral and its grain size is similar that of the equigranular granite.

The greisens contain variable amounts of quartz, topaz, Li-Fe mica, muscovite, fluorite, hematite, and clay minerals (illite, kaolinite group minerals). The modal composition of the Vykmanov greisen is shown in the quartz-topaz-mica diagram (Kühne et al. 1972) in the fields with more than 50 modal % of quartz, typical of granite greisens (Fig. 7). Three mineralogical types of greisens were distinguished:

a) Medium-grained quartz-topaz greisen is composed of quartz (from 75 to 90 %), topaz (5–22 %), muscovite and Li-Fe mica (1–5 %), and wolframite (ferberite $Fe_{09}Mn_{01}WO_4$, 0.5–1.2 vol%), and clay minerals (predominantly kaolinite group minerals, 1–2.5 vol%). Ferberite (Plate IIa, b) forms thin plates, 0.005 to 1.2 mm in size, that are isolated or in clusters within intergrowths of topaz or muscovite or protolihionite. Ferberite rarely contains accessory Fe-columbite or is accompanied by scheelite. Topaz forms subhedral to anhedral grains, and in places it occurs as crystals in small cavities. It is commonly altered to sericite and other clay minerals (Plate IIa, b). Similar to the topaz, the rare protolithionite is partly replaced by fine-grained sericite (illite). Bismuth was observed as an accessory mineral in intergrowths with quartz. Very rarely the greisen contains alkali feldspar with abundant minute intragranular cavities, similar to the late alkali feldspar of feldspathite.

b) Medium-grained quartz-topaz-mica greisen (Plate IIc, d) contains predominant quartz accompanied by equant or columnar grains of topaz, and plates of muscovite and green Li-Fe mica. It also contains fluorite, kaolinite group minerals, and sericite which often replace topaz.

c) Medium-grained quartz-mica greisen (Plate IIe) is dark-grey in colour and is composed mainly of quartz and brown-green protolithionite (8 %), which predominates over muscovite by which it is partly replaced. Muscovite is in places altered to illite. Euhedral topaz is subordinate. Biotite (protolithionite) enclosed in quartz is probably a relic of a mica from the granitic precursor. In drill hole Vy-1 (Fig. 8) the quartz-mica greisen forms the lower part of the greisen body at the contact between the quartz-topaz greisen and unaltered granite, or it occurs as a main greisen type at the flanks of the greisen body (Vy-3).

The spatial mineral zoning of the greisen assemblages probably reflects the degree of hydrolytic alteration. The uppermost part of the greisen body is formed by the quartz-topaz greisen, whereas the lower levels are formed by quartz-mica or quartz-mica-topaz greisens. The greisen-to-granite transition is remarkably sharp. This sequence may, however, be more variable as shown at the greisen outcrop at the elevation of 671.5 m. At the flanks of the greisen body the zone of topaz-quartz greisen is completely missing, and the greisen body is represented by a quartz-mica greisen (Vy-4).

Greisenized granites were observed at the upper contact of the hidden granite body west of the greisen body (granite analysis from Vy-8, see Table 5). Greisenized aplites with predominant muscovite and rare arsenopyrite were documented in a steep dyke up to 50 cm thick in the envelope of the granite in the area of drill hole Vy-1. The aplites are interpreted as being post intrusive, crosscutting the main type of the Vykmanov granites, as observed also in the Vladimír mine (Trvala et al. 1962). The quartz-muscovite greisen contains rare topaz and sericite, scarce relics of feldspars, and accessory cassiterite.

Orthogneiss greisen

Greisenized orthogneisses consisting of micas and quartz (Plate IIf) with subordinate topaz, in bands about 0.1 to 1.5 m thick, were observed in the northern exocontact zone of the granite stock. A significant textural feature is the preservation of the planar rock fabric with the alternations of dark and light bands. The light bands consist mainly of quartz and muscovite with relics of biotite, rare Li-Fe mica and sphalerite and chalcopyrite, whereas the dark bands are

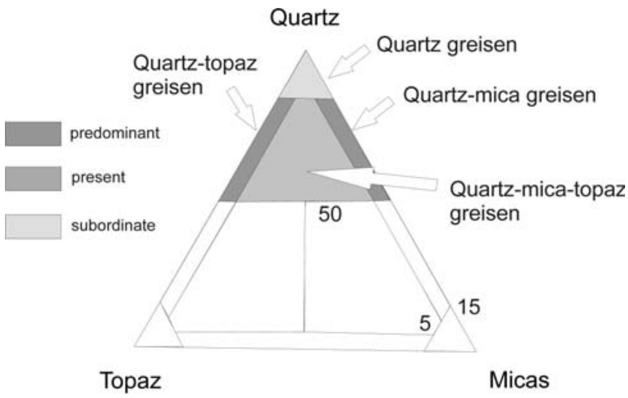

Figure 7. Classification of the Vykmanov greisens using the diagram by Kühne et al. (1972).

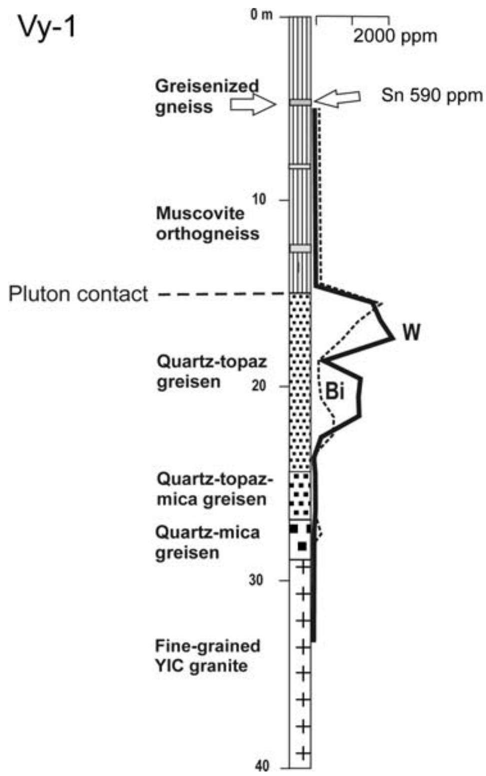

Figure 8. Variations of the tungsten and bismuth contents in drill hole Vy-1.

mixtures of the newly formed muscovite and relics of the original biotite. Irregularly shaped muscovite typically occurs in skeletal intergrowths with quartz, marked by abundant inclusions of muscovite in quartz in the vicinity of muscovite aggregates (Plate IIf). This greisen also contains relics of zircon from the original orthogneiss.

Mineralogy

Topaz

Topaz occurs as an accessory phase in the two-mica granite, in the quartz-mica and quartz-topaz greisens. Crystals described by Berwerth (1917) display 110, 120, 021, 001, and

Table 2. Selected microprobe analyses of topaz from the Vykmanov greisens

Sample	449/7	449/11	449/8	448/1	448/5	448/3
SiO_2 (wt.%)	32.66	32.59	32.60	32.44	32.56	32.66
Al_2O_3	56.26	55.83	56.96	56.17	56.67	56.63
FeO	0.05	0.03	0.06	0.00	0.03	0.05
CaO	0.02	0.02	0.00	0.01	0.00	0.01
MnO	0.00	0.00	0.05	0.00	0.00	0.00
P_2O_5	0.00	0.03	0.00	0.00	0.01	0.07
H_2O^+	1.58	1.18	0.85	1.18	1.12	0.48
F	15.16	15.63	16.30	16.65	15.85	16.78
Cl	0.00	0.00	0.01	0.00	0.00	0.00
Total	105.73	105.31	106.83	106.46	106.24	106.68
O = F, Cl	–6.38	–6.58	–6.86	–6.59	–6.67	–7.07
Total	99.35	98.73	99.97	98.87	99.57	99.61
F/(OH+F)	0.82	0.85	0.91	0.92	0.87	0.94

448 – quartz-topaz greisen, 449 – quartz-mica greisen, water content H_2O^+ calculated from stoichiometry

111 faces in a granoblastic greisen variety. Topaz is generally one of the youngest minerals in the crystallization sequence of the studied rocks. Fluorine concentrations in the topaz of all the greisens, as measured by electron microprobe, are very similar and range between 15.2 and 16.8 wt.% (Table 2), while the chlorine contents are below 0.01 wt.%. Chemical analyses show low contents of FeO (max. 0.17 wt.%) and P_2O_5 (max. 0.07 wt.%), and H_2O recalculated from the stoichiometry reaches 1.58 wt.% (Table 2).

Micas

Protolithionite (lithian siderophyllite)

Dark mica is a subordinate component in granite (usually less than 5 vol%), but a substantial component in the quartz mica greisen (Fig. 7). It displays dark-brown to orange-brown pleochroism and it is commonly partly intergrown with muscovite. Selected chemical analyses of micas in the granite greisen are shown in Table 3, while the trace element compositions are given in Table 4. The protolithionite from the granite differs from that of the greisen by higher MgO and lower F contents. The contents of TiO_2 in the granite reach 1.43 wt.%, whereas the TiO_2 concentrations are lower in the greisen (up to 0.82 wt.%).

Greisenization causes changes in the mica colouration, especially in the quartz-mica greisen, to pale-green despite the absence of detectable changes in the chemical compositions of the micas (Table 3). Likewise, no differences were detected by comparing the X-ray records. According to chemical composition (Table 3) with regard to Li content (1.00 to 1.09 wt.% Li_2O), both micas correspond to protolithionite (Foster 1960), or in a more recent classification to lithian siderophyllite (Rieder et al. 1998). We prefer to use the original name protolithionite in consideration of the prevailing terminology used for the Krušné hory/Erzgebirge

Table 3. Selected microprobe analyses of micas from Vykmanov (each point is an average of 3 measurements)

Sample	Granite		Greisen		Granite	Greisen		Greisen	
	447		449		447	448		449	
	Protolithionite				Muscovite				
SiO_2 (wt.%)	37.29	38.45	37.51	38.33	46.85	49.36	46.85	49.65	45.22
TiO_2	1.08	1.09	0.24	0.82	0.34	0.29	0.20	0.10	0.08
Al_2O_3	23.00	23.67	23.89	22.91	28.76	30.58	28.15	27.66	30.34
FeO	20.37	17.81	21.87	21.20	6.66	4.07	5.8	6.34	6.32
MgO	1.57	1.56	0.26	0.88	1.24	1.09	1.06	0.53	0.23
MnO	0.49	0.43	0.32	0.41	0.26	0.20	0.18	0.04	0.11
CaO	0.00	0.07	0.02	0.12	0.00	0.23	0.10	0.01	0.00
Na_2O	0.22	0.22	0.20	0.51	0.26	0.40	0.08	0.04	0.37
K_2O	9.94	10.04	9.79	8.79	10.96	9.56	9.68	10.59	10.85
Rb_2O	0.57	0.59	0.64	0.62	0.48	–	0.31	0.49	0.42
F	0.18	0.24	0.90	0.95	0.18	0.68	0.62	0.15	0.43
Cl	0.10	0.08	0.08	0.17	0.00	0.10	0.00	0.03	0.02
Li_2O	1.09*		1.00*			0.10*			
X	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Y	6.04	5.96	5.79	5.98	4.13	4.08	4.16	4.04	4.04
Z	2.08	2.04	2.08	1.91	2.05	1.78	1.81	1.92	2.07

447 – medium-grained porphyritic granite, 448 – quartz-topaz greisen, 449 – quartz-mica greisen
* wet chemical analysis by V. Chalupský, in a mica separate from sample 447, in 449 protolithionite prevails (> 90 vol%), 448 is a mixture of muscovite and illite
$X = Si + Al^{IV}$, $Y = Al^{VI} + Fe + Mn + Mg + Ti + Li$, $Z = Ca + Na + K + Rb$ (site occupancies calculated from the number of ions on the basis of 22 atoms of oxygen)

Table 4. Trace elements in protolithionites from the granite and quartz-mica greisen of Vykmanov

Element (ppm)	Granite (447)	Quartz-mica greisen (449)*
As	4.1	112
Ba	< 150	< 180
Co	8.00	1.56
Cl	1131	1063
Cr	8.66	< 4
Cs	34	23.8
Ni	< 160	< 200
Rb	4222	4570
Sc	34	23.8
Sr	< 180	< 220
Ta	68.4	125.2
Th	38.1	3.23
U	21.9	< 4
W	218	11590
Zn	484	352
Zr	268	< 220
La	32	1.44
Ce	64	3.64
Nd	28	< 11
Sm	8.61	0.55
Eu	0.70	0.05
Tb	1.34	< 0.3
Yb	1.62	< 0.7
Lu	0.285	< 0.1

* protolithionite prevails (> 90 %), analyst: Z. Řanda

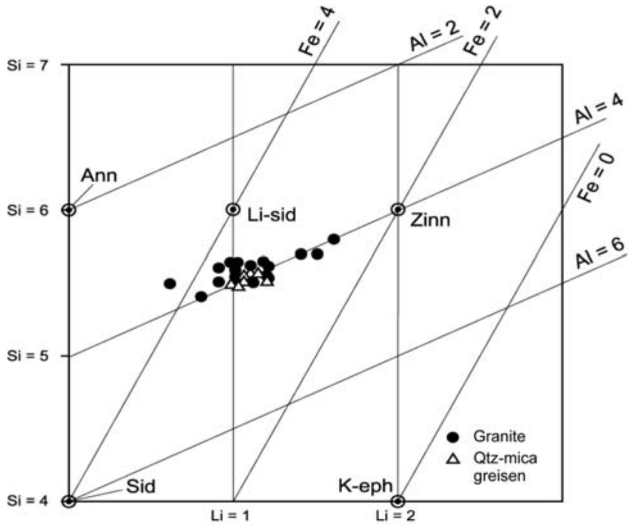

Figure 9. Vector diagram (atomic) for analyzed dark Li-micas (atoms per formula unit on 22 oxygen basis) from Černý and Burt (1984). Note that the Al contents refer to the sum of octahedral and tetrahedral Al. The plots show microprobe data. Li contents are derived from Si, Al, and Fe ratios. Sid = siderophyllite, Ann = annite, K-eph = K ephesite, Zinn = zinnwaldite. Si and Li values correspond to Si and Li [apfu].

Li-Fe micas. The dark micas classified in the vector diagram of Černý and Burt (1984) are shown in Fig. 9 where they plot close to protolithionite composition. The micas from the granite and the greisen do not differ markedly in their positions. In the classification diagram of feal-mgli coordinates proposed by Tischendorf et al. (2004), the protolithionite from the greisen falls close to the boundary of lithian siderophyllite-annite.

Muscovite
White mica close to a muscovite composition (see Table 3) occurs in thick tabular grains or polycrystalline aggregates, and is mostly a product of the replacement of dark micas in the granite and the greisens. Several muscovite grains from the granite that may be interpreted texturally as primary are exceptions. The secondary origin by replacement of dark micas is indicated by the relatively high Fe contents that vary from 1.14 to 9.21 wt.% FeO in the granite, and from 6.30 to 7.75 wt.% FeO in both greisen types corresponding to the Fe phengite composition. Some muscovites in greisens, mainly in the quartz-topaz type, are altered. Such alteration may be detected by the high Si/Al ratio accompanied by the deficient K_2O in relation to muscovite. This process is most intensive in the quartz-topaz greisen, where fan-like aggregates of illite have Si/Al ratios > 1 and lower K contents (< 2.2 wt.% K_2O). Additionally, the decreasing totals of microprobe analyses (down to about 85 wt.%) documents a high level of hydration. The composition of the white micas of the granites and greisens corresponds to phengite and Fe-phengite according to the classification by Tischendorf et al. (1997). The Fe contents are higher and Al contents are lower than in the muscovite end member (Table 3).

Granite and greisen geochemistry

Both the textural types of the Vykmanov granite are typical high silica peraluminous granites with increased amounts of Li and F, and with low contents of CaO and TiO_2 (Table 5a). These are classified as Li-F granites by Förster et al. (1999) or as topaz granites by Taylor and Fallick (1997). Their phosphorus concentrations (0.2–0.4 wt.% P_2O_5) lie within the range of granites from the Western Krušné hory/Erzgebirge pluton (Štemprok 1986, Förster et al. 1999). The unusual increase in tungsten abundances is apparently caused by the presence wolframite mineralization. The increased Ta content noted in one analysis (Table 5b) is not correlated with other data and it is not accompanied by an equivalent increase in Nb. The granite is moderately rich in Sn (average 12.5 ppm), though in concentrations lower than most typical tin-bearing granites of YIC in the Czech part of the Western Krušné hory pluton (Absolonová and Matoulek 1975, Štemprok 1986) which cluster at Sn values of about 30 ppm.

The variations of trace element abundances of the Vykmanov granites coincide with the YIC granites of the Karlovy Vary massif (Štemprok et al. 1996), and are illustrated in the spidergrams (Fig. 10). The averaged trace element abundances in the various rock types intersected by

Table 5a. Chemical composition of granites and greisens from the Karlovy Vary pluton and the Vykmanov massif

Rock type/ Oxide (element) wt.%	YIC granite	YIC granite	YIC granite	Greisenized YIC granite	Quartz-mica greisen	Quartz-topaz greisen
Analyses number	1 (1)	2 (6)	3 (646)	4	5 (644)	6 (645)
SiO_2	76.86	75.26	73.80	71.64	79.84	82.84
TiO_2	0.10	0.08	0.15	0.05	0.13	0.35
Al_2O_3	12.99	13.73	13.77	15.48	12.20	12.82
Fe_2O_3	0.19	0.12	1.11	0.43	1.56	0.97
FeO	0.52	0. 87	0.54	0.60	2.05	0.08
MnO	0.013	0.030	0.03	0.023	0.06	0.02
MgO	0.10	0.12	0.10	0.43	0.03	0.01
CaO	0.17	0.39	0.67	0.70	0.67	0.89
Li_2O	0.030	0.059	0.071	0.080	0.127	0.008
Na_2O	2.34	3.32	3.21	0.71	0.05	0.06
K_2O	5.89	4.63	5.07	4.56	1.23	0.09
P_2O_5	0.20	0.23	0.22	0.46	0.20	0.25
CO_2	0.02	0.02	0.07	0.02	0.09	0.09
C	0.06	0.04	–	< 0.01	–	–
H_2O^+	0.89	1.00	0.62	3.31	0.99	0.66
F	0.21	0.29	0.15	0.54	0.90	1.06
S	0.02	0.07	–	0.01	0.02	0.05
$H_2O^–$	0.04	0.11	0.18	1.48	0.08	0.08
Total	100.64	100.37	99.77	100.52	100.23	100.33
S-equiv.	–0.01	–0.02	0	–0.01	–0.01	–0.025
F-equiv.	–0.09	–0.12	–0.06	–0.23	–0.38	–0.46
Total	100.54	100.23	99.71	100.28	99.84	99.84

the drill core analyses are shown in Table 6. The equigranular granite has mean Rb values of 919 ppm, while the Nb contents range between 17 and 23 ppm with a mean value of 20 ppm. The granite from drill hole Vy-8 varied in Rb between 550 and 700 ppm, thus showing contents lower than in the granites from the stock crest.

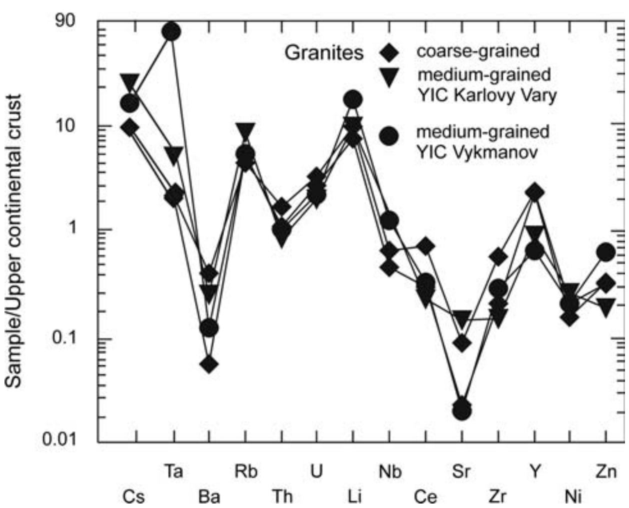

Figure 10. The spidergram of the Vykmanov main granite compared with the YIC granites from the geological section of Karlovy Vary – Březová (Štemprok et al. 1996, normalizing data from Taylor and McLennan 1985).

The REE patterns of the least hydrothermally altered Vykmanov granite and greisens (Table 5c) are shown in Fig. 11. The chondrite-normalized REE patterns indicate a typical decrease in the LREE and HREE in the greisen compared to the original granite, and a more pronounced Eu anomaly than in the greisens. The preservation of the Ce values in the greisens at a level typical of some granites may indicate the negligible dissolution (or a low dissolution rate) of a Ce-bearing accessory mineral (such as monazite), though this has not been verified by the microprobe study. We note, however, the parallel course of granite and greisen REE patterns.

The behaviour of individual elements during the greisenization of a medium-grained porphyritic granite is illustrated by separate isocon diagrams for major element oxides (A) and trace elements (B). Whole rock data were normalized to 100 % including H_2O^+, $H_2O^–$ and F. The constant volume isocons were calculated using the density measurements of rocks by Polanský (1981). The isocon diagrams compare the composition and mass changes during the formation of the quartz-mica greisen (Fig. 12) and of the quartz-topaz greisen (Fig. 13).

The isocon diagram for the quartz-mica greisen (Fig. 12) shows a major enrichment in fluorine and Fe_2O_3, while the TiO_2, Al_2O_3, CaO, and P_2O_5 contents are preserved. The contents of K_2O, Na_2O, and MgO show major depletions. Of the trace elements, U, Bi and W are strongly enriched, while

Table 5b. Trace element composition of granites and greisens from the Karlovy Vary pluton and the Vykmanov massif

Rock type/ Trace elements (ppm)	YIC granite	YIC granite	YIC granite	Quartz-mica greisen	Quartz-topaz greisen
Analyses number	1 (1)	2 (6)	3 (646)	5 (644)	6 (645)
As	< 2	< 2	9.7	57.4	21.7
B	10	23	31.6	11.9	–
Ba	220	< 40	67	12	11
Be	11	16	8.3	11.9	0.5
Bi	3	< 2	15.2	352	489
Cr	< 7	< 7	22	43	42
Co	<1	< 7	3	2	1
Cs	25	38.2	56	162	6.4
Cu	< 1	< 1	3	2	7
Ga	20	29	31	26	2
Hf	2.0	2.1	2.8	2.2	1.9
Mo	< 1	< 1	4.2	1.08	9.2
Nb	8	11	30.8	40.4	12.3
Ni	4	3	4	4	3
Pb	8	< 7	9	6	12
Rb	598	640	577	549	21
Sc	1.97	2.53	2.4	4.4	5.2
Sn	14	18	21.8	23.0	2.8
Sr	23	15	7	5	30
Ta	3.0	4.8	179.4	20.8	12.5
Th	10.3	7.6	10.8	5.0	4.7
U	7.0	< 1	< 7	12.6	18.8
V	< 2	< 2	–	–	–
W	< 3	4.5	28.0	428	858
Y	51	55	14	8	7
Zr	11	16	53	31	32
Zn	37	17	43	78	73

Nb and Sc are moderately elevated. Sn and Rb are relatively immobile while most of the other trace elements are depleted. The depletion of Zr is interesting, in that it suggests the dissolution of zircon during greisenization.

The isocon diagram for the quartz-topaz greisen shows that the changes in the quartz-topaz greisen compared to the precursor granite include a characteristic increase of F and TiO_2, while most other major and minor elements are variously depleted (Fig. 13). There is a significant increase of Bi and W, while most other trace elements are removed during this stage of greisenization. Individual mass changes (i.e. element gains and losses) during greisenization are quantitatively expressed in the diagrams of relative mass changes for the quartz-mica (Fig. 14) and the quartz-topaz greisen (Fig. 15).

In general, the elements hosted by accessory minerals become moderately depleted during greisenization (such as Zr, Y, Hf, Th, Ta), and oxides/elements are removed due to feldspar dissolution (K_2O, CaO, Na_2O, Ba). The REE diagrams indicate a similar course of REE patterns in granite and greisen, suggesting a partial and congruent dissolution of the refractory accessory minerals, but not their complete removal. In both the types of greisen a marked preservation or depletion of Sn and Nb occurs relative to the parental granite. A single high Ta content found in the porphyric

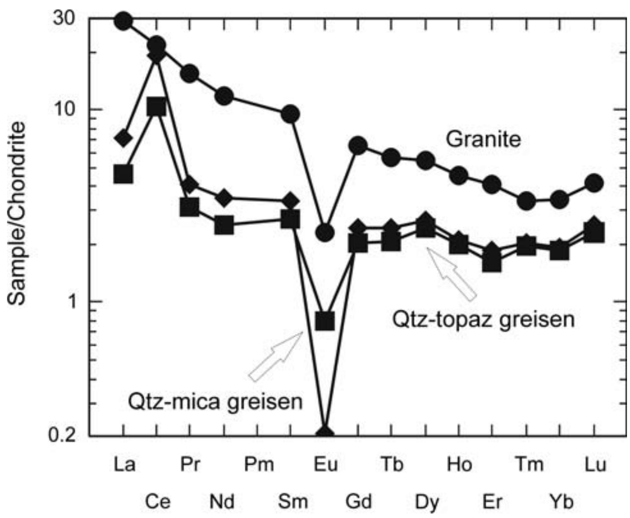

Figure 11. REE normalized pattern of the granites and greisens from Vykmanov (normalizing data from Taylor and McLennan 1985).

Table 5c. Rare earth element concentrations of granites and greisens from the Karlovy Vary pluton and Vykmanov massif

Rock type/Element (ppm)	YIC granite	YIC granite	YIC granite	Quartz-mica greisen	Quartz-topaz greisen
Analyses number	1 (1)	2 (6)	3 (646)	5 (644)	6 (645)
La	8.5	5.5	10.63	2.63	1.70
Ce	20.9	13.5	20.70	18.2	9.86
Pr	< 2.4	< 2.4	2.10	0.56	0.43
Nd	8.6	5.52	8.39	2.49	1.79
Sm	2.03	1.56	2.20	0.77	0.62
Eu	0.16	< 0.2	0.20	0.02	0.07
Gd	2.14	1.37	1.98	0.74	0.62
Tb	< 2.0	< 2.0	0.33	0.14	0.12
Dy	2.64	2.27	2.09	1.01	0.92
Ho	0.43	0.47	–	–	–
Er	< 1.0	1.07	1.01	0.46	0.40
Tm	–	–	0.12	0.07	0.07
Yb	1.06	1.39	0.84	0.48	0.46
Lu	0.14	0.20	0.16	0.10	0.09

Sample descriptions for Tables 5a–c:
1 – coarse-grained YIC granite, Karlovy Vary, valley of the Teplá River, Diana (Štemprok et al. 1996)
2 – medium-grained YIC granite, Karlovy Vary, valley of the Teplá River, restaurant Toscana (Štemprok et al. 1996)
3 – medium-grained porphyritic YIC granite, abandoned quarry and gallery entrance, NE of Vykmanov
4 – greisenized YIC granite, drill hole 8, 230–235.0 m, NE of Vykmanov
5 – quartz-mica greisen near topographical point 671.5 m, NE of Vykmanov
6 – quartz-topaz greisen, near topographical point 671.5 m, NE of Vykmanov

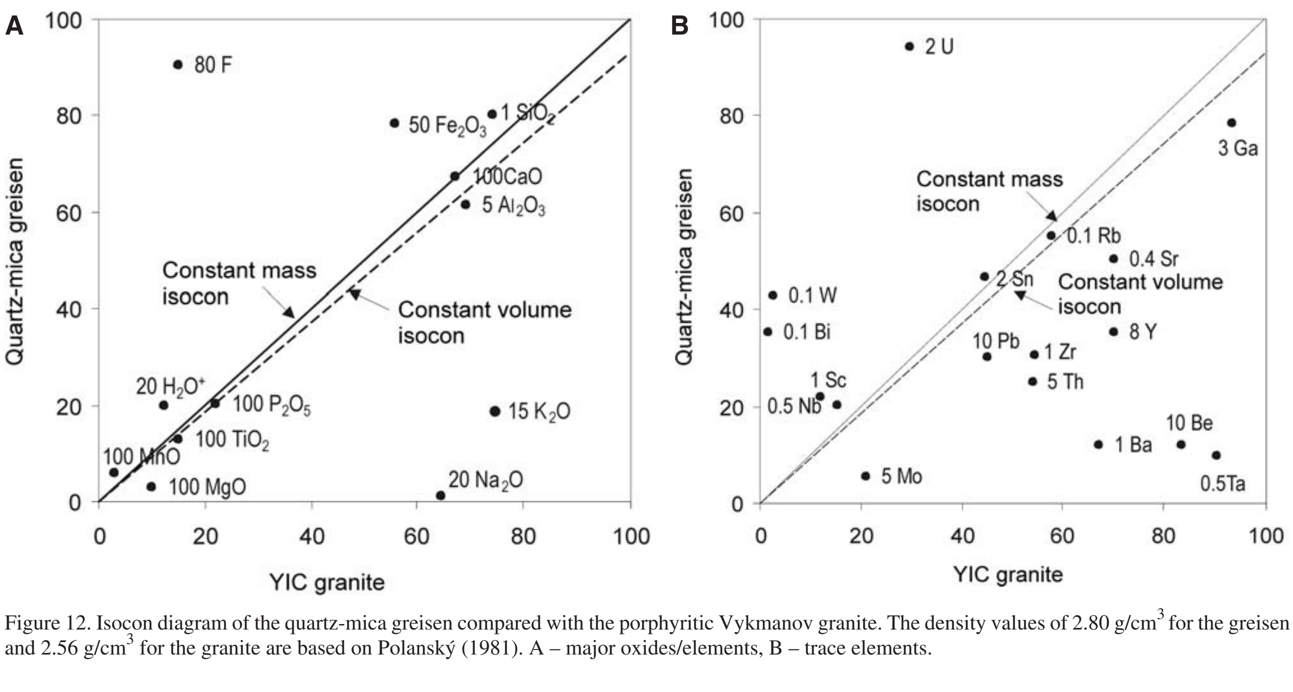

Figure 12. Isocon diagram of the quartz-mica greisen compared with the porphyritic Vykmanov granite. The density values of 2.80 g/cm^3 for the greisen and 2.56 g/cm^3 for the granite are based on Polanský (1981). A – major oxides/elements, B – trace elements.

granite is apparently anomalous and is not supported by the observation of any Nb-containing accessory minerals. The immobility of phosphorus is characteristic of most greisens from the Krušné hory/Erzgebirge batholith (Štemprok et al. 1998). The quartz-mica greisens generally preserve more trace elements from the granite than the depleted quartz-topaz greisens. This is evidently due to the larger capacity of micas to incorporate various cations in cation sites or crystal vacancies compared to topaz.

The geochemistry of the greisen is typical by an overall increase of W and Bi, but the lack of associated Sn mineralization is evinced by the analyses of the drill cores. Fig. 8 shows the striking association of the W-Bi enrichment within the quartz-topaz greisen stage, and this observation is consistent with that of Absolonová and Pokorný (1983) at Boží Dar (Fig. 16). This is also documented by the binary diagrams for the various rock types (Fig. 17) from Vykmanov as analysed in the drill cores. There is a positive

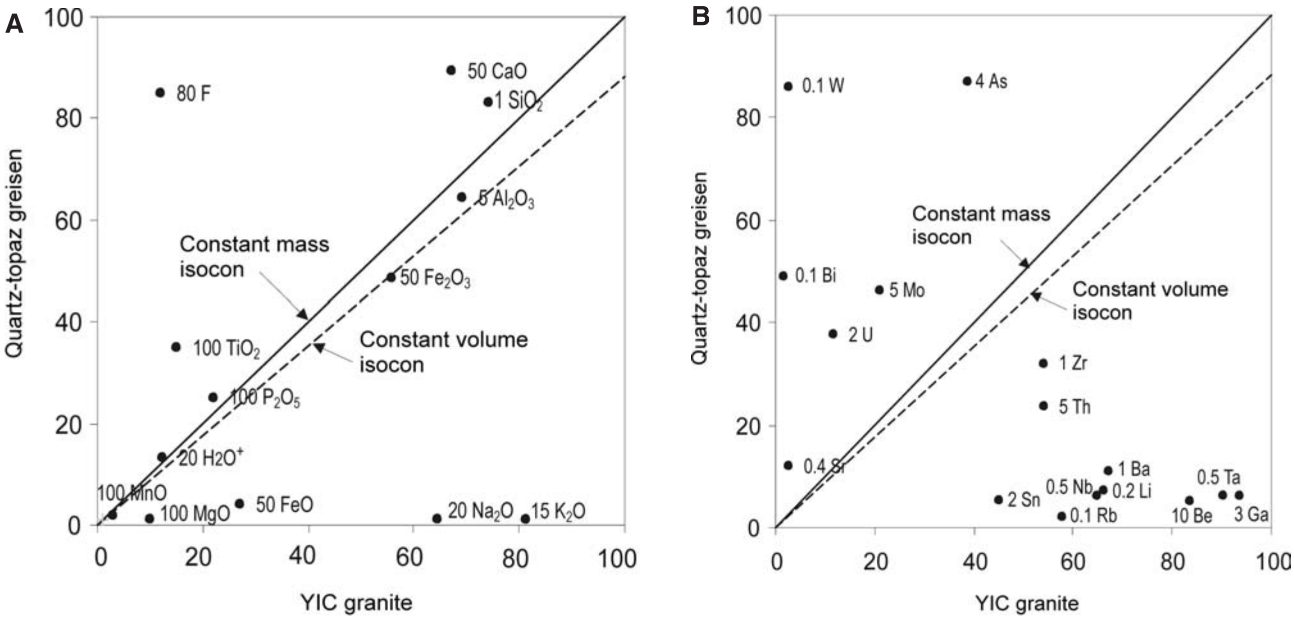

Figure 13. Isocon diagram of the quartz topaz greisen compared with the porphyritic Vykmanov granite. The density values 2.90 g/cm^3 for the greisen and 2.56 g/cm^3 for the granite are based on Polanský (1981). A – major oxides/elements, B – trace elements.

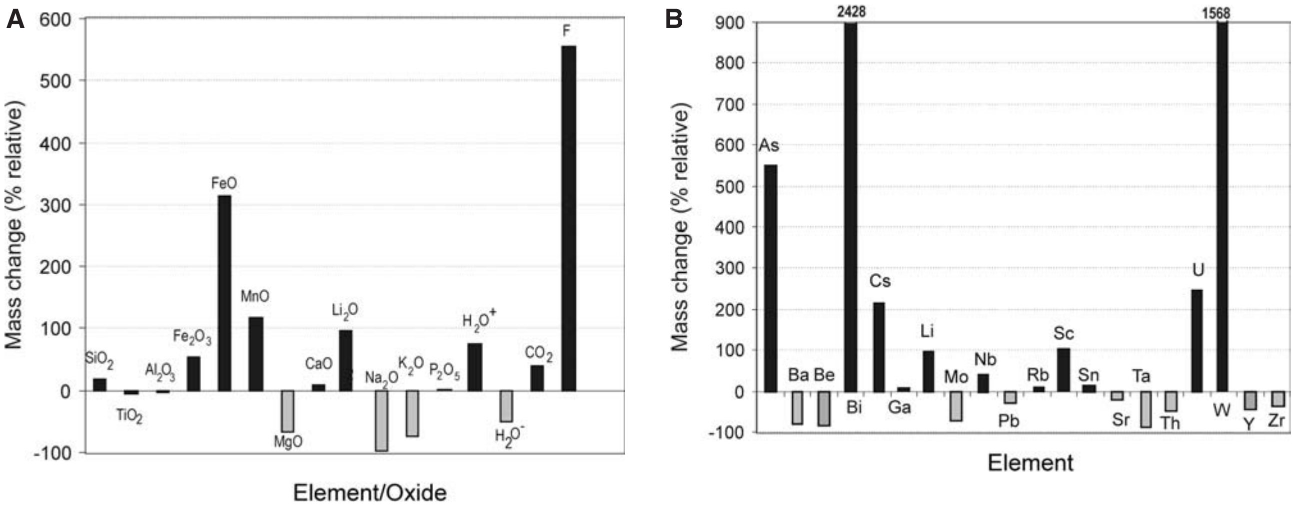

Figure 14. Relative mass changes of the quartz-mica greisen compared with the porphyritic Vykmanov granite. A – major oxides/elements, B – trace elements.

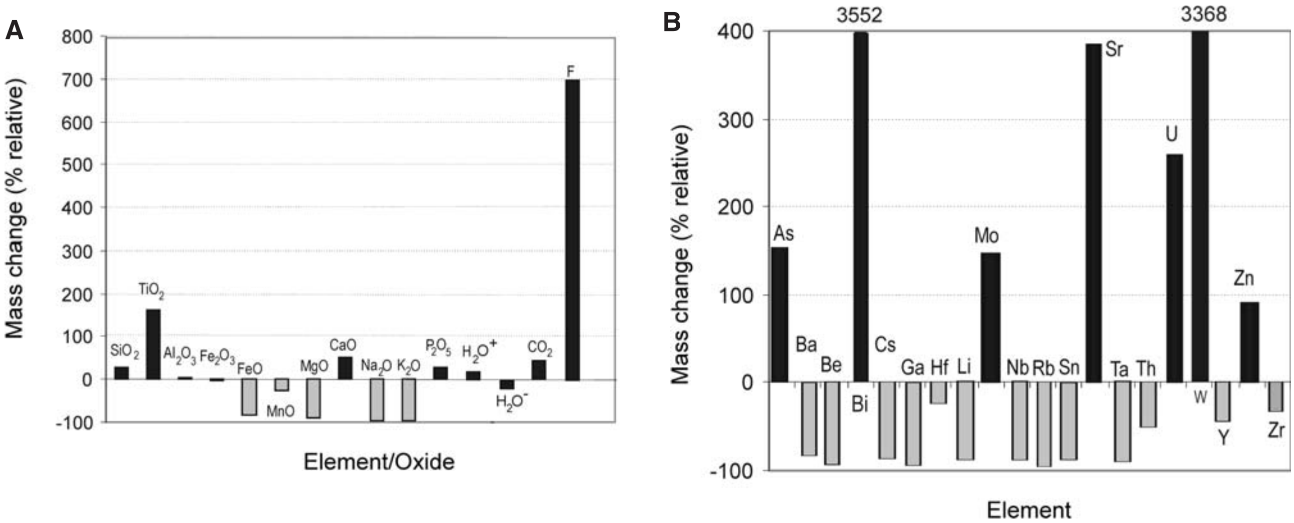

Figure 15. Relative mass changes in the quartz-topaz greisen compared with the porphyritic Vykmanov granite. A – major oxides/elements, B – trace elements.

Table 6. Median values (in ppm) of selected trace elements in the main rock types based on the core analyses of the drill holes Vy-1, Vy-2 and Vy-3

Rock	Number of analyse	Rb	W	Bi	Sn	Nb	Zn	As	Cu
Orthogneiss (migmatite)	8	376	15.6	57.9	37.4	8.7	71.4	42.1	29.5
Greisenized orthogneiss	9	517	15.3	18.5	105.3	7.0	118.7	72.9	28.0
Stockscheider	4	106	9.0	17.4	14.4	5.0	45.8	24.2	11.0
Equigranular granite	25	919	10.8	10.3	12.5	20.1	49.8	14.3	8.0
Quartz-(topaz-)mica greisen	10	256	197.2	65.5	29.7	33.8	52.7	20.0	18.9
Quartz-topaz greisen	16	148	996.0	309.5	21.5	33.8	20.6	17.8	10.0

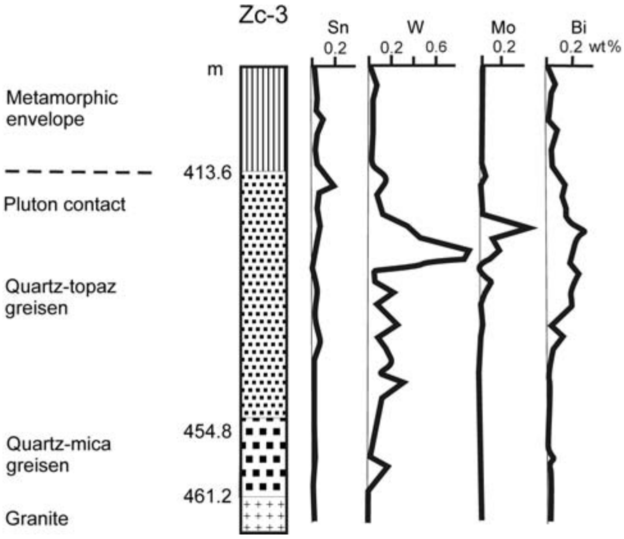

Figure 16. Variations in Sn, W, Mo and Bi concentrations in drill hole ZC-3 at Boží Dar (according to Absolonová and Pokorný 1983).

pair correlation between Bi and W (r = +0.54) but a less significant positive correlation between Sn and W (r = +0.36) (Fig. 17). The greisen at Boží Dar contains, in addition to increased W and Bi as in Vykmanov, Mo and relatively more Sn (Absolonová and Pokorný 1983), suggesting local metallogenic differences in the regions within and around the Western Krušné hory pluton.

Discussion

Tungsten-bearing greisens of the Western Krušné hory pluton are spatially related to the younger suite of granites (YIC), thus differing from the quartz-wolframite veins hosted in or occurring around the granites of the Older Intrusive Complex (Freels and Štemprok 1996), which some authors have linked genetically with the earlier granites (Tischendorf 1989). The existence of the massive tungsten specialized greisens, however, suggests that the younger, F-rich granites can also produce tungsten enrichment without concomitant tin increase. The Vykmanov and Boží Dar greisens are spatially confined to small cusps of the upper granite surface. At Vykmanov it is an eroded elongated stock not exceeding 0.8 km in length, whereas at Boží Dar the greisen is bound to a small blind granite elevation at a depth of about 400 m under the present surface (Fig. 2). These two cases suggest that even these seemingly insignificant changes in the morphology of the pluton roof served as suitable sites for focusing hydrothermal fluids that produced alterations subsequent to pluton crystallization.

The variations in the granite textures along the contacts in these cusps may reflect the successive emplacement of individual granite pulses and/or differences in the rate of their crystallization. The medium-grained granite in the contact part of the Vykmanov massif occurs also as separate dyke sheets. These are comparable to the aplitic granite (Teuscher 1936a) identified among the YIC granites of the Western Krušné hory/Erzgebirge pluton, which were classified as separate intrusions. Škvor (1960) observed a sharp contact between fine-grained (aplitic) and medium-grained porphyritic granite at Přebuz, suggesting that aplitic granite was emplaced along the contact of the earlier medium-grained granite and the phyllite envelope, similar to observation by Zoubek (1951) at the Blatná massif. Absolonová and Pokorný (1983) described an aplitic granite from the Boží Dar hidden granite body which they considered as product of local differentiation of the cooling coarse-grained granite.

At Vykmanov, in drill hole Vy-2, a transitional zone about 20 m thick was observed between the equigranular medium-grained and the porphyritic medium- to coarse-grained granite. However, in other drill holes (Vy-1 and Vy-3) an abrupt contact was noted between these two textural varieties, suggesting the possible later intrusion of the equigranular medium-grained variety at the top of the granite sequence (see above). Tungsten-bearing greisens that formed at the expense of the predominant coarse-grained granite of the Western Krušné hory pluton at Boží Dar (Absolonová 1978, Absolonová and Pokorný 1983) confirm that the granite texture was not decisive for the development of greisen alteration in this part of the Krušné hory/Erzgebirge granite batholith.

The YIC granites of the Nejdek-Eibenstock pluton area are characterized by common accessory topaz and muscovite as secondary minerals (Teuscher 1936b, Zoubek 1951, 1966). According to Dolejš and Baker (2004) the magmatic crystallization of topaz is restricted to peraluminous granite compositions, which are typical of the YIC granites of the Western Krušné hory pluton. The most pronounced hydrothermal alterations in Li-F granites of the Nejdek-Eibenbstock massif are expressed as the albitization of K-feldspars (Zoubek 1966), the K-feldspar metasomatism of plagioclase (Škvor 1960), and the lithionitization and muscovitization of biotite and alkali feldspars along with pervasive sericitization and hematitization. All YIC granites and their greisens in the Western Krušné hory pluton are altered by sericitization and hematitization, while chloritization as an independent alteration remains limited to the biotites in the granites. These alterations are identical in the YIC granites in spatial relationship with tin-bearing and tungsten-bearing granites (Novák and Štemprok 1997), and indicate the similarity of late and postmagmatic processes in YIC granites from various ore districts. Late magmatic to post-magmatic albitization and K-feldspathization are common features of Li-F granites (broadly termed as autometasomatism by Teuscher 1936b), and are comparable to the observations of metasomatic alterations in highly evolved granites in Transbaikalia (Beus et al. 1962, Koval 1975) and other regions (Pollard 1989). In the apical parts of some granite bodies (Krásno, Cínovec) massive pervasive albitization preceded the Li-rich Sn-W greisenization (Dolejš and Štemprok 2001). Schwartz and Surjono (1990) assumed an evolutionary relationship between greisenization and albitization and proposed that the albitites at Tikus in Malaysia formed by solutions released by greisenization of the granite. The massive, pervasive albitization preceded the origin of the greisens in all greisen assemblages of the Krušné hory/Erzgebirge. These processes are therefore not contemporaneous, but proceeded in a definite sequence. Albitization (II) and K-feldspathization (II) subsequent to the greisenization were very local feldspar metasomatic processes in the greisens, leading to the replacement of quartz by alkali feldspars – K-spar and albite (Novák and Štemprok 1997), and were also noted in the Vykmanov greisen. Late stage feldspathization is probably related to the boiling of aqueous fluids or aqueous-carbonic fluids (Dilles and Einaudi 1992).

The greisens at Vykmanov are typical massive greisens with no significant fissure control of greisenization. The upper contact of the greisen coincides with the upper granite contact. The lower contact is characterized by an insignificant transition zone between granite and greisen, with local developments of greisenized granites and topaz granites. The greisenization at Vykmanov is a typical post-solidus type of granite alteration, as manifested by the feldspar and biotite decomposition (Rundkvist et al. 1971, Štemprok 1987) and hydrolytic leaching. While the early stages of most greisenizations observed in the tin provinces of the world are characterized by the development of quartz and mica assemblages, the massive topaz growth marks the advanced metasomatism leading to the origin of topaz-rich greisens (Škvor 1960, Wasternack et al. 1995), both in Li-rich and Li-poor quartz-mica greisens. The most typical zoning of the subhorizontal greisen bodies at Vykmanov and Boží Dar corresponds to quartz-topaz greisen at the top and the quartz-mica greisens at the bottom (see Figs 8 and 16) within a horizontal lens in the granite cusp. It may have an intermediate zone of quartz-topaz-mica greisen such as at Vykmanov, the position of which may be variable. This zoning is horizontal, asymmetrical, and probably related to fluid flow parallel with the granite contact or pervasive laminar upflow.

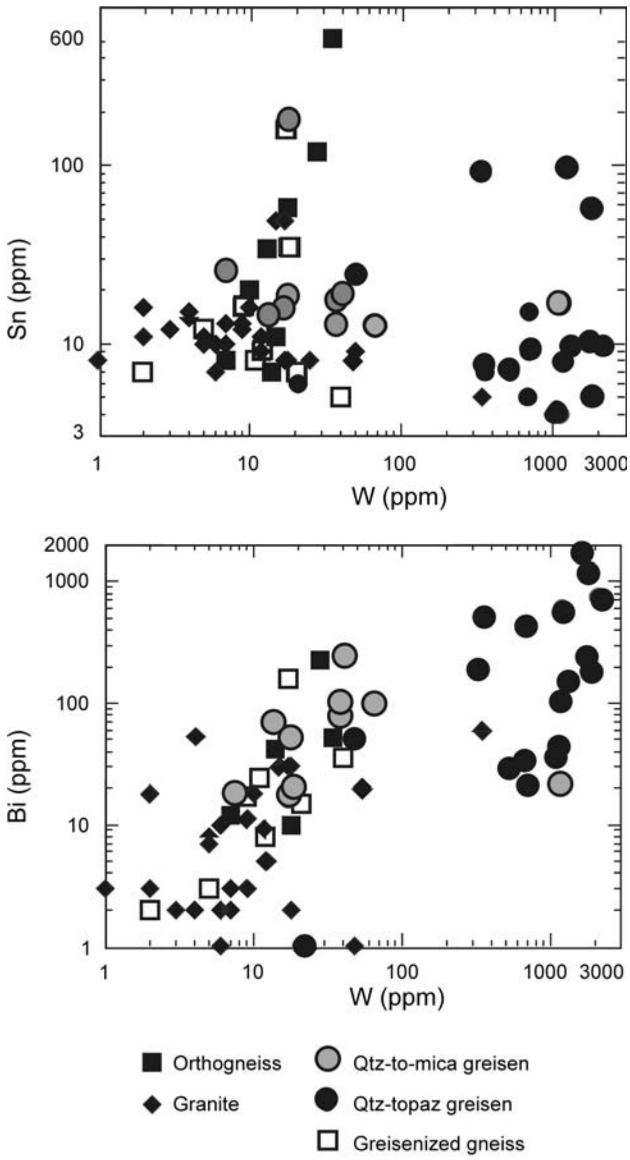

Figure 17. Sn-W and Bi-W relationships in the main rock types of the drill holes (Vy 1–3) in the northern contact zone of the Vykmanov massif (median values of lithological units are given in Table 6).

Zoning in the Vykmanov greisen may be compared with the general schemes of greisen zoning as derived by alteration modelling or empirical observations. Thus at East Kemptville in Canada, Halter et al. (1998) predicted an idealized zoning pattern around a central vein (modelled at 480 °C, 4 kb) as follows: 1. K-feldspar being consumed first, replaced by albite (quartz-mica-albite assemblage), 2. muscovite forming at the expense of albite (quartz-sericite greisen), 3. muscovite replaced by topaz with pyrrhotite and cassiterite precipitation, 4. the most altered topaz and quartz assemblage (quartz-topaz greisen). At Gottesberg, Wasternack et al. (1995) interpreted the greisenization as forming the earliest quartz-sericitic zone (quartz-sericite greisen) next to the unaltered granite, followed by the quartz-topaz greisen and quartz greisen in the inner zones (Fig. 17 in Wasternack et al. 1995). A stable quartz-albite-muscovite assemblage is absent at Vykma-

Table 7. The homogenization and melting temperatures of fluid inclusions in greisen minerals from Vykmanov, drill hole Vy-1 (Ďurišová 1984, presentation modified)

Greisen type	Depth (m)	Mineral	Inclusion type V = vapour-dominated L = liquid-dominated S = solids	Homogenization temperature (°C)	Melting temperature (°C)	Melting temperature of the last crystal (°C)	Notes
quartz-topaz	20.3	topaz	V L	406–409 328–332	–51.0	–2.3 to –1.7 –3.8 to –1.0	
quartz-topaz	20.3	quartz	V L	383–393 316–367	–26.0 –26.0	~ –2.0 –2.0 to –0.2	
quartz-mica	24.7	quartz	L S	228–280 350 356	–47.0 –50.0	–29.0 (hydrohalite) –0.8 (ice) –43.0 (ice)*	*gas disappears at 169 °C, halite at 356 °C, solid phase with birefrigence, not solved: $CaCl_2$ + NaCl (?)
quartz-mica-topaz	26.8	topaz	V S	385–400 443–496*			*halite dissolved at 360–382 °C
	26.8	topaz	L V	350–357 388–408	–44.0	–23.9 (hydrohalite?) –0.8 to + 0.3 (ice)	 fluid boiling at 406 °C
	26.8	quartz	L V	200–270 319–355 386–400			

nov and in the greisen assemblages in the Krušné hory/Erzgebirge (Kühne et al. 1972, Kaemmel 1961, Wasternack 1995, Štemprok et al. 1997). Such an assemblage may be an artefact of isobaric models of greisenization (Halter et al. 1997, 1998).

The greisen mineral assemblage at Vykmanov is a result of hydrogen metasomatism by hydrothermal fluids in the apical parts of a solid granite body. This proton metasomatism liberated alkalies by feldspar destabilization and the development of phyllic assemblages. The constant ratio of the alkalis (Na^+, K^+)/H^+ in the fluid phase with decreasing temperature shifted the univariant boundaries of alkali feldspar/muscovite/andalusite, pyrophyllite and kaolinite towards higher K^+/H^+ or Na^+/H^+ values (Meyer and Hemley 1967), and thus the solution with the same Na^+/H^+ or K/H^+ ratio, with the decrease of temperature, produced kaolinite. Even if isothermal acidification can produce the same effect, the proposed cooling path appears as the most probable explanation of the constant presence of the phyllic and argillitic mineral assemblages in the greisens and surrounding granites at Vykmanov and elsewhere in the Western Krušné hory pluton area.

The origin of topaz from the micas suggests the presence and incorporation of fluorine in the system. Zaraisky (1998) experimentally reproduced a topaz-bearing greisen, with fluorite in a zone immediately adjacent to a F-bearing solution (T = 500 °C, P = 1 kb, 1.0 m HF), in the original starting solution, with quartz and Al_2O_3 in excess, and in which a quartz-mica greisen zone came next. The topaz-mica relationships are shown on the phase diagram calculated from thermo-chemical data in Dolejš and Štemprok (2001) in Fig. 18, where the field of topaz stability approaches, at lower HF activity, the stability fields of feldspars and muscovite in this three-dimensional phase representation. Large quantities of Al + Si can be transported as $Si(OH)_xF_{4-x}$ (x = 0–4) and (Al, Si) (OH, F) complexes in F-bearing fluids at higher temperatures. The experiments by Haselton et al. (1988) in the system K_2O-Al_2O_3-SiO_2-H_2O-F_2O_{-1} (at 1 kb and 400–700 °C) showed that the concentrations of fluoride complexes are in fact extremely low for most elements at the temperatures less than 500 °C, because the topaz and fluoride-bearing assemblages buffer aqueous fluoride species to low concentrations.

The homogenization temperature as measured by fluid inclusion studies (Ďurišová 1984) shown in Table 7 ranged between 409–383 °C in vapour-dominated inclusions and between 357–328 °C in liquid-dominated inclusions in topaz. In quartz-hosted inclusions the homogenization temperature ranges were similar. Ďurišová (1984) explained the coexistence of the two fluid populations by separation of parental hydrothermal fluid into highly concentrated brines with salinity of about 40 wt.%, and dilute solutions with 2.5–4.5 wt.% of salts. The predominant salt in the inclusions was NaCl, but low melting temperatures pointed to concentrations of up to 20 wt.% of $CaCl_2$ or another additional constituent. No CO_2 was detected in the gas phase. These two separate fluids can be related to boiling, or else they record the mixing of magmatic and meteoric waters.

The temperature range found in the inclusions at Vykmanov is considered as typical for greisen hosted tin-tungsten ore deposits (Rundkvist et al. 1971). The temperatures between 410–380 °C found in primary vapour-rich inclusions indicate the beginning of greisenization, while the decrease of temperature to about 230 °C is evidenced by secondary inclusions in quartz. These temperatures are higher than the formation temperatures of Sn, W, and Mo deposits related to granites (350–250 °C, Somarin and Ashley 2004), but are lower than the temperatures of mineralization of the Bolivian tin and tungsten deposits (400–550 °C, Kelly and Turneaure 1970) in a subvolcanic geological setting.

The specific association of ferberite with the quartz-topaz greisens at Vykmanov and Boží Dar is difficult to explain in light of the known speciation of tungsten in hydrothermal solutions. Tungsten transport in fluoride and carbonate complexes plays a subordinate role (Wood and Samson 2000), while the significant chloride complexing of tungsten does not occur in hydrothermal solutions under geologically realistic temperatures, ligand activities, and pH conditions (Wood 1992). The tungsten transport is achieved by the dominant tungsten species H_2WO_4, HWO_4^-, WO_4^{2-} (Wood and Vlassopoulos 1989, Samson and Wood 1997).

In order to explain the precipitation of ferberite in the apical parts of solid intrusions the iron should be available to greisenizing fluids. The transport of Fe^{2+} in chloride solutions is controlled by $FeCl_2$(aq) complexes in the temperature range below 200 °C. However, in NaCl-bearing supercritical solutions iron mainly occurs as $NaFeCl_3$ (aq) complexes, the stability of which increases with temperature but drops with pressure (Tagirov and Korzhinskiy 2001a). In HCl-H_2O-(CO_2) fluids at 500–600 °C and low CO_2 concentrations the $FeOHCl^0$ (aq) complex predominates, whereas $FeCl_2^0$ (aq) is the most common species in low-density fluids and at high CO_2 contents (Tagirov and Korzhinskiy 2001b). Samson and Wood (1997) studied the ranges of concentrations of W and Ca/Fe ratios in solutions in equilibrium with scheelite and ferberite over a wide range of physical-chemical conditions (T = 200–600 °C and P = 500–1000 bars, pH 3–6 and 0.1–5 m NaCl). The solubility of tungsten depends on temperature and salinity due to the formation of iron chloride complexes, and on decreasing pH owing to the protonation of the WO_4^{-2} species. The predominant NaCl in the greisenizing solutions as observed in Vykmanov favours the mobility of iron derived from the altered granite (see iron loss on the isocon diagram in Fig. 13).

Kühne et al. (1972) separated greisenization in the Erzgebirge/Vogtland into: a. greisenization with Fe-Li micas (Li-biotite, siderophyllite, protolithionite, zinnwaldite), and b. greisenization with Li-poor white micas (phengitic muscovite). Both of these converge towards the topaz or quartz facies (Novák and Štemprok 1997). The spatial distribution of these types is schematically presented in Fig. 19. The Vykmanov greisen corresponds to the type with protolithionite as the main lithium mica, and is therefore close to the greisens of the first group. However, this Li greisenization is strongly overprinted by the later muscovitization typical of the second greisen group.

In the Eastern pluton of the Krušné hory batholith, in the Cínovec-South deposit (Čada and Novák 1974), these two greisen stages overlap. The tin content of the greisens is gained by muscovitization of the original Li-rich greisen, while the tungsten content is associated with the earlier Li-rich mica greisen. In the Western Krušné hory pluton, the Li-rich and muscovite greisens are spatially separated, though they may coincide in some deeper parts of the fissure systems (Novák and Štemprok 1997). However, at Vykmanov later muscovitization is not tin-bearing, as observed at Cínovec by Čada and Novák (1974), and the concentration of tin assemblages into the granite envelope is typical of both the Vykmanov and Boží Dar ore districts.

It is still questionable whether the quartz-sericitic greisens rimming some quartz-muscovite greisen bodies are the products of the initial muscovitization (Wasternack et al. 1995), i.e. high temperature greisenization, or whether the sericitization affects certain zones of greisens in consequence of low-temperature alteration during temperature decrease, and thus does not represent the earliest stage of

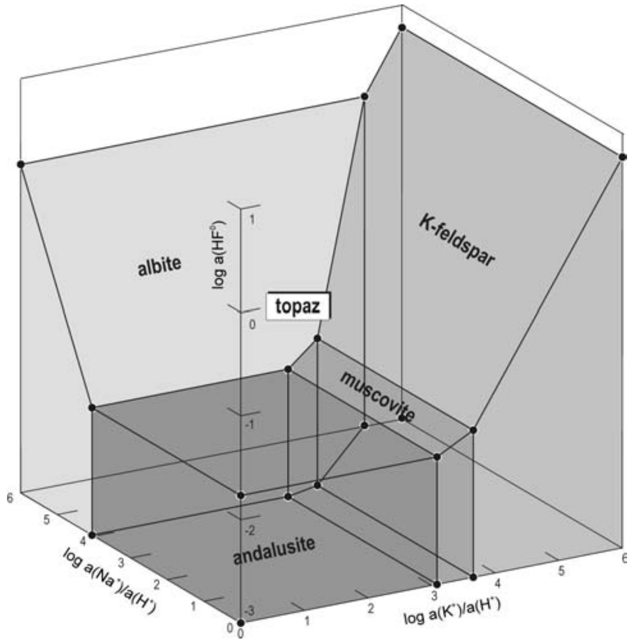

Figure 18. Activity-activity diagram of the end member phases in the system K-Na-Al-Si-O-F at 500 °C and 1 kbar, and quartz saturation (Dolejš and Štemprok 2001).

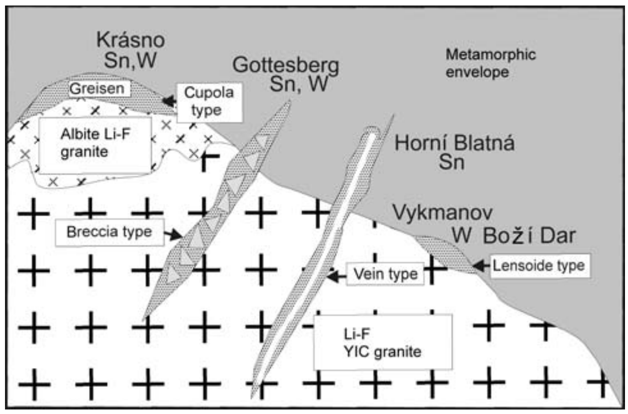

Figure 19. Schematic geological position of the greisens in the Western Krušné hory/Erzgebirge pluton.

greisenization (Novák and Štemprok 1997). As the sericitization is regionally more wide-spread and affects the feldspars (and the relics of feldspars in the greisens), topaz, and Li-Fe micas, we prefer the latter explanation.

The zoning in most greisens is in many respects comparable to that around some porphyry copper deposits. Burt (1981) characterized quartz-muscovite greisens as being similar to sericitic or phyllic alterations in porphyry copper deposits, while the quartz-topaz greisens correspond to advanced argillic alteration, the difference being in the larger amount of fluorine present in the greisen assemblages. In most models of porphyry copper deposits evidence has been documented of the participation of meteoric waters in mineralization. Genetic models (Lowell and Guilbert 1970, McMillan and Panteleyev 1985) for the emplacement and deposition of porphyry copper deposits (Gustafson and Hunt 1975) include: 1. shallow emplacement of usually complex porphyritic dykes and stocks in and above the cupola zone of a calc-alkaline batholith; 2. separation of magmatic fluids and simultaneous metasomatic introduction of Cu, other metals, S, and alkalies into the porphyries and wall rocks; 3. establishment and inward collapse of a convective ground-water system that reacts with cooling mineralized rocks.

Such a model is possibly acceptable for the tungsten-bearing system at Vykmanov, where the mineralization is tungsten-specialized in contrast to copper specialization in copper porphyry systems. The geological situation in the Western Krušné hory pluton suggests that the granites were shallowly emplaced, and that separated magmatic waters were responsible for the transport of tungsten and some other metals to the contacts of the granite. Even if the participation of the meteoric waters at the tin-tungsten mineralization is not unequivocally documented by isotopic evidence at this locality, Dolejš and Štemprok (2001) suggest that meteoric waters may have reacted with the cooling granites at Cínovec in the Eastern pluton of the Krušné hory/Erzgebirge batholith. The possibility of interactions between the mineralized granites and the groundwaters has been shown by Fouillac and Rossi (1991) for the Beauvoir albite granite cupola in the Massif Central of France, where a thick granite dyke interacted with external fluids during magmatic and late magmatic stages.

In the porphyric systems, most models postulate the separation of hydrothermal fluids from magmas in stocks or cupola-shaped granite porphyries or granite contacts. The study of the greisens at Vykmanov has shown that the greisenizing fluids progressed in the solid granite and were focused into a granite cusp. Small granite elevations in the granite surface morphology documented at Vykmanov and at Boží Dar hardly established suitable conditions for a long-term hydrothermal system gradually involving meteoric waters. However, the dilution of highly concentrated magmatic waters with meteoric waters was a possible prerequisite for the start of mineralization and the progressive development of phyllic and clay mineral alterations, even during a short mineralizing episode.

Conclusion

The Vykmanov wolframite-bearing greisen of the Western Krušné hory pluton consists of quartz, Li-poor Li-mica (protolithionite), topaz, and muscovite. In contrast to predominant cassiterite-bearing greisens in the Krušné hory/Erzgebirge, it contains wolframite (ferberite) as the main ore mineral and is enriched in bismuth similarly to the tungsten-bearing greisen from Boží Dar. Cassiterite vein assemblages accompanied by greisens occur in the crystalline envelope of the granite or in skarns distant from the tungsten-bearing greisen. The greisen is immediately adjacent to the equigranular, medium-grained, topaz-rich YIC granite forming a small crest in the youngest part of the Younger Intrusive Complex granites of the Western Krušné hory pluton. The area was hydrothermally overprinted by the U vein mineralization mined in the northern contact zone of the massif, which did not mineralize the granite. This genetic explanation is analogous to the concepts of porphyry copper deposits, postulating a primary concentration of ores by magmatic waters in a cupola-shaped intrusions, and influenced by meteoric waters in later stages.

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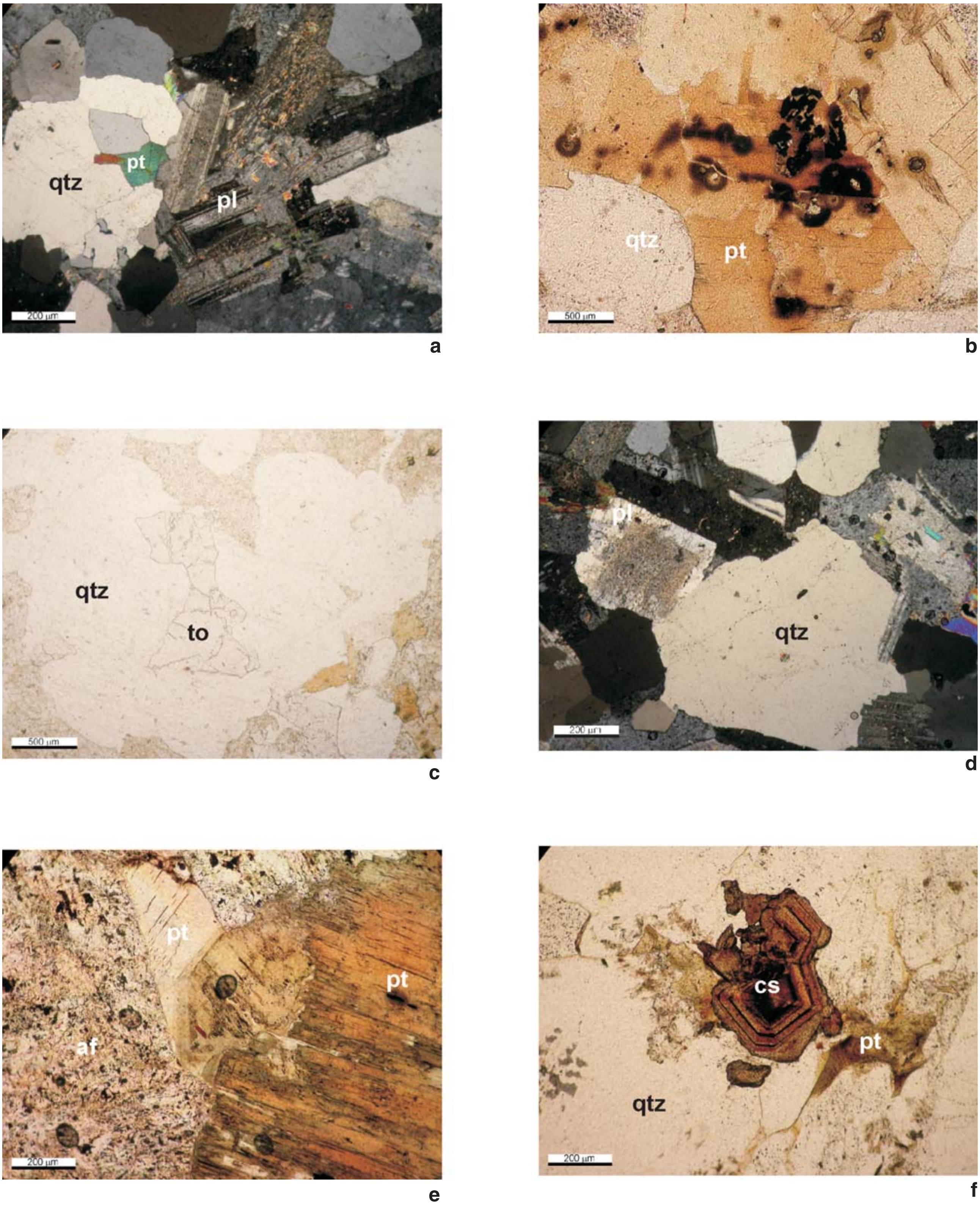

Plate I
Photomicrographs of the granitic and hydrothermal assemblages (abbreviations: qtz = quartz, pt = protolithionite, pl = plagioclase, to = topaz, af = K-feldspar, cs = cassiterite).
a – texture of the equigranular medium-grained granite, Vykmanov, drill hole Vy-1, 57.1 m (cross-polarized light).
b – protolithionite with inclusions of accessory minerals, Vykmanov, drill hole Vy-1, 57.1 m (plane-polarized light).
c – anhedral topaz in granite,Vykmanov, drill hole Vy-1, 57.1 m (plane-polarized light).
d – sericitized plagioclase with albite rim in equigranular medium-grained granite, Vykmanov, drill hole Vy-1, 74.9 m (cross-polarized light).
e – protolithionite in K-feldspathite, Vykmanov, drill hole Vy-2, 41.9 m (plane-polarized light).
f – zoned cassiterite in a quartz vein, Vykmanov, dump near the drill hole Vy-6 (plane-polarized light).

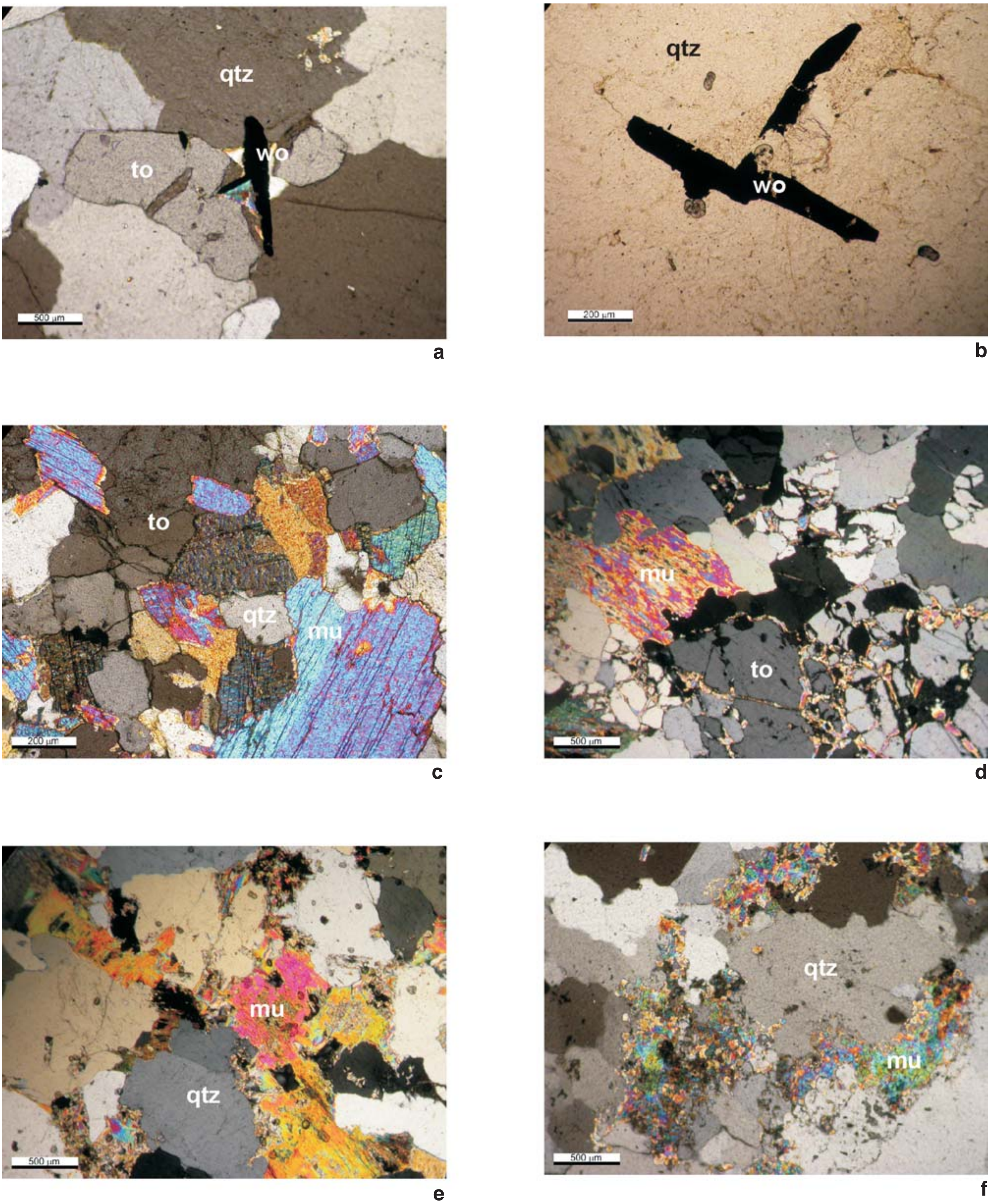

Plate II
Photomicrographs of greisen assemblages (abbreviations: qtz = quartz, pt = protolithionite, to = topaz, wo = wolframite, mu = muscovite).
a – wolframite with topaz in quartz-topaz greisen, Vykmanov, drill hole Vy-1, 20.3 m (cross-polarized light).
b – wolframite crystals in clusters in quartz-topaz greisen, Vykmanov, drill hole Vy-1, 20.3 m (plane-polarized light).
c – quartz-muscovite-topaz greisen from the aplite, dumps near drill hole Vy-6 (cross-polarized light).
d – quartz-muscovite-topaz greisen from the granite, Vykmanov, drill hole Vy-1, 24.7 m (cross-polarized light).
e – quartz-muscovite greisen from the granite, Vykmanov, drill hole Vy-2, 23.5 m (cross-polarized light).
f – quartz-muscovite greisen from the orthogneiss, Vykmanov, dump near drill hole Vy-6 (cross-polarized light).