Mineralium Deposita (1999) 34: 505–521 

ARTICLE

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# Variscan silicic magmatism and related tin-tungsten mineralization in the Erzgebirge-Slavkovský les metallogenic province

Received: 4 August 1998 / Accepted: 5 January 1999

**Abstract** Integration of geochemical, mineralogical, isotopic, and geochronological data with geodynamic considerations suggests that the Variscan granites in the Erzgebirge-Slavkovský les domain originated from repeated melting events and were emplaced over a period of about 40 Ma (330–290 Ma). Several lines of evidence exist supporting the idea that Erzgebirge granites assigned to different types (biotite granites, two-mica granites, strongly peraluminous P-rich Li-mica granites, and slightly peraluminous P-poor granites) are in most cases not genetically related via continuous fractional crystallization from a common magmatic reservoir. The genesis of the Slavkovsky les granites, however, might be discussed in terms of an uninterrupted fractionation series. Geological models of Sn-W deposits based upon geochemical and structural results imply that the main ore depositional events followed immediately the emplacement and solidification processes of melt via fluid-melt immiscibility, breccia-pipe formation and/or pervasive rock-fluid interactions.

## Introduction

The main metallogenic history of the Erzgebirge (Krušné hory)-Slavkovský les (Kaiserwald) ore field, which lasted from the late Carboniferous to the Mesozoic, temporally succeeded the emplacement of large masses of granitic-rhyolitic melts as a result of thermal perturbations in the middle and lower crust during the Variscan orogeny.

During and after the Second World War, the expansion of the metalliferous mining industry combined with the search for undiscovered ore deposits stimulated detailed studies on the major and trace element geochemistry of both exposed and hidden granite intrusions. The main purpose of this research was to establish convincing criteria for separating barren granites from those exhibiting a potential for hosting economic Sn-W mineralization. It is generally accepted that early tin-tungsten ore-forming processes are connected with the crystallization and cooling history of fractionated and Sn-W-Li-Rb-Cs-F-specialized granitoid plutons (Tischendorf comp. 1989; Tischendorf and Förster 1990, 1994; Breiter et al. 1991; Štemprok 1993a; Seltmann and Faragher 1994).

The more complicated and variegated genetical relationships of late-Variscan (U,Pb-Zn) and post-Variscan mineralization phenomena (F-Ba) to the exposed or hidden granite bodies are less understood and the subject of controversial discussion (Tischendorf and Förster 1994). However, these metallogenic events temporally disconnected and in part spatially displaced from the Variscan magmatism cannot be fully understood when ignoring the role of the many plutonic and volcanic rocks in the upper crust as a source of metals in the frame of subsequent leaching processes initiated by infiltrating fluids of late-magmatic, formational or meteoric origin, or as a source of heat which promoted the onset of thermally-driven fluid convection systems. Consequently, a detailed study of the widespread, composite granite bodies with respect to their individual petrogenetic, geochemical, and mineralogical peculiarities as well as late- to post-magmatic history has a key position in better understanding the metallogenic evolution of the ore province.

The aim of this work is to give an overview of the present knowledge regarding the complex relationship between the Variscan silicic plutonic and volcanic rocks and subsequent mineralizing processes in the Erzgebirge and Slavkovský les.

Editorial handling: DR

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## Geological setting

The Variscan granitoid rocks in the Erzgebirge and Slavkovský les (Fig. 1) form a discontinous belt extending about 160 km along the Czech Republic-German border in a NE-SW direction. The belt comprises an area of about 6000 km$^2$ and is positioned near the southern border of the Saxothuringian Zone, at the northwestern edge of the Bohemian Massif.

The granitoid rocks were successively emplaced in the late Carboniferous and early Permian and intruded into folded and metamorphosed lithostratigraphic units, consisting of (from east to west) Proterozoic paragneisses, late Proterozoic-Cambrian mica schists and micaceous gneisses, and phyllites as well as quartzites of predominantly Ordovician age. In the central Erzgebirge, the occurrence of shallowly intruded granites is proved mostly by drilling (Pobershau, Satzung, Seiffen, Hora sv. Šebastiána) whilst the abundance of large masses of granitoid rocks is well documented by surface outcrops in other parts of the domain. Areas of granite exposure range in size from from some hundreds of square metres (Knötl at Krupka, Sadisdorf) to hundreds of square kilometres (Eibenstock-Nejdek pluton); all bodies exhibit sharp contacts with the country rocks.

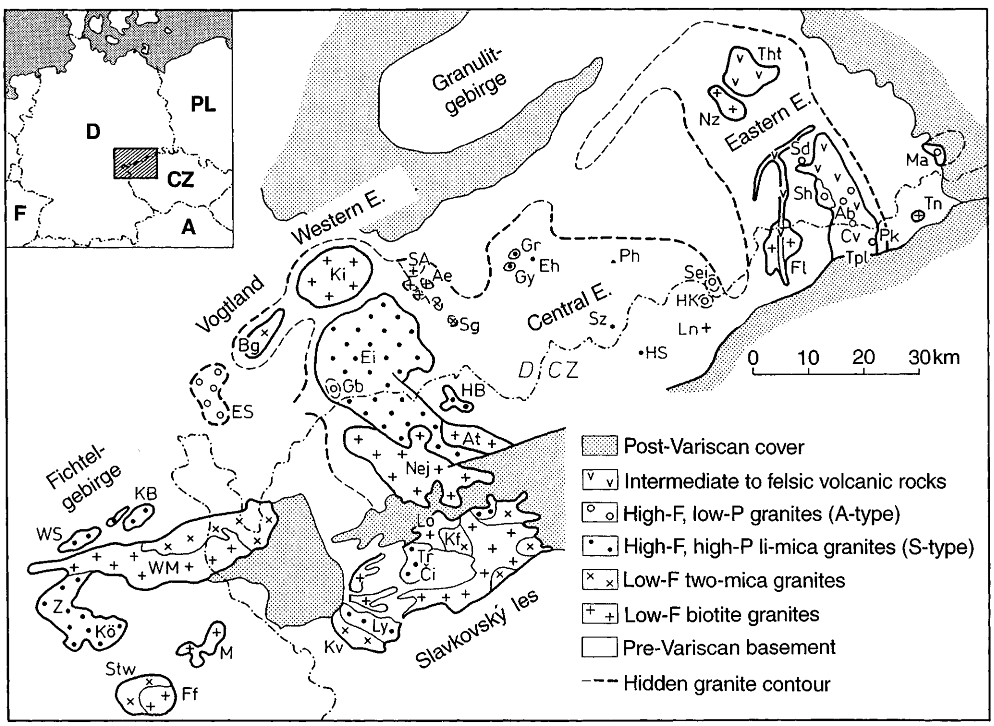
All granite types are free of autoliths and restites. Xenoliths of the country rocks are rare and restricted to marginal granites (YIC/MG). Field evidences in the Slavkovský les and Nejdek plutons proved the succession of the suite: OIC/S – TG – YIC/MG – biotite-bearing YIC/S – YIC/S with Li-mica. In Gottesberg, the YIC/A dyke system cuts biotite granites of YIC/S. Until now, there is no geological evidence for relative age between the OIC/S and OIC/I suites. In the eastern Erzgebirge, the YIC/A granites followed the extrusion of the Teplice rhyolite and intrusion of granite porphyry dykes.

Several granites form composite bodies built up by a succession of texturally (Fig. 2) and geochemically distinct sub-intrusions. These sub-intrusions are often indicated by numbers in the order of decreasing ages and show usually the following textures: 0, fine- to medium-grained porphyritic (marginal phacies); 1, coarse-grained porphyritic (megacrystic) or coarse-grained seriate textured; 2, medium-grained equigranular; 3, fine-grained equigranular or slightly porphyritic; 4, very fine-grained (aplitic). Impressive examples are the multistage massifs of Kirchberg, Bergen, and Eibenstock positioned in the western Erzgebirge-Vogtland area (Förster and Tischendorf 1994). However, weak conditions of exposure does not always allow us to distinguish definitely between truly sub-intrusions and only textural-petrochemical variabilities developed within a single granite differentiate.

Although granitoids largely predominate among the igneous rocks produced in response to the Variscan orogeny, plutonic activities were interrupted by multiple extrusion of rhyolitic-rhyodacitic lava flows and dykes which were preserved from erosion in the eastern Erzgebirge in particular (Teplice and Schönfeld rhyolites-rhyodacites, granite porphyries from Altenberg and Fláje-Frauenstein).

Evidence of distinct episodes of K-rich basaltic (lamprophyric) volcanism is preserved in dykes composed of minettes and kersantites which cross-cut granites of different age and composition, and are concentrated in the western and central Erzgebirge. These rocks are supposed to be comagmatic with the potassic volcanic suite of shoshonitic affinity in the Erzgebirge foredeep (Kramer 1988). One genetic model involves derivation of the lamprophyres, which display high concentrations of metallogenic important ele-

**Fig. 1** Sketch map showing the regional distribution of Variscan silicic plutonic and volcanic rocks in the Erzgebirge (Krušné hory), Vogtland, Fichtelgebirge/Oberpfalz, and Slavkovský les (Kaiserwald) (slightly modified after Förster and Tischendorf 1994). *Fichtelgebirge/Oberpfalz: WM*, Weißenstadt-Marktleuthen; *WS*, Waldstein; *KB*, Kornberg; *Z*, Zentralmassiv; *Kö*, Kösseine; *Stw*, Steinwald; *Ff*, Friedenfels; *M*, Mitterteich; *Vogtland: Ech*, Eichigt; *Bg*, Bergen; *western Erzgebirge*: *Ha*, Hartenstein; *Ki*, Kirchberg; *Ae*, Aue; *Sg*, Schwarzenberg; *Ei*, Eibenstock; *Nej*, Nejdek; *At*, Abertamy; *HB*, Horní Blatná; *central Erzgebirge: Ln*, Lesná; *Gy*, Geyer; *Gr*, Greifensteine; *Eh*, Ehrenfriedersdorf; *Sz*, Satzung; *Ph*, Pobershau; *HS*, Hora Sv. Šebastiána; *Sei*, Seiffen; *HK*, Hora Sv. Kateřiny; *eastern Erzgebirge: Nz*, Niederbobritzsch; *Fl*, Fláje; *Tn*, Telnice; *Ab*, Altenberg; *Sh*, Schellerhau; *Sa*, Sadisdorf; *Cv*, Cínovec (Zinnwald); *Pk*, Preiselberk and Knotl; *Ma*, Markersbach; *Tht*, Tharandt; *Tpl*, Teplice; *Slavkovský les*: *Lo*, Loket; *Kf*, Kfely; *Tr*, Třídomí; *Ci*, Čistá; *Ly*, Lysina; *Kv*, Kynžvart. See accompanying text for further explanations



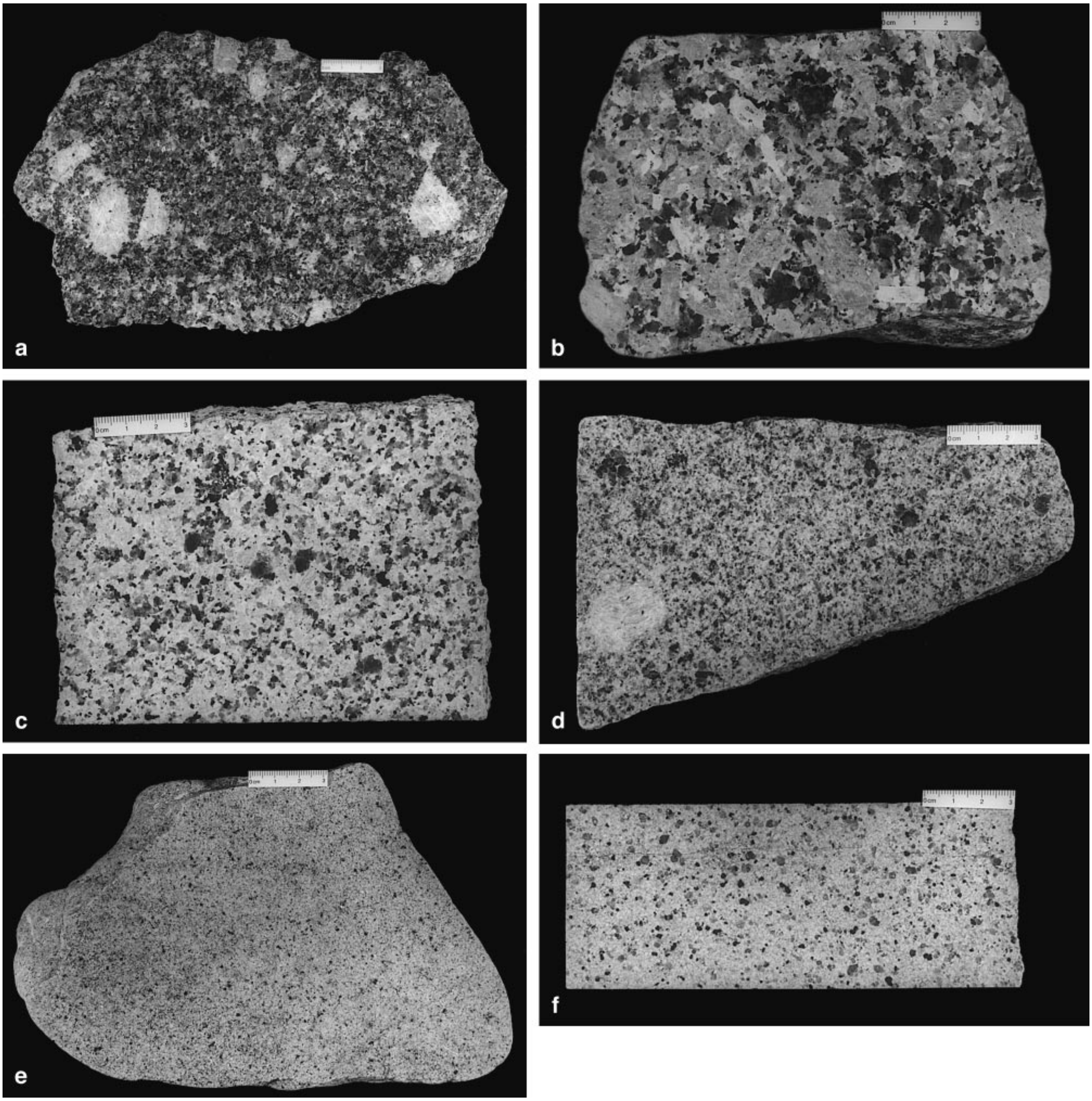


**Fig. 2a–f** Representative samples of Erzgebirge granites to illustrate their textural variability. **a** coarse-grained megacrystic biotite monzogranite (Kirchberg pluton, sub-phase 1), **b** coarse-grained seriate textured Li-mica syenogranite (Eibenstock pluton, sub-phase 1), **c** medium-grained equigranular Li-mica syenogranite (Eibenstock pluton, sub-phase 2), **d** medium- to fine-grained slightly porphyritic biotite monzogranite (Kirchberg pluton, sub-phase 2), **e** fine-grained equigranular biotite monzogranite (Kirchberg pluton, sub-phase 3), **f** medium- to fine-grained porphyritic topaz-albite-zinnwaldite dyke granite (Zinnwald, drilling 20/1970, depth 178 m)

ments such as Ba, F, Bi, Hg, Cr, Ni, Th, and U, from metasomatized portions of the upper mantle (Kramer 1988). Alternatively, Tischendorf et al. (1992) stressed the possibility of coordination of part of them to the granite evolution and directed the attention to the substantial degree of crustal contamination affecting the uprising mantle-derived melts.

## Granite types

The Variscan granites of the Erzgebirge-Slavkovský les region have been traditionally interpreted as belonging to two major plutonic series with the connotation of different ages, the Older (OIC) and Younger (YIC) Intrusive Complexes, composed mainly of biotite monzogranites (for example Kirchberg and Nejdek) and topaz-bearing Li-biotite syenogranites to albite-zinnwaldite alkali feldspar leucogranites (examples Eibenstock, Ehrenfriedersdorf, Cínovec), respectively (e.g. Figs. 1, 2). This classification goes back to Laube (1876) who, more than a hundred years ago, differentiated the granitoid rocks exposed in the Czech part of the western

Erzgebirge into two groups: the older, barren "Gebirgsgranite" and the younger, Sn-bearing "Erzgebirgsgranite". The subdivision is substantiated by various petrochemical, petrographical, mineralogical, and metallogenic features which, in part, show remarkable differences between these distinctly categorized granite suites (Lange et al. 1972; Štemprok 1986; Tischendorf comp. 1989; Tischendorf and Förster 1990; Breiter et al. 1991; Breiter 1993; Štemprok 1993a; Förster and Tischendorf 1994; Breiter and Seltmann 1995).

Two-mica granites, present here in many texturally different facies, have been interpreted in different ways. Some of them, found as huge enclaves (up to hundreds of meters) in, or occupying a marginal position to, YIC granites were classified as Marginal Granites (MG). These granites are suggested to represent earlier differentiates of YIC granite magmas, however, influenced to variable degrees by country rock contamination. A further group of two-mica granites have been described from the Slavkovský les by Fiala (1968) and termed Transitional Granites (TG). Most workers (Tischendorf and Förster 1990; Štemprok 1993a) have emphasized their coordination to the OIC evolution because of broad similarities in geochemistry and petrography (OIC/TG). In contrast, Breiter (1993) categorized these granites as a link between OIC/S and YIC/S granites.

Recent geochemical and mineralogical investigations (Breiter et al. 1991; Förster and Tischendorf 1994; Förster et al. 1995; Tischendorf and Förster 1992) suggest that all previous classifications oversimplify the matter. Among both OIC and YIC granites, two suites with distinct geochemical characteristics are to be distinguished:

a. Strongly peraluminous granites (A/CNK = 1.1–1.3) with a trend to enrichment in P and depletion in HREE (heavy rare earth elements) and other high field strength elements (HFSE). These are the S-granites in the sense of Chappell and White (1974), syn-collisional granites of Pearce (Pearce et al. 1984) and calc-alkaline to peraluminous granites according to Cuney et al.(1994).
b. Slightly peraluminous granites (A/CNK = 1.0–1.1) with very low P and high REE and HFSE, often in coincidence with subvolcanic to volcanic activity. These granites, which are a rather rare type among the European Variscan granitoids, can be with some reservations compared with the within-plate granites (Pearce et al. 1984) or high-K calc-alkaline granites (Cuney et al. 1994). The more fractionated of them show chemical features of A-type granites (Loiselle and Wones 1979), those less fractionated seem to belong to I-type of Chappell and White (1974).

Differences between both suites are well expressed within the younger, more fractionated granites (YIC), but have been established also within the older, less fractionated members (OIC) (compare Figs. 3, 4, 5, 6).

None of the proposed classification schemes can adequately explain the specific features of all granite types. However, we believe, that the here introduced, more genetic and less descriptive classification (Table 1) is capable to better explain the major differences in chemical, mineralogical and structural features between the individual intrusions.

## Geochemistry

A tremendous wealth of comprehensive and specialist publications have been devoted to the chemistry of granitic rocks. Major reviews are provided by Lange et al. (1972), Jarchovský and Štemprok (1979), Štemprok (1986), Tischendorf et al. (1987), Tischendorf (comp. 1989), Breiter et al. (1991), and, most recently, by Förster and Tischendorf (1994), and Breiter and Seltmann (1995).

The main data on composition of the different types of granitoid rocks and of the Teplice rhyolite are listed in Table 2. Magmatic evolutionary trends of typical plutons are well documented by changes in some major and trace elements and their ratios (Figs. 3, 4, 5).

Both types of OIC granites correspond roughly to common (high-K) calc-alkaline granites. Their evolution is determined by the increase in Si, distinct decrease in Ti, Mg, Fe, Ca, Sr, Ba, Zr, and only a slight increase of large ion lithophile elements (LILE, Rb, Li, Cs) and F. The OIC/I granites of Kirchberg pluton reached in their late aplitic subphases a substantial enrichment in Rb, Cs, U, Th, Nb, Ta, Y, and HREE, features which resemble those of granites assigned to the YIC/A group.

Among the YIC granites, the major element trends (with the exception of phosphorus) are also similar. The most distinct feature there is the increase in Al, Na, F, compared by the decrease in Si and K. Contents of Ti, Mg, Fe, and Ca are constantly low. Some differences between both suites could be seen in the trends to enrichment in LILE (Li, Rb, Cs), and also in F, U, Sn and W. This trend is in the case of the strongly peraluminous YIC/S granites more expresive.

The principal differences between both suites are given in the contents of phosphorus and high field strength elements (HFSE). This is well illustrated by Si-P, Th-Rb and REE plots (Figs. 3, 5, 6) which delineate divergent elemental fractionation patterns between the YIC/S and YIC/A granite suites.

The evolved nature of YIC granites is well reflected by the Rb/Sr ratio, ranging from about 1 to more than 100 (Fig. 4). However, especially the late albite-zinnwaldite-bearing YIC intrusions are distinguished by an increase in Sr concentration which cannot be explained by fractional crystallization differentiation, and highlights the efficiency of late- and post-magmatic processes. Similar Sr-enrichment in late phases was recently found in similar rocks also in other provinces (Beauvoir granite, France; Raimbault and Azencot 1987; Ghost lake pegmatite, Canada; Breaks and Moore 1992; Moldanubian P-rich granites; Breiter and Scharbert 1995).

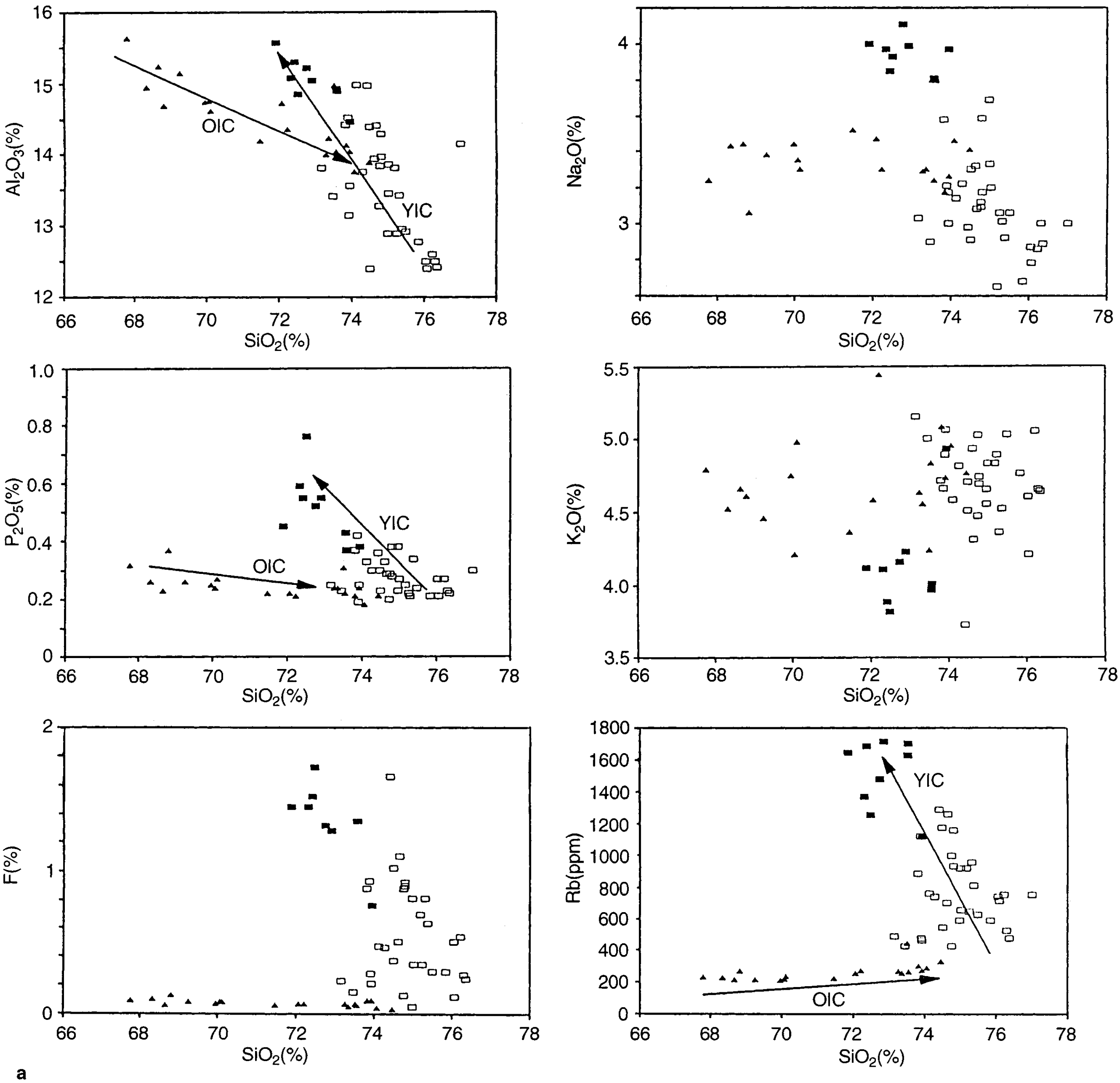



**Fig. 3a, b** Harker diagrams Si versus Al, Na, K, P, F, and Rb for most typical examples of silicic rocks: **a** strongly peraluminous suite e.g. Eibenstock-Nejdek pluton: *triangle*, OIC/S; *open square*, biotite granite of YIC/S; *solid square*, Li-mica granite of YIC/S. **b** Mildly peraluminous suite, e.g. Kirchberg pluton (*solid triangles*), Teplice rhyolite (*asterisks*) and associated granite porphyries (*X*), Preiselberg and Cínovec granites (*open* and *solid squares*). Arrows indicate magma evolution during progressive fractionation. Remarks: compare difference between two complexes (*OIC/S* and *YIC/S*) within the Eibenstock-Nejdek pluton and especially differences between both suites

The LILE-enrichment in most of the YIC rocks is mineralogically best expressed in dark micas. Figure 7 shows an example of the Nejdek pluton the gradual increase of Li-content and Al/Fe ratio from biotites from OIC/S granites to zinnwaldites from YIC/S granites. The content of Ca in YIC/S granites is too low to compensate for all available phosphorus as apatite. Thus, the main portion of P entered the alkali feldspar lattice (Frýda and Breiter 1995). In the most fractionated intrusions the $P_2O_5$-content in orthoclase reaches more than 1%.

Almost all YIC granites were the subject of fluid-rock interaction giving rise to a disturbance of the magmatic geochemical patterns. The compositional and mineralogical effects of late-stage overprinting are observed particularly in those granites related closely in space to Sn-W mineralization (Cínovec, Sadisdorf, Altenberg, Ehrenfriedersdorf, Čistá). In general, the extreme enrichment in rare alkaline elements (Li, Rb, Cs) and HFSE (Nb, Ta, Sn, W, U) is the result of strong differentiation coupled with elemental supply by fluids penetrating the granites (e.g. Table 2).

Concentrations of light rare-earth elements (LREE) decrease with evolution in multiphase plutons, and is related to early allanite (its abundance is restricted to the

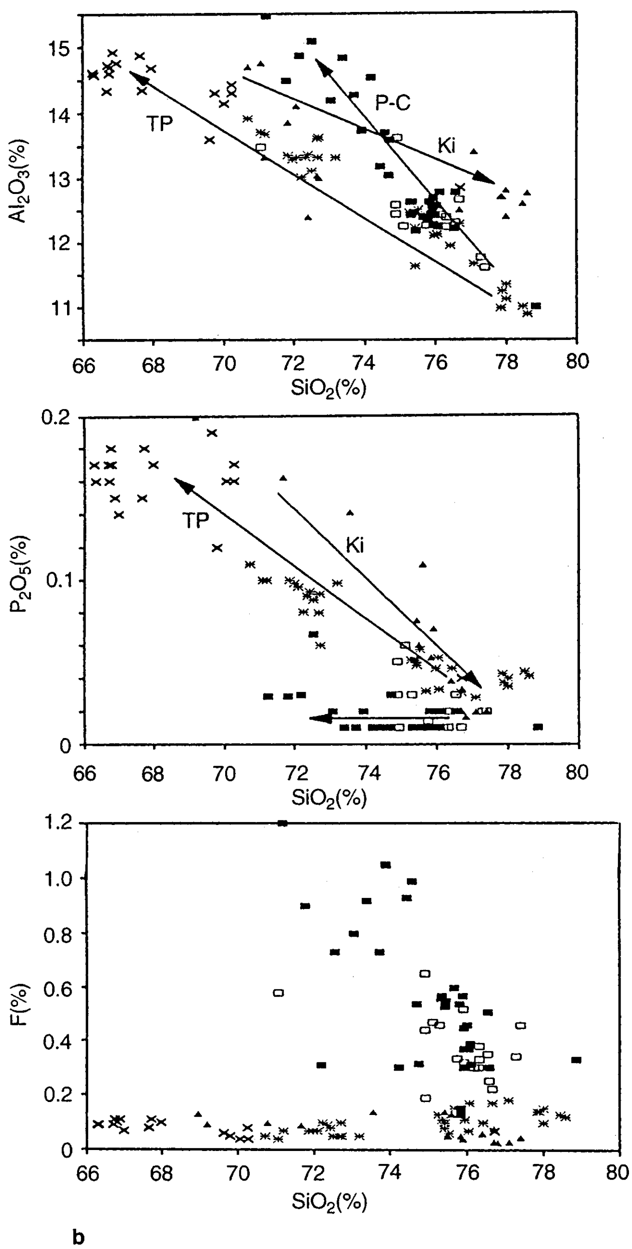



**Fig. 3b**

most primitive biotite granites) and monazite fractionation (Fig. 6). The concomitant decrease in Eu concentration is consistent with fractionation of early feldspar. The Eibenstock REE patterns should serve as an example for the simultaneous lowering of LREE and HREE contents and flattening of chondrite-normalized patterns during ongoing differentiation of YIC/S granites due to combined monazite-xenotime fractionation. In contrast, YIC/A granites are significantly higher in REE and show progressive flattening of chondrite-normalized patterns ($La_N/Yb_N$ = 4–1) with nearly constant LREE contents and marked negative Eu anomalies, until xenotime joined the crystallizing REE-bearing mineral assemblage. The REE also appear as a tool to demonstrate fluid-magma interaction. Phenomena known as the "tetrad effect" (e.g. Bau 1996) are widely present in the both types of YIC granites but also in volatile-rich, evolved late differentiates of OIC and OIC/TG magmas. Cocherie et al. (1991) described the tetrad effect in altered Cínovec YIC/A leucogranites, which show evidence of strong interaction with fluids enriched in F and $CO_2$, resulting in significant disturbance of primary compositional patterns and formation of secondary accessory minerals such as U-rich pyrochlor, bastnaesite (Ce), and synchisite (Johan and Johan 1993). In contrast, pervasive alteration of the biotite granites which is manifested mainly in sericitization of plagioclase and chloritization of biotite, mobilized REE on a local scale only, leaving whole-rock abundance unchanged.

The Teplice rhyolite, for which comagmatic relation to the slightly peraluminous YIC/A granites is under discussion (Breiter and Seltmann 1995), fits well with

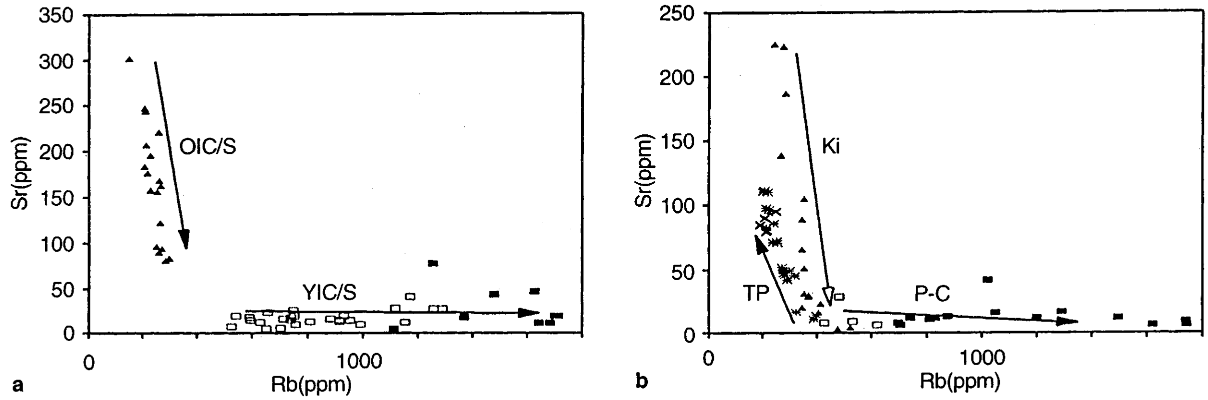



**Fig. 4a, b** Rb versus Sr diagram for most typical plutons. **a** Strongly peraluminous suite, e.g. Eibenstock-Nejdek pluton; **b** mildly peraluminous suite. See Fig. 3 for abbreviations

chemical evolutionary path of granites. The apparent antidrome trend of the main stage of rhyolite extrusion from Si-rich rhyolitic tuffs to relatively Si-poor dacitic cumulate-rich lavas and granite porphyries can be explained as a result of step-by-step exhausting of a stratified magma chamber (Tischendorf comp. 1989; Breiter 1997).

## Physico-chemical characteristics of granite magmas

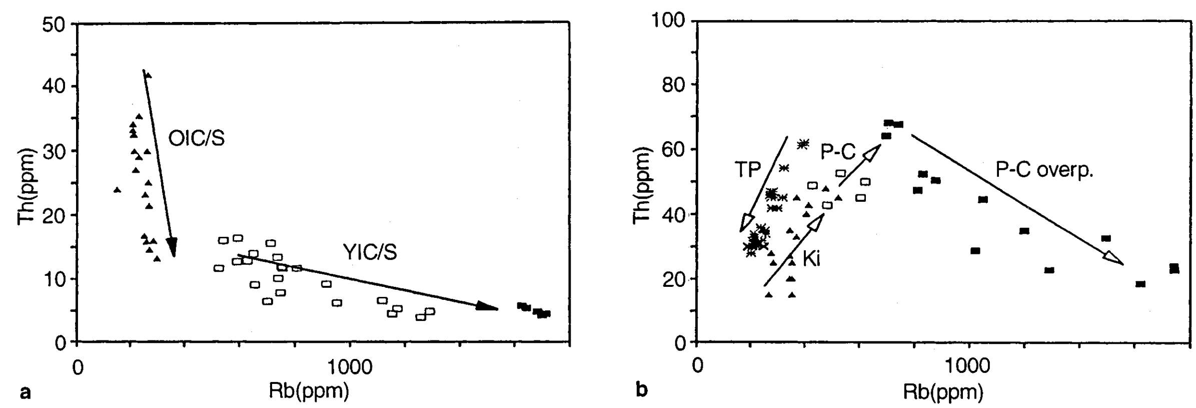
A considerable body of experimental and analytical work on melt inclusions has been amassed over the last decade to constrain the PTX-signatures of the Erzgebirge granites (Thomas et al. 1991; Thomas 1992). Minimum total melting temperatures of OIC granites were found at ≤850 °C, whereas those of YIC granites cluster at 900 °C. The depth of magma generation can be approximated to 20–25 km. The granite melts were water-undersaturated for most of their history, with an initial water content between 4 (OIC) and 3 (YIC) wt.%. With differentiation the magmas became progressively enriched in water. Occasionally, in most-evolved YIC granites water concentrations reaching 10 equivalent wt.% are recorded, stabilized by extremely high F abundances close to 4 wt.%. Steadily increasing fluorine concentration during YIC granite differentiation was responsible for shifting the solidus temperature from nearly 700 °C in least evolved sub-intrusions to less than 600 °C in final differentiates. In contrast, OIC granite solidus temperatures extended usually over a more restricted interval ranging from 730 °C to 680 °C. The level of granite emplacement can be roughly estimated to ≥4 km (OIC) and above 2.5 km (YIC).

Igneous trioctahedral mica composition was used to infer the oxygen, HF and HCl fugacity signatures for representative OIC and YIC granite suites (Förster and Tischendorf 1992). Granites which have generated tin mineralization (YIC) crystallized at low $fO_2$ close to and below this defined by the QFM buffer (e.g. Hecht 1993). OIC granites, non-productive with respect to tin, are apparently distinguished by moderately reducing conditions near that defined by the NNO buffer. Substantial enhanced fluorine fugacity expressed by lg ($fHF/fH_2O$) = −3 ± 0.3 is typical for YIC granites whereas in OIC granites this value is lower at about one order of magnitude.

## Radioactive isotopic composition and geochronology

Currently available Rb-Sr isotopic and geochronological data are limited mostly to granites positioned in the

**Fig. 5a, b** Rb versus Th plot. **a** strongly peraluminous suite, e.g. Eibenstock-Nejdek pluton; **b** mildly peraluminous suite. See Fig. 3 for abbreviations. (*P-C overp.* – trend of the late-magmatic to post-magmatic overprinting)



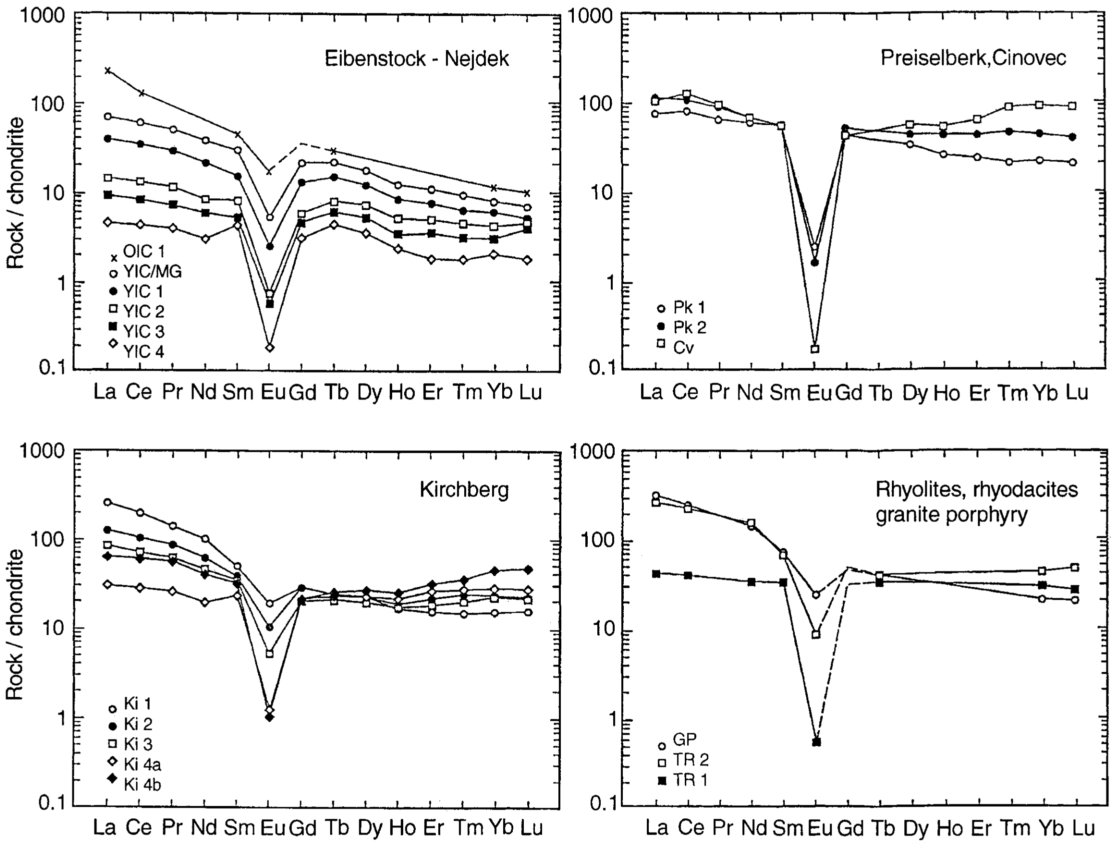



**Fig. 6** Chondrite-normalized REE distribution patterns of selected magmatic rocks. Strongly peraluminous suite, e.g. Eibenstock-Nejdek pluton. Slightly peraluminous suite, e.g. Kirchberg pluton, Teplice rhyolite, Preiselberk and Cínovec granites

German part of the Erzgebirge. Rb-Sr studies performed by Gerstenberger et al. (1995) yield ages of 309.4 ± 3.8 Ma for the Kirchberg OIC biotite granite pluton and 312.8 ± 7 Ma for the two-mica OIC/TG Bergen granite. Rb-Sr isotope datings undertaken separately for the first and second sub-intrusions within the Eibenstock YIC/S granite massif revealed isochron ages of 305 ± 4 Ma and 299 ± 6 Ma, respectively (Velichkin et al. 1994). These data are consistent with Rb-Sr ages calculated for the Pobershau-Satzung YIC/S granite suite (e.g. Fig. 1) in the central Erzgebirge (305 ± 7 Ma; Seifert 1994). However, attention has to be drawn to the fact that the significance of all these ages must be evaluated critically.

The $Sr_i$ value obtained for the OIC/I Kirchberg granites (0.7074 ± 30; Gerstenberger et al. 1995) is neither strictly indicative of I- or S-type magmatites. $Sr_i$ for the YIC/S Eibenstock pluton equals to 0.711–0.713 (Velichkin et al. 1994) and is interpreted as indicating generation of the Eibenstock granite magma from relatively old felsic rocks of the continental crust. Consequently, the deviations in $Sr_i$ between the Kirchberg and Eibenstock granites imply their derivation from isotopically and compositionally different protoliths, respectively with some I-type and S-type affinity.

## Granite protoliths

The nature of the granite progenitors is poorly known and subject of controversial discussion. The peraluminosity and low magnetic susceptibility (between 2.7 and $0.01 \times 10^{-3}$ SI; Štemprok 1993a; Förster and Tischendorf 1994) are interpreted by Štemprok (1993a) as strongly favouring a sedimentary source. As stressed by Miller (1985), however, peraluminous magmas may be derived also from evolved magmatic sources. The magnetic properties are also compatible with partial melting of relatively reduced, magnetite-poor protoliths of magmatic origin.

We can further hypothesize that small degrees of melting and subsequent strong fractionation account for their extreme evolved chemical composition.

Data on isotopic composition and absolute temporal position of the YIC/A granites is missing. The specific geochemistry of those rocks is consistent with models involving differences in (a) time of magma generation, (b) tectonic setting, (c) nature of source rocks, (d) *PT*-conditions during anatectic melting, and/or (e) duration of magma uprise relative to those in the central and western part of the Erzgebirge domain (Förster and Tischendorf 1994; Seltmann and Faragher 1994).

**Table 1** Comparison of the traditional with the new chemical classification schemes for the Variscan Erzgebirge-Slavkovský les granites with examples of the "type" plutons

| Traditional classification | Petrographic characteristic | Chemical classification: Strongly peraluminous | Chemical classification: Slightly peraluminous |
|---|---|---|---|
| OIC | Biotite monzogranite | OIC/S<br>Nejdek<br>Loket in Slavkovský les | OIC/I<br>Kirchberg |
| OIC/TG | Two-mica granite | OIC/TG<br>Bergen<br>Kfely in Slavkovský les | No equivalent |
| YIC/MG<br>YIC | Oligoclase-two mica granite<br>Albite-biotite granite to albite-Li-mica-topaz granite | YIC/S<br>Eibenstock-Nejdek, Čistá in Slavkovský les, Ehrenfriedersdorf | YIC/A<br>Sadisdorf, Cínovec-Zinnwald, Seiffen, Gottesberg, Krupka |

## Granite-related metallogenesis

Common compositional, mineralogical, and physico-chemical characteristics between certain granite types and spatially associated, high-temperature, tungsten and tin deposits were interpreted as indicating a genetic link of W-(Mo) assemblages to the OIC granites, on one side, and Sn or Sn-W-(Mo) assemblages to the YIC granites, on other side (Förster and Tischendorf 1992; Tischendorf and Förster 1994; Seltmann and Breiter 1993). Contrary to the model of temporally and genetically disconnected, multiphase mineralizing events which accompanied the origin of all productive suites, Breiter (1993) and Štemprok (1993a, b) postulated the existence of only a single, tungsten and tin ore-forming episode postdating the emplacement of the youngest YIC granite. It is suggested that separation of W and Sn cations occurred in a long-lived magmatic column, most probably as result of thermogravitational differentiation. This process gave rise to mutual separation of W and Sn oxygen-silica clusters and created metal-enriched melts. Thermogravitational differentiation was stimulated by the flow of volatiles and alkalies from the mantle into the lower crustal bottom of the magmatic column.

No unambigous evidence exists that tungsten mineralization spatially associated with OIC granites is actu-

**Table 2** Major (in wt.%) and trace element (in ppm) composition of representative granite plutons and rhyolite lava flows from the Erzgebirge and Slavkovský les

| | Slavkovský les and western Erzgebirge-Vogtland | | | | | | | Eastern Erzgebirge | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Type<br>Locality | OIC/S<br>Loket | OIC/I<br>Kirchberg | OIC/TG<br>Bergen | OIC/TG<br>Kfely | MG<br>Bílá skála | YIC/S<br>Eibenstock | YIC/S(az)[a]<br>Čistá | EC[b]<br>Teplice | YIC/A<br>Sadisdorf | YIC/A(az)[a]<br>Cinovec |
| n | 5 | 32 | 24 | 3 | 6 | 35 | 10 | 40 | 4 | 36 |
| $SiO_2$ | 62.9–69.6 | 68.1–78.0 | 70.3–75.8 | 71.6–74.2 | 73.5–76.4 | 71.0–75.1 | 71.8–75.2 | 68.8–81.3 | 71.9–75.3 | 71.8–78.9 |
| $TiO_2$ | 0.58–0.92 | 0.05–0.60 | 0.05–0.37 | 0.19–0.21 | 0.19–0.30 | 0.03–0.14 | 0.02–0.15 | 0.04–0.52 | 0.03–0.22 | 0.005–0.12 |
| $Al_2O_3$ | 14.6–16.9 | 11.2–15.0 | 13.3–14.6 | 14.0–15.8 | 12.4–13.6 | 13.1–15.4 | 14.0–15.3 | 10.7–17.1 | 13.8–15.2 | 11.0–15.1 |
| $Fe_2O_{3t}$ | 3.0–5.1 | 0.4–3.5 | 0.6–2.3 | 0.8–1.4 | 1.7–2.3 | 0.9–1.7 | 0.7–2.0 | 0.52–2.7 | 0.4–1.6 | 0.90–1.6 |
| MgO | 1.2–2.0 | 0.07–1.3 | 0.09–0.8 | 0.25–0.38 | 0.15–0.29 | 0.04–0.20 | 0.04–0.16 | 0.07–0.30 | 0.06–0.28 | 0.03–0.20 |
| CaO | 1.5–2.9 | 0.36–1.9 | 0.34–1.2 | 0.44–0.61 | 0.50–0.78 | 0.29–0.71 | 0.23–0.60 | 0.05–0.96 | 0.57–0.83 | 0.03–0.9 |
| $Na_2O$ | 3.2–3.8 | 2.7–3.6 | 3.0–4.0 | 3.1–3.4 | 2.9–3.2 | 2.6–4.3 | 2.5–4.3 | 0.9–2.7 | 2.9–4.3 | 2.7–4.0 |
| $K_2O$ | 4.0–4.7 | 4.1–5.6 | 3.8–5.5 | 4.5–4.8 | 4.6–5.1 | 3.7–5.1 | 3.5–4.5 | 4.3–6.3 | 3.4–5.4 | 3.1–5.7 |
| $P_2O_5$ | 0.25–0.45 | 0.02–0.26 | 0.30–0.14 | 0.22–0.33 | 0.19–0.25 | 0.22–0.56 | 0.30–0.50 | 0.01–0.21 | 0.03–0.18 | 0.01–0.03 |
| F | 0.10–0.12 | 0.03–0.13 | 0.04–0.15 | 0.11–0.12 | 0.13–0.28 | 0.50–1.3 | 0.30–1.2 | 0.02–0.44 | 0.37–0.98 | 0.20–1.0 |
| Ba | 1100–1450 | 11–810 | 6–540 | 190–300 | 110–270 | 5–115 | < 50 | 55–410 | 30–480 | < 60 |
| Cs | 8.2–10.4 | 14–53 | 16–90 | 25–42 | 31–42 | 39–157 | 50–110 | 10–12 | 12–49 | 20–42 |
| Li | 50–70 | 14–190 | 39–290 | 150–240 | 160–230 | 220–870 | 560–720 | 20–100 | 100–1080[c] | 190–1100[c] |
| Nb | 16–22 | 12–42 | 14–42 | 14–21 | 17–21 | 14–39 | 17–41 | 10–25 | 14–94[c] | 47–103[c] |
| Rb | 160–230 | 200–510 | 260–650 | 320–330 | 420–490 | 400–1480 | 730–1200 | 240–440 | 590–1970 | 645–1940 |
| Sn | 5–13 | 3–12 | 10–19 | 10–20 | 14–19 | 17–82 | 17–267[c] | 2–95[c] | 20–662[c] | 8–564[c] |
| Sr | 170–400 | 3–240 | 5–190 | 60–76 | 20–44 | 4–35 | 5–37 | 9–57 | 10–62 | 5–23 |
| Ta | < 1–2.6 | 3.2–15.6 | 4.9–16 | 2.5–3.3 | 1.8–3.0 | 4.1–23 | 6–17 | 1.2–3.5 | 5–140[c] | 8–43 |
| Th | 21–33 | 15–36 | 0.8–24 | 10–13 | 19–23 | 1.5–14 | 2.0–8.4 | 18–31 | 15–30 | 19–67 |
| U | 3.6–5 | 3.4–55 | 3.6–31 | 4.4–9.9 | 5–13 | 3.6–26 | 4–17 | 5.8–10 | 6–32 | 13–32 |
| Y | 22–34 | 20–47 | 2.1–21 | 22–27 | 26–30 | 3–19 | < 5 | 30–70 | 32–44 | 18–212 |
| Zr | 267–365 | 57–272 | 19–176 | 87–91 | 117–186 | 18–86 | < 5–48 | 40–228 | 34–122 | 20–156 |

[a] az: albite-zinnwaldite granites
[b] EC: Extrusive Complex
[c] concentrations in mineralized samples

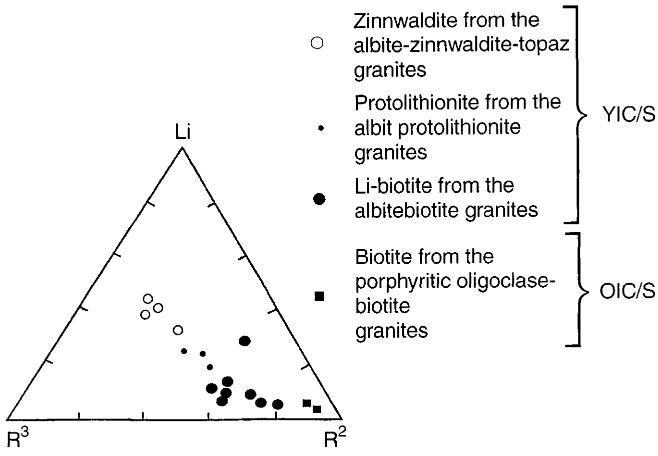



**Fig. 7** Trioctahedral mica classification plot after Foster (1960) for granites of Eibenstock-Nejdek pluton

ally of orthomagmatic origin, i.e. formed from granite residual solutions exsolved from solidifying magma batches or deep-seated remaining melts. An alternative view recently formulated by Kempe and Belyatsky (1994) involved W remobilization from earlier, metamorphogene depositions initiated by hydrothermal fluids genetically related to the Variscan granites.

A further question to address is what is the reason for the occurrence of both barren and mineralized plutons among the OIC as well as YIC granites. If one accepts a certain autonomy in the melting and fractionation history of the individual plutonic bodies (see the following section), then discrete mineral deposition histories are the logical consequence. Among others, slight differences in: (a) source rock composition, (b) degree of partial melting, (c) degree of magma differentiation, (d) depth of pluton emplacement, (e) nature and content of volatile constituents, and (f) efficiency of late- to post-magmatic alteration processes may result in distinct ore-producing capacities of similarly classified granites.

On a global scale, the Erzgebirge mining province is unique in that it is characterized by the occurrence of the two major types of tin-specialized granites in close spatial and temporal association. The YIC/A granites match the geochemical signatures of tin deposit-generating granitoids situated in North Queensland (Pollard 1988), SE Asia (Clarke and Beddoe-Stephens 1987), and Alaska (Newberry et al. 1990). Contrastingly, specialized granites of the Cornubian ore field (Charoy 1986), the French Massif Central (Cuney and Raimbault 1991), and Nova Scotia (Richardson et al. 1989) are similar in composition and elemental behaviour during fractionation to the Sn-bearing YIC/S plutons, although differences in the absolute abundance of certain elements may occur. Altogether, tin mineralization might be linked to evolved S-type, I-type, as well as subaluminous to peraluminous A-type granitoid rocks. Thus the degree in fractionation is critical in production of Sn-specialized magmas, not the protolith composition and/or tectonic position.

The widespread occurrence of thermally abnormal granites in the upper crust is suggested to have contributed to the high metallogenic potential of the Erzgebirge ore field (Tischendorf 1986; Förster and Tischendorf 1994). It seems reasonable to assume that the steady-state thermal anomaly caused by the generally high internal heat production in part was responsible for thermally weakening the lithosphere and so creating fault-induced fractures (e.g. Willis-Richards 1993). Such fracture systems stimulated the circulation of ore-bearing fluids and acted as important hosts for vein mineralization. Continued heat flow throughout the Mesozoic and Cenozoic promoted long-lived, thermally driven, non-magmatic solution convection which, under appropriate physico-chemical conditions, might have mobilized and redistributed ore-forming elements from both the various granites and their country rocks by leaching processes.

## Models of selected Sn-W deposits

In the following three genetic models for typical Sn-W deposit proposed in the last years will be introduced. We have selected examples, in which different processes played the main role: a subvolcanic breccia-related mineralization, a mineralized aplite-pegmatite system, and a pervasive greisenization-feldspatization. Also the methodology of the models is different, based either on the physico-chemical investigations, or field relations in outcrops and drillholes. This selection also gives an overview about the existing knowledge of the area discussed.

### The Sadisdorf tin deposit as example for a breccia-pipe related porphyry tin mineralization within a caldera setting (according to Seltmann 1994, Seltmann and Schilka 1994, Breiter and Seltmann 1995)

#### *Geological setting*

In late stages of the Variscan orogeny related to crustal extension and rapid uplift especially of the Eastern Erzgebirge region, a fracture tectonic activation in the upper crust took place, localized in upper Proterozoic gneisses. Volcanic and subvolcanic rocks (Teplice ignimbrites, Altenberg granite porphyry) extruded and intruded along a NNW-striking fault zone forming the Teplice-Altenberg caldera. Finally, in post-caldera stages and related to the caldera collapse, pipelike apical intrusions of leucogranites intruded into this volcano-tectonic activated region. Structurally and genetically they are mostly connected with polyphase formations of explosion and intrusion breccias (Seltmann 1994). The intrusive zonality of the geochemically specialized granite stocks (F, Li, Sn, W, Rb, Cs, Sc, Ta) is to be seen by their intrusion sequence of syeno- to monzogranite to albite granite (Gl-G2-G3-G4, from the outer rim to the centre). Each of the breccia stages is followed by a granitic intrusion stage, connected with intensive fluid migration processes which caused metasomatic alteration.

Channelized longlasting fluid flow is the prerequisite for the generation of economic ore deposits within the stock- and pipelike intrusions (Altenberg, Sadisdorf, Cínovec/Zinnwald, Krupka).

The granite-related tin-tungsten mineralization (quartz-cassiterite mineralization and related metasomatites) in the Eastern Erzgebirge belongs to the following structural types (Fig. 8):

1. Lode/stringer type (endo/exocontact)
2. Stockworks (endo/exocontact)
3. Mineralized cupolas and bed-like bodies (endocontact)
4. Breccia pipes (endo/exocontact)

5. Bedding-parallel metasomatism and mineralisation (exocontact)

The large number of types is a reflection of the multiple-stage (pulsed) nature of brecciation, intrusion and mineralization processes.

*Tin mineralization*

In the minor apical intrusions of the Teplice-Altenberg caldera there is an evolutionary sequence of breccia pipe formation, multiple intrusions, multi-stage metasomatism and mineralization. The Sadisdorf tin granite is the most extreme example of this evolution, with regard to brittle deformation and long-term fluid metasomatic processes. The mine has been abandoned since the 1950s. Traces of intensive old mining are evident through dumps, pits, and subsidence (Pinge). The most important old mining outcrop is the Kupfergrübner Pinge, which was formed in the seventeenth/eighteenth century through the collapse of sub-surface cavities in the area of a high-grade ore body. Mining started in the area before 1500, and continued with breaks until 1954. Tin and copper ores were extracted, and later W, Mo, and Bi minerals.

*Geology*

The deposit is related to a structurally-complicated cataclasite and sub-volcanic complex, located within Proterozoic gneisses. The deposit occurs at the intersection between a NNW-trending cataclasis zone and a NE-trending brittle fracture zone, that had been reactivated many times. The centre of the deposit is formed by a multiple intrusion of tin granite (G1–G4) into a large fluid explosive breccia. At the surface rocks of G1–G3 granites (outer granite) outcrop.

The polymict cataclasite (BC) occurs in the form of a large central body, as well as along granite contacts (in the form of mantle breccia), and small stock-like breccia body. The cataclasite contains millimetre up to several metre long angular fragments and blocks of various gneisses, remobilized quartz, metagneiss greisen, and gneisses greisenized by multi-stage veinlets and veins.

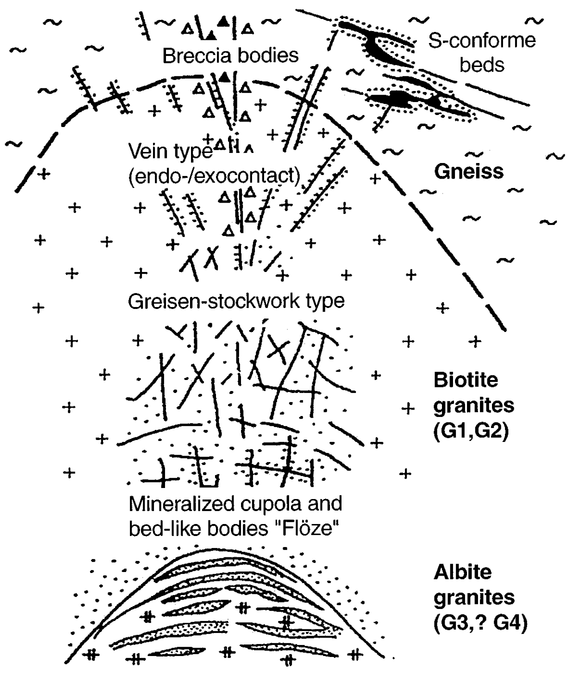



**Fig. 8** Genetic model of Sadisdorf Sn-Cu deposit (according to Seltmann 1994). Structural types of metasomatosis and mineralization for tin ore deposits of quartz-cassiterite association in a schematic vertical profile as typical for minor intrusions in the Altenberg caldera

The formation of the cataclasite body was succeeded by subvolcanic intrusives (G1–G3). They can be distinguished by their textural characteristics from fine-grained porphyritic (G1) to seriate facies (G3). The stock-like G1 intrusion is the largest (250 by 150 m), and trends NW. G2 froms a ring dyke at the northern contact between G1 and gneiss (surface diameter 90 by 140 m), that tapers with depth. The thickness of this conical fracture varies from centimetres to metres. Small radial fingers pass into the wallrocks. Topaz-albite-bearing apophyses have been found as part of this conical ring dyke. The ring dyke may have been formed as a collapse structure due to cooling and contraction of G1. The third intrusive phase, in the northwestern part of the G1 stock, forms the stock-like G3 body. This occurs only within the ring dyke, and G3 may represent a residual biotite granite genetically related to the collapse structure. The maximal diameter of G3 body is up to 40 m at the 0 m mining level (95 m below surface).

The youngest intrusive phase is a sequence of fine- to medium-grained, mainly seriate leuco-microgranites (summarized as G4) known from mining and drill cores. These were formerly called "inner granite" or "albite granites". In the central part of the deposit these are conical, with steep dipping flanks; however, with depth these form an E-W trending ridge.

Fluid transport processes in relation to magma cooling, e.g. the interaction between greisen fluids and granite tectonics produces structural mineralization types as schematized in Fig. 8.

*Metallogeny*

The emplacement of the fluid explosive breccia and of the subvolcanics is connected with multiple metasomatic processes. The consequence of this is a large number of different metasomatic and mineralization types.

The metasomatites are mostly pseudomorphic greisen, dominantly mica-greisen but also mixed types with increased topaz and/or quartz content. The pseudomorph greisen of a single mineralization event has a typical zonal differentiation, in which mica greisen (outer greisen) has been overprinted by topaz and quartz greisen (inner greisen). Less frequent metasomatites are metablastites, dominantly forming steep-dipping, schlieren to pipe-like bodies of centimetre to metre size. Veinlets with infilling paragenesis are only rarely found. The proportion of metasomatite types is a feature of a high-temperature system. An interesting mineralization zoning seems to occur in the apical part of G3 granite (outcrops and debris in the "Pinge"): in the upper parts Cu mineralization dominates, in the deeper parts Mo mineralization; both disseminated. At the 0 m level there is mainly Sn greisen mineralization. Disseminated mineralization, its relation to breccia pipes and small stocks, and boiling of the ore forming fluids allow us to describe the mineralization as of porphyry style. The source and age of greisenising fluids is controversial. In the fluid explosive breccia (BC), which is older than granite G1, greisenised gneiss fragments were found, suggesting a pre-G1 metasomatism.

The last metasomatic event (post-G4) was responsible for producing a quartz cupola between the inner granite (G4) and the outer granites (G1–3). Greisenization was intensive in the endocontact to depth. Hydrothermal vein mineralization is not of economic interest.

The rare-metal granite-pegmatite system
of the Ehrenfriedersdorf/Erzgebirge

This is an example of magmatic fractionation and magmatic-hydrothermal transition processes in a greisen vein-type Sn-W deposit (according to Seltmann et al. 1995). It is located in the Ehrenfriedersdorf tin mine. Melt and fluid inclusion studies suggest that there is in general a continuous evolution from a magmatic stage through a pegmatitic stage to a high-temperature ($T$ > 450 °C) hydrothermal stage. Structural and geochemical discontinuities, in the evolution from the pegmatitic minerals to the hydrothermal greisen mineralization they host locally in greisen pockets ore cutting vein dykes, may be caused by decompression of the residual melt in the root zone of the intrusion, and as a consequence, the decompression of the intergranular space. Thus, it is probable that highly evolved residual fluids percolate the granite and then the pegmatite. Because this happens in a late stage of melt consolidation, only regions with high permeability (e.g. granite roof, contraction ruptures) are available for fluid flow. However, the compositional changes of melt and aqueous fluid show a continous evolution of the granitic system (internal differentiation) in space and time, indicated by melt and fluid inclusion data. Nevertheless, individual samples indicate discontinuity within the evolution of magmatic to hydrothermal stages. This is caused by progressive crystallization combined with melt and aqueous fluid evolution and chemical transport from the higher evolved melts into formerly emplaced rocks producing epigenetic textures.

## *Geological setting*

The tin ore district of Annaberg-Ehrenfriedersdorf is situated in the border region of the Central Erzgebirge Anticlinal Area (Neoproterozoic) and the Erzgebirge Northern Border Zone (Cambro-Ordovician). The metamorphic grade decreases from SE (amphibolite-facies gneisses) to NW (greenschist-facies phyllites). The metamorphic series were intruded by Upper Carboniferous, highly evolved rare-metal granites, which is subdivided into four intrusive phases (A–D). The stock-, cupola- and ridge-shaped apical parts of the Central Erzgebirge granite pluton were exposed by erosion, mining and drilling. The granitic system investigated has a shallow intrusion level.

Granitic pegmatites occur as marginal-pegmatites (stockscheider) in the roof zones of the granite cupolas and pegmatite-aplite dykes cutting the granite contact. The origin of these bodies is magmatic as determined by the existence of melt inclusions found in quartz, feldspar and topaz. Pegmatite-aplite dykes as well as a few mineralized hydrothermal veins have diffuse root zones originating in the stockscheider bodies, which is indicative of the fractionation process between melt and aqueous fluid. Multiphase pegmatite-aplite formation in stockscheiders and dykes indicates magmatic and tectonic pulsation in the evolution of the pegmatitic residual melt. Three generations of aplitic dykes exist (pre-, syn-, post-granitic), the youngest ones rooting in the granitic apex.

Tectonically controlled mineralization was deposited from focused fluid flow in stringer and vein zones, vein-like greisen zones, stockwork-like greisen and, of lesser importance, skarns. A subsequent hydrothermal mineralization (characterized by boiling fluids) overprints the primary system only in vuggy caverns, druses, schlieren, where late fluids could be collected.

Texturally, the magmatic-hydrothermal system is composed by the following rock types characterizing its evolution:

1. Granitic system (alkali-feldspar to topaz-albite granites)
2. Fine-grained (aplitic) topaz-albite granites near the contact
3. Subhorizontal protholithionite layer below the stockscheider
4. Stockscheider (pegmatite-aplite system)
5. Aplitic dykes (pegmatite-aplite dykes)

## *Petrography of the granite-pegmatite system*

The four intrusive phases of the granitic system *sensu stricto* are texturally subdivided into:

1. Phase A: the oldest granite is a fine-grained porphyritic biotite granite, occurring as xenoliths in granites of phases B and C.
2. Phase B: this granite consists of fine- to coarse-grained seriate textured, porphyritic to porphyric alkali-feldspar granites. Dark mica is characterized by increased Li contents.
3. Phase C: this widespread equigranular topaz-albite-protholithionite granite turns from a fine- to medium-grained into a medium- to coarse-grained texture at deeper levels.
4. Phase D: this is the youngest granite phase; comprising a fine to medium-grained, equigranular, sometimes seriate textured granite. Compared to the forerunner intrusions, these topaz-albite-protholithionite granites display an even more pronounced abundance of muscovite, lack of biotite and late-magmatic/metasomatic overprinting. They typically occur as aplitic dykes and sills. As indicated by geochemical features, aplites from the stockscheiders and pegmatite-aplite dykes belong to Phase D, too.

In the sequence A to D the granitic textures change from mainly granophyric to granoblastic ones, indicating increasing reactivity of fluids exsolved from the melt. Typical late-magmatic recrystallization patterns (K-feldspar blastesis: A to C) turn to re-equilibration textures such as perthitization, albitization (chess-board albite) caused by deuteric alteration (C to D) and finally sericitization, chloritization and weak argillization as low-temperature alteration products. Aplites from stockscheiders (D) are characterized by K-feldspar blastesis and graphic quartz-orthoclase intergrowths. According to the modal composition of the granitic rocks from the Central Erzgebirge subintrusions of Ehrenfriedersdorf-Annaberg and their granite-pegmatite system, granite A yields biotite, but lower abundances of topaz. The other types display, from B to D, decreasing K-feldspar and increasing Na-plagioclase abundances. All analyzed plagioclases are determined as albite (with $An < 5$).

## *Geochemistry of the granite-pegmatite system*

Chemical distribution patterns portray systematics which suggest continuous fractional crystallization as the dominant petrogenetic process, with fluid overprint in the most evolved granite phases. Deuteric (autometasomatic) alteration and hydrothermal element redistribution control dominantly the ore concentration in the apical parts of the granitic subintrusions.

Positive correlation of Nb and Ta reflects the enrichment of these incompatible, relatively immobile elements during fractional crystallization from the relatively low differentiated granites of phase A towards the formation of pegmatitic residual melts (phase D).

Rb enrichment and Sr depletion are typical trends in the magmatic evolution of the granite-pegmatite system. The granites of the studied rock suite (A to C) fit into the range of the extremely evolved subintrusions of the Erzgebirge granite province. The scattered distribution of Sr is dominantly caused by autometasomatic Sr redistribution (A to D). The extraordinary trend of the aplitic dykes (decrease of Rb/Sr ratio) characterizes the magmatic-hydrothermal transition stage and the influence of a highly reactive aqueous solution.

The properties of the alkali-feldspars vary in the evolution of the granite-pegmatite system. Two trends can be distinguished. The first one represents the alkali-feldspar trend of the magmatic system from phase A to aplitic granite (D). The second trend is characterized by the separation of orthoclase-rich aplite of the stockscheider, and of albite-rich aplite dykes derived from the primary melt system (aplitic granite). The different feldspar distribution in the stockscheiders and aplite dykes correlates with the distribution of rare-metal elements. Late-magmatic Sn enrichment is encountered in KCl-dominated fractions of the aqueous-rich residual melt, whereas W, Nb and Ta are enriched in the NaCl-dominated fractions and, in consequence, are enriched in the albite-rich parts.

## *Conclusion*

The genetic model (Fig. 9) summarizes the pertinent geological, petrological and geochemical features of the granite-pegmatite system studied at Ehrenfriedersdorf. The evolutionary sketch refers to main trends of typical trace element variation diagrams. Additionally, schemes of normalized REE distribution patterns demonstrate the granite evolution by progressive fractional crystallization (Fig. 9a), the separation of the albite-rich residual melt is indicated by a positive Eu anomaly (Fig. 9b). Tetrad effects caused by highly reactive aqueous solutions exsolved from the melt (Fig. 9c) are exclusively related to the apical parts of the granitic cupola and are not found in the aplite dyke. This is interpreted as indication for a closed system because subsequent metasomatic

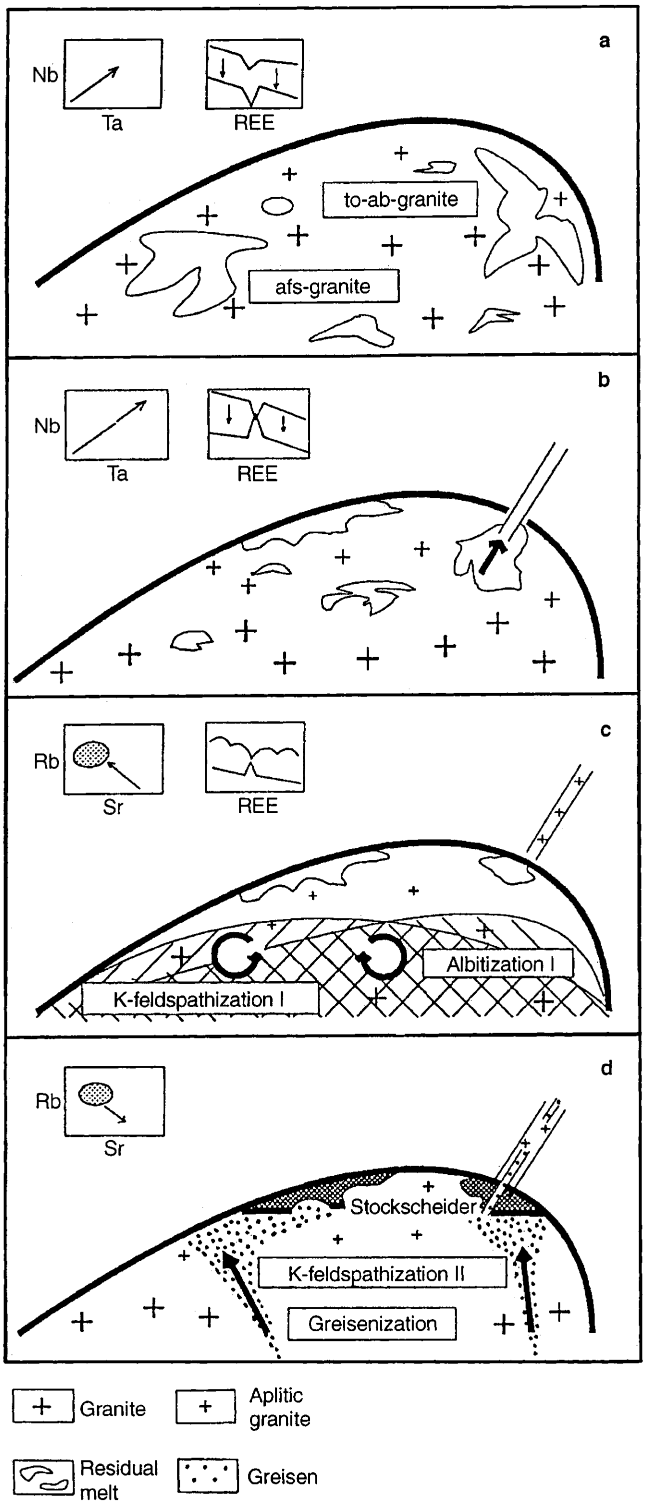



**Fig. 9** Genetic model of Ehrenfriedersdorf Sn-W deposit (according to Seltmann et al. 1995). See accompanying text for further explanations

overprint does not affect the aplitic dykes. The late-magmatic evolution is producing partly overlapping autometasomatic alkali fronts of albitization and K-feldspathization. Post-magmatically, greisenization and younger K-feldspathization lead to intense element redistribution (Fig. 9d).

Sn-W mineralization in the Krásno-district (according to Jarchovský 1995)

*Geological setting*

The Krásno ore-district comprises four mineralized granite cupolas along the SE contact of the Krudum pluton in the Slavkovský les area. Due to post-granitic faults with a vertical displacement of about 300–400 m, more or less hidden, but also deeply eroded cupolas can be observed at outcrops. The inner structure of the cupolas is well stratified, comprising (from the top, compare Fig. 10):

a. Pipe of gneissic breccia cemented by topaz-microgranite
b. Quartz-zinnwaldite-topaz greisen
c. Greisenized albite-zinnwaldite-topaz granite
d. Mica-poor aplitic albite granite with layers of feldspathites
e. "Normal" albite-protolithionite-topaz granite identical with the Čistá type granite from the nearby Krudum pluton

*Proposed model*

The autometasomatic phenomena observed in the rare metal granites elsewhere were formerly explained as the result of post-magmatic solid state metasomatism (albitization in the sense of Beus and Zalaškova 1962). According to the studies of the magmatic nature of albitic dykes (ongonites, Kovalenko 1977), we may suppose that also the albite of YIC granites in Erzgebirge is of primary origin.

The albite-protolithionite granite underlying the whole cupola is rather homogeneous in chemical composition and does not contain any vertical vents of alkali-bearing fluids. All the sodium necessary to local albitization has been released by a breakdown of feldspars during greisenization in the upper part of the cupola.

The first portions of magma (microgranite) sealed the brecciated gneiss roof and the fluid components accumulated under a quickly cooled granite in the upper part of cupolas. Neutralization of fluids by the alkalies released from the decomposed feldspars formed favourable conditions for feldspar enrichment after cooling. The underlying leucogranites and feldspathites represent a low-temperature residual petrogenic system oversaturated in alkalies. The subhorizontal layering of feldspathites can be classified as a late magmatic stratification. Recycling and convection processes around 100–200 m of such a system are a highly probable cause for the accumulation of fluid components including fluorine that must have substantially lowered the viscosity and solidus temperature of the magmatic melts.

It follows from the behaviour of the silicate systems containing fluid components that the solidification of the underlying Li-F granite occurred solely in the course of degasing, due to the increase of solidus temperature after the system was drained of fluids, probably earlier than the crystallization of the overlying aplitic albite granite and felspathite. Residual alteration and differentiation processes in the cupola then took place in a closed magmatic system.

## Discussion

Several mechanisms have been invoked to explain the origin of the Erzgebirge-Slavkovský les granites. The favoured model involves widespread crustal melting initiated in response to crustal thickening by thin-skinned tectonics and concomitant radioactive heating in a continent-continent collision setting (Förster and Tischendorf 1994). Large-scale crustal fusion triggered by an elevated heat flux in relation to mantle-derived magmas is a further scenario advocated by some workers.

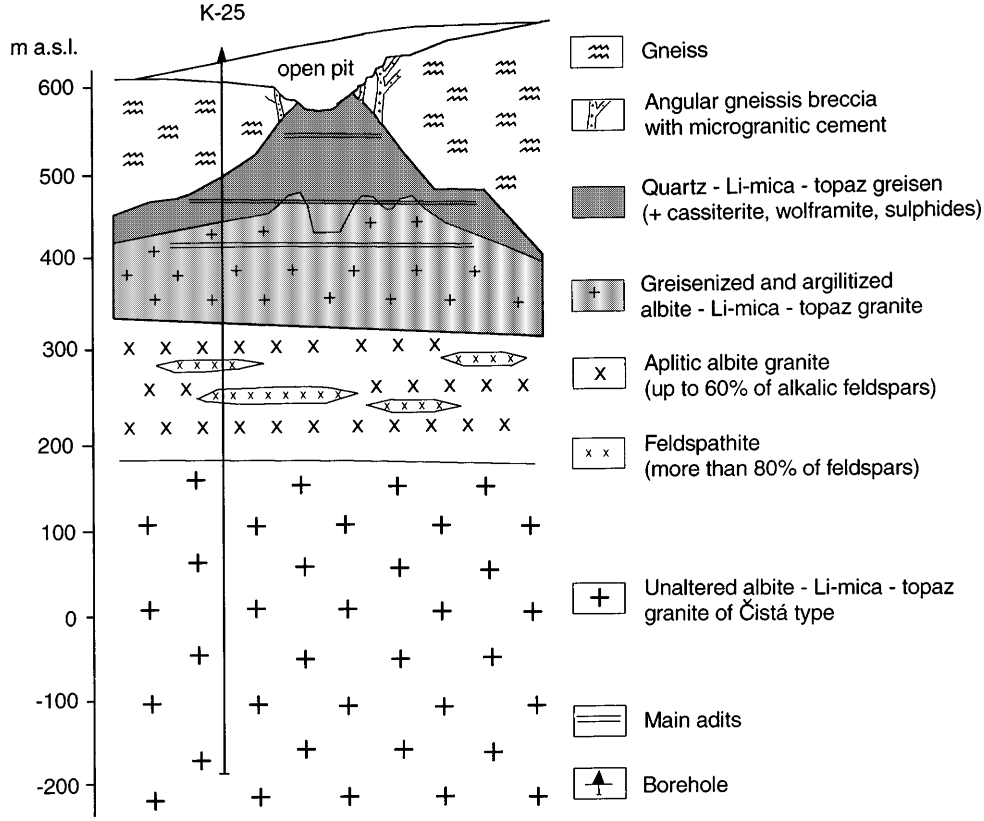



**Fig. 10** Idealised cross-section of mineralized cupola in Krásno mining district (according to Jarchovský 1995)

However, present-day seismic patterns (1) show no evidence for downward gradation of granites into rocks of mafic composition, (2) imply a felsic nature of the Erzgebirge crust down to the Moho and (3) argue against a widespread occurrence of mafic granulites and amphibolites (Bankwitz and Bankwitz 1994). On other side, mantle activities accompanying spatially and temporally the emplacement of granitic intrusions are manifested in several generations of lamprophyre dykes. As emphasized by Skjerlie and Johnston (1993a), a dyke complex resulting from crustal extension may prohibit underplating and accumulation of basaltic magma and heat in the crust. Views involving derivation of granites by fractional crystallization of mantle-related magmas are irreconcilable with the compositional and isotopic characteristics presented herein as well as the large masses of evolved granites as essential components of the upper crust.

Presently, there are two main schools of thought regarding the genetic relations of the different types of granites. Several workers proposed a continuous magmatic evolution from the Late Carboniferous to the Early Permian and suggested the formation of YIC/S granite magmas by fractional crystallization of OIC/S magmas with two-mica OIC/TG and MG as connecting members (Breiter 1993; Štemprok 1993a). Other workers favoured a multi-stage magmatic evolution leading to the production of discrete magma batches over a time of several million years. (Tischendorf and Förster 1990; Förster and Tischendorf 1994).

Chemical, mineralogical, isotopic, and geochronological data for both granite suites in the Erzgebirge presented here are irreconcilable with models involving a continuous magmatic line. A more likely scenario requires separate events of melting, with most of the individual massifs having a discrete evolution after separation from a comparable source. In contrast, the geochemical signatures of the different granite types exposed in the Slavkovský les suggest, but do not unambigously give evidence of, their derivation from a common parental magma by progressive differentiation which culminated in albite-zinnwaldite granites.

The exact nature of the granite protoliths remains unresolved. An extended contribution of lower crustal, relatively young (Cadomian) and F-poor felsic (compared to the average composition of the lower continental crust) orthometamorphic rocks to the Kirchberg biotite OIC/I granite petrogenesis is implied, but not evidenced by various geochemical and isotopic criteria (Tischendorf et al. 1992). Considering their Rb-Sr isotope systematics, the authors demonstrated that pre-Variscan rocks of parametamorphic nature could not have acted as major sources for low-$Sr_i$ OIC-type granites. Zircon typology characteristics are discussed in terms of a mixed mantle and crustal origin of OIC/S granites studied by Kodymová and Štemprok (1993). Precambrian and Paleozoic parametamorphic sequences such as phyllites, mica schists, and gneisses might have played a comparatively more significant role in the genesis of the high-$Sr_i$ YIC/S plutons. Contrasting chemical patterns of the YIC/A granites suggest partial melting of sources different from those suspected for the aforementioned magmatites. We assume that the A-type features of these granites, emplaced in a tensional regime, are source-related, perhaps a F-enriched granulitic residue left behind after previous anatectic events, or a non-restitic halogen-rich source of granodioritic-tonalitic composition (e.g. Skjerlie and Johnston 1993b). Garnet-free Variscan charnockitic xenoliths in Tertiary basalts in the Czech part of the eastern Erzgebirge are interpreted as representing another plausible protolith for the water-undersaturated YIC/A melts generated under high-temperature conditions (Seltmann and Faragher 1994).

The granites of both major series can be regarded as transitional or mixed I-S-types (Tischendorf and Förster 1990). The simple bipolar S-I-type classification cannot successfully explain the heterogenity of all the granitoid rocks under consideration (e.g. Breiter et al. 1991). One possible explanation for this involves magma generation from more than a single source rock. There are several lines of evidence showing that the Erzgebirge crust is built up by compositionally and mineralogically layered metamorphic rocks including those of both sedimentary and magmatic nature.

As demonstrated by Hall (1993), cesium can be an good indicator for the relative proportions of feldspar and mica entering the granitic melt during anatexis. Cs-rich granites such as the YIC/A and, particularly, the YIC/S granites, which additionally exhibit an abnormally high level of rubidium and lithium, and distinctly negative Eu-anomaly, are thought to result from partial melting under vapour-absent conditions favouring the relative segregation of mica into the melt and feldspar into the restite. Seltmann and Faragher (1994) also suggested that the ratio plagioclase to biotite melting exerted a significant control on the different ore-generating potential of the various granite types in the Erzgebirge.

The compositional zonation of volcanic sequences predating the YIC/A granite magmatism in the east of the Erzgebirge, characterized by evolution toward more basic members with decreasing age, is best explained by successive multiple eruptions of magmas from a vertically zoned silicic magma chambers (Tischendorf 1988; Breiter 1997). The rhyodacitic lavas may represent denser, more mafic, lower portions of a zoned magma chamber that had errupted rhyolites earlier.

## Conclusions

The Variscan history of granite magmatism in the Erzgebirge-Fichtelgebirge-Slavkovský les anticlinorium is obviously more variable than previously assumed, and far from being fully understood. Integration of the limited geochronology with field relations as well as granite chemistry and evolutionary pattern requires an emplacement history that differs from traditional views. Neither the present concept of a continuous evolution which implies the existence of a single, long-lived active magma chamber over a period of some 10 My, nor the idea of two or three episodes of magma generation assuming a nearly contemporaneous emplacement of similarly categorized granites are able to adequately explain the distinct pecularities of the individual composite plutons across the entire domain.

Several indications exist supporting the idea that the granites in the Erzgebirge-Fichtelgebirge anticlinorium originated from repeated melting events encompassing a time span of about 40 Ma. More or less pronounced differences with respect to geochemical patterns, fractionation regularities, isotopic signatures, and geochronology between the individual plutons imply multiple and genetically separated episodes of melting which led to the formation of independently evolving granite magmas. In case of the Slavkovský les, geochemical patterns are compatible with an uninterrupted fractionation from OIC to YIC(N) granites. Nonetheless, isotopic and geochronologal data are warranted to test the latter hypothesis strictly.

Recent isotopic and fluid- and melt-inclusions study on the Sn-W deposits discussed favoured a late-magmatic to early post-magmatic models of mineralization with Sn,W-source in the crystallized granite, more than classic post-magmatic metasomatic models with distal ore-source. The main processes involved in the mineralization are the fractional crystallization, fluid-melt immiscibility, hydrofracturing and breccia-pipe formation, and/or pervasive fluid-rock interaction.

Tin deposits in the Eastern Erzgebirge show causal relationships between caldera formation, fracture tectonics, multiple late-Variscan magmatism as minor intrusions emplaced into high crust levels, postmagmatic mineralization associated with high-temperature metasomatism. The Sn-W deposits the Central Erzgebirge (Ehrenfriedersdorf, Geyer, Annaberg, Pobershau) are an example of continuous fractional crystallization of S-type melts and its transition into an aplite-pegmatite system and hydrothermal processes. Nb/Ta, Rb/Sr and $Na_2O/K_2O$ distribution patterns indicate overlapping of fractionation processes, deuteric (autometasomatic) alteration and hydrothermal element redistribution controlling the ore concentration in the apical parts of the granitic subintrusions (Seltmann et al. 1995).

The Sn-W deposits in the Krásno district show stratification of residual granitic system with differentiation into alkali-poor and alkali-rich domains.

In order to verify the ideas presented, future studies have to be concentrated on the determination of stabile and radioactive isotopic as well as high-precision geochronological data for both the individual granite intrusions and spatially related, high-temperature ore associations. Many fundamental questions (continuous/discontinuous magmatic evolution, para-/orthometamorphic nature of magma sources, significance of the mantle for granite melting, single/multiple events of orthomagmatic Sn mineralization, lower/upper crustal source of ore-bearing solutions,...) still require solution before the evolution of this classic metallotect can be satisfactorily understood.

**Acknowledgements** The authors are gratefully indebted to G. Tischendorf and M. Štemprok who essentially contributed to our present understanding of the magmatic-metallogenic history characterizing the Erzgebirge-Slavkovsky les ore field. Their helpful and critical discussions stimulated many of the ideas formulated here. We are grateful to T. Jarchovský for permitting utilization of his genetic model for the Krásno deposit, to Mrs. Scharbert for permitting to use unpublished Ar/Ar data from the Nejdek pluton and to two anonymous reviewers for their inspiring comments. This is a contribution to 1GCP-373.

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## Note added in proof

According to the first set of Ar/Ar data from the Eibenstock-Nejdek pluton (Scharbert, unpublished), the intrusion of the YIC/S should be older than was expected from the Rb/Sr analyses. The Li-biotite granite of YIC/S from the Horní Blatná body gives 312–315 Ma. The geologically youngest rock of the pluton, the stock of phosphorus-rich albite-zinnwaldite-topaz granite at Podlesí gives 310–312 Ma.