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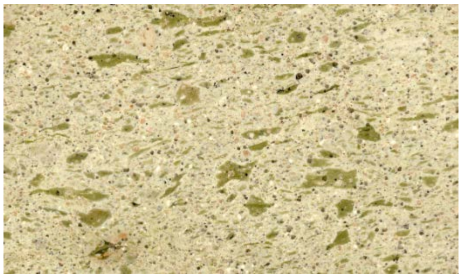

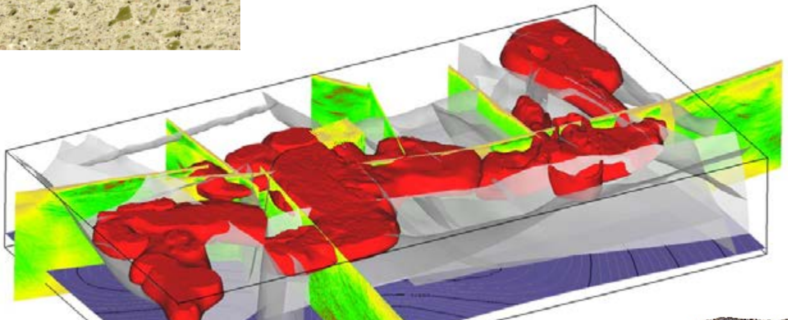

Christoph Breitkreuz and Uwe Kroner (conveners)

Workshop on

“Late Paleozoic magmatism in the Erzgebirge / Krušné hory: Magma genesis, tectonics, geophysics, and mineral deposits”

- Abstracts -

42 pages, 23 contributions

Content

Preface

The Erzgebirge / Krušné hory at the northern margin of the Bohemian Massif is one of the centre pieces of the Late Paleozoic Variscan orogen. It stands out for medium to high-grade metamorphic nappes, large plutonic and volcanic complexes, and, of course, for diverse mineralisations, mined for over 800 years.

The Erzgebirge / Krušné hory has been in the focus of geoscientific research for more than two centuries. In recent years, a large number of studies were carried out or are under way, including tectonics, magmatic and metamorphic petrology, physical volcanology, economic geology, petrophysics, paleomagnetics, and geochronology. The Erzgebirge / Krušné hory comprise a large and diverse set of existing data gained from outcrop, mine edifice and drilling. Current activity, such as high-accuracy geochronology, mineral chemistry and isotopes, reprocessing of seismic lines, remote sensing and geometric modelling, adds to the understanding of this unique structural unit.

Among others, the magma genesis, the plutonic-volcanic connection, and the related mineralisation are important topics. The Erzgebirge / Krušné hory is not just “Local Geology – *Heimatkunde*”: It’s a prime example of a well exposed and well-documented block evolved in a late- to post-continent-continent collisional setting – associated with complex mineralisations: The community should know about it!

We are very pleased about the strong response to the call of this field workshop – More than 40 participants from Armenia, Chile, Czech Republic, Germany and Poland registered! Our thanks go to the organisation team of the Institute of Geology of the TU Bergakademie Freiberg!

Welcome to Freiberg, with kind regards,

Christoph Breitkreuz and Uwe Kroner

Vertical evolution of the Cínovec granite cupola – chemical and mineralogical record

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The 1597 m deep borehole CS-1 located in the centre of the Cínovec pluton represents an ideal object for evaluation of vertical structure of rare-metal bearing magmatic systems. A combination of textural and chemical methods was applied to whole-rock and mineral samples to define chemical and mineral composition of all granite facies and to identify the extent of magmatic and metasomatic processes during differentiation of the pluton and formation of the deposit. New evolutionary model of the deposit was proposed.

The Cínovec rare-metal granite in the eastern part of the Krušné Hory/Erzgebirge (Czech Republic/Germany) was formed in the final stage of magmatic evolution of the late Variscan volcano-plutonic system of the Teplice caldera. The granite is slightly peraluminous; enriched in F, Li, Rb, Cs, Nb, Ta, Sn, W, Sc and U; and poor in P, Mg, Ti, Sr and Ba. The uppermost part of the granite cupola hosts a greisen-type Sn-W-Li deposit. The fully cored borehole CS-1 permits study of the vertical evolution of the pluton to a depth of 1597 m.

Based on the macroscopic inspection, automated mineralogy (TIMA) measurements, detail study of rock-forming and accessory minerals and whole-rock chemical data, the following lithological units were distinguished within the CS-1 borehole:

1. The uppermost part of the cupola from the current surface to a depth of 260 m (the "canopy" of the pluton) is composed of mostly leucocratic equigranular fine-grained albite-zinnwaldite granite (ZiGC). The granite consists of subhedral albite, anhedral quartz and zinnwaldite and sericitized K-feldspar. Typical accessory minerals are fluorite, topaz, zircon, cassiterite and columbite; in lesser amounts xenotime, thorite, and monazite.

2. Quartz- and quartz-zinnwaldite greisens (GR) were encountered in the 34–213 m interval; the largest greisen body was found at a depth of 147–167 m. Greisens are mostly medium grained, composed of anhedral mica flakes and aggregates of quartz grains, anhedral fluorite and euhedral topaz crystals. Along with ore minerals (cassiterite, columbite, scheelite>wolframite), zircon, xenotime, thorite and different REE-fluorocarbonates appear in accessory amounts. The contacts between granite and greisen are sometimes relatively sharp, with only a mm-sized transition zone, but are also fuzzy with a m-sized transition.

3. Mica-free granite (MfG) was encountered at a depth of 260-369 m as a medium-grained porphyritic rock composed of up to 10-mm-sized perthite phenocrysts, subhedral quartz (up to 2 mm across, sometimes with a well-developed snow-ball texture) and anhedral Kfs and albite in the groundmass. Zinnwaldite is present here only incidentally or is entirely absent. Fluorite, zircon, rutile, thorite, cassiterite and columbite are typical accessories.

4. Potassium-dominated fine- to medium-grained feldspatites (FSP) form several layers up to 5 m thick within the MfG body in the interval 270-368 m. This rock is composed of large (~5 mm) irregular poikilitic grains of pure (non-perthitic) K-feldspar, fine-grained (<0.5 mm) subhedral albite, minor subhedral quartz and late very fine sericite partly replacing K-feldspar. Zircon was found in accessory amounts. The texture of FSP differs significantly from all the other rock types within the Cínovec pluton, including the surrounding mica-free granite, and indicates the replacement of former minerals by poikilitic K-feldspar.

5. A light gray fine-grained strongly porphyritic variety of zinnwaldite granite, traditionally known as zinnwaldite microgranite (ZiGm), appears at a depth of 369-530 m. On the border between ZiGm and the underlying ZiG is an approximately 50-m-thick transition zone with irregular alternation and local mingling of both facies. Texturally, the ZiGm is a typical "two-phase rock", with assemblages of euhedral quartz and perthite and subhedral albite phenocrysts (up to 5 and 10 mm across, respectively) cemented by a fine-grained (<0.5 mm) matrix of the same composition. Macroscopically black poikilitic zinnwaldite is common; euhedral topaz and anhedral fluorite are minor constituents; and zircon, rutile and thorite are accessory.

6. The medium- to coarse-grained albite-zinnwaldite granite (ZiG) at the depth of 530-735 m is almost white and is texturally and mineralogically homogeneous. It is composed of isometric to shortly columnar subhedral crystals of perthite 5–10 mm in size, subhedral quartz (up to 5 mm), subhedral to anhedral albite (1–3 mm) and macroscopically black zinnwaldite (2–4 mm). The granite further comprises topaz, fluorite, zircon, xenotime, thorite, monazite, rutile, cassiterite, columbite, scheelite and pyrochlore.

7. The suite of biotite granites *sensu lato* at the depth of 735-1596 m is homogeneous in mineral and chemical composition but exhibits various textures. The pink color of the rocks is characteristic. Slightly porphyritic medium-grained biotite granite with local transitions to coarse-grained equigranular facies (BtG) prevails. A fine-grained distinctly porphyritic facies ("biotite microgranite" BtGm) with a highly variable quantity and size of quartz and perthite phenocrysts in very fine-grained groundmass (~0.2 mm) are subordinate. All textural varieties of BtG contain accessory amounts of zircon, xenotime, thorite, monazite and rutile.

The Following evolutionary model of the Cínovec deposit was developed:

a) Magma of the biotite granite intruded into the volcanic pile of the Teplice caldera and crystallized into several facies differing in texture (BtG, BtGm) but very similar in chemical composition. This magma was already slightly enriched in Sn, W, Nb and Ta, but due to low contents of water and other fluxing agents, it was unable to fractionate and/or segregate ore elements into the fluid.

b) The ZiG magma intruded along the western contact of the BtG, reached subvolcanic conditions and crystallized along the upper contact (ZiGm).

c) The magma under impermeable carapace enriched in water. Subsequently, separation of oversaturated fluid from the melt caused explosive degassing, partial destruction of the ZiGm-carapace and origin of breccia pipe (pipes).

d) The breccia pipes are cemented with zinnwaldite granite, volatiles in the magma migrated upward, and stockscheider crystallized along the upper contact of the intrusion. Individual solid blocks of ZiGm plunged into the relatively low-viscosity magma. The ZiG magma evolved through *in situ* magmatic fractionation: water and fluxes migrated upwards, contents of lithophile elements such as Li and Rb upwards increased, and Zr and other compatible elements slightly decreased. Fine-grained columbite and cassiterite disseminated in granites crystallized mainly during this process from a residual interstitial melt.

e) Water and volatiles became concentrated in the residual melt up to saturation and following sudden segregation (“second boiling”). Rare metals, F and Li partitioned to fluid. The segregated fluid escaped upwards, causing hydrofracturing of the overlying granite of the canopy.

f) The water-poor residuum of melt crystallized as a mica-free granite. F- and Li-rich fluid migrated upwards and caused greisenization and originated quartz-zinnwaldite veins. Alkalis liberated from destroyed feldspars partly escaped the system and partly caused “albitization” (i.e., crystallization of thin coatings of pure albite on primary albite feldspar crystals) and “K-feldspatization” (i.e., local K-metasomatism inside the MfG). The main episodes of Sn- and W-transfer and cassiterite, wolframite and scheelite crystallization are contemporaneous with or slightly younger than the greisenization.

g) Later, a portion of fluid poor in Li and F caused pervasive sericitization of the granite in the canopy and local muscovitization of the zinnwaldite in veins. Local scheelitization of wolframite and the replacement of columbite by pyrochlore can also be assigned to this stage.

h) Crystallization of the sulfide assemblage with native Bi required a temperature of less than 270 °C.

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The Late Paleozoic volcanic centres in Central Europe – What do we know and what we need to know!

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Numerous voluminous and differentiated volcanic centres formed in central Europe during the Late Carboniferous to Lower Permian (c. 325 to 290 Ma): the Athesian Volcanic Group (N Italy), various centres in the Saar-Nahe Basin, in the NE German Basin and in W Poland; the Halle Volcanic Complex, large centres in the Intra-Sudetic Basin, the North Saxony Volcanic Complex and the complexes in the eastern Erzgebirge (Benek et al. 1996, Awdankiewicz 1999, Lorenz and Haneke 2004, Breitkreuz et al. 2007, Geißler et al. 2008, Hoffmann et al. 2013, Willcock et al. 2013, Schmiedel et al. 2015, and references therein). Many of these late- to post-Variscan complexes are dominated by crystal clast-rich ignimbrite sheets (35 to 58 vol%, Repstock et al. under review). This suggests presence of large, relatively cool magma chambers characterized by the dominance of a crystal mush. Explosive eruption was presumably triggered by reheating due to magmatic underplating/injection by mafic melts (Bachmann and Bergantz 2008, Huber et al. 2012).

The Rochlitz and Wurzen Volcanic Systems in the North Saxony Volcanic Complex (NSVC) qualify as supereruptions (≥ M8, Mason et al. 2004). Caldera margin features and the presence of central, NW-SE-trending subvolcanic bodies suggest pyroclastic fountaining from large fissures as the principal eruption mechanism (a similar process has been documented for volcanic centres in the western Snake River Plain, Branney et al. 2008). This, and geo-barometric calculations suggest relatively deep seated magma chambers (21 to 28 km depth, Heuer et al. this volume, Repstock et al. this volume) for the NSVC systems. In contrast, the eastern Erzgebirge volcanic centres (Tharandt Wald Caldera, TWC; Altenberg-Teplice Volcanic Complex, ATVC) are associated with high-level plutons. Only the ATVC forms part of the diverse and rich mineralization belt that characterizes the Erzgebirge / Krušné hory.

The formation of large ash-clouds originating from moving pyroclastic flows causes systematic compositional change in the flow deposits, particularly in the case of crystal clast-rich systems. Nevertheless, studies in the last two decades on (sub-)recent caldera systems proved the usability of data obtained from co-caldera ignimbrite sheets to reconstruct the magmagenetic evolution of large intra-continental systems. Large ignimbrite sheets also resemble excellent tools for regional terrestrial lithostratigraphy. Adapted to Central Europe, apart from whole geochemistry and geochronology, we should focus on mineral chemistry and isotopes of plag, qtz, pyx, amph, bt, and in particular of zircon (Słodczyk et al. 2016). Doing so, we need to treat volcanic-subvolcanic-plutonic complexes as co-genetic entities. Recognition of type and geometry of calderas, together with geo-barometry allows for estimates of magma chamber depth. We should constrain volumes, timing and pace of each magmatic centre. We have to understand why Central Europe harboured so many high-volume, differentiated magmas in the aftermath of the Variscan orogeny!

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The initial phase of the Late Carboniferous Altenberg-Teplice Volcanic Complex: Volcanosedimentary evolution of the Schönfeld–Altenberg Depression Complex

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The Altenberg–Teplice Volcanic Complex (ATVC) exposed on both sides of the German–Czech border in the Erzgebirge / Krušné hory is among the earliest late- to post-Variscan volcanic centres in Europe. The ATVC comprises an early volcanosedimentary succession preserved in the Schönfeld–Altenberg Depression Complex (SADC), partly covered by voluminous ignimbrites and lavas of the Teplice Rhyolite (TR). Published radiometric age dating of ATVC rocks and associated mineralisations suggest a Lower Namurian (Serpukhovian) age for the SADC. For the first time, pre-existing and new data sets of the SADC have been synthesized from outcrops and wells located in Germany and Czech Republic, including lithostratigraphic, volcanological, petrographical, petrophysical, geochemical, isotopic and geochronological results.

The SADC (present in an area 10 by 15 km) is subdivided into the Schönfeld-Pre-Eruptive Sediments (SPES), and the volcanosedimentary successions of the Lower Schönfeld Complex (LSC) and the Upper Schönfeld Complex (USC; Fig. 1). The SPES (maximum thickness of 60 m) is deposited on metamorphic basement and consists of sandstones and conglomerates containing different types of metamorphic clasts; it also contains carbonaceous layers. The LSC starts with widespread, fine-grained ignimbrites of rhyolitic composition (maximum thickness of 153 m near Hermsdorf). The explosive phase of the LSC is followed by the formation of (trachy-)dacitic lava(s) and subvolcanic bodies. The USC starts with coarse-grained talus deposits, dominated by metamorphic clasts, indicating a major tectonic activity. Lavas and pyroclastic rocks comprises the USC in the southern part, whereas in the Schönfeld area (northern part), lava dome explosion-related pyroclastic and sedimentary deposits, alternating with carbonaceous layers, prevail.

The SADC volcanic rocks are classified as dacites, trachydacites and rhyolites, having unusually elevated concentrations of Ti and compatible elements like Cr and V. Compared to the LSC, the USC volcanics show a less alkaline affinity. Charcoal fragments and fine charcoal dust is present in all SADC units as layers, or in the matrix of volcanosedimentary deposits. Allochtonous anthracite seams in the USC that were subject to historic mining in the Schönfeld area consist of a bedded alternation of carbonaceous deposits and clays to siltstones. Presumably, formation of charcoal was related to explosive eruptions and/or wild fires, and to redeposition by alluvial processes.

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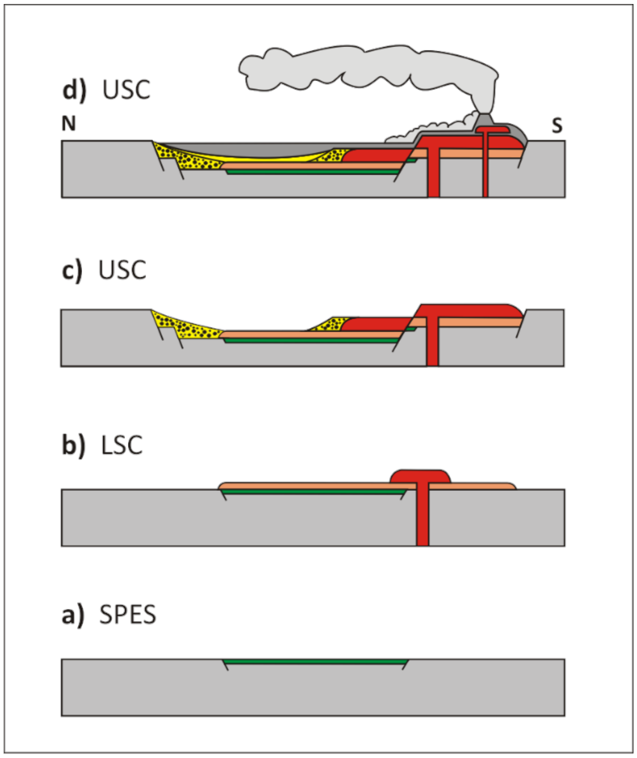

Fig. 1: Evolution of the SADC depicted in schematic N-S-oriented sections: a) Schönfeld-Pre-Eruptive Sediments, SPES; b) eruption of LSC (Lower Schönfeld Complex) ignimbrites and lava complexes; c) tectonic activity and sedimentation of talus at the onset of the USC (Upper Schönfeld Complex); d) USC eruptions producing ignimbrites, lavas, lava-derived mass-flows and fall-out (from Walther et al. in press)

Reprocessing of deep seismic reflection profiles from the Erzgebirge / Krušné hory area

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Deep seismic reflection profiles constitute a major component for the construction of reliable geological models of the Earth's crust and upper mantle. The large penetration depths and comparably high resolution of seismic waves allow to image geological structures in great detail and for that reason provide a profound basis for a reliable geological interpretation of geodynamic processes.

Recent developments in seismic imaging methodology offer a great potential to improve previous seismic processing results both in terms of increased resolution as well as with regard to image steeply dipping structures. So called focusing imaging techniques, e.g. Fresnel-Volume-Migration (Buske et al., 2009), are one example for such developments. Within this approach the seismic wave energy is back-propagated into the subsurface along it actual travel path and focused to its origin point on the reflector, thereby increasing the seismic image quality significantly.

We have applied this Fresnel-Volume-Migration technique to several deep seismic reflection profiles from the Erzgebirge area which were acquired more than two decades ago: MVE90 (Schimschal, 2003), GRANU9501+2 (Klemt, 2003), FB01+EV05 (Bubner, 2013), 9HR (Mullick, 2015). This talk presents the principles of the new imaging approach as well as the results of the reprocessing together with a comparison to the previous findings and the corresponding improvements.

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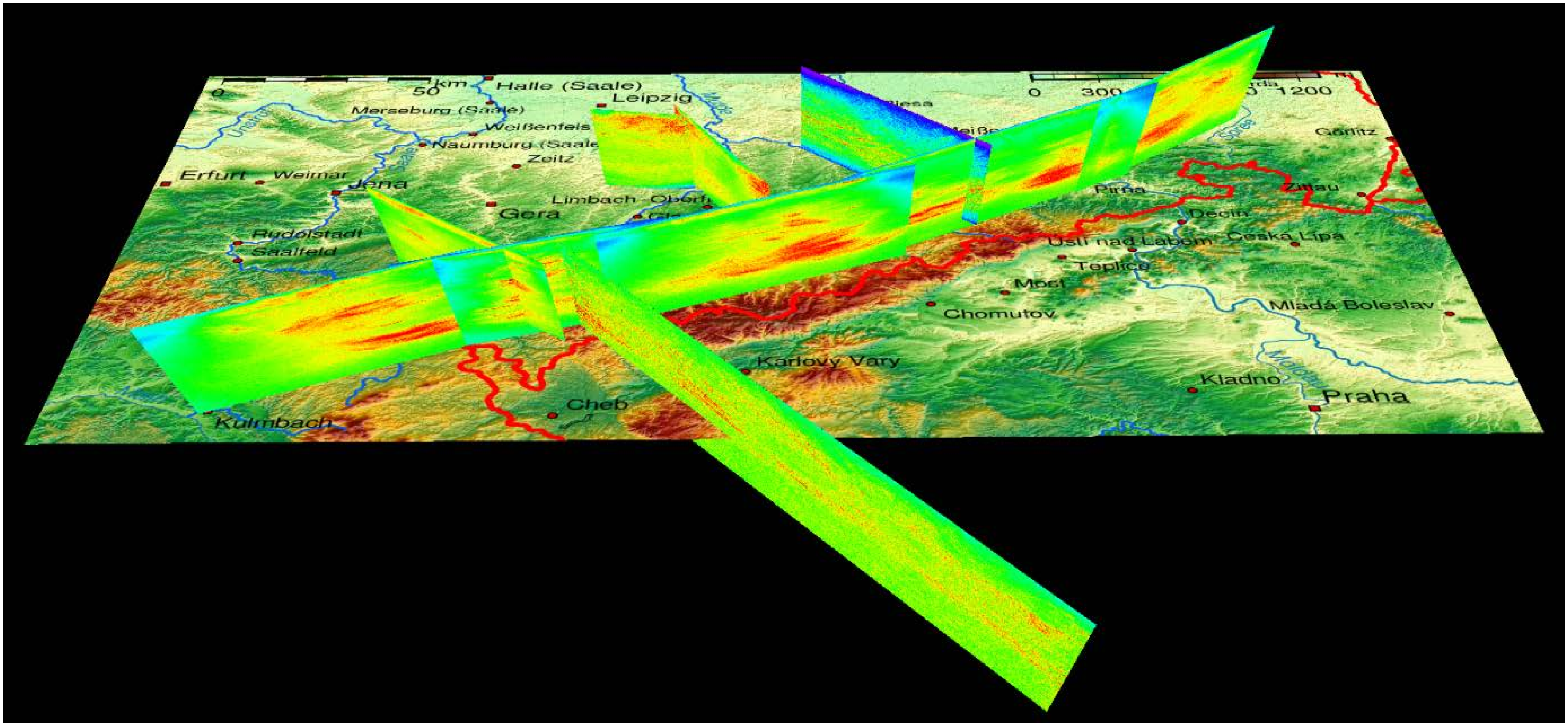
Figure 1: 3D view of reprocessed deep seismic reflection profiles (next page)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Correlating the lithofacies schemes of the Late Paleozoic Teplice Rhyolite, Central-European Variscides (German-Czech border)

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The Altenberg-Teplice Caldera recorded the most prominent volcanic phase of the entire Erzgebirge/Krušné hory (Germany/Czech Republic) during the late- to post-tectonic regime of the Variscan orogeny (ca. 320 Ma). The peak eruption of the caldera is represented by the Teplice Rhyolite (TR), which acted as the trigger to the subsidence of the complex. Available mineral and whole-rock chemical analyses of the TR come from the Mikulov-4 (Mi-4) borehole in Czech Republic. Here, a *vertical reverse chemical zoning* (Zr, Rb) has been observed and explained as a result of a constantly emptying of the magma chamber (Breiter et al., 2001).

Two current, and rather different, classifications based on lithofacies are known from the TR: (1) *A German scheme* set by Lobin (1986), recognizing eight litho-types (Fig. 1) distributed from north to south and (2) *a Czech division* (Jiránek et al., 1987, Fig. 1) that encompasses seven petro-types, extending from west to east. On the German portion of the TR, phenocryst-poor to phenocryst-rich rhyolitic lava have been described, as well as rhyolitic ignimbrites and tuffs. In contrast, the dominance of rhyolitic ignimbrites over rhyolites is notorious in Czech Republic. These two schemes do not match across the German-Czech border nor elsewhere and their correlation has never been carried out. Facies analysis is a valuable tool for the identification and interpretation of depositional conditions of volcanic units (McPhie and Allen, 1992), yet not sufficient to reveal details of their magmatic evolution. Moreover, volcanic facies analysis itself poses difficulties arising from correctly distinction between coherent rhyolitic lava and rhyolitic ignimbrites (Allen et al., 2008). Conversely, geochemical (mineral and whole-rock) information provides robust constraints on the origin and evolution of rocks but cannot discern their depositional processes. Thus, these two methods complement each other and render a much better interpretation for the origin, evolution, and emplacement mechanisms of volcanic rocks.

The ongoing investigation is focused on *establishing a volcanic facies model* for the whole TR, based on previous studies, available outcrops and drill cores. Our approach includes lithofacies analysis and new mineral (mafic minerals and feldspars) and whole-rock chemical data of each rock type from the aforementioned classifications in order to correlate particular eruptive phases.

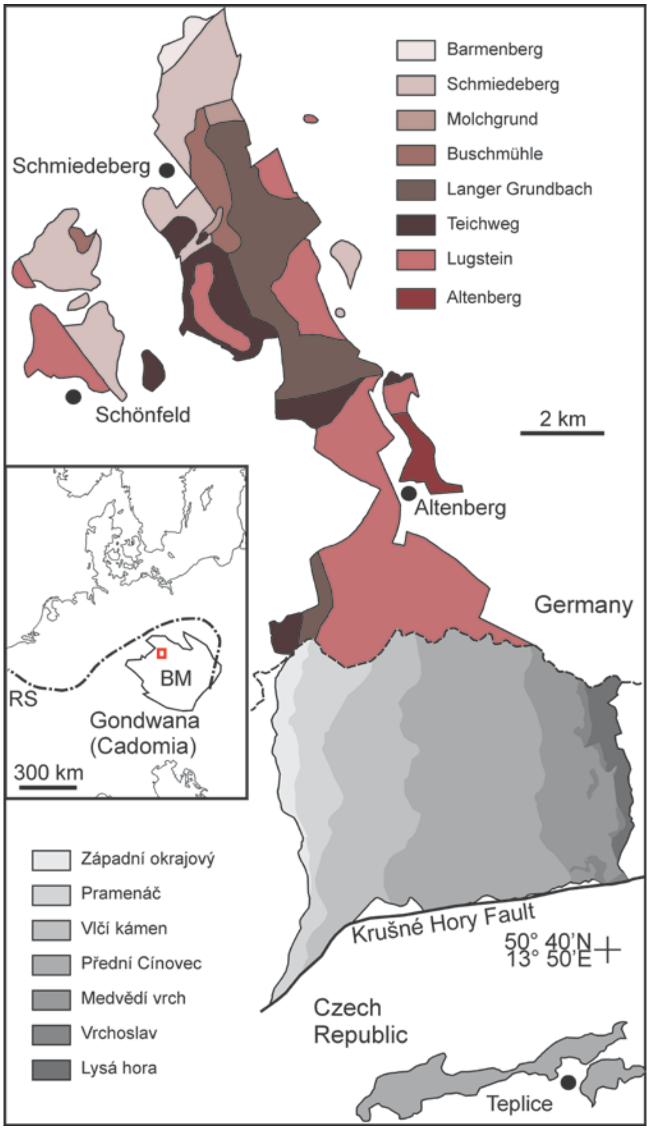

Figure 1: Sketch map of the Teplice Rhyolite from the Altenberg-Teplice Caldera showing the current contrasting lithological divisions of TR on both sides of the Czech-German border. Map based on Lobin (1986, colors) and Jiránek et al. (1987, grey scale). Inset presents the regional location of the caldera system on the NW margin of the Bohemian Massif (BM), south of the Rheic Suture (RS) in the Saxothuringian Zone.

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The exhumation channel of the Erzgebirge: From heat advection to the emplacement of Sn-W enriched granites

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The rapid exhumation of (ultra) high-pressure / (ultra) high temperature units accompanied by the syn- and postkinematic intrusion of vast volumes of granites is a striking features of the Allochthonous Domain of the Saxo-Thuringian Zone in Central Europe (Kroner et al., 2007). For example, the formation of Sn-W enriched melts in the Erzgebirge resulted from the emplacement of deeply subducted continental crust into tectonically accumulated metasedimentary rocks (Romer and Kroner, 2015). Voluminous melting and subsequent intrusion occurred in lower and upper parts of the nappe pile, respectively. Testing this hypothesis, we investigate the architecture and the tectonics of the Sn-W enriched granites and their country rocks and present first results.

A crustal scale 3D model (http://efc.giga-infosystems.com/) reveals the spatial link of the Sn-W deposits of the Erzgebirge and the E-W strike of the particular granites. The fractures of these granites displays an overall existent (N)NW/(S)SE - (W)SW-(E)NE conjugated joint system.

High and medium-pressure units, i.e. the country rocks of the granites, contain a complex structural pattern. In the medium-pressure units a NE-SW oriented stretching lineation is obliterated by a lineation with WNW-ESE azimuth. Close to the high-pressure units the WNW-ESE lineation represents the pervasive fabric of the medium-pressure mylonites. Inside the high-pressure units a WSW-ESE oriented stretching lineation is observed. WSW directed shear is indicated by the occurrence of sigma-clasts and shear bands. Constrictional fabrics as well as the occurrence of a NNW-SSE oriented lineation are indicative for coeval NNW-SSE shortening.

We postulate a two-step model for the tectonic accumulation of the sediments and the emplacement of high-pressure rocks and granites. First, NE-SW directed plate convergence (D1) resulted in nappe stacking during continent-continent collision. The final emplacement of the deeply buried continental crust occurred in a transpressional regime with NNW-SSE horizontal compression (D2) typically for the Late Variscan tectonics in this part of the orogen (Stephan et al., 2016). West directed lateral escape of the isothermally exhumed high-pressure units resulted in the formation of an exhumation channel. Advective heat transfer from this channel is seen as the underlying cause for high-temperature melting of metasedimentary rocks and the subsequent formation of E-W oriented Sn-W enriched laccoliths. The fracture pattern inside the granites corroborates the view that the granites intruded and cooled during prevailing NNW-SSE compression.

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The Late Paleozoic crystal-poor vitrophyric Planitz-ignimbrite of the Chemnitz Basin, eastern Germany: Indications for crustal contamination and magma mixing

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The Asselian crystal-poor Planitz ignimbrite situates in the Chemnitz basin located north of the Erzgebirge. As an integral part of the 25 to 50 m in thickness of the Upper Planitz formation (Schneider *et al.*, 2012), the Planitz ignimbrite is assumed to be the outflow facies of the Rochlitz ignimbrite (Fischer, 1991) which formed by a supervolcano eruption in the North Saxony Volcanic Complex (NSVC). A special characteristic of this pyroclastic flow sheet is well-preserved volcanic glass in the groundmass in the region of Zwickau-Planitz. According to this phenomenon, the local name “Planitz vitrophyre” was given.

The whole rock composition is clearly identified as dacitic to rhyolitic ignimbrite (Fig. 1) and reflects calk-alkaline affinity. In comparison to its suspected equivalents in the NSVC, the Planitz ignimbrite is depleted in alkali metals. The calk-alkaline geochemical affinity in the extensional Chemnitz basin could be explained by crustal contamination (Zegers & van Keken, 2001).

There is an opportunity to trace the crustal contamination from basic to evolved magma by the chemical composition of ferromagnesian minerals. In this context, Leterrier *et al.* (1982) and Abdal-Rahman (1994) illustrated the affinity of either calcic clinopyroxene or biotite-group minerals for volcanic rocks. Following to fractional crystallization, clinopyroxene - especially in the glomerophyric accumulates - represents early magmatic stages, whereas biotite-group minerals are formed in later stages. The chemical composition of these ferromagnesian minerals from the Planitz ignimbrite suggests an evolution from tholeiitic basalt to calk-alkaline dacite and rhyolite during magma evolving and mixing processes (Fig. 2).

Calculation of pyroxene and feldspar geothermo- barometry enabled the reconstruction of the depth of the magma chamber. With the assumption of a geothermal gradient of western USA during the Cenozoic, the depth is estimated between 21 and 28 km.

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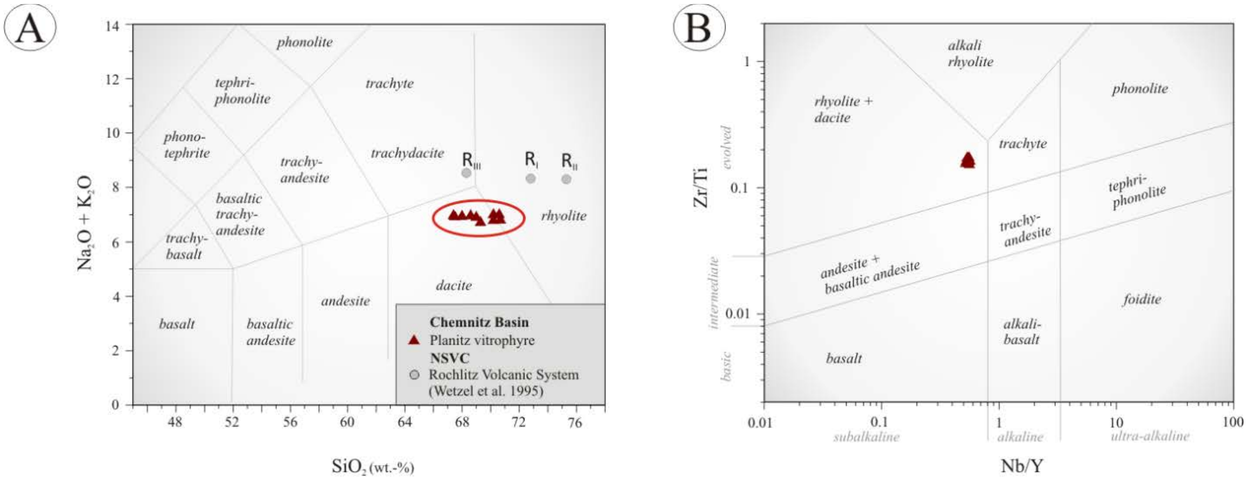

Figure 1A: whole rock composition of the vitrophyric Planitz ignimbrite of the Chemnitz Basin in comparison to the Rochlitz ignimbrite in the North Saxon Volcanic Complex (NSVC); B: diagram of Pearce (1996) confirms the subalkaline dacitic to rhyolitic trend of the vitrophyric Planitz ignimbrite

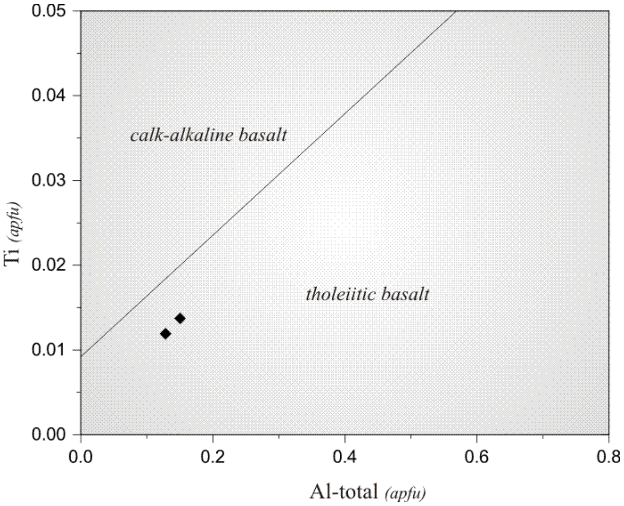

Figure 2: Discrimination diagram for calcic clinopyroxene (Leterrier et al., 1982) shows tholeiitic affinity for the augite in the glomerophyric accumulates of the vitrophyric Planitz ignimbrite.

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The Lower Permian Rochlitz Supervolcano, Northern Saxony Volcanic Complex, Germany: Characterization of large crystal-rich ignimbrites

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The Rochlitz caldera is situated in the North Saxony Volcanic Complex (NSVC). It comprises large volume crystal-rich ignimbrites and related subvolcanic bodies. The presumed caldera covers an area of 3109.9 km² with a maximum diameter of approximately 95 km making the Rochlitz Volcanic System (RVS) the largest Permocarboniferous caldera in Central Europe. The Planitz ignimbrites in the southerly adjacent Chemnitz basin may present caldera-outflow facies (Fischer 1991). The RVS (294.4 ± 1.8 Ma, Hoffmann et al. 2013) resembles the first caldera-forming eruption in the NSVC. A second caldera, the Wurzen Volcanic System, developed c. 289 Ma (Wendt et al. 1995, Hoffmann et al. 2013).

The volcanic activity was initiated by the deposition of the crystal-poor Lastau ignimbrite and pre-caldera tuffs ("Mittleres Tuffrotliegend") underlying the crystal-rich Rochlitz ignimbrite (Eigenfeld, 1978). The main caldera eruption led to the deposition of pyroclastic flow sheets with a minimum thickness of 400 m (Walter, 2006). Lithostratigraphically, the Rochlitz caldera-fill ignimbrites are subdivided into four units, R_I to R_{III}, with only little differences in the felsic crystal-clast content, and R_N with strong deviations in the crystal-clast content from the former and a distribution restricted to the margins of the caldera. The felsic crystal-clast population is heterogeneous throughout the entire RVS (k-feldspar, plagioclase, quartz). Regarding the mafic crystal-clasts only R_{III} reveals pyroxenes (Fig. 2), whereas biotite occurs throughout the RVS. The groundmass, varying from 60 to 64 vol.-%, underwent devitrification processes during cooling and diagenesis (Eigenfeld, 1978), however, locally, vitrophyric domains are preserved.

The chemical composition of the RVS caldera-fill pyroclastics suggests rhyolitic ignimbrites for R_I, R_{II} and R_N, and trachydacitic ignimbrites for R_{III}. Within the diagram of Pearce (1996) a subalkaline (rhyolite + dacite) to alkaline (trachyte) trend can be observed. Distinct negative Nb- and Ti-anomalies and a subalkaline affinity resemble a pattern typical for destructive continental margins. However, the RVS formed clearly in a post-Variscan setting. Bergantz et al. (2015) stated that these geochemical anomalies may results of magma mixing and crustal contamination.

Huber et al. (2012) compared several crystal-rich and -poor pyroclastic flow sheets of large caldera systems. The deposition of crystal-rich ignimbrites requires reheating of un-eruptible locked crystal mush to generate an eruptible melt. This process leads to the homogenization of the precursory zoned magma chamber forming a dacitic melt. However, the highest crystal-clast contents are observed in the R_N rhyolitic ignimbrite. The rhyolitic R_I is far more crystal-rich than, e.g., the Lava Creek Tuff and the Tshigere Member of the Bandelier Tuff (Fig. 1). Only R_{III} has a trachydacitic composition plotting near the "monotonous intermediates" (Huber et al. 2012).

Following the model of Mason et al. (2004) we estimate a magnitude of 8.4 for the Rochlitz caldera eruption rendering the RVS caldera as a supervolcano. For comparison: the Cerro Galan Caldera has 8.4, Ammonia Tanks Member (Timber Mountain) has 8.3, Kilgore Tuff (Snake River Plain) has 8.3 (Mason et al. 2004).

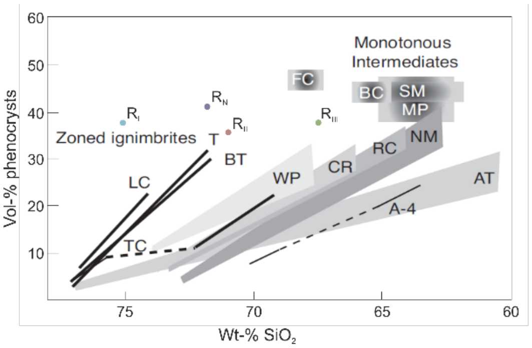

Fig. 1: Crystal clast and SiO_2 content for ignimbrites in western USA (LC- Lava Creek Tuff, FC – Fish Canyon Tuff, BC – Blue Creek Tuff, T – Tshigere Member of Bandelier Tuff) in comparison with Rochlitz ignimbrites (R_I to R_N) (modified after Huber et al. 2012).

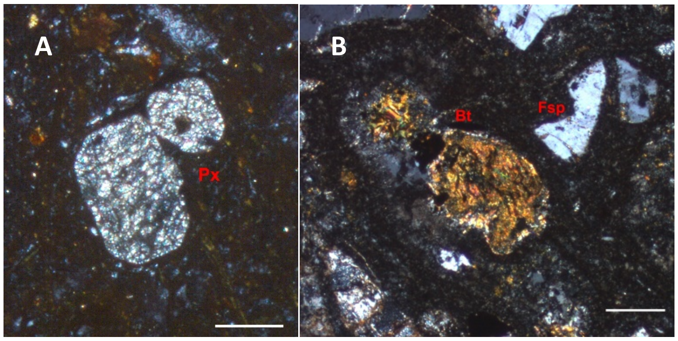

Fig. 2: Microphoto of (A) pyroxene pseudomorphosis in R_{III} and (B) biotite and feldspar in R_{II}. Scale = 200 µm.

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Cassiterite of the hydrothermal polymetallic “Felsitzone” mineralization of Großschirma (Saxony, Germany): New insights into mineralogy and geochemistry

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The Sn-polymetallic “Felsitzone” mineralization of Großschirma is situated in the N of the Freiberg mining district, Erzgebirge. The mineralization is hosted by metamorphic rocks of the Preßnitz Group, consisting predominantly of two-mica gneisses and mica schists and it is characterized by intercalations of amphibolites and muscovite gneisses. All metamorphic units are deformed by several NE-SW striking fault zones.

Applying whole-rock geochemistry, light microscopy, and SEM-MLA of selected drill core samples from Großschirma, we show that the “Felsitzone” mineralization is structurally controlled. Hydrothermal Sn-bearing fluids migrated within shear and breccia zones that developed primarily at the contact between gneisses and metamafic rocks. These zones are characterized by a strong pervasive metasomatic alteration with replacement of rock-forming minerals by ore and gangue minerals.

Bulk geochemistry of samples from shear and breccia zones indicates the metasomatic alteration with grades up to 0.28 wt. % Sn, 0.15 wt. % Cu, 300 ppm Pb, 140 ppm Zn, 1.1 wt. % F, 250 ppm Li, 820 ppm Rb, 90 ppm Cs, and 130 ppm W. Three different mineralization stages can be distinguished within these altered zones. Fine-grained Fe-rich chlorite and quartz as well as some cassiterite, fluorite, rutile, apatite and scheelite are associated with the first mineralization stage. Cassiterite appears in three habits: drop-shaped cassiterite (< 100 µm), isometric cassiterite (< 650 µm) and acicular cassiterite (< 100 µm). CL-analyses indicate that the different habits can be considered as different cassiterite generations. The drop-shaped cassiterites might be the oldest generation, whereas the acicular are the youngest one. Some larger cassiterite aggregates feature a spongelike intergrowth of drop-shaped and isometric crystals. The second stage is characterized by large amounts of pyrite, while marcasite, chalcopyrite, pyrrhotite, galena, sphalerite, arsenopyrite, and bismuthinite appear only subordinately. The third one is dominated by different carbonates and fine-grained Fe-oxides.

The LA-ICP-MS trace element composition of selected isometric cassiterite grains comprises 0.5 wt. % Fe, 0.1 wt. % Ti, 730 ppm W, 1 40 ppm V, 60 ppm In, 50 ppm Zr, 40 ppm Mn, 25 ppm Ga, 15 ppm Nb and 1 ppm Ta. Higher Fe in addition to very low Nb + Ta contents indicate a hydrothermal origin of these cassiterites. Enriched Fe, Ti and W concentrations infer that the “Felsitzone” cassiterites likely belong to a cassiterite-sulfide paragenesis.

An enrichment of Sn, F, Li, Rb, Cs and W suggests a genetic link between the Sn-polymetallic ‘Felsitzone’ mineralization and the late-Variscan Sn-W association which is common in the Erzgebirge. The origin of the ore-forming fluids still remains unexplained. They might be associated with several porphyritic microgranite dikes in the Großschirma-Halsbrücke area that are probably related to late-Variscan granite intrusions in the Erzgebirge.

Re-evaluation of the mineral resource potential of the German Ore Mountains (Erzgebirge) using artificial neural networks

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Saxony possesses a unique, but only limited used treasure: detailed regional geological, geochemical and geophysical data covering the former mining area of the Ore Mountains in Germany. This “old” data and the empirical knowledge accumulated over centuries were the basis for a completely new approach to data integration and re-evaluation of the mineral resource potential of the Erzgebirge executed in the last years.

In the first step, the different data sets were reviewed and pre-processed in order to use them later on for the to-be-executed predictive mapping task. Based on the available stream sediment sampling point data, rastered / gridded geochemical data sets were created covering the whole Erzgebirge area for the analysed elements of As, Ba, W, Mo, Co, Cr, Sn, Cu, Li, Mn, Ni, Pb, Ti, Be, B and Zn in 50 metres resolution. Besides this, detailed geophysical data sets have been created based on the existing point information data from the “old” airborne measurements for magnetics (delta T), gammaspectrometry (Th, K, U), and gravimetry (Bouguer anomaly).

Based on the available gravimetric data and by additional use of limited borehole data, isolines of the depth of the granite hanging wall were created. These isobaths were used to model the granite top surface and to calculate the depth to this surface measured from the earth surface. Furthermore, the detailed information from the existing geological map sheets at scale 1:50,000 was used to create applied geological maps with only selected geological rock units that control the known mineral deposit locations in this area. Finally, different tectonic structures were classified according to their type, size and especially strike direction. Vector data sets (rock units and tectonic structures) were transformed into either binary data sets (here: existence of a specific geological unit) or into continuous rastered data sets by calculating the Euclidian distance to the nearest object (in this case: closest tectonic structure of a certain type or specific geological unit).

This large amount of newly processed data sets was then used as model input data for setting up scenarios for different commodities and different types of deposits. For predictive mapping itself, artificial neural networks (ANN) has been employed. The core component of the ANN-technology is the advangeo® Prediction Software, which has been developed in the frame of a research project that was partly funded by the BMWi (German Federal Ministry for Economy and Technology). By simulating the empirical-analytic way of thinking of the human brain, the ANN “learned” by itself on the basis of examples (so-called training process). Reliably, it found the “footprints” of the known mineral deposits in the German Ore Mountains. This “knowledge” was then used to interpret the data across the whole Erzgebirge area.

In summary, by using ANN to interpret the data from Saxony, a significant contribution to the prediction of the local mineral resources of Germany was made. With the expected medium-term availability of new and/or more detailed data, further improvement and refinement of the validity of the method can be expected in the future, too, especially for exploration targeting in individual mining districts as well as in 3D-space.

The tectonic framework of the Erzgebirge /Krušné hory

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The Erzgebirge represents an essential part of the Allochthonous Domain of the Saxo-Thuringian Zone and belongs to the Internides of the Central European Variscides (Fig. 1). The Allochthonous Domain (sensu Kroner et al. 2007) constitutes a Variscan nappe pile that was finally affected by the emplacement of various (ultra)-high pressure units at different middle to upper crustal levels. Their common feature, i.e. (U)HP metamorphism of continental crust at ca. 340 Ma, is indicative for an intracontinental subduction zone setting at the final collisional stage at the Bohemian Massif (Kroner and Romer, 2013). Coeval with and subsequent to the exhumation process, voluminous syn- and postkinematic granites evolved (ca. 338-318 Ma). The intrusion of the synkinematic granites (ca. 338- 333 Ma) is spatially related to the initial extrusion of high pressure/ultrahigh-temperature complexes. The K-rich Meissen Massif includes material from the continental lithospheric mantle and intruded along the late Variscan crustal scale strike-slip fault of the Elbe Zone. The coeval isothermal emplacement of the adjacent HP/UHT Saxon Granulite Massif is accompanied by synkinematic anatectic melts in the roof detachment. Granitic dykes and stocks cutting the core of the granulite massif constitute mainly molten felsic granulites indicating a fluid source beneath the massif. The release of these fluids is probably related to prograde LP/HT metamorphism beneath the hot granulites due to the thrusting onto low grade metasediments.

The voluminous postkinematic granites of the Erzgebirge-Fichtelgebirge Zone constitute different laccoliths intruding the nappe pile. The country rocks contain already exhumed (U)HP units. Because there is tectonic as well as geophysical evidence of the existence of voluminous UHT/HP units beneath the Erzgebirge-Fichtelgebirge Zone, we propose the former existence of a hot, E-W striking extrusion channel beneath the exposed part of the Allochthonous Domain (see Hallas et al., this volume). Advective heat transfer caused high temperature melting of tectonically accumulated lithologies and the subsequent emplacement in higher levels. The geochemically different granites (ca. 330-320 Ma) reflect different sources. This can be exemplified by the formation of the Sn-W specialized granites of the W Erzgebirge (Romer and Kroner, 2015). These highly specialized granites evolved exclusively in the region that is characterized by a vast antiformal stack of Sn-W enriched metasediments. The geochemical fingerprint of the Ordovician protolith is inherited by the granite. This model predicts that extrusion tectonics from the intracontinental subduction zone lasted over a time span of at least 20 Myr. Variscan compressional tectonics terminated around 300 Ma and was subsequently followed by extensional tectonics and the formation of the Central European Extensional Province. Heat advection from the mantle caused the widespread post-orogenic magmatism in Central Europe including the Allochthonous Domain. Hence, the Saxo-Thuringian Zone contains continental crust highlighting the importance of mass and heat transfer from late orogenic subduction zones and from subsequent tectono-thermal events during the final equilibration of collisional orogens.

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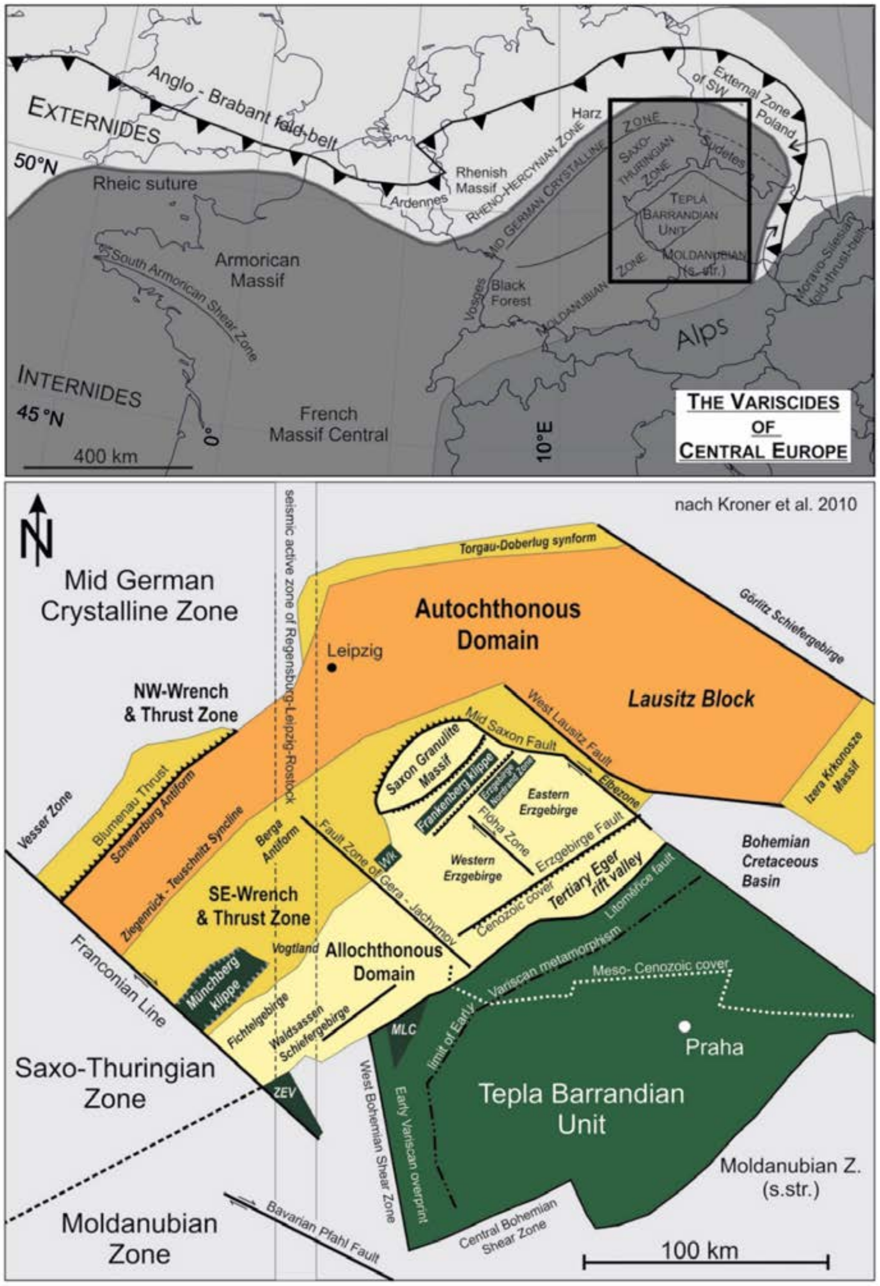

Fig. 1: The Saxo-Thuringian Zone as part of the Internides of the Central European Variscides. The intensively deformed Allochthonous Domain is juxtaposed with the Lausitz block and the Tepla Barrandian Unit that are comparatively little affected by the Variscan collision. The Erzgebirge is separated from the Lausitz and the TBU by the Elbe Zone and the Litomeřice Fault respectively (modified from Kroner et al. 2008).

Chemical and isotopic characterization of the Hämmerlein tin-skarn deposit, western Erzgebirge, Germany

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The Hämmerlein Sn-skarn deposit is associated with gneisses and schists which reached peak metamorphic conditions at 340 Ma. The deposit formed around 320-325 Ma, when the Eibenstock granite was emplaced, resulting on the migration of magmatic fluids along the contacts of different units. This induced decarbonation of the marble layers and the development of a series of contrasting skarns. The different units are garnet skarn, amphibole skarn, pyroxene skarn and magnetite skarn, with intercalated layers of schist and gneiss. Cassiterite is the main ore mineral. It occurs as coarse grains (up to 1mm) in the schists, as medium grains (~500 µm) at contacts between amphibole and magnetite skarn and as fine (<100 µm) and disseminated grains in the amphibole skarn. Relatively high content of In has been found in exsolutions of Cu-Fe-rich sphalerite in chalcopyrite patches within the magnetite skarn and in the Fe-rich sphalerite layer beneath or crosscutting the magnetite skarn.

Skarns bulk rock compositions are quite similar. Modeling the T-XCO_2 conditions of the skarn units from their bulk rock compositions shows that the skarns formed at different XCO_2 and temperature. Garnet skarn formed at high temperature and XCO_2, whereas amphibole, pyroxene and magnetite skarns formed at lower temperature and lower XCO_2. The T-XCO_2 conditions have changed with the distance from the source of the fluid and with time. By flowing at the contact between silicate and carbonate rocks, the fluid induced decarbonation and the formation of the different skarn units starting with garnet skarn at high temperature high XCO_2. With time the locus of fluid flow at the contact with the carbonate rocks migrated with the newly formed skarn until all the carbonates were consumed, resulting in a sequence of mineralogically contrasting skarns.

Fluids responsible of the skarn-forming reactions enriched the rocks in Sn, W, In, Sb, Cd and F. The enhanced contents of Bi, As and U in the skarns are likely to be related to later events such as the important 180 Ma old U mineralization in the region and the multiple later redistribution of U and addition of Bi and As. Major and trace elements as well as the REE seem to have been largely immobile and to be inherited from the protoliths, as indicated by their pattern. All skarns are characterized by similar flat UCC-normalized REE pattern with a positive Eu anomaly, whereas, the gneisses and schists do not have any Eu anomaly. The REE pattern of cassiterite-bearing schists is the same as the one of the unmineralized schists. The εNd values of schists and skarns overlap and correspond to those of unmetamorphosed sedimentary rocks and are clearly lower than those of the granite. The distribution of Sn and In within the different units is heterogeneous, indicating that mineralization is not controlled only by fluid flow alone, but also by precipitation at reaction fronts with selective mineralogically controlled scavenging of ore elements and the reaction history of the fluid, in particular whether the fluid had lost its metal content during earlier fluid-induced reactions.

Trace-element chemistry of quartz during magmatic-hydrothermal transition in the evolved granitic system of the eastern Krušné hory/Erzgebirge

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Magmatic and hydrothermal processes play a major role in element transport, decoupling and deposition as well as formation of economic ore accumulations. The greisen deposits associated with cupolas of Sn-W-Mo-bearing Li-F-rich peraluminous granites in the eastern Krušné hory/Erzgebirge provide a unique opportunity to study the magmatic-hydrothermal transition in evolved mineralized granitic systems. The Knötl granite cupola in Krupka/Graupen exhibits complex structure with prominent vertical zoning and diverse textural features including unidirectional solidification textures, stockscheider pegmatite, quartzolite apical part as well as hydrothermal stockwork accompanied by greisenisation.

We use cathode luminescence and laser ablation ICP-MS analysis of quartz to assess its trace-element composition and differentiate between the processes of magmatic fractionation, disequilibrium separation and hydrothermal replacement and precipitation. Quartz from granites, pegmatites, quartzolites, greisens and hydrothermal quartz veins hosts variable concentrations of B, Be, Li, Al, Ti, Ge, Na, K, Fe, P, Mn and Rb. Most of these elements are enriched in the highly evolved granites, but their concentration decreases in gneisses and hydrothermal quartz veins. Quartz from pegmatites shows enrichments in Ti, K, Na, Li, Mg, Fe, Mn, Rb, Cs, and Be when compared to parental granites.

The rocks of the magmatic-hydrothermal transition, represented by quartzolites, record the highest concentration of Ti in quartz whereas concentrations of other elements approach those observed in the granites. Quartz from granite-derived greisens hosts very low Ti concentrations but has elevated abundances of K, Na, Li, Mg, Fe, Mn, Rb, Cs, Sn, W and Ta in quartz. By contrast, quartz from gneiss-derived greisens exhibits bimodal distribution of Ti, elevated contents of Ge and Mg. During recrystallization and secondary growth, quartz is frequently depleted in Al, Ti and K. Overall, the magmatic evolution of the Krupka/Graupen system is characterized by increasing concentrations in quartz of most trace elements, as they are generally incompatible, accompanied by a concomitant decrease in Ti.

The Early Permian Wurzen Caldera System of northern Saxony, Germany: Mineral chemistry and texture disclose insights into an intra-continental magma reservoir

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The c. 290 Ma Wurzen Volcanic System (WVS) is recognized as a telescoped caldera within the older Rochlitz caldera and which covers an area of 2111 km² east of Leipzig. The WVS comprises small pre-caldera ignimbrites, large voluminous caldera-fill ignimbrites, subvolcanic porphyries from syenitic to granitic composition, and crosscutting mafic and felsic dykes. Some WVS rocks have been only slightly affected by alteration allowing for mineralogical and petrological studies. The WVS provides windows to disclose the secrets of a magnitude 8.4 super volcano eruption, placing it among the largest Permocarboniferous caldera systems of Central Europe. Important questions are raised here:

(1) *Which eruption type was active to produce crystal-rich ignimbrites (<58 vol.-%)?*

(2) *What are the depths of the processes in the magma reservoir?*

(3) *What is the trigger for the magmatic activity and the indicator of the basin development?*

The answers can be found in the textures and chemical composition of the crystal clasts/phenocrysts in the WVS rocks (see *e.g.* Best & Christiansen, 1997; Bachmann *et al.*, 2002). Resorption textures are a frequent feature in plagioclase of the WVS caldera-fill ignimbrite (Fig. 1A). These features indicate corrosion or change of melt conditions. This can be stimulated by thermal reactivation that occur when the cooled silicic magma chamber induced by basaltic underplating (Huber *et al.*, 2012). Basaltic melt obviously played a role in the North Saxonian magmatic system confirmed by high An-contents (0.705 Ca*pfu*) in some plagioclase.

The occurrence of the whole pyroxene solid-solution series from subcalcic (enstatite-ferrosilite, pigeonite) to calcic pyroxene (augite-diopside) is another peculiarity. Regardless of the Ca-content, pyroxene from the WVS caldera-fill ignimbrites appears as single grains (Fig. 1A), as pyroxene aggregates and in glomerophyric crystal accumulations (Fig. 1C). Within the coarser parts of the Trebsen mafic dyke, the augitic to diopsidic pyroxene constitutes an intracumulus crystal (Fig. 1D).

The broad range of ferromagnesian minerals (forsterite, Ca-poor and Ca-rich pyroxene) allows the application of some thermo- and barometers. Tests for equilibrium conditions were successful for WVS volcanic rocks (Fig. 1C, D). It was presumed that the geothermal gradient of the Permocarboniferous North Saxonian Basin was similar to the one during the Cenozoic in western USA. Therefore we calculated crystallization depths of 27 km and 23 km for the basaltic melt and for the silica-rich batholith, respectively.

Two types of clinopyroxene can be distinguished: an alkaline diopside to augite for the mafic dyke near Trebsen and a tholeiitic clinopyroxene for the caldera-fill ignimbrites (Fig. 2A and B; Leterrier *et al.* 1982). Only the rims of the tholeiitic clinopyroxene plot in the calc-alkaline field indicative of an ongrowth during magma mixing processes. Presence of tholeiitic and alkaline magmas plead for a rifting system as it has been assumed for the neighboring Chemnitz Basin (“Westsaxonian Rift”, Fischer 1991).

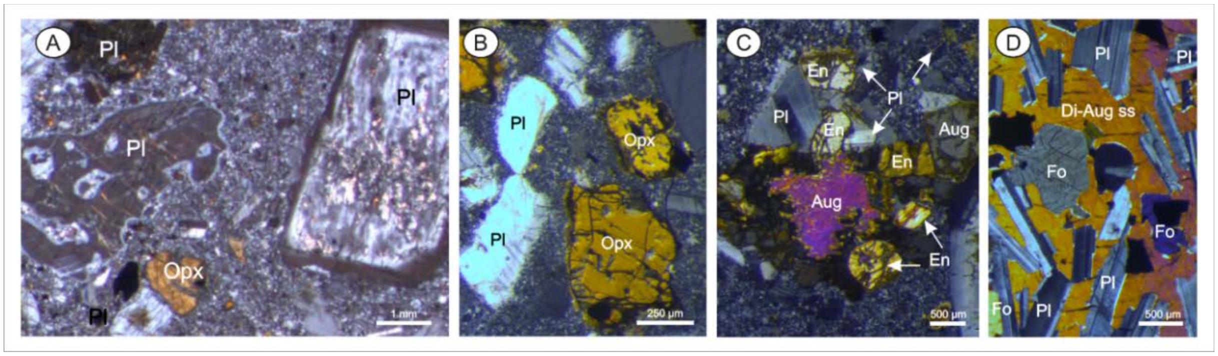

Figure 3: Thin section photographs of the ignimbrite (A-C) and the mafic dyke show different occurrences of plagioclase (Pl), pyroxene (Opx = orthopyroxene, En = enstatite, Aug = augite, Di = diopside) and forsterite (Fo). Localities: A = Spitzer Berg; B-D = Kolmberg.

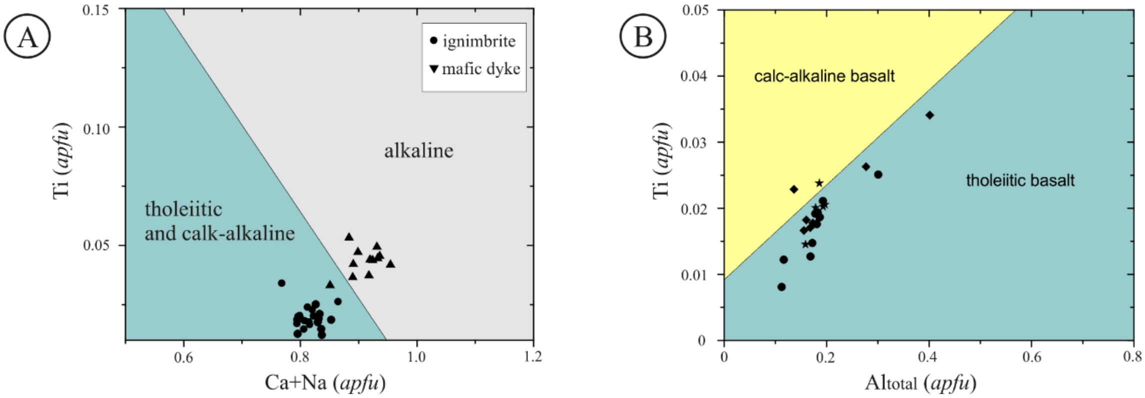

Figure 2: Discrimination of calcic clinopyroxene (modified after Leterrier et al., 1982) from the Zinkenberg and Spitzer Berg quarries and the Trebsen mafic dyke at the Kolmberg quarry.

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Tin, tungsten, and tantalum mineralization – more than just the result of magmatic fractionation

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Primary Sn, W, and/or Ta mineralization is closely related to highly evolved granitic rocks. Not all highly evolved granitic rocks show associated mineralization, which implies that magmatic processes (e.g., fractionation, phase separation) certainly are necessary, but not sufficient. Instead, the potential of highly evolved granites to form Sn, W, and/or Ta mineralization may be primarily related to their source rocks and the melting of these source rocks.

The formation of Sn, W, and/or Ta mineralization involves a sequence of processes that operate in different tectonic settings and that may be widely separated in time, i.e., (i) source enrichment, (ii) source accumulation, and (iii) metal mobilization from the source. The sequence of these processes controls the distribution of mineralization in belts (and gaps within these belts). Magmatic processes and interaction of the melts and fluids with the wall rocks at emplacement level, however, control size, grade, shape, and kind (vein, greisen, skarn) of mineralization.

(i) Intense chemical alteration of silicate rocks at the surface results in the preferential loss of most feldspar-bound elements (e.g., Na, Ca, Sr, and Pb) and in the residual enrichment of elements incorporated in or adsorbed on clay minerals (e.g., Li, K, Rb, Cs, Sn, and W). Thus, exogenic processes produce some of the hallmark geochemical signatures of tin granites that are also obtained by extreme magmatic fractionation of granitic melts. Intense chemical alteration occurs in tectonically stable areas with limited topography, as for instance in the interior of large continental masses.

(ii) Source accumulation involves two separate processes, i.e., sedimentary and tectonic accumulation. Sedimentary accumulation occurs when these blankets of chemically intensely altered sediments are redistributed from the “top” of the continent to the margins of the continent during supercontinent fragmentation. Tectonic accumulation may occur when passive-margin sedimentary packages are reworked in an active margin setting. Source accumulation may be particularly important when delta deposits become tectonically stacked.

(iii) The nature of heat source controls the type of melting of the crustal source rocks and the partitioning of metals between melt and restite. Sn and W are preferably bound to biotite and are distributed into the melt during biotite consumption at high melting temperature. Ta is enriched in muscovite that melts at lower temperature. High melting temperatures are only possible by heat input from the mantle by (a) mantle-derived melts in subduction settings, (b) emplacement of ultrahigh-temperature metamorphic rocks that had been subducted to mantle depth during continental collision, and (c) mantle-derived melts in extensional settings. Internal heating in orogenically thickened crust only generates minimum-temperature melts. The age of mineralization reflects the event of heat input.

The superposition of source enrichment (on supercontinent), source accumulation (at continent margin), and heat input (at plate boundary) explains both (i) the distribution of Phanerozoic primary tin, tungsten, and tantalum mineralization and (ii) their irregular distribution along these belts, (iii) their contrasting age within a particular belt, (iv) their relation to contrasting tectonic settings within a single belt, and (v) their presence on both sides of major sutures.

New 3D model of the Cinovec deposit

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Cinovec is one of the largest granite-hosted hard rock lithium deposits in the world, with an inferred resource of 532 Mt grading 0.43 % Li_2O at 0.1 % Li cut-off, with significant tin and tungsten credits. Initial mining of alluvial cassiterite started at Cinovec in the 14th century. More recent hard rock mining was focusing on flat-lying quartz veins with Sn-W mineralization in apical part of the Cinovec granite cupola. Extensive exploration in the 1970 to 1980 identified large scale greisen bodies with Li-Sn-W disseminated mineralization south of the mined out vein system. All activities at the Cinovec deposit ceased in 1990 due to political and economic changes.

Since 2014, a Czech exploration company Geomet has been carrying a drilling programme at the Cinovec deposit, with the aim to define a Li-Sn-W resource and prepare the deposit for underground mining. So far, 18 confirmation and infill drillholes totalling 6,618 m have been completed, and 4 drillholes are underway (~1,200 m).

Based on the historical drilling and underground development work and Geomet's surface drill holes, a large database incl. simplified lithology and Sn, W and Li assays was created. After that a geological model was constructed in 3D modeling software Leapfrog Geo (Aranz Geo Ltd.). The geological model comprises Cinovec granite intrusion with greisen and greisenized granite zones and rhyolite country rock. Respecting the greisen bodies and structural trends from the geological model, a robust block model and JORC-compliant mineral resource estimate was produced by an independent consultant, Mr. Lynn Widenbar of Widenbar and Associates.

The geologic model provides not only a guideline for definition and exploration drilling in places with paucity of historic analytical data, but also geologically constraints the block model. Geomet’s current drilling is proving the model’s robustness and high degree of accuracy.

Altenberg-Teplice Caldera revealed by the airborne and ground gamma-ray spectrometry

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New airborne maps embracing the area of the Altenberg-Teplice Caldera (~ 900 km^2) limited by the points of Litvínov (SW) – Mulda (NW) – Mühlbach near Dohna (NE) – Chabařovice (SE) was constructed in the frame of the project „Groundwater balance in the selected area of the Czech Republic“ led by the Czech Geological Survey through the years 2010-2015. The airborne systematic measurements were supported by ground gamma-ray spectrometry analyses of representative lithology.

The different contents of the natural radioactive elements (potassium, thorium and uranium) enabled to obtain surface view about spreading of individual rock types in the Altenberg-Teplice Volcanic Complex (ATVC). Especially for the Teplice Rhyolite is it possible to correlate our data with the previously published differentiated petrographic types. The seven individual types of the rhyolite ignimbrites in the Czech part (Eisenreich and Jeřábek 1978) and similarly, eight petrographic types on the German side (Lobin 1986) were defined.

In the Czech part of the ATVC the seven types of the rhyolite ignimbrites are characterized also by distinct concentrations of naturally radioactive elements as proved by ground gamma-ray measurement. Merging of the airborne gamma-ray spectrometry data from Germany and Czech Republic enabled cross-border correlation of the radioactive properties of the ATVC. The next step of the research is coupling of both national subdivisions.

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Tectonic framework of Sn-W enriched magmatism: Examples from NW Iberia and SW England

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The Erzgebirge, SW England and NW Iberia are famous examples for Sn-W enriched granites that intruded into a thick pile of tectonically accumulated sediments (Romer and Kroner, 2015). For example, in the Erzgebirge the emplacement of such granites is associated with the exhumation of hot (ultra)high-pressure rocks. In contrast, the Cornubian Batholite of SW England has been formed in a post-Variscan extensional setting, whereas Late-Paleozoic Galician granites are related to both, syn- and post-collisional processes. For a better understanding of the relation between tectonics, magma generation and emplacement, we compare the structural grain of the particular regions. Here we present preliminary results from field studies in NW Iberia and SW Cornwall comprising 2648 structural measurements, 44 samples and 76 thin sections.

The allochthon of NW Iberia comprises a high-pressure nappe complex (Cambro-Ordovician Gondwana shelf sediments, Early Devonian ophiolitic units and distal pre-Devonian Gondwana shelf sequences) that overthrusted the passive continental margin of Gondwana. During the late-Variscan collisional stage (330-295 Ma), mantle derived-melts and/or emplacement of UHT rocks, as well as mantle derived melts during post-Variscan extension (295-275 Ma) led to two generations of Sn-W deposits.

Structural investigations in NW Iberia reveal three periods of deformation (D1-3). Early strain increments (D1) indicate shear directions towards N or NE. Ductile fabrics and recrystallisation structures within the allochthonous complexes indicate minimum deformation temperatures between 500-700° C during D1. A retrograde trend towards more brittle structures (300-400 °C) is associated with D2. Correlating deformation conditions with cooling ages, D1 and D2 are associated with HP metamorphism and subsequent exhumation, respectively (390–360 Ma). Low-grade par-autochthonous rocks are missing any structural overprint during D1. Rocks of the lower allochthon and the par-autochthon contain evidence for N(W)-S(E) extension prior to final folding D3. This event is related with partial melting at ca. 320 Ma. Final folding and an axial-plane parallel crenulation cleavage affected all units and implies NW-SE to NE-SW shortening. Brittle-ductile fabrics and related mineral recrystallisation within allochthonous and par-autochthonous rocks reveal that the deformation temperature did not have exceeded 400 °C implying upper crustal conditions. The latest Variscan oroclinal bending of the entire Iberian massif has rotated older strain increments (310 Ma).

The Variscan geology of SW England is characterized by a 400 Ma ophiolite that thrusted on Avalonian shelf. Contemporarily, syn-orogenic sedimentary basins were formed and subsequently folded and thrusted. After the termination of the Variscan orogeny, melting of the accumulated tectonic pile due to the upwelling mantle led to the formation of Sn-W specialized granites.

In SW-England NW-SE oriented mineral lineation, recumbent folds and thrusts are related with a first deformation episode (D1). This event can be correlated with the ophiolite obduction and subsequent thrusting and folding of the Avalonian shelf at the hinterland (< 390 Ma). The youngest deformation is characterized by N-S folding with an axial plane parallel crenulation cleavage. Superimposed folds and subordinately occurring NE-SW folding indicate an oblique reactivation of D1 mechanical anisotropies that are located underneath the Culm Basin. Because of evidence for syn-sedimentary deformation and the absence older strain increments within the sedimentary rocks of the Upper Carboniferous Culm Basin, the final folding has taken place at ca. 310 Ma. The post-Variscan intrusion of the NE-SW elongated Cornubian Batholite appears to be geometrically unrelated to the latest Variscan N-S shortening.

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Fold/cleavage relationships as indicator for late Variscan sinistral transpression: the Rheno-Hercynian–Saxo-Thuringian boundary zone, Central European Variscides

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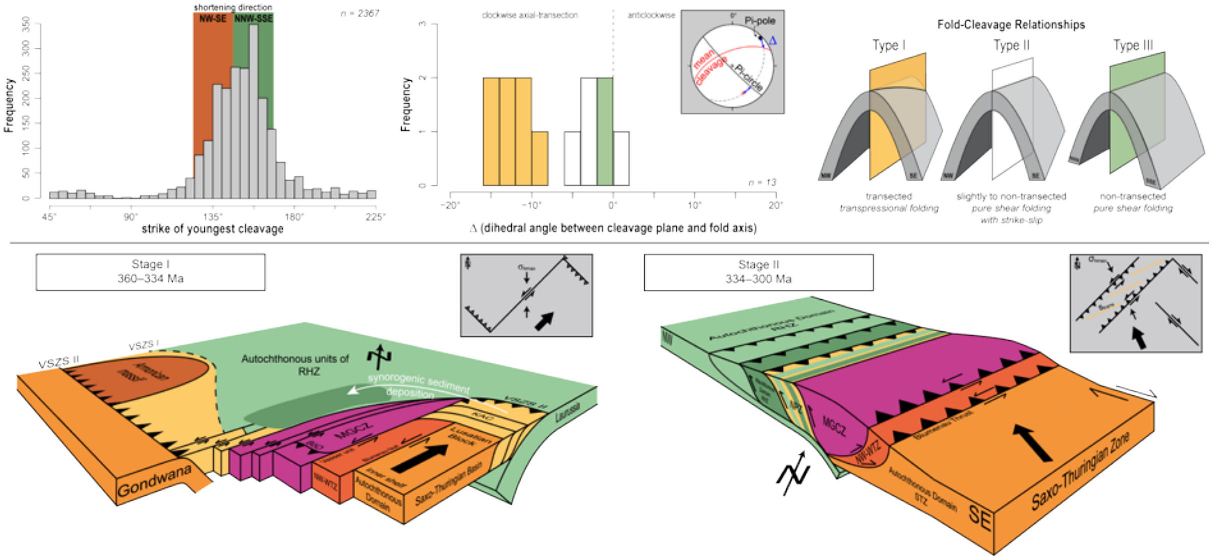
The boundary between the Rheno-Hercynian and the Saxo-Thuringian zones of the European Variscides is characterized by a NE–SW striking late orogenic fold-and-thrust belt affecting the intervening Rheic suture. Classical models used the first-order strike of this zone as an indicator for perpendicular plate convergence, i.e. NW–SE (Oncken et al., 1999; Schäfer et al., 2000).

We present structural data from both sides of the suture, focusing on fold–cleavage relationships (Stephan et al., 2016). The statistical analysis reveals an orientation maximum of the youngest cleavage that deviates from the strike of the fold-and-thrust belt by c. 22°. The presence of clockwise transection of the folds by the cleavage (up to −16°) indicates pervasive sinistral transpression. Three types of fold–cleavage relationships are observed: NE trending folds (I) with or (II) without a transecting cleavage, and (III) non-transected ENE trending folds. We explain the occurrence of different fold–cleavage types by strain partitioning due to NNW convergence obliquely to pre-existent NE trending mechanical anisotropies. In terms of plate tectonics we propose that the classical boundary of the Rheno-Hercynian and the Saxo-Thuringian Zone represents an initial transform plate boundary that was finally affected by sinistral transpression.



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The "Older" and "Younger" granites from the Western Erzgebirge – comparison of different zircon dating methods

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Introduction

Traditionally, Variscan granites in the Erzgebirge have been subdivided into two major rock groups: i) unmineralized "mountain granites" ("Gebirgsgranit") and ii) the "ore bearing granites" ("Erzgebirgsgranite" according to Laube, 1876). "Mountain granites" are presented by biotite and two-mica granites whereas "ore bearing granites" consist of "highly evolved" tin-bearing Li-mica granites. Later, the two plutonic series were assigned as "older intrusive complex (OIC)" and "younger intrusive complex (YIC)" (e.g. Lange et al., 1972; Tischendorf et al., 1987). There is still an ongoing discussion, if there is an age difference which can be resolved by radiometric age dating between these two groups (e.g. Kempe et al., 2004; Romer et al., 2007). Here, we focus on two granite plutons from the Western Erzgebirge, one belonging to YIC (pluton Eibenstock -EIB) and the other to OIC (plutonites from Aue-Schwarzenberg-ASB).

Comparing different zircon dating methods from literature

Previously, zircons (sometimes also monazites and uraninites) were dated by various methods and laboratories from different samples yielding mean sample ages between 314 - 321 Ma for the YIC pluton EIB, and between 320 – 324 Ma for the OIC pluton ASB with no clear age difference (Fig. 1).

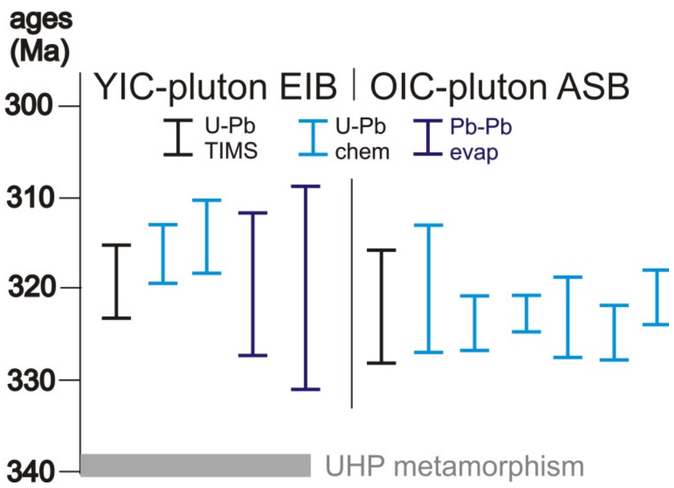

Fig. 1: Comparison of zircon ages from literature (compiled in Tichomirowa & Leonhardt, 2010). Each bar represents a mean age for one sample.

Different zircon dating methods applied on the same samples

We dated zircon grains from several (4-6) samples from both plutons by different methods (LA-ICP-MS, evaporation, SHRIMP, CA-ID-TIMS). The mean sample ages for both plutonic complexes vary roughly between 310 – 330 Ma (errors not included) and do not show clear differences.

For each sample, different zircon dating methods show in a few cases identical mean ages within their errors. More frequently, the age of one dating method is shifted by 1-2% (corresponding to 3-6 Ma for the considered age range) compared to another method for the same sample. Figure 2 shows the mean ages for two selected samples from each pluton. LA-ICP-MS ages are sometimes identical to SHRIMP ages (samples 1, 2) but can be shifted by up to 4% (corresponding to about 13 Ma; e.g. sample 4). For the SHRIMP method, three samples were dated in different laboratories yielding a similar (systematic?) shift of about 1.5% between both laboratories (e.g. samples 1, 2). For the CA-ID-TIMS method, six samples were dated in different laboratories (laboratories 1, 2, 3). These mean ages are only slightly distinct differing by less than 1% between laboratories (Fig. 2).

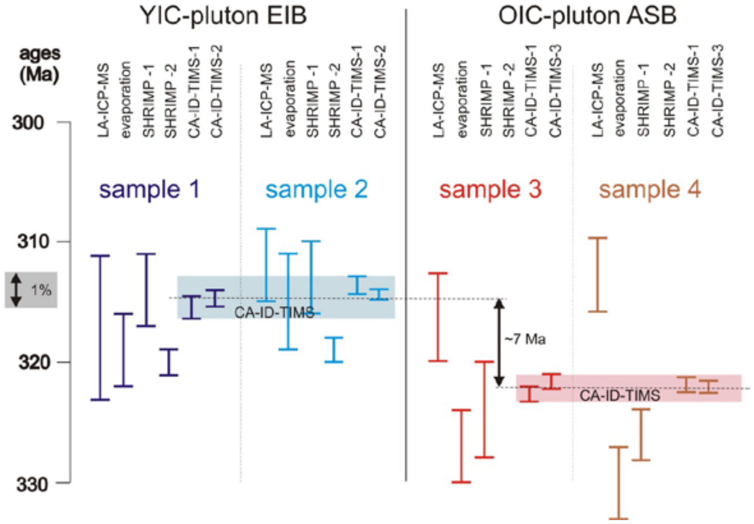

Fig. 2: Four samples were dated with different methods. SHRIMP and CA-ID-TIMS dating were duplicated in 2 to 3 laboratories. Each bar represents a mean zircon age for one dating method. The blue and pink boxes show the variation of CA-ID-TIMS ages as a rough mean for two samples from EIB and for two samples from ASB.

Discussion

The zircon U-Pb isotopic system is one of the most widely used and robust geochronometers as zircon is remarkably stable against secondary alteration. In addition, this decay system is one of the best calibrated methods with several international zircon standards and is therefore used to calibrate the geological time scale. However, even the U-Pb system may yield age differences up to several % for the same sample. The precision of SHRIMP/SIMS ages at 2σ was estimated as 0.5–5% (Kosler & Sylvester, 2003), and 1-3% (Kryza et al., 2014; Schaltegger et al., 2015) while that of LA-ICP-MS ages as 1-10% (Kosler & Sylvester, 2003).

Each zircon dating method has its advantages and drawbacks. The LA-ICP-MS method is by far the quickest dating method and not very expensive. Rocks with age differences >10% can quickly and reliable be distinguished. This method is very well suited to date large zircon populations and to distinguish between different sources in sedimentary rocks. Both the LA-ICP-MS and SHRIMP/SIM methods have the major advantage that zircon grains can be dated in situ so that old cores can be distinguished from younger overgrowths. The evaporation method yields ages within 1-3% reproducibility and can be also regarded as a quick and cheap method to get a first overview about the mean age, abundance of inherited zircons and the level of common Pb. However, if the age of a rock has to be established with an external reproducibility and precision <1%, the only choice should be the high-precision CA-ID-TIMS method although this method is time consuming and expensive. Our new data - based on high-precision CA-ID-TIMS dating - for the first time discriminate the intrusion ages of the YIC pluton EIB and the OIC pluton ASB reliable with an age difference of ~7 Ma.

ID-TIMS ages were not always as precise and reproducible as they are today. Considerable improvement was obtained by calibrations within the Earth-time group (www.earth-time.org: e.g. common standardized data reduction procedure) as well as by application of chemical abrasion (CA) to zircons before dating that both led to much smaller age differences between laboratories.

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Geochronology and magnetic fabrics of the Altenberg-Teplice granite porphyry: implications for emplacement style of a caldera ring dike

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The Altenberg–Teplice volcano-plutonic complex is an erosional relic of late-Variscan, ~NNW–SSE elongated trap-door collapse caldera (~18 × 35 km) of late Carboniferous age in the northern part of the Bohemian Massif, Czech Republic and Germany (e.g. Benek 1991, Mlčoch & Skácelová 2010). The oldest pre-caldera intrusion is represented by the westerly Fláje porphyritic monzogranite. To the east, the caldera fill includes an up to ~2 km thick sequence of several different facies of rhyolite to rhyodacite tuffs, ignimbrites and lavas, locally intercalated with sedimentary and volcaniclastic layers. Finally, the post-caldera igneous activity is marked by intrusion of a microgranite porphyry ring-dike along the caldera marginal fault. This was followed by late emplacement of sub-volcanic Cínovec A-type granite cupola in the center of caldera and associated greisen mineral alteration (e.g. Lobin 1983; Jiránek 1987; Breiter et al. 2001; Štemprok et al. 2003). The complex has been deeply eroded due to Cenozoic uplift, providing direct insights into the dynamics of a buried magma plumbing system and into the structure of the intra-caldera volcanic products.

This contribution focuses on quantification of magnetic fabrics and parameters of the microgranite porphyry dike as determined by the anisotropy of magnetic susceptibility (AMS). We have examined a total of 651 specimens from 57 sampling sites. The average bulk susceptibility (k_m) is 10^{-3} (SI) implying a ferromagnetic mineral as a dominant carrier of magnetic susceptibility, however, several specimens also indicate paramagnetic signal (10^{-4} and 10^{-5}). The average fabric intensity (P) is very low on most sites (0.1–0.3 % of anisotropy), and the site average shape factor (T) varies greatly between –0.6 and 0.8. Both site average P and T parameters do not show any spatial pattern. The site mean principal magnetic axes show three different groups where (1) all axes are clustered, (2) k_1 and k_2 display a girdle and k_3 a cluster, and (3) k_1 is clustered and k_2 and k_3 form a girdle. The magnetic fabric pattern is rather homogeneous throughout the dike, comprising both dike margin-parallel and -oblique orientations. On about half of the sampling sites, the AMS foliation (pole to k_3) is parallel or subparallel with magmatic K-feldspar foliation (where visible), whereas the rest shows oblique and perpendicular orientation. This behavior suggests more complex magmatic strain during flow and emplacement of crystal-rich felsic magma than, for instance, observed in mafic dikes, and requires further detailed investigations of magnetic mineralogy.

Given by large uncertainties in the available ages of all units, we have conducted radiometric age determinations on three zircon separates from the Fláje-Loučná, Frauenstein and Altenberg segments of the microgranite porphyry. The specimens were measured using the laser ablation ICP-MS. Zircon population from all three samples consists of mainly clear euhedral fragments or prismatic grains with a length of ~150–300 μm. Cathodoluminescence images show mostly euhedral oscillatory magmatic growth zoning with rare featureless unzoned cores. The individual data yielded relatively wide scatter in concordant or near-concordant ages between ~320 and ~305 Ma that constitute single concordia crystallization ages of 312 ± 3 and 312 ± 4 Ma (2 sigma). No inherited zircon core ages significantly differ from magmatic growth zoning ages. These new data thus also provide a lower limit of explosive and effusive volcanism in the Altenberg-Teplice caldera.

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Tin distribution between melt and restite during partial melting of metasedimentary rocks

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The distribution of ore elements between melt and restite critically influences the potential of a granitic melt to develop granite-bound mineralization. Distribution of Sn between restite and melt during partial melting is largely controlled by the presence of tin sequestering phases such as biotite, muscovite, titanite and magnetite in the restite. The stability of these phases controls whether or not Sn is available for dissolution into the melt. Tin released during breakdown of one Sn-bearing phase does not necessarily accumulate in the melt. Released Sn may be retained in restite rather than partition into the melt if there is a tin sequestering phase like biotite.

Modeling using the Theriak/Domino program (De Capitani & Petrakakis 2010) demonstrates that major controlling factors apart from protolith composition are whole rock (WR) water content, water activity (a(H_2O)), oxygen fugacity (fO_2) and melt volume and sequential melt extraction. WR water content controls the modal abundances of OH-bearing minerals and, thus, influences the position of the solidus and the volume of melt produced during dehydration melting. In terms of biotite stability, WR water content plays a subordinate role, becoming only important at very low water contents. Oxygen fugacity - ranging between $Fe_{total}=Fe^{2+}$ and the hematite-magnetite buffer - influences biotite stability, extending it towards higher temperatures at elevated fO_2 values. A decrease in a(H_2O), on the contrary, not only lowers biotite stability towards lower temperatures, but also shifts the solidus towards higher temperatures.

Even though biotite has higher contents of Sn than muscovite, in muscovite-rich rocks a substantial proportion of bulk Sn can be hosted by muscovite. Anhydrous melting of such rocks does not necessarily lead to a Sn-rich melt, as large quantities of the released Sn may be re-distributed from the melt into restitic biotite. Biotite has a higher thermal stability than muscovite and acts as a tin sequestering phase. Therefore, temperatures of metamorphism need to exceed biotite stability to generate tin enriched melts. Those conditions are not met by internal heating alone. Additional advective heat input is needed to reach biotite stability limits.

Sedimentary, tin enriched protoliths show a distinct enrichment in Al and K and depletion in feldspar bound elements (Ca, Na, Pb, Sr). Prograde metamorphism of these protoliths produces considerable amounts of muscovite. Dehydration melting of this muscovite results in the generation of large amounts of melt over a narrow temperature interval. The increase in melt volume also increases the probability of melt extraction from the migmatite. As the melt volume produced during biotite dehydration melting is relatively small and previous melt extraction(s) are very likely, tin released during biotite breakdown is distributed into a small amount of melt. These melts have elevated tin concentrations, even before further enrichment during magmatic fractionation starts.

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Tectonic setting of late-orogenic plutonism in the Bohemian Massif

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The Variscan Bohemian Massif is an example of a ʽfossil' hot collisional orogen wherein the plutonic activity spanned about 100 M.y. of its development from initial oceanic subduction(s) through crustal thickening to final collapse and gravitational reequilibration. While the early stages of arc plutonism (ca. 380–340 Ma) have been interpreted as closely related to dehydration of subducted slabs, the causes, heat sources, and tectonic setting of post-thickening, late-stage plutonism remain poorly understood. Spatial and temporal distribution of Variscan plutons in the Bohemian Massif clearly demonstrates that the ʽhot domains' in the orogen migrated outward from the Teplá–Barrandian unit and during the waning stages of orogeny wrapped around this central and cold lithospheric block.

The tectonic setting and emplacement styles of the younger plutons, commonly assumed to be post-tectonic, are also notably different from those emplaced during synconvergent crustal shortening/transpression. Structural analysis of two large plutonic complexes revealed two different emplacement styles associated with the late-orogenic plutonism: (1) Large-scale anatexis of hot Moldanubian crust triggered diapiric ascent of elongated granite-migmatite domes, large volumes of which comprised both S- and I-type granites at around 330–325 Ma (the Moldanubian batholith), and (2) already cold Saxothuringian upper crust hosted strike-slip fault-related I-type plutonism. The latter is greatly exemplified by the ca. 320–312 Ma Krkonoše–Jizera Plutonic Complex, which was constructed as vertically zoned magma chamber of I-type granites with mantle component and was syntectonic with movements along NW–SE major faults (Intra-Sudetic and Machnín faults).

The key issue for future research is what was the emplacement style and tectonic setting of broadly coeval plutons in the Erzgebirge and Fichtelgebirge and adjacent areas. While some isolated steep-sided stocks penetrated discordantly the cold crust at around 327 Ma (e.g., the Sedmihoří pluton), some plutons were interpreted as being emplaced along NW–SE faults and later intrusions were interpreted as tabular or domal (laccolithic?) bodies. Nevertheless, in all cases, heat flow from the lithospheric mantle seems to play a major role at deeper crustal sections, perhaps with major faults acting as pathways for mantle-derived melts that contributed to upper-crustal chambers. This peripheral tectonothermal activity was perhaps driven by widespread mantle delamination around the consolidated Bohemian Massif's core until the late Carboniferous/earliest Permian times.

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