800 years of mining activity and 450 years of geological research in the Krušné Hory/Erzgebirge Mountains, Central Europe

800 anos de mineração e 450 anos de pesquisa geológica em Krušné Hory/Erzgebirge Mountains, Europa Central

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Abstract: For over 800 years the Krušné Hory/Erzgebirge Mountains were one of the most important European mining districts and source of Ag, Sn-W, As-Co-Ni, Pb-Zn, and U. The growth of mining activities set the conditions for the appearance of the first geological maps, printing of technical books and foundation of the first mining high school. Economic geology itself developed and established as a distinct discipline right there in the Krušné Hory/Erzgebirge Mountains. Several chemical elements, namely U, Bi, W, Rb, In, Ge, Ra, Po, were discovered in ores or minerals from that region. More recently, based on extensive research database, evolutionary models of some types of granite-related deposits were also developed in this region.

Keywords: Krušné Hory/Erzgebirge. Mining. History. Tin ores. Granites.

Resumo: A região de Krušné Hory/Erzgebirge Mountains foi, por mais de 800 anos, um dos mais importantes centros europeus de mineração de Ag, Sn-W, As-Co-Ni, Pb-Zn e U. O desenvolvimento da mineração criou as condições para o surgimento dos primeiros mapas geológicos, dos primeiros livros-texto e o estabelecimento da primeira escola superior de mineração. Aqui, a Geologia Econômica desenvolveu-se como uma disciplina científica específica. Vários elementos químicos (U, Bi, W, Rb, In, Ge, Ra, Po) foram descobertos em minérios ou minerais dessa região e, recentemente, com base em uma longa experiência em pesquisa, aqui foram desenvolvidos modelos evolutivos acerca de depósitos minerais relacionados a granitos.

Palavras-chave: Krušné Hory/Erzgebirge. Mineração. História. Minérios de estanho. Granitos.

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INTRODUCTION

The mining district of Krušné Hory/Erzgebirge (Ore Mountains in English), located along the Czech/German border, is one of the few major metallogenic provinces in Europe characterized by granite intrusion-related ore deposits (Figure 1). For about 800 years it produced silver, tin, lead, zinc, bismuth, cobalt, nickel and arsenic. From the end of 19th century, it also produced tungsten, fluorite, barite and uranium.

The oldest documented mining activity in the Erzgebirge is the Freiberg silver mining, which dates back to 1168. Silver was later followed by tin mining in the 13th and 14th centuries. Tin was initially mined from placers and later from primary occurrences. The second and main cycle of silver production began around 1470 with the foundation of privileged mining towns like Schneeberg, Annaberg, Marienberg and Jáchymov/Joachimsthal. After more than one hundred years of expansion, the

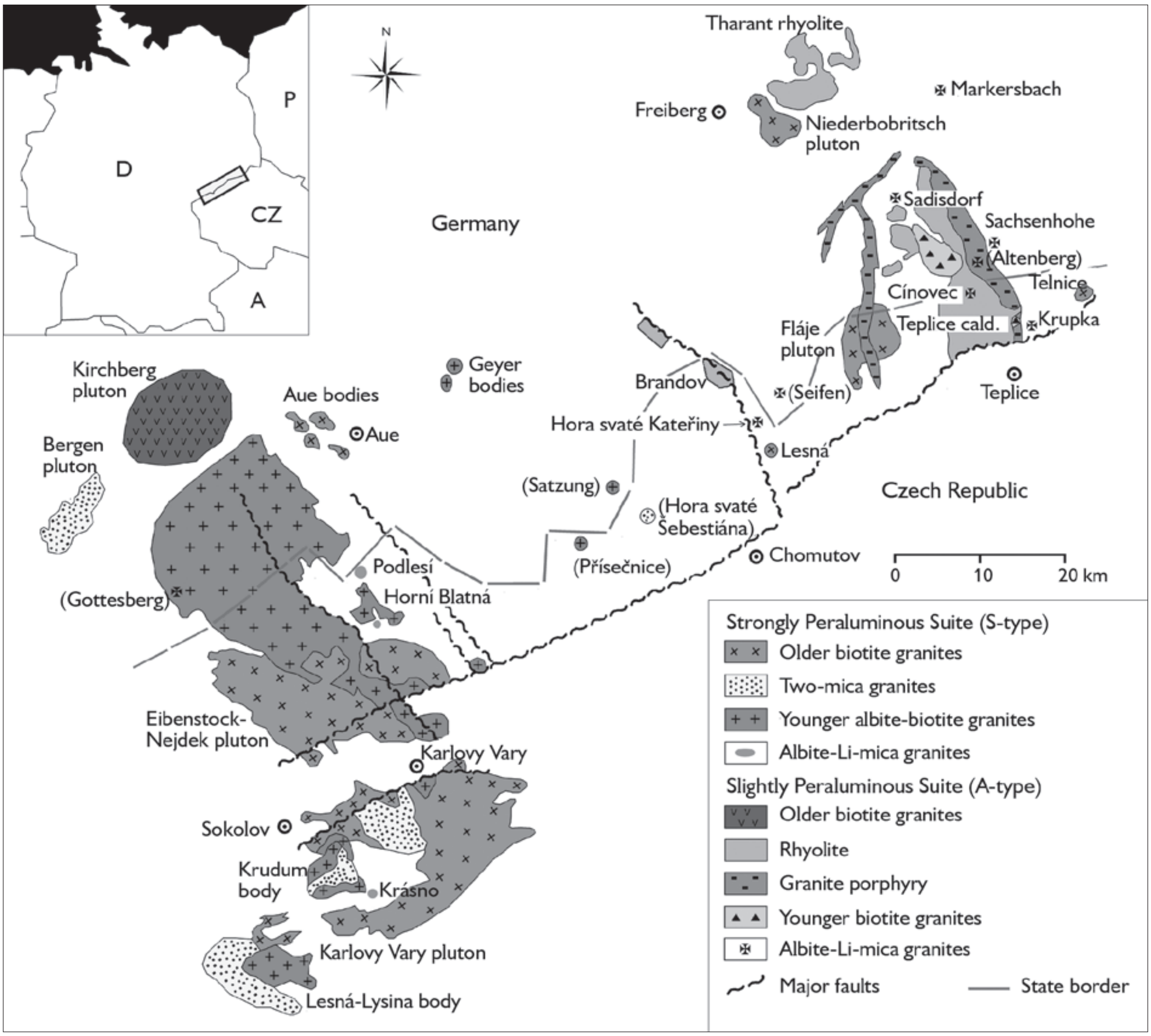

Figure 1. Geological sketch map of the Krušné Hory/Erzgebirge Mountains.

mining activity collapsed during the devastating Thirty Years' War, from 1618 to 1648, when a series of wars in central Europe that stemmed from conflict between Protestants and Catholics and political struggles between the Holy Roman Empire and other powers. Next period of prosperity, starting in 1770, mining of bismuth, cobalt and nickel together with some silver and tin, dominated the local production. Lead and zinc mining (+ silver from silver-rich galena) grew important in the 19th century. Later on, tungsten (during World War I – WWI) and uranium (after World War II – WWII) became the most important metal commodities mined in the district. The mining activity in the entire area was temporary disrupted for economic reasons in 1990 (Freels *et al.*, 1995).

Rapid development of a prolific mining district with a variety of different metal commodities and the appearance of wealthy mining towns enabled the unprecedented development of the geoscience disciplines. The first mining guides were written in this district by Georgius Agricola in Jáchymov, already in the mid-16th century. The oldest geological, mining and metallurgical school in the world was also founded in 1765 in Freiberg.

The chemical elements bismuth (1540, by Agricola), tungsten (1783, by the D' Elhuyar brothers), uranium (1789, by Klaproth), rubidium (1861, by Bunsen and Kirchhoff), indium (1863, by Reich and Richter), germanium (1886, by Winkler), polonium and radium (1898, by Marie and Pierre Curie) were discovered in ore minerals from this region.

Petrological research of granites, conducted from 1850 in tin-mineralized areas, allowed sorting the barren and mineralized facies of the plutons.

The German segment of the Erzgebirge has been geologically mapped on a 1:25,000 scale since 1895. During and after the World War II, expansion of the metal mining industry combined with the exploration of new ore deposits stimulated detailed studies on major and trace element geochemistry of both outcropping and concealed granite intrusions. The main objective of this research was to establish convincing criteria for separating barren granites from those ones with better potential to hosting Sn-W mineralization of economic significance.

It is generally accepted that the tin-tungsten ore-forming processes are closely connected with the crystallization and cooling history of fractionated Sn-W-Li-Rb-Cs-F-specialized granitoid plutons (Tischendorf, 1989; Tischendorf & Förster, 1994; Breiter *et al.*, 1991; Štemprok, 1993; Breiter *et al.*, 1999). However the more complex and variable genetic relationships of the late-Variscan (U, Pb-Zn) and post-Variscan (F-Ba) mineralizations with the exposed or concealed granite bodies are less understood and remains a controversial subject (Tischendorf & Förster, 1994; Breiter & Seltmann, 1995).

The aim of this paper is to give a brief overview of the evolution of the mining history of the Erzgebirge District, mainly of the Sn-W and Ag-U occurrences, and its relation with the development of geological knowledge from Middle Ages to date. A few typical Sn-W and Ag-U deposits were chosen from a large number of mineral deposits in the Krušné Hory/Erzgebirge District (Hösel *et al.*, 1995, 1997) to illustrate the structural and mineralogical diversity of the ore deposits in this area and its significance for the development of economic geology as a scientific discipline.

It is opportune to remind that political borders do not necessarily coincide with geological boundaries. Both German and Czech sides of the Krušné Hory/Erzgebirge mining district evolved together, and the main evolutionary aspects mentioned in this article are valid for the whole Krušné Hory/Erzgebirge area. However the detail mineral deposit description were preferentially chosen from the Czech segment, where the author has been actively working for many years.

MINING HISTORY

Tin mining on the Czech side of the Erzgebirge has been continuously documented since 1250 (Figure 2). The most important period of this mining cycle ended with the war devastation and the disruption of long-distance trade routes during the Thirty Years' War (1618-1648).

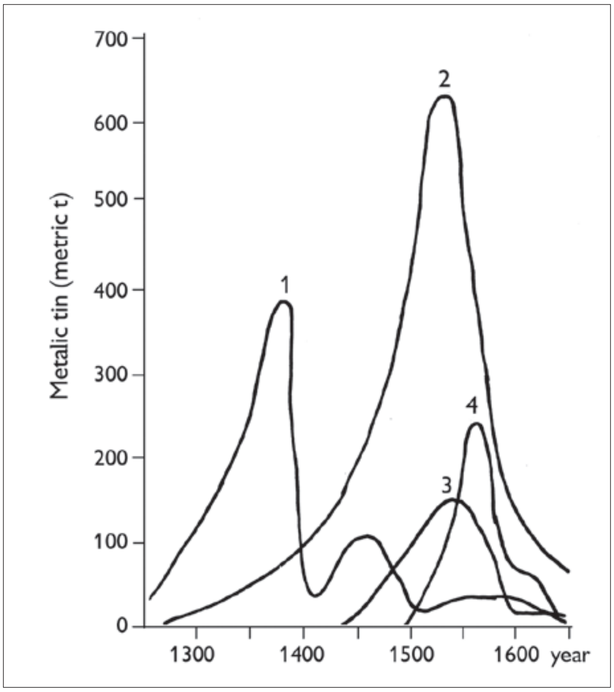

Figure 2. Historical mining of tin: 1) Krupka; 2) Krásno; 3) small mines at the dyke greisens; 4) Cínovec-Zinnwald.

Recovery of the mining industry and the rise of new towns took place in the second half of the 18th century, but the high-grade portions of the smaller ore deposits were quickly exhausted and the production of the local mines could not compete with cheaper tin imported from South America and South East Asia. Only mining in the largest tin districts (Krásno and Cínovec in the Czech part, Altenberg and Geyer-Ehrenfriersdorf in the German part) remained active, though some disruptions were reported in the second half of the 19th century. The last cycle of intense exploration and mining started during the WWII and ended in the wake of major economic changes that swept in the Czech Republic and Eastern Germany from 1989 on.

MINING HISTORY IN THE KRÁSNO – HORNÍ SLAVKOV AREA

Tin mining from placers started around the 12th century and continued through the 18th century. Mining permits for primary ores were granted to the two neighboring towns of Krásno and Horní Slavkov (known also as Schönfeld and Schlaggenwald in German language) in 1355.

A large scale tin mining took place in the 16th century, following the discovery of the mineralized Huber and Schnöd stocks in 1516 and 1548, respectively. By that time, primary tin deposits were mined by sinking shafts and inclines. Water for mills and pumps was conveyed from nearby forested hills along a 24 km long water race. Miners used fire to heat up the rocks and poured cold water to disintegrate then. Underground workings inside the stock were rather chaotic, without properly designed plans. Some mined chambers in both stock achieved dimensions of 30-40 m in length, 10-20 m in width and 15-20 m in height. Thes lack of proper technical planning caused major collapse of the underground operation, with numerous fatalities in 1568 (Beran & Sejkora, 2006).

Historic production

According to historical studies, the total output from the mining district from 1500 to 1620 was about 32,000 metric tons of metallic Sn. The Hub deposit alone yielded about 10 to 12 thousand tons of metallic tin during its six hundred years of operation. The ore grade lowered from initial 1.5-1.7 wt% Sn (in 1540, near the surface) to 0.2-0.4 wt% Sn (in 18th century, in deep portions of the deposit). The Hub stock operations were finally closed in 1820. During WWI, wolframite was hand-picked from its waste dumps, and the Hub mine was reopened in 1955 with average ore grade of 0.15-0.25 wt% Sn and 0.045 wt% W. The mine output was about 300,000 metric tons per year. In the periods of 1973-1976 and 1984-1987 an open pit mining of greisen were conducted along with the underground developments. All mining operations stopped in 1991 due to economic constraints (Jarchovský *apud* Breiter & Seltmann, 1995).

In the gneiss series at Horní Slavkov, several NW-SE striking uranium-bearing veins were mined in the 1950s. During this period, about 23 main shafts and more than

40 km of adits were developed in an area of 16 km^2, leaving several waste dumps behind.

In 1960 the mining of an alkali-rich leucogranite body started in the Vysoký Kámen quarry to supply the ceramic industry with a substitute of pegmatite feldspar.

MINING HISTORY IN THE EASTERN ERZGEBIRGE

The town of Krupka, situated in the eastern part of the Krušné Hory Mountains, is probably the location of the oldest known tin deposit in Bohemia. Placers were mined there in times as early as the Bronze Age, and primary ores since the 13th century. Tin mining reached its peak in the 16th century. During the WWI, wolframite was exploited from Lukáš vein, molybdenum started to be exploited during WWII, and ceramic feldspar from the 1950's.

The Cínovec/Zinnwald tin deposit was discovered by miners from Krupka at the beginning of the 14th century. Large scale mining began in 1450. Tungsten has been mined since 1879, lithium in limited extent after 1950. The first mined Sn-W deposit was composed of 14 quartz-zinnwaldite veins. Those veins were loaded with coarse crystallized cassiterite and wolframite, occurring as 20-80 cm-thick sheet-like bodies, placed near the top of the granite cupola (Figures 3-4). The new mine developed in the Cínovec-south greisen. This deposit consisted of two bodies of greisenized granite with fine-grained disseminated ore minerals with average thickness of 20 m. From 1959 to 1978, the Cínovec vein deposit yielded 658,700 tons of high quality ore (0.222% Sn, 0.207% W and 0.307% Li). From the Cínovec-south greisen deposit, from 1980 to its closure in 1990, a total of 451,300 tons of ore (0.183% Sn and 0.024% W) were produced.

SILVER AND URANIUM MINING IN JÁCHYMOV

In the beginning of the 16th century, silver-rich ores were discovered in the vicinity of Jáchymov town (Joachymsthal in German, St. Joachim Valley in English)

Figure 3. Mining of the outcropping part of the Cínovec/Zinnwald deposit during WWI (old postcard).

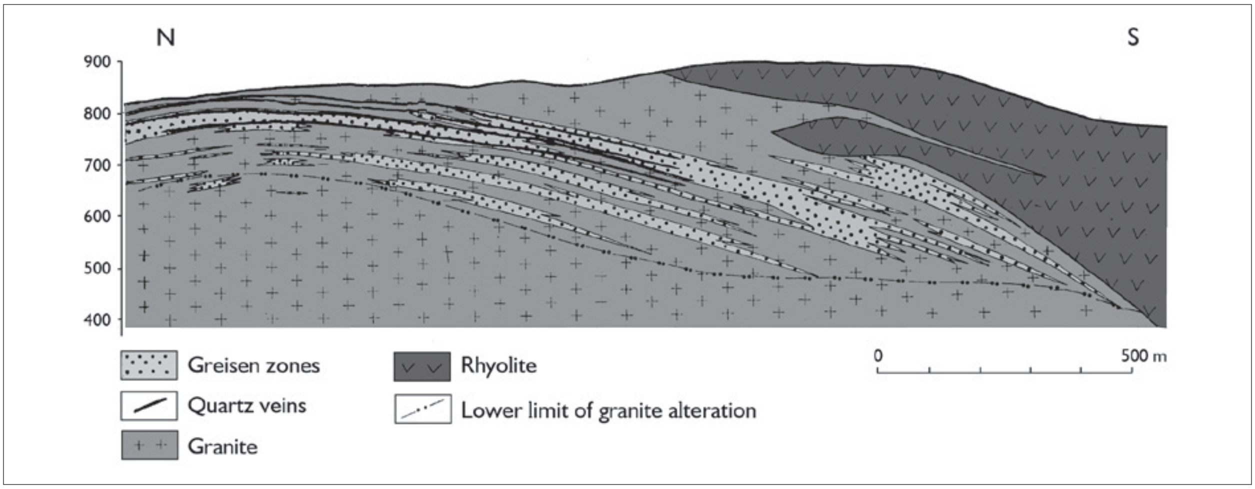

Figure 4. Cínovec-geological cross-section through the granite cupola with Sn-W deposit (acc. to Čabla and Tichý, 1965).

triggering a silver-rush in the area. In a matter of a few years, Jáchymov became the second largest city in the Czech Kingdom with more than 20,000 inhabitants and a reference center for mine development and of metallurgical techniques. In 1520, a Mint Office was established. Silver coins, bearing on one side the portrait of King Louis Jagello (later the Czech Lion), and the image of St. Joachim on the other side, were called by his place of origin – Joachimsthalergulden. The word dolar derived originally from Thaler, that was later changed to 'tolar', and finally to 'dolar' (Figure 5).

The hydrothermal vein-type Jáchymov ore deposit consisted of NW-SE and W-E trending mineralized veins rich in minerals of Ag, Bi, Co, Ni, As, and U – native silver, native bismuth, argentite, proustite, Ni-Co arsenide and sulfo-arsenide. The main source of uranium was uraninite, named locally 'pechblende' (mean 'unlucky ore', since its occurrence in the deeper part of the vein system, marking the end of the Ag-mineralization). Uranium ores had no value for medieval miners and were disposed in the dumps.

Interest in uranium appeared long after the depletion of silver ores in the mid-19th century, shortly after the discovery of the 'uranium colors'. The industrial processing of the U-ore uraninite started in 1853 and produced the so-called 'uranium yellow' (sodium diuranate, $Na_2U_2O_7$) for the glass industry because uranium salts added beautiful yellow hues to the glass artifacts. This technological process was developed by the Austrian chemist Adolf Patera (1819-1894). The factory employed about ten workers and the annual production was about 10,000 kg of sodium diuranate.

Figure 5. Silver coin from Jáchymov – the 'Thaler' (repro from Wikipedia).

The existence of well-known uranium deposits in Jáchymov was one of the reasons why the Czechoslovakia was occupied by the end of the WWII by the Russian army (large-scale uranium deposits in the USSR would be discovered only years later). From 1945 to 1963, Jáchymov (along with several much larger deposits that were later explored and mined in the German portion of the Erzgebirge and in other parts of the Czech Republic) supplied uranium for soviet nuclear weapons.

SEMI-PRECIOUS STONES FROM CIBOUŠOV

Under the rule of Bohemian King and Roman Emperor Charles IV, from 1347 to 1378, the walls of the most luxurious gothic chapels were decorated using precious stones to create artistic patterns and to portrait biblical scenes inspired by the St. John's Gospel. It demonstrated not only the power and wealth of the King and Emperor, but also highlighted the cultural, economic and technological achievements of a developed society.

The St. Venceslav Chapel at the Prague castle and the 'All Saints Chapel' in the Karlštejn castle (Figure 6) were decorated with more than one thousand polished amethyst and jasper slabs ranging from 10 x 10 to 40 x 40 cm in size. All those stones were mined from hydrothermal quartz veins near the village of Ciboušov in the central part of the Krušné Hory Mountains (Figures 7-8). Archeological research in the early 1980's documented the technology applied in the quartz medieval mining as well as stone cutting and polishing techniques (Skřivánek, 1985).

TOPAZ FROM SCHNECKENSTEIN

In 1727, Christian Kraut discovered a rock cliff rich in large topaz crystals located deep in the forests of the western Erzgebirge. From a geologic standpoint, the cliff consisted of explosive phyllite breccia, with many cavities filled by hydrothermal quartz, developed at the cupola of an A-type granite stock, emplaced at shallow depth.

Figure 6. Castle Karlštejn, Chapel of the Holy Cross. The walls are covered by polished amethyst and jasper plates. Constructed in 1350-1360 (repro from Středočeský Kraj, 2008).

Figure 7. Ciboušov-amethyst from the medieval mining place (ca. 10 cm across), recently found (repro from Krušné..., 2009).

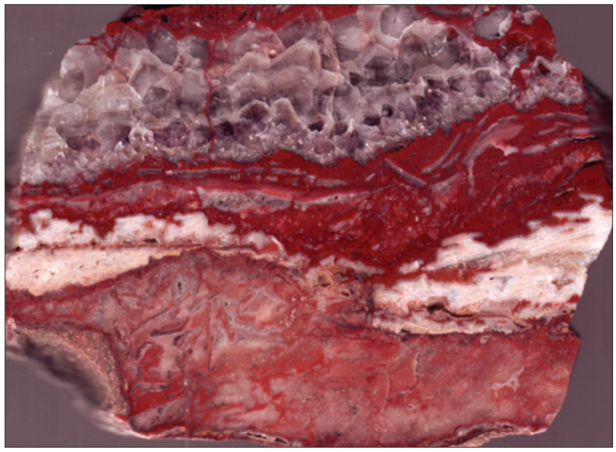

Figure 8. Ciboušov-jasper from the medieval mining place (15 x 12 cm), recently found, author's collection.

Mining from 1734 to 1800 (Zeche Königskrone = Royal Crown Mine) found extraordinary crystals of gem quality, including wine-yellow topaz crystals measuring several centimeter in length. Approximately two-thirds of the original cliff was removed. The best specimens of topaz were used to ornate the Crown of Saxonian kings. In 1800, the remaining portion of the outcrop was given to the Mining Academy of Freiberg as an object of research. Since 1938, the rock stands as a natural monument. Small topaz crystals are commonly found until today (Kern, 1792; Leithner, 2008).

SCIENTIFIC RESEARCH INSPIRED BY MINING

THE OLDEST BOOKS ON MINERALOGY, MINING AND METALLURGY

The publication of the oldest illustrated European books on mineralogy and mineral deposits is closely related with the history of the silver mining in the town of Jáchymov in the mid-16th century. Their author, the eminent German scholar Georg Bauer, better known under the Latin name Georgius Agricola (George Farmer in English), was born in 1494 in Glauchau, Saxony. He had studied classical philology, theology and philosophy at the University of Leipzig, and then natural sciences and medicine. In 1527, Georg Bauer became the town's doctor and pharmacist in Jáchymov, which had just experienced its greatest period of prosperity. Agricola was interested in mining and established contact with important representatives of the mining authorities and companies.

The first Agricola's book on mineralogy and mining was the 'Bermannus sive de re metallica Dialogus' (Bermannus or dialogue on mining), published in 1530 in Basel. Later Agricola moved to Chemnitz (Saxony), where he spent the rest of his life. He described the properties of bismuth in detail and told how it was extracted from ores mined near Schneeberg in the German part of the Erzgebirge. His key work is 'Twelve books on mining' (De re metallica libri XII), probably written in 1550, but published one year after his death, in 1556. It contains descriptions of geological prospection of ore deposits, mining methods, metallurgical technology and assaying of precious metals. Those books present 273 beautiful woodcuts by Basilius Weffringer (Figures 9-10). They summarized the contemporary knowledge and became for the next 200 years the most widely used guide for ore mining and metallurgical processing.

MINING ACADEMY FREIBERG

The first high school for mining experts and officers was funded in Freiberg in 1765 by Prince Franz Xaver, regent

Figure 9. Hand windlass for ore transportation from the mine (haspel-machine) (from Agricola: De re metallica…).

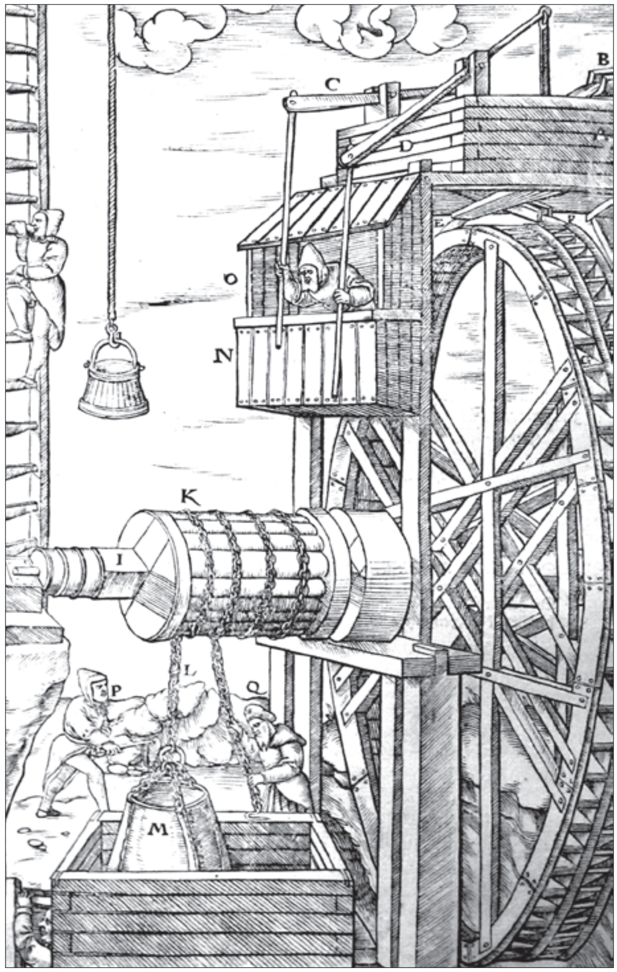

Figure 10. Large water wheel for ore transport, moving in both directions (from Agricola: De re metallica…).

of Saxony. Teaching began in the spring of 1766 with a course in chemistry and mathematics for 19 enrolled students. Many prominent figures of different geological and mining disciplines lectured at the Academy, including Abraham Gottlob Werner (1749-1818) who worked as inspector of mines and professor of mining and mineralogy. He is well known from the Plutonism *versus* Neptunism controversy stablished at the end of the 18th century. His 'Short classification and description of rocks' from 1787 and his lectures laid the foundations of classification of rocks based on their relative ages indicated by the sequence of layers. He has been called the 'father of German geology'.

Johan Friedrich August Breithaupt (1791-1873) developed the concept of mineral paragenesis (the book 'Die Paragenesis der Mineralien' from 1849). He is credited with the discovery of 47 valid mineral species. The mineral breithauptite (NiSb) was named in his honor. His work included important contributions to crystallography and the physical and chemical properties of minerals.

In Freiberg two new chemical elements were discovered. In 1863 the chemist Hieronymus Theodor Richter (1824-1898) and the physicist Ferdinand Reich (1799-1882) discovered the metal Indium (acc. to indigo-blue spectral line). Clemens Alexander Winkler (1873-1902) isolated Germanium in 1886. This discovery confirmed Mendelejew's Periodical System of Elements. Mendelejew had predicted an element with the characteristics of Germanium as 'Ekasilizium'.

GEOLOGICAL MAPPING

Simple maps of mines (adits, galleries, shafts, and ore veins) were already common in the 16th century and became today important source of information about mining history.

The first modern geological maps were created after 1850 in Bohemia, under the supervision of the Geological Survey of Austria (Geologische Bundesanstalt Wien) on a scale of 1:75,000. In Saxony, maps were created under supervision of the Ministry of Finance (Königliche Finanz-Ministerium Leipzig) on a scale of 1:25,000 (Figures 11-12). High-quality geological maps covered much of the Erzbebirge area by 1900, with locations of ore veins and mines.

The current geological map (Hoth *et al*., 1995) and map of mineral resources (Hösel *et al*., 1995) of the whole Krušné Hory/Erzgebirge area, both on 1:100,000 scale, were published in co-operation of the Czech Geological Survey and the Geological Survey of Saxony. The latter map was accompanied with brief English (Freels *et al*., 1995) and detailed German explanation notes (Hösel *et al*., 1997).

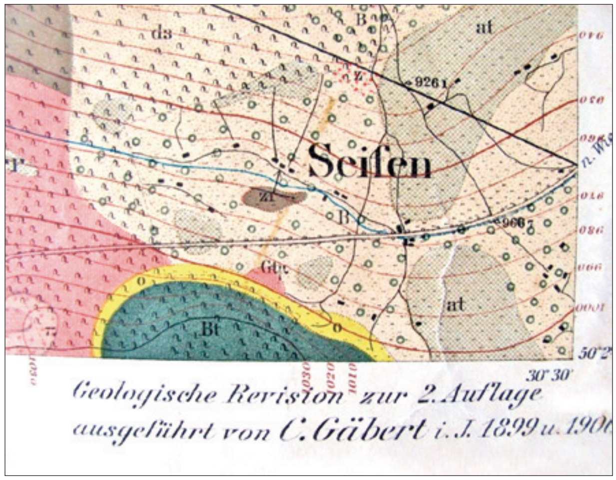

Figure 11. Detail from the oldest geological map of the Erzgebirge 1:25,000 (Geological map of Sachsen, sheet Oberwiesenthal, printed in 1900). Red = granite; gray = phyllite; black-green = basalt; yellow = tertiary sediments with cassiterite placers.

Figure 12. Geological cross-section from the geological map on Figure 11.

STUDY OF THE RADIOACTIVITY

Maria Curie-Sklodowska (*1867 in Warsaw, Poland, †1934 Paris, France) was a distinguished personality in the world of science, twice Nobel Prize winner, discoverer of polonium and radium, the first female professor at the Sorbonne, personage who cannot be overlooked in the history of the 20th century science and technology.

In 1891, she went to Paris to study physics and chemistry and in 1896 began to study the new phenomenon discovered in the mineral uraninite – the radioactivity. She soon realized that besides uranium, another chemical element with much stronger radioactivity ought to be also present. She called this new element radium. To isolate the new, very rare element a lot of uranium-bearing material was needed and Jáchymov was at that time the only place in the world where uraninite was mined. So she sought help from the Austrian government and the emperor Franz Josef II gradually sent to her approximately 23.5 ton of material containing radium as a gift. From this material, Marie Curie prepared the first 100 mg of $RaCl_2$ in 1902 and later the first metallic Ra.

Radioactivity and its expected therapeutic qualities soon became very popular. In 1906, the first facilities for bathing in radioactive mine water, containing high concentration of dissolved Rn, were available. As early as 1910-1912, true spa installations were built.

Industrial production of radium for therapeutic purposes started in the state manufactory in Jáchymov in 1909. The production processes consisted of oxidation of the ore, conversion of all metals to sulphates, followed by precipitation of $RaSO_4$ together with $BaSO_4$ and $PbSO_4$, and repeated fractional crystallization. Until 1918, the factory produced about 15 g of Ra, from 1919 to 1937 about 50 g of Ra, which were most of the world production of this element.

MODERN STUDIES OF GRANITES AND GRANITE-RELATED MINERAL DEPOSITS

ORE-BEARING GRANITE PLUTONS

The detailed petrographical and chemical characterization of the granites from Krušné Hory/Erzgebirge have conducted systematically since mid-19th century due to their obvious association with tin mineralization. Krušné Hory/Erzgebirge district is one of the classical regions in the geologic literature on granite-related mineralization in the world. Hochstetter (1856) and Laube (1876) had already distinguished two fundamental granite types in this area – the older, barren 'Gebirgsgranit' (Figure 13) and the younger, ore-bearing 'Erzgebirgsgranit'. A detailed microscopic study of granites of the Nejdek-Eibenstock pluton allowed Teuscher (1936) to coin the term 'autometasomatism' to refer to alteration of granites in the early postmagmatic stages by their own cogenetic hydrothermal fluids. This theory influenced significantly the genetic interpretation of fractionated granites around the world for more than 50 years (e.g., Beus & Zalaškova, 1962; Štemprok, 1986; Tischendorf, 1989).

Regional exploration and geochemical work after 1970 generated new ideas on the nature of granitic plutons of Krušné Hory Mountains. Breccias cemented by granitic material were found at many localities and their magmatic origin was also proven (Seltmann *et al*., 1987, 1992; Jarchovský & Pavlů; 1991; Gottesmann *et al*., 1994).

Partie Rudohorské žuly u Neydku.

Figure 13. Outcrop of the older biotite granite in the town of Nejdek. Drawing from the oldest modern geological description of the Czech side of the Krušné Hory/Erzgebirge (Jokély, 1856).

Geochemically, two types of tin-bearing granites were distinguished, namely high-phosphorus, strongly peraluminous, typical S-type granites, and low-phosphorus, HFSE-enriched, weakly peraluminous, A-type granites (Breiter *et al*., 1991; Breiter, 2012).

Also from the new established study on melt inclusion in minerals of granitic rocks important data about temperature, pressure, intrusion level, water contents of granitic melts could be obtained (Thomas & Klemm, 1997 and Thomas & Davidson, 2012, as an example).

Geological setting

The NE-SW trending crystalline belt of the Krušné Hory/Erzgebirge is located along the Czech-German border, within the Saxothuringian Zone of the Bohemian Massif. This belt (from East to West) consists of Proterozoic paragneisses, Late Proterozoic-Cambrian mica schists and micaceous gneisses, and mainly Ordovician phyllites and quartzites.

All these units were intruded by Late Carboniferous granitoids (Figure 1). Whereas large, relatively deeply eroded plutons are characteristic of the western part of the province, small isolated granite bodies prevail in its central and eastern parts. In many other places, mainly in the central part of the Krušné Hory Mountains, granites were reached by drilling at shallow depths. Several of those granites are, from a textural and geochemical standpoint, composite bodies made up of distinct granitic phases, such as the Krudum and Nejdek-Eibenstock plutons. However, poor exposure does not always make it possible to distinguish true intrusive phases from mere textural-petrochemical varieties developed within a single granite pulse.

The existence of a single coherent 'Erzgebirgspluton' under the whole Krušné Hory/Erzgebirge Mountains, as assumed by Watznauer (1954), was later questioned and the existence of several smaller, more or less independent plutons (the western-, central- and eastern- 'Partial plutons' (Tischendorf, 1969), was preferred instead. The recent results of geochemical investigations support the existence of more independent magmatic centers (Breiter *et al*., 1999). However, interpretation of gravity maps (Bouguer anomaly) supports the existence of a coherent 'granitoid' layer underlying the whole area. In the eastern Krušné Hory, the plutonic activity was followed by multiple extrusions of rhyolitic-rhyodacitic lava flows and dykes, which are still preserved in the Teplice caldera depression.

Granite types

The Variscan granites of the Krušné Hory/Erzgebirge region have been traditionally divided into two major plutonic series: the Older Intrusive Complex (OIC), consisting mainly of biotite monzogranites, and the Younger Intrusive Complex (YIC), comprising a suite of topaz-bearing Li-biotite syenogranites to albite-zinnwaldite-alkali feldspar leucogranites. This subdivision has been based on numerous petrographic, chemical and metallogenetic features (Laube, 1876; Lange *et al*., 1972; Štemprok, 1986; Tischendorf, 1989; Breiter & Seltmann, 1995 and references therein). Recent geochemical and mineralogical investigations (Breiter *et al*., 1991, 1999; Förster *et al*., 1999) suggest that 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 marked by the enrichment in P and depletion in HREE (heavy rare earth elements) and HFSE (high field strength elements). These plutons are *sensu stricto* S-type granites (Chappell & White, 1974);

b) slightly peraluminous granites (A/CNK = 1.0-1.1) with very low P as well as high REE and HFSE, often associated with subvolcanic to volcanic activity. These granites, which are a rather rare type among the European Variscan granitoids, can to a certain extent be compared to the within-plate granites (Pearce *et al*., 1984) or A-type granites (Loiselle & Wones, 1979).

The older peraluminous granites (OIC-S) are distributed throughout the whole region. They consist mainly of medium- to coarse-grained biotite granodiorites/monzogranites to biotite or two-mica monzogranites composed of quartz, zoned and sericitized plagioclase (An_{15-35}), poikilitic K-feldspar, biotite, subordinate amounts of muscovite and accessory apatite and zircon (Figure 14A). Near the town of Loket they contain Carlsbad-twinned orthoclase phenocrysts with sizes of up to 5 x 8 cm. These granites were often affected by cataclasis and show evidence of magmatic assimilation at the contact zones.

The main phase of the younger peraluminous granites (YIC-S) in the Eibenstock-Nejdek pluton is characterized mainly by a coarse- to medium-grained pink biotite granite. The presence of topaz and drop-like quartz crystals is typical of these granites. According to the degree of differentiation, they can be divided into three subtypes: (i) relatively less differentiated syenogranite with biotite, oligoclase, but topaz just in accessory amounts, in the SW part of the pluton; (ii) more differentiated alkali-feldspar granite with protolithionite, albite and more than 1% topaz, in the central part of the pluton and in the Blatná body; and (iii) the strongly differentiated albite-zinnwaldite granites forming small stocks at Krásno, Podlesí etc. Bodies of the latter granites are often rimmed by marginal pegmatites (stockscheider) and contain cassiterite, apatite, monazite, fluorite and uraninite.

The oldest metaluminous rocks are volcanics of the Teplice caldera, covering an area of 35 x 10 km in the Eastern Erzgebirge. The whole volcanic sequence is about 500 m thick and is composed of several effusive phases (tuffs, ignimbrites, lavas) separated by layers of tuffitic sediments (Breiter, 1997; Mlčoch & Skácelová, 2010; Breiter, 2012). Volcanic activity was followed by the intrusion of the Altenberg granite porphyry, filling fissures generated by the cauldron subsidence (Müller *et al*., 2005).

The volcanic rocks were intruded by two types of granites of distinct geochemical A-type character. The multiple intrusion of the Preiselberg granite formed a large hidden body with a small outcrop NW of Krupka. The equivalent in Saxony is the Shellerhau granite. All varieties contain drop-like quartz and orthoclase phenocrysts in a matrix consisting of quartz, oligoclase, perthitic orthoclase and Li-biotite. Fluorite and zircon are common accessories (Figure 14B).

The relatively younger Cínovec granite forms an elongated concealed body with a few, small, NW-SE trending outcrops. The main petrographic facies is characterized by a medium-grained granite with phenocrysts of K-feldspar and drop-like quartz embedded in a quartz, albite, perthitic

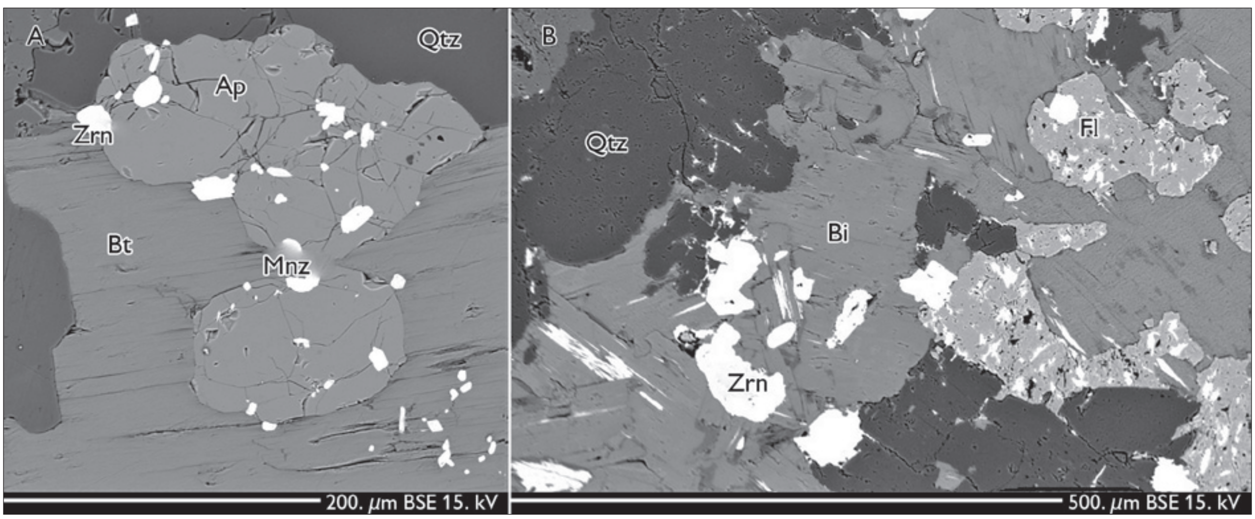

Figure 14. Typical association of accessory minerals: A) apatite (Ap), zircon (Zrn) and monazite (Mnz) embedded in biotite (Bt), S-type biotite granite of the Nejdek pluton. Qtz = Quartz; B) zircon and fluorite (Fl) with fine-grained inclusions of REE-fluorocarbonates associated with biotite (Bi), A-type biotite granite Hora svaté Kateřiny.

K-feldspar and protolithionite matrix. Zircon, topaz, fluorite, cassiterite, monazite, thorite, xenotime and rutile occur in accessory amounts. The upper level of the cupolas consist of medium-grained, non-porphyritic granite composed of quartz with albite inclusions, K-feldspar, albite, zinnwaldite, topaz and fluorite. Cassiterite, scheelite, columbite, zircon, U-pyrochlore, bastnaesite and uraninite are the common accessories (Johan & Johan, 1994; Breiter & Škoda, 2012).

Small bodies (stocks and dykes) of similar Sn, Nb, Ta-enriched granite were recently found at Seifen (Förster & Rhede, 2006) and Hora svaté Kateřiny (Breiter, 2008), in the central part of the Erzgebirge.

Geochemistry

Many articles have been devoted to the chemistry of the Krušné Hory granites. Major reviews were given by Lange *et al*. (1972), Štemprok (1986), Štemprok & Šulcek (1969), Tischendorf (1989), Breiter *et al*. (1991), and, more recently, by Förster *et al*. (1999). The S-type, Older Intrusive Complex (OIC-S) granites correspond roughly to common (high-K) calc-alkaline granites. Their evolution was marked by increase in Si, significant decrease in Ti, Mg, Fe, Ca, Sr, Ba, Zr, and only a slight increase in large ion lithophile elements (LILE: Rb, Li, Cs) and F.

Among the S-type, Younger Intrusive Complex (YIC-S) and A-type, Younger Intrusive Complex (YIC-A) granites, the major element trends are similar (with the exception of phosphorus). The most distinct feature is the increase in Al, Na and F, compared to the decrease in Si and K. Contents of Ti, Mg, Fe, and Ca are invariably low. Some differences between both suites could be seen in the trends of enrichment in LILE (Li, Rb, Cs), and also in F, U, Sn and W. In the case of the strongly peraluminous YIC-S granites this trend is more expressive. The principal differences between both suites refer to the contents of phosphorus and HFSE. This is well illustrated by plots in Figures 15-16.

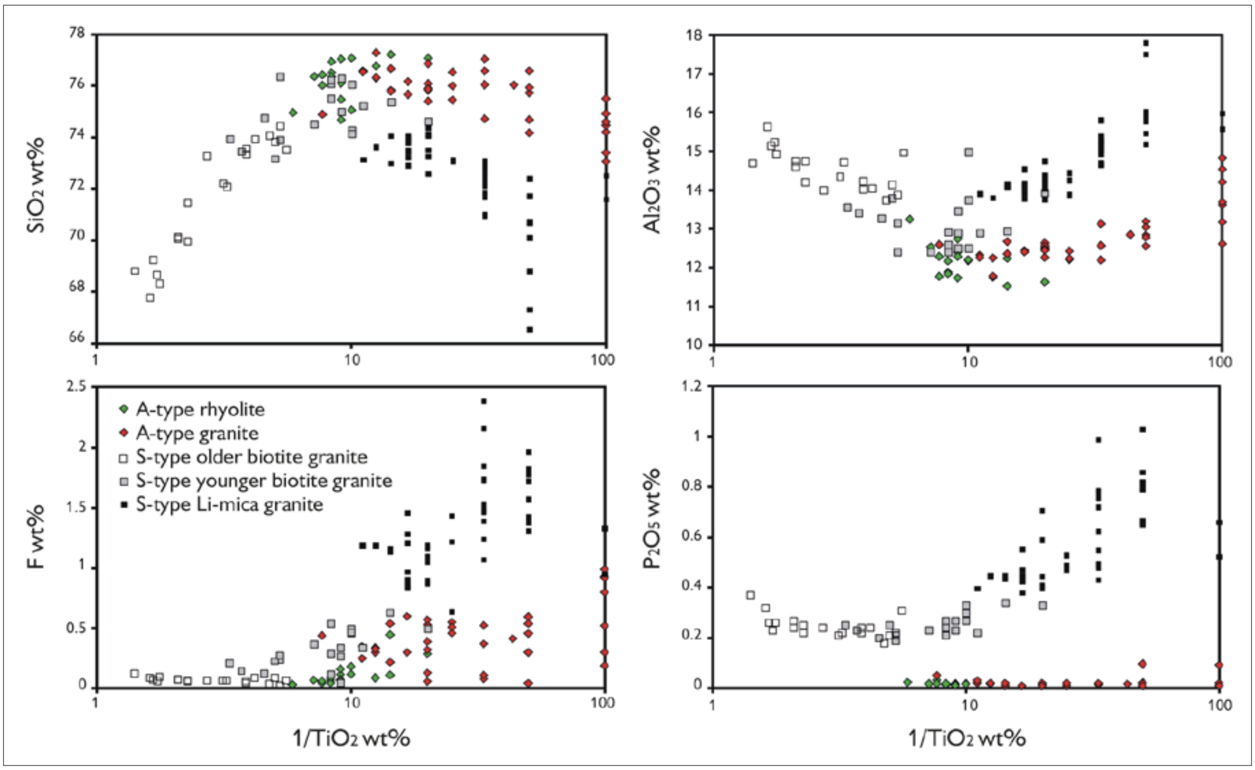

Figure 15. Geochemical composition of granites and rhyolites in the Krušné Hory/Erzgebirge – major elements.

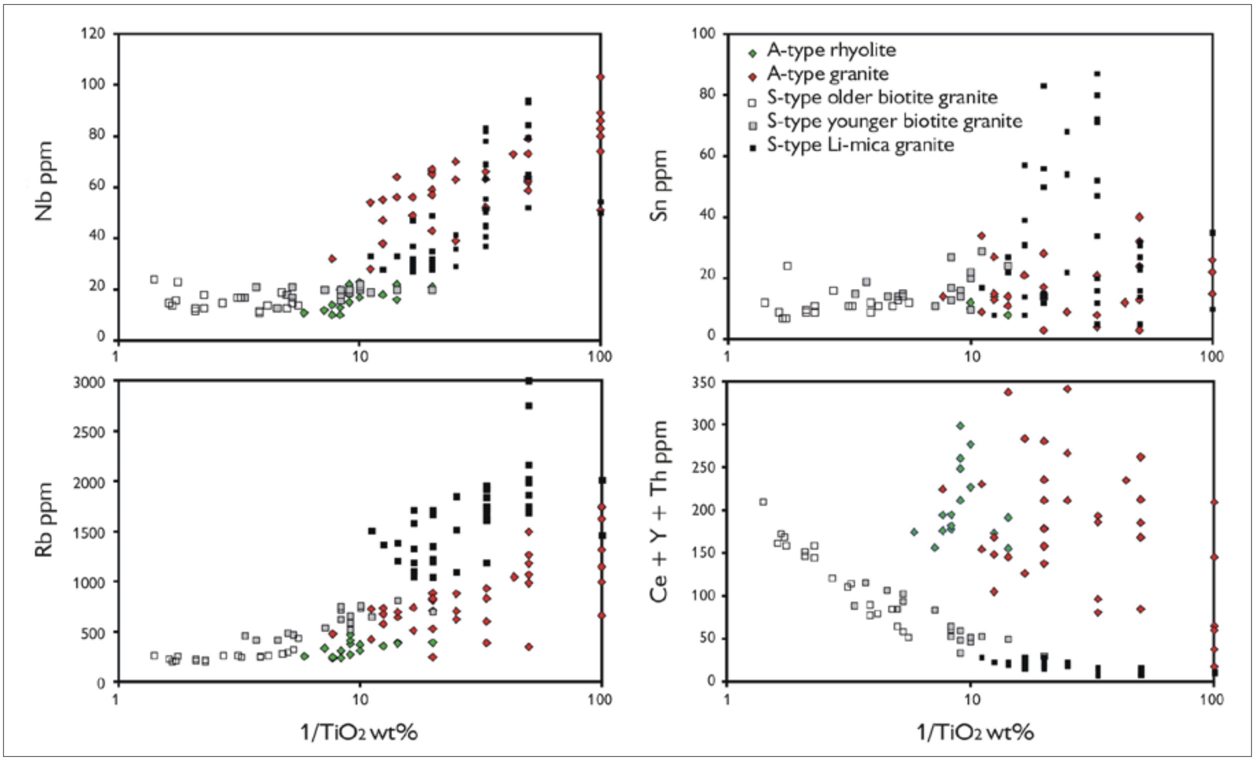

Figure 16. Geochemical composition of granites and rhyolites in the Krušné Hory/Erzgebirge – trace elements.

The evolved nature of the YIC granites is reflected by the Rb/Sr ratios, ranging from about 1 to more than 100. The Zr/Hf ratio ranges from 40 to 10, and U/Th from 0.1 to 5.

The Ca content in YIC-S granites is too low to balance all available P as just apatite. Thus, most P entered the alkali feldspar lattice (Frýda & Breiter, 1995). In the most fractionated intrusions, orthoclase contains more than 1% P_2O_5.

Almost all YIC granites were subjected to fluid-rock interaction that disturbed the magmatic geochemical patterns. The compositional and mineralogical effects of late-stage overprinting are observed particularly in granites spatially related to the Sn-W mineralization. In general, the extreme enrichment in rare alkalis (Li, Rb, Cs) and HFSE (Nb, Ta, Sn, W, U) is the result of strong differentiation in the upper parts of granitic systems enriched in water. The total REE contents and the LREE/HREE ratios decreased progressively during fractionation of peraluminous granite types. On the contrary, in the YIC-A granites the HREE increased and LREE/HREE decreased during fractionation. The 'tetrad effect' phenomena were documented in YIC-A leucogranites from Cínovec and Hora svaté Kateřiny, showing evidence of strong interaction with fluids enriched in F and CO_2 (Breiter *et al.*, 2009; Förster *et al.*, 2011).

SUBVOLCANIC INTRUSION OF FRACTIONATED GRANITES, MAGMATIC BRECCIATION AND LAYERING

The subvolcanic nature of the late small-scale mineralized intrusions is a typical characteristic of the ore-bearing systems in the Krušné Hory/Erzgebirge. The magma emplacement was marked by explosive-magmatic brecciation that caused the opening of the magmatic system, followed by a sudden pressure drop, undercooling, and evolution of layered textures and comb layers (Figures 17-18). Macroscopic evidences of this phenomenon had been observed more

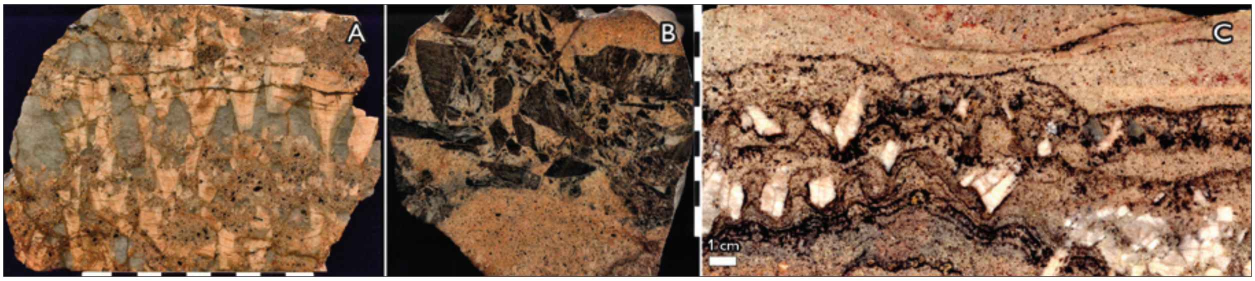

Figure 17. Magmatic textures from Podlesí granite stock: A) stockscheider at the upper contact of the granite stock: some large crystals of K-feldspar were broken and altered during brecciation, which followed shortly after stockscheider solidification; B) explosive breccia at the top of the granite stock: fragments of phyllite with fine-grained granite matrix; C) layered texture of the dyke granite in Podlesí with individual large K-feldspar and continuous layers of dark zinnwaldite.

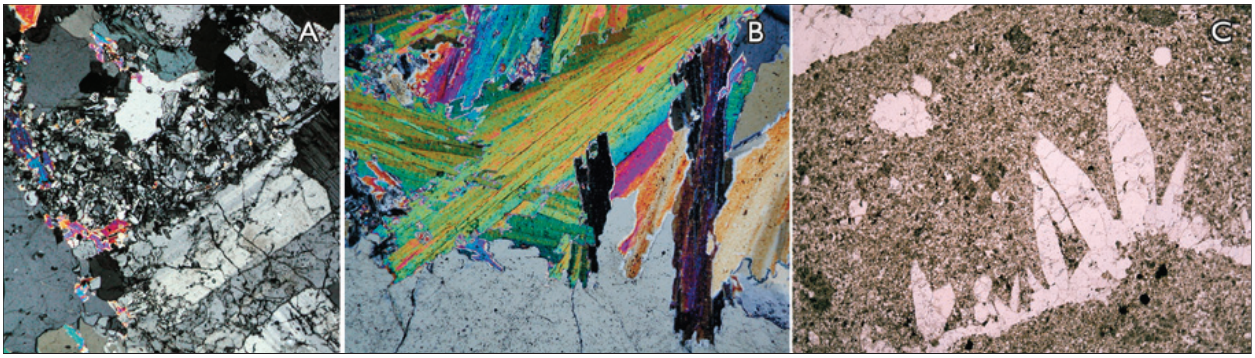

Figure 18. Examples of small-scale textures: A) two-phase rock (medium-grained crystals and very fine matrix) – response of sudden drop of pressure in the dyke granite at Podlesí (ca. 12 x 10 mm); B) aggregate of oriented zinnwaldite crystals from the dyke granite at Podlesí (12 x 10 mm); C) comb-quartz layer in the A-type granite, Hora svaté Kateřiny (area of 3 x 2 cm).

than one hundred years ago, but the igneous origin of the breccia was recognized only recently (Seltmann *et al*., 1987, 1992; Jarchovský & Pavlů, 1991). The most striking expression of these subvolcanic granite intrusions was described in detail in Podlesí (Breiter *et al*., 1997, 2005, 2006, 2007; Breiter & Kronz, 2004; Breiter & Müller, 2009).

The Podlesí granite stock in western Krušné Hory Mountains represents the most fractionated part of the Nejdek-Eibenstock pluton. Internal fabric of the stock has been studied in several boreholes down to 350 m depth (Figure 19). The stock is composed of two tongue-shaped bodies of albite-protolithionite-topaz granite (stock granite) which coalesce at depth. These rocks were intruded into Ordovician phyllite unit and into a biotite granite belonging to a Younger Intrusive Complex (YIC) of the Nejdek pluton. The uppermost part of the intrusion is bordered by a layer of marginal pegmatite (stockscheider) up to 50 cm thick. Explosive breccia was mapped at the southwest contact of the stock. It is made up of fragments of phyllite, variying in size from several millimetres up to 5 cm, cemented by a fine-grained granitic matrix of similar composition to that of the stock granite. Within the uppermost 100 m, the stock granite is intercalated with several mostly flat-lying dykes of albite-zinnwaldite-topaz granite (dyke granite) with thickness of up to 7 m. A prominent example of layering with unidirectional solidification textures (UST) was described in the upper part of the major dyke. Individual quartz-akali feldspar laminae are separated by comb-quartz layers, comb-orthoclase layers and/or by layers of oriented fan-like zinnwaldite aggregates. Post-magmatic processes, particularly greisenisation, developed only to a limited

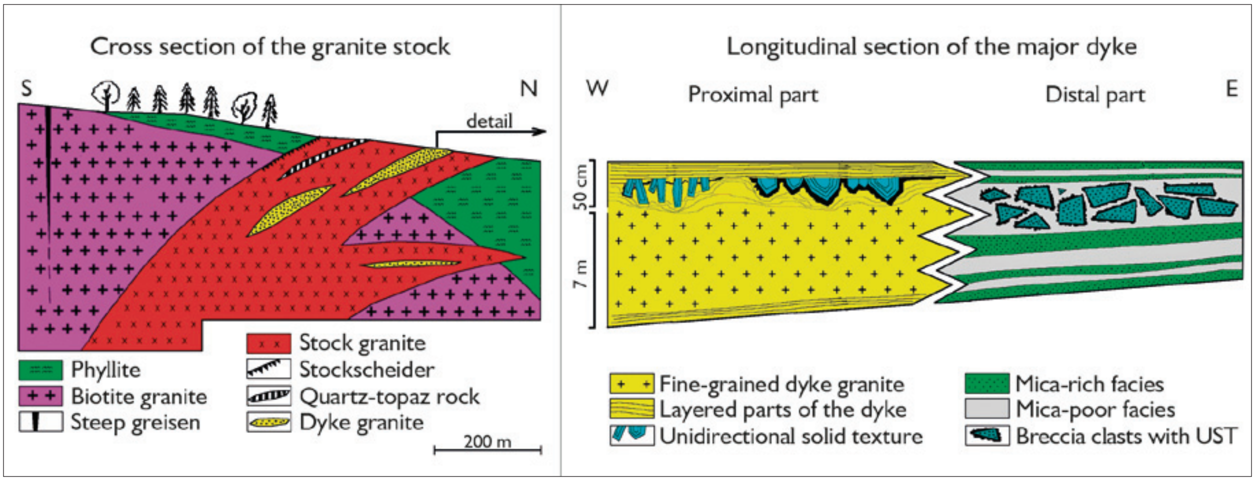

Figure 19. Podlesí idealized cross-section of the granite stock (left) and detail of the major dyke (right).

degree. The uppermost flat dyke of the dyke system was partly altered into white quartz-rich (+topaz, Li-mica, wolframite) greisen. Scarce thin, stringers of biotite greisen were reported on outcrop and in drilled portions of the stock granite and the enclosing biotite granite. The stock granite is strongly peraluminous (A/CNK = 1.15-1.25), enriched in incompatible elements such as Li, Rb, Cs, Sn, Nb, W, and poor in Mg, Ca, Sr, Ba, Fe, Sc, Zr, Pb, and V. The rock is rich in phosphorus (0.4-0.8 wt% P_2O_5) and fluorine (0.6-1.8 wt% F). A high degree of magmatic fractionation is indicated by low K/Rb and Zr/Hf ratios (22-35 and 12-20, respectively) and high U/Th ratio (4-7). The dyke granite is even more enriched in Al (A/CNK = 1.2-1.4), P (0.6-1.5 wt% P_2O_5), F (1.4-2.4 wt%), Na, Rb, Li, Nb, Ta, and depleted in Si, Zr, Sn, W and REE. The K/Rb (14-20) and Zr/Hf (9-13) ratios are lower than those from the stock granite.

Based on all available data, the following evolutionary model was developed: pronounced fractionation of the YIC-melt (Younger Intrusive Complex of the Nejdek pluton) produced small amounts of residual F, P, Li-rich melt (stock granite melt) which was emplaced at a shallow depth as a tongue-shaped body. The rapid emplacement was accompanied by brecciation of the overlying phyllite. Composition of the emplaced 'primary' melt was similar to the present stock granite. Its crystallization started from the outer upper part of the stock. This represents the rapidly cooled primary melt without major late- and post-magmatic alteration. Beneath the rapidly crystallized carapace, the melt became enriched in water and volatiles. In deeper parts of the stock, subsequent fractionation produced a very small amount of residual melt extremely enriched in F, P, Li and water. When cooling of the upper part of the stock allowed opening of brittle structures, the residual melt intruded upwards, forming a set of generally flat dykes. Crystallization of the major dykes proceeded in closed-system conditions from the bottom upwards. Volatiles and exsolved bubbles of water-rich fluid migrated to the upper-most part of the dykes. When the exsolved water pressure overcame the lithostatic pressure and cohesion of surrounding rocks, the system opened. Propagation of the pre-existing cracks or opening of new cracks started. Vapor escaped and the adiabatic decrease in pressure resulted in sudden decrease in temperature. The UST crystallized from the undercooled melt. This process was repeated several times. Non-equilibrium crystallization in layered rock produced small domains with contrasting chemistry and finally very small amounts of liquids of unusual composition.

GRANITE-INDUCED MINERALIZATION

The Krušné Hory/Erzgebirge area is the classic area of tin mineralization in continental Europe (Oelsner, 1952; Schröcke, 1954; Breiter & Seltmann, 1995; Freels *et al*., 1995; Hösel *et al*., 1997; Weinhold, 2002). The following main types of tin (+W, Nb, Ta, Li) mineralization can be distinguished:

- Sn-W-bearing zinnwaldite-topaz greisens in the cupolas of the youngest intrusions of complex granitic plutons. Greisenisation of varying intensity affects the entire mass of the granite body. High levels of rare alkalis (Li, Rb, Cs) and fluorine are characteristic. This type of mineralization is related to both geochemical types of granites. Mineralized cupolas of S-type granite occur in both subvolcanic (Krásno deposit, Jarchovský & Pavlů, 1991) and plutonic (Ehrenfriedersdorf and Geyer deposits, Seltmann *et al*., 1995) settings. Mineralization in A-type granites is known only in the subvolcanic setting where intense hydrofracturing occurred, e.g. Cínovec/Zinnwald, Altenberg and Sadisdorf deposits (Seltmann, 1994);
- Sn-W-bearing muscovite-topaz greisens (Li-poor) with Cu-sulphides and intense brecciation were developed exclusively in subvolcanic stocks and dyke swarms of A-type granites and rhyolites (Seifen and Gottesberg deposits, Gottesman *et al*., 1994);
- Sn-bearing muscovite greisens of vein morphology (Li, Rb, Cs, F-poor) are typical of the S-type Nejdek-Eibenstock pluton. They were formed by fracture-related greisenisation affected by fluids rising from deep intrusions of more fractionated magma (Rolava and Přebuz deposits);
- Small, mainly W-bearing muscovite greisens in the apical parts of moderately fractionated facies of S-type granites of Nejdek-Eibenstock pluton (Vykmanov and Boží Dar deposits, Absolonová & Pokorný, 1983);
- Quartz veins with wolframite in the late differentiated products of the OIC granites (Rotava deposit in the Nejdek-Eibenstock pluton and Pechtelsgrün deposit in the Kirchberg pluton).

Recent studies of fluid and melt inclusions support a late-magmatic to early post-magmatic origin for the Sn-W mineralization with metal sources in the granite itself. Hydrothermal processes with distant (deep-seated) sources of metals are less likely (Rickers *et al*., 2006; Borisova *et al*., 2012).

TIN-TUNGSTEN KRÁSNO DEPOSIT

The area of Slavkovský Les Mountains (located to the SW part of the Krušné Hory/Erzgebirge region) consists of a series of Upper Proterozoic to Lower Palaeozoic high-grade deformed metamorphic rocks into complex faulted and folded structural patterns. The post-orogenic Variscan granitoids are divided into three groups (Fiala, 1968):

1. Older Intrusive Complex of mainly porphyritic biotite granites with large orthoclase phenocrysts (Carlsbad twins);
2. Transitional two-mica granites; and
3. Younger Intrusive Complex of two-mica Milíře granite and F, Li, Rb, Sn, U-enriched Li-mica albite granite of the so-called Čistá type.

The latter forms a laccolith body which was intruded between gneisses and the older granites at the southern margin of the Krudum pluton. The NE-SW trend of the intrusion corresponds to the elongation of mineralized cupolas and – at the same time – to the strike of mineralized vein structures. The eastern part of the Krudum pluton was cut by a regional NW-SE-trending fault. A thrust of around 300-400 m along this fault enabled the upper parts of three Li-F granite cupolas (stocks) under the gneiss cover to be preserved. Cupolas located to the west of this fault were deeply eroded exposing their lower parts in the outcrops.

The main type of granite forming the cupolas (local name 'Čistá granite') is a medium-grained alkali-feldspar granite of hypidiomorphic texture. It contains albite (An_{5-8}) as a primary constituent together with quartz, perthitic orthoclase, protolithionite-zinnwaldite mica and topaz (+apatite, zircon). Geochemically, it is peraluminous, enriched in Li, Rb, Cs, F, Sn, Be and Nb and poor in Ti, Ba, Sr, Th, and Zr.

All the known mineralized cupolas in the Krásno district (Hub, Schnöd, Konik, and Vysoký kámen) exhibit truncated cones shapes, looking ellipsoidal in plan-view. Their contact with the surrounding gneisses is sharp and discordant (Figure 20). The first product of granitic magma emplacement was an albite-topaz microgranite cementing brecciated gneiss and forming dykes penetrating the gneiss roof. Then the marginal pegmatite (stockscheider) developed in the form of lenticular bodies at flat-dipping contacts of the granite cupolas and as rims at lower margins of gneiss xenoliths. The stockscheider consists of large elongated K-feldspar crystals, arranged perpendicular to the contact surface. From the zone rich in feldspar crystals the stockscheider passes gradually into a fine-grained albite granite. Most of the apical parts of the cupolas were to some extent greisenized. The greisen bodies are structurally controlled, following approximately the gneiss contacts or are developed along irregular fracture systems (Jarchovský in Breiter & Seltmann, 1995).

Greisens, as products of metasomatic replacement, present a variable structural patterns, depending mainly on the grain size and structural preparation of the parental rock. The prevailing greisen type found in cupolas in the Krásno ore district is massive from a structural stand point, and consist of a quartz-zinnwaldite-topaz mineral assemblage. In thin sections, aggregates of lobate quartz grains (52-85 vol.%) surround topaz (8-20%) and flakes of pale brown Li-mica (8-30%). Quartz contains parallel streaks of minute fluid inclusions. Apatite is a typical accessory. A light coloured quartz-topaz greisen prevails at the top of cupolas. Relics of zinnwaldite are often preserved in quartz. Locally extreme greisen varieties, practically free of quartz, e.g. 'topazite' (topaz + fluorite + dickite) or 'micafels' (muscovite + fluorite + apatite), occur in 'pockets' near the fluid-feeding fissures. The total vertical extent of the greisen zone is about 150-200 m.

At lower levels, it is observed a continuous transition of greisens into partly greisenized granite. These levels show additionally intense low-temperature alteration (argillization) which partly affected even topaz and mica in the overlying greisens. Typical minerals are sericite, kaolinite, and fluorite. This type of alterations is devoid of ore minerals.

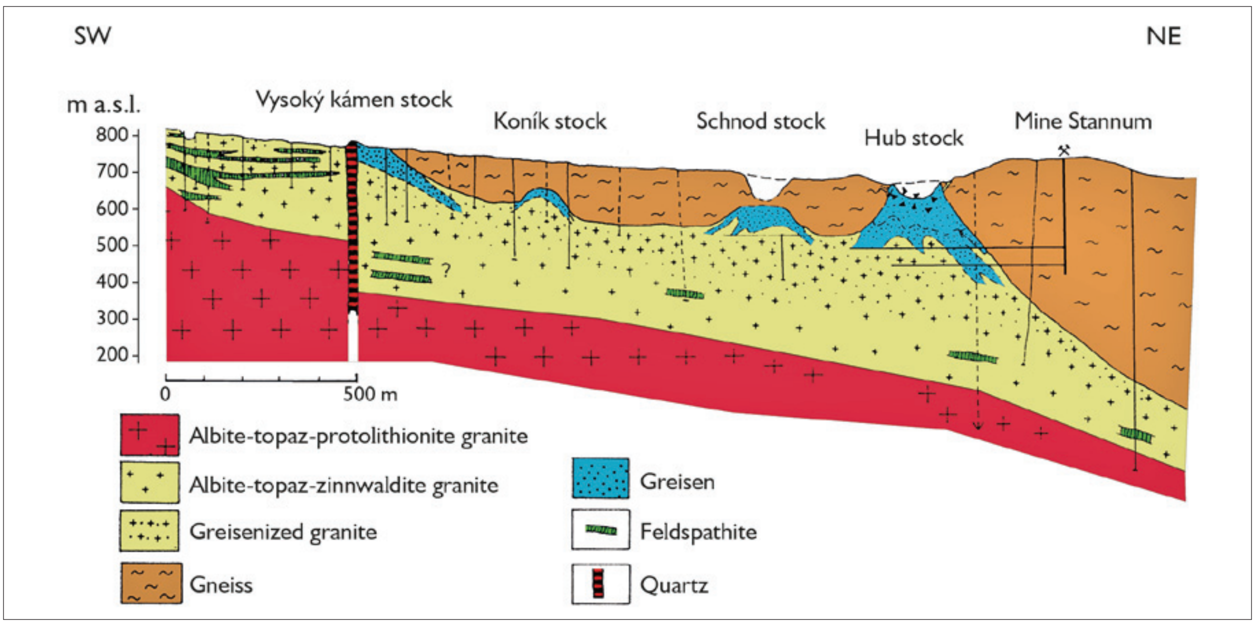

Figure 20. Krásno: longitudinal cross-section through the main mineralized granite cupolas (acc. to Jarchovský). Legend: m a.s.l. = metres above sea level.

At deeper levels, a gradual transition into fine-grained, mica-poor, fine-grained aplitic albite granite can be observed. This granite is composed of quartz (30-40%) and up to 60% of feldspars-albite (An_{3-5}) and K-feldspar (7 to 11% of unexsolved Na component). Albite prevails slightly over orthoclase. Zinnwaldite, muscovite, apatite, rutile, topaz and rare garnet are the main accessory minerals. Ore minerals are absent.

This granite contains several sub-horizontal layers and lens-shaped bodies of feldspathites, with thickness that varies from tens of centimeters up to 35 meters (Figure 21). The feldspathites are composed mostly of orthoclase and albite, with subordinate amounts of quartz and green apatite. The bulk content of alkali oxides in feldspathites is up to 15%. The aplitic albite granite passes downwards into an unaltered 'normal' YIC lithium-fluorine granite; the contact is sub-horizontal and mostly sharp. Geochemically, it is marked by a strong increase in Fe and Li contents in the Li-F granite identical with the Čistá granite (YIC) from the nearby Krudum body.

The main core of the ore-grade mineralization is confined to the greisen bodies (Figure 22). The top of the stocks consists mainly of light-colored quartz-topaz greisen with embedded Sn-W-As-Cu minerals, whereas at the lower level the rock consist of darker quartz-mica-topaz greisens with accessory cassiterite. The Sn/W ratio (~ 5:1) slightly increases with depth. Sporadically, greisen bodies contain high grade 'ore pockets' filled with cassiterite (less often with wolframite) and topaz (Jarchovský, in Breiter & Seltmann, 1995).

About 228 minerals (Beran & Sejkora, 2006) have been described in rocks from the Krásno district. Common minerals of this area include quartz, zinnwaldite, muscovite, topaz, cassiterite, wolframite, chalcopyrite, sphalerite, arsenopyrite, apatite, fluorite, hematite, albite, adularia, calcite, and siderite. Less common are carpholite, stannite, molybdenite, triplite, isokite and other phosphates, bornite, covellite, rhodochrosite, scheelite, cookeite; rare species include emplectite, beryl, bismuthite, stibnite, bismuth, stannoidite and djurleite, wittichenite. Recently, also 25 new secondary minerals for the Czech Republic have been identified.

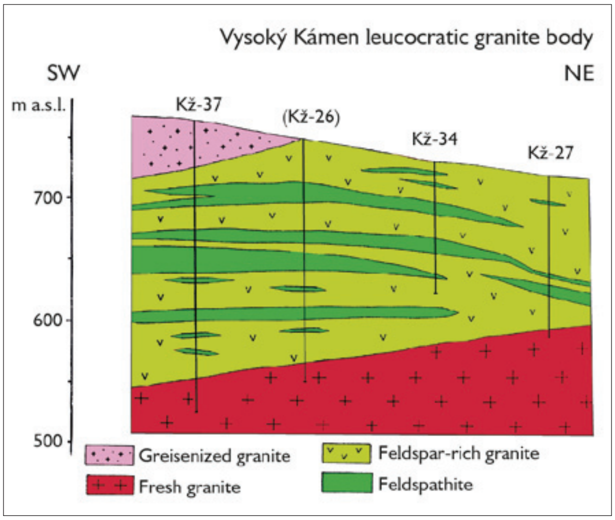

Figure 21. Krásno-Vysoký kámen quarry: cross-section through the deeply eroded granite cupola showing alkali-enriched deeper part of the ore-system (acc. to Jarchovský). Legend: m a.s.l. = metres above sea level.

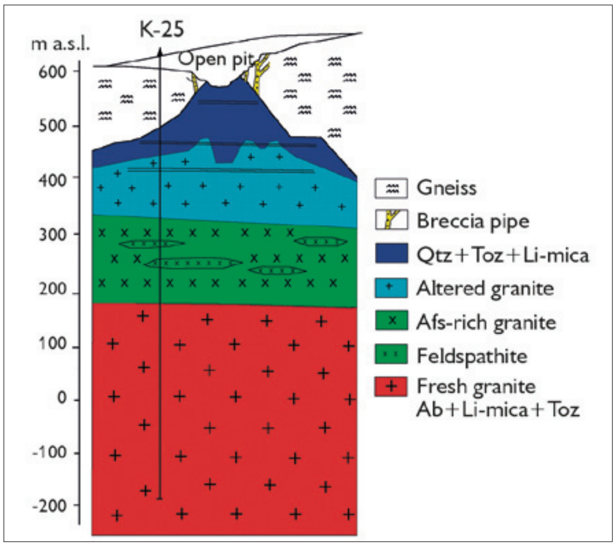

Figure 22. Krásno: schematic inner structure of mineralized granite cupolas in the Krásno ore district (acc. to Jarchovský). Legend: m a.s.l. = metres above sea level.

Few quartz veins have roots in the greisen zone of cupolas and pass usually into the surrounding rocks. Some of them have been mined to depths of 50 or even 100 m.

Reported thicknesses were up to 50 cm. Besides cassiterite and wolframite, a small amount of copper sulphides is commonly present. Worthwhile mentioning, it is the influence of the country rocks on the mineralization. For instance, a quartz vein passing through amphibolite changed its composition to orthoclase + zinnwaldite + cassiterite instead of quartz.

Cassiterite from the Krásno deposit is mostly dark red-brown, grown as idiomorphic multiple twins. The Nb_2O_5 content is 0.4-0.8%.

TIN DEPOSIT OF KRUPKA

The broader vicinity of the Krupka deposit is formed by Upper Proterozoic crystalline rocks (paragneisses, orthogneisses, metagranites). In the Westphalian, huge amounts of acid volcanic rocks, the Teplice rhyolite, were extruded. This volcanic activity culminated in the development of the Teplice caldera with a surface of 25 x 45 km and intrusion of porphyry dykes around the caldera margins. The caldera development was followed by intrusion of two distinct types of granites along NW-SE trending faults that cross the central part of the caldera (Figure 23).

The older biotite granite forms the Preiselberg (Cranberry hill) pluton NW of Krupka. The body has an elliptical surface (850 x 500 m) and extends downwards in a shape of a cupola.

The younger albite-zinnwaldite granite forms, within the Czech territory, a hidden 10 km long ridge in the NW-SE direction, which continues further NW to Germany. From the hidden ridge, several distinctive elevations run up, only one of which (the Cínovec/Zinnwald deposit directly at

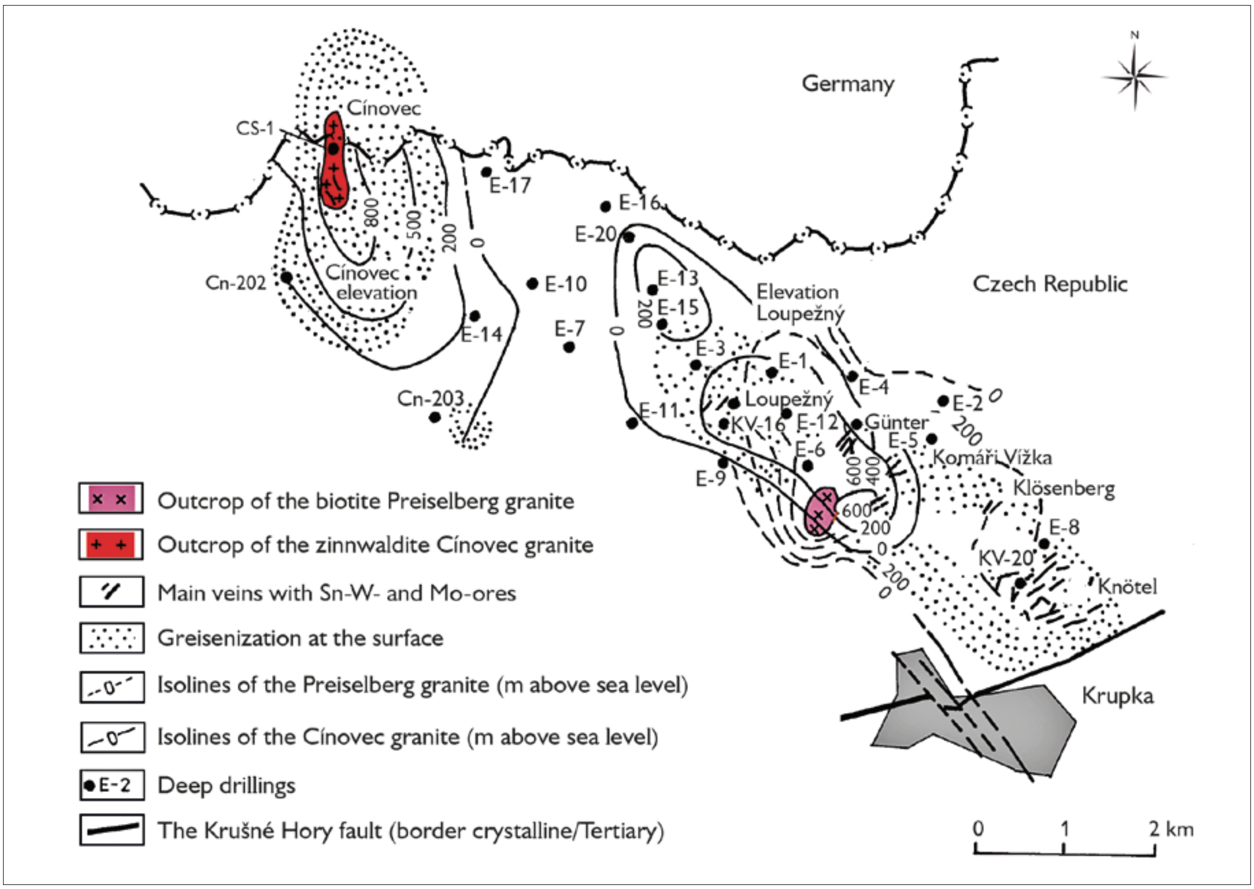

Figure 23. Krupka – sketch of mostly hidden granite pluton between Cínovec and Krupka.

the Czech/German border) is exposed at the surface and partly eroded. Other elevations are completely preserved. The Krupka district consists of two major elevations: the Preiselberg cupola and the Knotl stock.

The Preiselberg cupola is a conical body 265 m across at the level of the entrance gallery, and 180 m high, terminated by two greisen caps with cassiterite, wolframite, and sulfide mineralization (Figures 24-25).

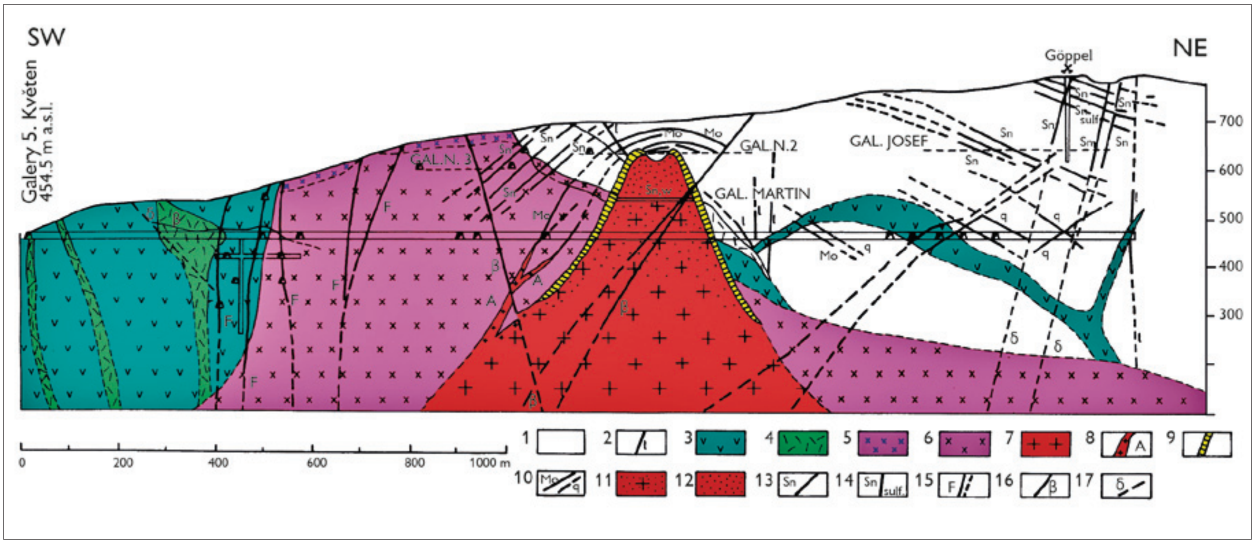

Figure 24. Krupka-Preiselberg cupola. Longitudinal section through the 5. Květen gallery acc. to Eisenreich & Breiter (1993): 1) gneiss; 2) lamprophyre dykes; 3) rhyolite; 4) felsic porphyry granite; 5) Preiselberg biotite granite, marginal fine-grained facies; 6) Preiselberg biotite granite, main medium-grained facies; 7) albite-zinnwaldite granite; 8) albite-zinnwaldite aplite; 9) stockscheider; 10) quartz veins with molybdenite; 11) greisenized granite; 12) greisen; 13) greisen with cassiterite; 14) quartz vein with cassiterite and sulphides; 15) fluorite veins; 16) basalt dykes; 17) faults. Legend: m a.s.l. = metres above sea level.

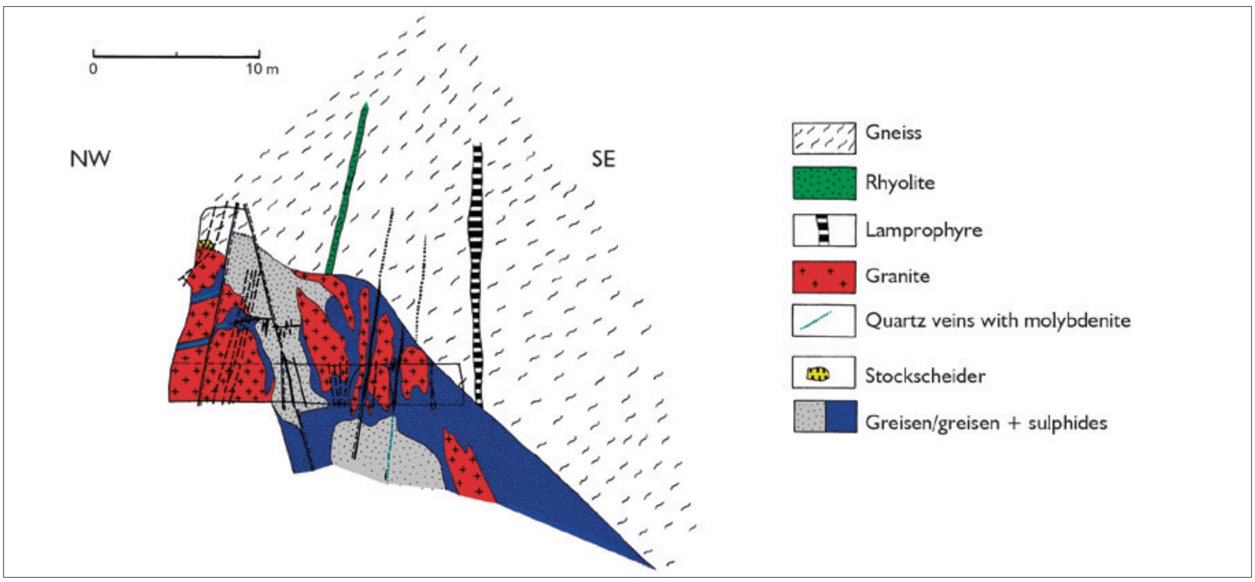

Figure 25. Krupka-Preiselberg – detail cross-section of southern cap of the Preiselberg cupola of albite-zinnwaldite granite (acc. to Janečka *et al*., 1971, unpublished report).

The Knotl cupola corresponds to a WNW-ESE ridge, which forms a steep stock that splits into many apophyses in the space of the former molybdenite mine (Figure 26). Compared with the Preiselberg cupola, greisenization is lower, but the stockscheiders and quartz-molybdenite mineralization are maximally developed. This stock continues upwards as a tabular breccia body and outcrops on the present surface. The breccia is composed of gneiss fragments cemented with fine-grained granite whose fragments vary in size from a few centimeters to meters. The breccia was silicified and ultimately greisenized.

The stockscheiders at Krupka are excepcionally well developed. Their mineralogical composition is quite simple – quartz, orthoclase, and Li-Fe mica. The mutual ratios of these components and their grain size are variable. The thickness of the stockscheider rims ranges from several centimeters to several meters. They never contain cassiterite, but may be mineralized with wolframite, molybdenite, and Bi-sulfides. At the contact with the Preiselberg biotite granite, the stockscheider is developed just locally with maximun thickness of 12 m. The stockscheider at the level of the Barbora gallery, in Knotl, forms a large body and was mined in the 1950's during a short period of time for the ceramic industry. In other places (Václav gallery in Knotl, Nový Martin adit in Preiselberg) the stockscheider consists of a pure quartz rim, 4-5 m thick, characterized by giant zoned crystals, whose increments are separated by mica coatings.

Results of extensive exploration over the past 100 years have been published by Beck (1914), Žák (1966), Štemprok *et al*. (1994), Eisenreich & Breiter (1993) and Sejkora & Breiter (1999).

Quartz veins with molybdenite are the oldest mineralization event which took place in the period between the intrusion of the albite-zinnwaldite granite and the main stage of its greisenization. Some of quartz-molybdenite veins are parallel to the granite-gneiss contact, while others developed within the breccia pipe at the top of the stock.

Greisens of the albite-zinnwaldite granite are mainly developed in the Preiselberg cupola where it forms large, irregularly banded bodies in the proximity of the contact zone, along both steeply dipping and flat joints. The amounts of major minerals (quartz, topaz, Li-Fe

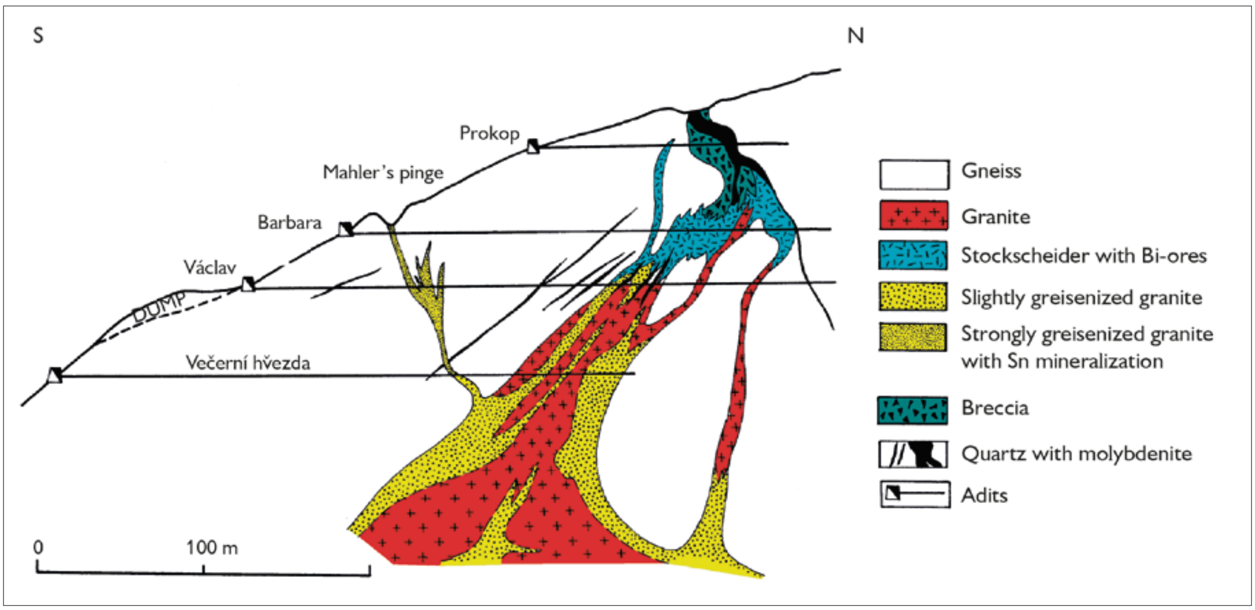

Figure 26. Krupka-Knotl: cross-section of the tin, molybdenum and feldspar deposit.

mica, muscovite) as well as the minor ones (cassiterite, wolframite, fluorite, sulfides, scheelite, apatite) are variable. Tin mineralization is developed in the form of lenses, irregular pockets, thin veinlets, and disseminated on the wall-rock, along both the steep and flat joint systems. Vertical zoning of the Preiselberg cupola is prominent. Very fine-grained quartz and quartz-topaz greisens with cassiterite, arsenopyrite, and Cu-sulfides occur in the caps of the stock in gallery No.2. At the Martin horizon, quartz-mica greisens are coarser-grained with average contents of 0.3 wt% Sn+W, characterized by flat quartz-zinnwaldite veins, with well developed greisen rims. At greater depths, at the main entrance adit level, unmineralized quartz-mica greisens alternate with sericitized granite.

The post-greisenization quartz veins with cassiterite were the main target of the mining in the past. The veins can be divided into two categories: the relatively older gently dipping and younger steeply dipping types. The Lukáš vein, mined in the Martin gallery, is the most important example of flat veins. Its average thickness was about 25 cm with dips of 25-30° to the SW, and average metal content of 2.2 wt% Sn. The neighboring gneiss is greisenized along a 10 cm thick alteration halo. Vertical zoning is also well developed. The upper part contains quartz with cassiterite, wolframite, Cu- and Bi-sulfides, scheelite, fluorite and apatite. Here, several cm-thick layers of nearly pure cassiterite were developed along the lower contact of the vein. The presence of cassiterite and sulfides decreases downwards, while feldspars and Li-Fe mica increases. At the lowermost levels, the vein presents a pegmatitic character. Steep 'ore veins' can be generally characterized as fills of joints and fractures in the upper levels of the albite-zinnwaldite granite body. They typically occur in gneisses. In rhyolite and biotite granite, they split and pinch out rapidly. The orebodies are mineralized with cassiterite, wolframite and sulfides; locally they consists of openings filled with quartz and exhibit prominent greisenization of the wall rocks. They are NE-SW trending, i.e. perpendicular to the overall granite ridge orientation, mineralization is irregular, commonly as lenses, and locally high-grade.

Succession of the magmatic and hydrothermal processes in the Krupka district and its environs can be summarized as follows:

1. intrusion of the barren pre-caldera S-type biotite granites in the Fláje and Telnice bodies (outside the ore district);

2. extrusion of the A-type Teplice rhyolite, formation of caldera, ring dykes of the granite porphyry;

3. intrusion of the A-type Li, F-enriched Preiselberg biotite granite;

4. intrusion of the A-type Li, F-rich albite-zinnwaldite granite along the NW-SE tectonic line, formation of cupolas and stocks, formation of explosive breccia at top of the Knotl stock;

5. crystallization of the Li, F-rich melt started with the stockscheider. At the same time, the first (main) generation of quartz-molybdenite veins was formed along gently dipping joints in the proximity of the granite;

6. in response to tectonic movements, the melt from the inner part of the body was pushed up into the already crystallized space where brecciation and immediate cementation with a new melt took place;

7. supply of greisenization fluids from the deeper part of the granite body, greisenization in both endo- and exo-contacts;

8. the youngest aplites were released from the magma reservoir, another stage of quartz-molybdenite vein formation;

9. formation of gently dipping quartz veins with cassiterite and wolframite; and

10. opening of the steep NE-SW trending tensional joints, new supply of fluids and formation of the youngest cassiterite-wolframite mineralization.

At present, the following reserves of Sn-W and Mo ores are registered here (not all economic):

1. greisenized granite of the Preiselberg stock: 6.7 milions tons of ore with 0.13 wt% W and 0.05 wt% Sn, and 409,000 tons of ore with 0.23-0.25 wt% Sn and 0.07-0.15 W;

2. greisenized rhyolite and gneiss at Preiselberg: 437,500 tons of ore with 0.417 wt% Sn;

3. vein-type ores: 549,000 tons of ore with 0.21 wt% Sn and 0.1 wt% W;

4. quartz vein with molybdenite: 5,800 tons of ore with 0.48 wt% Mo.

TIN DEPOSIT OF VEIN-GREISEN TYPE

The western part of Krušné Hory/Erzgebirge consists of Ordovician chlorite-sericite phyllites interlayered with quartzites, metabasites and skarns. All these rocks were intruded by the Upper Carboniferous peraluminous granites of the Nejdek-Eibenstock pluton.

Several types of tin and tungsten mineralization in the northern part of the Nejdek-Eibenstock pluton and the surrounding phyllites can be distinguished, but only the so-called 'vein-greisen' type was important from an economic standpoint, where Hřebečná, Horní Blatná, Rolava (Figures 27-28) and Přebuz were the most important ones.

The morphology of the greisen veins is controlled by a network of fractures. The ore bodies consist of systems of joints which are in places filled with quartz veinlets loaded with cassiterite, and greisen bands. The individual greisen bands vary in thickness from a few centimeters up to tens of centimeters; in places, parallel bands merge into a compact ore zone, often several meters thick. The joints, which appear in the middle of the greisen veins, are mostly closed, without any observable displacement. Tectonic gouge has been recognized only scarcely in the center of the structure. The intensity of greisenization decreases outwardly, but the greisen/granite boundary is sharp.

The zones of greisen veinlets may be up to 100 m wide and more than 1 km long.

Greisen zones of the deposits in the central and western parts of the pluton exhibit a prevailing orientation (Rolava and Přebuz deposits), whereas in the surroundings of Horní Blatná there exist tin deposits with greisens oriented in every direction.

Figure 27. Rolava – processing plant constructed during WWII. From Fotoarchive of the Czech Geological Survey.

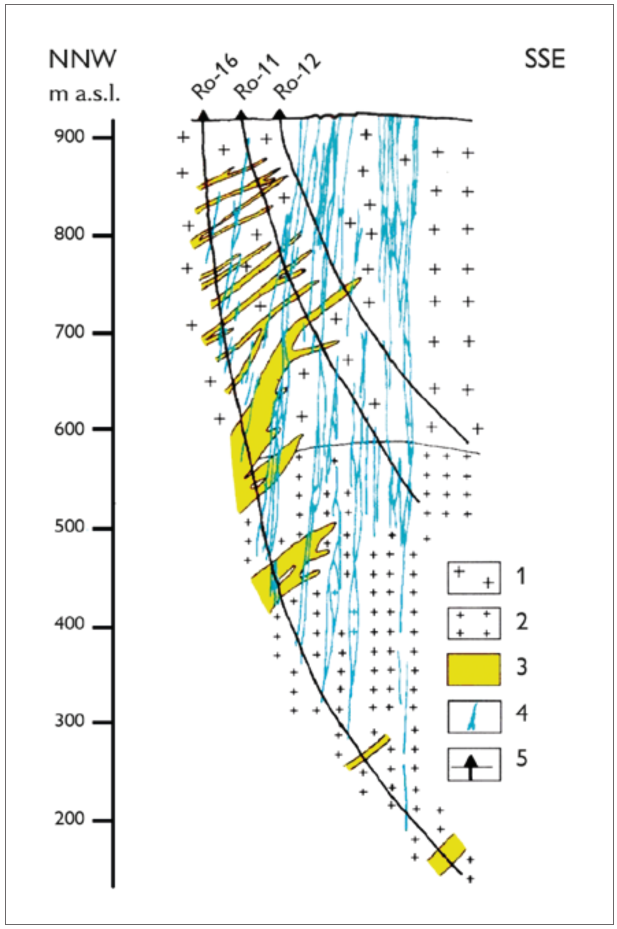

Figure 28. Cross-section of the Rolava deposit: 1) coarse-grained biotite granite; 2) medium-grained biotite granite; 3) topaz aplite; 4) 'vein' greisens; 5) boreholes. Legend: m a.s.l. = metres above sea level.

The greisens of the Horní Blatná body display a variety of mineral phases, namely quartz, topaz, muscovite, tourmaline, chlorite and adularia; apatite, fluorite and zircon occur in accessory amounts. The greisens in Rolava and Přebuz are quite monotonous, being formed by quartz and muscovite with some topaz. Cassiterite is the main ore mineral and precedes the greisenization itself. Short, prismatic, remarkably zoned dark-coloured cassiterite crystals occur as impregnation and irregular clots in the greisen. The Sn content in the exploited greisens ranged from 0.5 to 1 wt% on the average. Other ore minerals are often represented by arsenopyrite, lollingite, Cu-sulphides and more scarcely by wolframite, molybdenite, native bismuth, lithium micas etc. Fluid inclusion studies (Ďurišová, 1984), indicate that the greisenization process started with high salinity solutions at 470-500 °C. The greisenization process itself took place at 400-300 °C and was affected by low salinity chloride solutions (< 10%).

The maximum vertical extension of the known mineralization is approximately 400 m (Rolava-East deposit).

Ag-Bi-Co-Ni-U JÁCHYMOV DEPOSIT

The Jáchymov deposit is located at the southern slope of the western segment of the Krušné Hory/Erzgebirge Mountains and occupies an area of about 30 km^2 (Ondruš *et al*., 2003a). The mineralized veins are hosted by a mica schist complex. The originally alternating pelitic and psamitic sediments with some intercalations of silicic rocks and basaltic lavas of Upper Cambrian age were metamorphosed and intensively folded during the Variscan orogenic event. The regional metamorphic grade decreases northward, where the mica schists give place to phyllites. Late Variscan granites of the Eibenstock-Nejdek pluton intruded this area well after the regional metamorphism (330-320 Ma). Relatively older barren biotite granites as well as younger tungsten-bearing granites crop out near the deposit. In the area of the deposit itself, granites form a coherent pluton at depths of 300-800 m. The Tertiary magmatism is represented by dykes and lava flows of various basalt varieties.

The Jáchymov ore deposit comprises roughly 200 ore veins, which can be divided into three groups:
(i) E-W-striking veins parallel to the host rock schistosity enclosing mylonitized rock fragments and clay minerals. This type is weakly mineralized. Higher grades are reported at the intersections with the N-S trending veins;
(ii) N-S-striking veins, which are much more important as far as mineralization is concerned;
(iii) NW-SE fault zones, where significant displacements of blocks are observed, are usually filled up only with quartz and hematite.

The N-S- and E-W-trending veins range on average from 20 to 30 cm thick (locally they can be up to 3-5 m thick) and up to 1 km in length. Their distribution is uneven. Lenticular mineralization concentrates particularly in sections where veins intersect reactive rocks (amphibolites, pyrite- and graphite-bearing rocks), at intersections of veins of different strikes, or at sections where the dip and strike deflects (Bernard, 1968). The main veins are accompanied by numerous offshoots.

The veins were formed by multiple mineralization pulses (Figures 29-30), but products of individual mineralization phases overlap spatially in the veins (Mrňa & Pavlů, 1967):

1. Pre-ore stage: quartz and chalcedony;
2. Older sulphide stage: common sulphides;
3. Uranium stage: dolomite, uraninite, some fluorite;
4. Arsenide stage: quartz, Ni-rich arsenide with native silver alternate with Co-rich arsenide with native bismuth;
5. Sulphoarsenide stage: dolomite with native arsenic and proustite (main carrier of Ag in the deposit), locally stephanite, pyrargyrite, argentite, sternbergite; and
6. Younger sulphide stage: calcite, galena, sphalerite, chalcopyrite, pyrite.

Modern mineralogical investigation (Ondruš *et al*., 2003b) recognized in Jachymov 117 primary ore minerals, 52 rock-forming minerals and 229 secondary minerals. Argentopyrite (in 1866), krutovite (in 1976), millerite (in 1845), sternbergite (in 1827), uraninite (in 1727) and

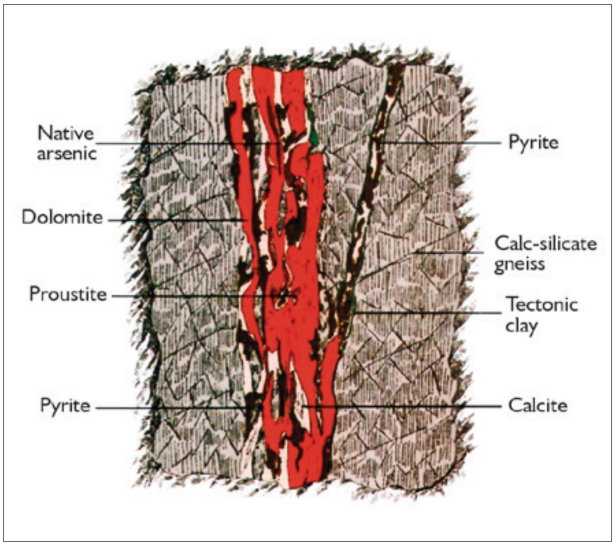

Figure 29. Jáchymov: example of the separation of an offshoot from the main vein, Svornost shaft, 1st Joachim level, Midnight Hildebrand vein. Drawn by J. Němeček in 1883. (acc. to Ondruš *et al.*, 2003a).

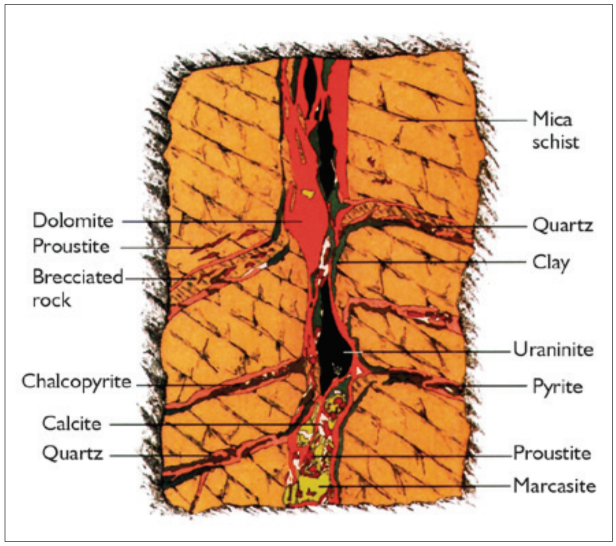

Figure 30. Jáchymov: typical example of a vein with many offshoots. Svornost shaft, adit level, Hildebrand vein. Drawn by J. Němeček in 1882. (acc. to Ondruš *et al.*, 2003a).

many secondary mineral species (after 1900) were firstly discovered and described in the very Jáchymov deposit.

CONCLUSIONS

All mining activities in the Krušné Hory/Erzgebirge temporary ended 20 years ago, but the knowledge accumulated along the years by exploration efforts and mine developments of a several local deposits such as Krásno, Krupka, Cínovec, Jáchymov, Freiberg etc., will support the generation of new geologic concepts to improve exploration programs to seek similar ore deposits in other parts of the world.

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