Geology and hydrothermal vein system of the Jáchymov (Joachimsthal) ore district

Geologie a hydrotermální žilný systém jáchymovského rudního okrsku

(26 figs, 1 tab)

PETR ONDRUŠ[1] – FRANTIŠEK VESELOVSKÝ[1] – ANANDA GABAŠOVÁ[1] – JAN HLOUŠEK[2] – VLADIMÍR ŠREIN[3]

[1] *Czech Geological Survey, Klárov 3, CZ-118 21 Prague 1*
[2] *U Roháčových kasáren 24, CZ-100 00 Prague 10*
[3] *Institute of Rock Structure and Mechanics, V Holešovičkách 41, CZ-182 09, Prague 8*

This contribution provides a brief review of geology of the Krušné hory Mts. (Erzgebirge) and specifically of the Jáchymov (Joachimsthal) deposit. Main types of rocks in the Jáchymov ore district and the role of tectonic processes are described. The position of the ore district is defined much like its tectonic borders. Geological factors controlling the mineralization (especially the so-called *five-element* mineralization) are summarized. Hydrothermal veins are divided into *Morning* and *Midnight* veins according to the classical historical speak of miners, and all vein clusters are listed. Vein hydrothermal *five-element* mineralization is chronologically divided into separate mineralization stages and their age is estimated.

Key words: Geology, Krušné hory Mts., Jáchymov deposit, rocks, tectonics, mineralization.

Review of geology of the Krušné hory Mts. region

The Krušné hory Mts. region belongs to the Saxothuringian Zone of the Variscan orogenic belt. In the Czech Republic, the zone is exposed in the Krušné hory Mts., Smrčiny Mts., and in the basement of the Ohře Rift (Eger Graben). The zone represents a fairly autonomous unit with a specific history of sediment accumulation, tectonics, granitic plutonism and metamorphism. The Krušné hory Crystalline Complex is composed of two main parts: 1. the Krušné hory Crystalline Complex *s.s.*, comprising Precambrian metamorphic rocks, 2. metamorphosed Lower Palaeozoic (Vogtland–Saxony Palaeozoic) volcanosedimentary unit. The main features of palaeotectonic evolution of the Krušné hory Complex belong to the Cadomian geotectonic cycle, including the deposition of marine sediments, intensive deformation and metamorphism which transformed the volcanosedimentary complex to phyllites, mica schists and gneisses. Large bodies of granite, emplaced in the Cambrian and dated to 524 ± 10 Ma [579] and ca. 550 Ma [580], were transformed into “red orthogneisses” during the Variscan orogeny. Relict contact metamorphism associated with the Cambrian granite intrusion is documented in some subareas.

The Arzberg Group of supposed Neoproterozoic to Cambrian age is usually considered to belong to the Cadomian cycle. The Lower Palaeozoic (Vogtland–Saxony Palaeozoic) volcanosedimentary unit was involved, together with intra-crustal thrust slices of the Cadomian basement, in the Variscan orogeny. The accompanying regional metamorphism features a wide range of conditions from the greenschist to eclogite facies.

The mobilistic concepts of nappe tectonics were proposed by Suess ([548], [549]), Kossmat ([417], [439]) and Scheumann ([541], [542], [543]) and later rejected. Modern studies, using quantitative estimates of metamorphic pressures and temperatures, result in the renaissance of kinetic models, including important thrusting (nappe) tectonics [409], [411], [496], [552].

In the central part of the Krušné hory (Erzgebirge) Mountains, the parautochthonous metasedimentary basement has been overthrust by a crustal nappe of orthogneisses [496]. Eclogites tied to structural base of the thick orthogneiss thrust unit show Variscan equilibration at 650–700 °C and 25 kbar. *Phengite–garnet–kyanite* mica schists from near the base of the orthogneiss thrust unit at Měděnec yielded estimates of 640 °C and 22 kbar (probably P_{min}) [496].

The crystalline complex shows a complicated Variscan structural record, with D_1 structures preserved in large eclogite boudins, D_2 structures with E–W-trending linear elements and flat-lying foliations corresponding to westward transport of the orthogneiss thrust unit, with late D_2 N–S-trending folds with flat-lying axes, and D_3 structures corresponding to a N–S compression resulting in refolds such as major E–W-trending Klínovec antiform and Měděnec antiform. Late brittle-ductile D_4 kink-band folds correspond to nearly vertical compression.

With regard to structural analysis, the traditional description of the regional structure in terms of NE–SW-trending Krušné hory Mts. (Erzgebirge) antiform and Smrčiny (Fichtelgebirge) antiform (Škvor [551]) may be more suited in morphological context or in connection with the Upper Carboniferous Krušné hory granite pluton.

An extensive contact metamorphism accompanying the emplacement of the Upper Carboniferous Krušné hory granite pluton is important as the granite pluton underlies much of the Krušné hory Crystalline Complex at subsurface level.

The Krušné hory Mts. region is characterized by prominent faulting. A majority of faults strike NW–SE and NE–SW, and also N–S- and E–W-striking faults occur in the Jáchymov area (Fig. 1). Among transversal (NW–SE) faults, the Jáchymov Fault is the most prominent one, with

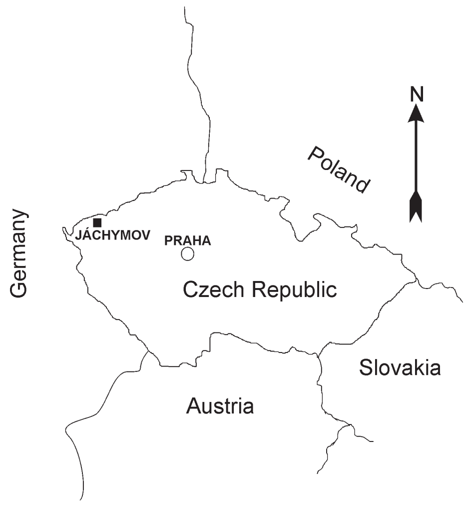

Fig. 1. Sketch map displaying the geographic localization of the Jáchymov ore district (black square).

interpreted continuation in deep crustal levels (so-called Boží Dar axial ramp of Máška and Zoubek [521], [537]). Numerous subparallel faults with spacings of several km show the same trend. The most important NE–SW-striking fault is the Krušné hory Fault. During the Late Tertiary and Early Quaternary, the Krušné hory Block was uplifted by 700 to 1000 metres along this fault (Škvor [551]).

Geology of the Jáchymov ore district

Large-scale mining produced extensive and detailed information on geology of the district [365], [390]. The main tectonic structure of the district is the E–W-trending Klínovec antiform. Steep flanks of the antiform are complicated by folds of a lower order. Metamorphic rocks are intruded by Upper Carboniferous granites of the extensive Krušné hory pluton. Granites are exposed on the surface in an elevated area southwest of the Bludná and Pernink fault zones and in greisenized small isolated massifs. The suite of dyke rocks associated with the granite pluton including granite porphyry, porphyrites, aplite, pegmatite and lamprophyres is also exposed on the surface. Tertiary magmatic rocks including alkali basalts, tuffs, volcanic breccias and minor trachyte belong to the Oligocene–Miocene neovolcanic phase of the Bohemian Massif (see Figs 2, 3).

Metamorphic rocks

Metamorphic rocks of the district represent an envelope of the Upper Carboniferous granite pluton, which reaches to the surface only on the southern margin of the district, near Mariánská. Nevertheless, subsurface extension of granites was documented by boreholes and underground works at relatively small depths below the whole ore deposit. Low- to medium-grade metamorphic rocks are represented mainly by mica schists and phyllites. Structurally lower parts consist of mica schists and micaceous gneisses of a probable Neoproterozoic and Cambrian age. Two-mica and *biotite* mica schists, sometimes with *graphite*, *garnet* and *pyrite*, are the most widespread rocks. Minor intercalations of calc-silicate gneiss, amphibolite, quartzite and orthogneiss are also present. The youngest metasedimentary rocks are phyllites of inferred Cambrian and Ordovician age.

Petrological studies indicate a complicated history of metamorphic evolution. Relics of *kyanite* in *muscovite–garnet* mica schists indicate elevated pressures. Mica schists of the Přísečnice Group contain *chloritoid* showing variable relations to *garnet*, including both *chloritoid* inclusions and overgrowths. The documented *chloritoid* localities constitute a belt between Měděnec, Antonín skarn deposit near Jáchymov and Gross Hammerberg near Oberwiesenthal. Some mica schists free of *garnet* carry *chloritoid* porphyroblasts up to 2 cm in size. Samples of schists from Jáchymov carry *garnet* with inclusions (including *rutile*), indicating syn-kinematic growth of *garnet*. Thermobarometry estimates on a *muscovite–garnet–chloritoid* schist from Srní near Jáchymov point to equilibration under amphibolite-facies conditions [496] (see Fig. 4).

Granite plutons

Postmetamorphic Variscan granitoids of the central part of the Krušné hory Mts. are represented mainly by the Karlovy Vary pluton. It is a compositionally inhomogeneous body of a lenticular or tongue-like shape up to 25 km wide, with a probable vertical extent of 10 to 12 km. Several successive intrusions are usually classified in terms of an older igneous complex (332–323 Ma), including a minor dioritic members and a dominant granite. The granite prevailing by volume is a medium-grained porphyritic *biotite* granite B with elevated thorium and uranium contents (Th > U). A younger igneous complex comprises dominantly leucocratic granite with uranium prevailing above thorium, and increased Nb, Sn and Be contents. Apical parts of these granite units are often greisenized and carry Sn mineralization, accessory *topaz*, *fluorite* and lithian *micas*. A *biotite*-rich zone up to 10 cm wide occurs at the contact of granite with metamorphic country rocks (schists). Some components enriched in the leucocratic younger granite (F, B, Li) functioned as solidus depressants, and the late melt fractions were strongly enriched in fluids. Metasomatic alterations superimposed on solid granite portions were dominantly of the acid leaching type resulting in greisenization, i.e., removal of primary feldspars, crystallization of secondary *albite*, *topaz*, *fluorite*, *tourmaline, Li-micas*, *wolframite*, *cassiterite*, minor *molybdenite*, *chalcopyrite* and *arsenopyrite*. A portion of the metals was probably derived from a similar source as the granite melts and brought up by fluids, using in part similar conduits as used by the intruding granite magma. Alkali elements released by greisenization were involved in the production of secondary *albite*- and *microcline*-rich domains to some extent. In the Jáchymov area, tin mineralization occurs rather in veins deposited by fluids rising along

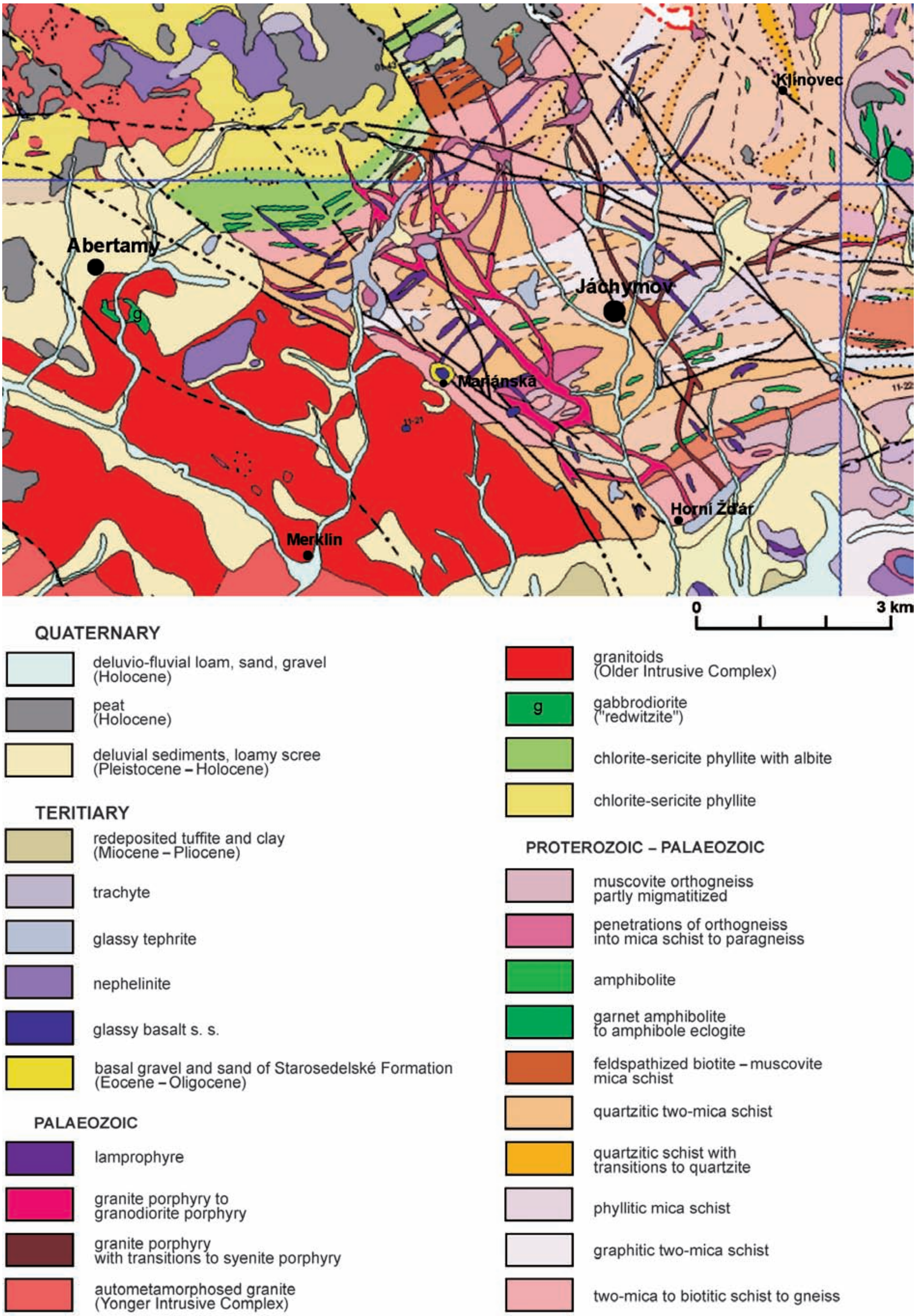

Fig. 2. Geological map of the Jáchymov area, simplified from 1:50 000 map (Czech Geological Survey, 2003).

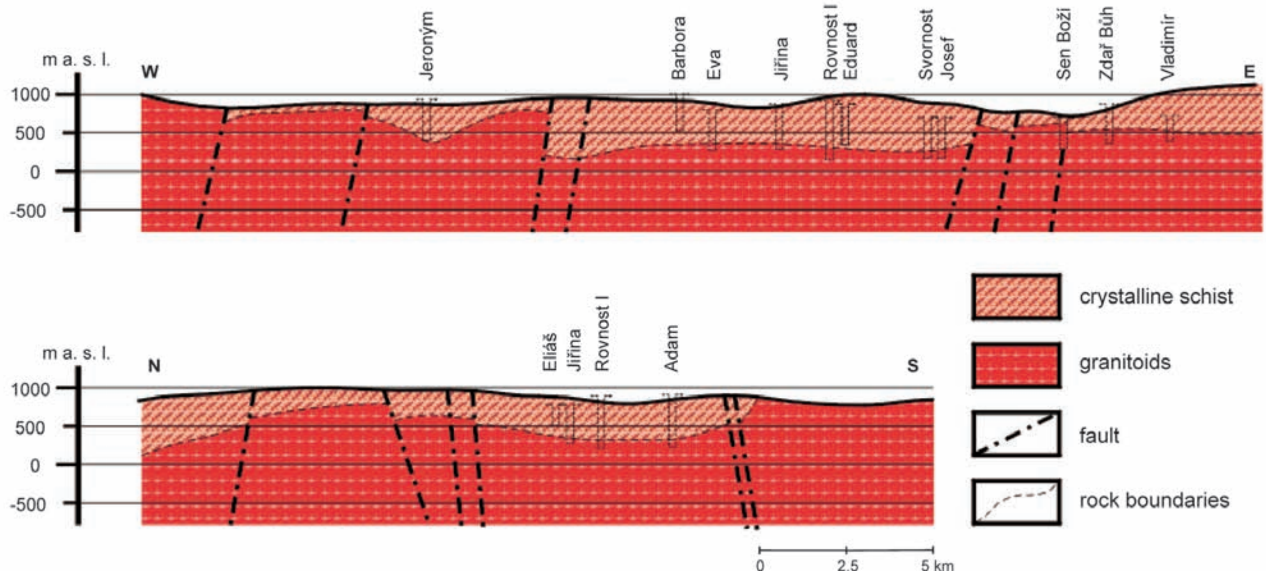

Fig. 3. Section of a part of the Jáchymov mining district, modified from [497].

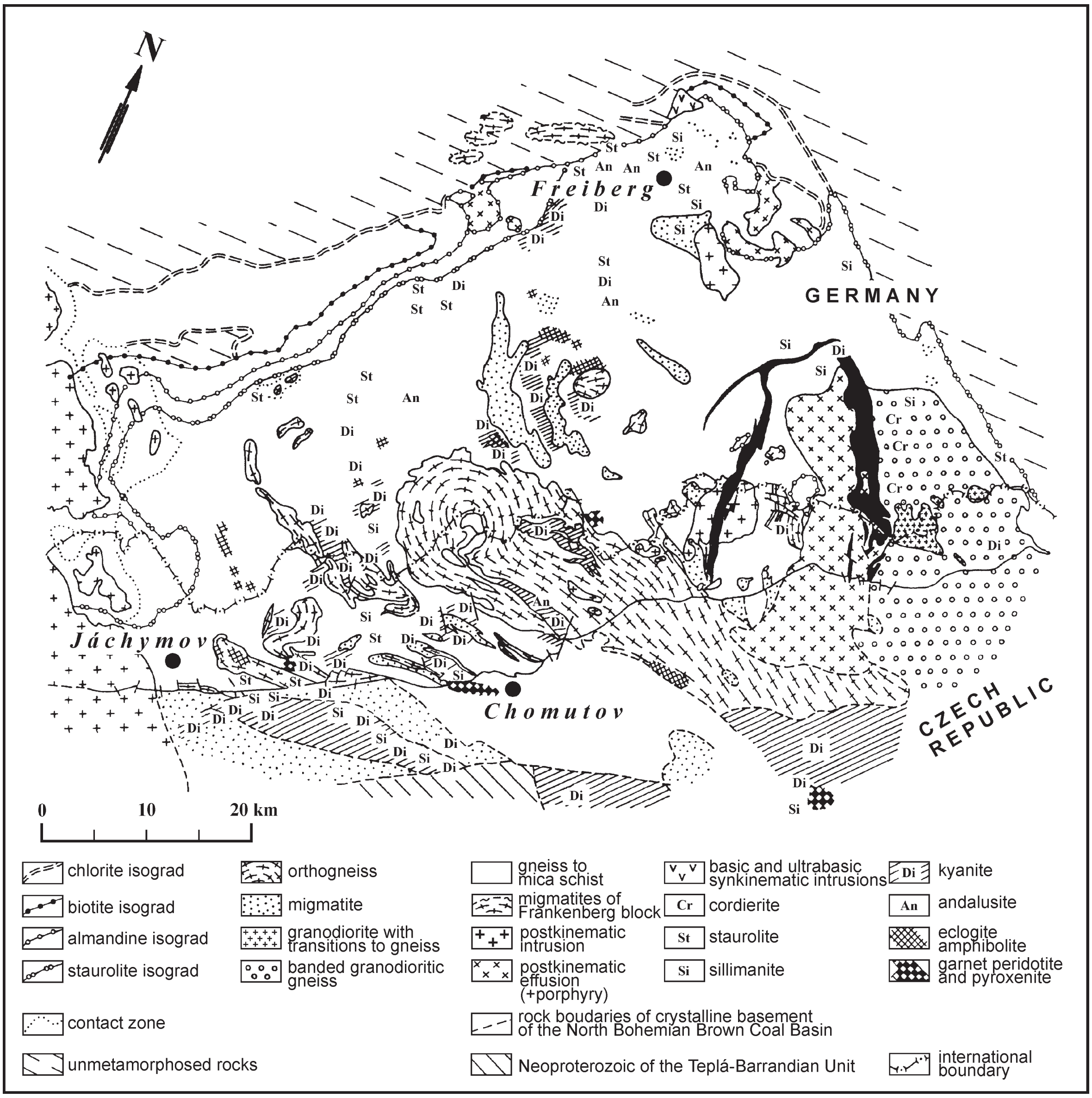

Fig. 4. Map of metamorphic facies of the central Krušné hory Mts. modified from [496] and [498].

fractures and faults rather than in greisens. These veins belong to the high-temperature hydrothermal phase. The formation of *quartz–cassiterite* and *wolframite* veins took place both in granite endo- and exocontacts.

Small veins of this type prevailed, but large trunks were exceptionally exploited to a depth of 300 m. *Cassiterite* was sometimes deposited along minor fractures in phyllite or older granite.

Skarns

Iron ores were mined in the past at several skarn-type deposits. Skarn formation was interpreted by metasomatism of calcareous sediments altered to marbles or by the transformation of alteration products of syn-sedimentary basic volcanism. Skarns occur in large blocks or roof pendants enclosed in the older biotite granite or in lenticular bodies in schists of the envelope. Skarns of these occurrences are composed dominantly of Ca-rich garnets (*andradite-grossular* series), Fe-rich *amphiboles*, *hedenbergite*, *epidote*, and *magnetite*. Some skarns carry also *sphalerite*, *chalcopyrite* and exceptionally tin which – apart from *cassiterite* – is bound to the borate *hulsite* at the Zlatý Kopec deposit near Boží Dar. Skarns in the Jáchymov ore district are either of *magnetite* type associated with *amphibolic* rocks (metabasites) in mica schists (Antonín mine) or of sulphide-bearing type with *sphalerite*, *chalcopyrite*, *pyrite*, *magnetite*, *cassiterite* and Fe-rich *chlorites* (Plavno mine). Later discovered *grossular–wollastonite* skarn (tactite) was formed by contact metamorphism of carbonate rocks by Variscan granite, while complex, Fe-rich and in part sulphidic skarns often carry polygenetic mineral assemblages. *Pyrite* recrystallization was observed in *graphite*-rich schists (up to 6 wt.% C) near the Adam mine.

Role of tectonic processes

Tectonic pressure brought by the Alpine cycle caused fracturing of the granite massifs and their metamorphic envelope. Ore-bearing solutions and exhalations were mobilized by a complicated process. This resulted in complex phenomena of mobilization and redeposition of components by meteoritic waters with deep circulation as well as juvenile fluids. Both ore veins and ore-free mineral veins were deposited during this stage, marked by a complicated syn-mineralization tectonic deformation on a local scale. This activity resulted in the formation of iron, manganese, silver, cobalt, bismuth, nickel, and uranium accumulations or deposits [367], [385]. A complicated network of veins of variable orientation and age is characteristic of the Krušné hory Mts. area. In the past, hematite mineralization in quartz veins was exploited. Similar veins in the younger granite carry manganese ores (Jelení, Nové Hamry, Horní Blatná). Pure ore-free *quartz* veins were exploited for glass production (Smolné Pece). Some quartz-chalcedony veins produced interesting banded *quartz*-jasper decorative materials, including varieties with brecciation, multiple deformation and mineralization. The Jáchymov ore district comprises several hundred ore veins and their offshoots. Since historic times, the veins have been classified in two main groups: 1) low-grade or barren veins striking E–W, and 2) high-grade veins striking N–S. Some veins of the second group range from NW–SE to NE–SW in their strike. Veins of the first group are older. The individual mineralization stages in the Jáchymov ore veins were separated by tectonic movements, resulting in crushing of previously deposited minerals and in opening of new fractures. New batches of mineralizing fluids were propagating from sources of mineralization along NW–SE-striking fault zones and along lower-order faults, finally depositing their mineral content.

Majority of tectonic activity associated with the Tertiary volcanism took place along E–W-orientated discontinuities, normal to ore veins. No significant relative movements were documented, but thick dykes of tuffaceous rocks (so-called "Putzenwacke") with a high water content, which filled extensional fractures, played a notable role. At intersections of these dykes with ore veins, the ore content was crushed and subjected to secondary alterations by large volumes of circulating groundwater.

The importance of relatively old NW–SE structures is documented by the elongation of subsurface granite elevations and the shape of small granite massifs exposed by erosion. This structural trend was important for the evolution of ore veins in the Jáchymov ore district, but also controlled the distribution of greisens with tin mineralization at an earlier stage. Another structural trend, somewhat older and orientated E–W, is related to structural patterns in the metamorphic country rocks. It controlled the orientation of dykes associated with the Karlovy Vary pluton and Tertiary volcanics. This trend was, however, insignificant in the localization of hydrothermal ore veins. Similar relative roles of the two structural trends recur in a number of other deposits in the Krušné hory Mts. area.

Tertiary volcanism

The Tertiary alkaline basaltic volcanism was the most important for the area south and southeast of Jáchymov, in the Doupovské hory Mts. volcanic centre. Related shallow basaltic intrusions, lava flows, and dykes of tuffaceous rocks or volcanic breccia in the crystalline basement occur in the Jáchymov district. Extensional tectonic setting accompanying volcanism is documented by the thicknesses of volcanic breccia (tuff) dykes, their complicated course and finds of fossilized plants in tuff dykes, observed in mine adits at considerable depths below the present land surface. Such phenomena are interpreted, based on the study of the Magistrála dyke near Kovářská, as due to sucking of erupted material caused by underpressure following volcanic eruption.

Brittle block tectonics

During the Tertiary, the levelled land surface in the present Krušné hory Mts. region experienced buckling induced by folding in the Alpine belt, and subsequent disintegration of the buckled domain, mainly along older fault zones. The subsided zone of the Ohře Rift became the site of accumulation of sedimentary and volcanic rocks of >400 m in thickness, while the uplifted domain of the Krušné hory Mts. was affected by strong erosion. The continued uplift of this domain during the Quaternary is estimated at 250 to 300 m, and measurements of the present uplift indicate values of 1.5 mm per year.

Quaternary

About 2 Ma ago, the climate turned to periglacial, with average temperatures near 0 °C. The estimated temperatures were near 10–12 °C during warm and wet interglacial periods, that is above the present average (7.2 °C). Mountain streams caused strong erosion along deeply incised valleys, resulting in the accumulation of rich detrital deposits of *cassiterite*, exploited mainly in the Middle Ages. Formation of extensive peat bogs in areas of a shallow groundwater level on levelled high parts of the mountains started ca. 11,000 years ago.

Fault tectonics

The Jáchymov ore district is bounded by the Krušné hory Fault zone in the south and by the northern fault zone against the Potůčky ore district in the north. The eastern border is formed by the Plavno Fault, and the western border is defined by the "Central Fault". After the emplacement of the Krušné hory pluton, the region was disrupted by NW–SE-striking faults (Fig. 5). The relative movements are indicated by the differences in subsurface position of apical parts of the pluton in individual fault blocks. The top of the pluton lies at 100 m a.s.l. in the south, but culminates at 450 to 980 m a.s.l. at the northern fault zone. Major faults can be classified into two groups. One group is parallel to the axis of the Krušné hory Mts. (NE–SW), the other group strikes NW–SE. The Krušné hory Fault (NE–SW), running across Krásný Les–Horní Žďár–Hluboká, ca. 150 km long, dips SE at an angle of 80°. The fault zone is up to 300 m wide, filled by mylonitic clay with ferruginous components. Major role in faulting in the Jáchymov district is played by NW–SE-striking faults (Fig. 5), associated with horizontal and vertical relative movements: including the southern, central, Panorama, Plavno, and northern faults. The documented vertical component is ~150 to 400 m, the horizontal component is max. 600 m. Material fill of these fault zones shows certain similarities: the wall-rock is disrupted, crushed to cataclasite, silicified and enriched in hematite. These fault zones intersect the Krušné hory Fault zone and are typically charged with groundwater. Lower-order, relatively narrow faults strike E–W. They are filled with mylonite, drusy *quartz*, *dolomite*, *siderite*, sulphides, arsenides and native metals. Some of these accumulations were subject to mining in the past. These faults, associated with some relative movements, transect the NW–SE-striking faults and split the whole district into numerous blocks (Fig. 5).

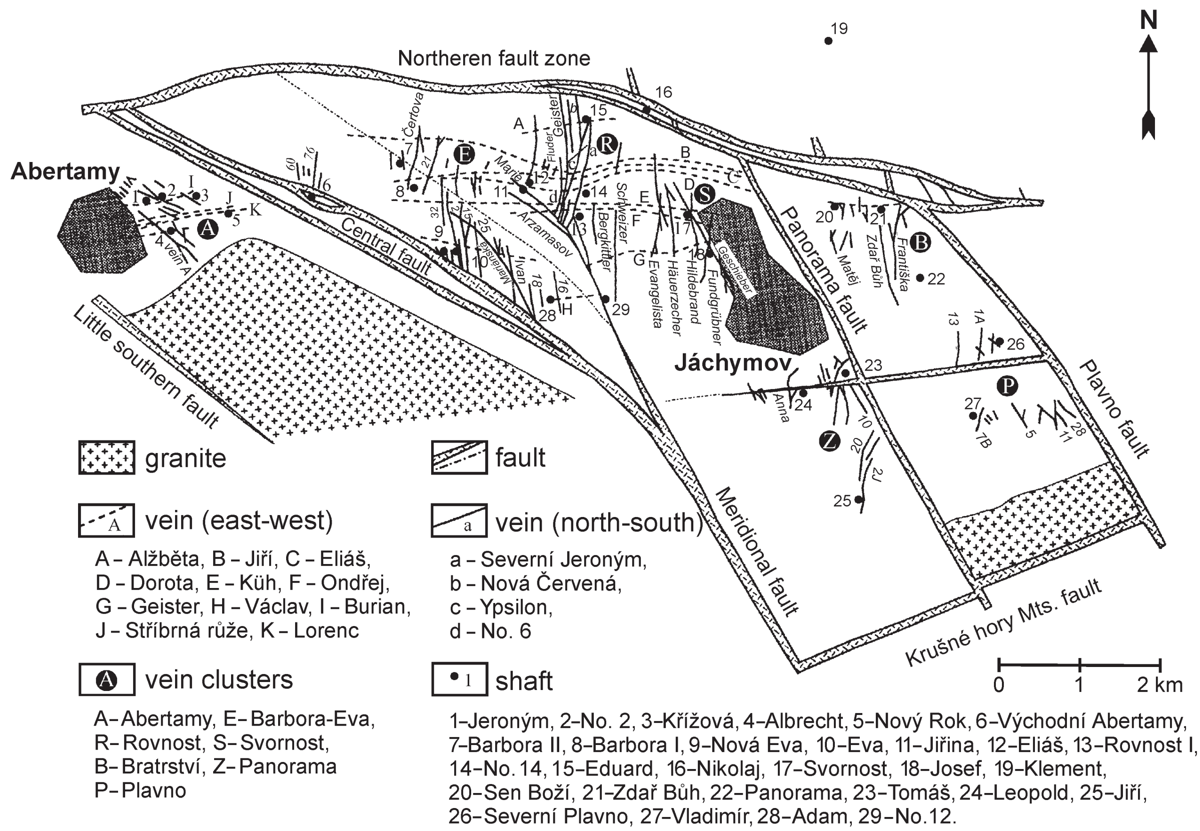

Fig. 5. Structural-geological map of the Jáchymov ore district. Modified from [187].

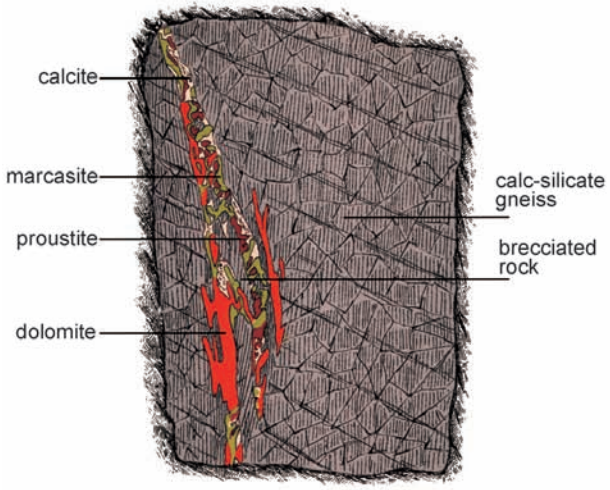

Fig. 6a. Example of a Jáchymov vein showing positive influence of calc-silicate gneiss on ore accumulation. Svornost shaft, Adit level, Hildebrand vein. Drawn by Buchal (1880) [422].

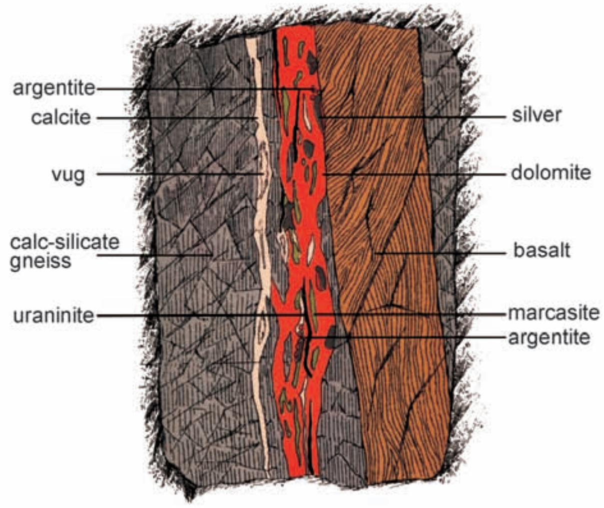

Fig. 6b. Example of a Jáchymov vein showing positive influence of calc-silicate gneiss on ore accumulation. Svornost shaft, 9th level, Junghäuerzecher vein. Drawn by J. Němeček (1883) [422].

Factors controlling mineralization

Ore deposition was controlled by two main groups of factors, namely structural and lithological ones. The influence of wall-rock lithology was noted already by J. F. Vogl (1856), who ascribed a positive role to layers of crystalline limestone as a country rock for ore veins. *Graphite*-bearing and *pyrite*-rich rocks also played a positive role in the concentration of ore minerals (Fig. 6a, b), and the distance from the granite massif was noted as important. Structural factors were important for the distribution of rich parts of the veins.

Structural factors

Ore-bearing veins in the district strike mostly between 300° and 30°. Veins striking E–W contained only small ore accumulations. Examples of rich ore were found also below intersections or coalescences of two veins (Fig. 7). In many cases, ore was concentrated in short offshoots of the main vein, which was largely barren. The strike and the dip of veins were also important. This was observed especially in prominent veins, such as Zdař Bůh, Schweizer and others, which continued through the whole metamorphic complex. In some instances, at intersections of two veins, mineralization from one vein ingressed the other vein. Also, mineralization formed a cross-shaped pattern at the intersections of E–W veins with N–S veins.

Characteristic is the branching of veins in the proximity of granite, however, at these places the payable mineralization declined (Schweizer vein). In a few cases, including the Pomoc Boží and Matěj veins, a rich uranium mineralization was encountered in parts of veins intersecting pocket-like gneissic roof pendants submerged between apophyses of granite. A tendency to ore enrichment in the proximity of large antiforms was observed in nearly all parts of the district.

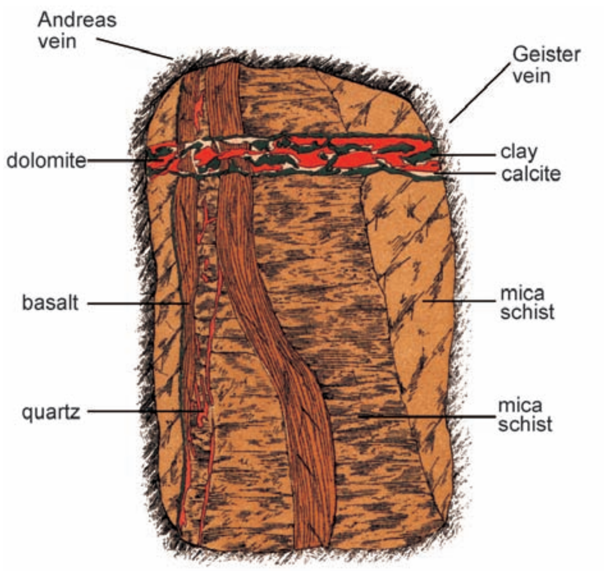

Fig. 7. Example of vein intersection, which often indicated rich ore accumulations. Rovnost I shaft, Daniel level, Andreas and Geister veins. Drawn by J. Hozák (1889) [422]

Lithological factors

The role of wall-rock composition follows from the fact that a particular country-rock composition induced changes in local chemical environment. This role was evidenced by the enrichment or decline of mineralization in dependence on the type of the country rock.

The presence of amphibolite bodies functioned as a favourable factor in adits near Potůčky and in the vein cluster near Abertamy East (Fig. 9). Hornfelsic rocks also played a favourable role in the Svornost and Panorama mines. Gently dipping fault zones filled with mylonitic

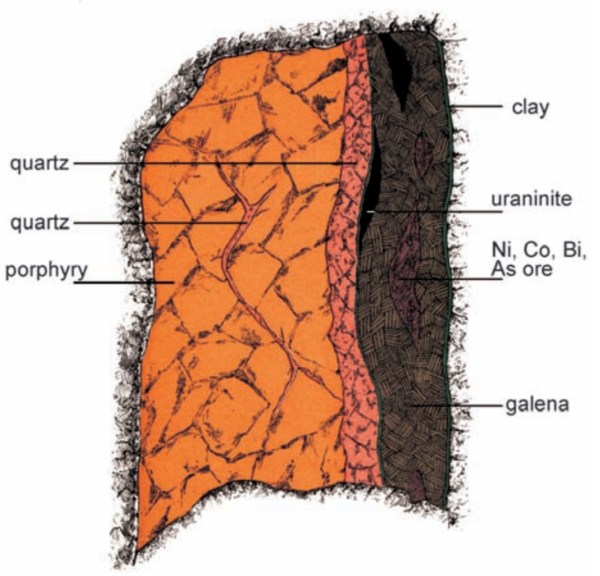

Fig. 8. Example of positive influence of granite porphyry on ore accumulations. Rovnost I shaft, Barbora level, Geister vein. Drawn by A. Mixa (1883) [422].

clay, sometimes associated with porphyry dykes, were favourable sites for uranium ore enrichment (Fig. 8).

As revealed by the analysis of relative ages of minerals in carbonate-uraninite veins, *uraninite* precipitation post-dated the crystallization of carbonates and hydrothermal alteration of wall-rocks with variable *pyrite* content. The correlation between *pyrite* abundance in altered wall-rock and the uranium mineralization in the respective vein parts shows the influence of *pyrite*. The questions of lithological controls in ore deposition in the Jáchymov district are not completely solved. *Biotite* and two-mica schists (Fig. 10) and *graphitic* schists with abundant *pyrite* generally affected ore deposition in a positive way. Quartzitic gneisses and silicified schists, in particular those belonging to the Klínovec Group, lamprophyres and usually also porphyries show adverse effects on ore deposition.

Radioactive springs in the Svornost ore cluster

Radioactive springs at Jáchymov are derived from the circulation of meteoritic water, descending along fault and fracture zones deep into the metamorphic complex and the underlying granite pluton. The capacity for the dissolution of mineral salts and gases is significantly enhanced due to increased temperature in domains of deep circulation. Ore veins and vein clusters, often fractured and cavernous, serve in part for deep circulation of water, which becomes enriched in radioactive elements. Fractured domains around ore veins also serve as conduits for gases, including radon and helium, which migrate at considerable distances [382], [384] (Fig. 11).

Hydrothermal vein system

Several hundreds of ore veins and ore offshoots branch from the main fault zones as pennate dislocations or complicate offshoots from the main fault zones. Since past centuries, the veins have been classified into: 1. *Morning veins*: E–W, weakly mineralized or barren veins, 2. *Midnight veins*: N–S veins ranging between NW–SE strikes and rare NE–SW strikes, including most of ore-rich veins. The ore-rich vein system is orientated nearly perpendicular to the major structure of the whole region, the asymmetric Klínovec antiform (Fig. 12).

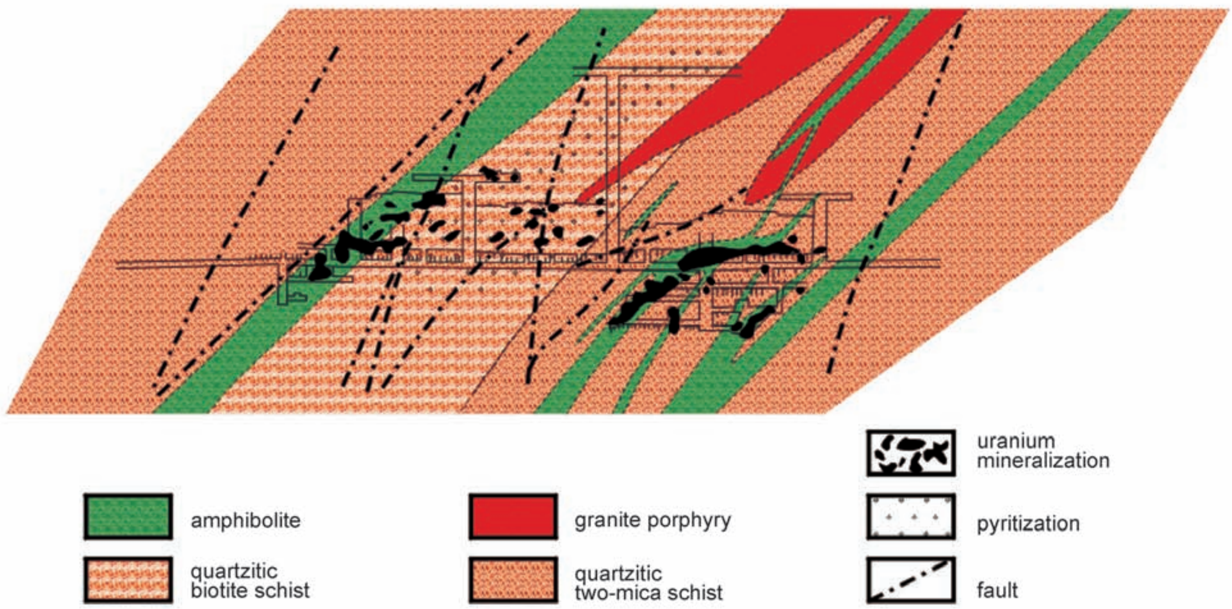

Fig. 9. Example of preferential location of mineralization in amphibolite. Exploitation map of vein No. 60, Eastern Abertamy field, 1:1500. Modified from [497].

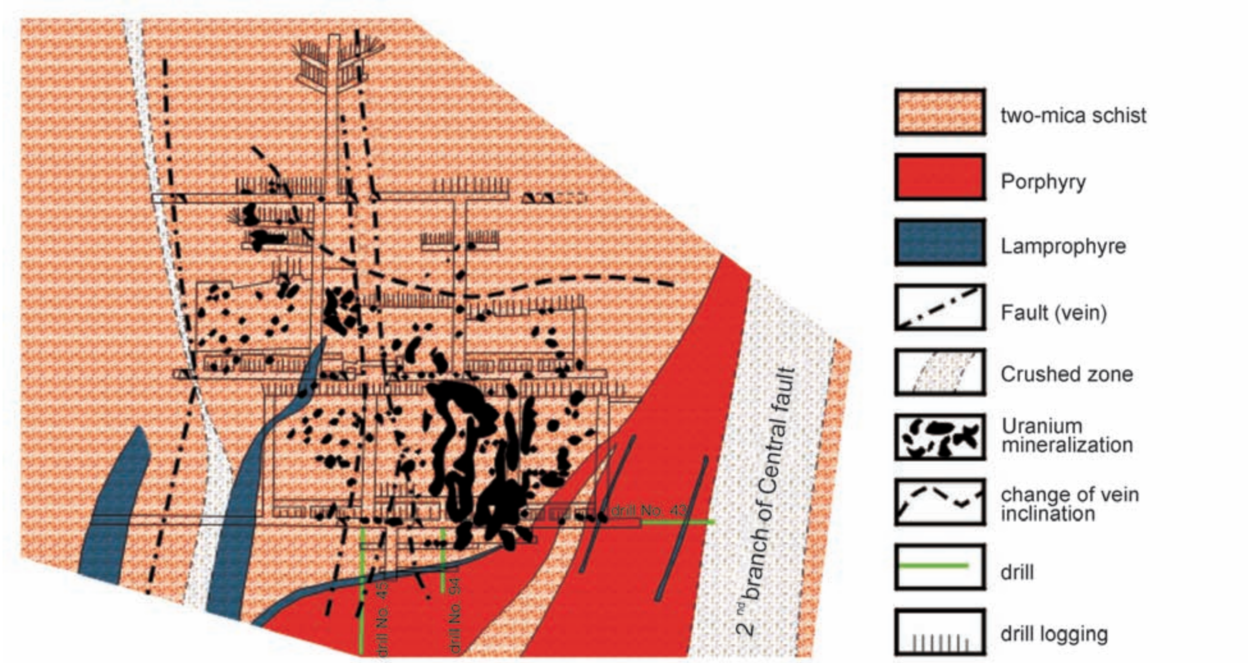

Fig. 10. Example of preferential location of mineralization in two-mica shist, above granite porphyry dyke, between two dislocations. Exploitation map of vein No. 117, Eva field, 1:1500. Modified from Topinka [497].

Variation in local mineralization indicates that the permeability of the general array of faults for hydrothermal solutions was uneven, with a tendency to local rich lenses or ore pipe and barren veins in other places (Fig. 18). The richest mineralization used to be in offshoots branching from the main vein or at vein intersections. The veins show a polyascendent character. Minerals of the individual stages are not represented in all veins, or in their whole extent. Minerals of younger stages often replaced older parageneses. Some veins in granite contain ore, alas

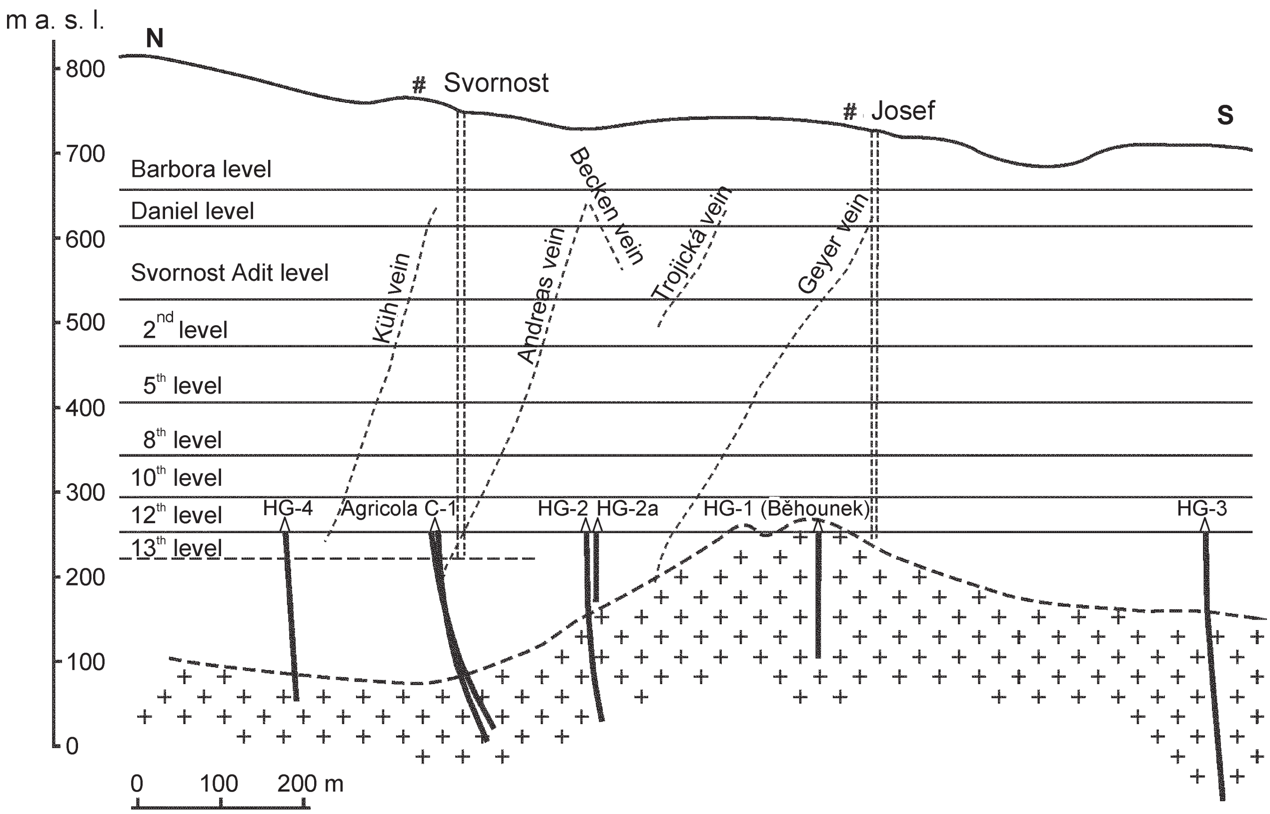

Fig. 11. Simplified section of Svornost shaft (Geschieber vein) mining field, with the main morning veins and boreholes (HG-1, HG-2, HG-3, HG-4, Agricola) into underlying granite. Modified from [384].

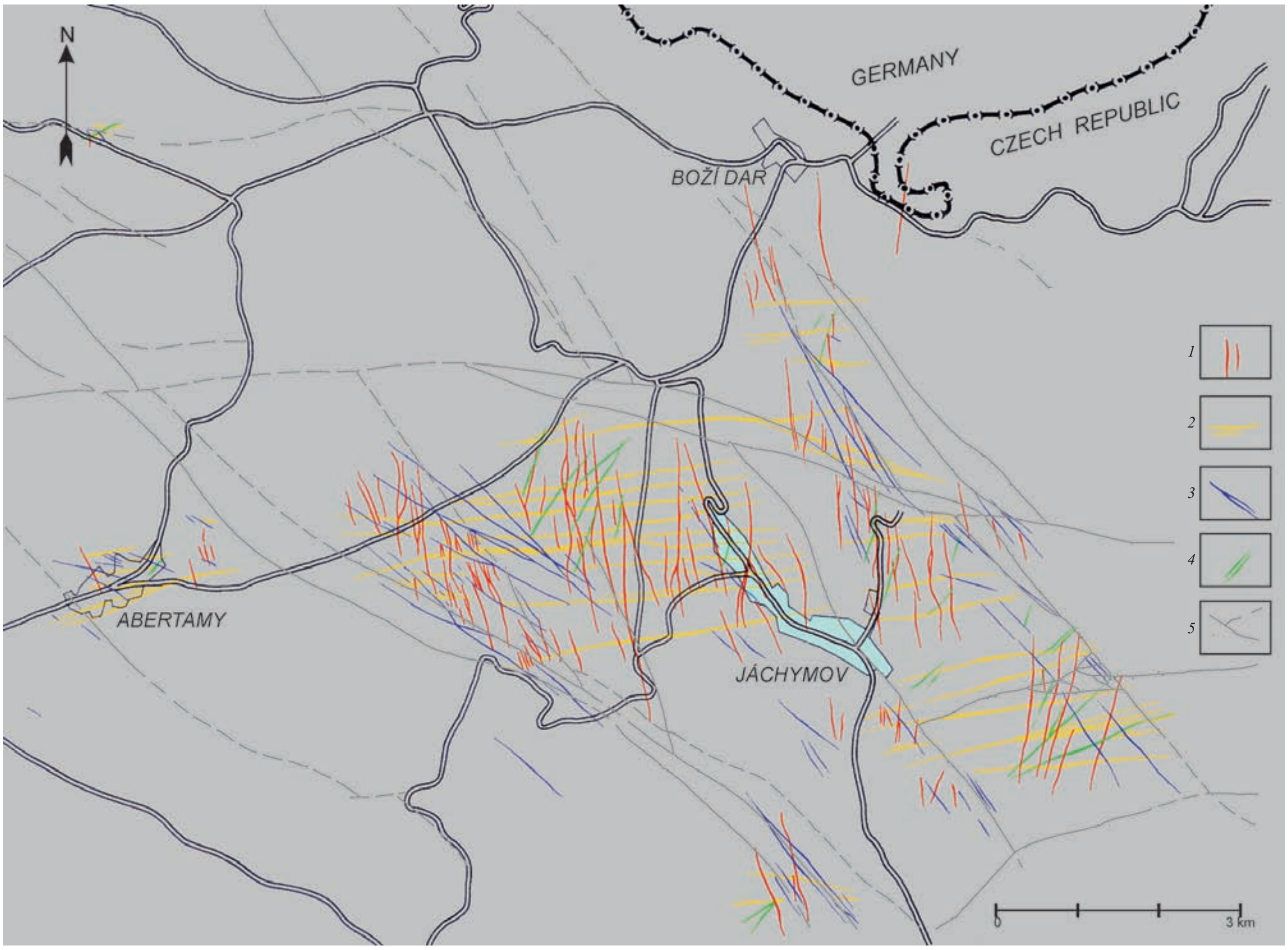

Fig. 12. Location and type of ore veins and tectonic faults in the Jáchymov ore district. 1 – Midnight veins, 2 – Morning veins, 3 – NW veins and tectonic faults, 4 – NE veins and fractures, 5 – fault; dashed line – assumed faults. Simplified from [432], [374].

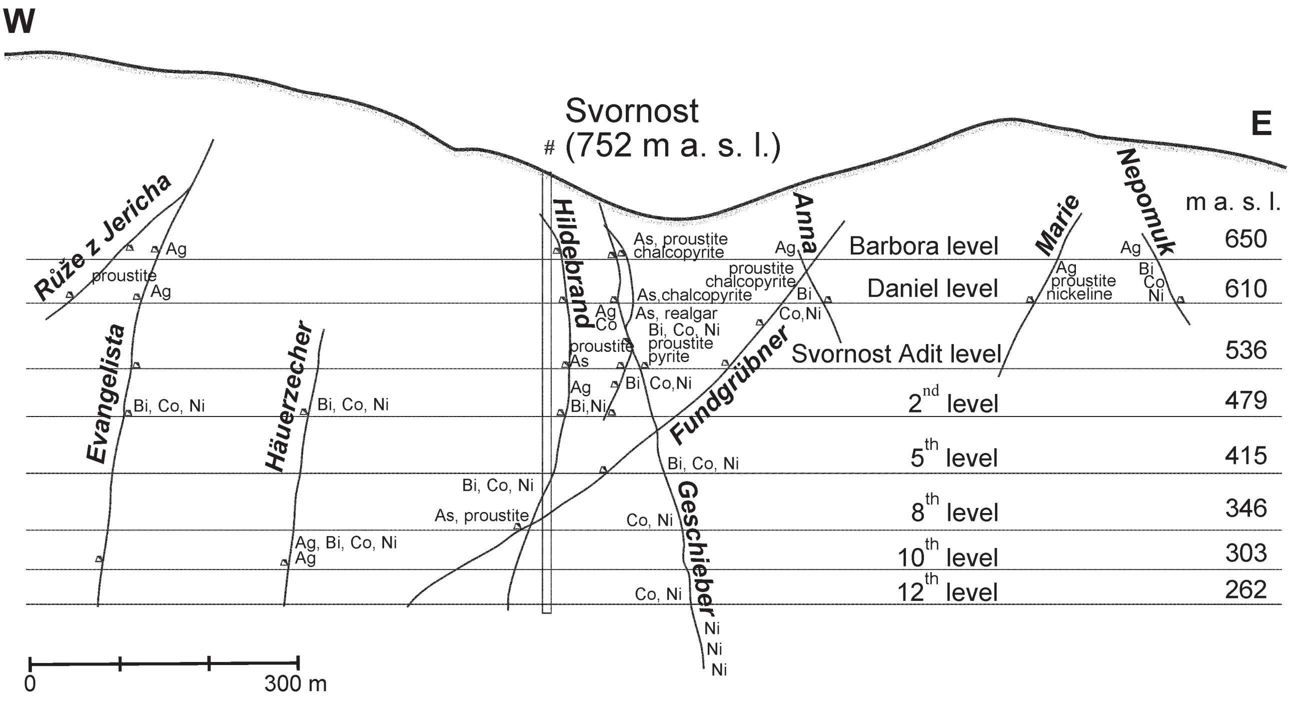

Fig. 13. Location of non-uranium mineralization in the Svornost field. Modified from [383].

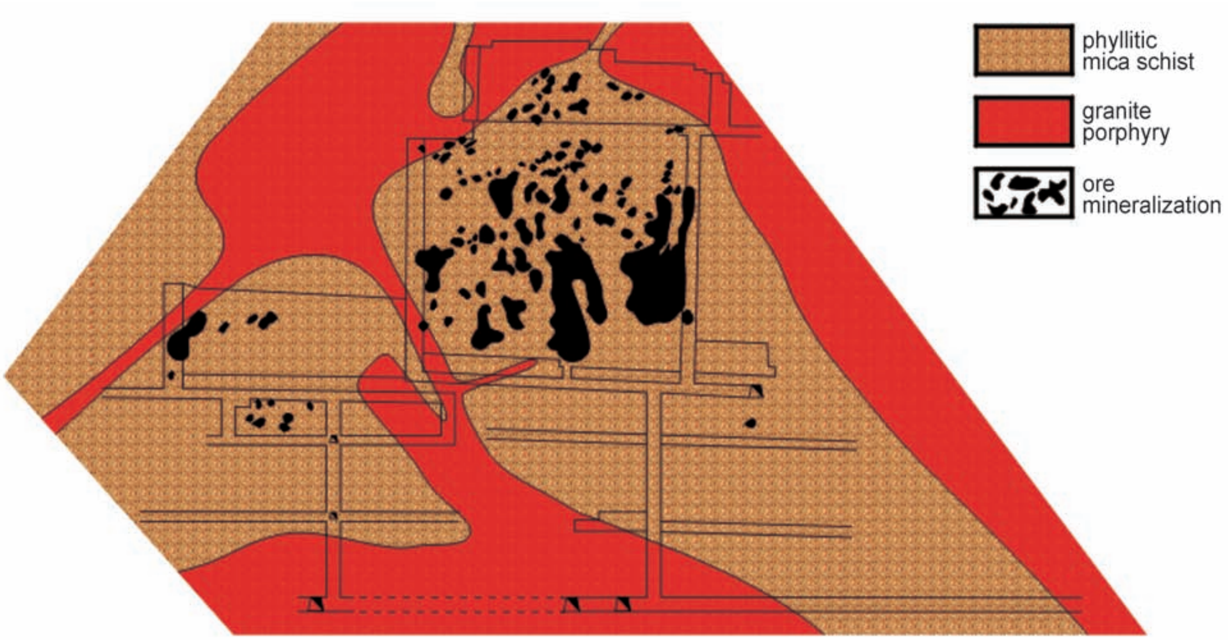

Fig. 14. Mineralization in separated ore lenses below granite porphyry. Exploitation map of the South Bergkittler 2 vein, Rovnost I field, 1:1000. Modified from [497].

of lower-grade, and for short distances only. The Geschieber vein in the Svornost Mine is exceptional, as nickel ores occur as deep as 100 m in the granite body.

Midnight veins

Midnight veins striking N–S carry the main mineralization in the ore district. The veins show a less regular course than the *Morning* veins, but they are more abundant and richly mineralized. Midnight veins exhibit frequent variations in their strike and dip (Fig. 19), variations in thickness and a tendency to split to offshoots (Fig. 20). Some offshoots show a curved course and some of them join the main vein at some distance again. Offshoots, which evolved as rather independent veins, may show a steeper dip and better ore content than the main vein. The highest ore concentrations occur at places where offshoots join the main veins.

Midnight veins show variations in their thickness, ranging from several centimetres to metres, with an average width of 10–30 cm. The distribution of these veins in the district is irregular, and the set includes veins with rich parts as well as nearly barren sections. Ore mineralization is localized in columns consisting of lenses mutually separated by barren parts of vein (Figs 13, 14). Mineralization in *Midnight* veins disappears as the veins continue from mica schists of the Jáchymov Group into granites of the Karlovy Vary pluton. There are few exceptions to this rule, e.g. the Geschieber vein [389].

Morning veins

Morning veins are positioned along E–W-striking fault zones, and their offshoots strike 330°–30°. They include veins up to 2 km long and 2.5 m thick as well as narrow mineralized fractures 150–300 m long.

The vein fill shows a simple symmetry, though an inverse, bilateral symmetry also occurs (Figs 21–24), characteristic for long parts of veins. Ore component in the veins shows a rather regular distribution but is often reduced to thin veinlets and small clusters.

Morning veins striking E–W are weakly mineralized veins or veins with barren sections in fault zones (Fig. 17) striking parallel to foliation in country-rock mica schists but showing differences in their dip. The faults are filled with mylonitic clay or brecciated fragments of wall rocks with sporadic *pyrite* or *chalcopyrite* mineralization. Ag–Bi–Co–Ni±U mineralization appears only in the proximity of their intersections with N–S veins. Ore enrichment was recorded only in parts adjacent to prominent fault zones. Taking advantage of soft material in the E–W fault zones, adits and cross-tunnels were preferably driven along E–W veins in historical times. The important *Morning* veins include the following: Schindler, Geier, Andreas, Küh, Dorothea, Eliáš, Georg and other veins. *Morning* veins are older than the *Midnight* veins, and the respective E–W faults remained largely closed during important episodes of mineralization.

Selected examples of Jáchymov ore veins (Figs 15–17)

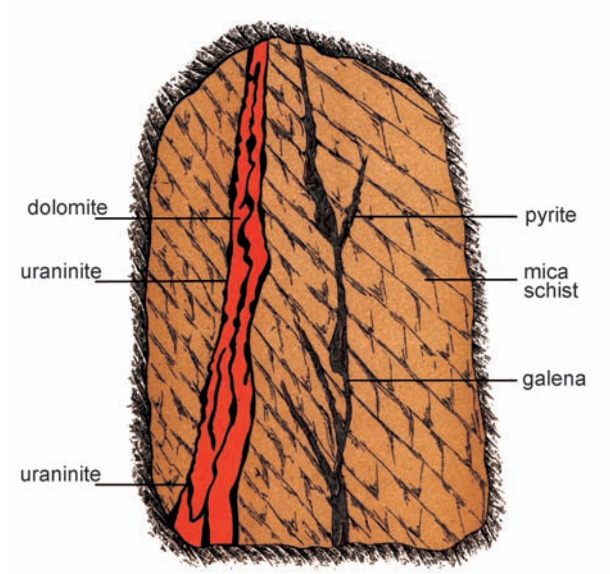

Fig. 15. Example of a second-order fissure complicating the main ore vein with prevailing dolomitic carbonate. Rovnost I, 2nd Werner level, Bergkittler vein. Drawn by A. Mixa (1887) [422].

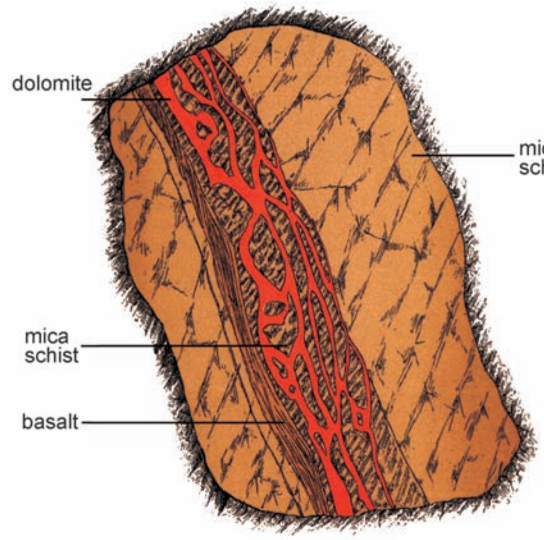

Fig. 17. Example of an inclined barren part of vein. Rovnost I shaft, 2nd Werner level, Schweizer vein. Drawn by A. Mixa (1885) [422].

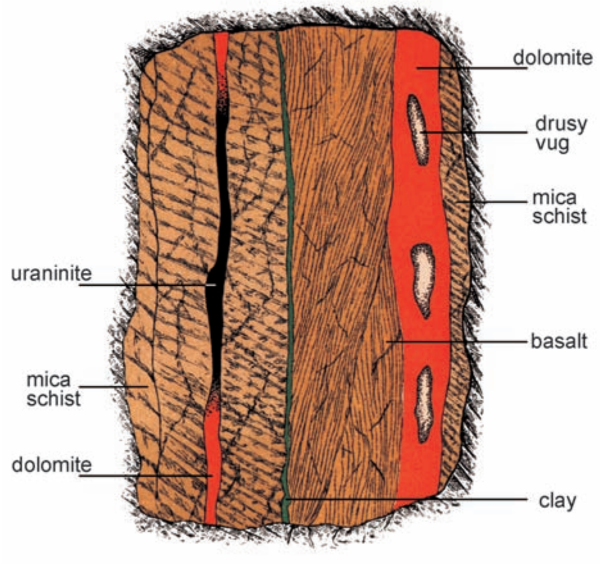

Fig. 16. Example of a second-order fissure complicating the main ore structure, with prevailing dolomitic carbonate. Rovnost I shaft, 1st Werner level, Schweizer vein. Drawn by J. Hozák (1889) [422].

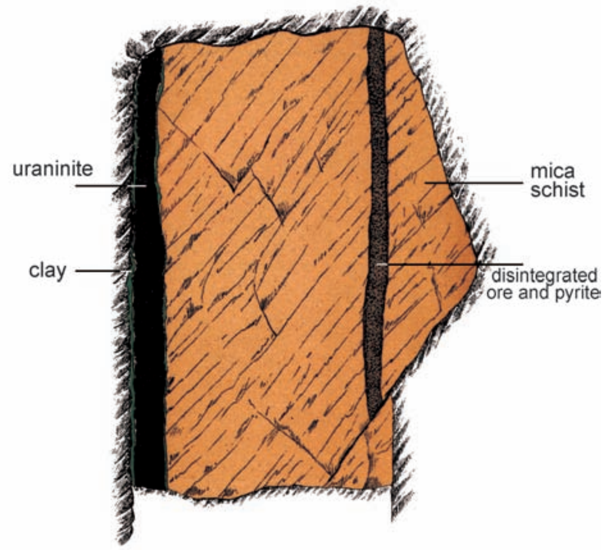

Fig. 18. Example of massive ore vein. Rovnost I shaft, 1st Werner level, Geister vein. Drawn by A. Mixa (1884) [422].

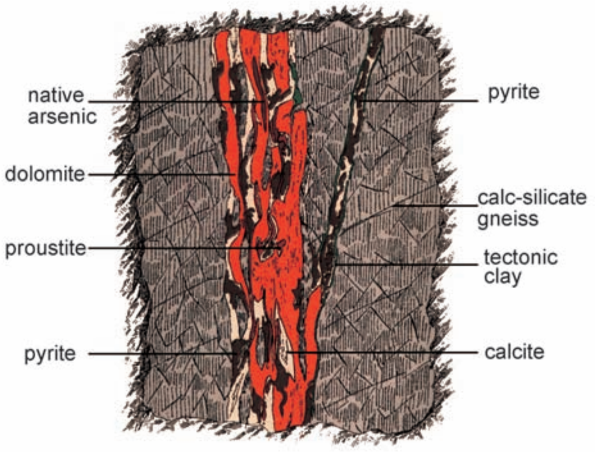

Fig. 19. Example of the separation of an offshoot from the main vein, Svornost shaft, 1st Joachim level, Midnight Hildebrand vein. Drawn by J. Němeček (1883) [422].

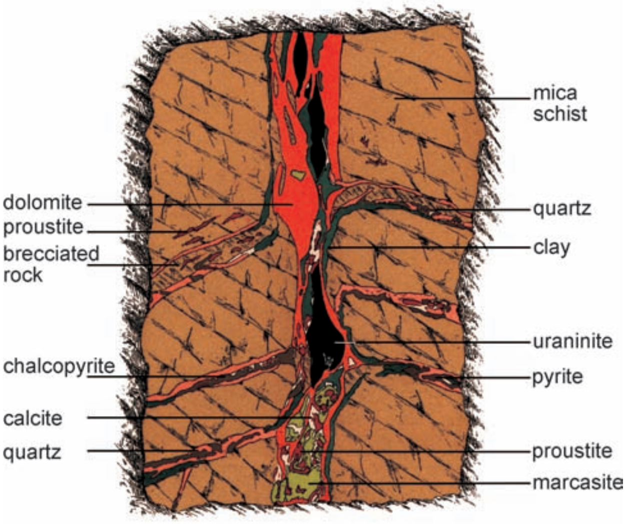

Fig. 20. Typical example of a vein with many offshoots. Svornost shaft, Adit level, Hildebrand vein. Drawn by J. Němeček (1882) [422].

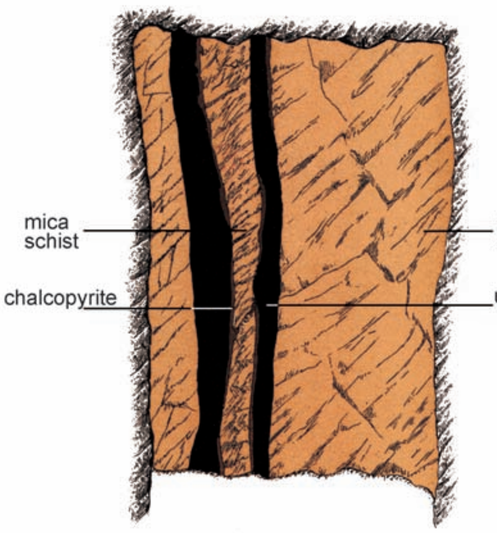

Fig. 21. Bilaterally symmetric part of a vein with massive mineralization. Rovnost I shaft, 1st Werner level, Geister vein. Drawn by A. Mixa (1884) [422].

Fig. 22. Symmetric texture of vein with sphalerite at margins and pyrite in the centre; calcite is white. Eliáš mine, 180 m level, Arsamasov vein. Photo D. Pavlů [350].

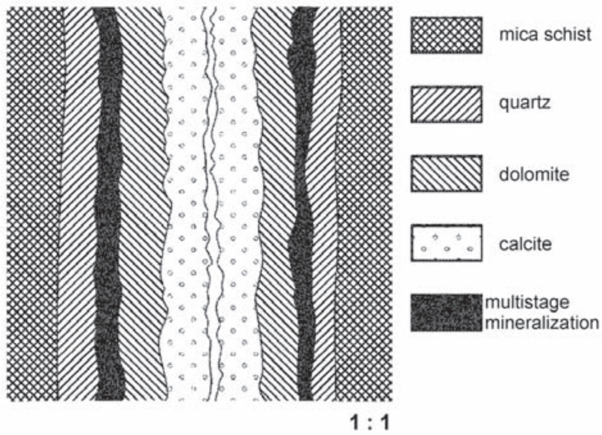

Fig. 23. Skech of incompletely filled vein structure with bilaterally symmetric texture. Eva shaft, 4th level – north, vein No. 2. Modified from [408].

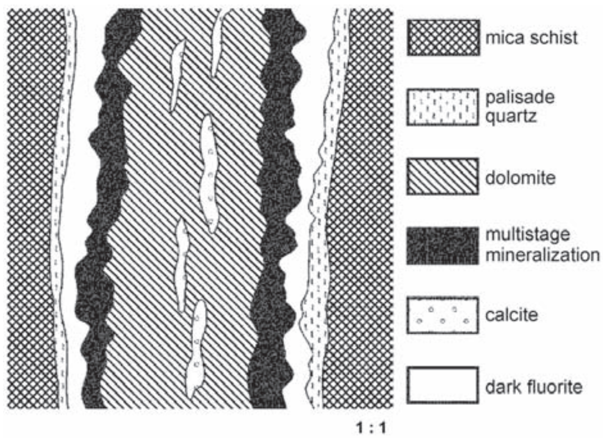

Fig. 24. Skech of non-uranium mineralization with bilaterally symmetric texture, Arsamasov vein. Eliáš mine, 180 m level – south. Modified from [408].

Definition of ore vein clusters

Based on the morphology of the ore district, mostly controlled by the major fault zones, the whole area was classified into six main ore vein clusters [412].

The N–S veins with uranium mineralization were classified into six ore vein clusters (Fig. 25): Barbora-Eva, Rovnost I, Svornost, Panoráma, Bratrství and Plavno. An isolated position is occupied by the infiltration-type deposit of Popov in the southern part of the district (Fig. 26). This whole set of clusters used to be designated as the Jáchymov deposit. The clusters of Svornost, Plavno, Panoráma and Popov rank as smaller deposits, which contributed less than 15 % to the total uranium production.

Five-element (Ag–Bi–Co–Ni±U) mineralization

The Jáchymov ore district is characterized by ores of the so-called *five-element* (Ag–Bi–Co–Ni±U) mineralization. Besides Jáchymov, a similar *five-element* hydrothermal association occurs in both parts of the Krušné hory Mts. (i.e., the German and Czech part) [351], [344], [346]. This type has equivalents in other continents, including the Great Bear Lake area [376], Cobalt area [434], Zimmer Lake area [353], and the Karuisawa mine [398].

At the above deposits, the *five-element* association comprises in fact two independent stages of mineralization (*Ag–Bi–Co–Ni–As formation* and *U formation*) with regard to different sources of ore-bearing fluids – namely the *uranium* and *arsenide* stages. This formation is characterized by superposition of minerals from both stages and by complicated remobilization of elements from both stages.

With respect to data from fluid inclusion study and conditions of formation of mineral assemblages (see the respective sections) and published data [359, 428], the hydrothermal veins are characterized as low- to medium-temperature ones.

Chronology of hypogenic mineralization

The time sequence of the mineralization stages is discussed later in the section *Paragenetic relations of the ore vein system*. The schematized sequence of hypogenic mineralization stages is as follows:

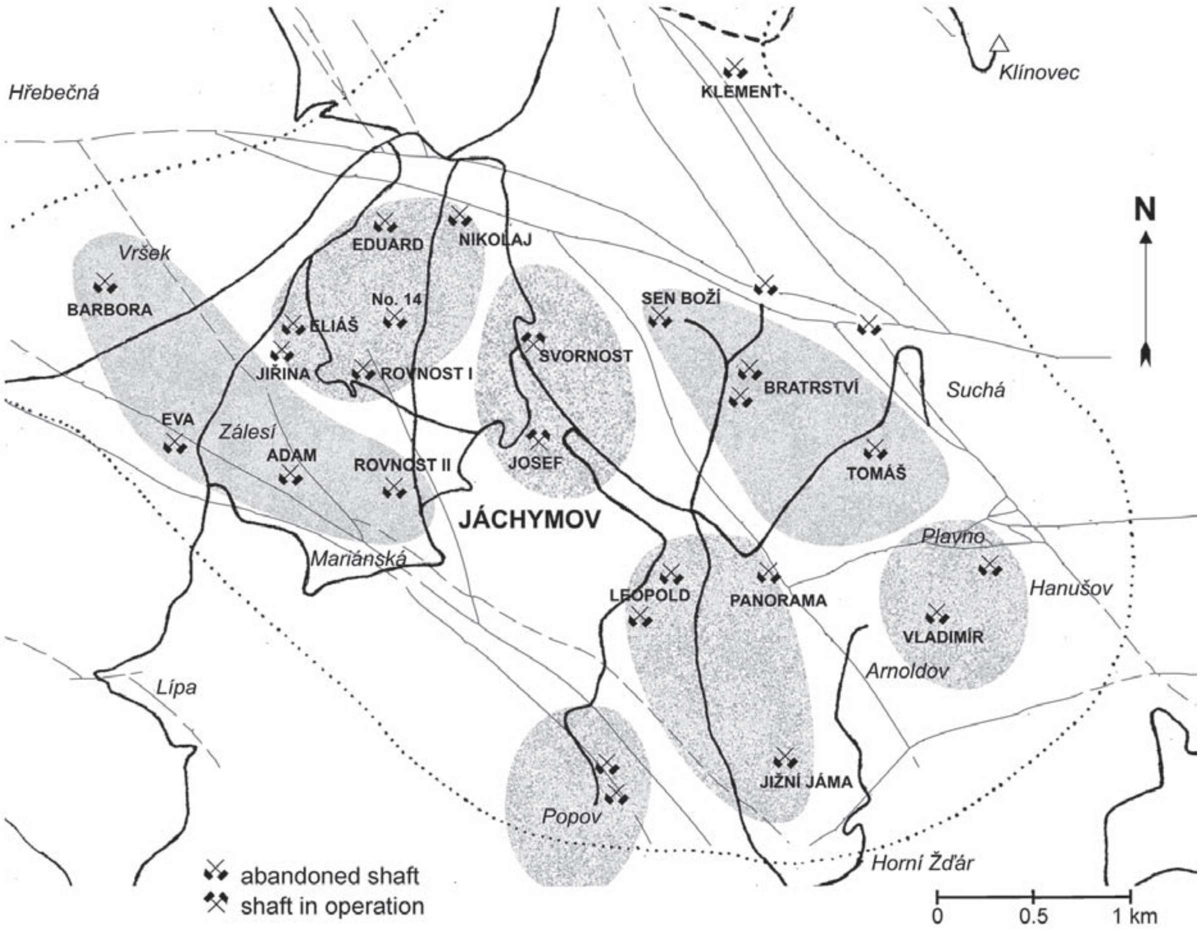

Fig. 25. Simplified map of location of the six main ore clusters (+ Popov cluster) in the Jáchymov ore district. Faults are shown by thin full and dashed lines.

Sn-W sulpharsenide stage
This stage is related to autometamorphism of younger granite, which underlies the whole district. This stage has no relation to the younger *five-element* mineralization. It produced the following minerals: milky *quartz, pyrite, arsenopyrite, tourmaline, phlogopite, tungstenian rutile, cassiterite, molybdenite, chalcopyrite, bornite, tennantite, argentotennantite, freibergite, aikinite, matildite,* dark *sphalerite, galena, stannite, kësterite, mawsonite and gersdorffite.*

Ore-free quartz stage
Chalcedony-like and ferruginous *quartz*, (Fe,Ca)-carbonates, light green *fluorite*

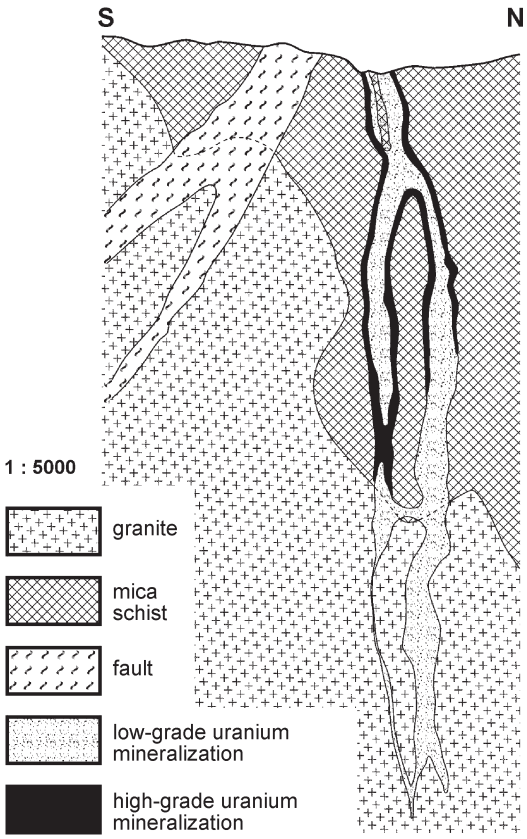

Fig. 26. Example of the infiltration type of mineralization in the Jáchymov ore district. Schematic section of the GRZ zone of Popov deposit. Modified from [408].

T a b l e 1 . The isotopic composition values of galena from Jáchymov [301], [307].

Mine	Sample	Pb206 Pb206/Pb204	Pb207 Pb207/Pb204	Pb208 Pb208/Pb204
Bratrství, 1. máj		**25.06**	**21.30**	**52.30**
		18.60	15.81	38.83
Bratrství, gallery	224A	**25.06**	**21.34**	**52.25**
		18.58	15.82	38.73
Bratrství	22	**25.06**	**21.34**	**52.25**
		18.60	15.84	38.79
Eliáš		**25.07**	**21.32**	**52.26**
		18.54	15.77	38.65
Rovnost, Bergkitler vein		**25.55**	**21.25**	**51.89**
		18.88	15.70	38.35
Svornost		**24.95**	**21.40**	**52.29**
		18.41	15.79	38.59

Carbonate-uraninite stage
Dolomitic carbonate coloured red by *hematite*, *uraninite*, *pyrite*, black violet *fluorite*

Arsenide stage
silver paragenesis: *silver, nickeline, rammelsbergite, nickel-skutterudite*
bismuth paragenesis: *bismuth, skutterudite, rammelsbergite-safflorite*
arsenide paragenesis (free of native metals): *nickeline, rammelsbergite, löllingite, nickel-skutterudite, skutterudite, gersdorffite, argentite*

Arsenic-sulphide stage
Arsenic, *realgar*, *proustite–pyrargyrite*, *pyrite*, *löllingite*, *argentopyrite*, *sternbergite*, *stephanite*

Sulphide stage
Pyrite, *marcasite*, *galena*, *sphalerite*, *chalcopyrite*, *calcite*

Post-ore stage
manganoan *calcite*, ferruginous *quartz*, chalcedony-like *quartz* to *opal*, *fluorite*, *barite*

Age estimation of the individual stages of hydrothermal mineralization

Sn–W sulpharsenide stage

Greisenization is tied to the emplacement and crystallization of the younger granite. K/Ar age determinations on micas fall in the range of 260–280 Ma [351].

Carbonate–uraninite stage

Uraninite ages from the German part of the Krušné hory/Erzgebirge are discussed in the publications [294], [515], [516].

The publication of [351] reviews older *uraninite* isotopic analyses. The calculated ages cover a wide range from 260 Ma to 5 Ma. Legierski measured the following ages on *uraninite* from Jáchymov: 76, 140, 165, 202, 247, and 285 Ma [301].

The low ages correspond to younger generations of remobilized *uraninite*.

Stages of polymetallic mineralization

The age of the (post-uranium) polymetallic mineralization is not constrained by direct and reliable data.

The isotopic composition values for galena from Jáchymov by Legierski are presented in Table 1. Samples 224A and 22 belong to the younger *arsenic-sulphide* and *sulphide* stages, which followed the main *arsenide* stage [301] [307].

Surprisingly, a single attempt at dating with paleomagnetometry methods [368] indicates a probable age of the mineralization near the Mesozoic/Tertiary boundary.

Geologie a hydrotermální žilný systém jáchymovského rudního okrsku

Je podán stručný přehled geologie Krušných hor se zaměřením na geologii jáchymovského ložiska. Jsou popsány hlavní typy hornin na tomto ložisku a role tektonických procesů. Jsou zde shrnuty geologické faktory rozhodující pro vznik mineralizace, především tzv. „pětiprvkové“. Všechny žilné uzly, hydrotermální žíly jsou rozděleny ve shodě s klasickým dělením starých horníků na „jitřní“ a „půlnoční“. Žilná hydrotermální „pětiprvková“ mineralizace je chronologicky rozdělena na jednotlivá mineralizační stadia spolu s odhadem jejich stáří.