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History of Uranium Mining in Central Europe

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Abstract

The Central European deposits were the first industrially mined uranium deposits in the world. Uranium minerals were noticed by miners in the Ore Mts. area (Saxony, Bohemia) for a long time prior the uranium discovery. The uranium mineral pitchblende was reported from this ore district as early as 1565. Pitchblende was firstly extracted for production of colouring agents used in the glassmaking industry. The German chemist Klaproth in 1789 detected uranium by analysing pitchblende. In 1896, A.H. Becquerel discovered the phenomenon of radioactivity. His student Marie Sklodowska-Curie recognized that pitchblende has higher radioactivity as pure uranium salts. Later, together with her husband P. Curie, they discovered two new elements: radium and polonium. Research by O. Hahn and its colleges led later to using of uranium as first nuclear weapons. The significant amount of uranium ores for producing of the Russian nuclear weapons and nuclear power plants in the former Eastern Bloc was mined in the East Germany (GDR) and Czechoslovakia. The total production of uranium ores in GDR from 1946 to 2012 was 219,626 t U. In Czechoslovakia, the total uranium production from 1945 to 2017 was 112,250 t U.

Keywords: pitchblende, uranium glass, radioactivity, radium, polonium, nuclear energy

1. Introduction

The Central European uranium deposits were the first industrially mined deposits in the world. Uranium minerals were noticed by miners in the Ore Mts. area (Saxony, Bohemia) for a long time prior the discovery of uranium by Klaproth in 1789. The uranium mineral pitchblende was reported from this ore district as early as 1565. Pitchblende was firstly extracted for production of colouring agents used in the glassmaking industry. Uranium glass became very popular in the mid-nineteenth century. The important glassworks on this time exist in North and South Bohemia (Jizera Mts., Krkonoše, and Bohemian Forest).

The German chemist Klaproth in 1789 detected a new element, uranium, by analysing pitchblende from the Johanngeorgenstadt silver deposit. Its name (uranit, later uranium) was derived from the planet Uranus, discovered in 1781 by F.W. Herschel. Later, A.H. Becquerel discovered the phenomenon of radioactivity. His student Marie Sklodowska-Curie by study of some pitchblende samples, including samples from the Jáchymov uranium deposit, recognised that pitchblende has higher radioactivity as pure uranium salts. Later, together with her husband P. Curie, in 1898, they discovered two new elements: radium and polonium. Radium was used in self-luminous paints and in medicine to produce radon gas. Research by O. Hahn, L. Meitner and F. Strassmann in 1934 led to using of uranium as a fuel in the nuclear power industry and first nuclear weapons.

2. Discovery of pitchblende and uranium

Uranium minerals were noticed by miners in some silver ore deposits from the Ore Mts. area (Krušné Hory/Erzgebirge) for a long time prior the uranium discovery. The uranium mineral pitchblende was reported from this ore district as early as 1565. However, the miners have found that in places with higher occurrence of uraninite silver and its minerals disappear. The first occurrence of pitchblende entails trouble (pitch). Along with silver ores, some cobalt-bearing minerals later were also mined, which were used for production of some enamels for glass and ceramic industry. In Jáchymov, main silver deposit on the Czech (Bohemian) side of the Ore Mts. area, the first enamel factory originated in 1780. After the discovery of organic ultramarine colours in 1828, the market for the more expensive cobalt colours was closed.

The German dispensing chemist Klaproth (1743–1817) had in his experimental laboratory in Berlin performed some experiments with pitchblende from the Johanngeorgenstadt uranium deposits in the Saxony. During these experiments in Berlin in 1789, Klaproth was able to precipitate a yellow compound (likely sodium diuranate) by dissolving pitchblende in nitric acid and neutralising the solution with sodium hydroxide. Klaproth assumed this yellow compound was the oxide of a yet-undiscovered element. By heating this substance with charcoal, he obtained a black powder, which he thought was the newly discovered element itself [1]. However, that powder was an oxide of uranium. Klaproth named the newly discovered element after the planet Uranus, which had been discovered eight years earlier by William Herschel. First sample of uranium metal was prepared in 1841 by Eugène-Melchior Péligot, professor of analytical chemistry on the Central School of Arts and Manufactures in Paris, by heating uranium tetrachloride with potassium [2].

3. Use of pitchblende in glass and porcelain industries

Klaproth had later experimented with using some yellow uranium compounds as glass colours. Some other chemists from silver metallurgical work in the Jáchymov started also with experiments using these yellow components in glassmaking industry. The Ministry for

tillage of the Austrian-Hungary monarchy in Vienna recognised high interest for this new business and delegated the young chemist Adolf Patera (1819–1894) to discover a cheap technology for the production of yellow uranium colour. In the years 1851–1855, silver metallurgical work was reconstructed to factory for production of uranium yellow colours (k.k. Urangelbfabrik). Later, a new young chemist Arnošt Vysoký (1823–1872), who was named in 1866 as the director of this metallurgical and chemical works, developed some new uranium colours for the glassmaking industry (uranium orange yellow colour, uranium ammonium yellow, and high orange uranium colour) and the “black uranium colour” for the porcelain industry [3]. All these uranium colours from the Jáchymov factory were highly valued in the European market, especially in the Great Britain and France. According to high international interests for uranium colours from the Jáchymov, the original silver metallurgical work and factory for production of uranium colours in 1871 was quite reconstructed, and in 1879, this work was named as the biggest world factory for production of uranium colours. Original production of uranium colours in 1853 (84.6 kg) rose in 1886 to 12,776 kg of uranium colours. However, 10 years later, interest for uranium colours distinctly declined. After year 1896, the production of uranium colours in the Jáchymov highly declined and mining of uranium ore was almost stopped. After World War I, new competitive uranium colour factories originated in Belgium, Great Britain and Canada. The uranium colour factory in Jáchymov and factory in the Oolen, Belgium, closed in 1926 with a cartel agreement for the European market with 40% quotient for the Jáchymov factory. However, majority of glass and porcelain factories in the Czechoslovakia bayed the cheaper uranium colours from the British firms. After occupations of Jáchymov by Nazis (1938), the new Germany company (St. Joachimsthaler Bergbaugesellschaft) was established in 1939 (St. Joachimsthaler Bergbaugesellschaft), which have mined uranium ore for the German nuclear experiments. The chemical factory for producing of uranium colours and radium was closed and settled. Distinctly lower quantity of uranium colours was produced in some small factories in the German part of the Ore Mts. area (Krušné Hory/Erzgebirge), which used pitchblende mined in the Marienberg, Annaberg and Johanngeorgenstadt silver-cobalt-nickel-uranium deposits [2].

4. Uranium glass

Uranium glass became popular in the mid-nineteenth century, with its period of greatest popularity being from 1880s to the 1920s [2, 4]. The most typical colour of uranium glass is pale yellowish-green, which in the 1920s led to the nickname Vaseline glass based on a perceived resemblance to the appearance of petroleum jelly as formulated and commercially sold at that time. Vaseline glass is usually used for any uranium glass especially in the United States. The first major producer of uranium glass is commonly recognised as Franz Xaver Anton Riedel (1782–1844) from the Dolní Polubný (Unter-Polaun) in the Jizera Mountains, North Bohemia. This glassmaker had started with the production of uranium glass in 1841 and had developed yellow and green uranium glass named after his daughter Anna yellow (Anna gelb) and Anna green (Anna grün). Some other uranium glassworks existed in this time in the Krkonoše Mts. (Riesengebirge), on the boundary between Bohemia and Poland

(Harrachov in the Czech Republic and Szklary in Poland) and in the South Bohemia (Lenora, Josefsthál near Zvonková). A glassmaker from the Nový Svět near Harrachov developed and on the fair in Prague (1831) presented new, partly opaque uranium “Chrysoprasglass” [5].

Production of uranium glass was popular also in the other European countries, especially in Great Britain, France and Germany. In the Great Britain, it was glassworks in London (White friars) and Sturbridge area (Thomas Webb glasswork). In France, the first uranium glass was produced in glasswork Choisy-le Roi in Paris in 1838. The uranium glass in France was later named as “Cristal Dichroide”.

The highly different uranium glass products produced by glassworks in the North and South Bohemia mainly pressed glass cups and polished vases and were very popular souvenirs sold predominantly in the West Bohemian health resorts (Karlovy Vary, Mariánské Lázně, Františkovy Lázně) [2]. These glass products from the uranium glass were very important utility products of the Biedermeier and Art Nouveau periods.

5. Discovery of radioactivity, radium and polonium

In 1895, W.C. Röntgen discovered new rays, later named as the “Röntgen rays”. One year later, in 1896, A.H. Becquerel (1852–1908) discovered the phenomenon of radioactivity by exposing a photographic plate to potassium uranyl sulphate. He determined that a form of invisible rays emitted by uranium salts had exposed the plate. His student, Maria Skłodowska-Curie (1867–1934), recognised that some samples of pitchblende, including pitchblende from the Jáchymov uranium deposit, have a higher radioactivity as pure uranium salts. Marie and Pierre Curie (1859–1906) discovered the new element radium, in the form of radium chloride, in 1898. They extracted the radium compound from residues originated by production of uranium colours in the Jáchymov factory. For first experiments of both researches in 1898, they obtained from the Jáchymov uranium colour factory 5 kg of these residues, later 100 kg of these residues. In these residues, Marie and Pierre Curie discovered along with radium a second new element, polonium [6, 7]. For isolation of both new elements, both researchers in 1899 obtained from the Jáchymov factory 1000 kg of residues. These residues were collaborated in bigger laboratories of the Société Centrale de Produits Chimiques in Paris [8]. In 1910, radium was isolated as a pure metal by M. Curie and A. L. Debirne thought a radium chloride electrolysis. Radium metal was first commercially produced in the beginning of the twentieth century by Biraco, a subsidiary company of Union Minière du Haut Katanga in its Oolen plant in Belgium. In the Jáchymov uranium colour factory, radium chloride was produced from 1908. In the years 1909–1937, the Jáchymov factory produced 64.3 g of Ra. In years 1908–1933, radium chloride was produced for its use in medicine to produce radon gas, which in turn was used in cancer treatment. In 1934, the Jáchymov uranium factory started producing self-luminous paints for watches, aircraft switches, clocks and instrument dials. The total production of uranium ores from the Jáchymov ore deposit in years 1853–1945 was 469.5 t of U [9].

After the isolation of radium by Marie and Pierre Curie from pitchblende from Jáchymov, several other scientists started to isolate radium in small quantities. Later, some small companies

purchased mine tailings from the Jáchymov uranium deposit and started isolating radium. In 1904, the Austrian government nationalised all mines in the Jáchymov and stopped exporting raw uranium ore. The formation of an Austrian monopoly and the strong urge of other countries to have access to radium led to a worldwide search for uranium ores. New uranium ore deposits were found in United States, Belgian Congo and Canada.

6. Discovery of radon and origin of radon spas

Ernest Rutherford and Robert B. Owens discovered radon in 1899. In 1900, Friedrich Ernst Dorn in some experiments found that radium emanates a radioactive gas, which was named radium emanation. Later, similar emanations for thorium and actinium were found, which were named as radon, thoron and actinon [10, 11].

The danger of high exposure to radon in silver-uranium mines has long been known. Georg Agricola, physician in Jáchymov, recommended ventilation in mines to avoid this mountain sickness (Bergsucht). In 1879, this condition was identified as lung cancer by investigation of miners from the Schneeberg silver-uranium deposit in the Saxony [12]. The first major studies with radon and health were performed in the context of uranium mining in the Jáchymov ore deposit [13, 14]. Recently, a detailed study of the influence of radon on miners' health in the Czech uranium mines was published by Řeřicha et al. [15].

Exposure to radon, a process known as radiation hormesis, has been suggested to mitigate diseases of movement system such as rheumatoid arthritis, spondylitis, ankylosing spondylitis, condition after orthopaedic surgeries, diseases of peripheral nervous system and metabolic diseases. Radioactive water baths have been applied since 1906 in Jáchymov, since 1912 in Bad Brambach and since 1918 in Oberschlema, Saxony [16–18].

Radioactivity of the first radioactive water springs in the Jáchymov mine Werner was measured by Austrian physicists Heinrich Mache and Stefan Meyer in 1905. They found higher radioactivity (2.5 kBq/l) [19]. These results started Jáchymov spa history. The first spa house was opened in 1911 (recently spa centre Agricola). In year 1912, a luxury spa house Radium Palace was opened. During years 1908–1924, the Štěp springs from the Werner mine was used for radon bath therapy. In 1924, spring Curie at the 12th level of the Svornost mine (30 l/min, 29°C, 5 kBq/l) was found. After closing uranium mining in the Jáchymov area, in 1960–1962, new hydrogeological exploration of radioactive springs at the 12th level of the Svornost mine was performed. Two new radioactive water springs were found (H-1 and HG-1 – Běhounek, 300 l/min, up to 36°C, 10 kBq/l). More recently performed hydrogeological exploration was found in 2000 spring Agricola (10 l/min, 29°C, 20 kBq/l) [20–24].

In Bad Brambach, a new spring of radon water was found by Max Weiding in 1911. The high radioactive water spring was later named Wetтинquele and was used for radiotherapy from 1915 and represented a mineral water spring with the highest radioactivity in the world (26 kBq/l). The radon spa in Bad Brambach from 1945 to 1948 was used as nursing home for the Soviet arms and since 1949 is used as a spa for all patients with diseases of movement system [16].

Today, the community of Bad Schlema is an amalgamation of the formerly separate communities of Niederschlema and Oberschlema. After rich radon springs were opened in the Marx-Semler gallery in Oberschlema between 1908 and 1912, the world's richest radium spa developed after 1918. Ten years later, it was counted among Germany's most important spas. Once the uranium mining was taken over by the Soviet occupation forces, the spa and the downtown of Oberschlema were utterly obliterated. After uranium mining came to an end in 1990, the mayor, Konrad Barth, organised Schema's revival as a spa town, which was realised in 1998 when the new "Spa house" (Kurhaus) was opened. The newly opened radon springs afforded ample bathing. In 2005, Saxony's state government bestowed upon the community official designation "Bad", after it had already been recognised as a radon spa since 2004 [18, 25].

7. Uranium as fuel in the nuclear weapons and in the nuclear power industry

Otto Hahn and Fritz Strassmann conducted the experiments leading to the discovery of uranium's ability to fission and release binding energy in 1934. Lise Meitner and Otto Robert Frisch published the physical explanation in February 1939 and named the process "nuclear fission". Further work found that U^{238} isotope could be transmuted into plutonium, which like U^{235} isotope is also fissile by thermal neutrons. These discoveries led to the United States, Great Britain and Soviet Union to begin work on the development of nuclear weapons and nuclear power. After World War II, following the Cold War between the Soviet Union and the United States, huge stockpiles of uranium were amassed and tens of thousands of nuclear weapons were created using enriched uranium and plutonium made from uranium ores. Uranium ore was, after 1949, a highly strategic mineral material. In Central Europe, the principal uranium ore deposits were discovered in the Czechoslovakia and the East Germany (GDR). Some small uranium ore deposits were also found in Poland. The uranium ore from these deposits was in the first place used for the Soviets' nuclear weapons, later also for nuclear power industry [9, 26–29].

8. Czechoslovak uranium mining after World War II

In 1945, the Soviet Union controlled all uranium resources in the Czechoslovakia and in the Soviet occupation zone in the Germany and later also in Poland. In East Germany and in Poland, the so-called stock companies for exploration and exploitation of uranium ore deposits were established in which the Soviet share represented fifty percent. In East Germany, the income from the uranium exploitation came on the account of war reparation up to 1953. In Czechoslovakia, talks between Czechoslovak Prime Minister Zdeněk Fierlinger and the Soviet diplomatic agent Ivan Bakulin about the uranium ore mining and exclusive export to Soviet Union from August 1945 were finished on 23 November 1945 when the "Memorandum of understanding between the governments of Soviet Union and Czechoslovakia about the

extension of exploitation of radium-bearing uranium and concentrates in Czechoslovakia and their delivery to the Soviet Union" was signed. The Memorandum contained also an attachment, which proclaimed this document to be highly confidential. According to the Memorandum, the Joachim Mines State Enterprise was founded. Leading posts in this enterprise were taken over by the Soviet experts. The Memorandum, however, did not specify the costs of exported uranium ores. This problem was progressively discussed between 1949 and 1952 [28]. In 1945, the Jáchymov ore deposit represented the only available uranium source on the territory of the Soviet block where uranium ores could be exploited immediately. In East Germany, the first exploitation of uranium ores started in 1947 and 1948.

From 1945 to 1949, in the Jáchymov uranium mines, the German war prisoners started to work, who were later replaced mainly by political and other Czechoslovak prisoners. The Jáchymov together with Horní Slavkov and Příbram became known as parts of the "Czech Gulag". In Jáchymov, 65,000 prisoners worked in concentration camps until 1961 [9]. For following exploration of uranium deposits on the Czechoslovak territory, in 1946, "Prospective geology group", which later evolved into the independent organisation, was established. Thirty Soviet geologists formed the nucleus of this group, and according to territorial responsibilities, the group was subdivided into seven subgroups. During 1948 and 1962, the Horní Slavkov uranium deposit was opened and exploited. In the Czech part of the Ore Mts. (Krušné Hory/Erzgebirge), some smaller ore occurrences and deposits (e.g., Potůčky, Abertamy) were exploited.

In the first stage of uranium exploration, the selected territories according to older geological studies and geological mapping were covered in 1958–1964 by emanometry, sampling from a depth of 1 m. Productivity of three-personnel groups was about 300–500 holes per day. Productivity of later used technique with 3 m holes was much lower, and with this technique, only limited areas were covered. Some other geophysical methods that were used for exploration of uranium deposits were ground and car-borne gamma-ray survey [30]. From 1946 to 1955, exploration for uranium ores was concentrated on the known vein deposits in the Ore Mts. area (Jáchymov and Horní Slavkov) and area of the known base-metal vein deposit Příbram. During systematic emanometry and gamma-ray surveys, a new type of hydrothermal uranium deposits evolved in mineralised shear zones (Rožná, Olší, Okrouhlá Radouň, Zadní Chodov and Vítkov II). The sandstone-hosted deposits in northern Bohemia (Hamr, Stráž, Břevniště, Osečná-Kotel and Hvězdov uranium deposits) were found after gamma logging of hydrogeological borehole [30]. In 1989, the decision was made to reduce all uranium-related activities. Following this decision, in 1990, expenditures decreased to about 7 million USD and have declined ever since. No field exploration has been carried out since the beginning of 1994 [31].

Most of the known uranium resources in the Czech part of the Bohemian Massif occurred in 32 ore deposits, of which 30 have been mined out or closed up to year 1993. Of two remaining deposits, the Rožná and Stráž were mined also from 1993 up to 1996 (Stráž) or up to 2017 (Rožná). The mining of the last Central European uranium deposit (Rožná) was stopped in April 2017. The very small recent production of uranium in the Stráž uranium deposit is part of remediation of the after-effects of the in-situ leaching that impacted a total 266 million m³

groundwater and an enclosure of 650 ha surface area. In former Czechoslovakia, a total uranium production from 1945 to 2017 was 112,250 t U. However, majority of uranium ore was mined in the Czech Republic. In Slovakia, in this time, only 211.4 t U was mined. In the Czech Republic from 2004, no prospection activities on uranium ore deposits exist. Recently, only different environmental remediation projects exist. The biggest project in area of the Stráž uranium deposit is expected to continue until approximately 2040 [31].

The mined uranium deposits in the Czech Republic could be divided into the three main genetic types: vein deposits, shear-zone deposits and sedimentary deposits (**Table 1**). The production of the 12 main uranium deposits is listed in **Table 2**. The Příbram, Jáchymov and Horní Slavkov uranium deposits represent the vein deposits. The Rožná, Zadní Chodov, Vítkov II, Olší, Okrouhlá Radouň and Dyleň deposits represent the shear-zone uranium deposits. The sedimentary deposits are evolved mainly in the Upper Cretaceous Uranium Ore District (Stráž, Hamr and Břevniště) (**Figure 1**). Only some small uranium deposits and occurrences were evolved also in the Carboniferous-Permian and Tertiary continental coal-bearing sediments.

The Příbram uranium ore district extends along the northwestern contact of the Central Bohemian Plutonic complex (CBPC) with Neoproterozoic and Cambrian rocks of the Teplá-Barrandian Zone. The 3200 km² complex crops out between two contrasting crustal units, in the Teplá-Barrandian Zone to the NW and Moldanubian Zone to the SE, in the central part of the Bohemian Massif. The plutonic complex is made up of multiple individual plutons and smaller magmatic bodies that vary in age, petrographic and geochemical characteristics, shape, size, internal fabrics and relationships to the host rock structures, from older calc-alkaline to potassium-rich calc-alkaline and ultrapotassic magmas. In the NW margin of the CBPC, in area of the Příbram ore district crop out biotite and biotite-amphibole granodiorites of the Blatná suite, together with the Marginal, high-K calc-alkaline biotite granites. The Neoproterozoic, a slightly metamorphosed flysch sequence, up to 2000 m thick, is overlain by a Lower Cambrian sediments, containing thin layers of quartz-pebble conglomerate at its base and slates at a higher stratigraphic position. A volcano-sedimentary complex underlies the Neoproterozoic flysch sequence, comprising intercalated claystones, siltstones and conglomerates. Both the Lower Cambrian and Neoproterozoic rocks are contact metamorphosed by the CBPC within an aureole that extends 1000 to 1200 m from the intrusive contact. This

Genetic type of deposit	Production, t U
Vein and shear-zone deposits	82,128
Cretaceous sandstones	29,014
Carboniferous-Permian sediments	608
Tertiary sediments	289
Total	112,039

Table 1. Genetic types of uranium deposits in the Bohemian Massif [32].

Uranium deposit	Mining	Production, t U
Příbram	1950–1991	50200.8
Rožná	1657–2017	22220.0
Stráž	1967–1996	14674.1
Hamr	1972–1993	13263.8
Jáchymov	1946–1964	7950.0
Zadní Chodov	1952–1992	4150.7
Vítkov II	1961–1990	3972.6
Olší	1959–1989	2922.2
Horní Slavkov	1948–1962	2668.3
Okrouhlá Radouň	1972–1990	1339.5
Břevniště	1982–1990	1107.8
Dyleň	1965–1991	1100.5

Table 2. Production of uranium in the main uranium deposits of the Bohemian Massif [32].

aureole is also cut by aplite and lamprophyre dykes. The Neoproterozoic host rocks form a simple fold, the Příbram anticline, with NE-trending axis, roughly parallel to the CBPC contact. Brittle structures in the Příbram ore district may be classified relative to the axial plane of the Příbram anticline as: (i) the most prominent, longitudinal NE-striking faults, i.e. subparallel to boundary of Neoproterozoic metasediments with the CBPC, (ii) transverse NW-striking faults, and (iii) oblique, E- or N-striking faults. Ore veins in the ore district strike NW (44% of veins), N (43% veins), and NE (13% veins). The ore veins are from a few metres to several kilometres long, from a few centimetres to more than 10 metres wide and comprise three mineral assemblages (from older to younger): (1) sulphidic with Pb, Zn and Cu-Fe sulphides, (2) uraninite bearing and (3) sulphide-selenide-carbonate. The main U-bearing minerals are uraninite and U-anthraxolite, coffinite being far less abundant. Uranium minerals occurred as veinlets, coatings and pods in calcite gangues. The deposit has been mined to a depth exceeding 1500 m and total mined amount of U was 50200.8 t [32].

The Rožná and Olší uranium deposits occur in the uppermost Gföhl unit of the high-grade metasediment series of the Moldanubian Zone. The host rocks of the Rožná U deposit consist predominantly of biotite paragneisses with intercalations of amphibole-biotite gneisses, amphibolites and small bodies of calc-silicate rock, marble, serpentinite and pyroxenite. The disseminated uranium mineralisation is coupled in the longitudinal N-S to NNW-SSE ductile shear zones, dipping WSW at an angle of 70–90°. The main mineralised shear zones of the Rožná uranium deposit are designated as the Rožná 1 (R1) and Rožná 4 (R4). In the less strongly mineralised Rožná 2 (R2) and Rožná 3 (R3) shear zones, numerous carbonate veins occur. Mineralised shear zones are segmented by steep, ductile to brittle NW-SE and SW-NE striking faults with younger carbonate-quartz-sulphide mineralisation.

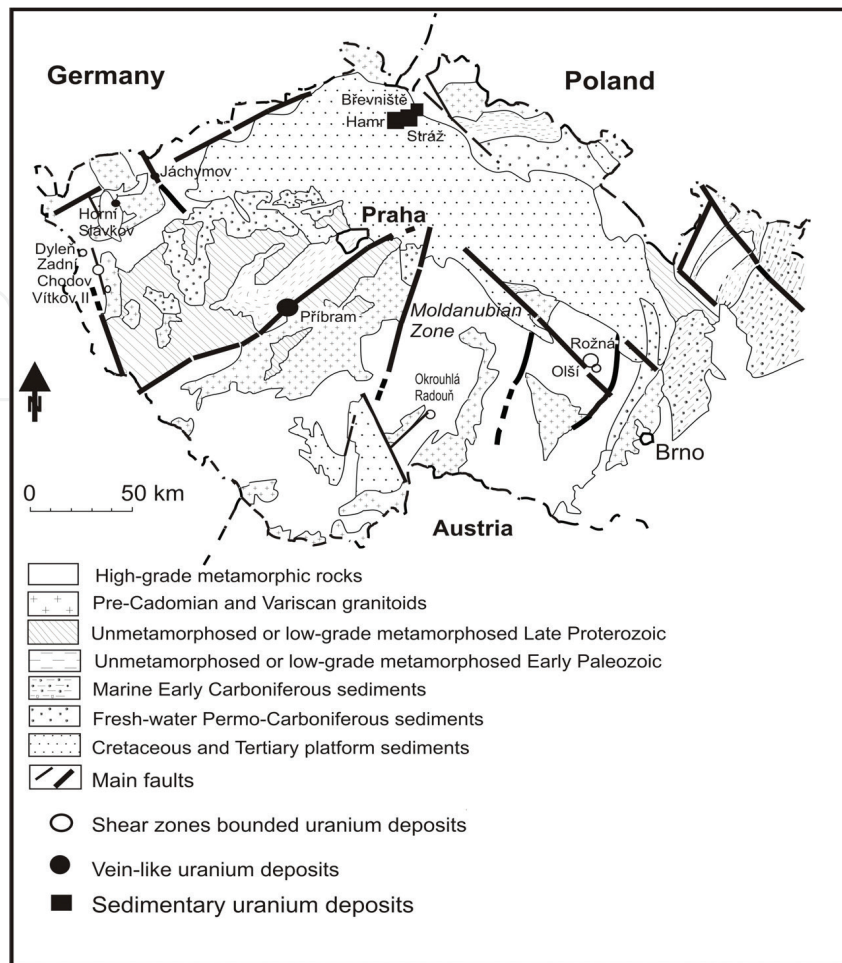


Figure 1. Main uranium deposits in the Czech part of the Bohemian Massif.

Ore mineralisation in the Rožná and Olší uranium deposits is formed by (i) disseminated coffinite > uraninite > U-Zr-silicate mineralisation evolved in chloritised, pyritised, carbonatised, and graphitised organic matter-enriched cataclastites of ductile shear zones, (ii) uraninite > coffinite mineralisation in carbonate veins, (iii) disseminated coffinite > uraninite in albitised and hematitised rock series (aceites) along ductile shear zones and (iv) mostly coffinite ore bound on the intersections of the ductile shear zones with younger NW-SE and SW-NE faults. Ore lenses of disseminated ore in fault zones R1 and R4 are 3.5 m thick on average, ore grade is around 0.5% U, up to 10% U locally. Ore bodies in ore zones R2 and R3 host a large number of carbonate veins up to 2 m thick with U-mineralisation of the average grade 0.6% U. Ore bodies in aceites with predominance of coffinite on uraninite and U-Zr silicate have U-mineralisation of a grade 0.1–0.15% U, exceptionally 0.3% U. Disseminated U-mineralisation bound to oblique fault zones is usually hosted by quartz-carbonate-sulphide breccias at intersections with diagonal and longitudinal structures. Compared to other types of mineralisation, the ore bodies are small but contain relatively high-grade ore of average grade 0.8% U and up to 20% U in some ore shoots. Total mine production of the Rožná-Olší ore district was 25,142 t U with an average grade of 0.24% U [32].

The North Bohemian Cretaceous uranium ore district (Stráž, Hamr, Břevniště ore deposits) is developed in the two Cenomanian formations, lower freshwater continental and upper marine sediments. The basement of the Upper Cretaceous sediments is formed in this area by low-grade metamorphic rock series (phyllites and quartzites) and small bodies of the Upper Proterozoic and Upper Devonian granitoids. The lower continental sediments are developed in the paleo relief depressions and are formed by conglomerates and pebbly to silty sandstones. All these sediments are usually enriched in organic matter. The sandstones of marine Cenomanian cover the whole area of uranium ore district. Its basal parts are formed by wash-out sediments, which are represented by silty sandstones. They are overlain by the sequence of Upper Cenomanian weakly cemented sandstones. Uranium mineralisation is developed in the basal part of the Cenomanian formation, and it is usually divided into four ore levels: A (freshwater sediments – stream and lacustrine sandstones), main B level is evolved at the base of marine Cenomanian in wash-out sediments; ore levels C and D are less extended and occur in the friable sandstones (C) and in the uppermost Cenomanian – fucoidal sandstone horizon (D). The mostly horizontal plates and lenses usually form the ore bodies. The thickness of these plates and bodies varies from decimetres to several metres. The mineralogical and geochemical composition of uranium mineralisation occurring in the North Bohemian Cretaceous uranium district is diversiform and unique [33–35].

Uraninite, complex U-containing gels, hydrozircon, baddeleyite and U-Th-Ca phosphates (ningyoite and brockite) are main carriers of uranium. For these uranium-enriched minerals (uraninite, hydrozircon, ningyoite and brockite) is highly significant enrichment in rare earth elements (REE) and Y. Uranium mineralisation is also coupled with occurrence of REE or Y minerals (crandallite, chernovite-(Y), rhabdophane and synchysite) [35, 36].

In 2012, in preparation of the new State Energy Concept of the Czech Republic, technical and economic re-evaluation of remaining uranium resources was undertaken. Total identified conventional resources in 2013 amounted to 119,256 t U. These resources are located in the North Bohemian Cretaceous basin (the Stráž, Hamr, Osečná-Kotel and Břevniště deposits). However, all these resources remain strictly protected due to environmental concerns (groundwater source protection zone) [31].

In Slovakia, from 1954 to 1990, small uranium deposit in the Slovak Ore Mts. (Novoveská Huta) was mined. The uranium ores were mined as by-product of copper mining. The uranium mineralisation in the Novoveská Huta ore deposit (Gemicum) occurs in two horizons of Permian volcano-sedimentary formation. The upper horizon is a part of volcano-sedimentary complex of volcanoclastic sandstones and conglomerates overlying rhyolites and their tuffs. Ore bodies form lenses mostly concordant to wall rocks. Their thickness reaches several metres. Uranium mineralisation is concentrated, however, largely in matrix of volcanoclastic rocks. The lower ore-bearing horizon occurs in breccias of the upper part of volcano-sedimentary complex with intermediate volcanic rocks. The length of the mineralised horizon is 4 km, the width varies from 200 to 600 m and the thickness reaches up to 80 m. Lenticular ore bodies are thick from several metres to tens of metres. Uranium mineralisation is disseminated or forms veinlets. Uraninite and molybdenite are dominant in uranium ore of both main horizons. U-Ti oxides, pyrite, chalcopyrite, tennantite, galena, sphalerite and arsenopyrite accompany them.

Hydrozircon also occurs in the lower ore-bearing horizon. Rich uranium mineralisation rarely occurs in faults cutting the U-Mo mineralised horizons in the western part of the Novoveská Huta deposit. Uranium and Mo mineralisation in these faults is represented by uraninite, coffinite and molybdenite.

Some small uranium deposits and occurrences were found also in the other West Carpathian geological units in Slovakia, namely in the Hronicum (Vikartovce, Kravany, Švábovce), Tatricum (Kálnice, Selec) and the Veporicum. All these geological units could be distinguished into two morphological types of uranium mineralisation, namely stratiform mineralisation in the Permian volcanoclastic complexes and vein mineralisation evolved in tectonic zones (quartz-carbonate, quartz-gold-bearing veins) [37].

In 2012–2014, new exploration licences for uranium ore were active in the Slovak Republic. The most perspective exploration licence covers uranium mineralisation in Kuriškova, near Košice in the Eastern Slovakia. In this area, conventional resources in amount of 15,830 t U were calculated and identified. In the Novoveská Huta, resources in amount of 3488 t U are recently registered [31]. However, mining of both uranium deposits is recently blocked by various environmental activities.

9. East Germany uranium mining after World War II

The uranium exploration and mining in East Germany (GDR) started in 1946 as the Soviet stock company, SAG Wismut. In the first stage of this mining activity, an old silver-uranium-cobalt-nickel ore deposit Johanngeorgenstadt was open. Later, the uranium ore deposits near Schneeberg and Oberschlema were found and mined. The second stage of uranium exploration had started in 1950 in the vicinity of the radium spa at Ronneburg. In both uranium ore districts, using a variety of ground-based and aerial techniques, the exploration activities covered an extensive area of about 55,000 km². About 36,000 boreholes in total were drilled in the area covering approximately 26,000 km². Total expenditures for uranium exploration were on the order of 5–6 billion of GDR mark [31].

In 1954, a new joint Soviet-German stock company was created (SDAG Wismut). Both governments held the joint company equally. At the end of the 1950s, uranium mining was concentrated in the region of Eastern Thuringia (Ronneburg ore district). From the beginning of the 1970s the Ronneburg ore district provided about two-thirds of uranium annual production in the GDR. In East Germany, in contradiction to Czechoslovakia, the prisoners were used in uranium mining in limited extent. The prisoners were used mainly in 1946–1947 and the total number of prisoners used in SAG Wismut from 1946 to 1949 was 59,492 [38].

Total production in East Germany in 1946–1990 was 219,517 t U, making it the third largest producer in history behind the United States and Canada. The uranium mining and processing of uranium ores in two processing plants were stopped in 1989. Decommissioning of uranium mines and production facilities started in 1990. Between 1991 and 2012, uranium recovery from mine water treatment and environmental restoration amounted to a total of

2540 t U. Since 1992, all production in former East Germany has been derived from clean-up operations at the Königstein mine. In 2007, the production in the Königstein mine has been 38 t U [31].

The uranium mining in East Germany was concentrated in two main regions: the Ore Mts. region in Saxony (Schneeberg, Niederschlema-Alberoda, Johanngeorgenstadt, Schwarzenberg and Pöhla-Tellerhäuser) and the Ronneburg district in Thuringia. Small uranium deposits were evolved in the Cretaceous sandstones near the Königstein in Saxony [39–41]. Uranium deposits in the Ore Mts. region are hydrothermal vein deposits. In these ore deposits, three uraniferous mineral associations were established (quartz-calcite-pitchblende, carbonate-pitchblende-fluorite and bismuth-cobalt-nickel-silver-uranium). Uranium in these associations is represented by pitchblende, sooty pitchblende and coffinite. In veins of the Niederschlema-Alberoda deposit, coffinite constitutes up to 5% of the uranium content. The main ore deposit in this region was Niederschlema-Alberoda and it was one of the largest vein uranium deposits in the world, which has produced 73,900 t U. Other uranium deposits in the Ore Mts. region produced distinctly lower amount of uranium (Oberschlema 6700 t U, Johanngeorgenstadt 3600 t U, Pöhla-Tellerhäuser 1240 t U, Schwarzenberg 670 t U and Schneeberg 160 t U).

The Niederschlema-Alberoda uranium ore district is located in the Western Ore Mountains, in Germany, near the state boundary to Czech Republic. This ore district is evolved in the intersection of the SW-NE striking Loessnitz-Zwoenitz syncline with NW-SE trending Gera-Jáchymov fault zone. The Loessnitz-Zwoenitz syncline is one from sectional tectonic structures, which are ingredients of the Erzgebirge-Fichtelgebirge anticlinorium in the fold framework of the Saxothuringian Zone. The most important and central tectonic element of the Gera-Jáchymov fault zone is the vein structure Red Ridge (Roter Kamm), also defining the border between the Niederschlema-Alberoda ore district in NE and the Schneeberg uranium deposit in SW. In the Loessnitz-Zwoenitz syncline, predominantly Upper Ordovician-Silurian-Middle Devonian “productive” rocks are folded into Lower Ordovician schists of the northern edge zone of the Erzgebirge-Fichtelgebirge anticlinorium. The rock series of the “productive unit” are phyllites with intercalations of metamorphosed black shales and metacarbonates. The uranium-bearing veins occur in the contact metamorphic zone of the syncline beneath the late-Variscan Aue granite pluton. This granite body, located within the Gera-Jáchymov fault zone, intruded early-Variscan metasediments, especially low-grade garnet phyllites and medium-grade mica schists. The Aue granite body comprises various biotite granites. The Aue granite should have served as a major source for U accumulated in post-granitic deposits of Schneeberg and Schlema-Alberoda ore districts.

The uranium ore veins have a common thickness from 0.1 to 0.3 m with a maximum of 1 m. However, some ore veins show a massive pitchblende mineralisation with a thickness up to 2 m, which were mined down to a depth of about 2000 m. The hydrothermal mineralisation is usually divided into three main stages. The most important is first pitchblende-quartz-calcite-fluorite-sulphide stage. The second, post-Variscan stage contains dolomite-selenide-pitchblende mineral association. For the third, Bi-Co-Ni stage, the predominance of arsenides

and sulphides Co and Ni and native Bi is significant. The main mined ores were uranium ores, and accompanying ores (Co, Ni, Ag, Bi, Se and/or Pb, Zn and Cu from older quartz-sulphide veins) have been extracted only temporarily and in small quantities [39, 40].

The second most significant area with uranium mineralisation in GDR was the Ronneburg district in Thuringia. This district is part of the Thüringisch-Fränkischen Schiefergebirge. The main geological structure of this district is the Berga anticlinorium. Uranium mineralisation occurs in the Upper Ordovician to Lower Devonian black schist series with total thickness about 250 m. The main part of uranium mineralisation is bounded on the Upper Ordovician Leder schists. In the Ronneburg ore district, three morphological types of uranium mineralisation, namely mineralisation in faults and shear zones, mineralisation in breccias and highly dispersed mineralisation in black schists, were distinguished. Uranium mineralisation was formed by two associations: carbonate-uraninite and uraninite-pyrite associations. The main mined association was uraninite-pyrite association containing uraninite, pyrite, coffinite, marcasite, chalcopyrite, arsenides, calcite, dolomite, hematite and hydrogoethite. The uranium deposits in the Ronneburg district were mined from 1951 to 1990 in three open pits (Ronneburg, Lichtenberg and Stolzenberg) and in seven shafts. Total open pit and mine production of the Ronneburg ore district was 112914.3 t U with average grade of 0.099% U [40].

Small occurrence of uranium mineralisation was also found in the Lower Permian hard coal-bearing sediments of the NW-SE Döhla basin near Dresden. The basin that evolved along the late Variscan Elbe lineament contains the Upper Carboniferous and Lower Permian freshwater sediments (conglomerates, breccias, schists and hard coal-bearing sediments). The Lower Permian hard coal sediments contain hydrothermal uranium mineralisation (uraninite and coffinite) together with sulphide (sphalerite, chalcopyrite and galena) and carbonate mineralisation. Main uranium mining area in the Döhla basin was by Dresden-Gittersee and Freital. Total mine production of the Freital ore deposit mined from 1968 to 1989 was 3691 t U with average grade of 0.11% U [40].

In the natural park Saxony Switzerland, near Pirna was from 1967 to 1990 mined uranium deposit Königstein. This deposit was developed in the local Cretaceous basin that is NW part of the North Bohemian Cretaceous basin. From this large basin, the local Pirna basin was separated by the NNW-SSE Elbe lineament. The uranium mineralisation is developed in the three Cenomanian formations: lower freshwater continental, middle lagoon sediments and upper marine sediments. Bodies of the Lower Cambrian granodiorites and Variscan granites of the Markersbach granite body form the basement. Freshwater sediments are developed in depressions of the paleo relief and consist of sandstones and clay-bearing schists. All these rocks are often rich in organic matter (coalified plant detritus). The sediments of marine Cenomanian contain different sandstone types. Mostly horizontal lenses form the ore bodies. The thickness of ore bodies was between 0.5 and 1.0 m, sometimes up to 2.5 m. Some part of uranium mineralisation occurs also in the younger faults. Uranium mineralisation is formed by uraninite, coffinite and fourmarietite. Total mine production of the Königstein ore deposit mined from 1967 to 1995 was 18526.9 t U with average grade of 0.03–0.08% U [40]. After closing all uranium deposits in 1990, various large-scale remediation activities were provided from 1991 to 2014 [31].

10. West Germany uranium mining after World War II

Starting in 1956, exploration for uranium ores in Federal Republic Germany (FRG) was carried out in several Variscan units, especially in Black Forest, Odenwald, Frankenwald, Oberpfalz, Bayerischer Wald and Harz. Three small uranium deposits were found: vein deposit near Menzenschwand in the southern Black Forest, sedimentary Müllenbach deposit in the northern Black Forest and the Grosschloppen deposit in the Fichtelgebirge. The total uranium production was about 700 t U [31].

11. Polish uranium mining after World War II

Exploration and exploitation of uranium ore deposits in Poland began in 1948 by opening of the vein uranium deposits in the Karkonosko-Izerski block of the Bohemian Massif (Wolnosc, Miedzianka, Podgorze, Rubezal, Mniszkow, Wiktorja, Majewo, Walowa Gora, Radoniów and Wojcieszce). For processing of uranium ores from these mined deposits, in 1948, an industrial plant in Kowary (Lower Silesia) was established. Later, small occurrences and deposits of uranium mineralisation were founded in the Ladek and Snieznik Klodzki metamorphic complex of the Bohemian Massif (Kopaliny-Kletno). During the period 1948 and 1967, approximately 650 t of uranium was mined and all uranium ores were exported to the Soviet Union.

In 1956, exploration of uranium ore deposits by the Geological survey in areas of the Upper Silesian Coal Basin and the Polish lowlands began. During these exploration activities, small occurrences of uranium mineralisation were discovered in the Lower Ordovician sediments (Rajsk), in the Triassic sediments (Perybaltic Syncline) and in the Sudetes area (Okreszyn, Grzmiaca and Wambierzyce). In May 2012, one concession for prospecting base metals and uranium deposit was granted in the Radoniów area. At present, research projects aimed at assessing the possibility of obtaining uranium from domestic low-grade uranium ores and waste rock piles left at historic uranium mining operations (Kowary) are being conducted. Special attention is being paid to the use of biological leaching. All these exploration activities concentrated on finding of potential uranium resources were provided from 2012 to 2014.

12. Hungarian uranium mining after World War II

The first prospecting for uranium ores started in 1952 with Soviet participation. During airborne and surface radiometry in the western part of the Mecsek Mts., the Mecsek deposit of sedimentary ore deposit was found in 1954. The first shafts in this area were placed in 1955 and 1956. In 1956, the Soviet-Hungarian uranium joint venture was dissolved and uranium production from this ore deposit became the sole responsibility of the Hungarian state. Uranium in the Mecsek deposit was mined from 1956 to 1997. Total production of uranium from this ore deposit was about 21,000 t U. The uranium ore in the Mecsek deposit occurs in Upper Permian sandstones that may be thick as 600 m. The sandstones were folded into the

Permian-Triassic anticline of the Mecsek Mts. The thickness of ore-bearing sandstone varies from 15 to 90 m. The ore minerals are represented by uraninite, coffinite, pyrite and marcasite.

Since 2006, four uranium exploration project areas were covered by seven exploration licences (Mecsek, Bátaszék, Dinnyeberki and Máriakémed). Only the Mecsek project, where new geological model of the Mecsek uranium deposit was established, remains active. Following recent resource estimate re-evaluation, 17,946 t U is now reported as in situ high-cost inferred resources. Large-scale remediation activities in the area of the Mecsek uranium deposit were provided from 1998 to 2008 [31].

13. Conclusion

The Central European deposits were the first industrially mined uranium deposits in the world. Uranium minerals, especially uraninite (pitchblende), were noticed firstly by miners in the Ore Mts. area (Saxony, Bohemia) for a long time prior the uranium discovery. The uraninite was in this time found by miners in places with higher occurrence of uraninite, the silver and its minerals disappear. The first occurrence of pitchblende consequently entails trouble (pitch). The German chemist Klaproth in 1789 detected uranium by analysing pitchblende from the Johanngeorgenstadt uranium deposit in the German part of the Krušné Hory/Erzgebirge Mts. In the nineteenth century, some chemists from silver metallurgical works in the Ore Mountains area, especially in Jáchymov, started with experiments using the yellow uranium-bearing components originated by processing of silver-uranium ores in glassmaking industry. Uranium glass became popular in the mid-nineteenth century, with its period of greatest popularity being from 1880s to the 1920s.

In 1896, A.H. Becquerel discovered the phenomenon of radioactivity. His student Marie Sklodowska-Curie recognised that pitchblende has higher radioactivity as pure uranium salts. Later, together with her husband P. Curie, they discovered two new elements: radium and polonium. In years 1908–1933, radium chloride from various uranium deposits, especially from the Jáchymov deposit was produced, for its use in medicine to produce radon gas, which in turn was used in cancer treatment. Later, radium was used for radon production. Highly radioactive mineral waters occurred in some localities in the Ore Mts. (Krušné Hory/Erzgebirge) and were used to mitigate diseases of movement system such as rheumatoid arthritis, spondylitis, ankylosing spondylitis, condition after orthopaedic surgeries, diseases of peripheral nervous system and metabolic diseases. Radioactive water baths have been applied since 1906 in Jáchymov, since 1912 in Bad Brambach and since 1918 in Oberschlema, Saxony.

Otto Hahn and Fritz Strassmann conducted the experiments leading to the discovery of uranium's ability to fission and release binding energy in 1934. Lise Meitner and Otto Robert Frisch published the physical explanation in February 1939 and named the process "nuclear fission". The first use of nuclear fission in nuclear weapons applied at the end of World War II in Japan (Hiroshima, Nagasaki) started the first boom of exploration and exploitation of uranium ores in the whole world. The significant amount of uranium ores for producing the

Russian nuclear weapons and nuclear power plants in the former Eastern Bloc was mined in East Germany (GDR) and Czechoslovakia. The total production of uranium ores in GDR from 1946 to 2012 was 219,626 t U. In Czechoslovakia, total uranium production from 1945 to 2017 was 112,250 t U. Some small amount of uranium ores after World War II was mined also in Poland (650 t U) and Hungary (21,000 t).

In the Czech Republic and East Germany, the exploration activities for uranium mineralisation were stopped between 1990 and 2004. In the Slovak Republic, Poland and Hungary, some small exploration activities on uranium mineralisation were provided between 2012 and 2014. Potential possibility of future exploration and mining of uranium ores is in the Central European countries recently blocked by various environmental and civil activities.

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