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Vein uranium deposits

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ABSTRACT

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Vein uranium deposits are epigenetic concentrations of uranium minerals, typically pitchblende and coffinite, in fractures, shear zones and stockworks. The uranium minerals are either the sole metallic constituents in the veins or, in polymetallic veins, they are accompanied by other metals, such as bismuth, cobalt, nickel, arsenic, silver and copper.

The deposits are hosted by (1) granitic or syenitic rocks (intragranitic veins), (2) rocks surrounding granitic plutons (perigranitic or peribatholithic veins), or (3) sheared or mylonitized, usually metamorphosed, sedimentary or igneous complexes (veins in shear and fault zones).

Intragranitic uranium veins are typically developed in highly differentiated granitic rocks, e.g., in two-mica leucocratic granites that were subjected to preceding alteration, such as albitization and desilicification (episyenitization). The deposits are spatially related to regional faults. The principal uranium minerals, pitchblende and coffinite, are commonly associated with sulphides and gangue minerals, such as carbonates, quartz, chalcedony, fluorite and barite. A region with such veins is the La Crouzille district of the Massif Central, France.

Perigranitic uranium veins are commonly developed in metasedimentary and metavolcanic rocks, at their contacts with intrusive granitic plutons. The host rocks are often cut by lamprophyre and aplite dykes. The deposits consist of subvertical veins, breccia zones, stockworks and irregular bodies spatially associated with major faults. The mineralization is either monometallic or polymetallic. The gangue minerals include carbonates (calcite, dolomite) and quartz. The wall rocks and the gangue in the vicinity of the uranium minerals are commonly hematitized. A region with perigranitic monometallic veins is the Přibram uranium mining district, Czechoslovakia. Typical regions with deposits of polymetallic type are the Jáchymov and Aue districts in Czechoslovakia* and East Germany, respectively.

Uranium veins in shear and fault zones are typically developed in areas affected by repeated orogenic deformations, which have resulted in reactivation of major fault systems, and mylonitization and metasomatic alteration of the rocks that became the hosts for the uranium mineralization. A region with such deposits is the former Beaverlodge mining district in Saskatchewan, Canada.

A conceptual genetic model for vein uranium deposits usually includes the following factors. Formation of the veins is commonly related to late phases of orogenic cycles. Deposition of the ore-forming minerals takes place from fluids due to changes in the pH, Eh, pressure and temperature of these fluids. The ore-forming fluids can be of various types, including juvenile, post-magmatic, connate, diagenetic, ground and meteoric waters. The mineralization often occurs in several stages, in which the physical–chemical characteristics of the fluids are different. Localization of the mineralization is structurally and lithologically controlled. Interaction between the fluids and the host rocks and ionization effects of the radionuclides result in alteration of the wall rocks and of the vein material.

Classification of the deposits as of vein-type is based on the traditional morphologic, rather than genetic, criteria. From the associational point of view many of the deposits are closely associated with unconformities and, conversely, many uncoformity-related deposits exhibit, at least in part, features typical of veins. Therefore both deposit types could be classified as discordant hydrogenic uranium/polymetallic deposits.

*Due to political changes some geographical names became obsolete, e.g., Czechoslovakia (now the Chech Republic) and East and West Germany (now Germany). Because of the date of acceptance, the names are not changed.

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Introduction

Vein uranium deposits have been the source of uranium since its discovery by Martin Klaproth in 1789. The element was extracted by Klaproth from a mineral "Pechblende", collected from veins that were mined for silver in the Erzgebirge, which is a part of the Hercynian (Variscan) orogenic belt in Central Europe.

For a long period of time the vein deposits contained a major part of the world's uranium reserves and yielded the bulk of global uranium production. Their role diminished after the discovery and the start of exploitation of sediment-hosted deposits, particularly those associated with sandstones and with quartz-pebble conglomerates. Significant production of uranium from the sandstone deposits in the United States and from the conglomerate deposits in South Africa and Canada commenced during the 1950's. Before the 1950's most of the Western World's uranium production was attributable to vein deposits, whereas recently (1988) less than 10 percent of uranium has been produced from deposits of this type (Table 1).

Despite a long history of research, exploration and exploitation of vein uranium deposits, many unresolved problems regarding genesis, regarding factors controlling distribution, regarding classification and regarding relationship to other deposit types remain.

TABLE 1

Uranium production in the Western World from deposits of various types, 1988. Estimates based on OECD–NEA (1988)

Deposit type	Tonnes U	Proportion (%)	Principal Producing Countries
Conglomerate	8 330	22.6	Canada, South Africa
Sandstone	6 397	17.4	U.S.A., Niger
Unconformity	12 135	33.0	Canada, Australia
Vein	3 372	9.2	France
Granite	3 103	8.4	Namibia
Other	3 453	9.4	U.S.A
Total	36 790	100.0	

Definition

Vein uranium deposits are epigenetic concentrations of uranium minerals, typically pitchblende and coffinite, in open spaces, such as fractures, fissures, shear zones and breccias, in igneous, sedimentary and metamorphic rocks. The uranium minerals occur either as the sole metallic constituents in a simple mineral assemblage or they are accompanied by other metallic elements, such as nickel, cobalt, arsenic, bismuth, copper, lead, zinc, manganese, selenium, vanadium, molybdenum, iron and silver. The metallic minerals are commonly associated with gangue, typically carbonate, quartz or clay minerals.

Deposits of economic interest consist of a variable number of veins ranging in size from short and hairlike stringers to those several kilometres long and as much as several metres thick. Uranium mineral concentrations in the veins range from small lenses of disseminated material to large bodies of massive ore.

The wall rocks immediately adjacent to the veins are commonly affected by alteration, such as hematitization, argillization, albitization, chloritization, carbonatization, silicification, sericitization and sulphidization.

Classification

Most classifications of mineral deposits are based on traditional descriptive, rather than genetic, criteria. Vein deposits are defined on the basis of their morphology. Definition of the various subtypes is commonly based on mineralogical and paragenetic aspects, and on the geological setting of the deposits. A genetic classification approach is often avoided because the ore-forming processes require detailed and sophisticated studies.

Many vein uranium deposits are closely associated with unconformities and resemble, to a certain degree, unconformity-related deposits. For example, the now depleted Fay–Ace–Verna uranium system in the Beaverlodge area, Saskatchewan, Canada, which was considered a typical representative of the vein-type deposits, was associated with the Middle Proterozoic sub-Martin unconformity. The Příbram deposit in Czechoslovakia was associated with the sub-Cambrian unconformity.

Conversely the Eagle Point deposit in Saskatchewan, Canada, which is classified as a deposit associated with the sub-Athabasca unconformity, contains pitchblende that fills cavities and fractures in Aphebian metamorphic rocks. The Nabarlek, Ranger I and III, and Koongarra deposits in Northern Territory, Australia, which are associated with the Middle Proterozoic sub-Kombolgie unconformity, also exhibit many features similar to those that are characteristic for uranium vein deposits, such as mineral composition of the ore bodies, host rocks and the wall rock alterations.

Mineralogical and paragenetic aspects

Complexity of the metallic mineral contents of the vein deposits is commonly used as a mineralogical criterion for their grouping into various classes or subtypes. Robinson (1958) and Lang et al. (1962), who developed genetic classifications of Canadian uranium deposits, distinguished two classes of vein deposits: (a) deposits with "simple mineral associations" (pitchblende, "thucholite", hematite, quartz and calcite), and (b) deposits with "complex mineral associations" (pitchblende, "thucholite", hematite, quartz, calcite, chlorite, chalcopyrite, galena, pyrite, arsenides, selenides and nolanite).

Ruzicka (1971), on the other hand, recognized three classes of uranium vein deposits: (i) pitchblende class (with simple mineral association); (ii) pitchblende-polymetallic class; and (iii) a class with pitchblende and associated hydrous aluminum silicates in shear zones.

Rich et al. (1977) distinguished hydrothermal (vein) deposits with simple mineralogy and deposits with complex mineralogy (e.g., cobalt–nickel–arsenide type). However, they noted that the complement of minerals accompanying pitchblende in deposits with simple mineralogy varied from district to district and sometimes from vein to vein within a single district. In the case of deposits with complex mineralogy they stated that the presence or absence of large amounts of base metals could reflect the presence or absence of a source for the metals rather than a fundamental difference in the conditions of transport and deposition. They supported this idea by referring to a study by Everhart and Wright (1953), who found a direct correlation between host rock composition and gangue mineralogy. The latter authors observed that deposits in metamorphic terrains have dominantly carbonate gangue, whereas deposits in granitic intrusive rocks generally have siliceous gangue.

As mentioned above, it is convenient to distinguish two groups of uranium vein deposits according to their metallic mineral composition: (i) monometallic, where uranium is the principal metallic ore constituent; and (ii) polymetallic, where uranium is accompanied by other metals, such as nickel, cobalt, arsenic, bismuth, copper, selenium, vanadium, silver and gold.

Typical examples of monometallic uranium vein deposits are the Fay–Ace–Verna zone in the Beaverlodge mining district, Saskatchewan, Canada; the Příbram zone in the Bohemian Massif, Czechoslovakia; the Schwartzwalder deposit in the United States; and the deposits in the Xiazhuang ore field, Guandong province, People's Republic of China (Fig. 1).

The principal metallic ore constituent of the mined-out Fay–Ace–Verna deposit, was pitchblende. The pitchblende was accompanied in

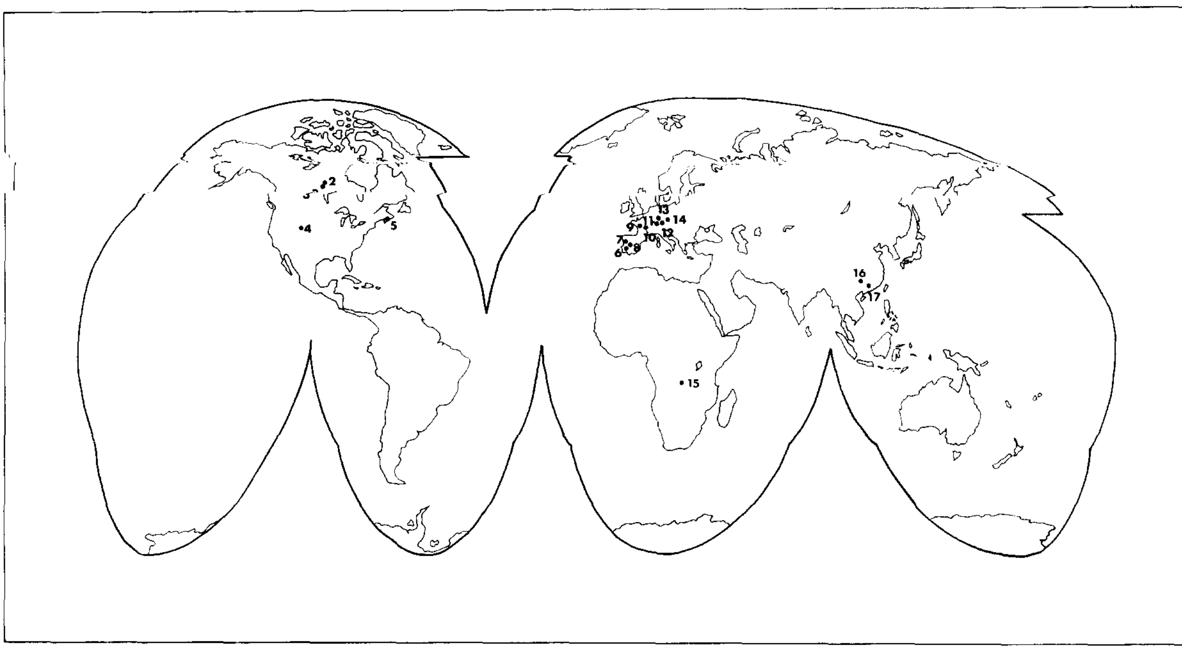

Fig. 1. Location of selected typical vein uranium deposits and areas of the world. (*1*) Great Bear Lake area, Northwest Territories, Canada (Port Radium deposit); (*2*) Beaverlodge area, Saskatchewan, Canada (Fay–Ace–Verna zone); (*3*) Gunnar deposit, Saskatchewan, Canada; (*4*) Schwartzwalder deposit, Colorado, U.S.A.; (*5*) Millet Brook deposit, Nova Scotia, Canada; (*6*) Alto Alentejo Area, Portugal (Nisa deposit); (*7*) Beira area, Portugal (Urgeiriça, Cunha Baixa, Freixiosa and Ázere deposits); (*8*) Ciudad Rodrigo area, Spain (Fé deposit); (*9*) Vendée area, France (la Commanderie, Chardon and Escarpiere deposits); (*10*) La Crouzille area, France (Fanay, Margnac and Bellezane deposits); (*11*) Vítkov II deposit, Czechoslovakia; (*12*) Příbram deposit, Czechoslovakia; (*13*) Jáchymov area, Czechoslovakia (Jáchymov deposit), and Aue area, East Germany (Niederschlema, Obserschlema and Johanngeorgenstadt deposits); (*14*) Rožná area, Czechoslovakia (Rožná, Olší and Slavkovice deposits); (*15*) Shinkolobwe deposit, Shaba Province, Zaïre; (*16*) Chanzipin deposit, Guanxi Province, China; (*17*) Xiazhuang area, Guandong Province, China (Zhushanxia, Shijiaowei and Xiwang deposits).

the upper parts of the deposit by some coffinite and nolanite. In the deeper parts of the deposit (below 500 m) the pitchblende was accompanied by large amounts of brannerite (Ruzicka and Littlejohn, 1982; Smith, 1986). Minerals of other metals were present only in small amounts. The principal metallic constituent of the Příbram deposit is pitchblende, locally accompanied by uranoan pyrobitumen, coffinite, small amounts of Fe, Cu, Pb and Zn sulphides, hematite and goethite. Other metallic minerals, such as tetrahedrite, cinnabar and native Ag, Sb, Hg and As, occur only in small amounts (Ruzicka, 1971; Kolektiv, 1984). In the Schwartzwalder deposit the principal metallic mineral is massive pitchblende, with carbonate, sulphide and adularia gangue (Wallace, 1986). The uranium veins in the Xiazhuang ore field contain pitchblende and coffinite, accompanied by quartz, some iron sulphides and fluorite (Li Tiangang and Huang Zhizhang, 1986).

Polymetallic veins are represented by the deposit at Port Radium in Northwest Territories, Canada; the Jáchymov deposits in the Erzgebirge region, Czechoslovakia; and the Shinkolobwe deposit in the Shaba province of Zaïre (Fig. 1). Uranium reserves of all these deposits have been depleted. Uranium oxides (pitchblende), arsenides and sulpharsenides of nickel and cobalt, copper sulphides, native silver, were principal ore constituents of the deposit at Port Radium (Campbell, 1957; Ruzicka, 1971).

In the Jáchymov region, veins with polymetallic assemblages prevailed, but veins of monometallic type were also present. Polymetallic veins contained early quartz-wolframite-cassiterite and quartz-sulphide assemblages. The most prominent mineralization stage included uranium-carbonate assemblage. This was followed by carbonate-arsenide, sulpharsenide and quartz-hematite stages. Zoning of the polymetallic concentrations was telescoped: the uranium ores occurred generally near the granite/metamorphite contact, the arsenides with bismuth further from the contact and arsenides with native silver in the distant areas (Ruzicka, 1971; Kolektiv, 1984). The monometallic veins contained pitchblende and coffinite in quartz-carbonate gangue with lenses of dark purple fluorite.

The primary mineral assemblages of the Shinkolobwe veins consisted of pitchblende, Co–Ni sulphides and selenides, molybdenite, pyrite, copper sulphides, gold selenides, tellurides and native gold, platinum group metals and monazite in carbonate-chlorite-quartz gangue. The pitchblende, closely associated with pyrite, constituted an early and separate stage in the paragenetic sequence. The later stages were represented by Co–Ni sulphides and selenides and the youngest stage contained selenium-bearing vaesite and siegenite, gold and copper minerals (Derriks and Vaes, 1955).

Geological setting

Classification of the uranium vein deposits, based on their geological setting, takes into account structural and lithological controls in their localization. The vein deposits are hosted by granitic or syenitic rocks (intragranitic veins), by whatever rocks surround the granitic plutons (perigranitic or peribatholithic veins) or by sheared or mylonitized, or comminuted metamorphic, sedimentary or igneous complexes (veins in shear mylonite and gouge zones).

Intragranitic vein deposits are typically developed in highly differentiated granitic rocks, and structurally controlled by regional faults. Their principal uranium ore minerals, pitchblende and coffinite, are commonly associated with sulphides and gangue minerals, such as carbonates, quartz, chalcedony, fluorite and barite.

Perigranitic vein deposits are typically developed in metasedimentary or metavolcanic rocks at their contacts with intrusive granitic plutons. They are also structurally controlled by regional faults or lineaments. Mineralogically they are monometallic and/or polymetallic.

Uranium veins in shear and fault zones are typically developed in areas affected by repeated deformations, which have resulted in reactivation of major fault systems and thus structurally controlled the mineralization. Deposits of this type (e.g., in the Rožná–Olší region, Czechoslovakia and the Dyleň–Maehring region, Czechoslovakia and West Germany) largely consist of mineralized nonrecrystallized gouge-breccia fills.

Intragranitic vein deposits

Intragranitic vein deposits are known to occur in France, in the Massif Central, particularly in the La Crouzille area, and in the Vendée area of the Armorican Massif; in Portugal, in the Beira uranium district; in Canada, in the Millet Brook area, Nova Scotia and on the south shore of Crackingstone Peninsula, Lake Athabasca, Saskatchewan; in People's Republic of China, in the Xiazhuang ore field; and in Czechoslovakia, in the Bor pluton in the western part of Bohemia.

In Europe the deposits in France, Portugal and Czechoslovakia are typically associated with Hercynian granites, which were emplaced during the Carboniferous and Permian periods. In Canada the Millet Brook deposit occurs in granitic rocks of the South Mountain batholith (372–361 Ma old), which intruded, deformed and metamorphosed sedimentary Cambrian–Ordovician country rocks (Clarke and Halliday, 1980; Reynolds et al., 1981). The Gunnar deposit contains mineralization in Precambrian anatectic-granitic rocks. The Chinese deposits are associated with Yanshanian granites (185–135 Ma old; Li Tiangang and Huang Zhizhang, 1986).

Perhaps one of the most representative areas with intragranitic vein deposits is the La Crouzille area of the Limousin uraniferous district in the Massif Central, France (Fig. 1; CEA, 1986; Poty et al., 1986). The uranium veins occur predominantly in leucogranites of the western part of the Saint-Sylvestre pluton, which is intrusive into the Gueret granodioritic complex. The deposits are associated with zones of potassic alteration, which caused removal of Si and Na from granitoids and of Na, Ca and Mg from mafic host rocks (commonly dykes). Because of the removal of quartz from the granitoids, which resulted in rocks with the apearance of syenite, this process is generally referred to as episyenitization.

The veins in the La Crouzille area formed in two stages: during the first stage deposition of pitchblende and pyrite was accompanied by crystallization of hematitic quartz, by deposition of ankerite and hematite and by hematitization of the wall rocks. During the second stage part of the pitchblende was transformed into coffinite. This process was accompanied by deposition of fluorite, barite and calcite. Muscovite in the wall rocks was altered to montmorillonite and adularia. Deposition of pitchblende during the first stage took place at 350°C. In the second stage coffinite was formed at 140°C and calcite was deposited at temperatures as low as 100°C (Poty et al., 1986). Emplacement of the Saint-Sylvestre granitic rocks took place about 350–360 Ma ago and the uranium deposits formed about 275 Ma ago (Leroy, 1978).

In the La Crouzille area the uranium ores have been exploited at Margnac, Peny, Fanay, le Fraisse, les Gorces, Bellezane and Montulat (CEA, 1986). The largest deposits, at Margnac and Fanay, are in two-mica granite. They are closely associated with zones of episyenitized granites. The episyenitization took place in two phases: the older phase was marked by feldspathization and the younger by glimmerization. The feldspatic phase consisted of removal of quartz, of alteration of muscovite to feldspar, and alteration of biotite to chlorite and potassic feldspar. These processes were apparently associated with deformation of the Saint-Sylvestre pluton (Chayes, 1955; Leroy, 1977). The mica episyenites formed by removal of quartz and by alteration of biotite and plagioclase to muscovite. The micaceous episyenitization was apparently associated with brittle deformation of the pluton and with intrusion of lamprophyre dykes (Leroy, 1978).

The first (pitchblende) stage of mineralization immediately followed emplacement of the lamprophyres and the micaceous episyenitization. In addition to uraniferous veins, disseminated mineralization is also present in the deposits. This is confined to episyenitic pipes and accounts for 30–40% of the reserves (Reasonably Assured Resources in the International Atomic Energy Agency terminology).

In a genetic model proposed for the La Crouzille deposits, Leroy (1978) considered that important aspects were (i) circulation of heated aqueous solutions related to intrusion of lamprophyre dykes; (ii) leaching of uranium from granitic rocks by CO_2-rich solutions and its upward transport as uranyl-carbonate complexes; (iii) deposition of uranium in micaceous episyenites or shear zones due to decrease in pressure and temperature and due to reduction of hexavalent uranium in the presence of pyrite; (iv) decrease in temperature, which was accompanied by growth of quartz and marcasite and by alteration of pitchblende to coffinite; (v) deposition of gangue minerals, such as fluorite, barite and white calcite, following the uranium mineralization process; (vi) supergene alteration that affected the near-surface parts of the deposits.

As in the la Crouzille area, some of the deposits in the Vendée area (e.g., la Commanderie; Fig. 1) are associated with leucogranites of the Mortagne pluton, which is a part of the Armorican Massif. However, the intragranitic veins in Vendée differ in that they are in many cases concentrated at the contact of the granites with the metamorphic country rocks.

The la Commanderie deposit occurs about 3 km from the contact of the Mortagne pluton with metamorphic rocks. The host rocks are calc-alkaline syenites, consisting largely of microcline and oligoclase, and containing relatively abundant apatite. The mineralization consists of pitchblende (massive and sooty), autunite, phosphuranylite, torbernite, uranotile and gummite, which fill fractures and impregnate wall rocks. Locally the uranium minerals are accompanied by quartz, limonite, goethite, pyrite, marcasite, greigite, galena, sphalerite, covellite, bornite and chalcocite (Gerstner et al., 1962).

The intragranitic vein deposits in Portugal are associated with calc-alkaline granitic rocks that were emplaced at the end of the Hercynian orogeny (around 280 Ma ago). Representative deposits occur in the Urgeiriça mining district and in the Alto Alentejo area (Fig. 1). In the Urgeiriça mining district, which includes the Urgeiriça, Cunha Baixa and Freixiosa deposits, the uranium mineralization is mainly monometallic (only locally is it accompanied by sulphides of Fe, Zn, Cu and Pb) and consists of pitchblende, coffinite and secondary uranium minerals, which occur in veins filled with chalcedony and quartz and as disseminations. Some of the mineralization is associated with episyenites. In the Alto Alentejo area the mineralization occurs only in quartz veins and in granite breccias.

Occurrences similar to those in Portugal have been discovered in Spain. They include the Los Ratones deposit in the Caceres district, Villar de Peralonso in the Ciudad Rodrigo district and the La Virgen deposit in the Andujar district (Fig. 1).

In Canada a typical intragranitic vein deposit, at present (1989) dormant, occurs in the

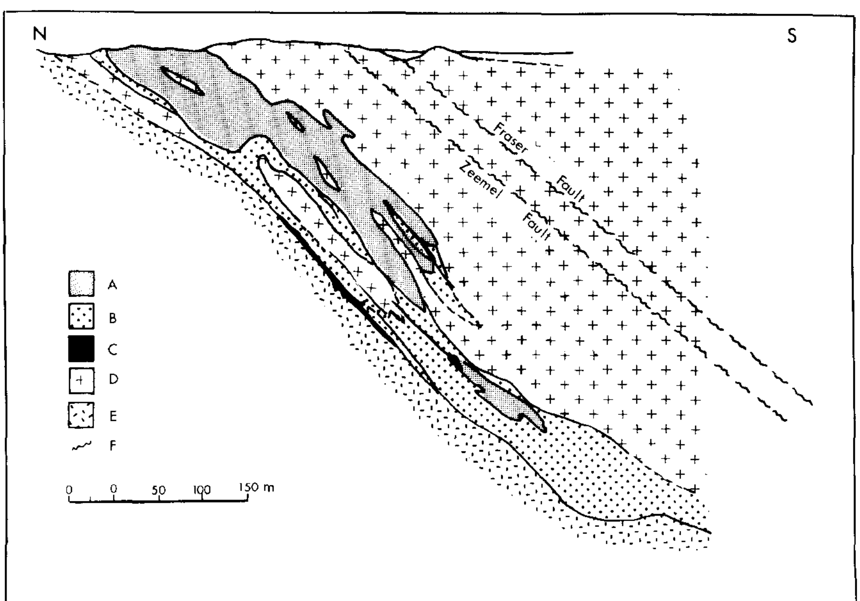

Fig. 2. Cross-section through the Gunnar deposit, Saskatchewan, Canada. *A*=uranium ore; *B*="episyenite"; *C*=schist; *D*=Gunnar granite; *E*=paragneiss; *F*=fault. After Evoy (1986).

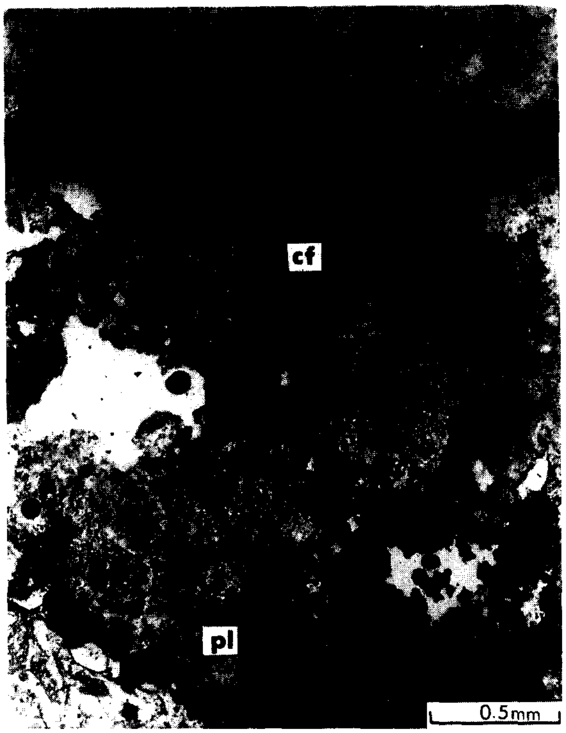

Fig. 3. Coffinite in ore from Gunnar deposit, Saskatchewan, Canada; cf=granular coffinite, pl=plagioclase. Photomicrograph, plain reflected and transmitted light.

Devonian–Carboniferous South Mountain batholith at Millet Brook, Nova Scotia (Fig. 1). The rocks of the South Mountain batholith intruded in several phases. The first phase was biotite granodiorite, and the later differentiates included adamellites. The youngest phases are alaskitic and leucoadamellitic (=quartz monzonitic) bodies (McKenzie and Clarke, 1975). The host rock of the deposit is a 370 Ma old biotite granodiorite, altered along fracture zones by potassic, sodic, ferruginous and carbonate fluids. The alteration caused removal of quartz (i.e., episyenitization) of the host rock. The deposit contains pitchblende and secondary uranium minerals, such as autunite, torbernite and saléeite, and locally copper, zinc, lead, silver and tungsten minerals. The alteration and mineralization appear to be related to hydrothermal activity associated with later intrusions, particularly of leucoadamellite (McKenzie and Clarke, 1975; Chatterjee and Strong, 1984). The Millet Brook deposit contains only limited uranium resources, amounting to less than 500 tonnes U.

In Canada, uranium ores associated with episyenite also occurred in the Gunnar deposit, in northern Saskatchewan, on the north shore of Lake Athabasca (Figs. 1 and 2). The deposit, which produced about 7,420 tonnes of uranium metal from ores grading 0.15% U, was depleted in 1963 (Evoy, 1986). The altered part of the rock, which hosted the deposit, the so-called 'sponge rock' (Lang et al., 1962), was derived from granitic rocks by replacement of quartz by albite and of some of the albite, in turn, by carbonate. Thus the host rock had distinct features of the episyenite in some Phanerozoic intragranitic vein deposits. A genetic model for the Gunnar deposit by Evoy (1960) included: (a) albitization of the Archean metasedimentary rocks (granite gneiss) of the Tazin Group, including Gunnar granite, a discrete leucocratic unit within the gneiss; (b) depletion of quartz and/or introduction of calcite along fracture zones within the Gunnar granite: (c) structurally controlled introduction of uranium, carried in alkaline-carbonate solutions in the granitic rocks, particularly into albitized portions of the Gunnar granite; (d) deposition of pitchblende, coffinite (Fig. 3) and uranophane in a pipe-like ore body due to decrease in pressure in episyenites and due to a change of conditions from alkaline to acid.

In the People's Republic of China intragranitic vein deposits contain a major part of the country's uranium resources. The most important deposits occur in the Xiazhuang mining district, Guandong Province, southern China (Figs. 1 and 4). The deposits (e.g., Zhushanxia, Shijiaowei and Xiwang) are associated with granitic rocks of the Yanshanian structural unit. The host granites were, however, emplaced during a preceding orogeny. The host rocks formed 185–135 Ma ago, but uranium was deposited 85–70 Ma ago (Chen Zuyi and Huang Shijie, 1986; Du Letian, 1986; Li Tiangang and Huang Zhizhang, 1986).

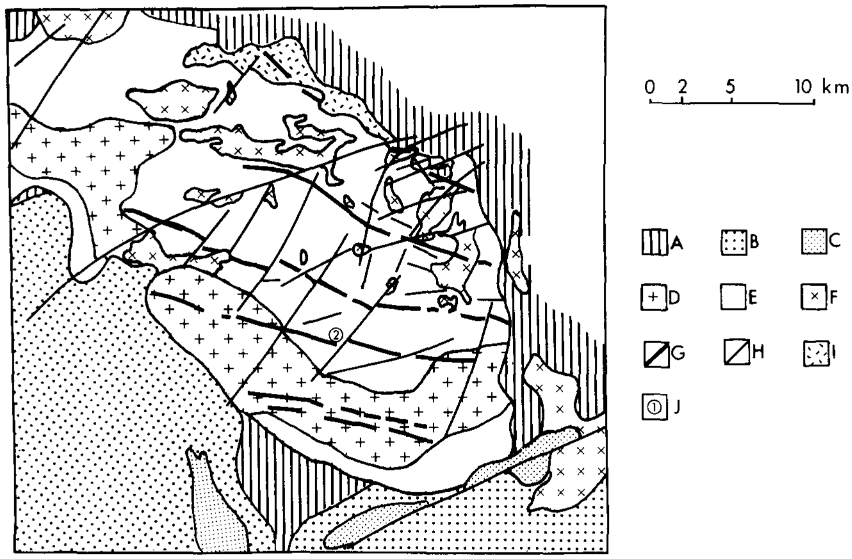

Fig. 4. Location of intragranitic uranium vein deposits in Xiazhuang area, Guandong Province, China. *A* = Early Paleozoic rocks; *B* = Devonian rocks; *C* = Late Cretaceous red beds; *D* = coarse-grained biotite granite; *E* = medium- to fine-grained biotite granite; *F* = two-mica granite; *G* = intermediate to mafic dyke; *H* = quartz vein and silicified zone; *I* = dacite; *J* = uranium deposit; (*1*) = Zhushanxia and (*2*) = Shijiaowei. After Li Tiangang and Huang Zhizhang (1986).

The deposits are confined to two-mica and to biotite-rich granitoids that are predominantly of the S-type and to a lesser degree of the I-type. The granitic rocks are siliceous, alkaline, peraluminous and relatively Ca-poor. The source of uranium in the deposits was the granitic rocks themselves. During cooling the granites were subjected to autometasomatic processes. After their consolidation tectonic activity and associated hydrothermal processes caused alkaline metasomatic alteration of the host rocks and extraction of uranium and other metals (e.g., gold and tungsten) from the granitic rocks. Uranium was transported by an ascending convection system along faults as uranyl-carbonate, uranyl-fluorine-carbonate and, possibly, as uranyl-sulphate complexes. Due to fracturing the CO_2 escaped from the system; the pressure of hydrothermal solutions then decreased and the fluids started to boil; the uranyl complexes dissociated and uranium, along with silica, began to precipitate. Thus the pressure and temperature (*P–T*) conditions, rather than pH and Eh, were the most important factors in the mineralization process. Uranium mineralization, which is monometallic, is accompanied by gangue, such as chalcedony, fluorite, carbonate, and products of argillization and alkaline metasomatism of the host rock (Chen Zuyi and Huang Shijie, 1986).

The Hercynian granitoids of the Bor pluton in the western part of Czechoslovakia host the Vítkov II deposit (Ruzicka, 1971; Kolektiv, 1984; Fig. 1). These granitoids consist of an older, granodioritic to dioritic, and a younger, granitic, phases, and have been intruded by flat-lying aplite and tourmaline granite bodies and by lamprophyre dykes. The deposit is controlled by two N–S trending regional tectonic zones (lineaments) that were developed prior to the intrusion of the pluton, but rejuvenated after its solidification. The zones are represented by fractured and clay-altered rocks with local concentrations of quartz and carbonate. The ore bodies within the deposit are also structurally controlled. The deposit formed in several stages: (i) The pre-ore stage included albitization, chloritization, epidotization and hematitization of the host rocks along fractures. (ii and iii) The two ore-forming stages were represented by deposition in finely disseminated brannerite and coffinite, accompanied by chloritization of the wall rocks; and by deposition of finely disseminated pitchblende, accompanied by deposition of quartz, hematite and pyrite. (iv) In the post-ore stage deposition of carbonates prevailed; however, locally lenses of Fe, Cu, Pb and Zn sulphides, Ni, Co and Fe arsenides, Cu, Pb and Ag selenides, native Bi and Ag, fluorite and regenerated pitchblende were formed (Kolektiv, 1984).

Perigranitic vein deposits

Perigranitic (or peribatholithic) uranium veins are typically developed in sedimentary and volcanic rocks, commonly metamorphosed, at their contacts with intrusive granitic plutons. The host rocks have been, as a rule, intruded by lamprophyre and aplite dykes. The deposits consist of veins, breccia zones, stockworks and ore bodies of irregular shape, which are spatially related to faults. Formation of the veins usually took place in several stages. The deposits are either monometallic or polymetallic. Deposition of the ore minerals was structurally, and frequently also lithologically, controlled. The gangue minerals include carbonates (calcite, dolomite, ankerite, siderite) and quartz. The wall rocks are commonly altered by such processes as hematitization, argillization, silicification and chloritization.

Monometallic deposits

Typical monometallic uranium veins situated in perigranitic setting are known from Czechoslovakia, e.g., the Příbram district in Bohemia; and from Spain, e.g., the deposits in the Ciudad Rodrigo district in the Iberian Meseta. Deposits of this type also occur in the Beiras and Alto Alentejo districts in Portugal.

In Czechoslovakia, the Příbram district occurs in Upper Proterozoic weakly metamorphosed pelitic rocks at their contact with the quartz-monzonitic phase of the Hercynian Central Bohemian Pluton (Figs. 1 and 5). The metapelites are overlain by a Cambrian sequence, containing a thin layer of quartz-pebble conglomerate at its base and red beds at a higher stratigraphic position. The pluton is a product of multiple intrusion that took place 417–285 Ma ago (Šmejkal, 1960; Svoboda, 1966).

The host rocks have been cut by aplite and lamprophyte dykes and folded into an anticlinorium and block-faulted by three tectonic systems: (i) The most prominent fault system trends north-easterly, i.e., subparallel to the granite – metapelite contact. It is represented by major regional faults, among which the Děda–Dubenec and the Clay faults control structural patterns of two major ore zones, the Příbram uranium zone and the Březové Hory lead-zinc-silver zone, respectively. The Děda–Dubenec reverse fault, which is closer to the pluton contact, restricts the width of the uranium-bearing ore zone, which is about 30 km long and averages several kilometres wide. (ii) The second fault system trends northwesterly. Faults of this system are well developed in the granitoid rocks of the Central Bohemian pluton, but gradually pinch out in the uranium zone and are absent in the hanging wall of the Děda–Dubenec fault. (iii) The third fault system trends northerly.

The uranium veins, about 1000 in number, are in more than twenty clusters between the southeasterly-dipping contact of the pluton and the northwesterly-dipping Děda–Dubenec fault (Ruzicka, 1971). They are from a few metres to several kilometres long and from a few centimetres to more than 10 m wide. They contain veinlets, lenses and disseminations of pitchblende (in at least two generations), coffinite, uranoan pyrobitumen (thorium-free thucholite), and locally small amounts of pyrite, sphalerite and galena. The Pb–U age of the

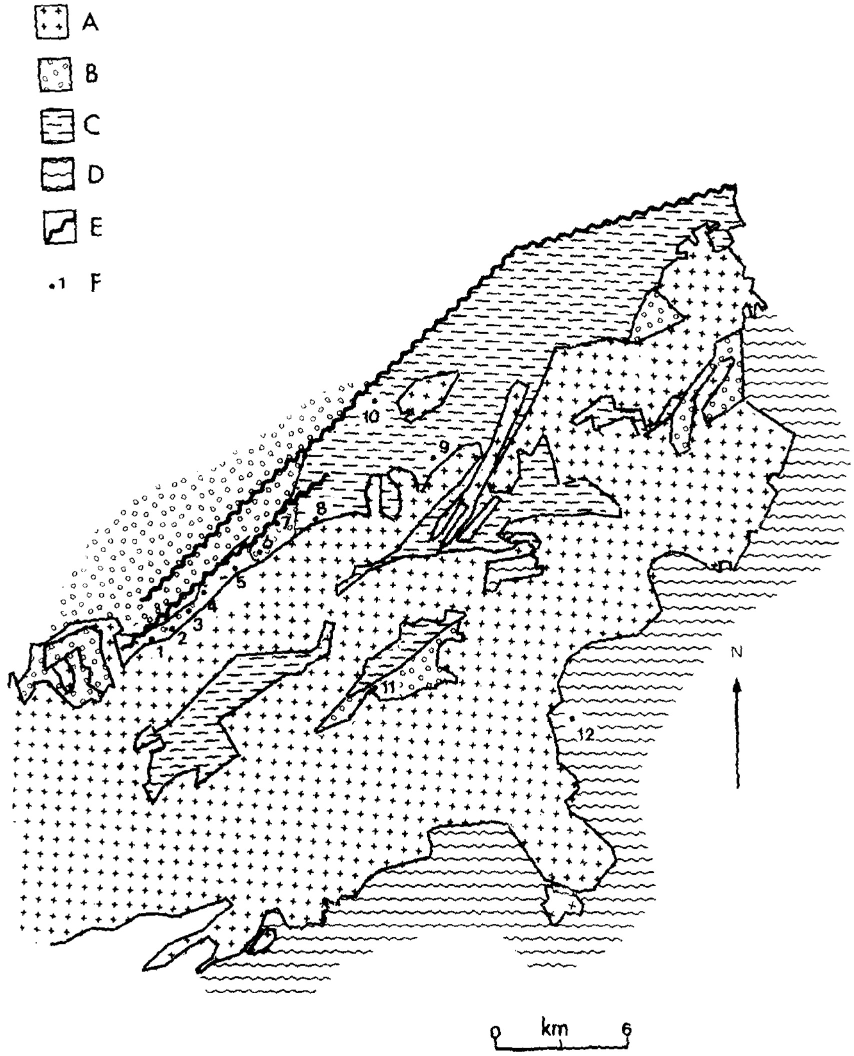

Fig. 5. Generalized geological map of a part of the Central Bohemian Pluton area, Czechoslovakia. *A* = Hercynian granitoids; *B* = Cambrian sedimentary rocks, including basal quartz-pebble conglomerate; *C* = Upper Proterozoic metasedimentary rocks; *D* = Migmatites and paragneiss; *E* = fault; *F* = shafts of selected mines; *1–2* = Kamenná; *3–4* = Lešetice; *5–8* = Bytíz; *9* = Nová Ves; *10* = Mníšek; *11* = Předbořice; *12* = Heřmaničky. Modified after Ruzicka (1971).

pitchblende is 265 ± 15 Ma, and of the coffinite 258–213 Ma (Kolektiv, 1984). The gangue is carbonate (predominantly calcite), which is present in several generations (Ruzicka, 1971). The deposit has been mined to a depth exceeding 1500 m (Kolektiv, 1984).

In Spain, deposits in the Ciudad Rodrigo district, in the western part of Salamanca province (Fig. 1), occur in Proterozoic and Phanerozoic pelitic rocks, spatially associated with Hercynian granites. The Fé mine represents the largest deposit in the district (Ziegler, 1984; OECD-NEA, 1986; Arribas, 1986).

The Fé deposit occurs in a slate-greywacke metasedimentary complex. Unlike most of the deposits in the area, which occur at the contact with the Hercynian granites, the Fé deposit lies horizontally 3–5 km from the contact, but vertically near the contact. The metasedimentary complex consists predominantly of carbonaceous pelites that contain elevated levels of uranium (30–200 ppm U; Arribas, 1986). The ore minerals, pitchblende, coffinite and secondary uranium minerals, occur in fractures and breccia zones, mainly in a carbonate and partly in adularia, gangue. They are locally accompanied by pyrite, marcasite, hematite and limonite and by small amounts of galena, sphalerite, chalcopyrite and fluorite. The wall rocks are commonly altered by chloritization and hematitization. Fluid inclusion studies of the carbonate gangue indicate temperatures of formation between 230°C and 70°C and fluid salinities range from 0 to 25% NaCl equivalent. The U–Pb isotope ages of 57 and 37 Ma have been determined on pitchblende (Arribas, 1986) and reflect Alpine orogenic events.

A conceptual genetic model for the perigranitic deposits in the Ciudad Rodrigo district takes into account a polygenetic origin of the mineralization (Moreau, 1977; Ziegler, 1984; Arribas, 1986): The ultimate source of uranium were apparently the pelitic carbonaceous rocks; tectonic and thermal events associated with intrusion of Hercynian granites caused mobilization and redistribution of uranium within the pelites and in the granitoids; tectonic deformation and generation of hydrothermal systems during the Pyrenean phase of the Middle Alpine orogenic activity concluded the main ore-forming process; the mineralization was afterwards partly modified by near-surface oxidation. In addition to the deposits in the perigranitic environment, some uranium-bearing veins occur within the granitoid plutons.

The deposits in the Ciudad Rodrigo district contained, in 1985, 25 300 tonnes U in the category of Reasonable Assured Resources, and 5 000 tonnes U in the category of Estimated Additional Resources. From the start of uranium mining operations in the district until 1985, in excess of 1 000 tonnes U have been produced from the deposits (OECD–NEA, 1986).

In Portugal, perigranitic vein deposits are located in the Beiras (e.g., Ázera deposit) and Alto Alentejo (e.g., Nisa deposit) regions (Fig. 1). As in Spain, the deposits in these districts occur in a slate-greywacke complex. Their ores consist almost entirely of secondary uranium minerals, such as autunite, autunite-uranocircite, saléeite, phosphuranilite, torbernite, metatorbernite and sabugalite, and, to a much lesser degree, pitchblende (Dekkers et al., 1983; OECD–NEA, 1986). The largest deposit (Nisa) contained (in 1983) about 2 000 tonnes U (Dekkers et al., 1983).

Polymetallic deposits

Polymetallic deposits in perigranitic (peribatholithic) environments have been an important source of uranium in the past. Among them the Jáchymov deposits, Czechoslovakia, the deposits in the Aue area, East Germany, and the Port Radium deposit at Great Bear Lake, Canada, are the most typical representatives of this deposit type. An interesting deposit that exhibits features, characteristic of deposits of this class, the Chanziping, occurs in the People's Republic of China. The deposits are in the exocontact aureoles of granitic plutons and contain, in addition to uranium resources, minerals of other metals, such as nickel, cobalt, bismuth, silver, copper, gold, selenium and platinum. The most common gangue minerals in the veins are carbonates (calcite, dolomite, ankerite) and quartz.

The Jáchymov district is located in the Bohemian part of the Erzgebirge range, in the western part of Czechoslovakia (Fig. 1). The mining district, which occupies an area of about 100 km^2, included sixteen major mining operations, of which the Rovnost, Svornost, Bratrství, Eliáš, Eva and Abertamy were among the largest ones. In addition, several small deposits of various types were scattered throughout a region extending for more than 500 additional square kilometres. Exploitation of the deposits ceased in the early 1960's (Fig. 6).

The deposits in the main Jáchymov mining district were hosted by katazonally metamorphosed rocks of Cambrian and Ordovician age. These rocks include pyritized graphite-biotite schists, intercalated calc-silicate gneiss and

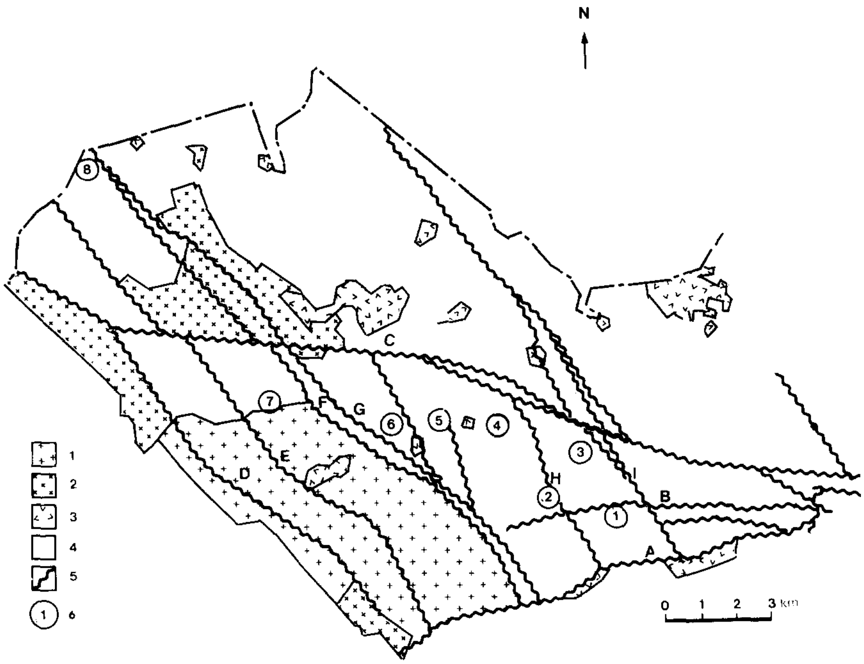

Fig. 6. Generalized geological map of the Jáchymov area, Czechoslovakia. Legend: *1*=normal granitoids; *2*=autometasomatic granitoids; *3*=volcanic rocks; *4*=Paleozoic metamorphic rocks; *5*=faults; *6*=former mines: (*1*) Plavno, (*2*) Panorama, (*3*) Bratrství, (*4*) Svornost, (*5*) Rovnost - Eliáš - Eduard, (*6*) Barbora - Eva, (*7*) Abertamy, (*8*) Potůčky. Modified after Kolektiv (1984).

hornfels and skarns; biotite-muscovite schists; garnet-muscovite schists, with intercalated amphibolites; and chlorite-sericite phyllites with intercalations of amphibolite. The metamorphic rocks are generally in a horizontal, locally undulating, contact with the plutonic rocks.

The metamorphic rocks have been intruded by granitoid bodies of the Hercynian Karlovy Vary massif (Eibenstock or Nejdek-Eibenstock massif of some authors), which are represented by two suites: the older suite exhibits dioritic to gabbrodioritic composition, and the younger suite is mainly granitic. The younger granitic suite consists of two phases. The earlier phase ("Gebirgsgranit", "mountain" or "normal" granite of some authors), which is about 320 Ma old (Šmejkal, 1960), includes porphyritic biotite granites and their diaschistic derivatives, such as dykes of aplite and lamprophyre. The later phase ("Erzgebirgsgranite", "Krušné Hory" or "autometasomatic" granite of some authors), about 280–260 Ma old (ibidem), is represented by leucocratic granites that were affected by autometasomatic processes, particularly by greisenization, albitization, muscovitization and fluoritization. The uranium mineralization, which yields isotopic ages of 270–230 Ma, is spatially associated with the later (autometasomatic) phase of the granites (Ruzicka, 1971). The arsenide (Bi+Ni+Co+Ag) assemblage, locally associated with the uranium mineralization, is younger (220–150 Ma; Kolektiv, 1984).

The metamorphic rocks of the main Jáchymov mining district are a part of the Krušné Hory anticlinorium, which trends northeast. They are dislocated by a system of block faults, among which a major, northeasterly trending lineament, the Krušné Hory fault, is more than 100 km long and as much as 300 m wide.

The deposits of the Jáchymov mining district consisted of more than 1000 veins that were mineralized in several stages and contained diverse mineral assemblages concentrated in shoots of various size and thickness (Fig. 7). Rare Sn+W+Mo mineral assemblages were deposited early in the mineralization process and their deposition was associated with formation of tourmaline, apatite, topaz and quartz. The widespread pitchblende mineralization was accompanied by deposition of carbonates (predominantly dolomite), quartz, fluorite and hematite. Native silver and bismuth were deposited, along with arsenides of nickel and cobalt, coffinite and some regenerated pitchblende, mainly in carbonate gangue. Sulpharsenides of silver, cobalt and nickel, and native bismuth and bismuthinite were deposited towards the end of the mineralization period. Distribution of the ore minerals exhibited, in general, telescopic zoning relative to the

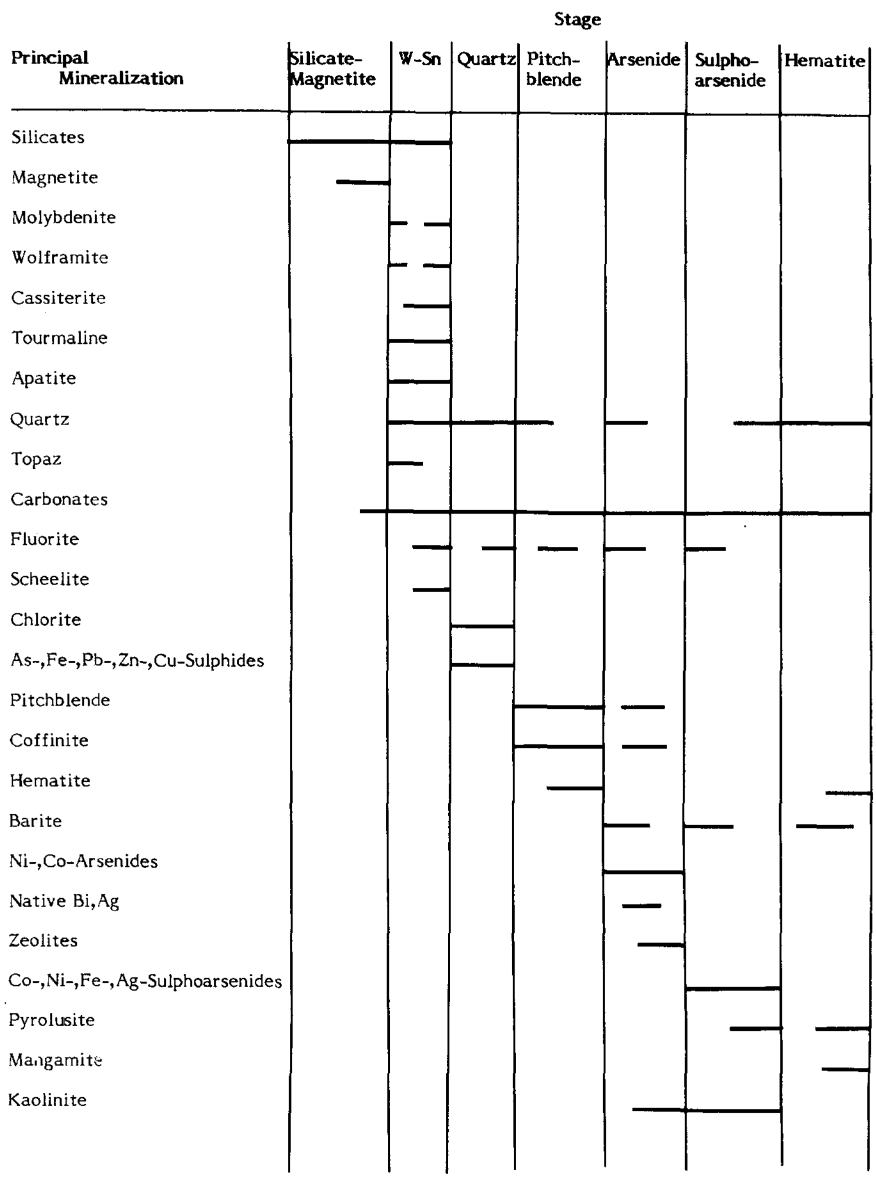

Fig. 7. Paragenetic succession of ore minerals of the Jáchymov deposits, Czechoslovakia. Modified after Kolektiv (1984).

granite contact. The uranium zone was in the immediate vicinity of the contact, the nickel-cobalt zone was some 200–300 m further above, and the silver-bearing ores were in most cases concentrated in the upper parts of the veins, i.e., 600–800 m above the intrusive contact (Mrňa and Pavlů, 1967; Ruzicka, 1971; Kolektiv, 1984).

Mineralization was accompanied by alteration of the wall rocks: silicification, carbonatization, chloritization and pyritization were associated with the earliest stage of the mineralization; hematitization and albitization were typical for the pitchblende stage; and kaolinization, silicification and carbonatization occurred during the latest stages of the hydrothermal process. The hematitization of the wall rocks was almost exclusively associated with shoots of pitchblende; it was caused by oxidation of Fe^{2+} to Fe^{3+}, which accompanied the deposition of pitchblende. This reaction was enhanced by ionization effects of the radioactive substances on the surrounding rocks.

The uranium deposition was controlled structurally and lithologically. The greatest concentration of ore took place in areas of abrupt morphological changes in the vein structures, such as flexures, vein intersections, anastomosing and branching; in areas of extensive brecciation; and in the vicinity of lamprophyre and aplite dykes. These morphological changes presumably changed the hydrodynamic system of the ore-bearing fluids. Environments lithologically favourable for mineralization existed predominantly in metamorphic rocks. High concentrations of uranium were generally associated with chloritic and sericitic phyllites with amphibolite intercalations, with amphibolites, with biotite schists, and with rocks exhibiting high contents of pyrite or ferromagnesian minerals. Dymkov (1960) suggested that pitchblende was deposited along with carbonates at pH 8.35. Decrepitation studies on the Jáchymov ores have indicated that the deposition of pitchblende took place at temperatures between 370°C and 470°C (Mrňa and Pavlů, 1967).

It appears that the Late Hercynian granitoid bodies acted as media that assimulated uranium and associated metals from the country rocks and redeposited them back into open spaces within the reducing rock units.

Uranium occurrences in the broader Jáchymov region included relatively small mineral concentrations in granitic rocks, such as Přebuz and Fojtov, and sediment-hosted deposits, such as Oděř, Hájek and Ruprechtov, in Tertiary lignite-bearing basins.

Polymetallic vein deposits also occur on the East German side in the western part of the Erzgebirge in the Aue region, e.g., near Schneeberg (Oberschlema and Niederschlema deposits), Annaberg and Johanngeorgenstadt (Roubault, 1958; Harlass and Schuetzel, 1965; Ruzicka, 1971; Fig. 1). These deposits are associated with the Karlovy Vary massif (Eibenstock massif).

The deposits occur in the contact aureole of the massif. Their distribution is controlled by regional faults. They consist of quartz-carbonate veins, which were mineralized in several stages (Harlass and Schuetzel, 1965): As in the Jáchymov area, the initial stages included (i) greisenization of the granitoid rocks, tourmalinization and pyritization of the metamorphic rocks, development of skarns and introduction of Sn+W+Mo mineralization along with quartz into the fractures. (ii) During the subsequent "pitchblende+calcite" stage uranium was introduced, along with calcite, quartz, fluorite and gypsum, into fractures. This process was accompanied by hematitization and silicification of the wall rocks. (iii) Unlike in the Jáchymov district, the subsequent stage of mineralization was represented by introduction of selenides. This stage was accompanied by hematitization, carbonatization and sericitization of the wall rocks. (iv) The polymetallic stages were characterized by introduction of Bi, Co and Ni arsenides and of Ag, Cu, Fe and

As sulphides. (v) The mineralization process was terminated by deposition of hematite and manganese oxides and by a widespread silicification.

Uranium was transported in hydrothermal solutions as a uranylcarbonate complex such as $(UO_2(CO_3)_3^{4-})$, and precipitated due to (a) decreasing temperature of the solutions, (b) decreasing concentration and pressure of CO_2 in the solutions, and (c) rapid changes in Eh and pH of the solutions, due to their reaction with the host rocks, and (d) changes in fluid velocity in the hydrodynamic system caused by structural conditions. The general chemical reaction took place according to an equation proposed by Harlass and Schuetzel (1965) which is comparable with similar formulas presented in the literature (e.g., Vinogradov, 1963; Ruzicka, 1971; Langmuir, 1978):

$$2Ca^{2+} + UO_2(CO_3)_3^{4-} + 2Fe^{2+} + 4HCO_3^- = UO_2\downarrow + Fe_2O_3\downarrow + 2CaCO_3\downarrow + 2H_2O + 5CO_2\uparrow$$

Janischevski and Konstantinov (1962) observed, in the case of an unnamed deposit in Saxony, that the richest ore accumulations were localized in those parts of the veins where the wall rocks contained reducing components, e.g., carbonaceous material, sulphides or ferromagnesium minerals. They considered that at least four types of rocks were most favourable for deposition of uranium ores: carbonaceous schists, quartz-sericite schists, skarns and amphibolites. They also estimated proportions of ore related to specific structural controls on the basis of the amounts of ore extracted from certain parts of the deposit: 29% was attributed to apophyses, 20% to vein intersections, 17% to vein terminations, 16% to flexures, 8% to multiply brached veins, 6% to gently dipping dislocations and only 4% to simple veins.

A typical representative of the perigranitic polymetallic deposits in the Northwest Territories of Canada is the Port Radium deposit, which occurs in the Great Brear Lake U–Ag–Cu metallogenic domain. It is situated in the Great Bear Batholith and its roof rocks (Figs. 1 and 8). Deposits in similar geological setting and of similar morphology, but of somewhat different mineralogical composition and lesser uranium contents, occur elsewhere in the domain.

The oldest rocks in the Great Bear Lake U–Ag–Cu metallogenic domain belong to the Lower Proterozoic Echo Bay Group, which consists of a lower, predominantly metasedimentary sequence, and an upper unit of prevalently volcanic rocks (Mursky, 1973). The rocks of the Echo Bay Group are unconformably (?) overlain mainly by sedimentary, and to a lesser extent volcanic, rocks of the Cameron Bay Group.

The sedimentary-volcanic complexes of the Echo Bay and Cameron Bay Groups have been intruded by a suite of igneous rocks including feldspar-hornblende porphyry, rhyolite porphyry, granite, quartz monzonite and granodiorite. These intrusive rocks are probably in most cases 1900–1840 Ma in age, in accord with zircon U–Pb results for plutons in the region (Bowring and Van Schmus, 1982), although, some could be related to a bimodal sequence of volcanic rocks (1663+/−8 Ma; Bowring and Ross, 1985) within the unconformably overlying Hornby Bay Group. Diabase dykes and giant quartz veins cut both the stratified complexes and the intrusive rocks.

The general regional structure of the domain is homoclinal, but locally the rocks are very complexly faulted and folded, especially at the contacts with intrusive bodies. A northeast trend predominates in the regional structural pattern. This structural pattern of the Great Bear Lake domain is reflected in the Port Radium deposit. The most prominent northeasterly-trending regional fault system is also predominant in the structural pattern of the deposit. The structural backbone of the deposit is the northeasterly trending Bear Bay Shear, a fault zone, 1.5–7.0 m wide, filled with

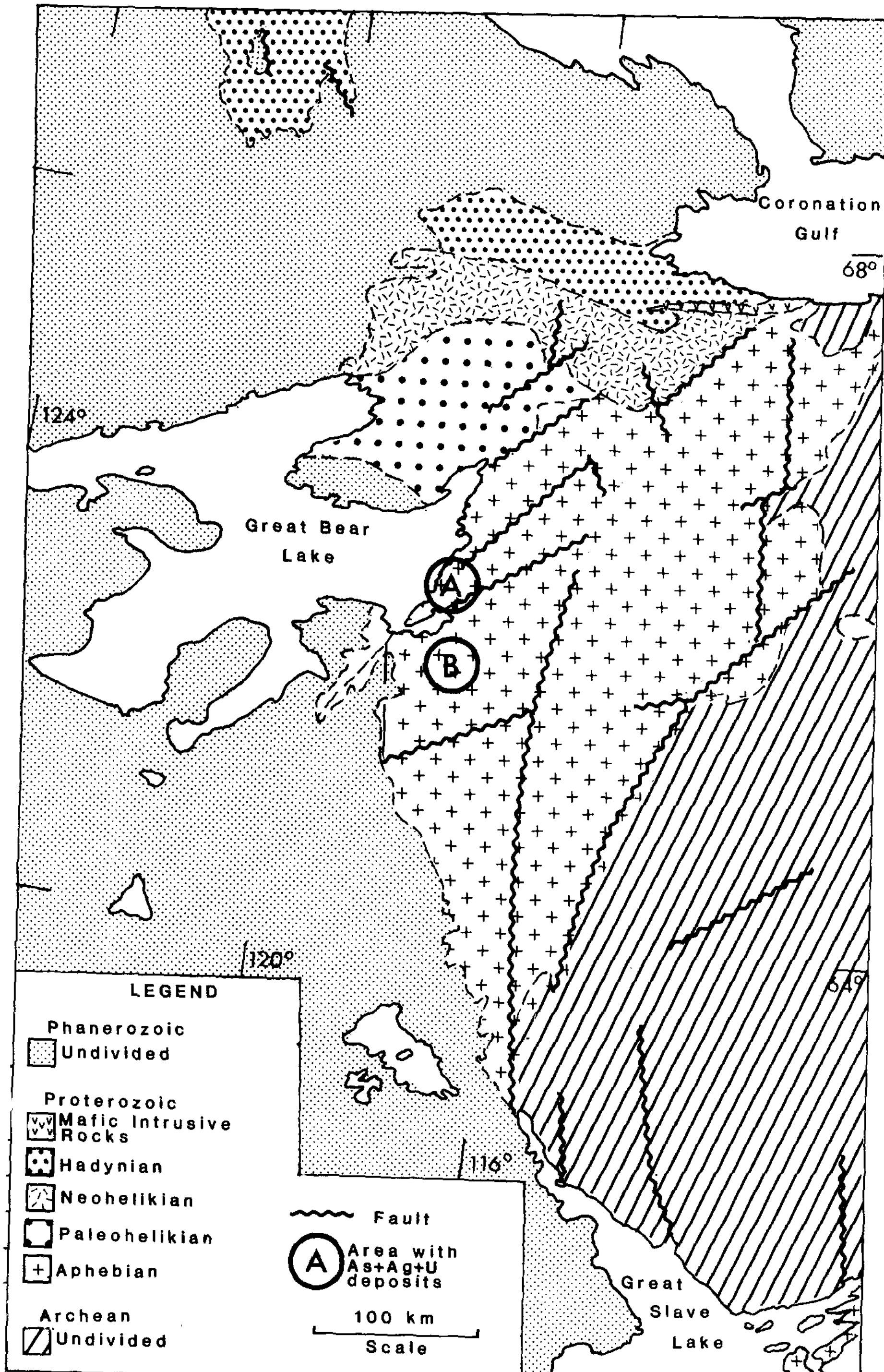

Fig. 8. Generalized geological map of the Great Bear Lake area, Northwest Territories, Canada. (*A*) Port Radium segment, (*B*) Terra Mine segment. Modified after the Geological Survey of Canada map 1475A.

brecciated rock, clay, hematitic and chloritic material and metallic mineral assemblages. It is a first order dislocation, to which the other ore veins are spatially related (Fig. 9).

The ore minerals were deposited as lensoid shoots in veins, breccia zones and shears to form several elongated ore bodies. They contained the highest concentrations of ore minerals in segments where the veins deflected, branched or were intersected by other veins, faults or dykes. The structural features of the veins were closely related to physical properties of the enclosing rocks. The mineralization was commonly better in competent rocks of the Echo Bay Group e.g., in tuffs, metamorphosed cherty sedimentary rocks and andesite that were favourable for fracturing and maintenance of open spaces.

Ore formation was related to thermal events in the Bear Structural Province. The minerals in the Port Radium deposit crystallized in several distinct stages interrupted by tectonic movements, which caused brecciation of the vein material. Individual mineralization stages were represented by specific elemental assemblages (Campbell, 1955; Jory, 1964; Ruzicka, 1971; Mursky, 1973; Fig. 10): (i) The first mineralization stage consisted predominantly of quartz and hematite and occupied extensively the peripheral structures of the deposit. (ii–iii) Mineral assemblages of the second and third (pitchblende and arsenide) stages contained pitchblende, nickel, cobalt and iron arsenides, sulpharsenides and Ni-sulphides associated with carbonates, chlorite and fluorite. These assemblages occupied all the veins throughout the mine with the exception of veins within the Bear Bay shear. (iv) The fourth (sulphide) stage included Cu, Fe, Pb, Zn, Sb, Mo, As, Bi and Ag sulphides associated with carbonate gangue. Minerals of this stage were deposited widely in all vein systems, but

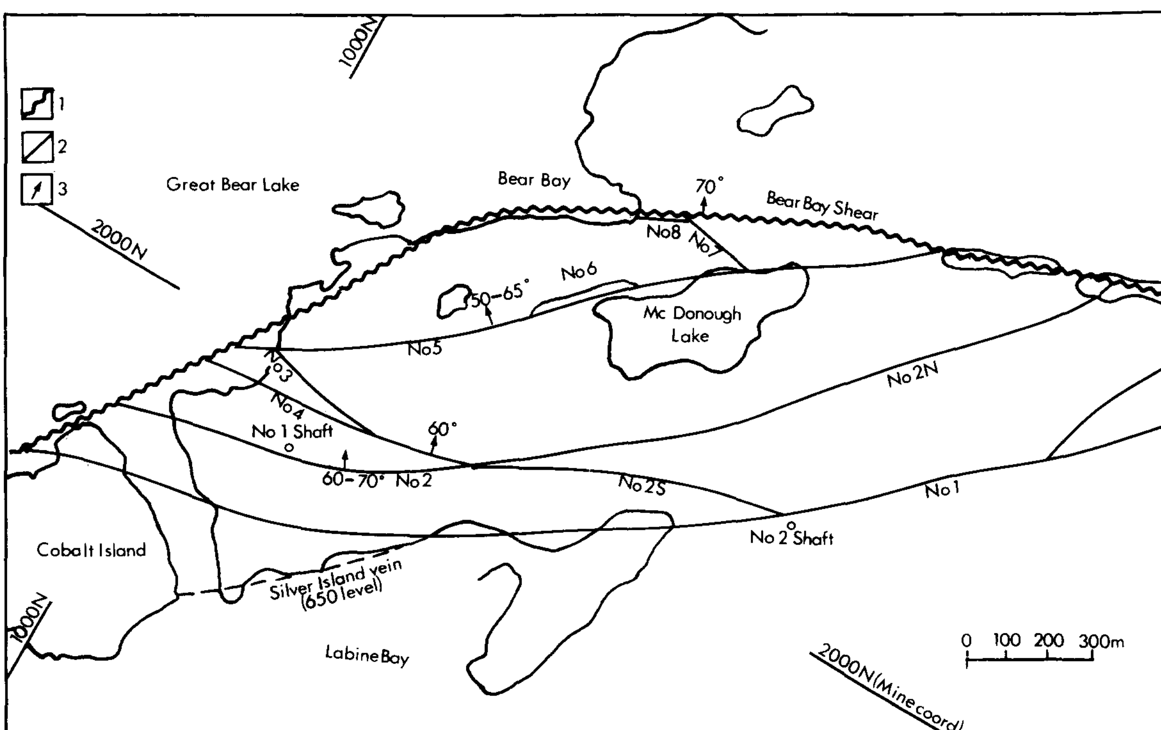

Fig. 9. Vein system of the Eldorado Port Radium deposit, Northwest Territories, Canada. *1*=fault; *2*=uranium vein; *3*=vein dip. The 1000 N grid line is in N–S direction. Modified after Jory (1964).

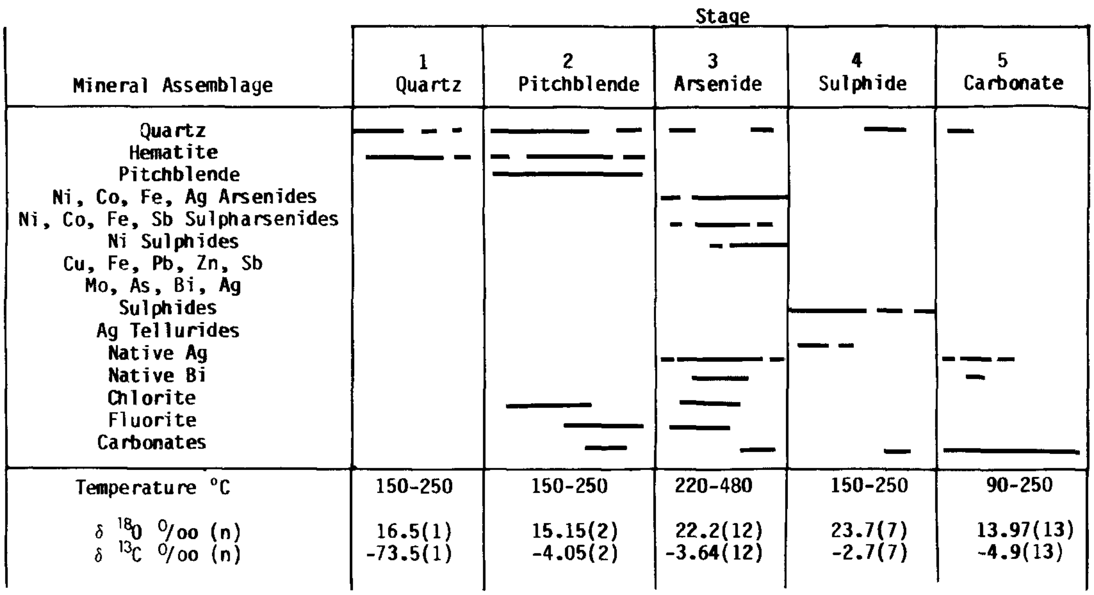

Fig. 10. Paragenetic succession of ore minerals in the Port Radium deposit, Northwest Territories, Canada. Modified after Campbell (1955), Jory (1964), Mursky (1973) and Changkakoti et al. (1986).

to a much lesser extent than those of the second and the third stages. (v) Mineral assemblages of the fifth (carbonate) stage comprised predominantly calcite, with some associated quartz, native silver and bismuth. They occupied the latest fractures and locally the central portions of the main veins.

Randomly collected specimens from the uranium veins in the Great Bear Lake domain contained, in addition to U, Co, Cu, and Ni, relatively high amounts of rare-earth elements (Ruzicka, 1971): yttrium (up to 2% Y), ytterbium (up to 0.2% Yb), lanthanum (up to 0.2% La) and cerium (up to 0.2% Ce). According to Mason and Moore (1982) the rare-earth elements are sensitive indicators of different igneous processes: elevated contents of lanthanum and cerium above their respective chondrite-normalized levels are characteristic for felsic igneous rocks, whereas elevated contents of rare-earth elements of higher atomic numbers, such as yttrium and ytterbium, indicate a relationship to mafic igneous rocks. Elevated contents of lanthanum, cerium, yttrium and ytterbium in the uranium vein samples from the Great Bear Lake domain apparently indicate affiliation of the mineralization to both felsic and mafic magmatic sources or processes.

The principal uranium mineral of the Port Radium deposit was pitchblende, Gummite, uranophane and zippeite were present only in the oxidation zone of the deposit. According to Mursky (1973) nickeline, safflorite–loellingite, gersdorffite and skutterudite were the principal minerals of the arsenide stage. Chalcopyrite, chalcocite, bornite, tetrahedrite and argentite were the principal minerals of the sulphide stage. Native silver and native bismuth constituted components of the arsenide and carbonate mineralization stages. Quartz, dolomite, montmorillonite, chlorite, rhodochrosite and hematite were the main gangue minerals. In addition, manganese oxides pyrolusite, psilomelane and polianite, were present in the oxidation zone of the deposit. These mineral assemblages are also typical for other occurrences in the Great Bear Lake U–Ag–Cu domain (Fig. 11). Proportional contents of uranium, arsenic, copper, cobalt, nickel and

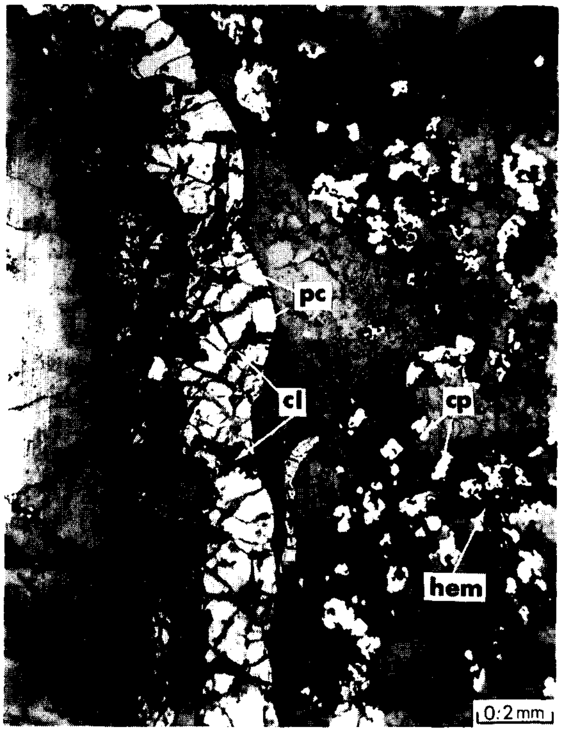

Fig. 11. A pitchblende vein (*pc*), accompanied by chlorite (*cl*); (*cp*) = chalcopyrite, (*hem*) = hematite. RAH occurrence, Great Bear Lake area, Northwest Territories, Canada. Photomicrograph, reflected plain light.

bismuth in gravity concentrates from the Eldorado Mine ores were, according to four-year mill records, approximately 20:13:7:7:4:1, respectively.

Diverse alterations of the wall rocks took place during individual stages of the ore-forming process (Campbell, 1955; Ruzicka, 1971): Pervasive hematitization developed during the earliest stages. Argillization and chloritization were associated with the pitchblende and arsenide mineralization stages. Carbonatization was associated with the sulphide and carbonate stages of mineralization. It affected all types of rocks, but its distribution was rather irregular and essentially restricted to those parts of the veins in which the carbonate-bearing hydrothermal solutions were in direct contact with the wall rocks. Locally the wall rocks were affected by silicification, sericitization, and development of sulphides and apatite.

In a genetic scenario presented here it is postulated that the deposits in the Great Bear Lake domain were formed by processes which mobilized the ore constituents from basement rocks and redeposited them in open fractures and cavities. The uranium was further concentrated in a reservoir within the clastic sedimentary rocks of the Hornby Bay Group, which overlay the basement rocks at the time of the mineralization. The mineral succession in the veins indicates that the mineralizing fluids increased in pH with time and changed from silicic to carbonatic and finally to sulphidic. The uranium mineralization took place from brines that were preconcentrated in the reservoir, descended along fractures in the basement rocks and released uranium at the redox front. Nickel-cobalt arsenides and most of the native silver and bismuth were deposited after reopening of the fractures. The sulphides and some native metals were deposited during the last stages of the mineralization process under high pH and low Eh conditions.

It appears that the mineralization can be correlated with emplacement of a diabase sill and with formation of magnetite-apatite veins and pods. A U–Pb age of about 1420 Ma (Jory, 1964) was obtained on pitchblende from the Port Radium deposit. However, it is not known if this is a primary age for the mineralization or simply a time of very extensive remobilization of uranium from the pre-existing veins.

According to oxygen and carbon isotope studies (Changkakoti et al., 1986) the character of the mineralizing solutions changed from hydrothermal endogenous to hydrothermal endogenous mixed with exogenous waters. The fluids reached a thermal culmination point at about 480°C during the arsenide mineralization stage (Fig. 10).

The Chanziping uranium deposit is located in the northern part of Guangxi province, in southeastern China (Ouyang Kun and Sun Renbao, 1986). The deposit is in Cambrian siliceous-carbonaceous slates that are in large part unconformably overlain by Cretaceous red beds consisting of conglomerate and sandstone. A small part of the Cambrian sequence is overlain by Devonian limestone and sandstone. The sedimentary sequence is in concordant contact with an Early Paleozoic (Caledonian) granite and has been introduced by Late Cretaceous (Yanshanian) granite.

The uranium ore emplacement was controlled by breccia and fracture zones and is locally accompanied by minerals of Zn, Mo, Ag, Ni, Y and V. According to Ouyang Kun and Sun Renbao (1986) the deposit formed by a multi-stage process: (i) sedimentary-syngenetic preconcentration in the carbonaceous pelites; (ii) partial redistribution due to regional and dynamic metamorphism; and (iii) final re-deposition from hydrothermal solutions. U–Pb isotope ages of pitchblende indicate that the final stage of mineralization took place at the end of the Yanshanian orogeny (74–78 Ma).

Veins in shear and fault zones

Uranium veins that are not associated with granitic plutons occur as fracture fillings and as shoots in fault zones. These veins typically occur in areas affected by repeated deformations, which resulted in reactivation of major fault systems, mylonitization, comminution and metasomatic alteration of the rocks. The Fay–Ace–Verna zone in the Beaverlodge area in northern Saskatchewan, Canada; the Shinkolobwe deposit in the Shaba Province, Zaïre; the Rožná-Olší deposits in the Bohemian Massif, Czechoslovakia, and the deposits Zadní Chodov, Dyleň, Hoehensteinweg and Waeldel in the western part of the Bohemian Massif, Czechoslovakia and West Germany, are typical representatives of the present type.

Rocks affected by brittle and ductile deformation along faults have been classified, for instance, by Wise et al. (1984) upon a relationship between a rate of strain and a rate of recovery into three groups: (i) cataclasites (including breccia, microbreccia, non-recrystallized gouge and pseudotachylite), which are products of brittle faulting at high rates of strain; (ii) mylonites, which are products of ductile faulting at high rates of strain with appreciable recovery rate; and (iii) metamorphic rocks, which exhibit pervasive recovery and recrystallization. This terminology was, for instance, adopted by Hodgson (1989) in a review of structures of shear-related, vein-type gold deposits. The terminology is also fully applicable to uranium vein deposits in shear and fault zones.

The now depleted Fay–Ace–Verna zone in the Beaverlodge area, Saskatchewan, which produced about 16 300 tonnes of uranium in ores grading 0.20% U (Ward, 1984) consisted of numerous ore bodies hosted by sheared feldspathic quartzite, brecciated and mylonitized granitic gneiss, phyllonite, and brecciated alterites. The host rocks are part of the Lower Proterozoic metasedimentary sequence of the Tazin Group, and to a lesser extent of the Middle Proterozoic sedimentary and volcanic rocks of the Martin Formation. The rocks of the area have been deformed during at least two orogenies: Kenoran and Hudsonian. The Kenoran Orogeny (ending ca 2.56 Ga, U–Pb scale; Stevens et al., 1982) affected the Archean rocks; during this orogeny gneiss domes and uranium-bearing pegmatite dykes have formed. The Hudsonian Orogeny (ending ca 1.8 Ga, U–Pb scale; Stevens et al., 1982) caused widespread cataclasis and mylonitization of Tazin Group rocks and reactivation of major fault systems, such as St. Louis, which is the controlling structure to the Fay–Ace–Verna zone. Terrestrial basaltic volcanism accompanied deposition of rocks of the Martin Formation during the late stage of the orogeny. Andesite dykes of the Martin Formation are exposed in mine workings (Ward, 1984).

Most of the uranium orebodies are spatially related to the St. Louis Fault and to the fracture systems associated with cross-faults, such as Larum, South Radiore and George Lake. The ore bodies occur near the Tazin-Martin

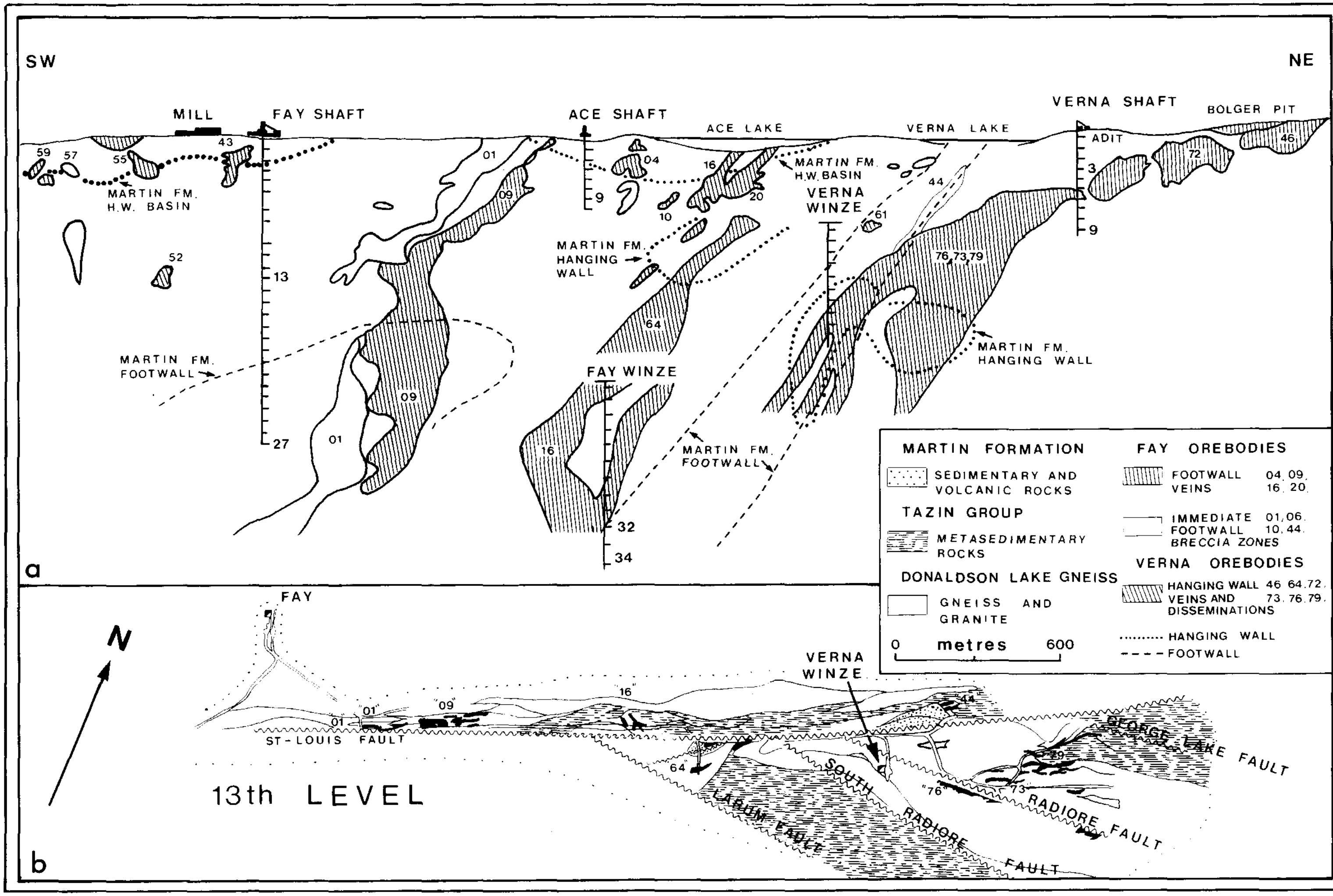

Fig. 12. Longitudinal section (a) and plan of the 13th level (b) of the Fay–Ace–Verna zone, Beaverlodge area, Saskatchewan, Canada. After Eldorado mine documentation and ward (1984).

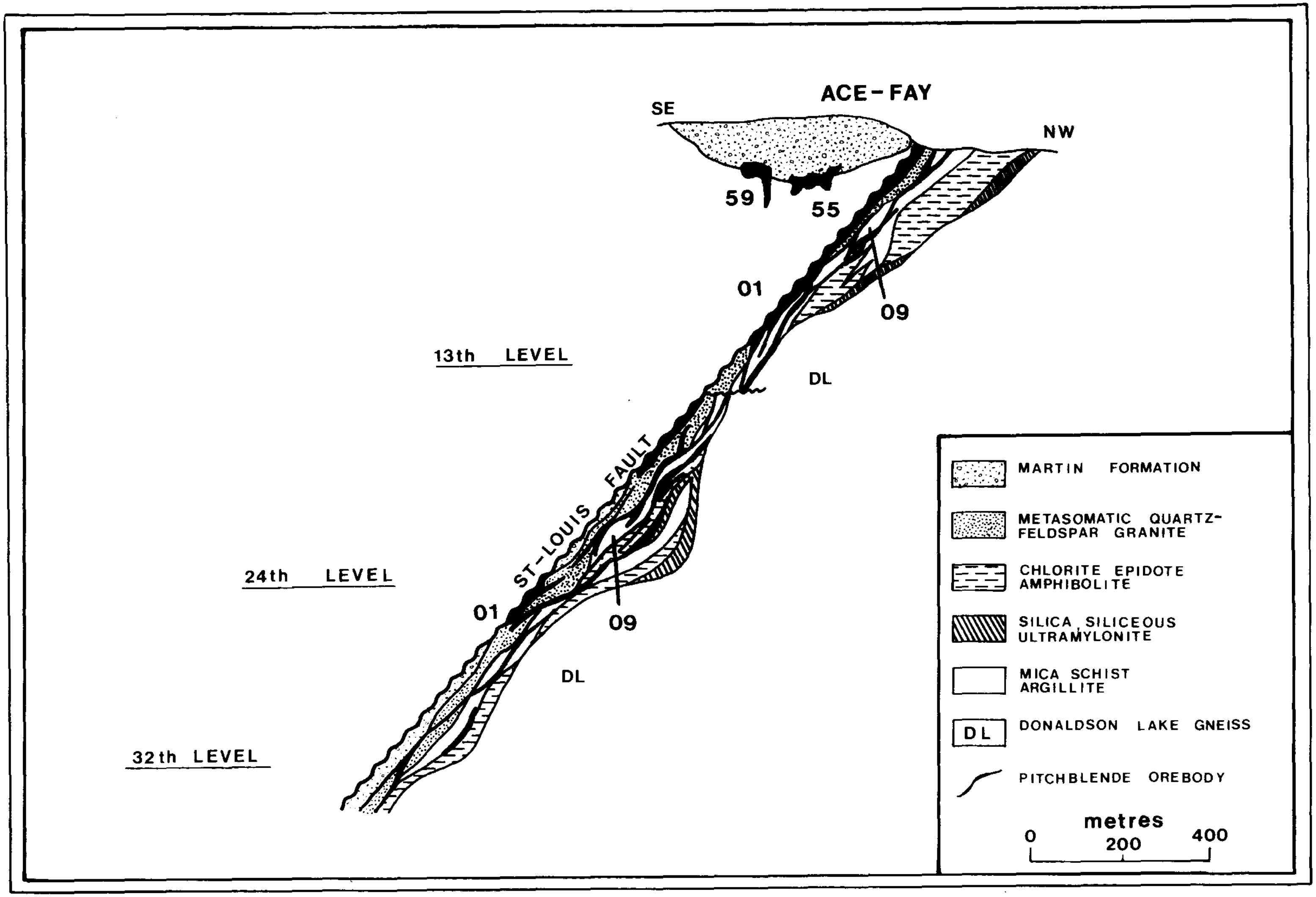

Fig. 13. Vertical cross-section through the Ace–Fay ore bodies, Beaverlodge area, Saskatchewan, Canada. Modified from Eldorado mine documentation.

unconformity. They were discordant, but most were associated with tectonites and metsomatites (Figs. 12 and 13).

The main episode of mineralization took place during the Hudsonian Orogeny, but the mineralization was later rejuvenated. Ward (1984) reported results of statistical analysis for a total of approximately 120 U–Pb age determinations made on pitchblendes from the Beaverlodge district. This analysis shows clustering of isotopic ages in three periods, namely: at 1.8–1.7 Ga, which corresponds to Hudsonian orogenic events; at 1.1–0.9 Ga, which corresponds with the Grenvillian orogenic events and falls within the period of mineralization of deposits associated with the sub-Athabasca unconformity farther east; and at about 0.2 Ga. The main trigger for the mineralization of the deposits associated with the sub-Athabasca unconformity was assumed by Ruzicka and LeCheminant (1987) to have been a thermal event associated with intrusion of the diabase dykes. However, this thermal event might be also related to the effects of the Grenvillian orogenic activity.

The main ore-forming mineral, pitchblende, occurs in euhedral, botryoidal, massive and sooty forms. The euhedral pitchblende may correspond to the metastable alpha-triuraniumheptaoxide ("tetrauraninite" sensu Voultsidis et al., 1982; or "Neouraninit" sensu Dill, 1982) which is known from the Key Lake, Eagle Point and Cigar Lake deposits in the Athabasca basin. The massive pitchblende occurs as veins and breccia cement. Sooty pitchblende represents a finely divided, hydrated variety of massive or botryoidal pitchblende. The botryoidal pitchblende is locally cut by selenides, particularly clausthalite (Robinson, 1955). Brannerite constitutes a substantial component of the ore from lower levels of the deposit. The ore contains brannerite grains consisting of two phases: one, composed mainly of Ti–U with traces of Fe and Si; and the other of U–Si with traces of Ti and Ca. Coffinite often occurs interstitially in anatase aggregates (Ruzicka and Littlejohn, 1982).

Fluid inclusion studies by Sassano (1972) on quartz and carbonate gangue minerals from the Fay–Ace–Verna deposit indicate that the mineralizing fluids were derived from fluids in the host rocks and that the exchange reactions took place initially at temperatures of 500°C, with a gradual drop in temperature to 80°C. Results of oxygen isotope analyses show that no additional fluids were later introduced and that the system was essentially closed, i.e., that only redistribution and redeposition of the original stock of uranium and associated metals took place during the following reactivations of the structure.

In the vicinity of the ore bodies the wall rocks have commonly been affected by hematitization, feldspathization, chloritization and carbonatization. Silicification and feldspathization of wall rocks with oligoclase occurred only in areas where they have been fractured and brecciated. Local albitization of the wall rocks represents relics of a sodic metasomatism that took place in the early stages of the mineralization process.

A conceptual genetic model for the Beaverlodge district is postulated by the writer as follows: The vein deposits were part of a major metallogenic cycle, which started with concentration of uranium into granitoid bodies during the Kenoran Orogeny. The uranium and associated elements were further concentrated in the sedimentary lithostratigraphic units of the Tazin Group that represent the uppermost part of the sequence. Anatexis, metamorphism, mylonitization and faulting during the Hudsonian Orogeny accompanied hydrothermal remobilization of the metals and their redeposition in fractures as veins and stockworks and disseminations in the host rocks. The mineralization was controlled by pH and redox changes. Complexing of uranium with titanium into at least two forms of brannerite took place under elevated temperatures and pressures in the deeper parts of the deposit

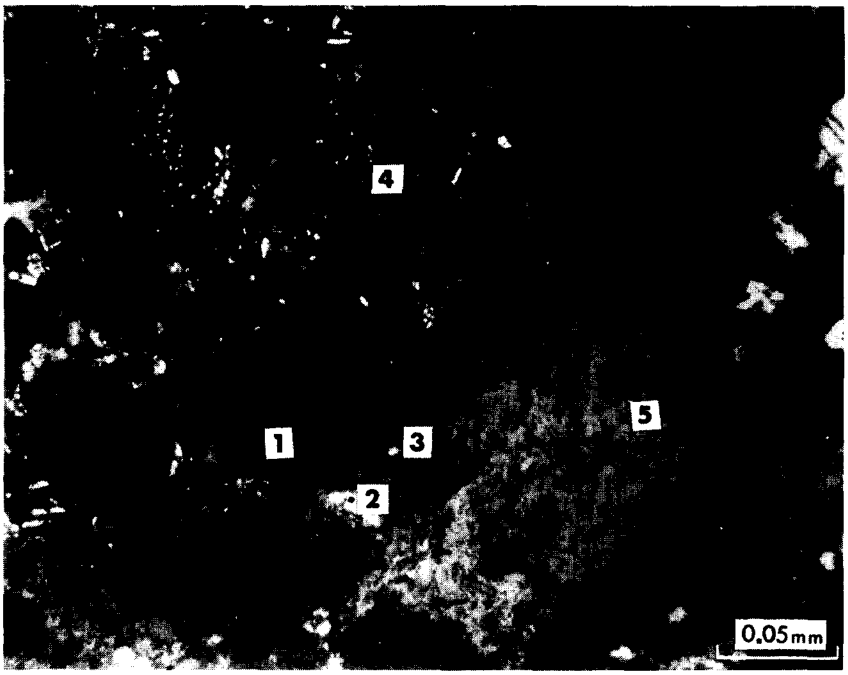

Fig. 14. Mineral assemblage of an ore sample from the Fay ore body, 23rd level of the Fay–Ace–Verna zone, Beaverlodge area, Saskatchewan, Canada. (*1*) albite; (*2*) anatase with minor U, Si, Fe and Ca; (*3*) U–Ti–Ca–Fe–Si phase; (*4*) chlorite and brannerite mixture with minor Fe, Ca, Si and Pb. Photomicrograph, plain reflected light. From Ruzicka (1989).

(Fig. 14), whereas pitchblende and coffinite prevailed in the upper levels. The established vertical extent of uranium mineralization in the Fay–Ace–Verna zone exceeds 1500 m (Fig. 12a).

The Shinkolobwe deposit in the Shaba Province, Zaire (Fig. 1), occurs in metasedimentary rocks of the Roan Group, which is part of the Katanga System (Derriks and Vaes, 1955; Derriks and Oosterbosch, 1958). The Roan Group consists of a coarse-clastic unit at the base, of a mixed fine-clastic–carbonate unit in the middle and of an upper dolomitic unit. The depositional age of the group is 1000–840 Ma (IAEA, 1986). The rocks of the Katanga System were subjected to deformation and metamorphism during several phases of the Lufilian orogeny (Derriks and Vaes, 1955; IAEA, 1986).

The Shinkolobwe mine produced an estimated total of 27 000–33 000 tonnes of uranium metal from oxide, silicate and phosphate ores (Heinrich, 1958), grading between 0.4 and 0.8 per cent uranium (IAEA, 1977; Meneghel, 1984). The deposit has been depleted.

Uranium, locally associated with nickel, copper, cobalt, molybdenum, tungsten, selenium, gold, platinum and rare-earth elements, occurred in veins and disseminated in the host rocks. Crystalline uraninite was the principal uranium mineral in the primary zone. The uranium was confined to the lower unit of the Roan Group. The mineralization took place in several stages (Meneghel, 1984): (i) magnesite; (ii) uraninite; (iii) pyrite-selenium-molybdenum-monazite-chlorite; (iv) cobalt-nickel sulphide; (v) chalcopyrite.

A U–Pb age for the Shinkolobwe uraninite between 620 and 670 Ma, which coincides with one of the phases of the Lufilian orogeny, and comparative studies on other deposits in the Katanga system, led Meneghel (1984) to conclude that: (a) the first concentration of metals was associated with a marine transgression over an ancient crystalline basement; (b) the metal concentrations were confined to the lowermost lithostratigraphic units of the Katanga system; (c) the concentrations represented a "protore", i.e., an early reservoir of sub-grade metals; (d) the deposits in the region were derived from these sedimentary-syngenetic concentrations; (e) the mineralization took place by mobilization of the metals and their redistribution into the veins; (f) the mobilization and mineralization processes were associated with individual phases of the Lufilian orogeny; and (g) the number of metallic elements de-

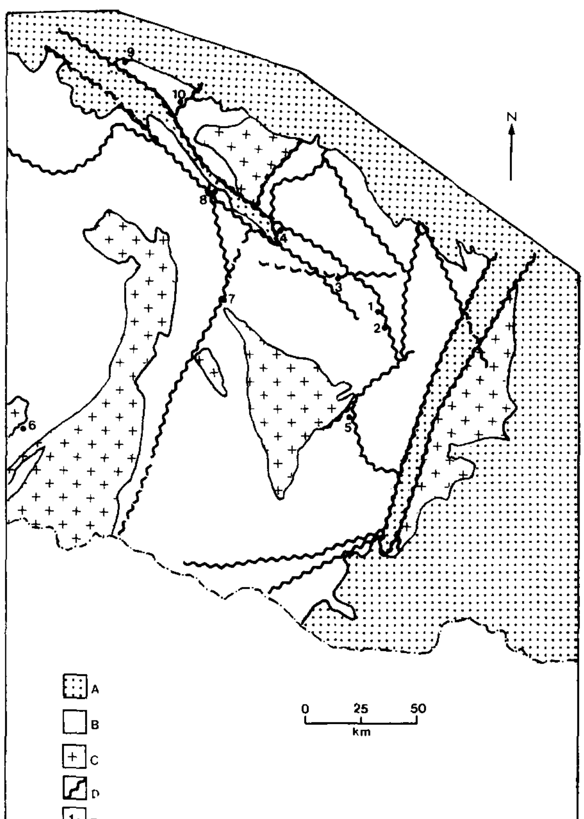

Fig. 15. Generalized geological map of a part of the East Bohemian and West Moravian uranium-bearing region, Czechoslovakia. *A* = Mezozoic and Cainozoic sedimentary rocks; *B* = Moldanubian metamorphic rocks; *C* = Hercynian granitoids; *D* = Faults; *E* = uranium deposits: (*1*) Rožná, (*2*) Olší, (*3*) Slavkovice, (*4*) Škrdlovice, (*5*) Jasenice, (*6*) Okrouhlá Radouň, (*7*) Polná-Brzkov, (*8*) Chotěboř, (*9*) Bernardov, (*10*) Licoměřice. Modified after Kolektiv (1984).

creased after each orogenic phase in the following order: Ni–Co–Cu–Fe–U.

Deposits of this type, e.g., Rožná and Olší, occur in the Bohemian Massif, Czechoslovakia; they are associated with a major tectonic zone — the Labe Lineament (Ruzicka, 1971; Kolektiv, 1984; Figs. 1 and 15). The deposits are localized near the eastern margin of the Moldanubian metamorphic complex and contain disseminated pitchblende and coffinite, accompanied by chloritized, calcite-veined and graphite-rich fault zones. Some deposits in the Železné Hory Mts, about 150 km to the northwest, are also controlled by faults associated with the Labe Lineament (e.g., Bernardov and Licoměřice). They contain pitchblende and coffinite, accompanied by pyrobitumen which was apparently derived from the surrounding carbonaceous schists. The schists are in contact with a granitoid pluton of Hercynian age. In contrast to Rožná, however, these schists are Cadomian.

Several fault-related uranium deposits are also situated on both sides of the border between Czechoslovakia and Federal Republic of Germany: Zadní Chodov and Dyleň in western Bohemia (Ruzicka, 1971; Kolektiv, 1984) and Hoenhensteinweg and Waeldel in northeast Bavaria (Barthel, 1977; Dill, 1980, 1982, 1983 and 1985). The Bohemian deposits were exploited, the Bavarian deposits were only explored by shafts and are at present dormant. The deposits occur in metasedimentary rocks of the Moldanubian "Variegated Group" consisting of a variety of rocks, such as gneisses, calcsilicates, metasapropelites and amphibolites. The Zadní Chodov ore shoots are confined to several zones of graphitized cataclasites, including non recrystallized gouge, and mylonites, within an aureole of hydrothermal alteration. The principal ore-forming mineral is coffinite and, rarely, brannerite. The Dyleň ore zone occurs in the marginal part of the Moldanubian zone consisting predominantly of migmatized paragneiss. The ore shoots are mainly confined to northeasterly-trending set of second-order mylonite zones, which are in the footwall of a major northerly-trending shear zone. The principal ore-forming mineral of the shoots is coffinite. The Hoehensteinweg and Waeldel ore zones are situated in Upper Proterozoic biotite gneisses and mica schists. The uranium mineralization consists of titanates, oxides and silicates. Dill (1982, 1989) considers that the psammo-pelitic sedimentary rocks containing elevated amounts of organic matter (graphite), P, U, W, Mo and REE, were the source of mineralization in these deposits. Some of these metabiolites, particularly the phosphorite-bearing black shales, contain up to 16 ppm U (Dill, 1989). The sediments have undergone amphibolite facies metamorphism and subsequent retrograde alteration. The mineralization took place in the fault zones subparallel to the foliation and, particulartly, at intersections of these fault zones with faults discordant to foliation. The uranium ores are associated with muscovite, chlorite and smectite. The non-radioactive mineralization consists of sheelite, arsenopyrite, native gold, pyrite, chalcopyrite, and Bi and Pb selenides (Dill, 1982).

A conceptual genetic model for vein uranium deposits

Analysis of metallogenic features of areas containing vein uranium deposits assists in establishing a conceptual genetic model, which involves the following postulates:

The vein deposits commonly form during major metallogenic epochs. Their formation starts with introduction of uranium into the geochemical cycle due to intrusion of granitoid plutons. Uranium tends to be concentrated, along with Th, in the latest phases of the igneous complexes, i.e., in late magmatic differentiates such as granites, alkaline rocks with high K or Na contents, residual melts and autometasomatic facies of igneous rocks.

The uranium and associated elements are liberated from the parent rocks by anatectic, metamorphic, thermal or weathering processes controlled by tectonism. Separation of thorium from uranium depends mainly upon the temperature at which these processes take place. At high temperatures the Th/U ratio is as great as 5:1. Low temperature hydrothermal and sedimentary processes separate Th from U in fluids, so that veins and epigenetic deposits that formed at temperatures below 500°C have Th:U ratios less than 1.

Transport of uranium from the parent rocks to the new depositional site takes place by various media depending upon the processes involved: uranium may be transported in melts, fluids or as detritus. For direct formation of veins, however, the uranium is transported in fluids. In high temperature fluids, uranium is transported as uranyl fluoride, uranyl sulphate or uranous fluoride complexes. In low temperature fluids, uranium is commonly transported as uranyl dicarbonate or uranyl tricarbonate complexes. Uranium transported in melts and in detritus leads to formation of new, possibly enriched, sources. Formational (connate) waters of sedimentary rocks in many cases serve as a reservoir of metals.

Formation of the veins is commonly related to late phases of orogenic cycles or to post-orogenic reactivation of the uranium-enriched sources or uranium-bearing structures. The uranium vein deposits represent epigenetic concentrations of uranium and accompanying metals and gangue minerals in open spaces, such as fractures, fault, shear and mylonite zones, brecciated rocks and vugs, from uraniferous fluids. The ore-forming fluids can be of various types, including juvenile, post-magmatic, connate, diagenetic, ground and meteoric waters.

Localization of mineralization within the deposits is due to structural and lithological features. The ore minerals become concentrated in areas of flexures, braching, intersections and changes of width of the veins. Wall rocks containing carbonaceous matter, sulphides and ferromagnesian minerals are favourable loci for deposition of the ores.

The mineralization is commonly accompanied by alteration of the host rocks and/or of the previously deposited vein materials. Sodic metasomatism (albitization) usually takes part in the early stages of the mineralization. Hematitization, chlorotization, feldspathiziation and carbonatization are the common forms of alterations associated with the main stages of mineralization.

Oxygen and carbon isotope studies on vein uranium deposits indicate that mineralizing solutions in many cases consist of hydrothermal solutions that have mixed with meteoric waters. During the mineralization process fluid temperatures may be relatively high, in excess of 400°C.

The vein deposits have many genetic features similar to deposits associated with unconformities. The common denominator for both deposit types is that their formation from uraniferous fluids is structurally controlled, and the fact that pitchblende is the principal ore-forming mineral. Therefore both the vein and unconformity associated deposits could be simply classified as discordant hydrogenic uranium/polymetallic deposits.

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