

MINERALOGICAL AND GEOCHEMICAL FEATURES OF THE URANIUM ORE COMPOSITION: SCIENTIFIC AND PRACTICAL IMPORTANCE

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Currently, more than 150 uranium and uranium-bearing minerals are known. Most of them pertain to the uranyl group formed under oxidative conditions reflecting physicochemical parameters in the mineral compositions or mineral assemblages. The uranyl minerals compose the following economic ores: (1) uranophane-beta – zeolites (Berezoviyi and Gorniyi deposits, Transbaikalia), (2) the uranyl minerals associated with zeolites (Severnii deposit, NE Russia, granite in Bulgaria), (3) parsonsite (La Chaux deposit, France), and (4) uranyl phosphates in argillic granite (Durulgui deposit, Transbaikalia). In addition, large uranium deposits as carnotite calcretes and calcretes with the other uranyl minerals are known from Australia and Namibia, respectively. Cut off ore (up to 0.01% U) and blocks with low uranium grade (up to 0.005% and lower) are economic at the deposits with the uranyl minerals in the case of geotechnological mining or heap-leaching processing, for example schrockerite deposits in Mongolia and Kazakhstan. Such deposits can be large and superlarge.

In the fresh economic ore, uranium (IV) minerals are oxides (nasturan, uraninite, sooty pitchblende), titanates (brannerite and its transition varieties), silicates (coffinite and silicates of variable composition), and less frequent uranium (IV) phosphates and molybdates. Uranium-bearing minerals are apatite, Ti, Zr, and Th oxides and silicates, and zeolites. The ore deposition is significantly affected by the near-surface and deep-seated supergene alteration. The additional exploration and estimation criteria for uranium deposits are proposed. These criteria allow discovery of uranium deposits in: (1) north of the Strel'tsovsk structure, South-East Transbaikalia, (2) Akitkan district and Chara-Olekma block, northern Baikal Region, and (3) Western Siberian Plate.

1 table, 7 figures, 56 references.

Keywords: uranium (IV) minerals, uranyl minerals, uranium-bearing minerals, large and superlarge uranium deposits, prediction of uranium deposits

According to the expression by V.I. Vernadsky on ubiquity of uranium, currently, more than 150 uranium and uranium-bearing mineral species are known. Most of them belonging to the uranyl group are formed under oxidative conditions; in this case, the composition of separate mineral species and mineral assemblages reflect physicochemical parameters of mineral-forming medium. The uranyl minerals are hydroxides, silicates, phosphates, arsenates, vanadates, carbonates, sulfates, molybdates, selenites, tellurites, and minerals of the more complex anion and cation composition. Iron and manganese oxides and hydroxides, apatite, zeolites, powellite, wulfenite, clay minerals, and other uranyl-bearing minerals are attributed to the U-bearing minerals.

In addition, amorphous phases and poorly crystallized uranyl hydroxides, as well as Fe, Si, Ti, Zr, Th, and more complex uranyl hydroxides and uranyl-bearing hydroxides are known. All these minerals are formed in

the oxidizing zone of uranium deposits whose fresh ores are below oxidizing zone. Recently, such fresh ore was the major object of mining. Mineralogy of oxidizing zone of uranium deposits was multiple reported in geological literature (Fron del, 1958; Heinrich, 1958; Gritsaenko *et al.*, 1959; Konstantinov and Kulikova, 1960; Evseeva and Perel'man, 1962; Supergene..., 1965; Formation..., 1976; Chernikov, 1981, 1982, 1996, 2001, 2008, 2009; Mineralogy..., 1983; Large..., 1984; Typomorphic features..., 1989; Kulish and Mikhailov, 2004; Chernikov and Dorfman, 2004; Chernikov *et al.*, 2009₁, 2009₂ and other). Redistribution of uranium in oxidizing zone of uranium deposits is important to be described.

Types of oxidizing zones formed after economic fresh uranium ores

According to distribution of uranium, the following types of oxidizing zone of uranium deposits are distinguished: (1) leached or sig-

nificantly depleted in uranium oxidizing zone in comparison with fresh ore; (2) oxidizing zone with uranium grade like fresh ore; (3) oxidizing zone with ore enriched in uranium in comparison with fresh ore. The first type is divided into three subtypes. Subtype 1a includes oxidizing zones without uranyl minerals or they are insignificant (Byk deposit, Caucasus Mineral Waters, Russia; Adrasman deposit, Kara-Mazar, Tajikistan).

Roll and similar deposits in Southern Kazakhstan, Central Asia, Siberia, Transbaikalia, and sedimentary basins in Bulgaria and other countries may be attributed to this subtype. Oxidizing zones with the uranyl minerals, which are economic ore only on the separate levels (Druzhnyi, Elkon, and Plato deposits, Elkon district, Aldan, Russia), pertain to the 1b subtype. Subtype 1c includes oxidizing zones with the uranyl minerals in ores depleted in uranium in comparison with replaced fresh ores (Strel'tsovsk, Luchisty, and Tulukuevo deposits, Southeastern Transbaikalia, Russia).

In the second-type oxidizing zones, subtypes 2a and 2b are distinguished. In subtype 2a, uranium grade in oxidized and fresh ore is approximately identical (Chasovoi deposit, Transbaikalia; Cherkasar deposit, Kurama Ridge, Uzbekistan). In subtype 2b, uranium grade at separate levels of oxidizing zone is lesser than in the fresh ore. Most oxidizing zones of the 1c subtype are similar to those of the 2b subtype. The major difference is that in subtype 1c, all oxidizing zone is depleted in uranium, whereas in subtype 2b, only separate levels are depleted in uranium. The Major Zone of the Tabashary deposit, Kara-Mazar, Tajikistan exemplifies this subtype (Chernikov, 1981₁). Geochemical and mineralogical features of both type oxidizing zones are applied for ore prediction below oxidizing zone. The composition of the uranyl minerals and associated minerals of the other elements and their zoned distribution determine the formation type of deposit and its economic importance.

The third-type oxidizing zones are divided into two subtypes: (3a) deposits with rich ore in all oxidizing zone and (3b) deposits with enriched oxidized ore at the near-surface level that gives way to oxidized leached zone. The Sernyi deposit located ~200 km east of Turk-

menbashi (former Krasnovodsk), Turkmenistan exemplifies subtype 3a. In the oxidizing zone of this deposit, hydroxides, phosphates and other uranyl minerals were identified. However, silicates (mainly uranophane) and uranyl vanadates (strelkinite, carnotite, and tyuyamunite) are more abundant. Completely oxidized ore of this deposit in which only uranyl minerals were identified contains three times more uranium and mixed ore (with uranyl minerals, sooty pitchblende and relic nasturan), – 2.8 times more uranium to 1 m depth in comparison with sooty pitchblende-nasturan ore. Oxidizing zone enriched in uranium in comparison with fresh ore is formed in U-V deposits, for example, Shakoptar and Maili Sai, Kirgizstan and Pap, Uzbekistan.

It is evidently that elevated uranium grade in oxidized coal whose fresh variety has a background concentration of this element should be attributed to subtype 3a. Uranium frequently concentrates with rare and noble metals in grade of $0.0n - 0.n\%$ in ash of oxidized coal of many coal basins in Siberia, Transbaikalia, Russian Far East, Mongolia, Kazakhstan, and Bulgaria. For example, ash of oxidized coal from the Adun-Chulun deposit, Mongolia contains 0.11–0.33% U, up to 0.45% REE, 0.36–2.1 g/t Au, up to 350 g/t Co, and elevated concentrations of other important chemical elements (Arbuzov *et al.*, 2008). The processing of ash of power-station utilizing such coal will be favorable for environment in the districts of its storage because recovery of uranium will solve a problem of radioactive environmental pollution.

The oxidizing zone of the Komsomolsk rare metal-uranium deposit, western outer contact and near-contact igneous rocks of the Kuu granite pluton, Central Kazakhstan (Chernikov, 1981₂; Chernikov and Dorfman, 2004) exemplify subtype 3b. In the uppermost part of the oxidizing zone of this deposit, shrinkingite (Fig. 1) and small amount of uranophane were identified. The clusters of shrinkingite form near-surface subzone (vertical extension from 2 to 5 m) significantly enriched in uranium. The mineral identified along tectonic fractures far from orebodies occurs as large clusters in the Quaternary loose sediments and at the upper levels of tectonic zones, which are not associated with major ore-bearing structures.

Subzone of leached uranium with small number of uranophane and autunite (probably, also uranospinite) is below the shrökingerite subzone down to tens to hundred meters. This subzone is followed by the zone enriched in uranium (vertical extension to several dozen meters) with sooty pitchblende and clay matter absorbing uranium; in turn this zone gives way to the zone depleted in uranium and low-grade zone. Nasturan, uraninite, and brannerite were identified in the low-grade zone.

Lead isotopic composition and radioactive isotopes in minerals and mineral assemblages clearly record intensity of supergene redistribution of uranium in geological section of the Komsomolsk deposit. The distribution of mineral assemblages and lead isotopic ratio and relationship of radioactive isotopes in these assemblages allowed hematitization of rocks before Early Triassic, when the main stage of erosion of Paleozoic sediments took place. Hematitization was strong at the Komsomolsk deposit. After that, during Jurassic, Tertiary, and Quaternary, at the deposits and occurrences located in near-contact igneous rocks and outer contact of the Kuu pluton to which this deposit is related, supergene minerals with highly redistributed uranium and other ore minerals were formed. The strong leached U and Mo lead to the limited formation of their minerals in the oxidizing zone and newly formed minerals precipitated in the cementation zone. Only during late Quaternary, gypsum and shrökingerite started to precipitate in soil, Quaternary sediments, and upper level of weathering profile, including upper level of previously leached oxidizing zone. Since shrökingerite accumulated during Upper Quaternary at different distance from source and leached zones are poor documented, the probability of finding of uranium economic concentration at deep level of the Komsomolsk deposit is high. In this case, near-surface clusters of shrökingerite are of economic interest for heap leaching.

Deposits of uranium minerals of oxidizing zone without evident relation to fresh economic ore

In addition to the deposits with aforementioned types of oxidizing zone, there are



Fig. 1. *Schrökingerite* in clay of the Komsomol'sk deposit, Central Kazakhstan. Size of segregation is 6.5×7 mm.

deposits, where the uranyl minerals are the major constituents of economic ore formed without evident relation to any fresh economic concentrations of uranium. At first place, these are uranophane-beta – zeolite ore of the Berezovyi and Gornyi deposits (Chernikov, 1981, 2001; Chernikov *et al.*, 1983), many occurrences of southern Central Transbaikalia, and some border occurrences in Mongolia. The ores with the uranyl minerals hosted in granite of the Severnyi deposit and some occurrences of NE Russia, and zones of zeolite altered granite in Bulgaria belong to this type.

In the zones of zeolite altered granite of the southern Central Transbaikalia (Chikoi-Ingoda structural zone), uranophane-beta is one or predominant uranium mineral of ore at deep level (from 150 – 300 to >700 m below surface). Small number of apatite, quartz-apatite, and silica veinlets were found, where the finest segregations of nasturan and coffinite with electron microscope had been established. Nasturan was identified with electron microscope in the core of radiated segregations of uranophane-beta (Fig. 2). However, the contribution of U-bearing apatite and silica veinlets and nasturan from uranophane-beta segregations to total uranium reserves at the deposits does not exceed 0.0n and 0.00n%. Uranophane-beta precipi-

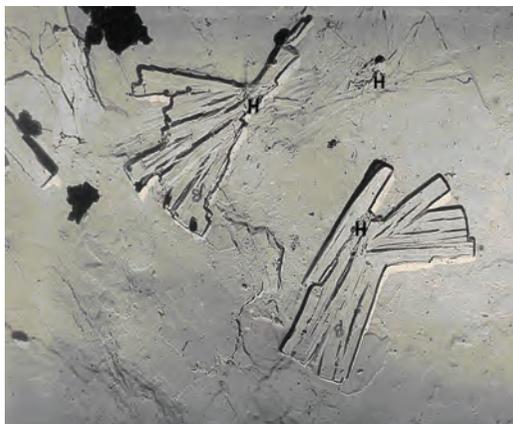


Fig. 2. Radiated segregations of uranophane-beta with nasturan (N) located in the cores of these segregations, Gornyi deposit, Central Transbaikalia. $\times 7500$.

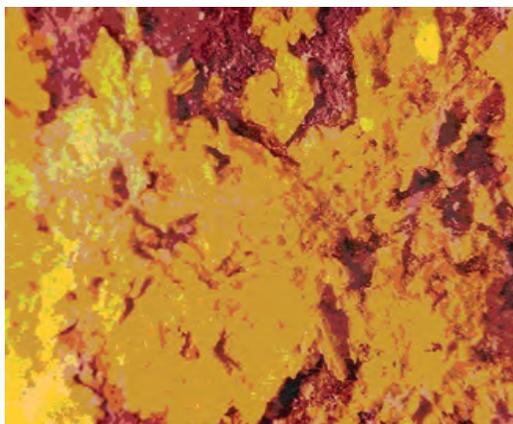


Fig. 3. Plates of yellow autunite on limonitized granite, Berezovyi deposit, Central Transbaikalia. $\times 10$.



Fig. 4. Plates of dark green autunite, Durulgui deposit, Central Transbaikalia. $\times 10$.

tated in alkaline environment is the major ore mineral at the Berezovyi and Gornyi deposits (Chernikov, 1981₁, 2001; Typomorphic features..., 1989). This mineral is replaced by uranophane upward due to pH increasing under effect of penetrated meteoric water, and at the depth of 50–150 m under weakly acidic conditions, by yellow autunite (Fig. 3). Upward, in weakly reductive acidic environment, yellow autunite, uranophane, and uranophane-beta are replaced by dark green autunite (Fig. 4) containing U^{4+} . In this case, near surface, the rare phenomenon is observable. Therein, the uranium (VI) contained in uranyl is reduced partly to trivalent state because of introducing organic matter removed from soil and swamped places, rather than oxidation level of ore increases.

At the Gornyi deposit, insignificant amount of kasolite was observed and at the Berezovyi deposit, among listed varieties of autunite, single grains of sabugalite were indentified. At the Severnyi deposit and occurrences of the Shumilovo pluton, where the greisen mineralization is abundant, in addition to uranophane-beta, uranophane, and autunite, torbernite and uranyl arsenates (zeunerite and uranospinite) are abundant.

Autunite is the most abundant in the ore of the Durulgui deposit, southern East Transbaikalia, where only uranyl mineral were found. Just at this deposit, dark green autunite, containing tetravalent uranium was found for the first time in Russia in 1958 (Chernikov *et al.*, 1964). Therein, torbernite (Fig. 5) and sabugalite are less frequent. Uranyl minerals are associated with clay minerals, limonite, and manganese oxides. At the La Chaux deposit, France, parsonsite is the major ore mineral (Branche *et al.*, 1951). It fills fractures and cavities in smoky quartz associating with opal-like quartz, cerussite, pyromorphite, limonite, and manganese oxides. Other uranyl minerals, torbernite, autunite, dewindite, and kasolite are rare in this assemblage. Only autunite was described from occurrences at the Sila Plateau, Calabria, South Italy (The Formation..., 1976).

Carnotite is one ore mineral identified in the Yeelirrie calcrete deposit, Western Australia forming large uranium reserves (Sofoulis, 1962; Premoli, 1976; The Formation..., 1976; Laverov *et al.*, 1983). This mineral

occurs as film along horizontal stratification of waterpenetrating carbonate or carbonate-rich rocks. In the other U-bearing calcretes of Western Australia, tyuyamunite is dominant over carnotite. Calcretes in Namibia and probably in Somali, Africa, are similar to the Yeelirrie calcretes, but in Namibia, uranyl minerals are closely associated with U-free gypsum. Like Yeelirrie, the films of carnotite in Somali fill interstices, fractures, and cavities in calcrete, marble, clay, and broken carbonate at depth down to 8 m below surface only over ground-water level.

Australian or African-type near-surface calcrete-type orebodies with different uranyl minerals were identified in the northern part of Uch-Kuduk deposit adjacent to the Paleozoic granite pluton, Uzbekistan. Orebodies occurred at the depth of 1–3 m below surface in the Quaternary loam are concentrated at the talus and proluvium bottom partly involving upper carbonatized sediments (calcretes). The Quaternary loam is strongly gypsinate and uranium minerals in it occur as eyes and small lenses ranging from few mm to 3 cm in size. These eyes and lenses are fine-grained loose clusters saturated by earthy uranyl silicates and carbonates. They are weakly gypsinate in the places of the thickest mineralized loam (3 m). Bands of strongly gypsinate are over uranium mineralization. As thickness of the Quaternary sediments decreases, ore band gradually joins to the bands of gypsinate loam. In this case, gypsification is accompanied with removal of uranium. According to bulk analysis of samples taken through the section of the Quaternary sediments, there is no clear relationship between uranium grade and concentration of Ca, Mg, Mn, and Fe. The samples enriched in SO_4^{2-} are dramatically depleted in uranium. Microscopically, the replacement of uranium minerals by gypsum is observable. In the places of the most abundant gypsum, uranium is leached down to 0.02–0.03%.

In the district of the Uch-Kuduk ore field, lenses of gravelite with carbonate cement are frequently identified, but they are mineralized only at the contact with granite, where relicts of uranium minerals are frequently observed. Uranium minerals, haiweeite, weeksite, and liebigite-type uranyl carbonate fill fractures and cavities in the upper cal-

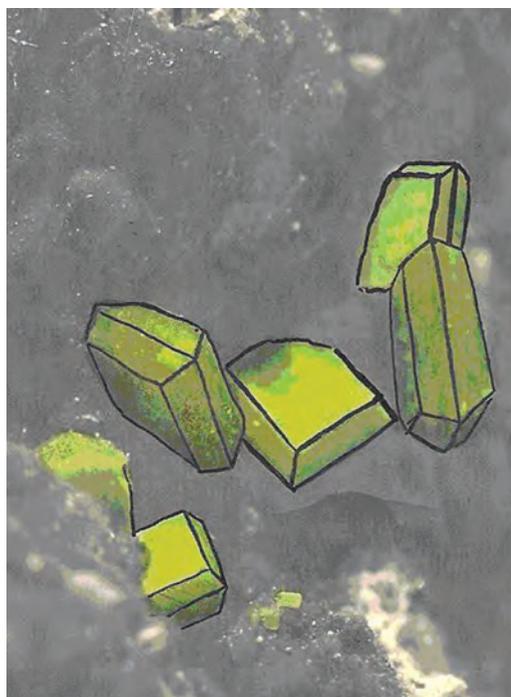


Fig. 5. Crystals of torbernite in leached cavity, Durulgui deposit, Central Transbaikalia. $\times 15$.

crete. However, their largest clusters are established in loam, where they occur as yellow band ranging from few cm to 10–15 cm thick following along rough of calcrete. Hence, uranium mineralization in the Quaternary loam was formed previously gypsinate rocks, but after carbonation. According to relationship of radioactive isotopes in the ore samples (Table 1), the rocks were carbonatized before 230 ky and gypsification, later 40 ky. These data are satisfactory consistent with previously results (Chernikov, 1981, 1982) concerning intensity of formation of uranium minerals during periods transited from warming to cold spell (Fig. 6).

Mineral assemblages and their zoned distribution determine the formation type of deposits and their economic importance. The deposits with uranyl minerals can be mined by underground leaching or heap leaching. In the case of such exploitation of orebodies, both rich and cut off (up to 0.01% U) ores are economic. Taking into account easy solubility of mineral, the rocks with 0.005% U and probably lower in the near-surface shrinkingite clusters of Kazakhstan, Mongolia,

Table 1. Age of uranium mineralization in calcrete and loam

Characteristic of sample	U^{234}/U^{238}	Io/U^{238}	Ra/U^{238}	Age, ky
Calcretes with the uranyl minerals	2.18	1.09	—	230
Lower loam enriched in the uranyl minerals	1.46	1.18	1.06	190
The same	1.68	1.25	1.18	185
Gypsinate loam with the uranyl minerals	1.45	1.27	—	180
Liebigite with gypsum	1.45	0.89	—	120
Weeksite and haiweeite with gypsum	1.46	0.39	—	40

and possibly the United States (Fronde, 1958; Sheridan *et al.*, 1961) and other arid areas are applied to exploit. The reserves of uranium in such deposits can be significantly increased to large and superlarge. For example, at the Nars deposit, Mongolia (Minerals of Mongolia, 2006), the shrokingerite clusters are followed by workings for 11 km along striking of ore-bearing beds. Broad areas of the shrokingerite mineralization were found in the other districts of Mongolia, Southern and Central Kazakhstan, and Kirgizstan.

Uranium minerals of fresh economic ore

In fresh economic ores, uranium minerals present lesser number of mineral species: oxides (uraninite, sooty pitchblende and nasturan), titanates (brannerite and its transitional varieties), silicates (coffinite and uranium silicates of variable composition), less frequent uranium (IV) phosphates and molybdates. In addition, at the Radium Hill deposit, where uranium ore is related to the high-temperature hydrothermal veins, ore minerals is davidite poor studied, in which Fe is partly substituted by REE and U. At the deposits of the Former Soviet Union, this mineral was not established. Many researches describe it as ilmenite with inclusions of uraninite.

Uranium-bearing minerals are apatite, titanium oxides and silicates, oxides and hydroxides of Nb, Zr, and Th, clay minerals, and zeolite. Mineral assemblages of uranium and uranium-bearing species and uranium-free minerals are widely variable (Laverov *et al.*, 1992); composition of uranium minerals and their properties are also significantly variable. The author described 11 ore types in Russia and neighbor countries (Chernikov *et al.*, 1997; Chernikov, 1996, 1998, 2006/2007). Among these types, there is no bornite and

chalcopyrite ore with nasturan (very rare barannerite), native gold, and silver minerals in hematite breccia, which are described from the Olympic Dam largest deposit, Southern Australia. Ores with uraninite (less frequent nasturan, brannerite, coffinite, and U-bearing carbonaceous matter) and native gold characteristic of the Witwatersrand Precambrian System, South Africa were also not found in Russia and neighbor countries. Brannerite ore type with native gold hosted in potassic feldspar alteration is original and infrequently described worldwide. All these ore types are characterized completely. Therefore, concrete change of ore composition allows estimating physicochemical parameters of ore deposition, formation type of mineral deposit and its age, and erosion level. For example, change of mineral composition and size of mineral segregations in the ore of the Strel'tsovsk deposit, southeastern Transbaikalia as groundwater penetrating downward (Chernikov *et al.*, 2008) is a feature of formation of minerals that is identified in wildlife. At the border between air and land, higher organisms having the greatest size habit together with protozoa, whereas at the depth of hundred meters to few km, there are only protozoa. At the upper level of the Strel'tsovsk structure, frequently well crystallized uranium minerals (Fig. 7) occur as large crystals. Downward, they decrease in size and from 1500 to 2600 m, they are poor crystallized or amorphous occurred as nanoscaled segregations of uranium silicates, U-Ti compounds, and less frequent uranium oxides. Usually, they are hydrated compositionally ranging from coffinite to brannerite or to uranium oxides and titanates of the anatase-, ilmenite- and titanomagnetite-type. PbO content in most these segregations is below 0.0n% indicating their young geological age and formation from meteoric water infiltrated from sur-

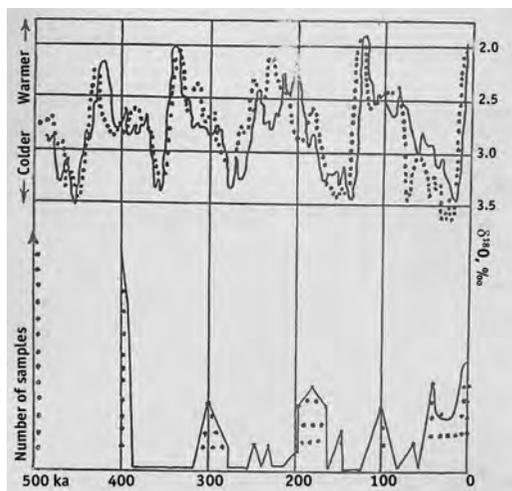


Fig. 6. Oxygen isotopic composition (upper curves) and intensity of mineral formation in oxidized uranium ore (lower curve) during 500 ky. Solid line was derived by Emiliani (1978); dot curve, by Kowi (1984), and lower curve, by Chernikov (1981, 1982).

Fig. 7. Crystals of coffinite (dark), Strel'tsovsk deposit, Southeastern Transbaikalia. $\times 2000$. Photo by V.T. Dubinchuk.



face to the deep level of the deposit. The conclusion of meteoric origin of mineralizing fluids is consistent with the previous results (Andreeva *et al.*, 1996, 1998; Chernikov *et al.*, 2008, 2009₂). Community of the formation of minerals and living being in vertical section at near-surface level of the Earth is basic feature.

Conclusions

The significant effect of near-surface and deep-seated supergene processes upon mineralization at the Strel'tsovsk deposit and some other districts appreciably changes prospecting and exploration guides, which were previously reported by Chernikov *et al.* (2009₁) for the main types of uranium deposits. Several districts fully corresponded to these criteria may be proposed. (1) North of the Strel'tsovsk structure: (a) sediments of the Eastern Urulyungui depression; (b) along the Urulyungui faults and in the basement structures; (c) in the rocks of basement of the northern side of the Eastern Urulyungui depression, first of all, along NNE-trending faults from Kislyi spring with U grade in water

of $1 - 2 \cdot 10^{-4}$ g/l and North of known Yamkun radon spring. Further north, in the Eastern Transbaikalia, the Olovskii deposit with stratiform and polygenic ore is poor-explored. In the first place, ores in the granite of basement should be estimated both along veins and zones, and to the depth. (2) Akitkan district, North Baikal Region (Golubev *et al.*, 2008; Tolkachev, 2008; Bavlov and Mashkovtsev, 2009; Shashorin, 2009) and Chara-Olyokma block completely correspond to these conditions. (3) West Siberian Plate, where combination of deep transformation of clay rocks enriched in uranium and discharge of ore-forming gley stratal water of oil-and-gas basins allow probable large uranium-multi-metall deposit in the Chulim-Enisei depression, infiltration deposit related to Altai-Sayan and Enisei Ridge, and different type deposits within the West Siberian Plate (Vorob'ev *et al.*, 2008; Domarenko *et al.*, 2008). At the southwestern margin of the West Siberian Plate (frequently reported as Ural region) infiltration uranium deposits, whose ore is located in sediments of paleovalleys cut rocks of basement are known (Kontrat'eva and Nesterova, 1997; Khalezov,

2000). Northeastern margin of the plate and regions related to the Altai-Sayan and Enisei Ridges are promised for this ore type. Finding of sufficiently long stratal oxidation zones or paleovalleys cut rocks of basement is important for these regions.

In addition to the complex U-V ore (Chernikov, 1997, 2001; Chernikov *et al.*, 2000, 2005, 2007, 2009), rare metal ore, especially carbonatite deposits taking into account complex nature of their ores (economic grade of U, Nb, P, and Zr) should be industrially used. Uranium as by-product produces from the Palabora apatite-bearing carbonatite, South Africa (The geology..., 1976; Laverov *et al.*, 1983) along with gold, silver, and PGE. Large copper deposit containing 0.001–0.001% U was found in this carbonatite. Copper ore occurred as stock-shaped body of 1.4×0.8 km in area in the centre of carbonatite pluton is followed downward more than 1000 m. Chalcopyrite, bornite, cubanite, chalcocite, pyrrhotite, pentlandite, millerite, bravoite, linneite, apatite, magnetite, titanomagnetite, U-bearing thorite, baddeleyite and vermiculite were identified in this ore. Uranium-richer carbonatite ore was explored at the Newman deposit, Manitou Islands, Nipissing Lake, Ontario Province, Canada.

Betafite (uranpyrochlore), uranium tantaloniobate of the pyrochlore-microlite group, is the major mineral of this ore. Its composition $(Ca, Na, U)_2(Ti, Nb, Ta)_2O_6(O, OH, F)$ differs from pyrochlore and microlite in higher U (up to 30% U_3O_8 with Nb_2O_5 ranging from 25 to 45%) and approximately identical content of Ta_2O_5 . In addition, few percents of Th and from 0.0n to few percents of REE also introduce in this mineral. Such complex ore frequently contains P, economic U, Ta, or Nb. For example, 5431 t of such ore with ~0.53% Nb_2O_5 and ~0.039% U_3O_8 were identified at the Newman deposit before 1955 (Rowe, 1954; Gill and Owens, 1956; Heinrich, 1958). Further exploration of uraniferous complex carbonatite deposits for uranium ore was terminated because of discovery in this region rich uranium deposits. Nevertheless, as a result of exploration only for complex Ta-Nb ore, about 50 uraniferous carbonatite deposits with one third in Russia were identified. Some complex carbonatite deposits contain 0.05%, occasionally up to 0.12% U_3O_8 . Howe-

ver, more frequently, uranium grade ranges from 0.01 to 0.03% and reserves of uranium reaches are medium to large with significant concentration of the other elements. For example, in certain zones of the Belaya Zima and Srednya Zima deposits, the demonstrated and inferred reserves of betafite ore are 10 kt of Ta_2O_5 and U_3O_8 with approximately identical grade in the ore, 0.012–0.028%. In the weathering profile of the Belaya Zima deposits, the demonstrated and inferred reserves are 1 mt Nb_2O_5 with grade of 0.5%, about 40 kt Ta_2O_5 and approximately identical U_3O_8 (with 0.014% of these oxides in ores); 3 mt REE with 1.8% REE_2O_3 , and 15 mt P_2O_5 with grade of 13.6% in ores (Belov *et al.*, 2008). There are other examples illustrating the presence of complex betafite ore with grade of 0.01–0.05% U_3O_8 forming great uranium reserves. Therefore, the exploitation of large carbonatite deposits in Russia is very promised taking into account imported niobium and tantalum and deficiency of phosphorus and uranium in our country.

In the nearest future, complex sulfide U-P deposits with rare metals from deposits in Kalmykia (Stolyarov and Ivleva, 2008; Sharikov, 2008) and similar ore objects in other regions will be exploited.

Thus, the great diversity of uranium and U-bearing mineral species and their assemblages allows determination of: (1) physicochemical parameters of formation of mineral segregations based on certain changes; (2) age of mineral species; (3) formation type of uranium ore; (4) intensity of supergene leaching or enrichment in uranium of certain levels of endogenic occurrences and deposits. In this case, increasing deficiency of energy resources (Laverov, 2009) can be compensated in the nearest future by exploitation of rich ores including newly discovered ores and poor complex and uranyl-bearing ores. Reserves of such ores can be large and superlarge with decreasing cut-off grade of uranium to 0.005% and lower. We have no alternative so far.

References

- Andreeva O.V., Aleshin A.P., Golovin V.A.
Vertical zonality of wall rock alteration at the Antei-Strel'tsovsk uranium deposits,

- Eastern Transbaikalian Region // Geol. Ore. Dep. **1996**. V. 38. N. 5. P. 353–366. (in Russian).
- Andreeva O.V., Golovin V.A.* Metasomatic processes at uranium deposits of Tulukuev caldera, Eastern Transbaikalia, Russia // Geol. Ore Dep. **1998**. V. 40. N. 3. P. 148–196. (in Russian).
- Arbuzov S.I., Mashenkin V.S., Rikhvanov L.P.* Resources of the oxidizing zones of coal deposits in Central Asia and perspective of their development // II Internal. Symp. "Uranium: resources and production", **2008**. VIMS, Moscow. Abst. P. 16. (in Russian).
- Bavlov B.N., Mashkovtsev G.A.* Uranium raw base in Russia: state and development. Proc // II Internal. Symp. "Uranium: resources and production". **2009**. VIMS, Moscow. P. 11–23. (in Russian).
- Belov S.V., Frolov A.A., Chistov L.B.* Economic perspective of uraniumiferous carbonatite deposits // II Internal. Symp. "Uranium: resources and demand". **2008**. VIMS, Moscow. Abst. P. 20. (in Russian).
- Branche G., Chervet J., Guillemmin C.* Nouvelles espèces uraniumifères françaises // Bull. Soc. Franc. minér. et crist. **1951**. N. 74. P. 457–487.
- Chernikov A.A.* Behavior of uranium in supergene zone. **1981**₁. Nedra, Moscow. (in Russian).
- Chernikov A.A.* Typomorphic features of uranium and their practical significance. **1981**₁. Sov. Geology. No 4. P. 85–98. (in Russian).
- Chernikov A.A.* Typomorphism of uranium minerals and its practical significance // Intern. Geolog. Review. **1982**. Vol. 24. N. 5. P. 567–576.
- Chernikov A.A.* The history of the study of uranium minerals by Russian mineralogists // Symposium on the History of Mineralogy, Petrology and Geochemistry. Abstracts. Munich (Germany). **1996**. P. 25.
- Chernikov A.A.* The relationship of the processes in weathering profile and endogenic factors in the formation of the Onega-type complex (V, Pd, Pt, Au, U) deposits. In: Major geological and economic types of deposits of weathering profile and placers, processing, estimation, and exploration. **1997**. IGEM, Moscow. P. 117. (in Russian).
- Chernikov A.A.* Mineralogical types of uranium ores of Russia and contiguous to countries, mineralogical types of large and superlarge deposits // 17th General meeting. International Mineralogical Association. Toronto. **1998**. P. A142.
- Chernikov A.A.* Deep-seated supergene processes, mineral and ore formation. **2001**. Fersman Mineralogical Museum RAS, Moscow. (in Russian).
- Chernikov A.A.* Mineralogical features of uranium ores, large and superlarge deposits of Russia and adjacent countries // Global Tectonics and Metallogeny. Vol. 9. Nos. 1–4, **2006/2007**. P. 21–30.
- Chernikov A.A., Dorfman M.D.* Mineralogy of rare metal-uranium, beryllium with emerald, and other deposits in near-contact igneous rocks and outer contact zone of the Kuu granite pluton, Central Kazakhstan. New data on minerals. **2004**. V. 39. P. 65–71.
- Chernikov A.A., Dubinchuk V.T., Chistyakova N.I., Nechelyustov G.N.* Structure, mineralogy, and geochemistry of deposits in southeastern Transbaikalian region for prediction of uranium ores // Proc. II Internal. Symp. "Uranium: resources and demand". **2009**₂. VIMS, Moscow. Abst. P. 275–285. (in Russian).
- Chernikov A.A., Dubinchuk V.T., Chistyakova N.I. et al.* New data of V-bearing hematite, micro- and nonocrystals of associated minerals of noble metals, copper, zinc, and iron. New data on minerals. **2005**. V. 40. P. 65–71.
- Chernikov A.A., Dubinchuk V.T., Ozhogin D.O., Chistyakova N.I.* Mineralogical features of some multimetal deposits of Russia, Central Asia, and Kazakhstan and importance of mineral-sorbents to concentrate metals in supergene zone. New data on minerals. **2009**₁. V. 44. P. 45–54.
- Chernikov A.A., Dubinchuk V.T., Tolkachev A.E. et al.* Mineralogical and geochemical features of deposits in southeastern Transbaikalia for local prediction of uranium ores. New data on minerals. **2008**. V. 43. P. 45–52.
- Chernikov A.A.* Scientific and practical importance of mineralogical features of uranium

- ores // V Internal. Symp. "Mineral diversity: preservation and researches". **2009**. Bulgaria, Sophia, P. 15. (in Russian).
- Chernikov A.A., Khitrov V.G., Belousov G.E.* Importance of carbonaceous matter to form large poxygenic complex deposits of the Onega type. In: Carbon-bearing assemblages in geological history. **2000**. KSC RAS, P. 194–199. (in Russian).
- Chernikov A.A., Pekov I.V., Minina E.L.* The history of investigation of the uranium minerals in Russia and USSR. Zap. RMO. **1997**. V. 126. N. 4. P. 111–128. (in Russian).
- Chernikov A.A., Sidorenko G.A., Knyazeva D.N.* New data of tetravalent uranium in dark green autunite. In: Chemical analysis of minerals and their chemical composition. **1964**. Nauka, Moscow. P. 94–104. (in Russian).
- Chernikov A.A., Zenchenko V.P., Shvrtorov I.V.* Assemblages of the uranyl minerals and zeolites in the novel type of uranium deposits. In: Mineralogy of ore deposits. **1983**. Nauka, Moscow. P. 5–13. (in Russian).
- Domarenko V.A., Vorob'ev E.A., Mazurov A.K., Novgorodtsev A.A., Rikhvanov L.P.* Criteria for uranium potential of the Western Siberian Plate // II Internal. Symp. "Uranium: resources and production", **2008**. VIMS, Moscow. Abst. P. 40–42. (in Russian).
- Emiliani C.* The cause of the ice ages // Earth and Planet, Sci. let. **1978**. V. 73. N. 73. P. 349–354.
- Vseeva L.S., Perel'man A.I.* Geochemistry of uranium in oxidizing zone. **1962**. Gosatomizdat, Moscow.
- FrondeI Cl.* Systematic mineralogy of uranium and thorium. Washington, U. S. Govt. Print. Off. **1958**. 400 p.
- Gill J.E., Owens O.E.* Niobium-uranium deposits near North Bey, Ontario // 20th Congr. Geol. Intern. Resumenes. **1956**. P. 90.
- Golubev V.N., Makar'ev L.B., Bylinskaya L.V.* Deposition and remobilization of uranium in the North Baikal region: Evidence from U-Pb isotopic systems of uranium ores. Geol. Ore Dep. **2008**. V. 50. N. 6. P. 482–490.
- Gritsaenko G.S., Belova L.N., Getseva R.V., Savel'eva K.T.* Mineralogical types of oxidizing zone of hydrothermal uranium and sulfide-uranium deposits of the USSR. In: Nuclear fuel and radioactive metals. **1959**. Atomizdat, Moscow. P. 69–84. (in Russian).
- Heinrich E.W.* Mineralogy and geology of radioactive raw materials. **1958**. McGraw Hill, New York.
- Khalezov A.B.* Uranium deposits in paleovalleys of the Urals. **2000**. VIMS, Moscow. (in Russian).
- Kondrat'eva I.A., Nesterova M.N.* The litho-geochemical features of uranium deposits in Mesozoic river paleovalleys. Lithol. Mineral. Resources. **1997**. V. 32. N. 6. P. 505–520.
- Kowi K.* Orbital of the Earth and glacial epochs. World of Science (Scientific American Mag). **1984**. N. 5. P. 303–316. (in Russian).
- Konstantinov M.M., Kulikova E.Ya.* Uranium provinces. **1960**. Atomizdat, Moscow. (in Russian).
- Kulish E.A., Mikhailov V.A.* Uranium ores in the World. Geology, resources, and economy. **2004**. Ukrainian NAS, Kiev. (in Russian).
- Large and superlarge deposits of rare and precious metals. St. Petersburg Mining Institute, St. Petersburg. **1984**. 324 p. (in Russian).
- Laverov N.P., Smilkstyn A.O., Shumilin M.V.* Foreign uranium deposits. **1983**. Nedra, Moscow. (in Russian).
- Laverov N.P., Velichkin V.I., Shumilin M.V.* Uranium deposits of CIS: Major genetic types and their deistribution. Geol. Ore. Dep. **1992**. V. 34. N. 2. P. 3–18. (in Russian).
- Laverov N.P.* Fuel and energy resources: state and rational utilization // Proc. II Internal. Symp. "Uranium: resources and demand", **2009**. VIMS, Moscow. P. 6–20. (in Russian).
- Minerals of Mongolia. **2006**. Fersman Mineralogical Museum, RAS, Moscow. (in Russian).
- Mineralogy of ore deposits. **1983**. Nauka, Moscow. (in Russian).
- Premoli C.* Formation of and prospecting for uraniferous calcretes // Australian mining. **1976**. Vol. 68. N. 4. P. 13–16.
- Rowe R.B.* Notes on geology and mineralogy of the Newman colubium-uranium depo-

- sit, Lake Nipissing, Ontario // Can. Geol. Survey. Paper 54. **1954**. P. 5.
- Sharkov A.A.* Uranium-rare metal deposits of Mangyshlak and Kalmykia: Genesis. **2008**. Eslan, Moscow. (in Russian).
- Shashorin B.N.* Tectonic evolution and uranium potential of the Akitkan volcanic belt // Proc. II Internal. Symp. "Uranium: resources and demand". **2009**. VIMS, Moscow. P. 286 – 295. (in Russian).
- Sheridan D.M., Maxwell C.H., Collier I.T.* Geology of the Lost Creek Schroekingite Deposits Sweetwater County, Wyoming // Geol. Surv. Bull. 1087-J. U.S. **1961**. P. 391 – 478.
- Sofoulis J.* The occurrence and hydrological significance of calcrete deposits in Western Ausstralia // Geol. Surv. Western Australia. Ann. Rept. **1962**. P. 38 – 42.
- Stolyarov A.S., Ivleva E.I.* Ergenino uranium-rare metal district of Kalmykia. Mineral raw. N. 19. **2008**. VIMS, Moscow.
- Supergene uranium deposits (Perel'man A.I., ed.) **1965**. Atomizdat, Moscow. (in Russian).
- The Geology and the Economic Deposits of Cooper, Iron and Vermiculite in the Palabora Igneous Complex. Geol. and Mineralog. Staff // Econ. Geol. **1976**. V. 71. N. 1. P. 177 – 192.
- The formation of uranium deposits. **1976**. Mir, Moscow.
- Tolkachev A.E.* Probable directions of prospecting for uranium in the Akitkan district // II Internal. Symp. "Uranium: resources and production". **2008**. VIMS, Moscow. Abst. P. 117. (in Russian).
- Typomorphic features of minerals. **1989**. Nedra, Moscow (in Russian).
- Vorob'ev E.A., Novgorodtsev A.A., Domarenko V.A.* Probable uranium-multielement mineralization in the West Siberian oil-and-gas basin // II Internal. Symp. "Uranium: resources and production". **2008**. VIMS, Moscow. Abst. P. 30. (in Russian).