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Special Conditions for the Formation of Large Exogenic Epigenetic Uranium Deposits

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Abstract—For uranium deposits to form from oxidizing waters of surface origin, it is necessary to combine several conditions and processes of different ranks that make up a specific mineral system. Analysis of exogenic deposits of different scales and ore quality from different regions of the world showed that, among all the critical processes necessary for the formation of large deposits and vast provinces, global tectonic movements play a particular role. A geodynamic regime with moderate vertical differentiation of crustal blocks is most favorable for development of a hydrodynamic infiltration ore-forming system under near-surface conditions. An infiltration artesian system is capable of functioning for millions and tens of millions of years, which makes it possible to accumulate large uranium reserves at the geochemical reduction barrier. The required regime is typical of regions with a certain geotectonic position. For example, the peripheral regions of orogenic belts along tectonic plate boundaries, as well as the frames of some long-lived intraplate deep faults. In the same regions, the proximity of infiltration and expulsion hydrodynamic systems is possible. In local areas where groundwater of various origin and composition interact, conditions occur for particularly efficient uranium concentration in ores. Limitations on the productivity of a hydrodynamic infiltration ore-forming system are imposed by historical factors that predetermine the formation of the uranium source and lithological conditions for ore localization, as well as the climatic conditions of the time in which the system functioned and postore conditions determining the preservation of mineralization accumulated in the system. The revealed patterns be used to predict ancient provinces of exogenic uranium deposits.

Keywords: uranium deposits, exogenic epigenetic class, genetic model, predictive criteria

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INTRODUCTION

Uranium deposits formed from meteoric waters in exogenic conditions are attributed to several geological and economic types according to the IAEA classification (*Geological ...*, 2018). Of these, the most important is “in sandstones” (type 9). The particular economic value of deposits of this type is that they are developed in an environmentally friendly and economical way with in situ borehole leaching, which in 2019 yielded about 57% of total global uranium production (*Uranium ...*, 2020).

Development of the theory of exogenic epigenetic uranium ore formation, completed mainly in the 1970s, made it possible to quickly discover numerous deposits of this and associated economic types around the world owing to an efficient search feature: the oxidation zone boundary, which controls ore accumulations. Most deposits of this genesis are modern (alpine), and the factors of their ore formation are accessible to analysis. This unique nature of the deposits, many of which continue to form right now, has made it possible to directly study the conditions

and process of their formation. The relationship of uranium concentrations with the oxidation zone boundary was discovered in the mid-1950s, and basic scientific publications had already appeared in the mid-1960s (Batulin et al., 1965; Finch, 1967). In these works, many of the ore localization features in the deposits under consideration were formulated, the regional prerequisites for their formation were established, and the most important search criteria and features were determined.

As of September 2019 (*World ...*, 2020), 1430 uranium deposits of this type were known (almost 40% of the total), with total reserves of ~5 mln t (about 8% of the world’s total uranium resources). Unfortunately, this practical success of the theory drastically reduced the likelihood of finding large new Alpine deposits. Almost all sedimentary basins have been well studied due to an effective exploratory feature. Prospects for the discovery of economic objects of interest are associated with ancient geological eras and unconventional conditions for an exogenic ore-forming hydrodynamic system.

An important theoretical stage in the practical activity of replenishing the mineral resource base is to identify the factors controlling the formation of deposits. This is also true for uranium, a raw material for nuclear energy. In the Russian tradition, the forecasting of new objects is based on genetic concepts; in the foreign tradition, the localization conditions of a standard. With respect to the considered uranium deposits in the Soviet Union, the term “exogenic epigenetic” was widely used (Batulin et al., 1965); in the USA, sandstone type (see, e.g., Hostetler and Garrels, 1962).

The systematization of uranium deposits, generally oriented towards the search for new objects, developed mainly in two directions: empirical and theoretical. The empirical approach, which was based on the features of the host rocks or the structure of orebodies, was most distinctly implemented by F. Dahlkamp (Dahlkamp, 1978) and subsequently became the basis for the classification adopted and developed by the IAEA (*Geological ...*, 2018). This approach, convenient for classifying data on uranium resources, makes it difficult to assess prospects for new regions and is completely useless in searching for as yet unknown types of uranium concentrations. The genetic approach, traditionally developed by the Russian geological school (Kazansky and Laverov, 1977; Konstantinov et al., 2010), also has limitations, for various reasons. Deposits, especially small ones, are mined out faster than they are studied; they are hampered by restrictions on access set by owners or the state; and lastly, many deposits are so complex that they end up among objects with a controversial genesis (and, therefore, in an uncertain forecast field) even after decades of scientific study. The most advanced global genetic classification of uranium deposits that form at different stages of the geological cycle is presented in (Cuney, 2009).

In all the above classifications, such a natural feature of ore-forming processes as their evolution, caused by a slow change in global conditions in the crust and atmosphere, which are mainly governed by endogenic and exogenic processes, favorable (or not) favorable (or not) for the emergence of ore-forming systems, practically falls out of consideration. A.I. Tugarinov in the 60s last century (Tugarinov, 1967). The first attempt to analyze uranium ore formation against an evolutionary background is presented in the work of V.I. Kazansky, N.P. Laverov and A.I. Tugarinova (1978).

M.V. Shumilin (2011, 2015) combined global and evolutionary analysis of the cycles of uranium ore formation. In simplified form, it looks as follows. New uranium deposits invariably occur in the same large blocks of crust, despite the fact that the global position of these blocks changes periodically in the evolution of supercontinental cycles. Uranium can be cycled within the same blocks of crust because in orogenic zones, uranium is dispersed from ancient formations, concentrating in young sediments in various exogenic

deposits. The entry of uranium into the depths of the Earth is associated with the subsidence of uranium-bearing sediments in subduction zones. There, they are remelted and uranium is again transported upward with magma products. As a result, in the evolution of all uranium-bearing provinces, there are alternating periods of predominantly exogenic and predominantly endogenic ore formation.

Another theoretical approach to classification of uranium deposits is formulated via systemic analysis, developed mainly by Australian geologists. Systemic analysis takes into account the structural organization of ore-forming processes in aggregate. This approach is called the “mineral systems concept” (Wyborn et al. 1994; *Descriptive ...*, 2020). The mineral systems concept analyzes all ranks of geological factors and processes playing a critical role in the mobilization of ore components from their source, transport, and accumulation in a more concentrated form, as well as preservation of ores in the subsequent geological history. From the standpoint of systemic analysis, each process is part of a more general process and, at the same time, consists of several individual processes. From the forecasting viewpoint, an ore-forming mineral system is a special case of geological processes involving the dispersion and concentration of matter. For this reason, the object for forecasting and exploration (region, district) is more extensive than a specific deposit and ore vein in it. A practical attempt to implement this approach in order to forecast new economic types of deposits for Australia, including sandstone deposits, was undertaken in (Skirrow et al., 2009).

In this article, the mineral systems concept is applied to critical processes necessary for forecasting large exogenic epigenetic uranium deposits. This is facilitated not only by modern theoretical developments, but also by the wide range of uranium deposits known to date, differing in uranium reserves and concentrations in ores, the conditions and age of formation, and degree of preservation.

EXOGENIC ORE-FORMING HYDRODYNAMIC SYSTEM: METHODOLOGICAL BASIS FOR FORECASTING

The genetic concept of an exogenic epigenetic uranium system is based on the specific geochemical properties of uranium, which govern its behavior under hypergene conditions. In oxidizing groundwater, uranium in the hexavalent state migrates perfectly in uranyl complexes, but as soon as the conditions in groundwater become reductive, the complexes are broken down; uranium passes into the tetravalent state and precipitates as uranium minerals. Direct measurements of the difference in uranium content between oxidizing and reducing waters prove the ore-forming role of meteoric groundwater. The geochemical theory of the formation of uranium concentrations at the

reduction barrier was substantiated in the classical work (Lisitsyn, 1975).

Crystalline basement rocks, usually granitoids, uranium-rich detrital rocks, and decaying ancient uranium deposits can serve as a source of ore mineralization. The mineral composition of ores is represented by pitchblende with a certain amount of coffinite and, more rarely, ningyoite. In addition to uranium in the presence of a source, its geochemical analogs, selenium, molybdenum, and rhenium, which are also capable of changing the valence state at the reduction barrier, can be present as accessory elements. The presence of other elements in epigenetic uranium ores, usually in trace amounts, is explained by a concentration mechanism other than reduction. Vanadium-uranium deposits are known in the United States (IAEA type 9.2.3). Vanadium is present there in oxidized rocks, where it is adsorbed on iron oxides or in the form of proper minerals - vanadates of 6-valent uranium (*Geological ...*, 2018).

Mineralizing fluids are an important component of any mineral system. In an exogenic infiltration system, this is oxygenated neutral, up to weakly alkaline, groundwater of atmospheric origin. It easily dissolves uranium (and its accessory minerals) and transports it to concentration sites. The penetration of oxygenated waters into near-surface aquifers is hindered by abundant tropical vegetation or frozen ground. Therefore, climate is an important factor in the considered exogenic ore-forming system.

Reducing conditions in an infiltration flow arise due to the presence of biogenic and abiogenic organic and mineral matter in rock, which is oxidized by oxygen dissolved in water, usually with the participation of microorganisms. In ore-hosting rocks, the change from oxidizing to reducing conditions is expressed by a change from yellow to gray color. Beyond this boundary, uranium mineralization accumulates in gleyed rocks.

Oxidative Epigenetic Deposits

Above a model was presented of classical exogenic uranium deposits with oxidative epigenetic zoning. The conditions for the migration of groundwater that is an ore-forming agent are divided into two classes depending on their hydrodynamic characteristics (Shmariovich and Lisitsyn, 1982):

(a) deposits of groundwater oxidation are formed by freely flowing oxygenated groundwater or moving under local pressure among local impermeable layers in near-surface conditions;

(b) stratal-oxidation deposits are formed by oxygenated groundwater moving in relatively submerged stratal pressure systems (artesian basins).

Groundwater oxidation deposits are the most common in nature. This class includes deposits localized in both Quaternary and ancient sediments. According

to the IAEA classification (*Geological ...*, 2018), they are attributed to type 11 "Surface" with two subtypes "In peat bogs" and "In river valleys," as well as to subtype 9.1 "In basal channels." As a rule, all of them are represented by small objects (a few 1000 t of U or less). The dimensions of bodies in the form of ribbons or lenses are small (up to the several kilometers with a thickness of meters), and the uranium concentrations are low (0.0n% U). Therefore, they are rarely practically significant. An example of this type of deposits is the Sanarka deposit in alluvium of the Sanarka River on the East European Platform in the Urals, Russia (Khalezov, 2017). Uranium deposits and ore occurrences controlled by modern groundwater oxidation zones are found both in orogenic zones and on platforms, without distinct selectivity of tectonic position. They are found in many landscape belts, ranging from desert to moderately warm taiga, i.e., wherever near-surface groundwater contains oxygen and has oxidizing properties, which allows it to transport uranium to an ore formation site at the geochemical reduction barrier. The climatic conditions of their formation are even more critical than tectonic ones. These modern uranium concentrations can be called ephemeral, because if they are not blocked from erosion, they will be broken down by hypergene processes.

Forecasting the location of erosional valleys in continental complexes of the sedimentary cover makes it possible to discover hidden deposits in paleovalleys buried under thick sequences of younger sediments. An example of the "paleovalley" type (IAEA 9.1) is the Mesozoic Dolmatov deposit in the Trans-Urals, Russia, (Khalezov, 2017) with reserves of less than 10000 t. Due to the ancient age of the ore-forming process, the ore-controlling oxidative zoning here was completely destroyed by overprinted secondary reduction processes, and the ore mineralization was preserved only because the paleochannels were protected by overlying sediments with a thickness of about 400 m.

The main factor constraining the formation of large-scale and rich ore accumulations of this type is the brief duration of the ore-forming groundwater-oxidizing process. The local nature of aquifers determines the instability of the hydrodynamic regime.

Stratal oxidation deposits (mainly "tabular" and "roll" subtypes, 9.2 and 9.3, according to the IAEA) are of major economic importance due to the large scale of the orebodies. The uranium concentration in ores is mature and relatively poor (usually 0,n% U). Orebodies occur in gleyed rocks of aquifers in artesian basins. A distinctive feature of the deposits is a pronounced ore-controlling boundary between mineralized gleyed and oxidized sands. This type includes the largest uranium deposits of this type in the world. An example is the Mynkuduk deposit (~200000 t) in the Chu-Sarysu basin, Kazakhstan (Fig. 1). In plan view, individual orebodies are separated by barren sections of pinch-out lines of stratal oxidation zones. As a

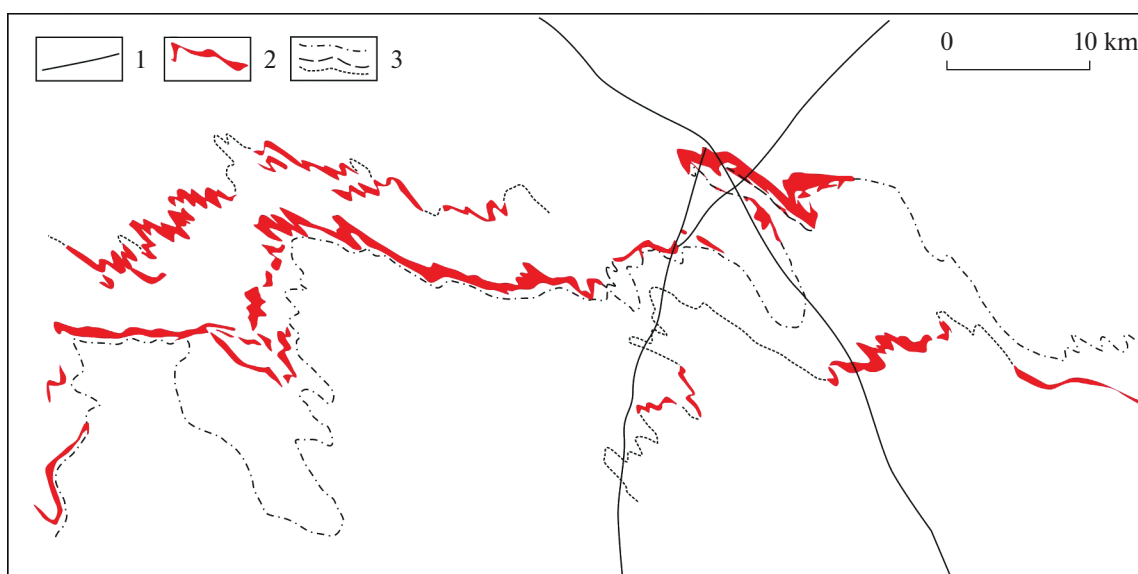


Fig. 1. Mynkuduk deposit. Localization map of ore deposits (*Geologo-promyshlennye ...*, 2008, simplified). (1) Faults; (2) orebodies; (3) boundaries of oxidation zones in different horizons.

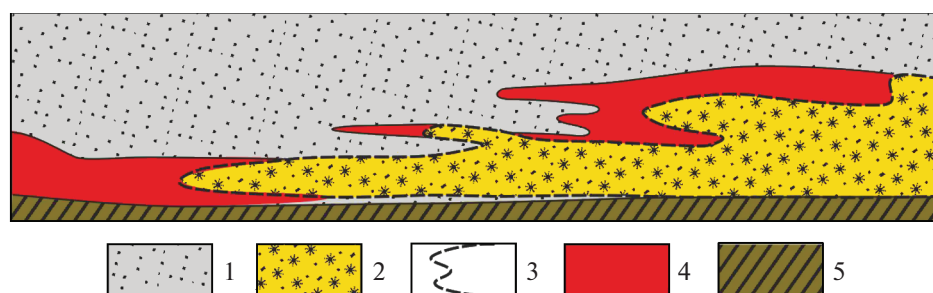


Fig. 2. Characteristic shape of ore deposits of Mynkuduk deposit: double roll (*Geological-economic ...*, 2008, simplified, diagram not to scale). (1) Primary gleyed gravel-sandy rocks and sands with silt lenses; (2) oxidized limonitized rocks; (3) pinch-out boundary of stratal oxidation zone; (4) orebodies; (5) Upper Paleozoic siltstones of lower aquiclude.

result, the deposit splits into a number of separate areas, which can be considered independent deposits (*Uranium ...*, 1995).

The scales of the Mynkuduk deposit are impressive. In plan view, uranium ore deposits fall into a sublatitudinal band about 80 km long and about 10–15 km wide, is controlled by thick “multilayer” stratal oxidation zones. In cross section, the orebodies are generally crescent-shaped (“roll”), complicated by lithological inhomogeneities of the host rocks (Fig. 2).

Stratal oxidation zones can form only in artesian basins with infiltration water drive. For stratal oxidation zones to develop, it is preferable to have an arid climate corresponding to belts of deserts and arid and chernozem steppes. The stratal-oxidative process is typical mainly of the inner basins of postplatform tectonic activation zones—“suborogenic” zones of the platforms, as well as for small artesian basins of a high-amplitude postplatform orogen and near-marginal parts of intermontane depressions within hypsometri-

cally highly elevated arched structures. The scale of uranium accumulations at the boundaries of stratal oxidation zones directly depends on several factors: the uranium content in oxygenated waters of the infiltration zone (usually 10^{-5} – 10^{-3} g/L), the speed of water movement, the duration of the process, and the uranium concentration reducing agents in the aquifer. The uranium concentration on the pinch-out of oxidation zones results from a reducing medium that forms due to the metabolism of bacteria feeding on carbonaceous plant residues. The presence of dispersed reducing agents in rock can only yield low uranium concentrations in ore due to the constant spatial displacement of the geochemical barrier as the front of the oxidation zone advances. The uneven distribution of carbonaceous residues determines the uneven distribution and concentration of uranium along the pinch-out of the oxidation zone (Lisitsyn, 1975).

The extent of oxidation zones depends on the size of the artesian basin and can reach hundreds of kilo-

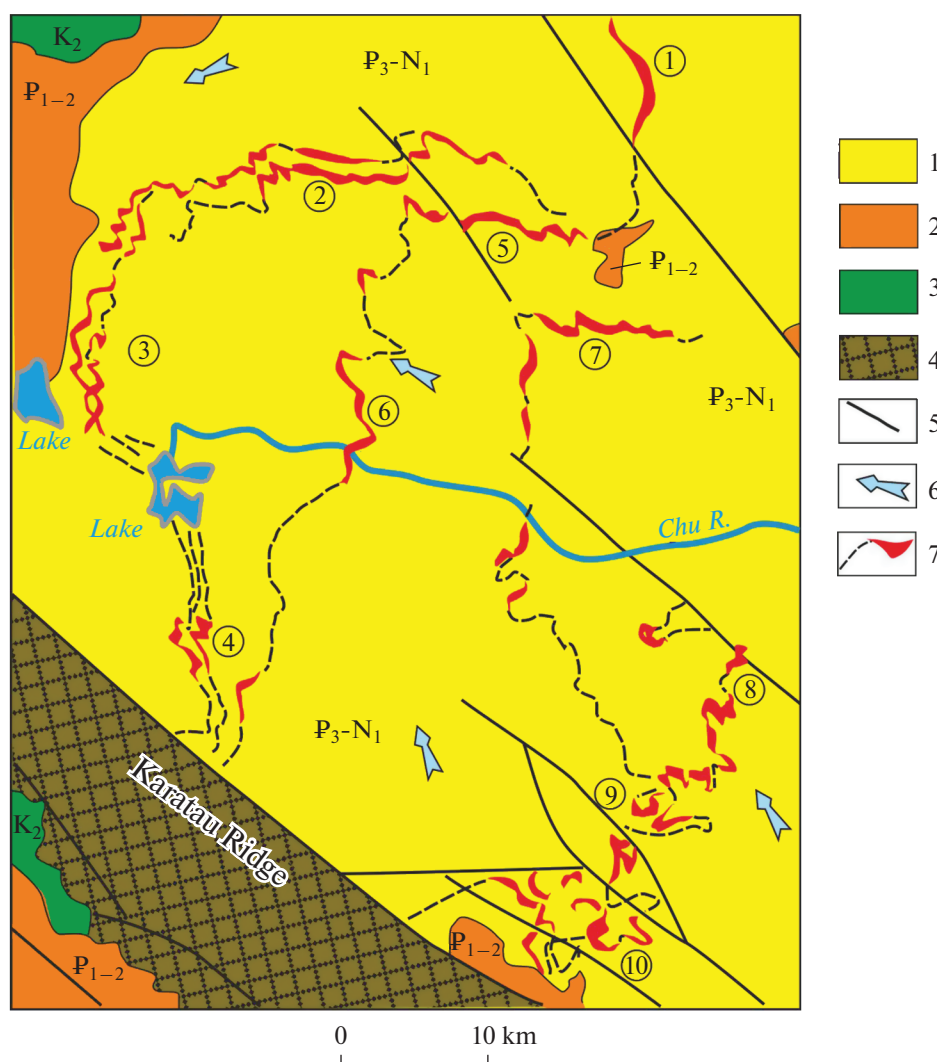


Fig. 3. Deposits of Chu-Sarysu basin (*Geologo-promyshlennyye ...*, 2008, with simplifications). (1–4) Age of rocks outcropping to surface: (1) Oligocene–Neogene; (2) Paleogene; (3) Cretaceous; (4) Paleozoic basement; (5) faults; (6) direction of filtration of pressurized groundwater; (7) orebodies at boundaries of the stratal oxidation zones.

meters. The best example is the Chu-Sarysu depression, which is located on the periphery of the Tien Shan orogenic zone. The total uranium reserves in it approach 1 mln t. The largest deposits of this type in the world were discovered here: the Mynkuduk, Inkai, and Budennov (nos. 2, 3, 4 in Fig. 3). The main deposits, Alpine in age, are localized in Cretaceous deposits; less significant deposits, in Paleogene sediments (Kislyakov and Shchetochkin, 2000).

It is believed that the infiltration of oxygenated waters in the Chu-Sarysu artesian basin began almost simultaneously with its formation as a result of Neogene–Quaternary tectonic activation about 20 Ma ago. Despite the very low uranium concentrations in oxygenated stratal waters ($n \times 10^{-5}$ g/L), during this time period, vast uranium resources accumulated in the deposits of this basin.

The uranium content in oxygenated waters of the infiltration zone is often associated with favorable sources of uranium and conditions for its additional enrichment of solutions. Such sources and conditions may be certain disintegrating deposits, rocks primarily enriched in uranium, and moderate water exchange in combination with evaporative concentration in an arid climate. The recharge area of the Chu-Sarysu basin is so vast that it is impossible to point to any specific sources of uranium. This, apparently, caused the overall low uranium content in stratal waters, which did not prevent the formation of one of the world's largest uranium provinces.

Reductive Epigenetic Deposits

Whereas in questions of the genesis (and, consequently, forecasting) of classical deposits, which are

localized at the pinch-out of oxidation zones, theoretical discussions all but ended in the 1980s, deposits with features indicating that they formed with the participation of endogenic matter became a subject of discussion and remain so to this day. This, in particular, concerns the questions posed in (Shmariovich and Lisitsyn, 1982) on the relation of exogenic and endogenic factors in the occurrence of certain uranium objects, interpretation of epigenetic alterations in rocks that developed within them, the zoning and stages of these alterations, and their control by disjunctive tectonics.

Reductive epigenetic deposits are formed with the participation of ascending reductive thermal solutions, which brings them closer to objects of the hydrothermal class. Based on the concepts presented in (Shmariovich and Lisitsyn, 1982), in deposits of reductive epigenesis, in addition to uranium minerals in tetravalent form and iron disulfides, which are paragenetically associated with them, there is a complex of rock alterations accompanied by additional input of elements in reduced forms: sulfide sulfur, ferrous iron, organic carbon, etc., including rock-forming elements.

Kochkin (2020) summarizes examples of “reducing neoformations” found in uranium deposits of the exogenic epigenetic class, mainly of the sandstone type (IAEA type 9). Not all of these neoformations, despite the apparent similarity in mineral expression, were involved in uranium ore formation. In some cases, the solutions responsible for this mineralization only ensured the preservation of ores at the postore stage. The Dolmatov deposit is such an example. In other cases, solutions ascending along faults, which impede stratal infiltration waters, was probably only responsible for the “immobility” of the reducing barrier and structural control of orebodies, since they themselves contained no reducing agents, such as carbonate waters at deposits in the Vitim ore district in Transbaikalia, Russia (Kochkin et al., 2014).

In basaltic and andesite–basaltic magmatic zones, ascending solutions usually have a carbonate composition and can be aggressive towards uranium mineralization. The spatial relations between uranium deposits and mafic volcanism on the Colorado Plateau (USA) was pointed out in (Kerr, 1958) long before the development of adequate ideas on the origin of sandstone deposits. Nevertheless, the partial destruction of previously formed deposits and even the formation of redeposited uranium mineralization in carbonates in an insignificant amount were established at the Semizbay deposit in northern Kazakhstan (Kondratyev et al., 1992) and in adsorbed form on iron hydroxides at deposits of the Vitim ore district (Amalat basalt plateau) (Kochkin et al., 2017). Vinokurov et al. (2017) suggest significant scales of uranium oxide redeposition by carbonate waters at the Vitim deposits are suggested based on indirect features.

Only ascending waters that transport uranium reducing agents to the ore-bearing horizon are important for ore deposition. These fluids primarily include groundwater of oil and gas basins, which flow in some way (usually along faults) into the ore-formation zone. An example is the Coastal Plain deposit in South Texas, USA. They are attributed to “roll” subtype in sandstones (9.3 according to the IAEA) and are Alpine in age. The host Neogene rocks may not contain carbonaceous fragments; therefore, hydrocarbons and hydrogen sulfide introduced into the ore-hosting horizons from underlying sedimentary aquifers with oil and gas specialization are also considered uranium reducing agents. The interaction of these waters with host rocks led to postore pyritization of local areas at the Felder and Lamprecht deposits and ores and secondary reduction of the stratal oxidation zone (Goldhaber et al., 1983). The relationship between sandstone deposits and petroleum basins in the United States is also indicated in (Jaireth et al., 2008). The IAEA classification identifies special classes of deposits (9.2.2, 9.3.2, etc.) with introduced (epigenetic in Russian terminology) uranium reducing agents (*Geological ...*, 2018).

Extensive centers of reducing neoformations were found in the Kyzylkum uranium province, Uzbekistan, where, due to their composition, they were called carbonate–bituminous (Shchetochkin, 1970). In addition to bitumen, they include pyrite, goethite, barite, carbonates, kaolin, quartz, and other minerals.

The oxidation zones within the Central Kyzylkum arch are widespread locally; they began to form later and are isolated from each other, in contrast to the regional oxidation zones of the Chu-Sarysu depression. They frame Paleozoic basement highs within the axial part of the arch. The width of the oxidation zones in plan view usually does not exceed a few tens of kilometers and is limited by the size of artesian basins. Deposits of this province have an Alpine age and are localized in Cretaceous and Paleogene sediments (*Uchkudukskii ...*, 1996; Kislyakov and Shchetochkin, 2000). The reserves of the largest deposits amount to 40000–50000 t of uranium (*Geological ...*, 2018).

The province, which has an arch–block structure on the whole, borders on the Bukhara–Khiva oil and gas basin (Fig. 4). This creates conditions for the interaction of two hydrodynamic systems: infiltration and expulsion. Whereas the infiltration water drive operates due to the difference in pressure between elevated recharge areas and lower relief areas at discharge centers, in the expulsion system, pressures in aquifers are created when sedimentation waters are squeezed out due to compaction of sediments within troughs in the crust. These pressure waters initially acquire upward movement. In areas of intense folding, heads may occur due to geodynamic stress, which, under the conditions of the Bukhara–Khiva region, may be of local importance near faults. Within the expulsion system,



Fig. 4. Kyzylkum uranium ore province (from *Geological-economic ...*, 2008, with simplifications). (1) Paleozoic basement highs from under sedimentary cover; (2) depth of basement roof (m); (3) faults; (4) deposits (numbers: (1) Uchkuduk; (2) Sugraly; (3) South Bukinay; (4) Sabyrsay); (5) ore occurrence.

various deposits are formed, including hydrocarbons, lead-zinc ores with subordinate amounts of fluorite, barite, calcite, and occurrences of celestine, sulfur, and bitumen (Pechenkin, 2014b). In the infiltration system, the most significant are uranium deposits, both groundwater and stratal oxidation zoning (Pechenkin, 2014a).

Groundwater coming from the expulsion hydrodynamic system of the Bukhara–Khiva basin is considered a supplier of epigenetic reducing agents to adjacent areas with an infiltration groundwater regime. In the south of the Kyzylkum province, near the junction of basins with different hydrodynamic groundwater regimes, uranium orebodies are sometimes combined

with bitumen halos, and stratal oxidation zones are rereduced (e.g., the Sabyrsay deposit). In the middle of the province (South Bukinay deposit), in the fault zones of the sedimentary cover, large halos of carbonate–bituminous neoformations are encountered. At a distance from the oil and gas basin and closer to the central axis of the Kyzylkum arch, carbonate–bituminous neoformations are less common, as well as near faults that cross both the basement and the sedimentary cover (Uchkuduk and Sugraly deposits).

On the whole, the group of deposits with reductive epigenesis differs by a number of features from classical oxidative zoning deposits. First, in plan view, uranium-bearing zones associated with reducing epigenesis often exhibit linear features and spatially coincide with discontinuities in the basement, representing stratal-superfractured, near-fractured, and sometimes simply fractured formations. Second, mineralization in these deposits is usually distinguished by higher uranium concentrations (up to n% U) and a higher contrast, and it sometimes has a more complex set of accessory elements than usual. Third, the deposits show signs of staged ore deposition or alternating oxidation and reduction stages. In some cases, the mineralization has a relict nature and signs of active destruction by infiltration oxygenated waters with redeposition of uranium as accumulations of regenerated uranium blacks. In other cases, the mineralization may be “buried” in a hydrogen sulfide or hydrocarbon gas-hydrogeochemical environment.

Because the considered mineral system is exogenic, the critical factor for its successful functioning is the composition of the atmosphere, climate, and life in all its manifestations. The oldest sandstone deposits were formed about 2 Ga ago. There was already oxygen in the Earth’s atmosphere at that time, but continental vegetation, the remains of which could have served as a reducing agent for uranium in terrigenous sediments, did not yet exist. It is believed that the formation of these ancient deposits occurred via precipitation of uranium with gaseous reducing agents of inorganic origin (methane, hydrogen), which came through faults from deep in the crust. More or less typical deposits with stratal oxidative zoning with carbonaceous organic matter as a reducing agent occur in terrigenous rocks younger than Ordovician (*Descriptive ...*, 2020).

TECTONODYNAMIC CONDITIONS OF EXOGENIC EPIGENETIC URANIUM ORE FORMATION

Features of Implementation of the Model in Different Conditions

Due to the above-mentioned features, some deposits with starkly pronounced reducing epigenesis have remained genetically controversial objects up to now. Today, the prevailing viewpoint is that uranium, as in the case of deposits with oxidative zoning, was

transported to its accumulation sites by exogenic infiltration oxygenated solutions, precipitating at the reduction barrier upon interaction with counterflows of ascending gaseous (H_2S , H_2 , etc.) or fluid (bitumens) reducing, often thermal fluids (Lisitsyn, 1975). According to the second viewpoint, the suppliers of uranium were deep thermal (150–200°C), relatively alkaline sulfide–carbonate solutions, which had fundamental features common with hydrothermal fluids that deposited pitchblende in veins (e.g., type 4 according to the IAEA). Ore was deposited as a result of acidification or additional reduction of these fluids and interaction with the host sedimentary rocks and infiltration waters and organic components therein (Oparysheva et al., 1973). Recently, the views on the endogenic source of uranium in deposits of Central Asia were supported in (Grushevoy and Pechenkin, 2003). The third viewpoint, which is stated in articles on deposits of the Vitim ore district, is that postvolcanic carbonate solutions redistribute and enrich initially poor oxidative zoning ores to high concentrations with the addition of some other elements (Vinokurov et al., 2017; Tarkhanova et al., 2014). The latter viewpoint, in our opinion, may explain particular problems in the genesis of specific deposits and is an example of the ad hoc hypotheses.

E.M. Shmariovich and A.K. Lisitsyn (1982) noted that ores of the genetic groups considered by them can not only occur separately, but also be spatially combined in one territory. When discussing regional regularities in the distribution of uranium deposits of reductive epigenesis, they noted, first of all, their relationship with territories that experienced postplatform tectonic activation, which is also typical of classical deposits of oxidative epigenesis. Further, they emphasized that the relationship of uranium deposits and ore-accompanying thermal reductive epigenesis with magmatism is not always expressed, but when it is present, basaltic or andesite–basaltic magmatism is more frequently manifested (the example of the Colorado Plateau in the United States was cited). In many regions, including in the absence of magmatism, there is a relationship between uranium deposits and oil and gas basins (e.g., the Fergana depression and Kyzyl Kum in Uzbekistan, South Texas in the USA, and others).

For deposits of oxidative epigenesis, reducing agents are usually syngenetic to the host rock — carbonaceous detritus in gleyed platform sediments. Examples are the deposits of the Chu–Sarysu uranium province in Kazakhstan and the deposits of Wyoming in the United States. Epigenetic reducing agents are less common, i.e., those introduced into the rock after its formation, but before the arrival of oxygen-rich uranium-bearing groundwater. This is approximately the view of uranium–humate deposits, e.g., Ambrosia Lake in the United States (IAEA class 9.2.2).

The appearance among classical deposits of oxidative zoning of objects with reductive epigenesis, in our opinion, is merely a regional or local feature of the ore-forming mineral system, which can be associated with the discharge of certain hypogene fluids into an artesian basin. Mineral formations of reductive epigenesis associated with two types of deep fluids are the most frequently distributed at exogenic uranium deposits (Kochkin, 2020). The first consists of formations associated with waters from petroleum-bearing basins. These fluids necessarily contain epigenetic uranium reducing agents: methane, bitumen, hydrogen sulfide, or hydrogen. They can take part in the formation of deposits spatially close to oil and gas basins laterally or with oil and gas horizons vertically. The most striking example is the deposits of the Kyzylkum province (Kislyakov and Shchetochkin, 2000). Another example is the Felder and Lamprecht deposits in Texas, USA (Goldhaber et al., 1983). The second type of hypogene fluid is postmagmatic thermal flows. By themselves, these thermal flows may not carry uranium reducing agents, but they can form a stationary (immobile) hydrodynamic barrier above faults, due to which very rich and contrasting ores are formed. At the postore stage, these thermal flows help to preserve the ore mineralization and alter the host rocks, including the oxidation zone. An example is carbonate waters in the deposits of Vitim ore district, Buryatia, Russia (Kochkin et al., 2017). More exotic compositions ascending fluids are known. For example, at the Sulucheka deposit (Iliy Valley, Kazakhstan), the ore-bearing horizon at the postore stage was flooded by deeply circulating nitrogen waters of atmospheric origin. In accordance with their fresh oxygen-free and hydrogen-free composition, there are practically no reducing neoformations in the rocks. Even the oxidation zone retained its yellow color (Kochkin et al., 1990).

Examples of overprinting, stages, and especially alternating reduction and oxidation processes known at the deposits in Kyzylkum (and in some other regions) indicate that multidirectional water flows from neighboring hydrodynamic systems may interact along their boundaries. Belova et al. (1982) propose a hydrodynamic model of the formation of epigenetic neoformations at the boundary, where groundwater flows descending along the formation and ascending along the fault occurs meet. Such a model explained the structural control of ores in deposits of reductive epigenesis, as well as the creation of long-term and spatially stable conditions for the accumulation of very rich uranium mineralization over local fault zones supplying epigenetic reducing agents. An important consequence of this model is that neoformations genetically related to descending and ascending waters should accumulate separately, i.e., on opposite sides of their dividing boundary. This was confirmed by the example of a real deposit in an open pit of the Uchkuduk deposit (Kochkin, 1989). This model explains the overprinting, alternation, and stages of

different types of mineralization in one area by an impulsive change in the ratio of flow rates of both types of waters (Fig. 5).

Uranium Megaprovinces

Exogenic epigenetic uranium deposits of different groups, due to the unified origin of infiltration oxygenated ore-forming solutions, can form regional ore-bearing zones (megaprovinces). The movement of the ore-forming flow can be unpressurized groundwater or pressurized water in an artesian basin. In both cases, the driving force is the gradient of groundwater pressures formed by the difference in elevation marks of the relief of the Earth's surface. This explains the localization of deposits of this genetic class in territories characterized by vertical differentiation of the relief, e.g., in orogenic and suborogenic areas of post-platform tectonic (tectonomagmatic) activation.

On the northern periphery of the Tien Shan Orogen, on the site of the Turan Plate, a suborogenic region formed in the Neogene–Quaternary, the basins of which contain the deposits of the Chu–Sarysu, Syrdarya and Kyzylkum provinces (Fig. 6). Rock erosion of in the area of the orogen itself mobilized huge masses of uranium. The confinement of these uranium provinces to a suborogenic region is a long known fact. The fact that this area itself is the periphery of the collision zone of the Indian and Eurasian plates was recently noted by G.V. Grusheva and I.G. Pechenkin (2003). They indicated that in this region “...most of the economic infiltration uranium deposits tend towards the outer front of attenuating collisional processes (towards the area of the suborogen)....” On the southern side of this collision boundary, several sandstone deposits of uranium of the tabular subtype (9.2 according to the IAEA) have also been identified in India. They are confined to Miocene–Pleistocene molasse deposits, filling the Sivalik basin, stretching from Jammu in the west to the Brahmaputra Valley in the east (*Uranium ...*, 2020).

The second example of confinement of large provinces of exogenic epigenetic uranium deposits to the tectonic plate interaction zone is deposits common in three provinces of the United States: the Wyoming Basins, Colorado Plateau, and Texas Coastal Plain (Fig. 7). These three districts can be combined into one megaprovince, confined to the activated part of the North American Platform on the eastern periphery of the North American Cordilleras. This mountain structure is actively rising on the Pacific–North American plate interaction boundary. The province also has classical oxidative zoning deposits (Wyoming), and those close to oil and gas districts (Texas) and to areas of basalt volcanism (Colorado). All of them occur in sediments that have formed since the Late Cretaceous and are represented by various terrigenous sediments.

Smaller areas of modern infiltration uranium ore formation are known in Alpine fold belts, which are distin-

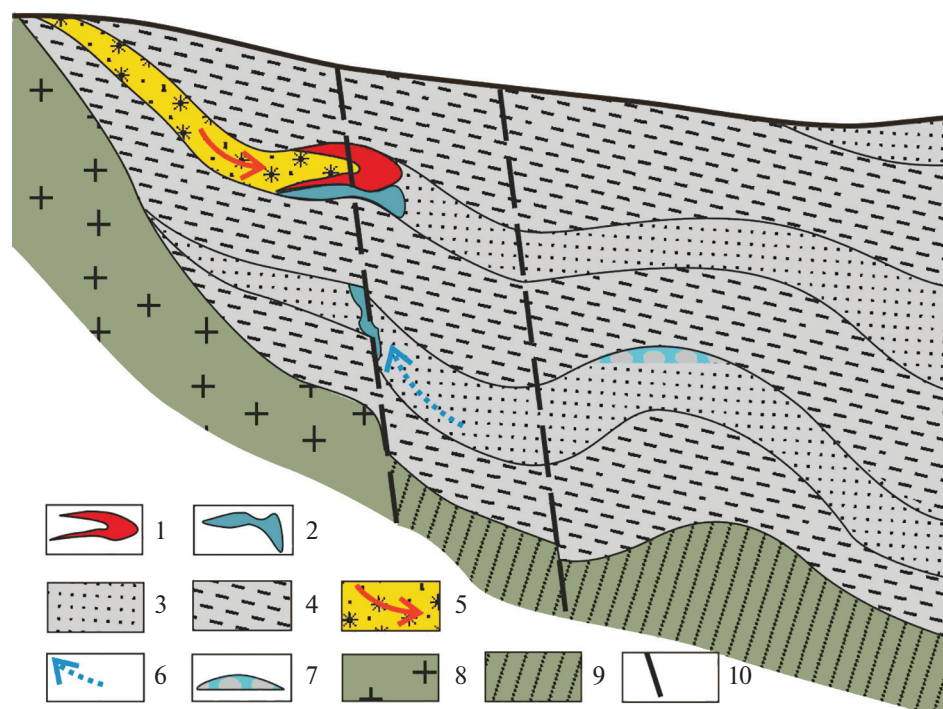


Fig. 5. Diagram of uranium ore formation at boundary of infiltration and expulsion hydrodynamic systems. (1) Orebody (roll); (2) near-fault reducing neoformations; (3) gleyed sands; (4) gleyed clays and silts; (5) yellow sands in oxidation zone; arrow, direction of oxygenated water filtration; (6) arrow, direction of movement of expulsion waters; (7) oil and gas accumulations; (8) granites; (9) metamorphic rocks; (10) faults.

guished by significant vertical differentiation of the relief and sometimes by mafic volcanism. For example, deposits in France, the Czech Republic, and Bulgaria in Western Europe and China and Mongolia in Asia are confined to such a belt (*World ...*, 2020). Pechenkin (2016) substantiated the position that the transcontinental belt of exogenic epigenetic uranium deposits localized in the sedimentary basins of Eurasia is spatially confined to the boundaries of collision and subduction of tectonic plates in the Cenozoic and Mesozoic. The western part of the belt is confined to the boundary between the Eurasian, African, and Arabian plates. The eastern part is an long-lived intraplate structure with elements of modern rifting and basaltic volcanism centers. On some tectonic diagrams, this part of the orogenic belt is designated as the Eurasian–China plate boundary. The subduction boundary of the Pacific Plate under the Eurasian is located significantly farther southeast.

Long-lived deep-seated intraplate faults separating the uplifted and subsiding parts of platforms (shields and plates) act as ore-controlling structures for some Mesozoic deposits. The Dolmatov deposit is a paleo-valley-type objects, which formed in the Mesozoic along the extended boundaries of the uplifted Ural and Kazakhstan shields with the subsiding West Siberian Plate (*World ...*, 2020).

Another extended district of Mesozoic uranium deposits with signs of stratal oxidative zoning is located in the vast territory of South and East Africa in

deposits of the Karoo Formation (Catuneanu et al., 2005; Shumilin and Ivliev, 2018; *World ...*, 2020). The formation dates back to the Upper Carboniferous–Early Permian to Upper Triassic. Sediments accumulated along the eastern boundary of the uplifting African continent. Today, the sediments fill a system of grabens (rifts) extending from the Atlantic in the south to the coast of the Indian Ocean in East Africa. It is logical to assume the presence of a long-lived intraplate structure here. The probable age of oxidation appears to correspond to Triassic–Jurassic. It is suggested that many of the deposits in the district are only surviving relicts of a vast uranium province.

The African and West Siberian examples illustrate some of the conditions that can ensure preservation of ores accumulated by exogenic epigenetic systems of the past. For example, the position of the Mesozoic Dolmatov deposit (and similar ones) on the side of the West Siberian Plate illustrates the favorable geodynamic regime of subsidence of ore-bearing strata at the boundary with the uplifted ancient fold belt. The subsidence and accumulation of younger sedimentary strata preserved the mineralization at the base of the platform cover. The African example illustrates other geodynamic conditions for the preservation of ancient deposits: subsidence of ore-bearing sand deposits in modern rift zones.

Because deposits of this genetic type are formed relatively close to the surface, they are easily destroyed

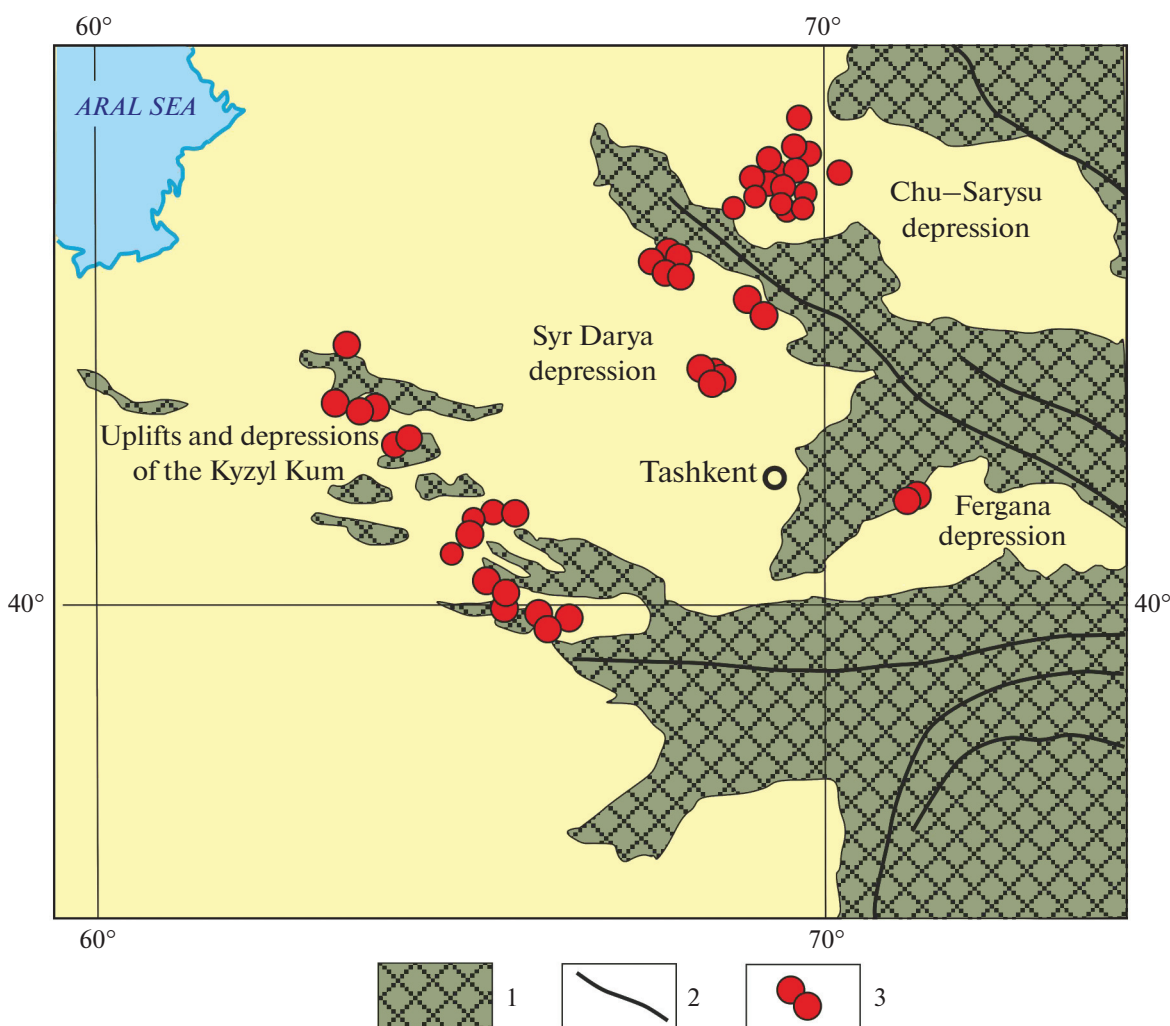


Fig. 6. Tian Shan uranium ore megaprovince (schematic diagram of localization of deposits from data of *World ...*, 2020 and *Geologo-promyshlennye ...*, 2008, with simplifications). (1) Basement outcrops; (2) faults; (3) uranium deposits.

after degradation of the ore-forming system. Therefore, the conditions for preservation of accumulated mineralization represent a special factor that should be taken into account when forecasting ancient deposits. A rare case of preservation of uranium ores was encountered at the deposits of the Vitim district: a permafrost screen that complements the strong basalt cover (Kochkin et al., 2017).

DISCUSSION: CRITICAL PROCESSES AND CONDITIONS

From modern approaches to genetic classifications of uranium deposits (Cuney, 2009; Shumilin, 2015; Wyborn et al. 1994; *Descriptive ...*, 2020), it follows that the class of exogenic epigenetic concentrations of uranium occupies a definite place in the natural uranium cycle.

Determining the boundaries of the exogenic epigenetic system is a controversial issue. The uranium transport agent is an aqueous solution, as in many

other mineral systems. Obviously, it is unacceptable to include in this model deposits in which uranium transport to ore formation sites is assumed to occur in the tetravalent state, and concentration, due to changes in the temperature and pressure of fluids, such as deposits “associated with volcanism,” type 4 (*Descriptive ...*, 2020). Less obvious is the situation with deposits in “calcretes” (type “river valleys” 11.2). There, uranium is transported in the hexavalent state, and the mechanism of uranium concentration in the form of salts is not reductive (*Descriptive ...*, 2020).

The reduction of uranium at a concentration site in classical deposits occurs via syngenetic reducing agents. At the same time, the oldest and many younger deposits attributable to this class were formed with the participation of epigenetic reducing agents, which were transported with ascending hypogene fluids. Hence it follows that the type of uranium reducing agent is a critical, but not disqualifying condition in the considered mineral system. The examples of deposits in the Fergana Valley, Uzbekistan (Kholodov

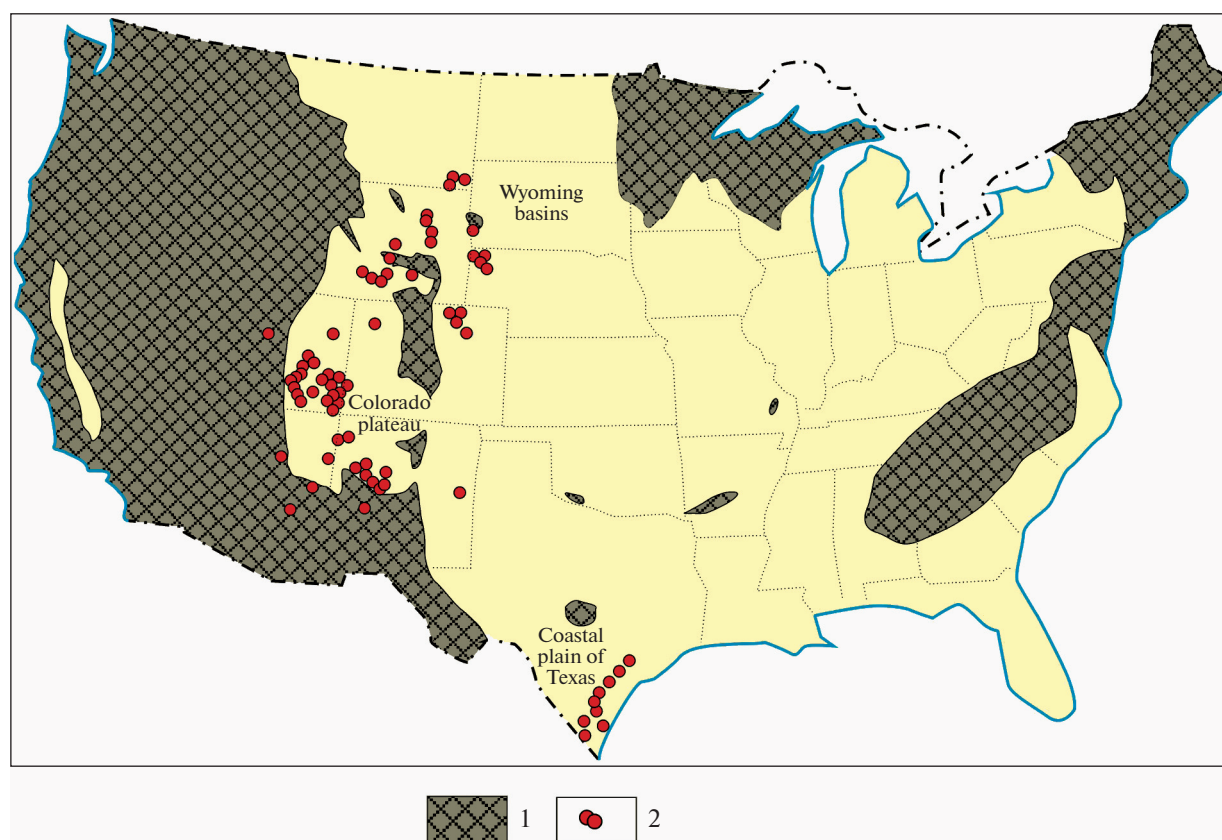


Fig. 7. Uranium sandstone deposits of various subtypes in United States (schematic diagram from data of *World ...*, 2020, with additions and simplifications): (1) basement outcrops; (2) uranium deposits.

at al., 1961), which are localized in limestones, as well as deposits localized in red sands above petroleum accumulations (Zelenova et al., 1969), show that the type of host rock is also not a disqualifying condition. The same applies to the system of the internal structure of the infiltration reservoir. An example of deposits of the Vitim ore district, where orebodies from the sand layer extend into basement faults and the impermeable basalt roof, shows that the pressurized hydrodynamic regime allows oxygen-containing waters with uranium to penetrate into both types of aquicludes and form bodies with a complex morphology (Kochkin et al., 2014). The internal structure of the reservoir only determines the shape that the orebodies will have: roll, tabular, or more complex (subtypes 9.4 and 9.5) from those given in the IAEA classification (*Geological ...*, 2018; *World ...*, 2020). This opens up opportunities for extending the boundaries of the system to deposits of such economic types as “unconformity-related” (type 7). Australian geologists followed this path in (Skirrow et al., 2009), combining deposits “in sandstones,” “at ancient unconformities,” and “Westmoreland” type in the Frome Basin (Australia), into one “basin” mineral system. It should be noted that the name of the system was given based on a morphological feature of the ore-bearing structure (localization criterion), not genetic.

The negative structure of the reservoir— a synclinal fold in sediments or a volcanic caldera—a critical condition also from a genetic standpoint. In such structures, the existence of artesian basins with infiltration of meteoric oxygenated waters to depth is possible. A source of metal must exist along the periphery of the structure. The climate of the region is also critical as a factor influencing the supply of oxygen and uranium to groundwater. In general, the most important process is vertical tectonic differentiation of the territory, which is necessary for the occurrence of an exogenic epigenetic ore-forming system with infiltration groundwater hydrodynamics. Thus, geodynamic regions of a certain type and certain climatic zones should be included in the number of mapped criteria when compiling forecasting materials for the deposits of the system under consideration.

CONCLUSIONS

The features of critical conditions and processes that must be taken into account when forecasting areas of formation of large exogenic epigenetic deposits and provinces are as follows:

1. A sedimentary or other groundwater reservoir as a future repository of artesian infiltration basins should be large in size. This condition is a conse-

quence of the geological prehistory of development of the potentially ore-bearing area.

2. The stability of the geodynamic regime with differentiated vertical tectonic movements for millions and tens of millions of years required for the accumulation of significant uranium reserves can be provided by peripheral regions of orogens along active plate boundaries and some long-lived intraplate faults.

3. There must be an abundance of uranium-rich rocks eroded in the recharge area of infiltration basins. This condition is also a consequence of a certain background history of the territory.

4. Potential ore-hosting rocks should be enriched in uranium reducing agents. The syngenetic or epigenetic origin of the reducing agents is a consequence of the prehistory of development of the territory. The formation of especially rich ores is more likely with the participation of epigenetic reducing agents, especially when they enter along faults, ensuring a stable position of the oxidation front and geochemical barrier. Since the Phanerozoic, the concentrated inflow along the faults of hypogene waters enriched in uranium reducing agents is usually a consequence of the proximity (or overlapping in the section) of infiltration basins with oil-and gas-bearing expulsion basins. In more distant geological epochs, inorganic sources of epigenetic uranium reducing agents played the main role.

5. The increased content of uranium in the surface waters of the feeding area during the period of ore formation is a consequence of additional evaporative concentration (climatic press) in especially arid and hot regions. Epigenetic deposits should not be expected in the epochs of the ancient time of the formation of the oxygen atmosphere. On the other hand, geological epochs before the appearance of continental vegetation were favorable for the penetration of oxygenated waters to depth in a wider climatic range, since oxygen was not consumed for the oxidation of organic matter in the soil layer.

6. Since the deposits of the class under consideration are formed relatively close to the surface, it is important to take into account the postore history when forecasting potential uranium-bearing regions and provinces of the past. The preservation of deposits from destruction can be ensured by such processes as burial of ore-hosting rocks under a thick sequence of younger sediments, the covering of ore-hosting rocks with a strong poorly permeable screen, such as a basalt cover, subsidence of ore-hosting rocks into local grabens, and flooding of the ore-hosting horizon with reducing waters.

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CONFLICT OF INTEREST

The author declares that he has no conflict of interest.

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