International Journal of Geology, Earth & Environmental Sciences ISSN: 2277-2081
An Open Access, Online International Journal Available at http://www.cibtech.org/jgee.htm
2026 Vol. 16, pp. 44-51/Akbarova et al.
Research Article

GEOLOGICAL AND GEOCHEMICAL FEATURES AND A PROSPECTIVE EXPLORATION MODEL OF INFILTRATION-TYPE URANIUM MINERALIZATION IN THE KYZYLKUM SUBPROVINCE (UZBEKISTAN)

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ABSTRACT

Using three promising areas, namely the Djasaga, Djengeldy, and West Ziaetdin sites of the Kyzylkum subprovince, the geological and mineralogical–geochemical prospecting and exploration criteria for infiltration-type uranium deposits of the Kyzylkum subprovince have been investigated. A typical mineral composition of ore-hosting sandy sediments (quartz and feldspars exceeding 70%) and ore minerals (uraninite and uranium black oxide phases) has been identified as characteristic of uranium mineralization in Paleogene (Upper Eocene) and Upper Cretaceous deposits (with the exception of the Cenomanian stage). An increase in near-background uranium contents within dispersion halos by two to fifty times, and within ore bodies by hundreds of times and more, has been noted. At the same time, a certain displacement of the levels of maximum concentrations of associated useful components is observed: selenium toward the rear parts, and rhenium, molybdenum, and rare earth elements toward the frontal parts of the uranium ore roll. Indirect indicator elements—thorium, vanadium, tungsten, cobalt, rubidium, and antimony—occur sporadically and are confined to sandy sediment layers.

Keywords: *Kyzylkum Subprovince, Promising Areas, Infiltration Type, Uranium Roll, Uraninite, Uranium Black Oxides*

INTRODUCTION

The Kyzylkum subprovince constitutes an integral part of the Tianshan piedmont uranium ore province **(figure 1)** and occupies an intermediate position between two rigid massifs — the Syrdarya massif to the north and the Karakum–Tajik massif to the south [Pechenki I.G.]. It is regarded as a mobile zone of an intracontinental type, composed of grabens, horsts, and rifts, extending for more than 1,000 km from Sultan-Uvais in the west to Sarydjaz in the east and having a width of one hundred to two hundred and fifty kilometers. Its total area is approximately 84,000 km². The metallogenic character of the pre-Mesozoic basement of the subprovince is determined by the widespread development of gold-bearing, tungsten, as well as uranium occurrences of the "black shale" type (with vanadium). The age of the latter ranges from four hundred million years to the present, and according to the conditions of formation they are considered polygenetic in origin [Pirnazarov M.M.].

STUDY AREA

Within the Tianshan piedmont Uranium Ore Province, alongside the Kyzylkum subprovince, the Chu-Sarysu, Syrdarya, and Fergana subprovinces are distinguished, which are characterized by a large number of uranium deposits and metallogenic potential of global significance. For example, in the western parts of the first two subprovinces, located in the territory of Kazakhstan, with large and unique deposits such as Inkai, Budennovsk, Kharasan, North and South Karamurun, and Mynkuduk, the total uranium reserves within the identified ore bodies approach one million tons. These are controlled by a regional multi-level Cretaceous roll-front oxidation zone, traced over a distance of 360 km [Taraborin G.V., Demina T.Y.].

The Kyzylkum subprovince is also highly ore-bearing, where uranium production was initiated in 1966 with the discovery of the unique Uchquduq deposit in the Bukantau Mountains. Here, despite the preparation of approximately forty industrial deposits with total uranium reserves exceeding 200 thousand tons, large-scale geological exploration continues to this day. Annual production exceeds 3,000 tons of uranium oxide is carried out by Navoi Mining and Metallurgy Combinat using in-situ leaching (ISL) technology.

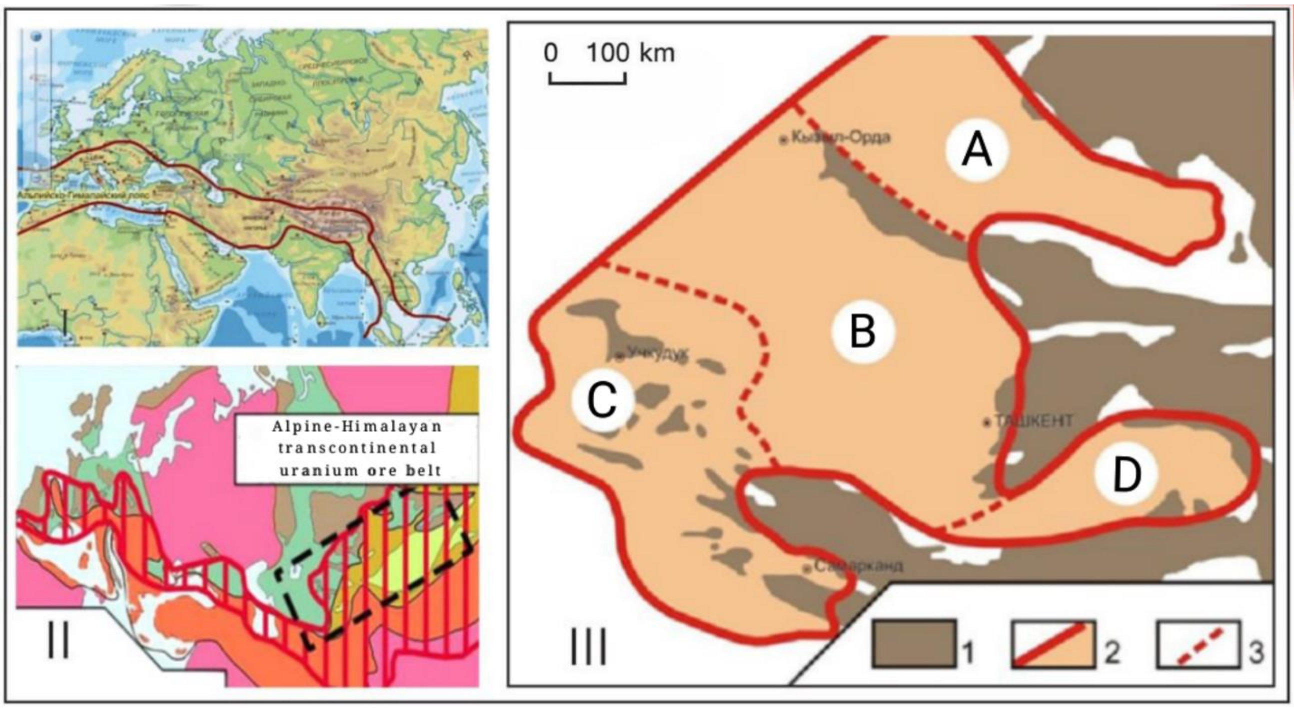

Figure 1. Position of the Central Kyzylkums within the global structures of the Earth's crust of various hierarchies

I – Alpine–Himalayan Transcontinental Uranium Metallogenic Belt; II – Central part of the Alpine–Himalayan Transcontinental Uranium Metallogenic Belt; III – Tianshan piedmont Uranium Ore Province. Uranium ore subprovinces: A – Chu-Sarysu; B – Syrdarya; C - Kyzylkum; D – Fergana. 1 – mountain uplifts with exposures of Paleozoic rocks; 2 – boundary of the Tianshan piedmont Uranium Ore Province; 3 – boundaries of subprovinces.

The objects of this study are the Djasaga, Djengeldy, and West Ziaetdin prospective areas, located in the foothill parts of the Bukantau, Tamdytau, Aristantau, Sangruntau, and Ziaetdin mountains **(figure 2)**.

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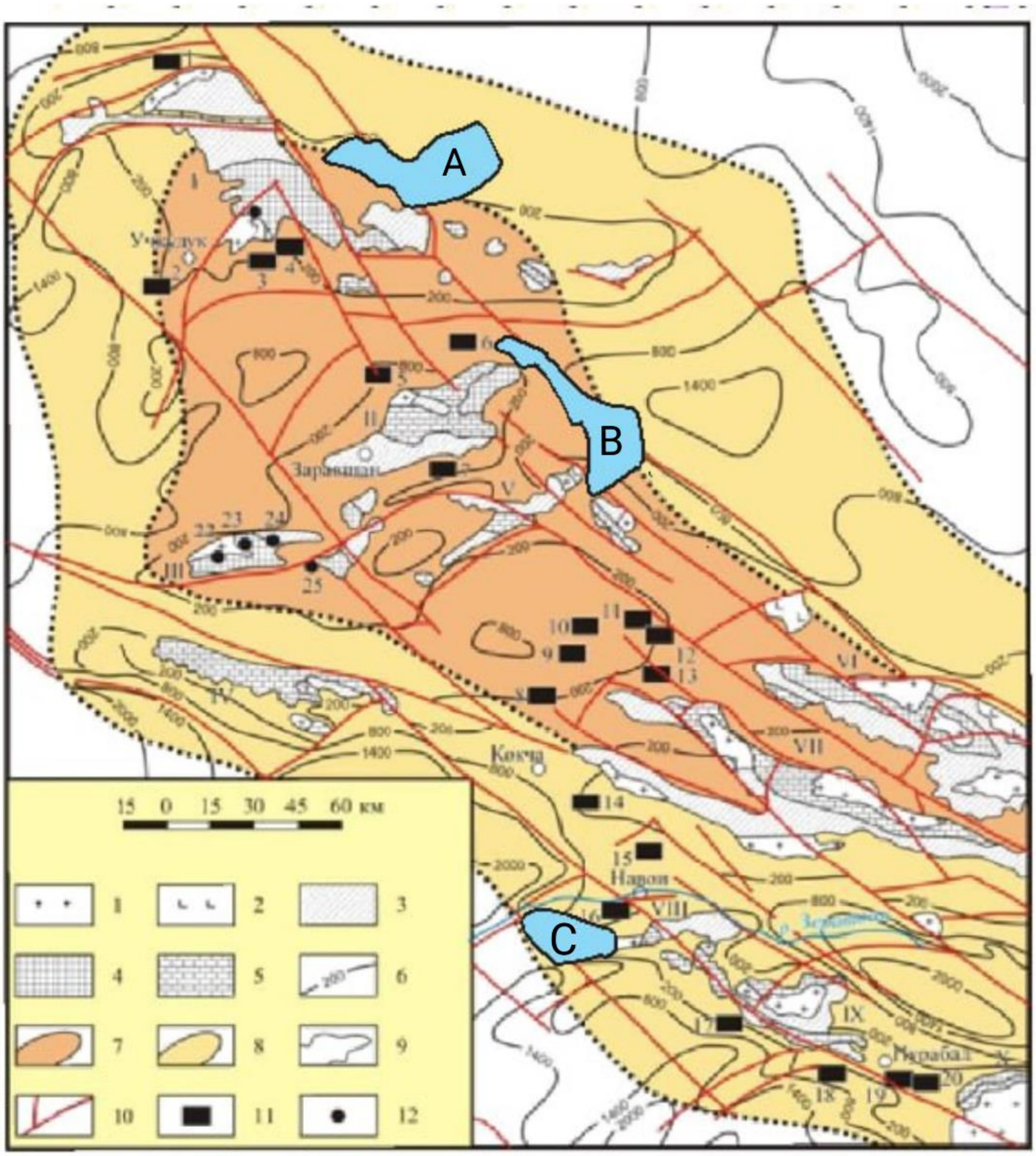

Figure 2. Scheme of the distribution of outcrops of the pre-Mesozoic basement, leading deposits, and prospective areas of uranium mineralization in the Kyzylkum region. 1 – acidic intrusive rocks; 2 – intermediate and basic effusive rocks; 3 – sandy–shale rocks; 4 – carbonaceous–siliceous and carbonaceous–clay–shale rocks; 5 – carbonate rocks; 6 – Mesozoic–Cenozoic sedimentary cover deposits and their isopachs. Boundaries: 7 – intra-geanticlinal uplift in the Paleozoic; 8 – arch uplift in the Mesozoic–Cenozoic; 9 – outcrops of folded basement rocks; 10 – fault dislocations. Uranium deposits: 11 – sedimentary cover; 12 – folded basement (1 – Bakhaly, 2 – Meylysay, 3 – Uchquduq, 4 – Kendyktyube, 5 – Sugraly, 6 – Aktau, 7 – Amantau, 8 – North Bukinay and Tokhumbet, 9 – Alendy, 10 – Beshkek, 11 – Lyavlyakan, 12 – Terekuduk, 13 – Varajan, 14 – South Bukinay, 15 – Kenimekh, 16 – North Maizak, 17 – Ketmenchy, 18 – Agron, 19 – Sabyrsay, 20 – Shark, 21 – Khodzhaakhmet, 22 – Zhantuar, 23 – Rudnoye, 24 – Koscheka, 25 – Voshod. Mountain massifs: I – Bukantau; II – Tamdytau; III – Auminzatau; IV – Kuldjuktau; V – Aristantau; VI – North Nuratau; VII – South Nuratau; VIII – Ziaetdin; IX – Zirabulak; X – Karatepe. Objects of study – prospective areas: A – Djasaga; B – Djengeldy; C – West Ziaetdin.

MATERIALS AND METHODS

The uranium deposits under consideration were formed during the Upper Cretaceous and Cenozoic periods by infiltration processes. They are controlled by a regional multi-level Cretaceous roll-front oxidation zone (RFOZ), traced over a distance of approximately 400 km. The total length of ore bodies in Paleogene accumulations reaches 200 km, while in Upper Senonian sediments it amounts to approximately 50 km [Taraborin G.V., Demina T.Y.].

The stratigraphic section of sedimentary deposits favorable for infiltration-type uranium mineralization of the cover formations is typicaly overlain by Quaternary deposits, including aeolian sands, proluvial, deluvial, and takyr sediments up to 50 m thick, and consists of [Karimov H.K.]:

- Jurassic variegated, carbonate, and coal-bearing rocks, reaching a thickness of 300 m and developed locally in the depressions of the ancient relief on a thick kaolin weathering crust of Paleozoic rocks;
- Cretaceous red, variegated, and grayish aleuritic–clayey and sand–conglomerate horizons and suites up to 700 m thick;
- Paleogene grayish and red terrigenous sedimentary deposits with a thickness of 600–800 m.

Specifically, deposits favorable for the formation of roll-front ore zones in the West Ziaetdin prospective area are Senonian sediments, excluding Maastrichtian; in the Djasaga area – Upper Turonian and Coniacian sediments of the Upper Cretaceous. The prospects of the Djengeldy area are associated with Campanian–Maastrichtian deposits of the Upper Cretaceous (K_2m) and Upper Eocene deposits (Lyavlyakan horizon – $Pglv_1$) [Khalilov A.A. et al.] **(figure 3)**. These rocks, hosting uranium-bearing zones (shown in blue) and ore bodies (red), are overlain in the section by Quaternary deposits and underlain at depth by rocks of the pre-Mesozoic folded basement.

Uranium mineralization zones in the studied areas develop in accordance with the general direction of the regional flow and are characterized by a relatively simple morphology, clearly controlled by the pinching-out boundary of the roll-front oxidation zone (RFOZ). The ore bodies distinguished within these zones have the shape of simple and complex rolls in cross-section, localized both in the wing and pocket parts of the roll. In plan view, they appear as elongated sinuous bands, with widths reaching hundreds of meters and lengths of several tens of kilometers.

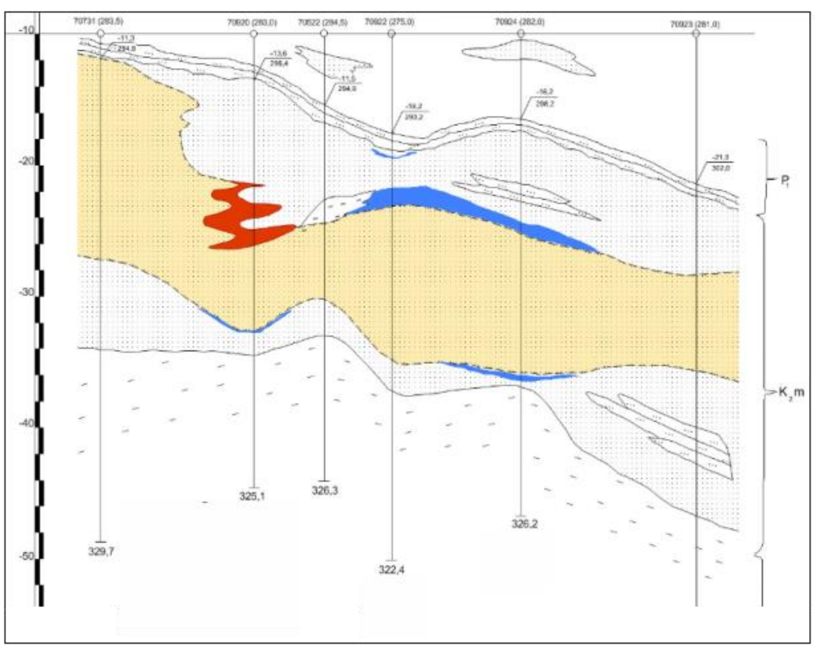

Figure 3. Geological section along profile No. 31-8 of the Djengeldy prospective area (horizontal scale is five times the vertical scale).

Comprehensive studies of Paleogene (Upper Eocene) and Upper Cretaceous deposits (excluding the Cenomanian stage) have identified, as the main mineralogical–geochemical local prospecting criteria for infiltration-type uranium mineralization in the Kyzylkum subprovince, a typical mineral composition of the ore-hosting sandy deposits across all studied objects. These deposits consist of clasts of quartz (in total exceeding 80%) and feldspars (in total exceeding 70%), respectively, subordinate amounts of micas (muscovite > chlorite), clay minerals (hydromica, kaolinite, montmorillonite, etc.), and carbonates (calcite, dolomite, etc.).
The principal ore minerals are nasturan (uraninite), amorphous uranium oxides, coffinite, native selenium, iordizite, and pyrite. Uranium mineralization occurs as black, powdery, and sooty films and coatings. At magnifications of up to 15,000× they appear as individual globules of uranium oxide ranging from 0.0 n to 0.6 µm, rarely up to 1.5 µm, on the surfaces of clastic grains in association with clayey material. The main source of uranium in the ores is free hexavalent uranium [Akbarova Z.T. et al.] **(table)**.
A significant role is played by natural concentrations of uranium oxide represented by fine-dispersed pitchblende mineralization. Spatially associated with them are the minerals jordisite and native selenium, which constitute the principal concentrators of molybdenum and selenium. An insignificant portion of uranium in sorbed form is present in the clayey material, phosphorite, and also sporadically within the composition of tyuyamunite and uranophane.
In barren zones of stratiform oxidation, uranium is detected at minimally anomalous concentrations of 4–9 g/t (1.8–4.2 times the geochemical background level). In dispersion halos, its concentrations amount to 5–50 times the geochemical background level. The maximum values of average contents, exceeding hundreds of times the geochemical background level (in certain intervals reaching up to 1000 g/t and higher), are recorded in uranium ores.

Table: Content of Hexavalent and Tetravalent Uranium and Values of the Oxygen Coefficient in Uranium Ores of the Djasaga Area

No	Rock type	Uranium concentration g/t			Content of hexavalent uranium relative to total uranium%	Oxygen coefficient
		Total (bulk) uranium content	Hexavalent	Tetravalent		
Coniacian K_2k						
1	Sand	98,5-155 129	82-116 96	20-46 33	67,2-83,6 74,4	2,67-2,84 2,74
2	Siltstone	350	343	7	98,0	2,98
Upper Turonian K_2t_2						
3	Clayey Carbonate Sandstone	479	444	35	92,6	2,93
4	Carbonate Sandstone	132-220 185	88-189 151	25-44 34	66,6-87,6 81,6	2,67-2,88 2,82
5	Siltstone	105-228 166,5	53-171 112	52-57 54,5	50,5-75,0 67,3	2,50-2,75 2,67

In addition to uranium, rhenium, selenium, scandium, molybdenum, rare earth elements, and other metals are of industrial interest. Native selenium is observed in the form of elongated acicular crystals and their aggregates within the intergranular space of sandstones and aleuropelitic sandstones with carbonate cement. Molybdenum sulfide (jordisite), identified by X-ray phase analysis and microchemical reactions, is similarly represented by black powdery and sooty coatings on the surfaces of clastic grains. Rhenium is most likely associated with isomorphic impurities in molybdenum minerals, as well as with coalified organic remains. The modes of occurrence of scandium and other rare earth metals require more detailed investigation; in most cases they are associated with radioactive mineralization (thorianite, uraninite, aeschynite, and others) and accessory phosphate mineralization (apatite, monazite, xenotime, and others).

Low-contrast halos of selenium, molybdenum, rhenium, and rare earth metals within intervals containing uranium ores increase in concentration to tens to hundreds of times the geochemical background level. At the same time, a certain displacement of the levels of maximum concentrations is characteristic: selenium mineralization is shifted toward the rear parts, whereas rhenium, molybdenum, and rare earth mineralization is shifted toward the frontal parts of the uranium ore roll. Indirect indicator elements of uranium—thorium, vanadium, scandium, tungsten, cobalt, rubidium, and antimony—due to the low intensity of their values, display a sporadic distribution pattern and are confined to the sandy sedimentary layer.

The statistical characteristics of chemical elements in the factor space of ore-bearing horizons are marked by deviations from the normal field. Rare earth elements show weak correlations with Se, Mo, and Re. The correlation is somewhat higher with Ca and increases with CO_2, while showing a a negative correlation with uranium. Rare earth elements demonstrate moderate correlation coefficients with the forms of occurrence of Fe [Khalilov A.A. et al.]. In the factor space of the Maastrichtian horizon, a weak correlation of rare earth elements is observed in barren oxidized rocks, in the uranium dispersion halo of the oxidized part of the section, in the subzone of selenium mineralization, in the molybdenum dispersion halo of the gray-colored part of the section, and in barren sandstones **(figure 4)**

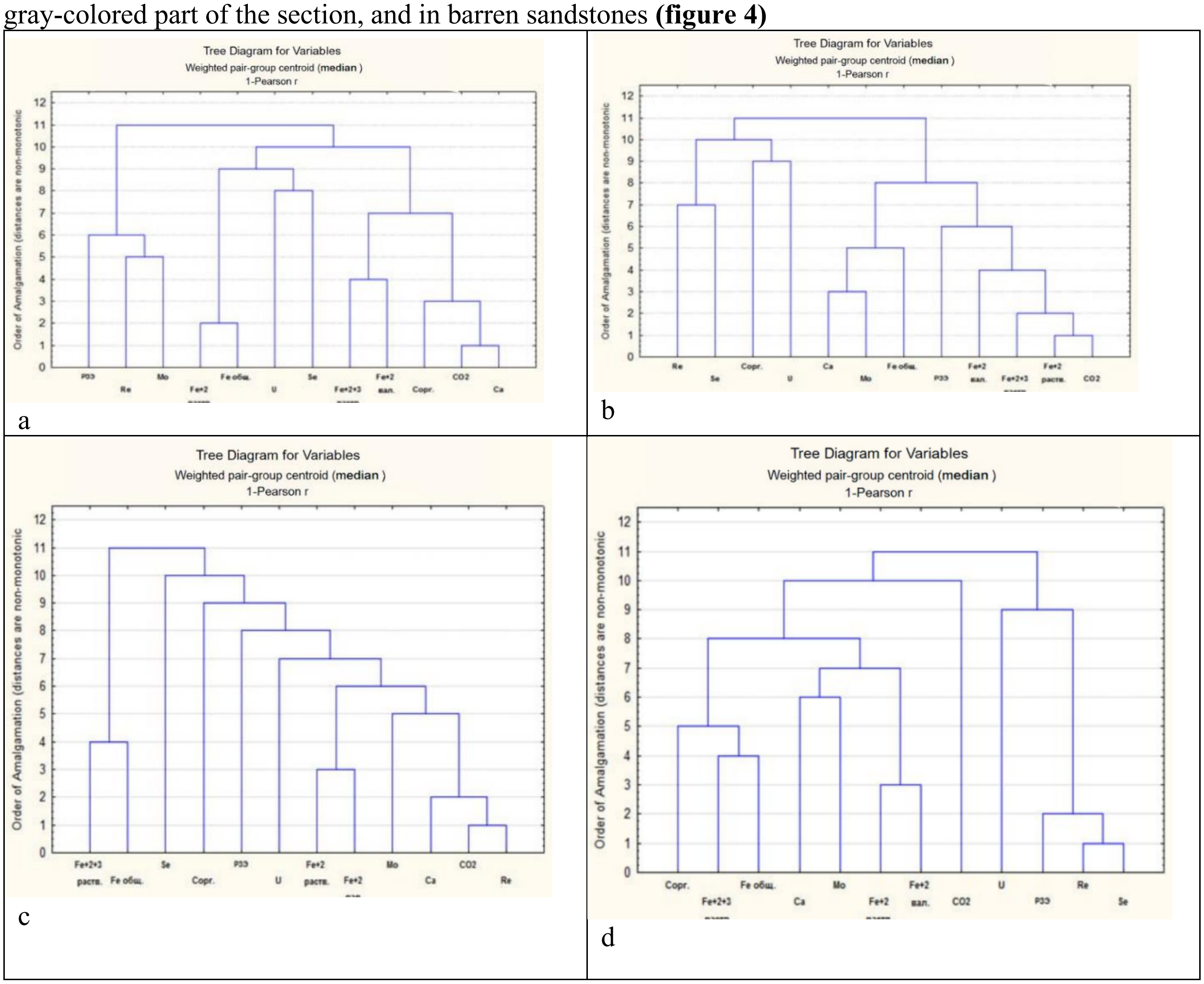

Figure 4. Dendrograms of relationships among chemical elements of the sediments: barren oxidized sandstones (a); oxidized (b) and gray-colored sandstones (c) with selenium mineralization; gray-colored sandstones with uranium–selenium mineralization (d) of the Maastrichtian stage**.**

Along with the above-mentioned geological, mineralogical, and geochemical exploration criteria, integrated into a unified model **(figure 5)**, it is necessary to note such a reliable indicator as the degree of radioactivity of the sediments, which reliably indicates uranium mineralization when the intensity of gamma radiation in the rocks exceeds 150 micro-roentgens per hour. New methods of remote space-based structural–geochemical forecasting of deeply seated mineralization are also being advanced (Pirnazarov M.M., Asadov A.R.).

In the direct examination of exploration geological materials, particular attention should be given, as favorable for the accumulation of high-grade ores, to positions of abrupt changes in the hydrodynamics of ancient watercourses—bends of paleochannels, bottom depressions, transverse scours, and similar features—which are poorly identifiable in geological exploration practice based on core from a sparse network of exploration boreholes, owing to the extreme deficiency of rock material and volumetric geological information.

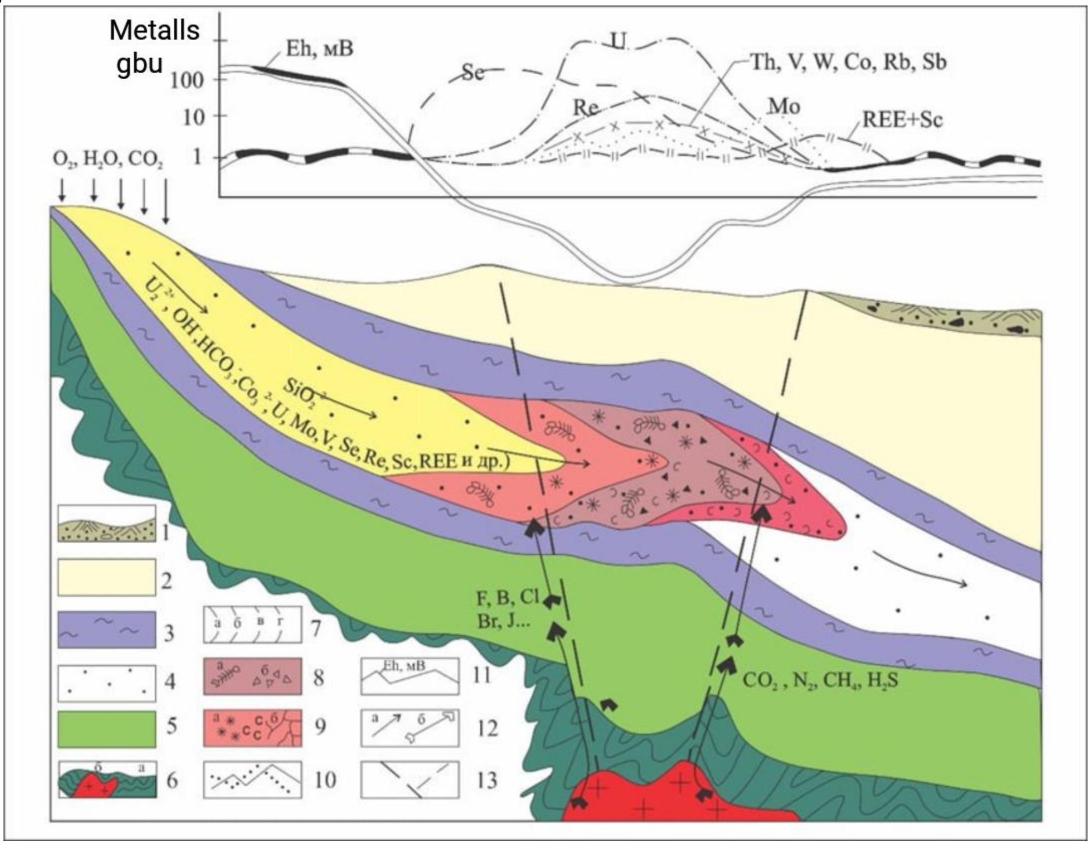

Figure 5. Model of geological, mineralogical, and geochemical criteria for uranium and other infiltration-type mineralization in the Kyzylkum subprovince. 1 – Quaternary deposits; 2 – Neogene–Paleogene deposits; 3 – Impermeable clayey deposits of the Meso-Cenozoic; 4 – Ore-bearing sandy deposits of the Eocene and Santonian (excluding the Cenomanian stage); 5 – Sedimentary–terrigenous sequence of the Lower Cretaceous; 6 – Pre-Mesozoic metamorphosed sedimentary (a) and intrusive (b) rocks; 7 – Ore-bearing layer zones: a – stratiform oxidation, b – partial oxidation, c – reduction, d – carbonatization, e – conditionally unchanged rocks; 8 – Syngenetic inclusions in the ore-bearing layer: a – organic remains, b – coarse-grained rock and mineral fragments; 9 – Epigenetic neoplasms: a – ore minerals of U, Se, Mo, and Fe, b – low-temperature alterations (carbonatization, decarbonization, sulfidization, etc.), c – fracturing; 10 – Geochemical anomalies of direct (U, Se, Mo, Re, REE, Se) and indirect (Th, V, W, Co, Rb, Sb, etc.) indicator elements; 11 – Redox potential indicator; 12 – Circulation direction and composition of mineralization in the aqueous (a) and juvenile hydrothermal-fluid (b) flow; 13 – Deep-seated faults.

CONCLUSION

The productive horizons of the Kyzylkum subprovince are characterized by distinctive lithological–mineralogical features and epigenetic geochemical zonation, expressed in the sequential variation of zonation indicators of the major components relative to the less significant ones, downward along the ore-bearing layer (from top to bottom): U^{4+} – O_2 – C_{org} – P_2O_5 – Fe – H_2 – S – V – Se – U^{6+} – Re – Mo – Sc, REE – Ca. The obtained results contribute to the understanding of the patterns of uranium mineralization formation in nature via infiltration processes and, in applied terms, to the exploration and forecasting of erosional sections of intervals intersected by boreholes along the axial section of the ore field.

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