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. 140-150/Bakhtiyar et al.
Research Article

RARE-EARTH POTENTIAL OF MINERAL RESOURCES OF THE CENTRAL KYZYLKUM URANIUM ORE PROVINCE (WESTERN UZBEKISTAN)

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ABSTRACT
Based on an analysis of new factual material and relevant scientific publications, this article addresses the potential of uranium-bearing formations in relation to their paragenetic association with rare-earth element complexes within the activated structures of the Central Kyzylkum region. The analysis reveals the regional nature and unified front of the formation oxidation zone, which begins in the southwest within the Bukhara-Khiva oil and gas province, crosses the Central Kyzylkum, and merges into the SyrDarya artesian basin to the northeast. The pinching out of the formation oxidation zone leads to the formation of ore concentrations of various metals along its entire extent (stretching hundreds of kilometers). This leads the authors to emphasize a multicomponent metallogenic specialization including U, Se, Re, Mo, V, Sc, Rb, Hf, Y, Yb, Eu, Lu, Au, and other elements. Patterns governing the co-formation of specific ore element complexes are determined. Attention is drawn to the fact that the transformation of the pinch-out line from monomineral (uranium) to polymineral-rare earth sharply increases the productivity of both hydrogenous and black shale deposits. This complexity multiplies the total value of the combined polyelement product several times over.

Keywords: *Formation Oxidation Zone (Foz), In-Situ Leaching (ISL), Epigenetic Uranium, Black Shale Deposits, Central Kyzylkum, Uranium Ore Province, Colorado and Sandstone Type*

INTRODUCTION
As a result of large-scale exploration, a number of uranium deposits have been discovered in Central

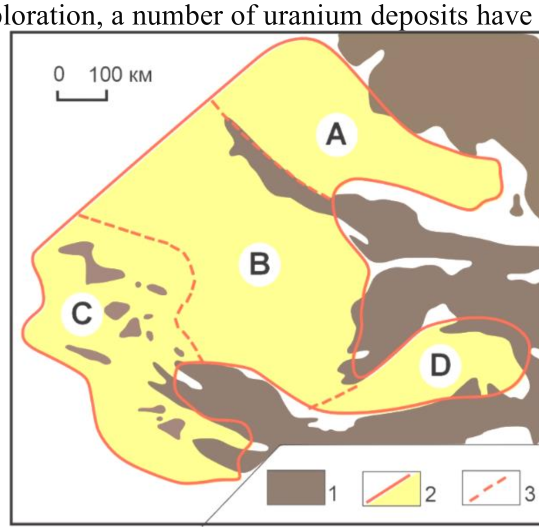

Figure 1: Tien Shan uranium ore megaprovince

Uranium ore provinces: A – Chu-Sarysu, B – Syrdarya, C – Central Kyzylkum, D – Fergana. 1 – ancient structures of the Tien Shan, 2 – outer boundary of the Tien-Shan mega provinces, 3 – conditional boundaries dividing uranium provinces.

Asia. These discoveries laid the foundation for the emergence of the world's largest Tien Shan uranium ore megaprovince. This first-order structure includes four uranium ore provinces: Chu-Sarysu, Syrdarya, Central Kyzylkum, and Fergana (Fig. 1).

The uranium ore province, which unites uranium ore regions and ore fields, includes a set of ore occurrences over a vast territory. It is confined to a single large geological structure of the second order, characterized by a similar development history throughout the Phanerozoic and a uniform response to the processes of recent activation. As a result, pre-orogenic artesian basins were formed. Within these basins, over large areas, uranium ores of exogenous epigenetic deposits were formed under the influence of filtered oxygenated waters in the permeable horizons of the platform cover. Polygenetic ore fields are found in uplifted blocks exposed in the formations of the lower structural level.

For example, the Central Kyzylkum province, as a second-order structure, is located within the artesian basin of the same name. This basin consists of a combination of interconnected systems of small graben-syncline artesian depressions and the separating horst-anticlinal structures composed of ancient basement massifs that contain hydrogeological reservoirs of fissure waters. This is the fundamental difference between this province and its neighbors—Syrdarya, Chu-Sarysu, and Fergana—where ancient mountain ranges only border the basins.

CURRENT PROBLEMS IN URANIUM GEOLOGY AND DIRECTIONS FOR THEIR SOLUTION

Radioelements, and uranium in particular, are excellent indicators of a wide variety of geological processes. Currently, it is not so much their total abundance but rather their forms of isolation and migration—determined by physicochemical conditions—that dictate their geochemical metallogeny, as well as the pathways for their dispersion and concentration. The formation of uranium-bearing provinces and regions is associated with regional processes of material differentiation during sedimentation, metamorphism, and magmatism, and ultimately depends on the degree of crustal structural mobility.

The appearance of certain migration forms of uranium always precedes the period of its ore deposition, but does not necessarily coincide with the period of bulk metal concentrations in black shale formations. The formation of uranium ore deposits is facilitated by dramatic changes in physicochemical, structural, and lithological conditions, which directly impact the element's migration ability. While in an aquatic environment the migratory form of uranium is determined by its hexavalent state, in magmatic melts and during metamorphic processes it exists in both hexavalent and tetravalent forms. However, it is important to emphasize that the formation of pitchblende is due to the coexistence of two main forms of uranium U^{4+} and U^{6+} which occurs at the interface between two geochemical environments: oxidative and reducing.

An equally pressing issue in modern geology is the genesis of uranium deposits. The solution to this problem is inextricably linked to understanding the patterns of migration, localization, and dispersion of radioactive elements, the age of mineralization, the conditions under which large deposits and small occurrences form, and the opportunities for scientifically based forecasting and successful exploration (Karimov *et al.,* 1996; Kislyakov & Shchetochkin, 2000; Kochkin, 2022; Perelman, 1989; REDBOOK, 2025; Wang *et al.,* 2018).

All uranium deposits identified to date within the platform cover of the Turan plate are confined to loose, unmetamorphosed rocks of the Central Kyzylkum province and belong to several genetic types. The primary type is the epigenetic type, which is due to zones of formation oxidation in terrigenous sediments. In the monograph *Ore Deposits of Uzbekistan* (2001), a classification of ore deposits based on the identification of geological-industrial types is adopted, in which they are classified as a "uranium stratiform infiltration type in sandstones due to formation oxidation processes". In foreign classifications, these deposits are categorized as the "Colorado" or "sandstone" type (Akhtar *et al.,* 2017; Jin *et al.,* 2023; Plant *et al.,* 2019).

In addition to this primary industrial type, the Central Kyzylkum province is highly likely to contain very promising uranium ore occurrences localized in environments unrelated to formation oxidation zones. These include:

- Syngenetic uranium deposits in Paleogene oil shales and phosphorites;
- Epigenetic uranium concentrations above oil and gas deposits;
- Exodiagenetic concentrations in ancient riverbeds (the so-called "paleochannel" type);
- Insolation accumulations of uranium in Pliocene carbonate soil-crust sediments (the calcrete type).

Overall, these uranium-bearing types are considered unconventional, and their development will likely begin in the first half of the 2030s when reserves at the main explored targets begin to deplete.

STATEMENT OF THE PROBLEM AND SOLUTION METHODS

The most important pattern of uranium concentration in epigenetic infiltration deposits is the formation of uranium ore bodies at the wedging out of formation oxidation zones (hereinafter referred to as FOZ), which has been the subject of numerous scientific studies over the past 40 years. The fundamental internal structure of the FOZ includes two main zones: the rear part or oxidation zone (limonitization) and the front part or uranium mineralization zone. It has been established that with an increase in the amount of soluble salts in groundwater, the solubility of oxygen in them decreases. Oxygen-rich formation waters enriched in uranium contain it in quantities exceeding 1 x 10^{-3} g/l and virtually all of the uranium is in the form of uranyl-carbonate complexes. In the aquifer wedging zone, the uranium content in formation waters drops sharply to 1 x 10^{-6} g /l indicating the destruction of these complexes with the precipitation of uranium from solution and the formation of uranium mineralization. The uranium precipitation process is explained by the reduction of U^{+6} to U^{+4}. The reducing agents are disulfides and organic matter present in the aquifer rock.

The concentration of uranium in a relatively narrow band at the outer boundary of the aquifer indicates the formation of a geochemical barrier (Kislyakov & Shchetochkin, 2000; Kochkin, 2020; Perelman, 1989; Shmariovich, 2007). Under favorable conditions, this barrier moves in the direction of the aquifer flow at an average rate of about 1 meter per 1,000 years (the rate directly depends on the filtration coefficient). This leads to the oxidation of the tail part of the uranium deposit and the growth of its head or pocket part. Thus, a uranium-bearing zone is formed, including subzones of rich, ordinary, and poor ores. Moreover, the formation of uranium ores at hydrogenic deposits according to this scheme has a regional character and reflects uranium ore formation across the entire Tien Shan Megaprovince.

Regional reservoir water discharge centers form in the megaprovince, playing a leading role in the formation of mineralization within hydrogenous deposits. Infiltration water discharge centers are ore-localizing, while exfiltration water discharge centers are gas- and oil-forming. The map below (Fig. 2) shows the main reservoir water discharge centers, the areal nature of which indicates the regional scale of their development.

Within the suborogenic zone (Fig. 2), designated as **C_2** and representing the Central Kyzylkum Artesian Basin, oxygenated waters are widespread, and ore deposits of various metals—uranium, selenium, rhenium, yttrium, vanadium, molybdenum, and others—form in the discharge foci. The regional direction of groundwater flow is indicated by blue arrows and has a northwesterly azimuth. It is in this direction that groundwater discharge foci shift, gradually developing into local recharge areas and forming localized zones of formation oxidation.

The regional nature of the development of the main hydrogeochemical parameters is also reflected on the map of Central Asia (Fig. 3), where the structures that form a single regional front of the layer oxidation zone cover almost the entire western territory of the Tien Shan megaprovince. The regional front begins in the Bukhara-Khiva oil and gas province, crosses the Central Kyzylkum Desert, and then continues northeast into the Syrdarya artesian basin (shown by the curved red line in Fig. 2).

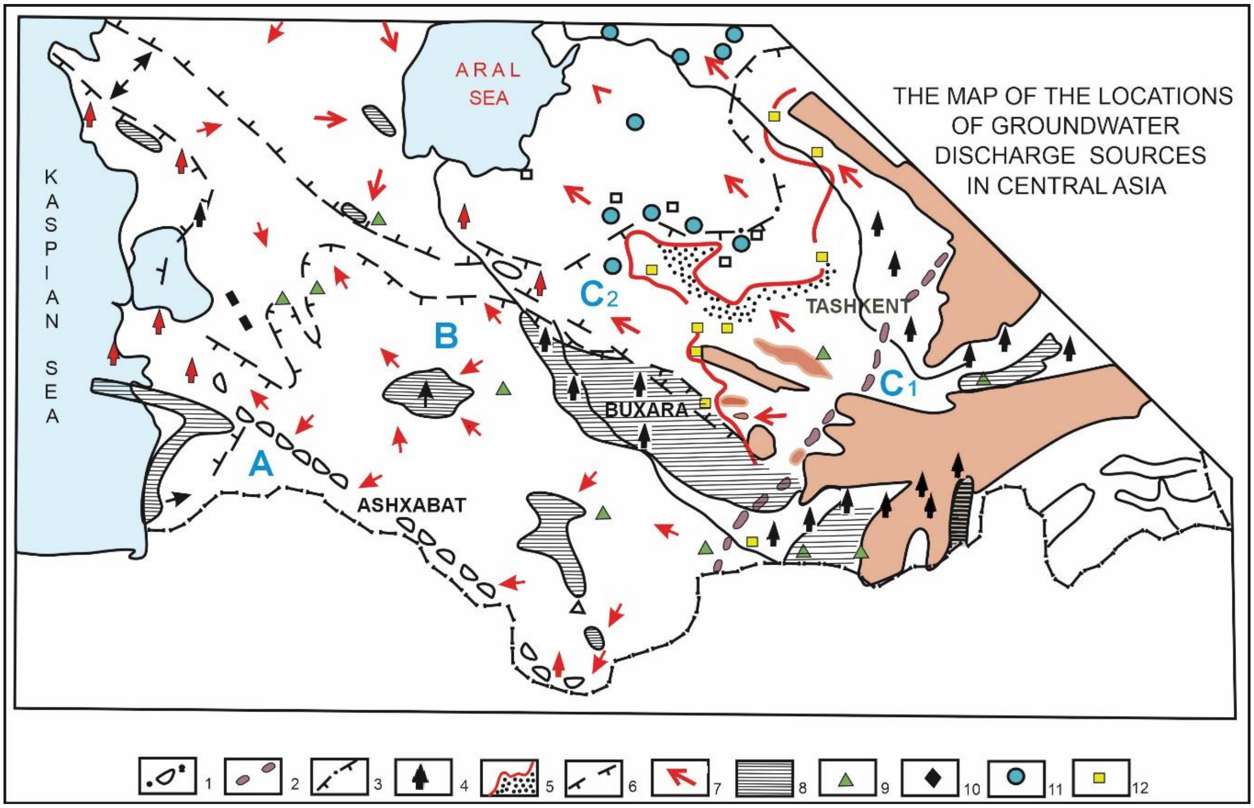

Figure 2. Regional centers of groundwater discharge in Central Asia

Legend. Boundaries: 1 - Alpine fold belt, 2 - epiplatform orogenesis, 3 - suborogenic region; 4 - upward flows of mineralized waters over oil and gas areas; 5 - boundary of distribution of infiltration oxygenated formation waters and associated zones of formation cooxidation ; 6 - boundary of distribution of elisional waters; 7 - main directions of regional movement of groundwater; 8 - oil and gas bearing areas; The main centers of discharge of various types of groundwater: 9 - hydrocarbon- chloride-sodium brines; 10 - carbon dioxide-hydrogen sulphide saline and brackish waters (Mangyshlak (27), Kukcha (31), Pitnyak (32), Uchkyrsen (33), Uyghursay (45), Tashkent (47, etc.); 11 - oxygenated brackish and fresh gley waters (Mingbulok (50), Keriz (52), Mullali (51), Akbaytal (53); 12 - oxygenated brackish and fresh waters (Uchkuduk (60), Aulbek (61), Loyliken (62), Karatau (59), Uzunkuduk (63), Kiziltepa (64), etc.). **A** - Alpine folded belt, **B** - platform, weakly activated part of the Turan plate, **C**$_1$ – orogenic structures proper, **C**$_2$ – suborogenic within the Central Kyzylkum arched uplift.

The illustrated megaprovince territory is conventionally divided by deep faults into the Central Kyzylkum (A), Syrdarya (B), and Chu-Sarysu (C) regions. The graphical model presented in this article reflects the current state of the main hydrogeochemical parameters, including the oxidation zone, its wedging out with the formation of a geochemical barrier, and the behind-ore zone of unaltered rocks. A key characteristic of this model is that the geochemical barrier, or oxidation-reduction front, formed within the three uranium ore provinces during approximately the same geological period and is regional in scale.

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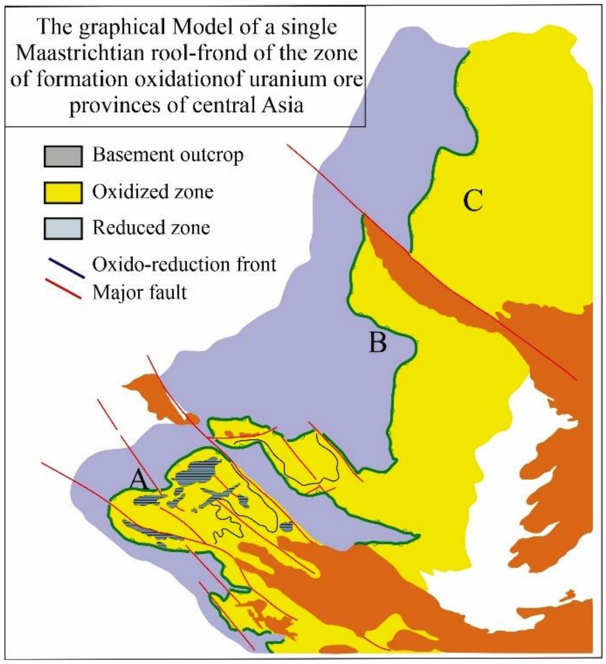

Figure 3. Graphic model of uranium ore provinces of Central Asia

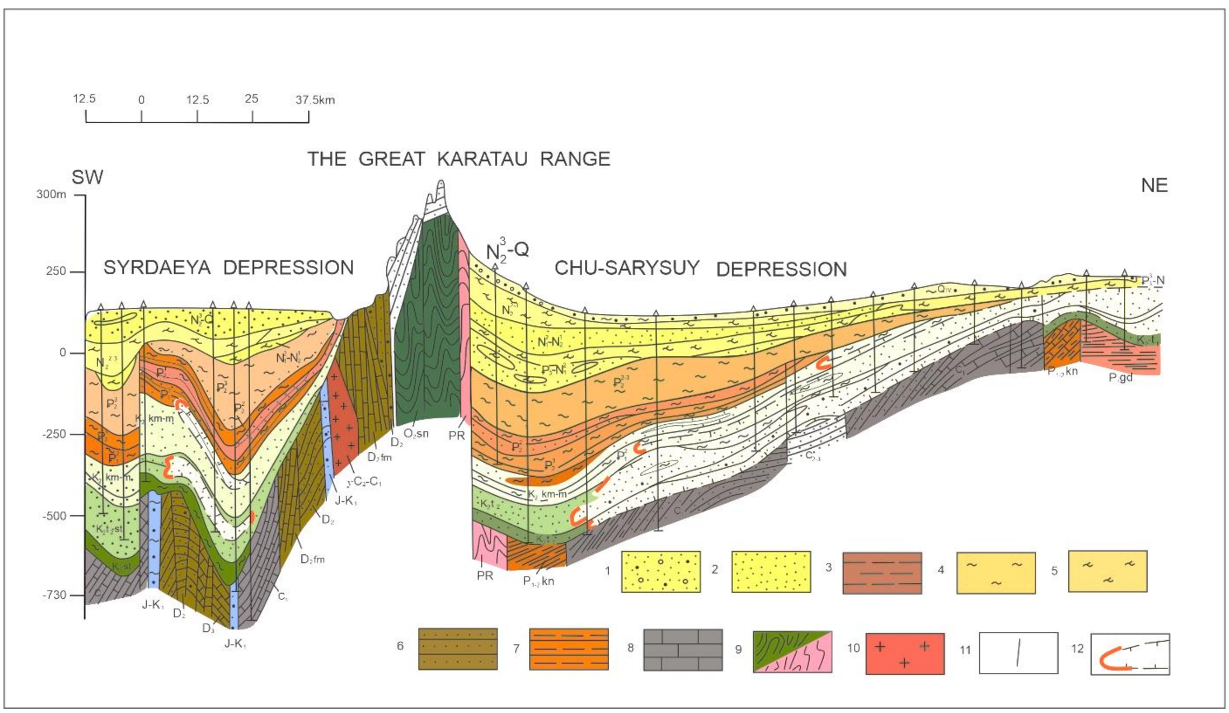

Figure 4. Geological section through the Syrdarya and Chu-Sarysu depressions
Legend. 1-granular sands; 2-fine-grained sands; 3-siltstones; 4-clays and siltstones; 5-calcareous clays; 6-sandstones; 7-siltstones; 8-limestones; 9-meta-sandstones (a) and crystalline schists (b); 10-granitoids; 11-faults; 12-wedging out boundaries of the FOZ and uranium mineralization (according to Petrov *et al.,* 2008)

Uranium ore provinces, which are also artesian basins of the same name, differ from each other in the specific conditions of formation of uranium mineralization. While within the Chu-Sarysu and Syrdarya provinces uranium ore formation in terms of mineral forms of migration, content, and physicochemical parameters is quite comparable, the formation of uranium deposits in the Central Kyzylkum is significantly different.

The Mesozoic-Cenozoic deposits that make up the marginal part of the platform of the Chu-Sarysu artesian basin have a very gentle, almost horizontal bedding (the dip azimuth rarely exceeds 3–5°). Therefore, the hydrodynamics of these aquifers are characterized by low groundwater filtration parameters. In connection with this, the transportation of uranium deposits occurs significantly more slowly than in the neighboring Syrdarya and Central Kyzylkum provinces, and the uranyl-carbonate complexes, when destroyed, form mainly poor uranium concentrations (Fig. 4).

Despite this relatively "sluggish" hydrogeological regime, the Chu-Sarysu depression is characterized by wide uranium ore fields removed from the source by tens and sometimes hundreds of kilometers, showing complete crystallization of uranium minerals—ranging from rich "barrier" to ordinary and poor ores (Fig. 5, A). In contrast, the platform deposits of the Syrdarya basin have dip azimuths from horizontal to 5–10° (and up to 30° in its central part). Therefore, hydrodynamic processes here are more intense, and the formation of uranium mineralization is somewhat faster than in the neighboring Chu-Sarysu, but much slower than in the Central Kyzylkum (Fig. 5, B). The latter is located in the mobile tectonic zone of the Southern Tien Shan—a subplatform orogen—and represents small artesian depressions where an active hydrodynamic regime prevails. Here, the migration of uranium occurs so quickly that the mineralization of "barrier" and sometimes rich ores often does not have time to crystallize (Fig. 5, C, D).

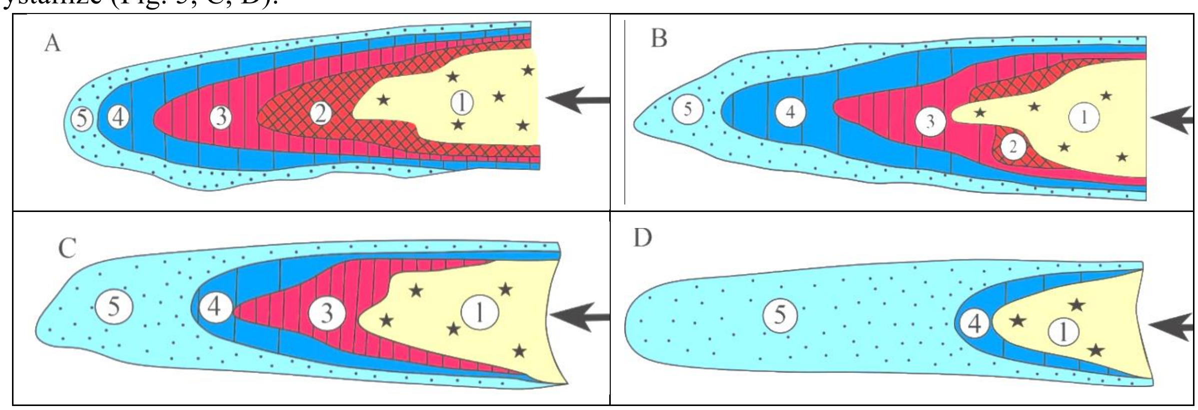

Figure 5. Schemes of formation of oxidation zone (FOZ) and uranium mineralization in uranium ore provinces.

Provinces: A. Chu-Sarysu, B. Syrdarya, C. Central Kyzylkum (typical); D. Central Kyzylkum (abbreviated). Legend. Zones: 1 – limonitization, 2 – rich (barrier) uranium ores, 3 – ordinary uranium ores, 4 – poor uranium ores, 5 – pore uranium ores. Arrow – direction of formation water movement) (Natalchenko & Goldstein, 1982)

NEW PROSPECTS FOR THE DEVELOPMENT OF URANIUM DEPOSITS

During ore formation, regional faults of the Central Kyzylkum massif play a crucial role as ore-forming and ore-conveying structures. At the same time, a characteristic feature of most second-order tectonic disturbances is a consistent decrease in their severity and amplitude from bottom to top in the Mesozoic-Cenozoic cover. Many of them displace sedimentary layers in the lower parts of the section and quickly attenuate upward, transforming into flexural-fault and flexural zones. Therefore, the relatively high degree of dislocation of the platform depression region is actually only apparent, due to the deeper erosional truncation observed here and the lesser thickness of the overlying Paleogene and Neogene deposits.

In artesian basins of the Central Kyzylkum type, dome structures represent local areas of uplift from which localized zones of formation oxidation develop. The increased tectonic activity of such basins typically creates conditions for the possible burial of formation oxidation zones within them (Evseeva, 2002; Karimov *et al.,* 1996; Shmariovich *et al.,* 1988). These basins are characterized by intensive reworking of water-bearing rocks by thermal hydrogen sulfide or gley solutions, leading to sulfidization, silicification, gleyization, and other transformations. In other words, the geodynamic regime forms a specific hydrogeological structure with a specific geochemical specialization.

As early as the late 1980s and 1990s, the formation of other useful components along with uranium on the line of wedging out of the FOZ became known (Goldstein *et al.,* 1992; Pechenkin & Grushevoy, 2015; Shmariovich, 2007; REDBOOK, 2025). In particular, at the Northern Kanimekh deposit, mineral forms of Sc, Re, Mo, V, and Se were established together with uranium, and later, concentrations of Y, Yb, Eu, and Lu were also found near the FOZ. High contents of Re, Mo, Sr, Y, and As were recorded at the Aulbek uranium deposit. Research by specialists (Natalchenko *et al.,* 1989; Shmariovich *et al.,* 1988) showed that this complex of useful components is also characteristic of other deposits of the Uchkuduk type—Beshkak, North and South Bukinay, Sabyrsai, and others.

Subsequently, the assumption about the complexity of mineralization at hydrogenic infiltration deposits of Central Asia received further confirmation and specific development (Bao & Zhao, 2008; Baskara *et al.,* 2024; Dakalo *et al.,* 2021; Pointurier *et al.,* 2015; Kato *et al.,* 1998; Mercadier *et al.,* 2011; Long *et al.,* 2010; Varga *et al.,* 2010). Further research into uranium deposits has shown that almost all exogenous epigenetic uranium deposits located in the Tien Shan megaprovince are complex. Most importantly, rare-earth elements (REE) are also controlled by formation oxidation zones and have the same localization scale as uranium. This crucial conclusion predetermines the future potential of uranium ore regions as sources of polyelement mineral resource bases in Central Asia.

The multicomponent metallogenic specialization (U, Se, Re, Mo, V, Sc, Rb, Hf, etc.) of the megaprovince's uranium-bearing complexes is associated with a single Alpine stage of exogenous epigenetic ore genesis in the Mesozoic-Cenozoic sedimentary cover of the Turan Platform. Therefore, the formation of rare-earth element concentrations in the uranium mineralization zone indicates a corresponding specialization of either the ore-bearing aquifers or the rocks of modern groundwater recharge areas. It has been demonstrated that useful components—primarily rare and rare-earth elements—can be localized not only on the high flanks of artesian basins but throughout their entire length, including formation water discharge zones (see Fig. 2). The ore-forming front of the FOZ, advanced by oxygen-containing groundwater, can form a geochemical barrier at a certain stage of its movement, accumulating a complex of useful elements in a strictly defined geochemical zonality.

Each of the types of groundwater identified in the regional discharge centers carries a specific set of elements that precipitate from solution at the wedging out of the FOZ, forming ore concentrations and potentially industrial deposits of the corresponding elements, such as:

- **In hydrocarbon sodium chloride brines**: Concentrations of J, Br, and B;
- **In carbon dioxide-hydrogen sulfide waters**: S, Sr, Ba, Cu, Mo, Fe, Mn, Co, Ni, Cr, Sc, and Y;
- **In infiltration oxygen waters**: U, Re, Sc, Se, Mo, V, Sr, Y, Hf, Au, and Ag;
- **In infiltration gley waters**: Al and lanthanides.

At many sandstone-type uranium deposits in the Central Kyzylkum, a clear spatial relationship is observed within the formation oxidation zone between the concentrations of Sc, Y, and La, which are an order of magnitude or more higher than their background values. This may indicate that the concentrations of rare-earth elements at the wedging out of the formation oxidation zone, as well as U, Se, Re, and Mo, are formed by a single formation infiltration process.

As a result, the following patterns of co-formation of certain complexes of useful elements were determined for the sandstone-type uranium deposits of the Central Kyzylkum uranium ore province:

- **In the selenium zone**: Mineralization is concentrated in Rb, Yb, Ta and V;
- **In the zone of ordinary and poor uranium ores**: Eu, Gd, Er, Ga, and La are formed;
- **In the zone of rich uranium ores**: Ce, Re, Hf, Sc, Dy, Tb, Au, Sm, Tm, Lu and Y;
- **In the molybdenum zone**: Mineralization includes Nb, Ta, W and Tc;
- **In the gray-colored zone**: The maximum amount of acid-soluble forms of La, Eu, Gd and Er precipitate in ore rocks.

Transforming a wedging-out line from a monomineral (uranium) to a polymineral one dramatically increases the productivity of not only hydrogenous deposits but also black shale deposits, making them complex and increasing the value of the combined polyelement product several times over. As a percentage of uranium, reserves of other associated useful components can amount to (according to Kiziltepageology): total rare-earth elements (TR) – 7.5%, Sc – 1.5%, Y – 2%, V – 50%, Se – 50%, Mn – 200%, and Mg – 450%. High contents of lanthanide elements have also been recorded in productive solutions.

Below, from the same source, are data on the content of useful components associated with uranium (Table 1).

Table 1: The content of rare, rare-earth and noble metals in hydrogenic infiltration uranium deposits of the Central Kyzylkum (in g/t)

Element*	(1)	(2)	(3)	(4)	(5)
Sc	5.4–11	3.3–4.5	2.1–13.2	1.0–1.4	3.2–7.5
La	20–30	1.6–1.1	11–64	5.2–6.6	32–100
Ce	39–64	800–900	20–160	7–34	28–58
Sm	6–8	1.03–2.75	0.1–37	1.0–1.5	0.0–5.6
Eu	1.0	0.1–0.18	0.2–8.5	0.25–0.35	5.6–15.8
Gd	5–9	2.18–1.42	-	-	-
Tb	0.9–4.3	1.74–5.32	0.1–1.0	0.07–0.2	0.0–6.0
Dy	3–5	0.59–0.79	-	-	-
Er	2–4	3.68–1.23	-	-	-
Tm	0.2–0.3	0.69–0.11	-	-	-
Yb	0.2–4	0.15–0.22	0.8–21	0.4–0.9	0.6–2.2
Lu	0.6–1.0	0.26–1.77	0.1–0.5	0.02–0.08	1.2–3.2
Y	20–34	1.7–2.03	10–240	1.2–5.2	14–120
Hf	3.0–4.5	3.2–38	2.0–14	-	0.8–2.5
Ta	0.9–2.5	-	0.1–7.6	-	-
W	1.0–1.5	-	0.3–48	-	0.0–73.1
Cs	3.7–6.5	-	1.5–5.0	-	1.2–4.5
Sb	0.2–0.5	-	0.2–4.8	-	0.4–2.9
Rb	60–80	-	49–170	-	42–159
Ag	0.07–0.10	-	0.05–2.2	-	-
Au	0.001–0.004	-	-	-	0.1–2.0

*In the numerators – the clarks of the elements (according to Taylor & McLennan, 1988),
(1, 2, 3, 4, 5) – reference numbers of uranium deposits.

The metallogenic complex of useful components along the line of the FOZ wedging out includes not only rare and rare-earth elements but also noble ones. If there are gold sources in the bedrock (primarily alkaline granitoids), a significant accumulation of epigenetic gold is possible in uranium ore deposits, the extraction of which by in-situ leaching can be profitable. For example, at the Northern and Southern Bukinay deposits, the gold content in industrial solutions ranged from 0.030 to 0.305 mg/l, against a background gold content in formation waters of $1*10^{-6}$ mg/l. Concentrations of Au ≥0.1 g/t are found mainly in the zone of formation oxidation wedging out, while in the limonitization zone the gold content is 0.05–0.08 g/t and in the zone of unaltered rocks it is 0.001–0.08 g/t (Goldstein *et al.,* 1992; Natalchenko *et al.,* 1989; Shmariovich *et al.,* 1988).

The process of gold redistribution in the profile of epigenetic zoning was confirmed by sampling formation waters at the Northern Kanimekh deposit. Gold in the section of the ore-bearing horizon of the infiltration uranium deposit is localized, forming classic rolls between the inner boundary of the selenium mineralization and the outer boundary of the rhenium mineralization.

CONCLUSION

All sheet-infiltration and black shale deposits are complex and contain rare, rare-earth, and trace metals. Uranium-associated ores in hydrogenic deposits are controlled by regional fronts of sheet oxidation zones and exhibit areal development alongside significant reserves. Almost all sheet oxidation zone wedging-out lines may be of commercial interest, even those that are not controlled by uranium mineralization.

All uranium-associated elements can be extracted in the same technological mode as uranium using in-situ leaching (for infiltration deposits) and heap leaching (for black shale deposits). For example, at the Kushkuduk deposit, according to the feasibility study, the annual production of the following metals was planned (in tons): uranium – 260; vanadium – 1225; scandium – 4.7; yttrium – 19.7 and ΣREE - 48.6. In the strip of the formation oxidation zone, a number of ore elements exhibit mobility: Au, Ag, La, Ce, Nd, Co, Sb, Cs, and Rb. At the same time, it is emphasized that profitable mining is only possible with certain concentrations of associated elements in industrial solutions.

Numerous publications concerning the formation of rare-earth elements, especially in relation to uranium deposits, clearly indicate a sharp increase in their popularity as the most important ores of the 21st century (Mineral Resources of High-Tech Metals, 2024; Kanazawa & Kamitani, 2006) and, therefore, emphasize the need for detailed research into the genesis, mineralogy, and geochemistry of the REY-complex with the aim of their further industrial development (Deep-sea mud..., 2011).

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