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FORECASTING ROLL-FRONT URANIUM PROVINCES BASED ON INTEGRATED GEOLOGICAL AND SATELLITE REMOTE SENSING DATA

An innovative approach has been developed to predict prospective areas for the exploration of roll-front uranium deposits. This method is based on the infiltration model of ore formation and incorporates the advanced exploration practices of roll-front uranium deposits in Kazakhstan, compared with global experience. The approach employs publicly available satellite Earth observation data alongside global geological datasets. Applying this methodology has allowed the identification of prospective areas for roll-front uranium ore exploration and provided a brief characterization of the most significant ones. Special attention is given to large depressions conducive to infiltration conditions, ranging from regions of atmospheric water recharge in arid and semi-arid climates to sedimentary areas under reverse climatic conditions with favorable environments for the formation of reductive geochemical zones. These zones are characterized by active sulfate-reduction processes mediated by microorganisms and the generation of hydrogen sulfide fluids.

Keywords: *uranium mineralization, roll-front, forecasting, ore formation model, exploration*
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Introduction

The development of nuclear technologies in the 20th century enhanced the industrial importance of uranium resources, increasing global attention to them [1]. In the latter half of the 20th century, large-scale exploration and prospecting activities for uranium led to the discovery of numerous deposits worldwide [2]. By the late 20th century, the rate of new discoveries had declined, while sustained high demand for uranium continues to drive the depletion of mineral resources [3]. In the 21st century, uranium production has outpaced the replenishment of its mineral resource base [4], prompting the need for innovative approaches to uranium ore exploration. The highest demand is most effectively met by deposits mined using the advanced in-situ recovery (ISR) method [5], predominantly represented by roll-front uranium deposits in Kazakhstan [6].

The genesis of roll-front uranium deposits is influenced by the solubility of uranium in atmospheric and carbonated waters, its migratory capacity in artesian aquifers, and ore-forming precipitation at geochemical barriers in reductive environments (**Fig. 1**). The depths of such deposits range from tens to over a thousand meters. Their exploration is complicated by deep burial under thick sedimentary cover, which significantly limits the effectiveness of airborne gamma surveys. Consequently, core drilling and borehole geophysics have proven most effective. Given the high costs and challenges in scaling such exploration activities, precise localization and a rational methodology are essential at every stage. The infiltration model of ore formation [7] provides clear criteria for prospective areas that can be relatively easily forecasted [8–10] for discovery.

Modern satellite Earth observation data, combined with geological portals that provide data, offer open-access materials for predictive research. An integrated analysis of these materials, using an innovative approach, enables cost-effective and time-efficient forecasting of large prospective areas for roll-front uranium ore deposits. This study analyzes publicly available satellite data and geological materials to substantiate forecasts of the most promising areas for roll-front uranium deposits worldwide.

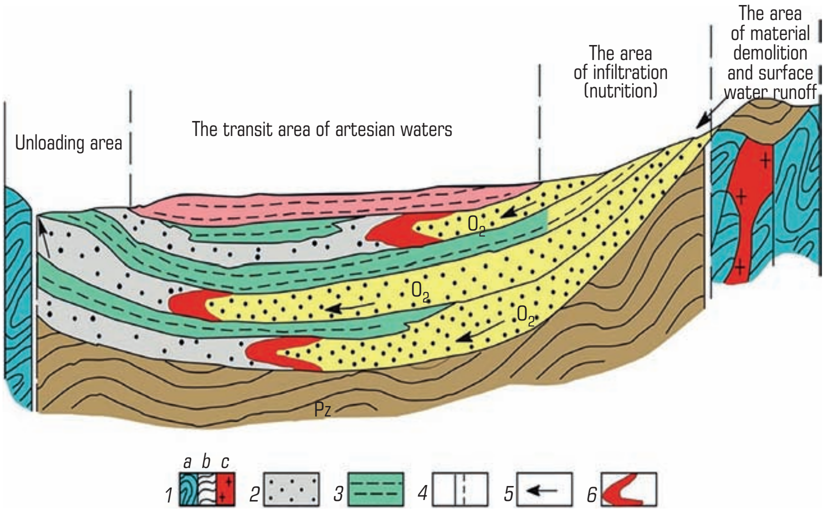

Fig. 1. Infiltration ore formation:
1 – pre-Mesozoic formations: *a* – metamorphosed Precambrian and Lower Paleozoic; *b* – lithified sedimentary Middle-Late Paleozoic; *c* – Intrusive; *2–3* – Mesozoic-Cenozoic deposits: *2* – gravel-sand, *3* – clay; *4* – large rupture faults; *5* – direction of the main flows of uranium-bearing oxygen waters; *6* – uranium ore deposits

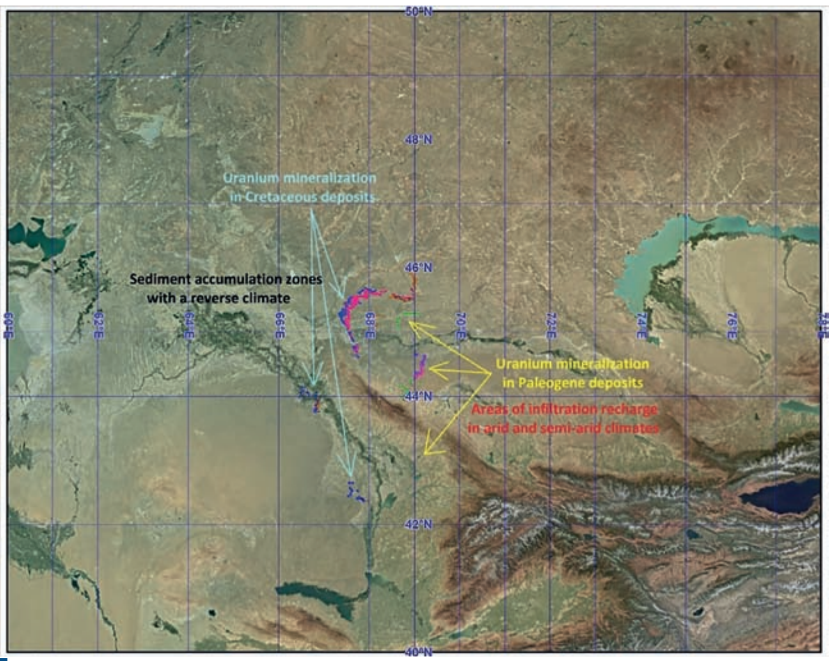

Fig. 2. Shu-Sarysu and Syrdarya Uranium Provinces (Satellite and Relief)

Methodology

The theoretical foundations of this method were partially explained during its development [8]. To continue the work on a global map, additional materials were integrated [11–13], and the method was expanded and refined. In the initial stage, preparatory works were revisited: detailed data from the Shu-Sarysu and Syrdarya roll-front uranium provinces in southern Kazakhstan—leading sources of natural uranium globally—were analyzed. Cartographic information from latitudes 40°–50°N and longitudes 60°–78°E, along with adjacent territories, was reviewed. Summarized uranium mineralization data were plotted on a small-scale map, and regional uranium ore localization was analyzed concerning major ore-controlling factors. Maps of these uranium provinces were prepared using open-access remote sensing data combined with geological exploration data (**Figs. 2** and **3**).

Relief maps were generated from satellite data and combined with visible light satellite imagery (RGB) to display surface climatic conditions against the backdrop of modern geotectonic relief at a detail level closely tied to ore-controlling factors. Summer daytime imagery with color palettes suitable for visualizing climatic conditions was preferred. Among numerous public satellite imagery services, Google Maps color scheme was selected for its effective display of climatic and landscape features combined with relief (see Fig. 2 and **Fig. 4**). Unlike prior studies, "https://maps-for-free.com" was used for relief visualization [14], with transparency set at 80% to enhance visibility of climatic conditions (see Fig. 2). This approach proved more suitable for global map construction (see Fig. 4). Color combinations ensured relief harmony with the climatic palette of study areas, with sufficient detail and quality for small-scale global research. For coordinate-referenced map creation, SASPlanet software [15] facilitated downloading and seamless stitching of thousands of satellite images. Combined maps were integrated into Mapinfo Professional, with 80% transparency applied to upper layers, and further enriched with thematic data (see Figs. 2, 3, 4 and **5**). To assess representativeness, the resulting maps were compared with geology (see Figs. 3 and 5) and IAEA uranium provinces and deposit maps [16]. Particular attention was given to foreland depressions in arid and semi-arid settings, with extensive outcrops of Mesozoic and Paleogene strata overlain by younger sediments toward zones with moderate or humid climates. These regions are favorable for forming large artesian basins with oxygenated and carbonated water recharge zones, capable of dissolving uranium and allowing enriched groundwater migration toward sedimentary regions in reverse paleoclimate zones. These zones, enriched with organic elements, impede further oxidation and provide a nutrient medium for ore-forming reductive geochemical barriers within roll-front oxidation zones. Older and younger sedimentary formations are less conducive to hosting all necessary conditions for large-scale roll-front uranium ore formation at a regional level. Mesozoic and Paleogene host rocks are most favorable for forming large uranium provinces [17] due to optimal artesian structures, differentiated permeability facies in reverse tectonic and climatic settings, and prolonged epigenetic ore-forming processes. Neotectonic activity signs along the dip of potential host strata [18] were also considered, as they promote discharge areas supporting groundwater movement (see Fig. 1) and regions

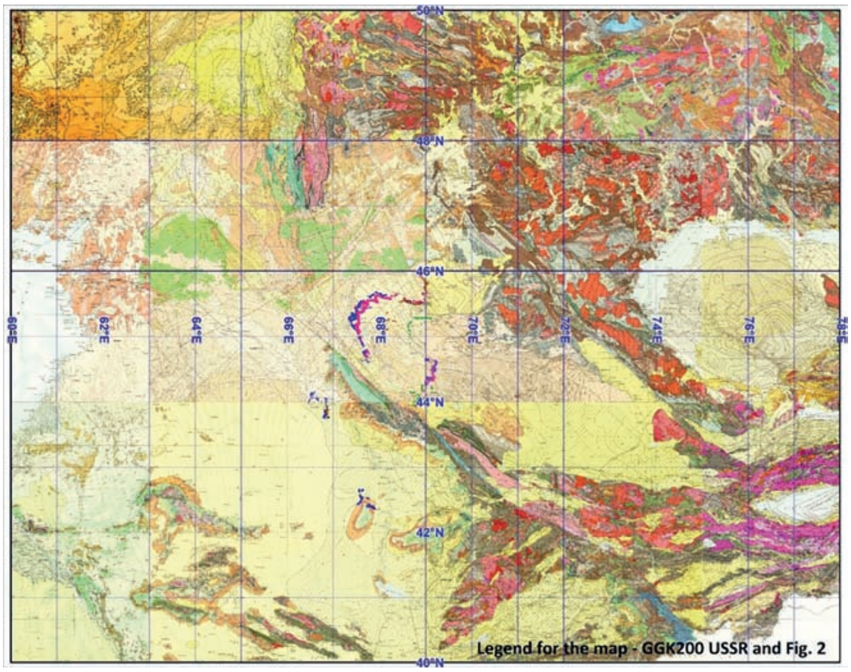

Fig. 3. Shu-Sarysu and Syrdarya Uranium Provinces (Geology)

with limited water exchange suitable for sulfate-reducing microorganisms that form reductive barriers with organic and fluid nutrition. Thus, zones with complex tectonic and geological conditions, featuring Mesozoic and Paleogene strata exposed at the surface and overlain by younger sediments, were identified. The global map (see Fig. 4) was compared with public data on global uranium deposits [19] and the world geological map (see Fig. 5). Based on these results, prospective areas for roll-front uranium province exploration were proposed (see Figs. 4 and 5).

Results and discussion

The satellite map, supplemented with relief and uranium mineralization zones of the Shu-Sarysu and Syrdarya uranium provinces, clearly highlights ore localization in sedimentation zones near climatic reversal zones, distant from foreland rock outcrops in arid and semi-arid settings (see Fig. 2).

On the geological map, uranium ore localization is characterized by a complex belt-like arrangement in depressions between rock outcrops of varying ages, from the Central Kazakhstan Shield in the east, the Tien Shan mountains in the south, to the younger uplift of the Karatau Ridge dividing the Pre-Tien Shan uranium province into Shu-Sarysu and Syrdarya, and the northern Mesozoic outcrops in the Zhezkazgan depression (see Fig. 3).

Geological settings impacting epigenetic uranium ores can be divided into three main categories:

· Enriching: mainly rock outcrops undergoing weathering processes, releasing uranium compounds for dissolution by atmospheric and carbonated waters, followed by infiltration to significant depths. Hydrothermal and vein enrichment of roll-front uranium provinces is relatively minor.

· Hosting: sedimentation of sandy-silty deposits with filtration coefficients of 1–10 m/day, conducive to forming reductive geochemical barriers due to microorganism-mediated sulfate reduction.

· Depleting: neotectonic destruction of epigenetic ores via altered hydrogeological regimes and cementation processes.

Optimal distances of hosting horizons, tens to hundreds of kilometers from enriching sources, favor the scale and quantity of uranium formations. Proper positioning relative to depleting settings ensures large-scale ore preservation under constant hydrodynamic regimes. Conversely, the complete absence of any of these categories within the first few hundred kilometers indicates a lack of significant uranium provinces, given the necessity of geochemical and filtration differentiation of deposits, along with established hydrogeological regimes for large-scale uranium mineralization accumulation.

Based on these considerations, satellite maps with relief (see Fig. 4) and global geology (see Fig. 5) were thematically supplemented with existing major uranium provinces (blue line contours) and potential areas for uranium province exploration (red line contours).

According to the criteria, 37 areas ranging from hundreds of thousands to millions of square kilometers were identified on the global map as potentially hosting large roll-front uranium provinces. These areas are of interest for conducting regional radio-hydrogeochemical surveys at a 1:1,000,000 scale to monitor radionuclide, mineral, and electrochemical composition changes in regional groundwater. Recharge zones of uranium provinces are characterized by positive electrochemical potential (around +200 mV), relatively low total mineralization (usually up to 1 g/l), and enriched radionuclide chemical composition (>10 μg/l U). Discharge zones feature negative electrochemical potential (around –200 mV), relatively high total mineralization (usually >10 g/l), and depleted radionuclide composition (around 1 μg/l U) [16]. At the transitional zone boundaries, structural geological mapping with core drilling is recommended to identify epigenetically oxidized facies horizons, regional aquitards, and reductive or epigenetically unaltered zones with negative electrochemical potential for geological prospecting. Exploration should involve continuous mapping of oxidized and reductive settings, searching for roll-front uranium cross-sections at their boundaries. These sections typically exhibit belt-like forms, hundreds of meters wide, tens of kilometers long, and thicknesses from a few meters to tens of meters. Drill core should be measured with portable radiometers and correlated with gamma logging data. Belt-like forms and distinct uranium deposit dimensions also favor indirect surface methods related to soil anomalies [20], such as isotopic-soil and other methods.

Of particular interest on the global map is the Arabian Peninsula. Despite its distance from climatic reversal zones and lack of pronounced geological-tectonic complications, this region possesses an extensive sedimentary basin with a vast recharge area of arid atmospheric precipitation and a unique petroleum basin beneath a potentially viable geochemical barrier. Faults near oil fields, such as Ghawar, may introduce significant hydrogen sulfide fluids into overlying Mesozoic and Paleogene aquifers, intersecting infiltration flow and forming reductive geochemical barriers akin to the Uchkuduk-type uranium provinces (Uzbekistan). These conditions could result in unique uranium deposits at relatively great depths (>1 km).

Detailed investigation of each potential zone requires individual studies, which would be too extensive for this work and are thus concluded here.

Conclusions

Roll-front uranium ores, the primary source of natural uranium due to their cost-effectiveness and scalability, form under widely distributed conditions on Earth. However, their discovery is hindered by deep burial under thick sedimentary cover, relatively narrow orebody widths in plan view, and low orebody thickness in sedimentary basins. Amid global uranium resource depletion, trends toward cost reduction and optimization in their discovery emerge. Breakthroughs in satellite Earth observation and computational technologies have made valuable materials publicly accessible, enabling solutions to the primary challenge of uranium ore depletion—the high cost and complexity of exploration. Step-by-step algorithms from forecasting, regional studies, reconnaissance surveys, to exploration and resource estimation offer a rational approach to

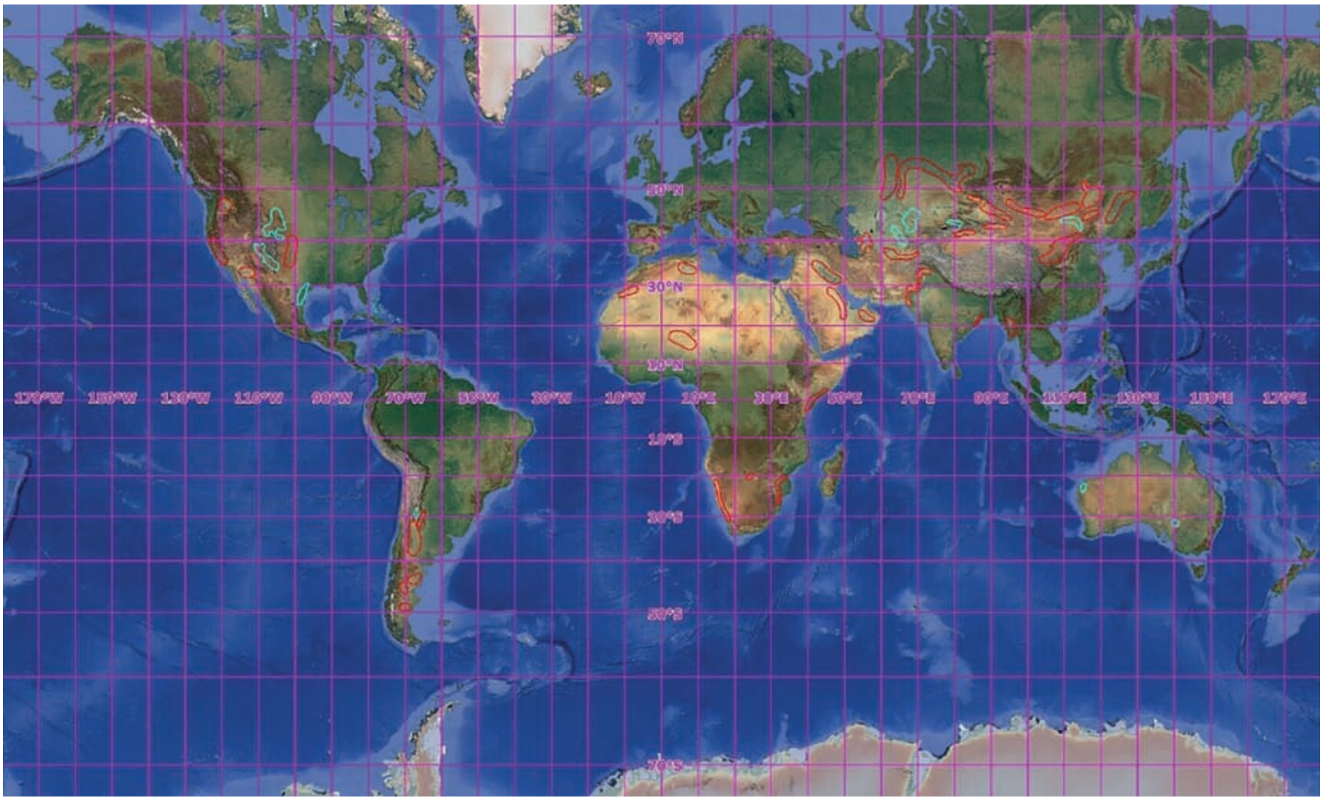

Fig. 4. Forecasting Uranium Provinces on the World Map (Satellite and Relief)

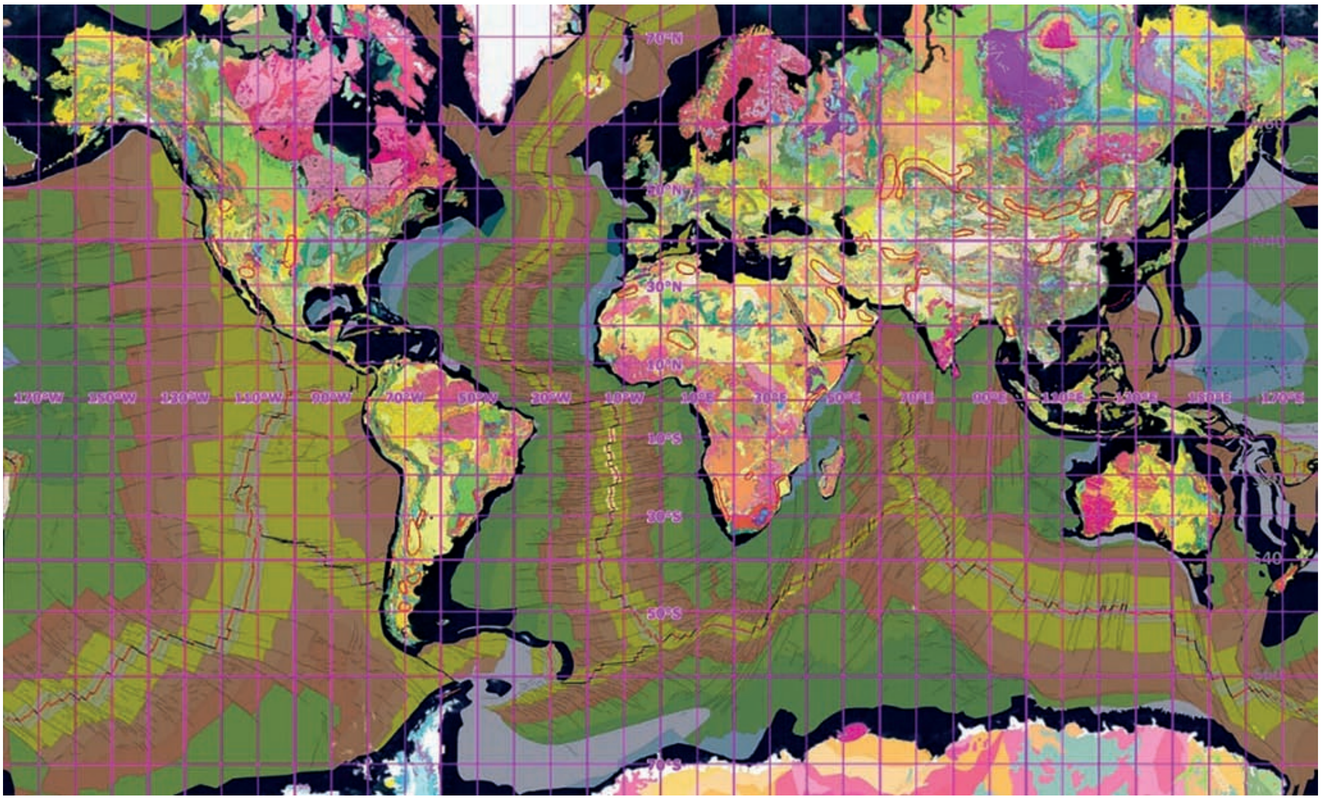

Fig. 5. Forecasting Uranium Provinces on the World Map (Geology)

addressing the deficiency in replenishing the world's uranium mineral resource base.

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GENETIC PRIMARY SOURCE–PLACER CONNECTION AS A CASE-STUDY OF THE GORNY PRIISK GOLD DEPOSIT, AVZYAN ORE PLACER FIELD, SOUTHERN URALS

The study of the Avzyan ore placer field shows that native gold of the Gorny Priisk deposit is predominantly small (up to 0...n mm) and has a high fineness (955–980). The main impurity is silver 3–5 wt.%, and insignificant amounts of Bi, As, Sb, Se, Te and Ni are observed. Morphologically, gold represents spongy and dendritic forms. Microparticles of very high-fineness secondary gold 0.1–0.5 μm in size are observed on the surface of grains.

Gold of the Kamenny Klyuch placer is larger and has a lumpy and irregular shape. This is a high-fineness gold (926–979) with a similar set of impurity elements. The morphology of gold grains from the Kamenny Klyuch creek deposits clearly indicates their short distance from the primary source.

The alluvial gold of the Avzyan placer has the largest sizes and belongs to the medium and large size categories with good roundness. The fineness of gold is 939–971. It is characterized by hypergene neoplasms on the grain surface in the form of a high-fineness rim. Grains covered with amalgam with mercury content up to 20 wt.% are revealed, which indicates the induced contamination of the area of mining.

A genesis and geology model of the bedrock–weathering crust–alluvial placer systems was built. It is shown that the valley of the Bolshoy Avzyan river is a valley of inherited development. The presence of gold of varying roundness (from poorly rounded to well-rounded grains with a high-fineness shell) is reflective of gold flow to the placer from the weathering crust (Gorny Priisk) through intermediate reservoir rocks (Kamenny Klyuch).

Keywords: *Southern Urals, Avzyan ore placer field, Gorny Priisk, native gold, placer, Zigaza–Komarovo formation, Riphean, weathering crusts, black shales*
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