EARTH SCIENCES

PROSPECTING FOR ORE DEPOSITS HIDDEN UNDER GLACIERS IN THE ARCTIC REGIONS

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Abstract

The article considers the results of geochemical studies conducted in the area of the high-mountain gold ore deposit Kumtor Sredinny Tien Shan. The work was focused on cold and warm glaciers: Petrov, Sary-Tor, Davydov, Lysy, No. 354 and Boordu, overlapping the mineralized zone and ore bodies. It was established that cryogenic geochemical fields (CGF) are formed in the ice of glaciers. The chemical composition of the CGF of glaciers reflects the composition of ore bodies and endogenous halos of the Kumtor deposit. The features of the CGF formed on the surface of glaciers in the epicenters of ore bodies with an established ice thickness of up to 175 m are characterized. The extent of geochemical anomalies of the CGF on the surface of glaciers from the epicenter of the ore body in the direction of ice movement varies from 50-100 to 600 m. Recommendations are given for the use of CGF in forecasting and prospecting work in glacial areas in the Arctic.

Keywords: ore deposits, geochemical prospecting, glaciers, the Arctic

Introduction

Large and easily discoverable mineral deposits in Russia are nearly exhausted. Geologists are forced to push ever deeper into the Arctic zone and remote regions of Siberia. The vast territory of Russia's Arctic zone holds promise for the discovery of new large deposits of strategic metals [1]. However, geological and geogeophysical research, as well as the state of the region's infrastructure as a whole, are insufficient to fully integrate their mineral resource base into the country's economic activity [2]. Inaccessible areas of the Russian Arctic still contain "blank" areas—completely unexplored territories. These territories include glaciated regions, the glacier-covered islands of the Russian Arctic, and the subarctic mountainous regions of the North, Northeast Siberia, the Koryatsky Highlands, and Kamchatka. According to the "Glaciers of Russia" database [3], there are currently 7,478 glaciers in the Russian Federation, grouped into 22 glacier systems. The largest glacial systems by area are located in the Arctic on the Novaya Zemlya (over 22,000 km2), Severnaya Zemlya (16,500 km2), and Franz Josef Land (12,500 km2) archipelagos. New large deposits may be located and discovered in glacier-covered Arctic and subarctic territories. In recent years, high global prices for precious metals have been one of the main drivers of geological exploration in remote Arctic regions. Historically, gold has been the primary target for geological exploration in these areas [4]. An example of such a deposit, partially located beneath a thick layer of glacial ice, is the Kumtor gold deposit. The deposit is located in the eastern part of the Central Tien Shan on the northwestern macroslope of the Ak-Shyirak glacier massif, at an altitude of over 4,000-4,200 meters above sea level, in the permafrost zone. The Ak-Shyirak mountain range is a weakly dissected mountain uplift with an average absolute elevation in the central parts of approximately 4,600 m. The relief is glacial: large glacial cirques and cirques with modern glaciers alternate with steep ridges and flat watersheds. The ice thickness of the Ak-Shyirak glaciers in the Kumtor deposit area averages 60-100 m, with a maximum of 175 m (Table 1).

Table 1.

Ice thickness of the Ak-Shyirak glaciers in the Kumtor deposit area, m [5]

Glaciers		Average	Maximum
Petrova		70	173
Lysy		60	-
Davydov	Eastern	90	175
	Central	100	160
	Western	85	170
Sary-Tor		-	165
Boordu		100	-

The climatic conditions are associated with the intra-mountain location of the region and are characterized by significant continentality and a harsh climate with a negative average annual temperature of -7.8 °C, which is comparable to the harsh climatic conditions of the Arctic (Novaya Zemlya) [6]. The coldest month is January, and the warmest is July. The absolute minimum temperature is -45 °C. The average long-term annual precipitation at the Tien Shan hydrometeorological station during the baseline observation period of 1961-1990 was 371 mm, of which only 49 mm, or 13.2%, fell during the cold period (November - March). The bulk of precipitation falls during the warm period, with most of it in the form of snow and only 8% of the annual amount falling as liquid precipitation, which is observed on only 11 days a year. Permafrost is continuously distributed, 90-370 m thick, and temperatures range from minus 1.7 to 4.9°C. Talik zones are found only beneath large valley glaciers [7]. The main waterway is the Kumtor River and its left tributaries, the Sarytor and Boordu Rivers. In winter (December-February), the rivers freeze to the bottom. The Kumtor gold deposit is unique in its reserves, making it a world-class gold mine. It is among the five largest mines in the world by gold reserves, with confirmed and projected reserves amounting to approximately 700 tonnes. From the start of commercial production in May 1997 to June 30, 2022, Kumtor has produced over 430 tonnes of gold [10]. The Kumtor mine is located at elevations of 3,600-4,400 meters above sea level in the nival-glacial belt of the Tien Shan. The Kumtor gold deposit is one of the highest-altitude deposits in the world, along with, for example, the Pascua Lama gold and silver mine, located at elevations of 4,800-5,200 meters. The geological structure of the deposit area is determined by its belonging to the miogeosynclinal zone of the Caledonian-Hercynian folding of the Tien Shan. Thick strata of Riphean-Vendian metavolcanic sedimentary rocks unconformably overlie the ancient granite-gneiss basement. The rocks are represented by high-carbon and siliceous schists and phyllites. Granitoid and metasomatic rocks are located along faults. The Kumtor gold-(tungsten)-sulfide deposit is controlled by the Main Mineralized Zone, along the strike of which metasomatites and mineralization are located. Ore bodies are localized in the Kumtor shear zone, more than 7 km long and 300-400 m thick. The deposit is partially hidden under thick ice layers of the Davydov, Sary-Tor, Lysy, Petrov, No. 354, and Bordu glaciers. Currently, the gold-bearing ore body being developed lies near and under the Lysy, Davydov, and Sary-Tor glaciers. The flanking areas: Petrov, Bordu, and other glaciers are promising [8]. The ore bodies are represented by linear mineralized zones with disseminated-veinlet and stockwork mineralization, which have distinct structural and lithological-stratigraphic controls, manifested in the confinement of the ore bodies to a zone of increased tectonic deformations in a carbonaceous pyrite-bearing phyllitic ore-bearing formation. The main ore mineral, which is associated with the bulk of the gold, is pyrite. The content of sulfides in the ores ranges from 5 to 20-30% (averaging 15-20%). The ore field is accompanied by complex endogenous geochemical halos: Au, Ag, Mo, W, Pb, Zn, Cu, Co, Ni, Ba, Ti, Mn, V, Be, K, and Na. The ore bodies are productive gold-tungsten-sulfide "deposits" of pyrite-feldspar-carbonate metasomatites accompanied by contrasting endogenous halos of Au, Ag, Mo, W, K, and Na. The potential for geochemical prospecting for glacier-covered ore bodies was studied at the Kumtor gold deposit in 1988-1989. Geochemical fields in glaciers were studied in glaciers located in the eastern part of the inner Tien Shan (Kyrgyzstan). Geological exploration at the deposit at that time was in the exploration phase and was concentrated in the northwestern part of the ore field near the Davydov Glacier. The location of ore bodies on the flanks of the ore field beneath the overlying glaciers was unknown.

Research Methods

Geochemical studies were conducted in 1988-1989 on the northwestern macroslope of the Ak-Shyirak Ridge in the area of the Kumtor gold deposit. During this period, exploration work was conducted at the deposit in the area of the Davydov Glacier. The locations of ore bodies beneath the remaining glaciers were unknown. Geochemical studies focused on cold and warm glaciers: Petrov, Sary-Tor, Davydov, Lysy, No. 354, and Boordu, which overlie the Main Mineralized Zone and ore bodies.

On each glacier, exploration routes were completed along the glacier from its crest to its tongue, with ice samples collected from the glacier surface. Ice samples were collected from the glacier surface immediately beneath the firn. The distance between samples was 50-100 meters. A total of 93 ice samples were collected from each glacier. The sample weight of 1.0-1.5 kg was limited to the required volume of melted ice for a comprehensive water analysis—1 liter. Ice melting and water packaging in chemically clean containers were carried out at room temperature in the village of Kumtor at the field base of the high-altitude laboratory of the Permafrost Institute (IP) SB RAS.

Analytical processing of geochemical samples was conducted in Yakutsk. A complete chemical analysis of water (ice) was performed in the Cryolithozone Geochemistry Laboratory of the IPP SB RAS. An approximate quantitative atomic emission spectral analysis of the trace element composition of water for 35 elements and atomic absorption determination of gold (Perkin-Elmer, with a graphite cuvette) were performed at the Central Geological Laboratory of the PGO "Yakutskgeologiya." Mathematical processing of analytical hydro- and lithochemical data was performed in the IT department of the Yakutsk Territorial Geological Administration using standard statistical applications such as Geoanalytics and others.

Results and Discussion

Geochemical studies have established that complex anomalies of indicator elements for gold mineralization are observed on the ice surfaces of glaciers overlying the mineralized zone and ore bodies. These geochemical anomalies on the glacier surfaces are due to the formation of cryogenic geochemical fields of indicator elements within the glaciers overlying the ore bodies. The composition of the superimposed halos corresponds to that of the ore bodies and endogenous halos. Clear geochemical anomalies of elements that determine the geochemical characteristics of the system—typomorphic elements for the ore body and endogenous halos—were established on the surfaces of all glaciers overlying the ore bodies and mineralized zone: Au, W, Pb, Cr, Cu, and Sn (Fig. 1

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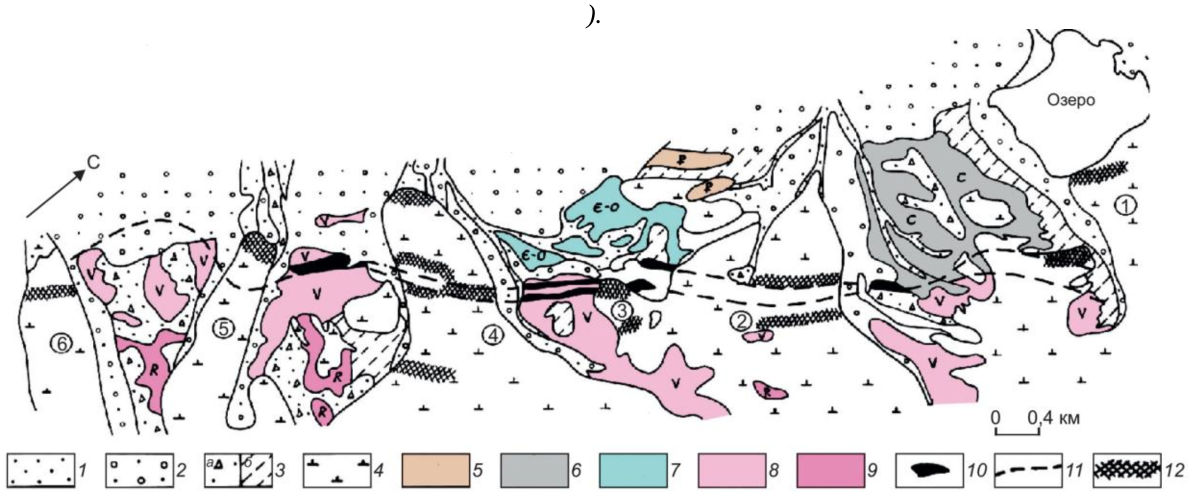

Fig. 1. Anomalies of cryogenic geochemical fields (CGF) on the surface of glaciers of the Kumtor ore field

Cenozoic deposits: 1 - alluvial, pebbles, sands; 2 - eluvial-deluvial, crushed stone, gruss, sands; 3 - glacial (a) and deluvial-proluvial (b), boulders, pebbles, crushed stone, sand, loams; 4 - glacial ice (glaciers: 1 - Petrov; 2 - Lysy; 3 - Davydov; 4 - Sary-Tor; 5 - Boordu; 6 - No. 354).

Geological formations: 5 - Paleogene and 6 - Lower Carboniferous sandstones, siltstones; 7 - Cambrian-Ordovician limestones; 8 – Vendian shales, phyllites; 9 – Riphean volcanogenic-sedimentary deposits; 10 – ore bodies; 11 – faults; 12 – cryogenic geochemical fields

Halos of gold and typomorphic elements are located on the glacier surface at the epicenter directly above the projection of the ore zone. The anomalies typically extend 150-200 m in the direction of glacier movement, sometimes reaching its tongue.

The southwestern flank of the Central Area of the deposit is overlain by the Davydov Glacier.

The glacier is 0.8-0.9 km wide at its base, and its ice thickness reaches 160-175 m, with an average thickness of 85-100 m. According to thermometry, the ice temperature is -6°C at a depth of 5 m and approaches the melting point at depths greater than 30 m. The depth interval of 40-109 m is filled with melted water, and the ice temperature in this interval is no lower than -0.5°C.

The glacier tongue is fractured in its middle and upper parts and is divided longitudinally into two branches by a medial moraine. The glacier branches exhibit varying activity. The surface velocity of the right branch of the glacier in summer is 1-2 cm/day; the left branch is more active, at 1-4 cm/day. The slope of the tongue is 5-6°. Below the glacier, between the tongue and the terminal rampart of moraine ridges 80-90 m high, there is a vast outwash field.

On the tongue of the glacier, the thickness of the accumulated snow layer varies from 20 cm at the base to 150 cm at the alimentation level, with a density of 0.36 g/cm³.

In cross-section, the glacier has an asymmetric structure, with the greatest ice thicknesses confined to its left side.

The bottom of the glacier is composed of ice with a relatively high content of moraine debris, with a total thickness ranging from several meters to 11 m. The upper layer of the glacier is composed of relatively clean ice. Geochemical sampling on the Davydov Glacier was conducted along two profiles along both branches of the tongue. Sampling intervals were generally 100 m. In areas where the ore zone is presumably overlain by a glacier, clear geochemical anomalies of elements typomorphic to the ore body and endogenous aureole are recorded on the glacier surface: Au, W, Pb, Cr, Cu, and Sn. The contrast of these anomalies, relative to the background content in glaciers of the Ak-Shyirak glacier massif, decreases in the following order: Au(20) - Pb(5) - Cr, Cu, Mo(3) - W, Sn(2).

The aureoles of typomorphic elements are located on the glacier surface at the epicenter of the ore zone, overlain by a thick layer of ice. The anomalies extend 150-200 m along the glacier's direction of movement. Two adjacent ore zones, northern and southern, are suspected to be located on the right branch of the tongue. These zones, exposed by subsequent mining operations (see Fig. 2), have a combined thickness of approximately 0.3 km and form a common anomalous region, extending approximately 600 m for gold and up to 900 m for sulfates.

Anomalies of indicator elements of gold mineralization on the surface of the Davydov Glacier form both above the ore body and within endogenous halos, reflecting the composition of the ore mineralization.

An increase in pH and Eh (with an Eh gradient of 70-84 mV) is observed directly at the epicenter of the ore zone. Indicator elements of endogenous halos—Cu, Mo, and Cr—form bimodal halos with modes on the sides of the ore zone projection [7]. Within the aureole formed above the ore zone, elevated contents of sodium and sulfate ions are noted. While somewhat more contrasting sulfate and sodium halos are recorded above the right branch of the Davydov Glacier, elevated contents of most heavy metals are observed above its left part. The extent of the aureoles also increases above the left branch of the glacier. For example, for gold halos, it almost doubles—from 0.7 km to 1.4 km. Moreover, the ice thickness is noticeably greater above the left branch of the Davydov Glacier. The extensive extent of the anomalies and their complexity indicate a more complex structure of the ore zone beneath the glacier and the existence of a sublatitudinal tectonic fault in the central part of the glacier. Indeed, the nature of the ore zone to the southwest of the Davydov Glacier changes significantly, as recorded during glacier penetration during subsequent geological exploration of the deposit [3, 5, 10]. Lysy Glacier is located 2.0 km northeast of the Central section of the deposit. A gold-bearing ore body is currently being mined within and beneath the glacier. Lysy Glacier is a hanging-type glacier located at elevations of 4,050-4,200 m. The ice thickness in the study area is 60 m. According to thermometry data from mine workings within the glacier, the ice temperature ranges from -6°C at the surface to -2.5°C at the bottom.

The glacier overlies the gold ore body for nearly 300 m (Fig. 2).

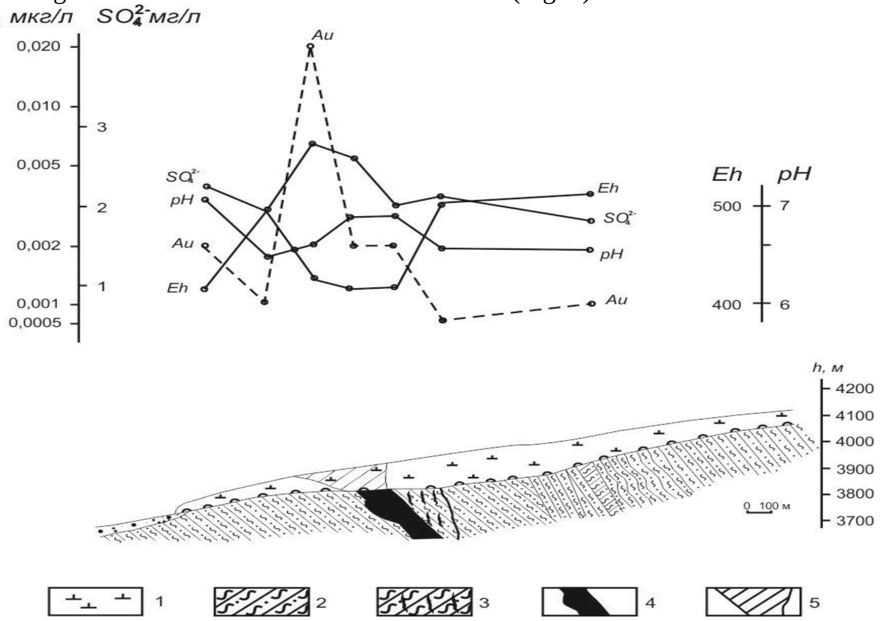

Fig. 2. CGP anomalies on the surface of the Davydov Glacier at the epicenter of the ore body.
1 - glacier; 2 - sandy-clayey shales; 3 - metamorphosed shales; 4 - ore metasomatites; 5 - endogenous and cryogenic geochemical halos

The base of the glacier, within the deepest part of the bed, is located at an elevation of 4,050 m. It has been established that the content of typomorphic elements in glacial ice in the contact zone with rock, 0.1-0.3 m from the ore, is tens of times higher than the background content in the glaciers of the massif. The penetration of chemical elements into ice is caused by cryogenic migration and the formation of a dispersion halo. The maximum contrast of the geochemical halo is observed directly at the contact of the ice with ore metasomatites and decreases with distance from the ore to the glacier surface. On the glacier surface above the ore

Anomalies of indicator elements for gold mineralization in the glacier form both above the ore body and within endogenous halos, reflecting the composition of the ore mineralization.

The distribution of chemical elements on the glacier surface is non-uniform. Directly at the epicenter of the ore body, anomalies of gold, zinc, copper, tungsten, and chromium are observed on the glacier surface with virtually no displacement. Negative anomalies above the deposit are formed by sulfates and the redox potential (Eh). In some places, a shift of gold halos toward the glacier tongue is observed, reaching 80 m in some areas. A number of indicator elements—Ag, Sn, Pb, Zn, Sc, and Be, form more contrasting anomalies on the glacier surface above the northeastern part of the enriched section of the ore body. Thus, superimposed cryogenic geochemical halos of indicator elements form within the glacier overlying the orebody. The composition of the superimposed halos corresponds to the composition of the orebody and the endogenous halos. More contrasting geochemical anomalies form above the richer sections of the orebody in the glacier. The vertical range of indicator element migration and, consequently, the thickness of the superimposed halos on Lysyi Glacier are limited by an ice thickness of 50-60 m.

The structure of cryogenic geochemical fields on the glaciers of the Kumtor deposit is characterized by qualitative (chemical elements and compounds) and quantitative (element concentrations, halos extent) parameters, regularly distributed within the ice mass on the surface. The composition of the cryogenic geochemical fields of the glaciers reflects the composition of the orebodies and endogenous halos at the Kumtor deposit (Table 2).

Table 2.

Composition of cryogenic geochemical fields (CGF) of glaciers and endogenous halos at the Kumtor deposit

Glaciers	Composition of cryogenic geochemical fields on the glacier surface	Length of cryogenic geochemical fields, m	Glacier thickness, m	Sources of KGP discovered by mining operations
Petrova	Au, W, V, Cr, Cu, Zn, Mo, Sn, Pb, Bi	250	70-173	Ore mineralization
Lysy	Cu, Zn, W, Au, Cr	200	60	Ore body
Davydov	Au, Pb, Cr, Cu, Mo, W, Sn, Na, S	200-600	85-175	Ore body
Sary-Tor	Be, Cu, Zn, Sn, Cr, Pb, Mn, Tl, Au, Mo,TR	50-100	165	Ore body
Boordu	Au, Cu, Zn, Mo, Sn, Pb, W, Bi, V, Cr, S	200-250	100	Ore mineralization
№ 121*	Au, W, Ag, Cr, Cu, Zn, Mo, Sn, Pb	100-150	50-60	Ore body
Kumtor deposit [8, 11, 12]				
Endogenous geochemical halos	Au, Ag, Mo, W, Pb, Zn, Cu, Co, Ni, Ba, Ti, Mn, V, Be, K, Na			Ore field
	Au, Ag, Mo, W, K, Na			Ore body

* a small hanging glacier in the area of the Davydov Glacier

The formation of local geochemical fields on the glacier surface occurs as a result of the upward cryogenic migration of chemical elements, including ore elements, from the ore body (endogenous aureole) to the surface within the glacial ice. The composition of the local geochemical fields corresponds to the composition of the ore body and the endogenous aureole (see Table 2). More contrasting geochemical anomalies form above the richer sections of the ore body within the glacier. The vertical range of indicator element migration, and consequently the thickness of the superimposed aureole, is limited by the ice thickness and ranges from 50-60 m (Lysy Glacier) to 165-175 m (Davydov, Petrov, and Sary-Tor Glaciers).

The thickness of glaciers in the continental and island regions of the Arctic and Subarctic can significantly exceed the ice thickness in the Kumtor deposit area (Table 3), particularly on Arctic islands (Severnaya Zemlya, Franz Josef Land, and others).

Table 3.

Thickness of glaciers in the island regions of the Arctic and Subarctic

Islands	Glacier thickness, m	Islands	Glacier thickness, m
Spitsbergen, Norway	80-500	Ushakov, Russia	250
Ellesmere, Canada	До 199	Franz Josef Land, Russia	300-450
De Long Island, Russia	**80 – 150**	Novaya Zemlya, Nordenskjöld Glacier, Russia	300-400
Severnaya Zemlya, October Revolution Island, Russia	up to 200-400	Severnaya Zemlya, Komsomolets Island, Russia	up to 500

The vertical range of cryogenic geochemical fields could theoretically reach hundreds of meters. The maximum thickness of their manifestation in the Middle Tien Shan (Kumtor) has not been established and is limited by the ice thickness of the studied glaciers – up to 175 m [5, 7].

The process of cryogenic migration of chemical elements during the formation of cryogenic geochemical fields is analogous to the cryogenic salt dispersion of ore components in permafrost deposits [13].

The concepts developed by Russian geochemists [13, 14, and others] regarding the characteristics of geochemical processes in the cryolithozone have made it possible to identify and study the previously unknown phenomenon of cryogenic salt dispersion of ore components. This phenomenon involves the migration of ore components from the ore body to the earth's surface (ice) at subzero temperatures in loose permafrost deposits and ice overlying ore bodies, caused by a concentration gradient of salts in non-freezing, ultra-thin films of bound water. In this case, superimposed cryogenic dispersion halos are formed over deep-seated ore bodies.

The high rate of formation of geochemical fields, their morphology, and the distribution of positively and negatively charged ions in ice on the glacier surface are satisfactorily explained by the electrochemical model of their formation [15, 16, 17].

Conclusion

Conducted studies have shown that geochemical methods are promising for solving the challenges of prospecting for ore deposits in glacier-covered Arctic and Subarctic regions.

Geochemical studies were conducted at the Kumtor high-altitude gold deposit in the Middle Tien Shan (Kyrgyzstan). The region's climate is characterized by its harsh climate, with an average annual temperature of -7.8°C, comparable to the harsh Arctic conditions (Novaya Zemlya, etc.). The study focused on cold and warm glaciers: Petrov, Sary-Tor, Davydov, Lysy, No. 354, and Boordu, which overlie the mineralized zone and ore bodies of the deposit. It was established that cryogenic geochemical field (CGF) anomalies form in the glacier ice at the epicenters of the ore bodies. The structure of the glacier-glacier ore bodies at the Kumtor deposit is characterized by qualitative (chemical elements and compounds) and quantitative (element concentrations, aureole extent) parameters, regularly distributed within the ice mass on the surface. The chemical composition of the glacier ore bodies reflects the composition of the ore bodies and endogenous aureoles of the Kumtor gold-tungsten deposit.

The glacier ore bodies form on the surface of glaciers at the epicenters of ore bodies with an established ice thickness of up to 175 meters. The extent of glacier ore body anomalies from the epicenter in the direction of ice movement ranges from 50-100 to 600 meters.

The formation of glacier ore body ore bodies on glaciers makes it possible to explore for mineral deposits overlain by thick ice sheets in the Arctic and subarctic regions of the North. In Russia alone, glacial systems in the northern regions of the country cover an area of approximately 53,000 km², within which large deposits can be found.

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