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Scientific note

The geochemical phenomenon—Local geochemical fields in a glacier

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Abstract: Geochemical fields in alpine cold and warm glaciers were studied. Local geochemical fields of typomorphic elements were found to form in the ice and on the surface of glaciers overlying ore bodies and endogenic geochemical haloes. The formation of local cryogenic geochemical fields in the glaciers results from sharp geochemical heterogeneity and geochemical processes in underlying rocks which cause cryogenic migration of chemical elements and compounds in the glacier. The thickness of geochemical fields, (134 m) is limited by ice thickness in the studied glaciers.

1. Introduction

It is believed that the chemical composition of glaciers is controlled by regional factors and reflects changes in the environment and atmosphere throughout the existence of glacier ice, and the material accumulated in a glacier changes very little after its deposition due to low temperature. Studies conducted by the author in alpine glaciers of the Tien-Shan indicate the existence of local geochemical fields, whose formation is caused by geochemical maxima in underlying rocks, in alpine glaciers.

2. Methodology

The chemical composition of rocks, glacier ice, snow cover and natural water was studied. Ice samples were obtained from the surfaces of glaciers and boreholes drilled through the glaciers. A wide range of chemical elements was analyzed in the samples using quantitative spectrometry and atom-adsorption methods. For gold determination, a flameless atomizer mounted on a Perkin-Elmer-603 spectrophotometer was used.

3. Results

Mountain glaciers accumulate and hold atmospheric moisture as firn ice for a considerable time; they represent a unique source of information on changes in the chemical content of the atmosphere. It is believed that precipitated material accumulated in the glaciers does not change significantly from the moment of its fall due to low temperatures (Langway, 1970; Kotlyakov and Gordienko, 1982). Our investigations conducted in the glaciers of the Tien-Shan enable us to establish the existence of local geochemical fields, the formation of which is not related to global climatic factors.

The formation of local geochemical fields in the glaciers results from the sharp geochemical heterogeneity and the geochemical processes occurring in underlying rocks. These geochemical processes cause migration of chemical elements and compounds within ice and snow layers. In the glaciers, migration of chemical elements occurs as ion diffusion along liquid pellicles covering ice and snow crystals at temperatures below or close to 0℃ (Fletcher, 1962; Kvlividse *et al.*, 1978; Makarov *et al.*, 1990). Cryogeochemical fields have been detected in glaciers of different types: in valley and hanging glaciers, in warm and cold glaciers.

Local geochemical fields have qualitative (chemical elements and their compounds) and quantitative (concentration of elements, parameters of geochemical fields) characteristics, which depend on the geochemical peculiarities of underlying rocks. These characteristics exhibit regular patterns within the glacier.

Geochemical fields were studied in alpine cold and warm glaciers situated at 4000–5000 m elevation. Cold glaciers are underlain by rocks with negative temperature. The frozen stratum consists of two layers, the upper layer being the glacier, and the lower one being the bedrock. Warm glaciers rest on positive-temperature rocks. The temperature profile of the glaciers consists of an upper 10–15 m zone with temperatures of 4–5℃ below zero, a middle zone down to a depth of 25–30 m with sharply increasing temperatures up to 1–0.6℃ below zero, and a lower zone extending to the glacier bed with a zero-gradient 0℃ isothermal curve.

Geochemical fields are discussed below for the example of Lysyi Glacier. It is a hanging glacier located at 4050–4200 elevation. The maximum ice thickness at the study site is 60 m. Thermometric measurements in holes drilled through the glacier show that the ice temperature varies from −6℃ at the surface to −2.5℃ in the bottom layer.

The glacier overlies an ore body of a gold-tungsten deposit over a length of about 300 m. An adit was made in the glacier (4070 m level). The ice was studied at the contact with and at several distances from underlying rocks. The rocks are ore metasomatites. The glacier bottom is at 4050 m elevation in its deepest part. The content of microelements in the ice at the ice-rock contact is a few tens times higher than the background chemical concentrations in the glacier (Table 1).

The maximum concentration of elements in the geochemical halo occurs at the immediate contact with metasomatites and decreases in the series (in parentheses are degrees of contrast of the anomalies, i.e. the ratio of anomalous concentrations to background values): Cu(80)–Zn(30)–W(20)–Au, Cr(10)–Ag, Sn(7)–V(5)–Mo, Pb(3). There is a clear relationship between the concentration of chemical elements in the ice contacting the rocks and the concentration of ore elements in the ores.

Concentrations of the elements typomorphic for the ore body and endogenic halos gradually decrease in the glacier with increasing distance from the ore zone (Table 2). Within 50–60 m (the glacier thickness) concentrations of heavy metals decrease nonuniformly in the series: Zn(60)–Cu(40)–W(10)–Au, Ag, Sn, Pb, Be(5)–Mn, Mo(4)–Cu, Ni(2). The most abrupt decreases occur in the concentrations of zinc, copper and tungsten. The least contrasting changes are characteristic of cobalt and nickel, whose concentrations decrease two-fold.

Concentrations of Be, Pb and Sn in the glacier decrease steadily, already reaching

Table 1. Content of components in the glacier at the contact with rocks.

Components	Ore*	Ice				Ore*	Lysyi Glacier ice, Background values, N = 28**
Distance between samples, m		0.3	35	25	15		
pH	7.9	7.4	7	6.9	7.1	7.75	7.3
Eh, mV	467	470	490	510	505	405	502
Mineralization, mg/l	0.027	40.6	35.6	35.1	38.2	0.020	49
Ca^{++}, mg/l	0.236	9.5	5.3	5.3	4.2	0.194	5.3
Mg^{++}, mg/l	0.095	0.6	1.9	0.3	1.3	0.112	1.6
$Na+K^{+}$, mg/l	0.161	4.8	4.0	7.9	7.8	0.100	6.2
NCO^{-}_{3}, mg/l	0.305	30.8	21.6	21.6	18.5	0.249	24.0
Cl^{-}, mg/l	0.020	3.3	3.7	3.3	3.3	0.018	4.1
$SO^{=}_{4}$, mg/l	0.167	6.6	6.6	7.8	12.3	0.139	9.6
Au, $10^{-3}\mu g/l$	1000	14	2	2	1	60	1.4
W, $\mu g/l$	200	20	15	10	15	20	1
Ag, $\mu g/l$	1.5	0.2	0.03	0.03	0.07	0.5	0.03
Mo, $\mu g/l$	7	7	2	2	5	10	2
Pb, $\mu g/l$	20	5	2	2	3	15	1.4
Sn, $\mu g/l$	5	3	2	2	3	2	0.4
Zn, $\mu g/l$	50	300	200	10	200	15	10
Cu, $\mu g/l$	500	150	150	100	50	20	1.8
Cr, $\mu g/l$	50	30	30	15	7	50	3
V, $\mu g/l$	200	20	5	5	10	30	4

Notes: *concentration of microelements in ore–g/t, Au–mg/t. **N = 28–number of samples.

background values at a distance of 35 m from the ore body, while Mn concentration, even at the glacier surface, remains five times higher than the background value. Concentrations of Zn, Cu and W decrease slightly within the first twenty meters from the glacier bottom, then decrease sharply near the surface. The reverse distribution is characteristic of gold and molybdenum, although their concentrations at the glacier surface are still higher than the background concentrations. The redox potential decreases with depth from 505 to 470 mV (specific Eh value is 0.3–1.1 mV/m).

Anomalies of indicator-elements of gold ore mineralization in the glacier form above both the ore body and the primary haloes, reflecting the composition of endogenic mineralization (Fig. 1).

The distribution of chemical elements along the glacier surface is also nonuniform. Anomalies of gold, zinc, copper, tungsten and chromium at the glacier surface occur above the ore body with practically no shift (Fig. 2). Negative anomalies above the ore zone are formed by sulfates and Eh values. Some indicator-elements (Ag, Sn, Pb, Zn, Sc, Be) form more contrasting anomalies at the glacier surface above the north-eastern part of the ore body. These anomalies coincide with the enriched sections of the ore body where concentrations of heavy metals increase 2–5-fold.

Thus, superimposed haloes of indicator-elements form in the glacier overlying the ore body. The composition of the superimposed haloes corresponds to those of the ore body

Table 2. Variation in chemical composition of ice with depth, Lysyi Glacier.

Component	Measurement unit	Depth		
		Surface	30 m	50 m
Elevation a.s.l.	m	4100	4070	4050
PH		7.2	6.95	7.45
Eh	mV	510	500	470
Mineralization	mg/*l*	32.4	33.9	40.6
Ca	mg/*l*	4.7	5.3	9.5
Mg	mg/*l*	1.6	0.95	0.6
Na+K	mg/*l*	5.0	5.9	4.8
Fe^{3+}	mg/*l*	0.3	0.25	0.3
NH_4	mg/*l*	0.2	1.0	0.1
HCO_3	mg/*l*	21.5	21.6	30.8
SO_4	mg/*l*	6.6	7.2	6.6
Cl	mg/*l*	3.3	3.5	3.3
NO_2	mg/*l*	0.01	1.0	0.01
Au	10^{-3} μg/*l*	1.75	2.0	14.0
W	μg/*l*	2	12.5	20
Mo	μg/*l*	2	2	7
Ag	μg/*l*	0.05	0.05	0.2
Cu	μg/*l*	4	125	150
Pb	μg/*l*	1	2	5
Zn	μg/*l*	15	100	250
Sn	μg/*l*	0.5	2	3
Cr	μg/*l*	1	22	18
Be	μg/*l*	0.06	0.18	0.30
Mn	μg/*l*	150	450	600
Co	μg/*l*	1.5	1.5	3
Ni	μg/*l*	3	6	7.5

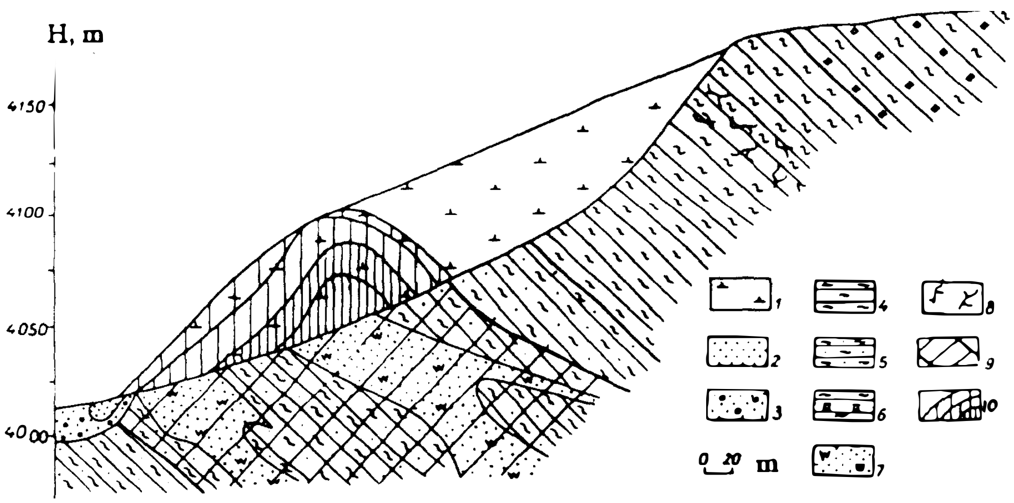
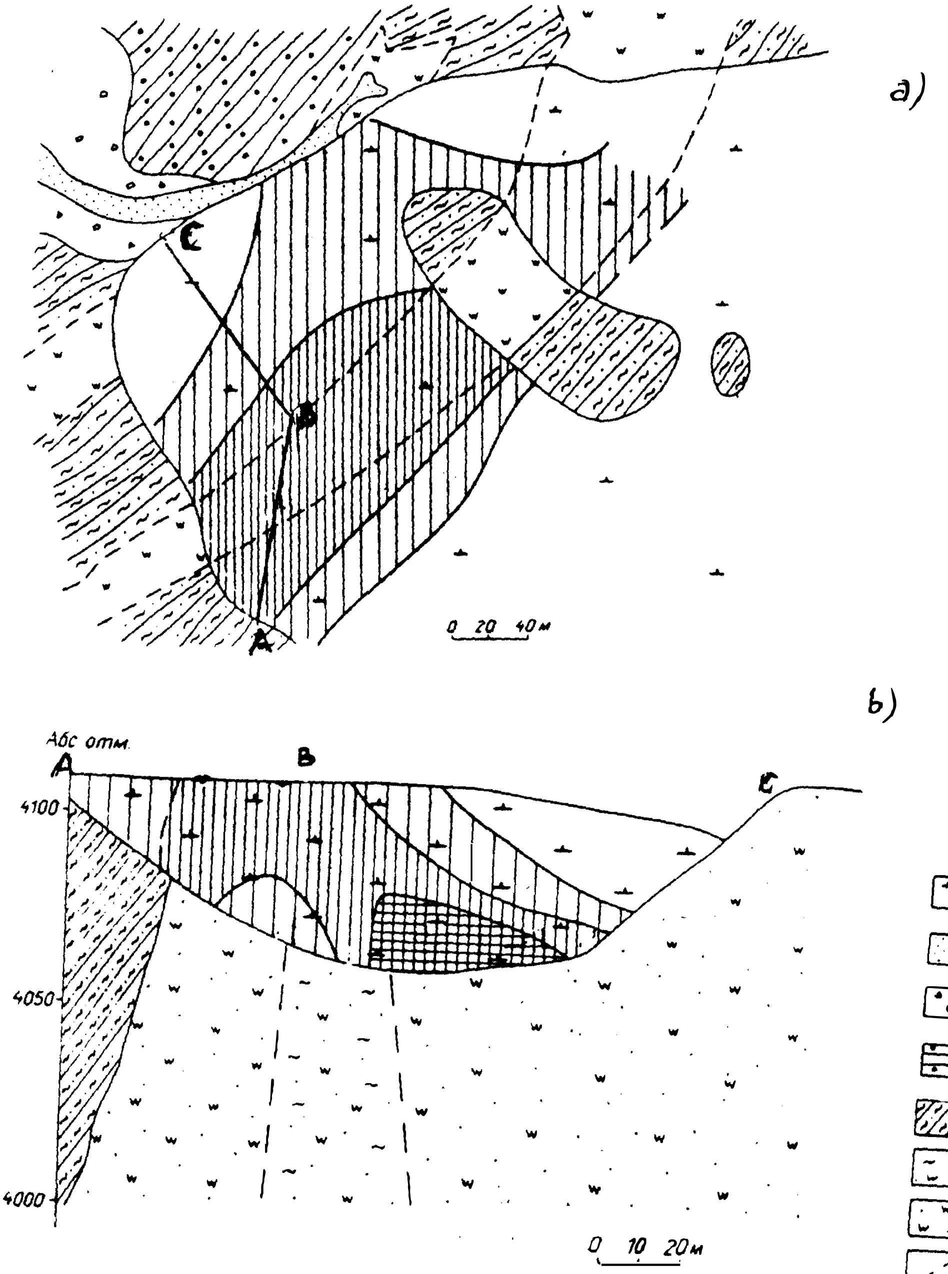


Fig. 1. The geochemical field above the ore zone and the endogenic halo.
1-ice; 2-sand; 3-gravel; 4-shale; 5-sandstone; 6-limestone; 7-ore body; 8-shatter zone; 9-endogenic halo; 10-geochemical field in the ice (spacing in cross-hatch shows the degree of contrast of the geochemical field).



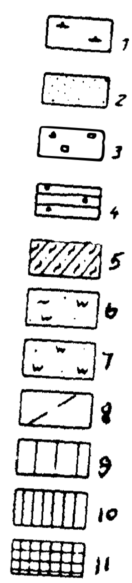


Fig. 2. *Geochemical anomaly of Cr at the surface of the glacier above the ore body in (a-plan, b-profile), A-B-C-line profile. 1-glacier; 2-alluvial deposits, sand; 3-morainic deposits; 4-sandstone; 5-sandy shale; 6-metasomatite; 7-ore metasomatite; 8-ore body; 9-11-Cr concentration on the glacier surface, μg/l: 9-3-10, 10-10-20, 11-20-30.*

and the endogenic halo. More contrasting geochemical anomalies form in the glacier above the greater enriched sections of the ore body (see Figs. 1 and 2). The vertical range of migration of indicator-elements (Au, W, Pb, Cr, Cu) and, correspondingly, the thickness of the superimposed halo in Lysyi Glacier is 50–60 m.

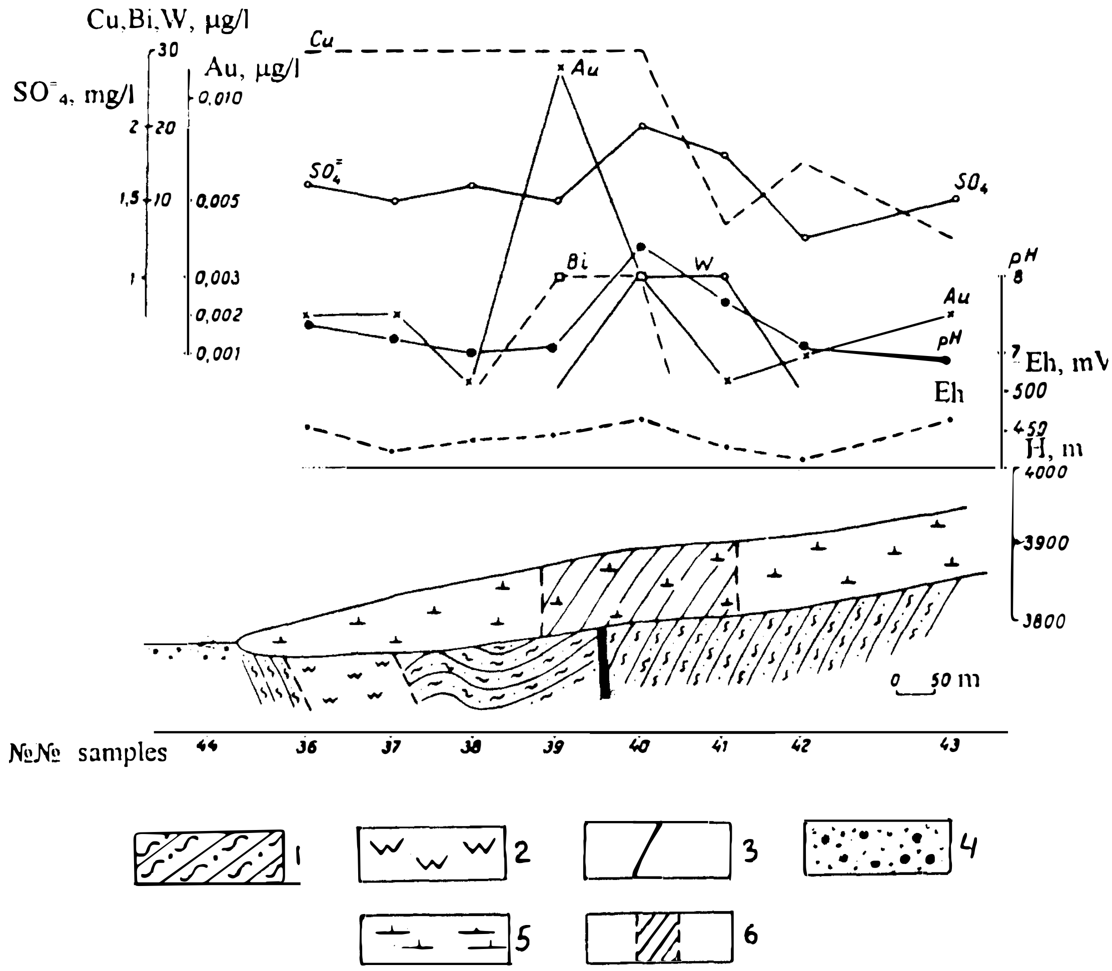


Fig. 3. *Geochemical profile along the surface of Boordu Glacier above the ore zone. 1-metamorphic shale; 2-metasomatic rock; 3-ore metasomatite; 4-sandy shale; 5-glacier; 6-cryogenic halo.*

Similar geochemical studies were also carried out in other glaciers: Boordu, Davidova, Petrova, Sarytor, and No. 121.

The study of ice geochemistry at the Boordu Glacier surface has shown that an anomaly of indicator-elements exists in the lower part of the glacier tongue. The complex anomaly (Au, Bi, W, $SO^{=}_4$) is located above the conjectured extension of the ore zone (Fig. 3). Contrasting geochemical anomalies were also found in Davidov Glacier. The width of the glacier in its lower part is 0.8–0.9 km; the ice thickness determined by radio sounding is up to 134 m with an average of 75 m. According to thermometric measurements, the ice has a temperature of −6℃ at a depth of 5 m and is near the melting point below 30 m depth. The depth range of 40 to 109 m is filled with pressure melt water; the ice temperature here is not lower than −0.5℃. A near-bottom layer of warm, water-containing (1–2% by volume) ice probably exists in the middle and upper parts of the glacier tongue.

The glacier tongue in its middle and upper parts has fissures and is divided longitudinally by a medial moraine into two branches. These branches differ in activity. The

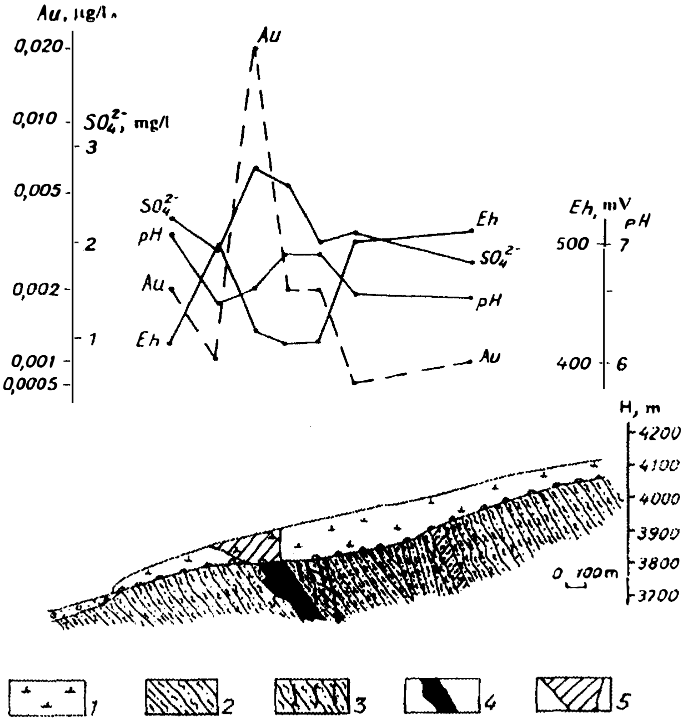


Fig. 4. Geochemical profile along the surface of Davidov Glacier above the ore zone. 1-glacier; 2-sandy shale; 3-metamorphic shale; 4-ore metasomatite; 5-cryogenic halo.

movement rate of the surface of the right branch in summer is 1-2 cm/day; the left branch is more active, moving at 1-4 cm/day. The angle of slope of the tongue is 5-6°. Down the glacier there is a large outwash plain between the tongue and the terminal ridge of the 80-90-m-high moraine.

The glacier is asymmetrical in cross section, with its ice thickening towards the left margin. The bottom layer of the glacier consists of ice containing a relatively large amount of morainic debris a few meters to 11 m in thickness. The upper layer consists of relatively clean ice.

Distinct geochemical anomalies of the elements typomorphic for the ore body and endogenic halo (Au, W, Pb, Cr, Cu; Sn) exist at the glacier surface. The contrast of anomalies decreases in the series: Au(20)-Pb(5)-Cr, Cu, Mo(3)-W, Sn(2). The geochemical haloes are located within the projection of the ore zone onto the glacier surface. The anomalies extend over a length of 150-200 m in the direction of glacier movement (Fig. 4).

It is known that the chemical composition of glaciers is controlled by regional factors and reflects changes in the environment and atmosphere throughout the existence of glacier ice, and the material accumulated in a glacier changes very little after its deposition, due to low temperature. Our studies indicate the existence of local geochemical fields in alpine glaciers whose formation is caused by geochemical maxima in underlying rocks, and is not dependent on regional climatic factors.

The rate of formation of geochemical fields in glaciers is of great interest. It is known that the movement rate of large glaciers in the Tien-Shan is 40 to 130 m/yr. Glaciologists estimate that the full mass cycle in glaciers of the inner Central Tien-Shan occurs within 450-900 years. Glaciers on flat mountain tops with the slowest mass circulation bear evidence of far earlier events. They may contain ice layers which formed as much as 1500–2000 years ago (Serebriakov and Orlov, 1988).

Therefore the migration rate of chemical elements forming geochemical fields at the surfaces of glaciers should be no less than 10 cm/yr for a cold glacier located on a flat top and more than 40 cm/yr for a warm valley glacier. Only at these rates of sub-vertical migration would geochemical fields form on the surface of a glacier, at least within its tongue. However, actual geochemical fields on the surfaces of glaciers are only slightly shifted in the direction of glacier movement. The high formation rates and the morphology of geochemical fields, as well as the distribution of positive and negative ions in the ice on the glacier surface, are adequately explained by the electrochemical model of geochemical field formation (Sato and Mooney, 1960; Semenov, 1955).

4. Conclusions

The formation of local cryogenic geochemical fields in the glaciers results from sharp geochemical heterogeneity and geochemical processes in underlying rocks which cause cryogenic migration of chemical elements and compounds in the glacier. Migration of chemical elements occurs as ion diffusion along liquid-like films enveloping ice crystals. Cryogenic geochemical fields have been detected in glaciers of different types (valley and hanging; warm and relatively cold).

Cryogenic geochemical fields have qualitative (chemical elements and compounds) and quantitative (concentration of elements, extension of haloes) characteristics distributed regularly within the glacier and on its surface. Theoretically, their vertical range may reach hundreds of meters; the measured thickness is limited by ice thickness in the studied glaciers, *i.e.* 134 m. The composition of geochemical fields depends on the geochemistry of underlying rocks.

When studying glaciers for paleoclimatic reconstruction and quantitative assessment of substance input, account must be taken of their geochemical heterogeneity related to the existence of local geochemical fields.

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