IAEA COORDINATED RESEARCH PROJECT (CRP)

The use of selected safety indicators (concentrations, fluxes) in the assessment of radioactive waste disposal

Report 2

Dispersion halos and fluxes of chemical elements in permafrost and periglacial regions

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Dispersion halos and fluxes of chemical elements in the cryolithozone (permafrost or periglacial regions)

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ABSTRACT


In this report, the studies of Russian researchers in the field of geochemistry of landscapes of ore deposits in the cryolithozone are analytically reviewed. Major types of oxidation zones in periglacial zones are presented, their morphology, mineralogy, regularities of geographic distribution, and physical-chemical conditions of formation are described.

Basic features of contemporary weathering crusts are characterized, including the properties of unconsolidated covers, groundwaters, and soils of permafrost regions, peculiarities of migration and accumulation of chemical elements. A generic scheme of the development of permafrost geochemical landscapes is given.

Secondary lithochemical haloes and fluxes of dispersion around ore deposits in the cryolithozone are considered in detail. Both the composition of these haloes and fluxes and influence of different factors on their formation are characterized.

Hydrochemical and biogeochemical haloes and dispersion fluxes of ore elements and their satellites in the cryolithozone are brought to light. Generic features of hypergene migration and cycling of elements in periglacial regions are expounded.

Frozen grounds as possible media for radioactive waste disposal are examined, pro and con arguments are discerned. Assessment of mechanical stability of walls and insulating characteristics of frozen grounds is made. Finally, a long-term geocryological prognosis for the territory of Russia is presented.
The IAEA launched a Coordinated Research Project (CRP) "The use of selected safety indicators (concentrations; fluxes) in the assessment of radioactive waste disposal" for the period 1999-2003. The CRP’s objective is to contribute, through the development of international consensus, to the assessment of the long-term safety of radioactive waste disposal by means of additional safety indicators based on the observation of natural systems.

The participation of Finland in the CRP resulted in a large amount of data and knowledge which must be adequately published, in order to ensure practical benefit for the purpose of application in a future safety case. Integration into a safety case can happen in different ways, most of which require the availability of the whole background material which has been compiled and treated within the project.

The Finnish contribution to the CRP consists to a large part of results of compilation of natural elemental concentration and flux data from existing data bases, but also from experimental work and from simulations and calculations.

In addition, a number of supporting generic studies on natural geochemical cycles and geochemical anomalies on a global, regional and local scale has been conducted which are indispensable for putting the results of the CRP into the context.

A publication of the material and the conclusions from the various parts in one report series seemed to be the most appropriate way to ensure a certain uniformity and a maximum accessibility. The individual reports are closely related and are complementing each other.

Most of the work published in the report series is a result of close cooperation between GTK (Geological Survey of Finland), VTT (State Research Center of Finland) and STUK (Radiation and Nuclear Safety Authority of Finland). The supporting studies are to a great part contributions by foreign experts.

The second report is intended to serve as background and supporting investigation within the CRP.

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Introduction

Comparatively not long ago, the cryolithozone was considered as "a kingdom of geochemical peace", the role of weathering in this zone was assumed to be practically inappreciable. Today, many specific features of cryogenic landscapes and cryogenic haloes may be regarded as subjects of rather good understanding. Not only qualitative, but many quantitative aspects of cryogenic processes have been revealed and investigated. These processes embrace slumping, solifluction, sliding, thermokarst, frost heaving and cracking, diverse phenomena of frost sorting of fragmental and dispersed materials. As a result of combined actions of physical and physical-chemical weathering, a well-formed profile of cryogenic crust appears.

In the study of cryogenesis of rocks and ores, the following factors are of paramount importance [23,34]. First, water, which is present in frozen grounds in its liquid phase, forms thin films on the surface of division of mineral particles; this water is not frozen in a wide interval of negative temperatures, owing to the deformation of its hydrogen bonds under the influence of an orientation effect of the surface of rock particles. Second, non-freezing water is capable to migrate in frozen grounds under the action of the changes of gradients of temperature, moisture, or concentration of dissolved substances. Third, negative temperatures promote an essential increase of mineralisation of soil and ground solutions, in consequence of partial freezing out of water and increasing of solubility of oxygen and carbon-acid gas in cold waters. These major factors have the strongest effects in upper horizons of frozen grounds, where a field of dispersion of chemical elements was a matter of intensive investigations, to a very considerable degree, of Russian geochemists (it is worth noting that the cryolithozone covers more than 2/3 of the territory of Russia). This report is based on the works of V. Pitul'ko, A. Perel'man, E. Ershov, N. Karavaeva, A. Kovalevsky, N. Romanovsky, S. Shvartsev, I. Tyutyunov, and others.

1. Oxidation zones of ore deposits in periglacial regions

1.1. Morphology and mineralogy of the zones of oxidation of ore deposits

Many ore deposits of the cryolithozone have zonal distribution of hypergene minerals which differs sharply from an usual scheme of secondary zonation of oxidized ores. The depth of a zone of oxidation can vary significantly. It is determined (as the intensity of hypergene alterations) by the differences of the extent of jointing of ore bodies. There are three groups of ore deposits of the cryolithozone that differ by their oxidation zones.

At the deposits with sulphate zones of oxidation, presenting the first group, ore bodies confined to negative relief forms are characterised by a rather small depth of the propagation of oxidizing processes, the predominance of limonite among secondary minerals, and the abundance of relics of primary sulphides. The second group of ore deposits in periglacial regions has another kind of the zone of oxidation called "oxide" due to a wide development of oxide compounds of iron among hypergene products. The depth of propagation of hypergene minerals may reach 100–150 m. The third group is characterised by a combined development of oxide and sulphate minerals over all the profile of the oxidation zone, so it has a sulphate-oxide composition.

Ore deposits in all sites of the cryolithozone underwent hypergene transformation. A long history of continental development of periglacial regions and repeated changes of climate, in combination with a differential erosion of different parts of the cryolithozone territory, caused a complex structure of oxidized zones and co-existence of heterogenous associations of secondary minerals. The zones of oxidation of ore deposits differ in the intensity of transformation of ore materials, in the depth of propagation of hypergene minerals, in the diversity of their species composition and paragenetic associations. Major differences are connected with the distribution of sulphate products of oxidation, many of them are typomorphic minerals of the zones of oxidation. Specific character of local zones of oxidation is distinctly traced in respect to other groups of secondary minerals as well. In particular, a near-surface distribution of carbonaceous, arsenate, silicate, phosphate, and molybdate complexes, oxides and native elements is marked out. With this, deep horizons of the zones of oxidation of different types differ weakly in their mineral composition, a deep penetration of metasomatic generations of sulphates into ores brings them together.
Comparison of mineral composition of the zones of oxidation in the cryolithozone and in non-periglacial regions shows that in the majority of cases upper ore horizons of permafrost are characterised by the combination of hypergene mineral associations developed under usual conditions at different parts of a zone of oxidation: native elements, a portion of secondary sulphides, limonites of deposition, all sulphates, oxides of Si and Cu (under usual conditions they are confined to lower horizons of the zones of oxidation) co-exist with phosphates, silicates, carbonates of Cu and Bi, antimonial ochres (they are developed usually at upper sections of the zones of oxidation). That is why there is no reason to consider the zones of oxidation of the cryolithozone as maintained roots of old pre-glacial zones, preserved by permafrost.

**Major features of oxide zones of oxidation** are as follows.

- Limonite is a predominant mineral in the composition of oxidized ores.
- Appreciable development of carbonate, arsenate and silicate complexes.
- Re-deposited generations of secondary minerals prevail over other minerals.
- Development of a contrast secondary stanniferous (residual), gold, silver, and, partially, sulphide enrichment.
- Significant expansion of intensively oxidized ores in depth (up to 30–40 m).
- Wide development of colloform, sinter, and leached textures.

In sulphate zones of oxidation, these indications can be observed “in miniature”, in a subsurface horizon, this shows that oxide products are formed over there at present. The rest of the profile of a typical sulphate zone of oxidation displays the following features.

- Soluble sulphates of Fe, Cu, Zn are major minerals in the composition of oxidized zones; metasomatic generations of hypergene minerals are absolutely predominant.
- Salts of other oxygen acids and oxides are developed at a small extent.
- Secondary stanniferous and gold-silver residual enrichments are confined to the surface.
- The domain of propagation of secondary sulphides of Cu is extended significantly in depth, but the quantities of these sulphides are very small.
- Intensively oxidized ores are insignificantly extended in depth (up to 5–10 m).

Sulphides of most metals are presented by crystal-hydrate compounds with a number of molecules of water which corresponds to contemporary thermodynamic conditions.

**Sulphate-oxide zones of oxidation can be described by the following.**

- Predominance of limonite and sulphates of Mg, Ca, Cu, Zn, Al over other hypergene minerals.
- Regular presence of carbonates.
- Prevalence of metasomatically substituted generations of hypergene minerals.
- Insignificant extension of intensively oxidized ores in depth (up to 5–10 m).

In general, the overwhelming majority of ore deposits in periglacial (permafrost) regions has a distinctly expressed zonation. Its origin, in a large extent, depends on the regime of permafrost and specific thermodynamic characteristics of the cryogene media. In the zones of oxidation, the processes of hypergene metasomatosis (alteration) are predominant. The processes of deposition can be observed only near the surface and, in a larger measure, in the zone of oxidation of the oxide type [23].

### 1.2. Regularities of a geographic range of the zones of oxidation of different types

All investigators connect the formation of oxide zones of oxidation with the existence of a warm and humid climate in pre-glacial time and with an active participation of solutions. There is no agreed opinion regarding the genesis of sulphate oxidized ores. Their origin can not be linked with pre-glacial weathering, because the existence of metasomatically substituted generations of soluble sulphates is incompatible with the circulation of natural solutions.

In a geographic range of different types of the zones of oxidation of northern deposits, there are certain regularities which are closely connected with the history of development of different regions of the cryolithozone. Long and complex history of continental development of periglacial regions appears to be a main reason which has determined the differentiation of physical-chemical conditions in ores at diverse stages of their hypergene transformation.

From Late Cretaceous, in the majority of regions of the cryolithozone, a regime of tectonic stability was manifested, it provided a wide propagation of peneplain areas at the territories of Anabar and Aldan antecfises, West and East Jakutia, Baikal highland, North-East of Russia, and North
America. Assessments of the duration of this stage, with which the formation of thick weathering crusts and the zones of hypergenesis at ore deposits is connected, vary significantly: till the beginning of Pliocene [25], or till Medial Oligocene-Early Miocene [3], or till Oligocene [12].

According to V.M. Pitul'ko, there is a genetic community of old weathering crusts and oxide zones of oxidation. Pre-Quaternary weathering crust in Western Jakutia covers a vast area. Its thickness, when including sedimentary rocks, reaches 5–8 m, and up to 20–30 m on traps and kimberlites. Within the Anabar antecline, where Quaternary erosion was more intensive, only residual linear and local weathering crusts of albite-ankerite metasomatites, kimberlites, and carbonatites are present.

Eastern Jakutia was also a peneplained land in the Paleogene, with the exception of big ridges (Stanovoy, Sette-Daban, Jugura, Verkhoyansky, Tchersky). Under conditions of warm, humid, and sometimes even subtropical climate, a thick weathering crust has been formed over there, its areal included the zones of hypergenesis of ore deposits of several regions: Central Aldan, Allakh-Yun, and Upper-Indigirka.

In the south of a periglacial zone, within the Baikal highland, there was an almost smoothed plain with well-developed river valleys, also in the Paleogene. Peneplain relics are preserved at many sites as flat-topped mountains. Climatic conditions were favourable to the development of weathering crusts over there. However, already in post-Pleistocene, the denudation, as a result of land elevation, has reached 90–100 m. It appears that subsequent erosion of weathering crusts and the zones of oxidation of ore deposits of the Trans-Baikal region was very intensive. Old zones of oxidation are not preserved, because ore deposits that are now bedding within frozen grounds are practically not affected by oxidation.

In the majority of regions of the Verkhoyan-Chukotka highland, from Late Cretaceous, the removal of the relief has been of selective character, corresponding to a quasi-platform state of this region. The processes of relief removal have reached their culmination in the Paleogene, when all North-East of Russia was covered by extremely rich vegetation of a sub-tropical appearance.

The history of the planation of relief in the North-East region of Russia has been studied by A.P. Valpeter, he has drawn up a map of areal extent of relics of the surfaces of planation and crusts of chemical weathering. V.M. Pitul'ko, using this mapping, has shown that distribution of the zones of oxidation of different types in the territory of North-East Russia reveals a close spatial correlation with a character of Early Pleistocene glaciation. Sulphate zones of oxidation are developed on areas which have not been covered by glaciers, and in the regions of mountain-valley glaciation sulphate-oxide and, partially, oxide zones of oxidation are developed. Passive character of glaciation was favourable to preservation of pre-glacial crusts of weathering and oxide zones of oxidation correlated with them. Thawing of ices and subsequent wetting of the territory caused partial washing of permeable sections of ore bodies.

In Early Pleistocene, the first deep freezing of the lithosphere appears to be occurred in North-East Russia. The areas located to the north from the areal of glaciation, were characterised, apparently, by the thickest and low-temperature permafrost. During interglacial periods, it underwent significant shortening in both area and thickness, but the northern part of the territory was affected by the processes of degradation in a small extent. Long denudation of the territory of North-East Russia has determined the youth and small thickness of Quaternary crusts of weathering. Even on the majority of relics of an old surface of planation, eluvium is of Anthropogen age. The depth of propagation of intensively oxidized ores corresponds to the thickness of a contemporary crust of weathering.

Thus, there is a genetic community of oxide zones of oxidation and Paleogene-Neogene crusts of weathering, sulphate and sulphate-oxide zones of oxidation and contemporary eluvium.

In North America, climatic and tectonic conditions were favourable to the formation of Paleogene-Neogene siallitic crusts of weathering. At the majority of ore deposits, well-developed zones of oxidation have been formed, they are preserved both among frozen grounds and within talik sites. The emergence of permafrost in North America is supposed to be connected with the fall of temperature in the beginning of Pleistocene. It is established that the largest thickness of frozen grounds occurs in regions that have never been covered by glaciers. Upon the rest of the territory, the formation of permafrost has begun only after annihilation of glaciers, i.e. 10–20 thousands years BP, and even later within several regions [4].

In Canada, modern climate is characterised by significant amounts of precipitation and rather high winter air temperatures. The location of the continent of America between the Pacific and
Atlantic, and its smaller dimensions (in comparison with Eurasia) are favourable to lesser losses of heat by the earth crust. As a result, the thickness of frozen grounds and the areal of permafrost in Canada are, as a rule, smaller than upon the same latitudes in Russia. All this, together with peculiarities of the formation of the regime of permafrost caused a certain inheritance of periglacial oxidizing process by local zones of oxidation. As in Russia, oxidation occurs most actively within the sites of taliks, where the circulation of groundwaters takes place.

Analysis of hypergene history of the regions of the cryolithozone shows that a type of the zone of oxidation is determined by the rate of denudation and the regime of permafrost. These factors stipulate also the distribution of different types of weathering crusts. This allows to draw the following conclusions.

1) Formation of old zones of oxidation of an oxide type goes in parallels with development of Paleogene-Neogene weathering crusts. A major condition of their preservation is a moderate rate of denudation (West Yakutia, Aldan Upland, Alaska and Northern Canada). Contemporary abundance of such zones of oxidation is controlled by the relics of residual weathering crusts.

2) Appearance of sulphate zones of oxidation goes in parallels with development of contemporary weathering crusts. Long denudation of the territory of North-East Russia, for example, has determined the youth and low thickness of Quartenary crusts of weathering over there. In accordance with the thickness of contemporary crusts of weathering (3–5 m), is the spreading of strongly oxidized ores (10–20 m). There is an important condition of the formation and conservation of sulphate zones of oxidation — an uninterrupted existence of compact permafrost.

3) Formation of the zones of oxidation of a mixed type also follows the regularities of sulphate oxidation in the Quartenary time. However, they are spread in areas which are within the territory of mountain-valley glaciation. During the periods of warming, significant degradation of a frozen terrane could proceed (the north of the Trans-Baikal region, the shores of the Arctic Ocean and the Sea of Okhotsk, etc). Sulphatisation of these zones of oxidation, which is observed at present, is linked with the most recent stages of the fall of temperature, these stages restored and deepened the regime of permafrost.

4) In the regions of island permafrost, contemporary zones of oxidation of oxide type are formed. Their development is restricted to the sites with permeable thawed grounds.

5) In general, all zones of oxidation of northern deposits are divided into old and contemporary. Nevertheless, the processes of cryogenic alteration of ores are revealed, to some extent, in any deposit located in the cryolithozone.

1.3. Physical-chemical conditions of the formation of the zones of oxidation

1.3.1. Oxide zones of oxidation

Oxide zones have been formed under conditions of descending movement of underground waters. The composition of solutions of oxidation zones changed in stages, this is expressed in the development of zonal distribution of paragenetic associations of hypergene minerals which are characterised by multiple re-deposition [32]. In the formation of oxide zones, apart from chemical processes, electrochemical and microbiological transformations of ore materials occurred, this resulted in the formation of secondary zonation in ores (subzones of leaching, of secondary enrichment, etc).

In the composition of oxide oxidized zones, minerals which are resistant to the action of oxidizing solutions dominate. Re-deposited generations of limonite, carbonates, arsenates, and other salts of oxygen acids are widely disseminated. Re-deposited sulphates can also be observed, but they are located below the zone of oxidation, within primary ores [28, 30]. With a sustained smooth uplift of the majority of regions of the cryolithozone is connected the propagation of hypergene disulphides of iron among primary ores which can be traced up to a significant depth at all northern deposits. Loop-shaped and colloform varieties of marcasite, developed upon pyrrhotite and pyrite, represent ones of the very initial hypergene products. This substitution is of regional character, it is observed practically at all ore deposits of the Earth. Some portion of secondary sulphides of copper is distributed in the zones of oxidation of northern deposits by the same way.

Linear weathering crusts of albite-carbonate metasomatites, developed within terrigene and carbonate rocks (North-West Yakutia) can be a good example of oxide zones of oxidation. The concentration of elements forming minerals which are resistant to hypergenesis are raised in the
products of weathering, because a significant portion of carbonates was evacuated. The weathering of albite-ankerite rocks was accompanied by evacuation of Na, K, Mg, Ca, CO₂, F, Ba, Cr, Ni, whereas such components as SiO₂, P, Al, Fe, Ti, Mn, V, Zr, Nb become enriched.

Development of an oxide zone of oxidation in essentially silicate ore leads to less significant, but nevertheless rather contrast changes of the composition of ore material. *A summarised series of mobility of chemical elements in the process of the formation of oxide zones of oxidation is as follows: (Zn, S, Fe²⁺) – (Ca, As, Mg, Cu) – (Na, K, Si) – (Pb, Al, Ti) – (P, Mn, Sn, Fe³⁺).* This series has been composed by V.M.Pitul'ko, it is based on the data concerning tin deposits of North-East Russia.

1.3.2. Sulfate zones of oxidation

Sulphate zones are formed also as a result of combined action of chemical, electrochemical, and microbiological processes, but in a specific setting of the cryogene environment. It is established that sulphides are relatively resistant to oxidation when liquid-phase reactions occur. However, in the cryolithozone (as in arid regions as well), a volumetric phase of solutions is insignificant, so it is only oxygen of the atmosphere which is a real driving force of oxidation.

For oxidation in a gaseous phase, only a value of partial pressure of oxygen is important, it can be calculated, using the relationship between a change of free energy in the course of reaction and this reaction's equilibrium constant. The reaction of sulphatisation proceeds under the pressure of oxygen from 10⁻⁷⁰ (sphalerite, pyrrhotite) to 10⁻⁴⁸ kg/cm² (cinnabar). Kinetics of low-temperature oxidation was studied experimentally [21]. It was shown, in particular, that the presence of a liquid phase accelerates the rate of oxidation in almost 1000 times.

The formation of permafrost and hypergene alterations of rocks and ores in the cryolithozone occur with the participation of different electrical phenomena. Besides electrical fields connected with the movement of free and fixed water in seasonally thawing layers at ore deposits possessing oxidation zones with sulphate composition, there is a natural electrical field of electrochemical origin. Availability of soluble sulphate minerals provides changes of pH values of free and fixed waters in a section of frozen grounds, this causes an appearance of the difference of potentials in ore bodies. Cathode area of natural galvanic elements coincides spatially with a zone of annual temperature changes (its thickness is of 15-20 m), and the extension of anode area reaches 100–200 m.

Natural electrical fields of ore deposits in the cryolithozone represent a factor of secondary dispersion of ore components. The presence of a difference of potentials during the freezing of covering sediments provides an annual renovation of hydrochemical anomalies and salt components of lithochemical haloes. Anyway, natural electrical fields are driving forces of migration processes proceeding beyond the limits of the layer of annual temperature changes.

*A summarised series of the mobility of chemical elements in sulphate zones of oxidation is as follows: (Zn, Mg, Ca) – (S, As, Fe²⁺, Ag) – (Na, Al, Si, Pb, Au, Sn) – (Mn, Cu, Fe³⁺, Ti, W, K).* Because major changes in the composition of ores occurred at upper horizons, it appears natural that the series of mobility of elements in sulphate and oxide zones of oxidation are similar to a large extent. Differences in the behaviour of ore elements can be revealed only after detailed studies of the composition of lower horizons of oxidized ores.

Thus, the main peculiarity of outcrops of ore bodies of sulphate oxidation zones is a significant abundance of soluble sulphates and important amounts of primary ore minerals. Coefficients of concentration of components in oxidized ores are increased (in comparison with primary materials) for elements which are mainly in the end of a migration series: Au, Sn, W, Mn, etc. Other elements are leached from ore outcrops.

1.3.3. Sulfate-oxide zones of oxidation

These zones appear to be developed to the greatest extent relatively other zones of oxidation of northern deposits, but their features are clearly manifested in low-grade sulphide ores. As to rich sulphide deposits, their traces of oxidation are disguised by strong development of sulphates. This shows that the quantities of appearing water were too small and insufficient for dissolution of large masses of sulphate minerals.
In the development of sulphate-oxide zones of oxidation, it is possible to distinguish four major periods: old oxidation, early sulphatisation, late oxidation, and modern sulphatisation. Many hypergene alterations of low-grade sulphide deposits at the time of old oxidation (Paleogene – Early Pleistocene) did not remain untouched, due to subsequent long-term erosion. Some quantities of secondary sulphides which can be observed at depth, appear to be connected with those alterations (gold-silver, tin and other deposits). During the formation of perennial permafrost (Middle Pleistocene), these deposits were subjects of profound sulphatisation. As a result of atmogenic oxidation, in the masses of frozen grounds, up to the depth of 100–150 m, accumulations of soluble sulphates with small amounts of crystallisation water have been formed.

The period of late sulphatisation (Late Pleistocene) was connected with the appearance of free water in the zones of oxidation. This process included, first of all, the ores of deposits which were located within the areal of old glaciation, in the regions where an active degradation of permafrost occurred: Alaska, Chukotka, the coast of the Sea of Okhotsk, the Okhotsk-Kolyma watershed, the Trans-Baikal region, North of East Siberia, the Polar Ural, Fennoscandia. Sulphates with small quantities of water were involved in the process of dissolution, so the degradation of permafrost proceeded faster in ore bodies (due to the liberation of dissolution heat). As a result, in the zones of oxidation, concentrated solutions of polythionates emerged locally, they intensively leached the masses of ore, this created favourable conditions to migration of many elements. Redistribution of ore components took place mainly at the planes of ore bodies, it affected lateral rocks a little, they remain, as a rule, at the state of permafrost.

The coming of a new wave of cold snap has marked the beginning of a modern stage of the development of sulphate-oxide zones of oxidation. In freezed parts of ore bodies, the reactions of atmogenic sulphatisation renewed and the movement of permafrost front down created favourable conditions for precipitation of hypergene minerals (sulphates, carbonates, phosphates, hydroxides) from freezing solutions, whose mineralisation increased. The composition of a solid phase was determined by solubility of salts and crystallo-chemical characteristics of formed minerals [27]. Ice with raised salinity has been developed in many ores.

Under contemporary conditions, major transformations of ore material in such zones of oxidation occur in seasonally thawing layers and in upper horizons of frozen grounds. Some contribution is made by infiltrating surface waters, however the major role in the formation of minerals is played by pellicle waters migrating in the upper level of frozen grounds and electrochemical processes.

The changes of the composition of oxidized ores are correlated, in general, with a geochemical profile of sulphate zones of oxidation. Coefficients of concentration in ore outcrops are increased for Mn, Cu, Ti, W, Sn, Pb, Au, Ag, Co; such elements as Mo, Zn, S, As, Ca, and Mg are strongly leached.

1.4. Generic scheme of the formation of oxidation zones of ore deposits

The bulk of ore deposits in periglacial regions is deprived of old oxide zones of oxidation, these deposits possess sulphate of sulphate-oxide zones of oxidation which are typical cryogenic by their conditions of formation. Cryogenic sulphatisation enveloped also deep horizons of sulphide ores, where old oxide formations are sometimes conserved.

The principal role in the process of cryogenic sulphatisation is played by freezing of ores. Crystallisation of free water is accompanied by release of solved air. In addition, the release of atomic oxygen can take place also in the course of formation of ice structure [34]. Crystallisation of water is an exothermic process with an extremely small value of an activation barrier, so the conditions for stimulation of the reaction of oxidation are created in the sphere of phase transitions. The reactions of oxidation of sulphide ions of monosulphides are mainly developed. The presence of atomic oxygen (its quantity is as much as 1–2% of a total gaseous mixture) provides more complete and rapid use of a reagent. The release of heat and decrease of temperature of freezing of formed solutions lead to a special behaviour of the front of freezing of ore bodies: this front falls behind the front of freezing of lateral rocks. That is why a site of oxidation appears as a kind of "accumulator" of oxygen releasing during the freezing of adjoining volume of lateral rocks (see Fig. 1).
In the course of progressing cooling of a medium, metastable equilibrium in the system "sulphide ore − newly-formed sulphates − sulphate solution" is shifted irreversibly towards a stable solid phase (sulphates − crystallohydrates and ice). Subsequent long stay of ores in frozen grounds prosmores further development of the processes of atmogenic sulphatisation in them. Variations of climate lead to the complication of mineral composition in cryogenic zones of oxidation.

**Major factors determining the development of cryogenic zones of oxidation** are as follows.

1) Geological-mineralogical peculiarities of ores (specifically selective oxidation of monosulphides);
2) Jointing of rocks (abundant cryogenic jointing is especially important, it may be developed up to the depth of 200–300 m);
3) Hydrogeological conditions at the moment of freezing of a territory (basically, the depth of bedding of an oxygen surface);
4) Thickness, rate and dynamics of the formation of permafrost;
5) Heat of the reactions of oxidation and their kinetics.

2. Contemporary weathering crusts in periglacial regions.

2.1. Properties of unconsolidated covers

2.1.1. Morphology of unconsolidated covers

In the cryolithozone, eluvial-diluvial sediments are mainly spread, they are represented by accumulations of host fragments, intervals between them are filled by loamy and sandy materials. Fragment cover sediments which are products of intensive physical disintegration of original rocks, are developed in regions with rugged topography. They are typical for Alaska, North-East Russia, Trans-Baikal region, where the slopes with a steepness more than 15° are basic elements of the relief.

Steep slopes are the sites of intensive denudation, so their unconsolidated cover is of rather small thickness: from 0.5–0.8 m on northern slopes and up to 2–4 m on southern ones. The profile types of fragment eluvium-diluvium depend on the steepness of slopes. An upper layer of an unconsolidated cover is presented by sandy-loamy materials with changeable amounts of shippings and larger debris, its thickness is usually of 0.1–0.3 m. On steep slopes, it is underlied by a layer of debris-shipping material without any filler. Evacuation of silt from these sites proceeds as a result of intensive filtration of underground waters. After atmospheric precipitation, silt and loam affected by peat formation from sites with vegetation, became redistributed both within a vertical section and on the surface.
On more gentle slopes, the evacuation of silt from lower parts of a section is significantly slowed down, and on the slopes with steepness less than $10^0$ it is absent at all. Accumulation of sandy-loamy materials occurs over there, this is accompanied by its epigenetic freezing. Among cryogenic structures, ice crusts upon large fragments and schlieren-type textures dominate, they are indicators of segregation in the course of the formation of ice.

Fragment products are characterised also by the widely developed process of frost-sorting and formation of different kinds of cryogenic microlief (stone "rivers", stone polygons, dells, solifluction terraces). An example of a stone polygon is given in Fig. 2.

In the regions with smoothed relief, fragment covering sediments are developed on elevated plateaux formed by metamorphic and magmatic rocks, and also along river banks, at the sites of rocky outcrops. Upon sediments rocks, essentially clayey high-iced cover sediments are formed, their sections are often disturbed strongly by permafrost processes. Plasticity of an unconsolidated cover provides an intensive appearance of solifluction. Thickness of clayey eluvium-diluvium is of 1–3 m.

Modern weathering crusts is of a linear type, connected with the sites of tectonic dislocations, their thickness is twice as much compared to area (field) crusts. Cover sediments are wedged as narrow "tongues" into a bed of original rocks.

Colluvial and solifluctional sediments are also widely disseminated in the cryolithozone. They are mostly developed on gentle slopes of southern and northern exposition, being represented by sedimentary rocks, the destruction of which led to the formation of silt covering the sediments. On sandstones and hornfels, the processes of solifluction are displayed at smaller scales, and on granites and effusive rocks they are often quite insignificant.

Solifluctional sediments are formed by shippings with large amounts of a dispersed material, they often include a lot of ice crystals and have net-like textures of ice inclusions, witnessing a syngenetic character of crystallogenesis. The most impressive example of syngenetic solifluctional processes is a formation of permafrost-solifluctional terraces on the slopes [37]. Thickness of solifluctional sediments is usually of 4–8 m, but sometimes it reaches 30 or even 50 m.

Alluvial sediments are propagated mostly at high latitudes of North America. In North-East of Russia and in the Middle Trans-Baikal region, they are developed within the zones of high- and middle-mountain relief, they often look like wide strips on the contacts of sedimentary rocks with granite massifs.

Glacial sediments are propagated mostly at high latitudes of North America. In North-East of Russia and in the Middle Trans-Baikal region, they are developed within the zones of high- and middle-mountain relief, they often look like wide strips on the contacts of sedimentary rocks with granite massifs.

Intensive denudation of the cryolithozone territory in the Quaternary period was not favourable for the accumulation of residual weathering crusts. That is why eluvial-diluvial covers are rather young formations. Their formation proceeded under conditions similar to contemporary ones, with a continuous existence of the regime of permafrost.
2.1.2. Composition of covering formations

Granulometric, mineral, and chemical compositions of the weathering products, together with their historical-geological setting are important characteristics providing the reconstruction of the conditions of their formation.

Granulometric composition of eluvium-deluvium of the territory of North-East Russia and North-West Yakutia has been studied by V.M. Pitul’ko. These formations are characterised by the high (no less than 50%) content of fragment material. In the composition of unconsolidated products, a coarse-grained fraction (particles with dimensions of 1–10 mm) usually dominate (eluvium of granites, andesites, dacites, sandstones). A fine fraction is presented mainly by dust-like particles, and granulometric composition changes rapidly with depth. Both dust-like and clayey fractions rapidly decrease with depth. At the same time, many sections demonstrate the enrichment of upper horizons in dust-like particles, even on the slopes affected by intensive denudation and washing. This witnesses a rather high rate of cryogenic pelitization of unconsolidated covers.

Initial composition of eluvium-deluvium reveals its significant variety, but a close inheritance of the composition of parented rocks is obvious. However, mineral composition of a fine fraction of weathered products is rather monotonous. In the fractions finer than 0.01 mm, such minerals as goethite, quartz, chlorite, hydromica and montmorillonite are present almost always. Crystallisation of clay minerals decreases with depth.

Maximum content of a new-formed dispersed material in upper horizons of contemporary crusts of weathering determines the strongest unification of chemical composition of these rocks in different regions of the cryolithozone. The processes of modern weathering are characterised by a disproportion between a low rate of alteration of original material and a high rate of evacuation of bases passed into solutions, this causes the appearance of an acid medium. In the cryolithozone regions with different climatic and geomorphological setting, different stages of this process are observed.

The youth of cryogenic eluvium-deluvium determines significant influence of chemical composition of original rocks on the spectrum of elements and levels of their concentrations. However, in spite of heterogeneity of eluvial-deluvial formations in detail, there is a large similarity in the distribution of bases, silica, alumina and iron oxides. Common features of these formations are accumulations of silica and "one-and-half" oxides of Fe and diminution of the content of base cations, this underlines predominance of ferrisiallitization in the course of contemporary weathering.

The order of distribution of elements according to their mobility is retained for both slope sediments and bottom silts of contemporary water-streams. Such consistency of the coefficients of accumulation witnesses a single whole trend of direction and intensity of the processes of weathering in landscapes of the cryolithozone.

2.2. Groundwaters of permafrost regions. Migration of elements in above-permafrost waters.

Chemical composition of above-permafrost waters representing a major factor of the formation of a geochemical field of secondary dispersion, is determined by recharge sources (precipitation, condensation of water vapors, migration of pellicular waters from frozen ground) and the composition of rocks composing the territory of drainage systems. Main processes are represented by leaching and dissolution of rocks, together with the interaction of free waters with fixed waters in upper horizons of frozen grounds.

Hydrocarbonate-calcium waters dominate over other types. Mineralisation of above-permafrost waters fluctuates in wide limits, from 30–40 up to 400–500 mg/l. and within ore-free sites it is directly proportional to the degree of disintegration of drained rocks.
The presence of perennially frozen water-resisting rocks is a reason of active washing of clastic (detrital) formations and of over-humidification of dispersed formations. The combination of increased amounts of free carbon dioxide (up to 30–50 mg/l) and oxygen (up to 20 mg/l), both of them being enriched in cold waters, makes them very aggressive agents of weathering. However, an oxidizing environment within a seasonally-thawing layer does not take place everywhere; in the basement of these layers, a gleyish setting is developed within dispersed sediments because water exchange is slowed down over there.

Analysis of the composition of above-permafrost waters shows that thermodynamic conditions within a seasonally-thawing layers are favourable for intensive migration of many chemical elements. Intensity of migration of elements in above-permafrost waters can be characterised by coefficients of water migration (\(K_e\)) introduced by Perel'man [19]:

\[
K_e = \frac{m_t}{a} \times 100,
\]

where \(K_e\) – coefficient of water migration; \(m_t\) – the content of element \(X\) in water, g/l; \(a\) – mineralisation of water, g/l; \(n_a\) – the content of element \(X\) in water-bearing rocks or in the Earth crust (Clarke value).

The values of \(K_e\) averaged for the cryolithozone have been assessed by Pitul'ko, they are as follows:

1) Very mobile \((K_e > 10)\) ………………. S, Zn, Mo, Ca, Mg
2) Easily mobile \((K_e = 1 – 10)\) ………………. Ag, Cu, Ni, Na
3) Mobile \((K_e = 0.1 – 0.5)\) ………………. Mn, Cr, V, Co, Fe, Pb, Ba
4) Weakly mobile \((K_e = 0.01 – 0.09)\) ………………. Al, Si, Sn
5) Very weakly mobile \((K_e < 0.01)\) ………………. Ti, Nb, Zr.

Comparison of these values, obtained for the cryolithozone, with the coefficients of water migration in humid landscapes without permafrost does not reveal any significant distinctions in both the values of \(K_e\) and the composition of efflux series. This points to the formation of weathering crusts of an acid-siallilte type in landscapes of the cryolithozone at present. There is only one specific feature of such formations – a difference in mobility of elements within frozen and thawed horizons of unconsolidated covers. In roofs of frozen layers, mobility of several elements (Ca, Mg, Si, Zn, Ni, Co, V, Ti, Nb) is increased. However, major alterations of rocks occur within seasonally-thawing layers, so the results of cryogenic weathering are hidden by the influence of the formation of upper horizons of weathering crusts.

2.3. Soils of periglacial regions. Trace elements and their migration

Soils of northern taiga and tundra zones are characterised by their shortened profiles and relatively weak dismemberment into genetic horizons. However, these facts do not witness the absence of chemical weathering because the composition of covering formations enveloped by soil profiles is a subject of strong fluctuations. Both qualitative and quantitative compositions of water-soluble compounds are not unchanged, this means that the process of migration in permafrost soils does proceed. Physical-chemical alterations in soils are supplemented by with intensive biogeochemical actions leading to the formation of organic-mineral compounds. Within a taiga section of the cryolithozone, superficial ferruginized frozen soils dominate, only at its periphery (southern and seaside regions), podsolized and podsolic soils are developed.

The formation of podsol in the zone of permafrost is a secondary process superimposed on the background of taiga frozen soils. Preceding phases of cryogenic ferruginization disguise the process of podsolization. Severity of climate, low temperatures of air and ground cause dehydration and coagulation of organic-ferriferrous compounds, the transition of iron into weakly mobile forms and its strong fixation in soils.

Soils developed on silt-loamy sediments differ significantly from soils formed on a rock debris substratum which is light in its mechanical composition. Their main peculiarity consists in wide development of gley processes. Between superficial ferruginized permafrost-taiga and gley soils, there are many transitional kinds and sorts. The distribution of different soils on areas depends on the degree of dispersion of covering formations and ruggedness of relief.
Humus of permafrost-taiga soils is represented by organic compounds of incomplete oxidation. The less humus is oxidized, the more intensively it can be dissolved in water [1]. That is why in tundra over-wetted soils, humus is evenly distributed along all the soil profile, whereas in the sections of permafrost-taiga soils it forms relatively deep leaks, impregnating low horizons of a seasonally-thawing layer. The quantity of humus in permafrost-taiga soils varies between 2% and 17%, fulvic acids dominate in its composition. These acids appear in the course of mineralisation of deciduous plants (defoliation). Fulvate humus intensively reduces compounds of "one and half" oxides, transferring them into solutions. So, metals which have been earlier adsorbed by ferriferous complexes, get a possibility to migrate.

According to the changes of their concentrations, chemical elements in permafrost-taiga acidic ferruginized soils can be divided into the following groups [23].

1) Group of progressive efflux ................. Si, Cu, Na, Zn, Ni, Cr
2) Group of progressive accumulation ............ Ca, Mg, Co, V
3) Group of relative accumulation ............... Al, Fe, Ti, Zr.

The efflux of the majority of metals from a humus horizon is clearly observed, this leads to the enrichment of the B₁ and B₂ horizons.

The process of ferruginization is revealed more clearly in soils formed upon slopes. The behaviour of Fe and Mn in profiles of these soils witnesses an oxidizing setting in all their horizons; however, the traces of former mobility of these elements can be observed in a large number of rusty spots, black dendrites and pellicles, they indicate reducing environments occurred during some period preceding the stage of development of a soil profile. In disturbed sections of such soils, the distribution of components can vary in wide limits. Nevertheless, a rather stable content of components is often observed. Acid ferruginized soils with such type of eluvial-illuvial re-distribution are developed in regions with flattened relief, on silty products of weathering of terrigenic, metamorphic, intrusive, and effusive rocks.

Permafrost-taiga acid gleyed soils (soils of dells, shallow hollows, upper parts of creak valleys) are formed, as a rule, on a heterogenous substratum, intermingled by solifluction. These soils are developed within sites of raised wetting; a substratum is mainly silty over there, enriched in dispersed materials; an increased thickness of a moss cover determines a small depth of seasonal thawing.

A humus horizon, being significantly inundated, is a zone of intense efflux of many components. In the horizon B₂, a gley setting takes place constantly, this is favourable for the efflux of Fe, Mn, Cu, Zn, and other elements into the horizon B₁ during autumn-winter periods, where their fixation occurs under oxidation conditions.

Tundra gley soils are propagated on stony covering formations in the zone of tundra and in upland regions. Their major features are small thickness of a humus horizon and development of the processes of gleying along all the profile caused by a low rate of thawing. As a whole, a content of the majority of chemical elements in such soils is less, than in a frozen substratum.

Pity-tundra gley soils are widespread on rare-stony loamy covering terrains formed in plain tundra and on northern slopes of hills in dissected mountain-tundra regions. The following features are typical for these soils: (a) persistent gleying developed to the greatest degree in above-permafrost part of a profile; (b) slowed decomposition of dead foliage and formation of pit-bearing organogenic horizons; (c) acid reaction of soil solutions and weak differentiation of a mineral part of the profile.

Ungleyed Al-Fe soils are developed under conditions of sufficient drainage, mainly in the zone of taiga. The influence of cryogenic processes on the formation of their profiles and their properties is insignificant due to deep and rapid thawing. The formation of these soils is accompanied by intense migration of elements beyond the limits of a profile, under conditions of an oxidation environment, and by a slowed efflux of Al and Fe, in comparison with the efflux of Si, Na, and K.

In a humus horizon, biogenic accumulation of many elements (Ca, Mg, Mo, Ni, Co, Cu, Zn, Cr, Mn, K, V) is observed. In below-bedded horizons, biogenic accumulation is weak. The above-permafrost horizon B₃ is a subject of intense washing, it is relatively enriched in elements with poor solubility (Si, Sn, Ti, Zr, Pb, etc).

Despite of the diversity of parental rocks and conditions of the occurrence of soils in the cryolithozone, it is possible to identify the following common properties of soils in periglacial regions.

1) Acid reaction, a high-dispersed upper horizon, and a leached humus layer (except Al-Fe soils);
2) Oxidation environment in upper horizons of the profile, and reduction environment in low ones;
3) Accumulation of many elements in an eluvial-diluvial horizon, and depletion of mobile components in an above-permafrost horizon;
4) The absence of humus horizons in disturbed sections, and the presence of the horizons $B_1$ or $B_1+B_2$ enriched in weakly mobile elements;
5) Generally increased content of all elements (except Ca, Mg, Na, Cu) and wide development of secondary concentrations connected to residual accumulation of weakly mobile compounds, fixation of mobile elements by sorption, biogenic accumulation, and cryogenic processes.

2.4. Biogenic migration in the landscapes of the cryolithozone. Bioaccumulation of chemical elements in plants

Landscapes of the cryolithozone differ in their bioproductivity. Bioproductivity of tundra landscapes is rather low (150–200 kg per hectare), so biochemical processes have weak influence on re-distribution of chemical elements in thin layers of tundra soils. Such elements as Ca, Mg, K, P and S are capable to be accumulated in tundra vegetation [11]. However, in the process of decomposition of dead foliage, Ca, Mg, and P are subjects of rapid moving off, they are not capable to be fixed in a soil. As to trace elements, there is no data regarding their accumulation in tundra vegetation.

The productivity of landscapes of northern taiga is much higher, up to 1.5–2 tons per hectare. Vegetation of these landscapes participates actively in re-distribution of many chemical elements. The processes of exchange of elements between a soil and plants includes biological sorption of elements, their efflux and concentration in dead foliage and in a superficial layer of a soil. These processes are characterised by coefficients of biological sorption $A_4$ proposed by Perel’man [18]. The values of $A_4$ are calculated relatively to the composition of soils. Despite of species differences, the distribution of elements according to their values of $A_4$ is rather stable, this allowed to identify the following classes of biological accumulations [23]:

1) Elements of very strong accumulation ($A_4 > 10$)………………….P, Mn, K, Mg.
2) Elements of strong accumulation ($A_4 = 1 – 10$)………………….Ca, (Zn), Cu, B,
3) Elements of weak accumulation and moderate capture ($A_4 = 0.1 – 1$)……………Zn, Na, Ni, Si, Fe
4) Elements of weak capture ($A_4 = 0.01 – 0.1$)………………………….Al
5) Elements of very weak capture ($(A_4 < 0.01)$…………………………….Ti.

The major factor influencing the formation of chemical composition of plants is the presence of soluble components which are concentrated in near-surface layers of soils, their concentration is induced by the processes of weathering intensified just in these layers. Cryogenic processes and migration of solutions towards the day surface in winter periods also contribute to enrichment of these horizons in soluble compounds.

There is a very specific feature of bioaccumulation of chemical elements by northern flora – elements have a tendency to be concentrated in old organs of plants. This explains why vegetation blocks the efflux of biologically important elements from a landscape. Only small portion of such elements becomes released (mainly, by dead foliage) into the sphere of dispersion.

Subsequent fate of elements accumulated in plants depends on the process of decomposition of dead foliage in a given landscape environment. Mineralisation of organic matter leads to significant changes in the element content due to the efflux of mobile elements and fixation of less mobile ones. Using the ratios of concentrations of elements in fresh plants and corresponding dead foliage ($K_{mob}$), it is possible to identify the following groups of elements, according to their capability for efflux in the course of decomposition of dead foliage:

1) Mobile elements ($K_{mob} > 2$) …………………….K, P, Ca, Mg, B, (Na)
2) Weak-mobile elements ($K_{mob} = 1–2$) …………………….Na, Ni, Cu, Mn, Zn
3) Inert elements ($K_{mob} < 1$) …………………….Pb, Cr, Ag, Si, Ti, Fe, Al.

These data indicate rather intense biogenic accumulation of a range of elements in upper parts of a humus horizon. The same has been established for North Canada [5]. However, owing to further decomposition of organic matter and formation of a humic horizon, the processes of efflux dominate, they lead to the leaching of this horizon and to eluvial-illuvial enrichment of deeper-seated soil horizons.

2.5. Generic scheme of the development of permafrost landscapes

The history of development of geochemical landscapes in the cryolithozone is comparatively short. Only the regions with smoothed relief were subjects of rather long weathering in the Quaternary
period. For the majority of regions of the cryolithozone, the formation of covering rocks appears as a typical example of the development of a cryogenic weathering crust.

Usually, in the description of landscapes of perennially frozen grounds, the term "polar cover association" is used, and its thickness taken into consideration is limited by a depth of penetration of frost clefs, i.e. about 5 or 6 m. This term is used in order to designate non-displaced layers of a cryogenic crust of weathering.

The initial period of the formation of polar cover association proceeds under an absolute prevalence of the processes of physical-mechanical destruction of rocks. Later, the role of physical weathering becomes much less significant; finally, it is restricted by the formation of frost clefs and permafrost dislocations of a loose cover. The development of vegetation also acts in the direction of lowering the role of physical weathering.

For the products of a cryogenic crust of weathering, the enrichment in dust fraction is extremely characteristic. This fraction develops due to, firstly, intense frost crushing of large granulometric fragments, and secondly, at the expense of secondary microaggregates arising by the interaction of derivative products of chemical decay. The processes of physical weathering and cryogenic aggregation determine the composition of fine fractions of polar cover association, whereas the correlation of coarse fractions and rock debris depends on the composition and properties of original (parental) rocks.

Chemical weathering is very intense in the regions of peneplanation (base-levelling) of the cryolithozone. Permafrost puts significant obstacles to erosion of such terrains and promotes an increase of chemical denudation, providing surplus wetting of a seasonally-thawing layer, where basic alterations of chemical composition of rocks take place. Huge volumes of dissolved substances may be carried out by permafrost thawing waters. Abundant inundation of a seasonally-thawing layer assists intense moving away of the products of weathering, so siallite-hydromica cover associations are formed everywhere, they represent different stages of an acid (persilic) crust of weathering.

As to the behaviour of chemical elements, two sub-zones should be considered: the sub-zone of cryogenesis and the sub-zone of hypergenesis. The sub-zone of cryogenesis is characterised by important efflux of Ca, Mg, Fe, Mn, Ti, Si, K and Na. Waters of the sub-zone of hypergenesis interact with a liquid phase of waters in the sub-zone of cryogenesis. As a result, the composition of the sub-zone of hypergenesis is changed, together with changes of the rocks washed. Distribution of chemical elements in the sub-zone of hypergenesis depends on the reaction of a medium, oxidation-reduction conditions, mineral composition of the products of weathering, and properties of biogenic migration. Acid and weak-acid environments dominate over there, they are favourable for active efflux of the most elements. On the other hand, the enrichment of upper horizons of cover layers in dispersed materials and iron hydroxides reduces the mobility of water migrants, providing their sorptive fixation. From the sub-zone of hypergenesis, the following elements are subject of efflux: Ca, Mg, S, Co, Ni, Mn, Cr, partly Cu, Zn, Si, Mo, Ag, V. But in this sub-zone, Fe, Al, Ti, rare earth elements, Zr, Pb and P are accumulated.

On the way of migration of chemical elements in permafrost landscapes, there is a range of geochemical barriers. The first one among them is a thermodynamic barrier, which is linked to the alteration of migration conditions at the border of sub-zones of cryogenesis and hypergenesis, where a transition from film waters to an volume phase of solutions takes place. A common increase of mobility of elements at this barrier is accompanied by slowing down of the efflux of Ti, Si, Al and Na.

The second barrier is observed within the limits of the soil profile, it is induced by the changes of oxidation-reduction conditions. Against a background of development of gleyish processes, on can see the influence of sorption. Probably, an acidic-alkaline barrier is also developed over there, it could lead to the accumulation of elements which underlines their eluvial-illuvial re-distribution.

Finally, the action of a biogeochemical barrier can be observed everywhere within the cryolithozone.

3. Secondary lithochemical haloes and dispersion fluxes of ore deposits in the cryolithozone

3.1. Composition of secondary haloes and dispersion fluxes

Secondary lithochemical haloes is an area of anomalous concentrations of ore-forming components disposed amongst solid products of weathering. Fluxes of dispersion are formed on the way of transit of solid and dissolved materials of the products of weathering.
Haloes and fluxes of dispersion are formed in the processes of physical-chemical and biochemical destruction of ores and host rocks under the action of numerous factors (geological properties of landscapes, generic landscape conditions, geochemistry of landscapes, their historical development, etc). Specific character of secondary dispersion of ore matter in the cryolithozone is determined by the following regional causes: features of the formation of oxidized ores, conditions of migration of elements in contemporary landscapes of northern taiga and tundra, cryogenic processes developing within a polar cover association.

The products of weathering of ore outcrops and lateral rocks provide materials for the formation of secondary lithochemical anomalies. In the cryolithozone, ore outcrops are seldom formed by primary ores. As a rule, they are presented by rocks of the zone of oxidation. Within any contemporary anomalous geochemical landscape, a range of elements-indicators and the conditions of discovering of secondary haloes and fluxes of dispersion depend on a type of the zone of oxidation of a deposit.

3.1.1. Mineral composition

The main feature of ore outcrops of deposits with cryogenic zones of oxidation is the presence of minerals of primary ores and soluble sulphate complexes (side by side with insoluble oxide compounds). In a seasonally-thawing layer, sulphides preserved from cryogenic sulphatisation of ores are subjects of intense and deep oxidation, following the scheme of oxide weathering. Permafrost lays obstacles to the penetration of the products of oxidation and promotes their efflux in the direction of run-off of above-permafrost waters.

In contrast to regions without permafrost, in the cryolithozone, even in essentially low-grade sulphide ores (the percentage of sulphides is about 1–2%), soluble sulphates are always present, this puts sulphide components (Zn, Cu, Pb, Mo, Ag, As, Ni, Co, In, Mn, Sb) into the range of indicator elements of any hydrothermal deposit. This situation exists in regions with “island” (insular) permafrost where contemporary zones of oxidation are developed within taliks; many well-known deposits including non-sulphide ones, are clearly marked out by increased amounts of many elements in covering layers and underground waters [35].

For haloes and fluxes of dispersion of northern deposits, the following combination of mechanical and salt forms of occurrence of components is typical: ore minerals (mainly stable under the conditions of hypergenesis, such as gold, cassiterite, etc), aggregates of vein and ore materials (including different sulphides – satellites of economically important ores), and various sorption-salt accumulations.

Ore compounds presented in haloes in both mineral and non-mineral modes of occurrence, are subjects of mechanical and salt dispersion. Mineral components of haloes are presented by minerals of primary ores conserved in ore outcrops, and also by hypergenic new-formed substances including both the products of the zone of oxidation and segregations of secondary minerals in seasonally-thawing cover layers. Such newly-formed substances envelop the segregations of gypsum, molybdate, powellite, carbonates of Cu, Zn, Pb, Bi and other metals, jarosite, limonite, psilomelane, scorodite and other minerals formed in the zones of geochemical barriers developing by the changes of the conditions of migration of elements. Non-mineral components of haloes are presented mainly by sorbed ore matter, occurring in a ferrisiallite material of the products of weathering.

In the Fig. 3, an example of a halo landscape of oxide type is shown, this is site Birguindinsky in North-West Yakutia, investigated by Pitul'ko [23]. Albite-carbonate metasomatic vein bodies are connected with carbonatite pipes, they host sulphide and rare-metal mineralisation and are accompanied by residual haloes of dispersion of Nb, Y, La, Ce, Zr, Pb, Cu, Zn, Ni, Co, Cr, Ti, Fe and Mn. These haloes are disposed in eluvial-diluvial rocks of rather low thickness. Ore bodies were subjects of intense old weathering of oxide type which has changed the ratio of ore components. The formation of residual haloes has led to subsequent transformations of an ore material.

The following primary minerals are observed over there: baddeleyite, pyrochlore, xenotime, zircon, rutile, magnesite, ilmenite, pyrite, gallena, and apatite. Among them, only baddeleyite, xenotime, and zircon do not have the traces of hypergenic alterations. The content of each of mentioned minerals in low horizons of covering layers at the central part of a halo is of 0.9–1.0%. These minerals occur basically in coarse fractions (0.1–0.3 mm), their dimensions decrease (to 0.01–0.1 mm) towards the periphery of a halo. Thus, taking into account the dimensions of primary mineral grains and the concentrations of these minerals in sections of haloes of dispersion, one can state that even stable in the zone of hypergenesis minerals are subjects of important physical-chemical changes in the formation of haloes.
Fig. 3. A residual dispersion halo of a rare-metal vein in a landscape of an oxide type. Site Biriguindinsky in North-West Jakutia; the depth of sampling is of 0.2 m [23].

1 – humic horizon; 2 – horizon B₁ (dark-brown loam with rock debris); 3 – horizon B₂ (light-brown loam with rock debris); 4 – border of a seasonally-thawing layer and permafrost rocks; 5 – dolomites; 6 – oxidized ore body, albite-ankerite breccia with limonite; 7 – fragments of dolomite and an ore material; 8 – spots-“lockets”; 9 – mine workings.

A salt phase of dispersion is presented by carbonates, sulphates, hydroxides and clay minerals, newly-formed in eluvium-diluvium. Calcite and dolomite dominate among carbonates. At the centres of haloes, total amount of carbonates is usually less than in their peripheries. In peripheral parts, carbonates of Pb and Zn appear, their origin is owing to salt dispersion of these metals. The content of carbonates in halo sections increases with depth, indicating intense leaching of covering rocks in a seasonally-thawing layer.

Sulphates (jarosite, plumbojarosite, anglesite, melankerite) are present only at the centres of haloes, especially in lower horizons of a seasonally-thawing layer, where oxidation of an ore material goes on, and new portions of sulphate compounds join the solution. Hydroxides of Fe and Mn make up to 15–20% of a total quantity of minerals. Their concentration is increased in a seasonally-thawing layer. Accumulation of Fe in this layer is due to regional reasons, they cause surface ferruginitation of permafrost soils. Hydroxides of Fe are presented by limonite, hydroxides of Mn – by asbolane and psilomane. The content of hydroxides of Fe and Mn decreases from the centre to the periphery of a halo.

Clay minerals make a basic portion of a fine fraction of a halo material, they are presented by hydromicas, montmorillonite, and kaolinite; their content reaches maximum (50–60%) near the day surface, it increases a little from the centre to periphery of a halo, at the expense of the products of weathering of host rocks.

So, the data of mineralogical analyses show that under conditions of a flattened relief, in dispersed cover rocks, primary and secondary minerals, being components of oxide oxidized ores, form mainly deep horizons of the centres of haloes. High content of dust of cover rocks which is determined by intense degeneration of rocks and minerals, together with abundance of effective sorbents, promotes wide development of the processes of sorption in the course of dispersion of ore materials. Hence, at the sites of deposits with oxide zones of oxidation, the leading role in the dispersion of ore matter is played by mechanical processes. Salt component of dispersion is formed by the products of contemporary oxidation of relict sulphide materials. Naturally, mineral composition of haloes of dispersion of such deposits weakly corresponds to the composition of primary ores (in unconsolidated ferrisiallite formations of the Biriguindinsky site, for example, only the grains of rare-earth minerals are reminiscent of the type of primary mineralisation).
Under conditions of a upland relief, a decrease of the degree of dispersion of unconsolidated covers takes place, the alteration of mineral composition of haloes, both in the section and on the plane, gives the same picture, which can be complicated due to the re-distribution of silt.

Regularities of the alteration of mineral composition of haloes developed over sulphate-oxide deposits have some essential differences, compared to dispersion haloes of oxide oxidized ores. Besides a revealed decrease of the degree of dispersion of unconsolidated formations, which is a consequence of the youth of local crusts of weathering, the composition of ores altered by cryogenic processes influences strongly the formation of haloes. Primary and secondary minerals of sulphate-oxide ores are disseminated to a greater extent, not only at the centres of haloes, but in their periphery as well. Salt dispersion is also propagated at large distances. A characteristic feature of a salt component of dispersion is its dynamics. It means that salt accumulations of most mobile elements are rather weakly anchored in haloes, so the contours of anomalies of some elements become changeable in different seasons of year.

Still bolder are distinctions of haloes formed over sulphide ores altered by cryogenic processes. Mechanical phases of dispersion can be less important, compared to salt dispersion. This is owing to intense re-distribution of sulphide minerals. It is worth noting that in haloes formed over ore bodies with sulphate zones of oxidation, there is always a possibility for active development of a salt component of dispersion. Realisation of this possibility depends on generic landscape conditions of a given site (the degree of dispersion and composition of cover rocks, intensity of water exchange in a seasonally-thawing layer, type of soils, etc).

Thus, for dispersion haloes of deposits in the cryolithozone, the following features are typical:
1) mixed phase state of compounds,
2) prevalence of mineral forms of indicator elements,
3) wide spreading of ore minerals in lower horizons of a seasonally-thawing layer.

The degree of conformity of mineral composition of lithochemical anomalies to the composition of primary ores increases regularly with an increase of the scale of cryogenic sulphatisation of zones of oxidation of deposits. A mechanical component of dispersion is individual for deposits of a concrete type, whereas a salt component is of common character for all deposits of hydrothermal genesis.

Further migration of elements is realised by fluxes of dispersion. In a heavy fraction of water streams, transportation of primary ore minerals proceeds resulting in the formation of a mechanical component of dispersion. These fluxes are linked tightly with haloes of dispersion. The list of minerals taking part in the formation of mechanical fluxes includes cassiterite, tungstenite, gold, cinnabar, etc). Non-mineral component of fluxes of dispersion is connected with deposition of dusty and clayey particles. Mechanical re-distribution of such particles is important, together with the processes of sorption of ore elements from water streams.

### 3.1.2. Granulometric composition

The features of granulometric composition of cryogenic crusts of weathering determine the concentration of the majority of ore elements in comparatively coarse classes of a fine fraction of halo cover formations. Table 1 presents data concerning average dimensions of particles, to which correspond the highest concentration of elements. This table has been composed by Pitul’ko after considering the results of about 800 analyses of samples of deposits of North-East Russia.

<table>
<thead>
<tr>
<th>Element</th>
<th>Ca</th>
<th>Mg</th>
<th>Fe</th>
<th>Mn</th>
<th>Co</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>Pb</th>
<th>Zn</th>
<th>Ag</th>
<th>Sn</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction, mm</td>
<td>4.0</td>
<td>0.4</td>
<td>0.8</td>
<td>0.9</td>
<td>0.3</td>
<td>0.23</td>
<td>0.6</td>
<td>0.35</td>
<td>0.5</td>
<td>0.3</td>
<td>0.6</td>
<td>0.7</td>
<td>0.6</td>
</tr>
</tbody>
</table>

These data clearly characterise a mechanical phase of dispersion, they can be explained totally after their comparison with the features of mineral composition of haloes. Indeed, Fe and Mn are concentrated in a clastic material of a brown iron ore and in primary iron-bearing minerals; Mo, Pb, Zn, Cu and Ag occurring in sulphides are confined to the fragments of a vein material; and the average dimension of a representative fraction depends on the degree of release of minerals-concentrators from an ore mass; a representative fraction of B is correlated with the dimensions of grains of tourmaline; trace elements are concentrated in finer fractions together with clay minerals and small grains of limonite.
However, correlation of the highest concentrations of ore elements with coarse classes of a fine fraction is not absolute. Sometimes, a distribution is of polymodal character, this indicates often the second type of enrichment corresponding to dusty-clayey particles. This is especially typical for elements presented in the composition of soluble secondary minerals, developed in unconsolidated formations.

### 3.1.3. Chemical composition

There is a common feature of dispersion haloes of deposits in the cryolithozone – contemporary development of sulfuric-acid weathering in a seasonally-thawing layer and in upper horizons of permafrost rocks. This weathering determines a degree of sulphatisation of covers. Certainly, this process depends on the degree of sulphatisation of primary ores and the type of their oxidation.

A lithochemical halo of dispersion in a near-surface layer of a cover appears as a result of the interaction of different processes of re-distribution of ore elements. Generalised mobility of elements in the zone of a halo can be assessed by the value of the coefficient of dispersion. This coefficient has been introduced by Solovov [31]. It is established that distribution of ore particles in a residual lithochemical halo of dispersion, above a thin vertical ore vein, follows a normal law:

\[ C_x = \frac{M}{\sigma \sqrt{2\pi}} \text{e}^{-\frac{x^2}{2\sigma^2}} \]

where \( x \) – a distance from an ore body; \( M \) – the linear productivity of a halo; \( \sigma \) – the coefficient of dispersion. Taking into account that the value \((x^2/\sigma^2)\) should be dimensionless, it is clear that \( \sigma \) should be measured in length units.

The value of coefficient \( \sigma \) may vary rather strongly, but within autonomous landscapes it remains more or less constant. Table 2 presents the values of the coefficient of dispersion for haloes developed just within autonomous landscapes with rare-metal deposits of North Jakutia (rare-metal metasomatites, carbonatites, kimberlites) and of North-East Russia (deposits of Au, Sn, W, Pb and Zn).

#### Table 2. Coefficients of dispersion of chemical elements \( \sigma^* \) for autonomous halo landscapes of the cryolithozone [23]

<table>
<thead>
<tr>
<th>Elements</th>
<th>North-West Jakutia</th>
<th>NE Russia</th>
<th>Elements</th>
<th>North-West Jakutia</th>
<th>NE Russia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Carbonate</td>
<td>Silicate</td>
<td>Silicate</td>
<td>Carbonate</td>
<td>Silicate</td>
</tr>
<tr>
<td>Ca</td>
<td>–</td>
<td>–</td>
<td>8±1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mg</td>
<td>–</td>
<td>–</td>
<td>15±3</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Ti</td>
<td>3±1</td>
<td>3±2</td>
<td>4±3</td>
<td>In</td>
<td>–</td>
</tr>
<tr>
<td>Fe</td>
<td>3±1</td>
<td>3±2</td>
<td>5±2</td>
<td>Ga</td>
<td>–</td>
</tr>
<tr>
<td>Mn</td>
<td>6±2</td>
<td>10±3</td>
<td>12±4</td>
<td>U</td>
<td>12±3</td>
</tr>
<tr>
<td>Ni</td>
<td>11±2</td>
<td>11±5</td>
<td>14±6</td>
<td>Th</td>
<td>5±2</td>
</tr>
<tr>
<td>Co</td>
<td>4±2</td>
<td>11±4</td>
<td>12±5</td>
<td>As</td>
<td>–</td>
</tr>
<tr>
<td>Cr</td>
<td>9±3</td>
<td>10±3</td>
<td>10±2</td>
<td>Bi</td>
<td>–</td>
</tr>
<tr>
<td>V</td>
<td>4±3</td>
<td>9±3</td>
<td>–</td>
<td>Sb</td>
<td>–</td>
</tr>
<tr>
<td>Zr</td>
<td>10±6</td>
<td>8±6</td>
<td>8±3</td>
<td>B</td>
<td>–</td>
</tr>
<tr>
<td>Cu</td>
<td>6±2</td>
<td>13±5</td>
<td>11±4</td>
<td>Au</td>
<td>–</td>
</tr>
<tr>
<td>Zn</td>
<td>3±2</td>
<td>14±5</td>
<td>12±3</td>
<td>Nb</td>
<td>6±2</td>
</tr>
<tr>
<td>Pb</td>
<td>7±3</td>
<td>11±4</td>
<td>9±2</td>
<td>Y</td>
<td>8±3</td>
</tr>
<tr>
<td>Mo</td>
<td>–</td>
<td>–</td>
<td>11±4</td>
<td>Yb</td>
<td>8±3</td>
</tr>
<tr>
<td>Ag</td>
<td>–</td>
<td>–</td>
<td>12±2</td>
<td>Ce</td>
<td>5±2</td>
</tr>
</tbody>
</table>

* For a horizon located at the distance 1 m from a roof of permafrost.

Significant values of the coefficient of dispersion (6–8 m and more) and their constancy in different landscapes indicate that many elements are mainly in the state of dispersion. Such elements as Mg, Mn, Ni, Mo, Cu, Zn, U, As, and partly, Co, Cr, Pb, B and Ga have high values of \( \sigma \) (10–20 m). An increase of mobility of all elements owing to transportation of silt through fragmental cover formations is observed under conditions of narrow ridge-like watersheds in upland regions.
3.1.4. Phase states of halo components

On the basis of calculation of the productivity of haloes around different deposits in the cryolithozone, rather clear division of halo component according to their mobility can be made. Following the regularities in the changes of the coefficient of dispersion $\sigma$, maximum concentration $C_{\text{max}}$, and the quantity of an element in its halo $M$, all elements are divided into three groups: (1) elements in the state of salt dispersion; (2) elements in the state of mechanical dispersion; and (3) elements with complex dispersion (see Fig. 4).

Fig. 4. Parameters of residual haloes of mechanical (a), salt (b), and complex (c) dispersion, and their changes with depth.

1–3 – parameters of haloes: 1 – coefficient of dispersion $\sigma$ (m); 2 – maximum concentration $C_{\text{max}}$ (%); 3 – linear productivity $M$ (m-%); 4 – border of a seasonally-thawing layer and frozen eluvial-diluvial formations.

1) In the state of salt dispersion, regularly associated with the efflux of elements, there are the following elements: U, Mn, Cr, Zn, Mo, Cu, partly Ni, Pb, As. In frozen horizons of covers, salt dispersion of these elements leads to a sharp decrease of $C_{\text{max}}$, to a decrease of the productivity of a halo $M$ (in comparison with an ore outcrop), and, as a rule, to maximum value of the coefficient of dispersion $\sigma$ (relatively to elements of other group of migration). In a seasonally-thawing layer, the productivity decreases spasmodically (as much as two times and more), this is accompanied by a still sharper decrease of $C_{\text{max}}$ (5–20 times), and by a decrease of $\sigma$.

Major factors of dispersion of elements of this group are as follows: waters of the sub-zone of cryogenesis and seasonally-thawing layer, permafrost microrelief, and physical-chemical conditions of a halo landscape.
2) In the state of mechanical dispersion, associated with the accumulation of elements, there are the following ones: Sn, W, Th, Ti, Zr, La, Ce, probably In. The productivity of haloes of these elements in frozen parts of an unconsolidated cover is always higher than the productivity of ore outcrops. As to $C_{\text{max}}$, it decreases insignificantly, compared to the concentration of an ore element in an ore outcrop (in cases of Th and Ti, it can even increase). In a seasonally-thawing layer, the productivity of haloes of this group slightly decreases, but still remains considerably greater than the quantity of an element in an ore outcrop. The coefficients of dispersion of this group of elements are essentially smaller, in comparison with the group of salt migrants.

Major factors of dispersion of elements of this group are fractures of winterkilling (frost clefts) in upper parts of an unconsolidated cover and cryogenic dislocations of grounds of a seasonally-thawing layer.

3) A large group of elements – Bi, Sb, As, Fe, Ag, Pb, Co, V, Nb, Y, B, probably Au – occupies an intermediate position, regarding the change of parameters of haloes in the section of covering formations. These elements are in the state of complex (intricate) dispersion proceeding under the influence of different factors (mechanical, salt, sorptive).

Phase states of components in lithochemical fluxes of dispersion are investigated quite insufficiently. According to Pitul'ko, mechanical dispersion dominates, independently of mobility of elements in a halo landscape [23].

3.2. Influence of different factors on morphology of secondary haloes and dispersion fluxes

3.2.1. Perpetually frozen grounds

The influence of perpetually frozen grounds on morphology of dispersion haloes appears, generally, in two forms: first, as a restriction of mobility of elements in the zone of cryogenosis, and second, as an increase of their dispersion in a seasonally-thawing layer. Restriction of mobility of elements in frozen horizons of an unconsolidated cover is of paramount importance for dispersion haloes of "mechanical" migrants, their re-distribution is minimum over there. At the same time, diffusion of mobile components is directed sharply upwards, corresponding to the direction of migration of fixed water. Dispersion of all components, irrespective of their geochemical mobility, is supported by the development of frozen clefts within frozen grounds, and sometimes – by the formation of veins, veinlets, and schlieren of ice, appeared as a result of percolation of above-permafrost waters.

The influence of permafrost on the form of haloes in a seasonally-thawing layer is more active and diverse. In its lower part, which is the most humidificated, a halo “runs” on the surface of permafrost, reaching its maximum width. An upper part of a seasonally-thawing layer is a subject of intense action of weathering agents, so the dimensions of a halo become significantly shortened.

In a seasonally-thawing layer, diffusion of components is developed not only aside, but, to a greater extent, upwards, with a subsequent removal out of the system. The latter is connected with the formation and destruction of permafrost relief, the depth of location of which is determined by dimensions of closed systems of large fragments. These systems regulate the process of freezing of a more humidificated silt material. That is why the form of haloes in an upper part of a seasonally-thawing layer is, as a rule, is strongly distorted. Permafrost microrelief favours the unification of partial lithochemical anomalies, connected with nearly located ore bodies, into a common halo of dispersion. Complete unification is typical for mobile components, whereas haloes of dispersion of weak migrants may keep their autonomy.

Under conditions of upland relief, permafrost processes (mainly, frost sizing of fragments) and above-permafrost waters determine the segregation of silt within solifluction terraces, dells, stony “rivers”, spots-lockets, and microcones of efflux, which yields a disconnection of a halo.

Thus, a common feature of dispersion haloes of deposits in the cryolithozone, is their mushroom-shaped form. By this indication, cryogenic haloes differ sharply from the haloes formed in the absence of permafrost, which are developed as a result of confused displacement of solid particles in unconsolidated covers, following the laws of diffusion. Under cryogenic conditions, oriented movements of particles dominate, both in vertical direction (permafrost microrelief) and especially in the plane of permafrost roofing (freezing-thawing of grounds).

Specific features of the form of the section of haloes condition their dimensions. In frozen horizons of unconsolidated covers, an area of a halo surpasses an area of an ore outcrop, on the average, two or three times, whereas in a seasonally-thawing layer – several tens times.
3.2.2. Relief

The most important distortions in the structure of haloes on slopes are due to solifluction displacements of a slope material. Owing to large widths of haloes in lower parts of a seasonally-thawing layer, even with significant displacements (100–200 m), an immediate connection of a halo and an ore outcrop is saved. However, a further displacement of a ground downhill leads to tearing off of a halo from an ore outcrop (or from a perennially frozen part of a halo).

Fig. 5. Train-shaped cryogenic haloes on a gentle concave slope (a) among dispersive covering formations (the site Biriguindinsky, Jakutia), and on a steep slope (b) among fragmental covering formations (Barylyelah deposit, Jakutia) [23].

1 – soil; 2 – brown clay with sandstone fragments; 3 – yellow-brown loam with fragments of sandstones and of an ore breccia; 4 – frozen yellow-brown sandy loam with fragments of sandstones and an ore breccia; 5 – albite-ankerite weathered breccia in sandstones; 6 – permafrost microrelief; 7 – cassiterite-chlorite veins; 8 – unconsolidated eluvial-diluvial formations with a thickness of 1–2 m.
Solifluction yields not only the formation of torn away haloes, but it causes also the existence of "buried" haloes in frozen parts of unconsolidated covers. These buried haloes can be divided into "temporarily buried" and "constantly buried". A hidden state of "temporarily buried" haloes may last several thousands years, after it they are transformed again into open haloes. Constantly buried haloes are confined to the sites where pre-glacial or cryogenic eluvium-diluvium is overlapped by a series of alluvial, glacial, or solifluction depositions. Such sites are widespread in depressions of mesorelief.

**Under the action of solifluction or defluxion, dispersion haloes of vein ore bodies of any composition gain a train-shaped (in the plane) form.** Dimensions and forms of such trains depend on the form of ore bodies and their disposition relative to the points of equal elevation of relief. The extent of train-shaped haloes downhill is determined by the angle of inclination of the surface, the character of a slope (concave, plane, convex), and the type of covering depositions. It makes up to several tens or even hundreds of meters for single ore bodies with a thickness of 0.5 m. Maximum length of a train is observed on gentle slopes with dispersed covering depositions in haloes of mobile elements (Zn, Mo, etc).

There is a difference of principle in the structure of train-shaped haloes developed on gentle concave and comparatively steep (20–25°) slopes. In the first case, the process of solifluction dominates, haloes have maximum dimensions in a lower part of a seasonally-thawing layer. These haloes become less contrast downhill (see Fig. 5,a). On steep slopes, the process of removal of silt particles dominates, and the dimension of a halo is usually determined by a slope length. At the foots of such slopes, accumulation of silt takes place, including a dispersive part of a halo material. As a result, the halo has maximum dimensions in an upper part of a seasonally-thawing layer (Fig. 5,b), and it becomes more contrast downhill.

Dimensions of dispersion fluxes depend on the ruggedness of relief. More extent are dispersion fluxes formed in sites of flattened relief, owing to the material of sedimentation. Under the conditions of flattened relief, irregular distribution of materials of denudation and sedimentation in fluvial deposits determines a spotted character of the plot of a flux of dispersion (Fig. 6).

![Fig. 6. Lithochemical flux of dispersion of Galimovskoe deposits of tin, along the creeks Pobedny and Poiskovik [23].](image-url)

Results of sampling: 1 – of a sandy fraction of bottom materials; 2 – of a silty-clayey material; a – tin; b – molybdenum.

A direct connection of dispersion haloes and fluxes is usually absent. In the majority of cases, dispersion fluxes characterise a parcel of an ore field as a whole.
3.2.3. Soil processes

At the centres of haloes, two major kinds of the patterns of element distributions co-exist [22]: the first corresponds to non-violated by cryogenic dislocations soil sections, the second includes violated sections, with different forms of permafrost relief.

The features of central halo soil profiles are distinctly manifested in non-violated sections. A concentration curve shows the following trend: the quantities of mobile elements at first grow gradually, then they diminish essentially (an above-permafrost layer), and after it, they rise again, rapidly and continuously. As to inert elements, the change of their concentrations in the section of a seasonally-thawing layer occurs just in the opposite direction.

In the soil profile of halo centres, all major genetic horizons are developed, corresponding to a local soil type. Furthermore, in the composition of the horizon B2 (in its upper part or in its full thickness), an ochreous sub-horizon usually appears. This sub-horizon presents a tiny zone of oxidation in which waters of a seasonally-thawing layer, rich in oxygen, contact with an ore material. The greatest depth of occurrence and thickness of an ochreous are observed at the centre of a halo.

The presence of an ochreous sub-horizon is a very important specific feature of haloes of dispersion in the cryolithozone, developed over ores in which sulphide components have undergone the process of cryogenic sulphatisation. In this sub-horizon, the efflux of the majority of elements takes place, owing to dissolution of sulphide minerals and further oxidation of preserved sulphides. This is indicated by a decrease of the content of mobile elements, which coincides with the sphere of low pH-values.

The action of zonal factors of soil formation at the sites of haloes is revealed against the background of the processes of dispersion of ore substances, directed to a decrease of the content of elements in an above-permafrost part of a seasonally-thawing layer (the horizon B2), in comparison with frozen halo formations. The enrichment of the horizon B1 in many elements is noted in all soils of the cryolithozone, at the sites of haloes it is supplemented by gravitational differentiation of elements. The role of sorption of mobile elements by hydroxides of Fe and Mn is especially important in this horizon.

The humus horizon A, which is actively washed by atmospheric waters, serves as a sphere of efflux of all trace elements, some portions of them can be re-distributed into the horizon B1.

The spreading of violated soil profiles, confined to different forms of permafrost microrelief, depends on the degree of general dispersion of covers and steepness of slopes, it reaches 40–80% of the area of a halo on a gentle slope covered by a sandy-loam-rock-debris unconsolidated material. The distribution of halo elements in the sections of cryogenic microrelief is determined by the conditions of formation of these specific microforms which are common for the whole territory of the cryolithozone.

Violated soil profiles do not follow a common regularity which requires a decrease of the degree of halo contrast in upper horizons of a seasonally-thawing layer. Haloes of Zn, Mo, Ni, Cu, and some other elements with high mobility in waters of this layer, appear as more contrast in such profiles, in comparison with non-violated profiles. The contrast index of weakly-mobile elements becomes several tens times higher in the forms of cryogenic microrelief. This is explained by the fact that lower horizons of a seasonally-thawing layer are moved to the day surface, but their time of stay in the zone of hypergenesis is significantly shorter, compared to near-surface layers of non-violated soil sections.

Observed distributions of indicator elements in violated sections within halo sites are formed with the prevalence of mechanical dispersion oriented upwards. In addition, physical-chemical processes (transport of elements by waters and their fixation in the soil profile under oxidation conditions, sorption by clay matter and hydroxides of Fe and Mn) act in the same direction. Thus, dispersion haloes can be very contrast in violated sections. Amplification of a contrast index of haloes in the soil sections depends on the depth of location of corresponding relief microforms. It is maximum in stony rings and spots-lockets.

3.2.4. Chemical composition of underground waters in permafrost landscapes

At the sites of dispersion haloes, the pH values of water extracts from a halo material increases slowly with depth: from 3–4 in the horizon A up to 5–6 in the horizon B2, having the minimum value (pH = 2–3) in an ochreous sub-horizon. Oxidation and reduction environments are demarcated just at the foot of an ochreous sub-horizon.
By passing from central to peripheral parts of haloes and further, beyond the limits of the contour of lithochemical anomalies, the pH value of humus horizon remains low, but in the horizons B₁ and B₂ the reaction of soil solutions becomes less acidic. The depth of penetration of oxygen in covering formations gradually decreases from the centre of a halo, repeating mesorelief of permafrost rocks.

The reaction of above-permafrost waters reflects acidity of soil solutions, it changes from acidic to weak-acidic. Metamorphization of the composition of halo waters proceeds smoothly, the conditions of migration in an acidic environment remain constant, so lithochemical haloes of mobile elements gain considerable dimensions. Heightened concentrations of elements of this group in halo soil profiles spread at the distance determined by the width of an acid-alkaline barrier, which may exceed considerably the zone of mechanical dispersion of an ore material.

More radical metamorphization of the composition of halo waters takes place at the sites of haloes of dispersion of ore bodies located in carbonate rocks. In this case, a lithochemical halo appears as a stretched sphere of an alkaline barrier for many elements, except U, Cr, V and some others which are mobile in the alkaline environment.

The combination of the processes of accumulation and efflux of chemical elements in soil profiles of lithochemical haloes of dispersion, in the course of metamorphization of halo waters determines both dimensions of haloes of easy-mobile components and their form in the section of a seasonally-thawing layer, this form is usually narrowed upwards in non-violated soils.

3.2.5. Vegetation

Availability of vegetation leads to slowing down of mechanical dispersion of an ore material, because turf-moss layers and root systems of trees and shrubs lay obstacles to re-distribution of silt, both over the area and in the section of covering formations. At the same time, vegetation appears as one of the factors of mechanical dispersion (the formation of cavities due to the decay of roots, the filling up of these cavities, etc). In the course of general fixation of fragmental formations by wood-shrub vegetation, at the sites of development of tundra soils, specific conditions arise which are favourable to increase the range of mechanical migration of halo elements.

The formation of tundra gley and peat-gley soils is accompanied by the production of large amounts of peat-formed, dust-like loam. Under the conditions of North-East of Russia, steep northern slopes which are basic areas of the development of tundra soils, this material is intensively spread by rains and thawed waters.

An active role of plants, as a factor of the formation of halo landscapes, is connected with selective accumulation of some elements. Mobility if elements is important in the process of mineralisation of dead foliage, this mobility depends on the strength of fixation of elements in organic matter. Plants promote the supporting of a certain level of contrastness of haloes of dispersion of Cu, Mn, Zn, Ni, Co, Cr, Ag, (Au). After the mineralisation of dead foliage, these elements go back to the soil profile.

Circulation of elements follows, of course, a non-closed cycle. Mineralisation of dead foliage and oxidation of organic compounds are favourable to the arising of acid reaction of soil solutions in a humus horizon, many elements become mobile in these solutions. Some of them do into horizon B₁, the rest undergo efflux beyond the limits of the profile and become re-distributed over an area of a halo.

Thus, living matter renders contradictory action upon dimensions and forms of haloes: it (1) restricts efflux of elements beyond the limits of a halo landscape; (2) re-distributes elements in the soil profile (promotes superficial leaching of a halo); (3) restricts mechanical dispersion of fragmental materials; (4) amplifies salt dispersion of hydroxides of Fe and Mn (during their reduction by fulvic acids); (5) amplifies mechanical dispersion of fine-grained fractions. Nevertheless, biogenic processes have no self-dependent significance in the formation of lithochemical haloes in landscapes of the cryolithozone [23].

3.3. Indicator elements of secondary haloes of endogenous deposits in the cryolithozone

Endogenous deposits with cryogenic zones of oxidation, occurring at the level of contemporary shear, in landscapes of the cryolithozone can be accompanied by residual lithochemical haloes of Zn, Cu, Pb, Ni, Co, Mn and Fe. Lithochemical fluxes of dispersion, being closely tied with these haloes, have the same set of indicator elements.
Specialisation of halo cover formations for individual deposits is a result of re-distribution of several ore components, so the following elements appear as indicators:

- Ag and Mo – for deposits of tin, gold (gold-quartz, gold-antimony, gold-silver), molybdenum, tungsten and polymetallic ores;
- Sn and In – for deposits of tin, gold-quartz, gold-silver, tungsten and mercury;
- As – for deposits of tin, tungsten, mercury, gold-antimony, polymetallic and sulphide copper-nickel ores;
- Cr – for deposits of tin, gold-quartz, gold-antimony, rare-earth elements, uranium-thorium (confined to carbonatites), diamonds, sulphide copper-nickel ores.

Specialisation of bottom sediments at the sites of dispersion fluxes is similar.

Superimposed lithochemical haloes are individualized to a small extent. They are formed over rich sulphide ores; irrespective of major components of ores, the following elements appear as indicators in such haloes: Ca, Mg, S, Zn, to lesser extent As, Fe, Mn, Cu, Ni. The majority of components of halo waters also has universal character: Zn, Cu, Pb, SO₄²⁻, ΣMe (the sum of mobile forms of trace metals), Mn, Fe, Cr, Ni form water haloes and dispersion fluxes around quite different sources of mineralisation. Specialisation of halo waters is revealed by the presence of the following indicators:

- Ti – for deposits of tin, gold, kimberlites, carbonatites, and sulphide copper-nickel ores;
- Cr – for deposits of tin, tungsten, gold-silver, kimberlites, carbonatites, polymetallic and sulphide copper-nickel ores;
- Sn and Ag – for deposits of tin, tungsten, gold and polymetallic ores;
- Mo – for deposits of tin, gold-quartz, gold-silver, molybdenum, and rare earth ores.

Geochemical specific features of cryogenic landscapes condition the formation of biogeochemical haloes of dispersion of Zn, Mn, Ni, Cu, and ΣMe. Specialisation of biogenic haloes of dispersion is revealed more distinctly, compared to lithochemical and hydrochemical phases of dispersion. The following elements play the role of indicators in such haloes:

- B – for tin and tungsten ores;
- Mn – for molybdenum and tin ores;
- Co – for tin and sulphide copper-nickel ores;
- Cr – for sulphide copper-nickel ores.

At the sites of lithochemical fluxes of dispersion, biogenic anomalies of Ca, Mg, Mn, Zn, Ni, Cu, sometimes Ag and Mo, are formed.

Table 3. The most typical elements – indicators of secondary dispersion of some endogenous deposits of the cryolithozone [23].

<table>
<thead>
<tr>
<th>Types of deposits</th>
<th>Lithochemical anomalies</th>
<th>Hydrochemical anomalies</th>
<th>Biogenic anomalies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cassiterite-quartz, cassiterite-silicate, and cassiterite-sulphide</td>
<td>Sn, B, In, (Ag), Zn, Pb, (As)</td>
<td>Sn, Ag, Zn, SO₄²⁻, ΣMe, Pb, B, Sr, (Cu), (As)</td>
<td>Sn, Ag, B, Zn, Mn, ΣMe, Pb</td>
</tr>
<tr>
<td>Quartz-wolframite</td>
<td>W, As, B, Bi, Ag, (Sn), Zn, Pb, (Sb)</td>
<td>Zn, SO₄²⁻, ΣMe, Cu, As, Ag, Pb, W</td>
<td>Ag, B, ΣMe, Zn</td>
</tr>
<tr>
<td>Gold-quartz</td>
<td>Au, Ag, Mg, Ca, Zn, Ni, (As)</td>
<td>Au, Ag, Zn, SO₄²⁻, ΣMe, Ca, Mg, Ni, Ti, (Cr)</td>
<td>Au, Ag, Pb, ΣMe</td>
</tr>
<tr>
<td>Gold-antimonite</td>
<td>Au, Ag, Sb, Mg, Zn, Ni</td>
<td>Au, Ag, Zn, SO₄²⁻, ΣMe, Mg, Ti, Sb, Sc, Ca, Ni</td>
<td>Ag, Pb, Au, ΣMe, Ni</td>
</tr>
<tr>
<td>Gold-silver</td>
<td>Au, Ag, Zn, Pb, Mn</td>
<td>Au, Ag, Zn, SO₄²⁻, Ba, Ca, Mg, Ti, ΣMe, Pb, (Ni, Co)</td>
<td>Au, Ag, ΣMe</td>
</tr>
<tr>
<td>Mercury</td>
<td>Hg, Ge, As, Zn, Cu</td>
<td>Zn, SO₄²⁻, ΣMe, Ag, Hg</td>
<td>No data</td>
</tr>
<tr>
<td>Polymetallic</td>
<td>Pb, Zn, Cu, (Ag, As), Ni, Co, Fe, Mn</td>
<td>Zn, Cu, Pb, SO₄²⁻, Ag, ΣMe, (As, Sn, Sb, Mn)</td>
<td>Zn, Pb, Ag, Mn, ΣMe, Cu</td>
</tr>
<tr>
<td>Sulphide copper-nickel</td>
<td>Ni, Cl, Zn, Co, Pb, Cr, Ti</td>
<td>Ni, Co, Cu, Zn, SO₄²⁻, ΣMe, Cr, Ti</td>
<td>Cu, Co, Ni, V, Cr, Ti</td>
</tr>
<tr>
<td>Kimberlites</td>
<td>Ni, Cu, Zr, V, Zn, Pb</td>
<td>Zn, ΣMe, V, SO₄²⁻, Ni, Cu, Cr, Co, Ni</td>
<td>Ni, Ti, Co</td>
</tr>
<tr>
<td>Carbonatites</td>
<td>TR, Th, Nb, Pb, Zn, U, Mn, Ni, Co, Cr</td>
<td>Zn, Cu, Pb, SO₄²⁻, U, ΣMe, TR, Zr, Nb, V, Ni, Co Cr</td>
<td>Nb, Ni, Zr, Pb, TR</td>
</tr>
</tbody>
</table>
Composition, morphology and contrastness of secondary haloes depend on the coefficients of concentration, forms of occurrence of elements in ore outcrops, and landscape conditions of the site. So, the role of different ore elements in the formation of a halo landscape can vary. In Table 3, indicator elements, which are the most typical for dispersion haloes of some types of endogenous deposits of the cryolithozone, are presented. Table 3 shows that such mobile elements as Zn, Cu, Ag, Pb, U, Mn, Co, Ni, Cr are important in the formation of a secondary geochemical field of any endogenous mineralisation in landscapes of the cryolithozone.

3.4. Classification of secondary haloes of ore deposits in the cryolithozone

Specific features of the structure and composition of secondary lithogeochemical haloes developed in the cryolithozone allow to systematize them, using the following indications.

1) Time of formation (the age of a halo). By this general indication, all dispersion haloes of ore deposits in the cryolithozone are divided into two classes. The first class includes deposits formed in the absence of permafrost, they can be called pre-glacial. The mechanism of their formation does not differ from the generation of geochemical anomalies developed in different landscapes without permafrost. Spreading of these haloes is restricted by the areas of relics of corresponding old crusts of weathering.

The second class envelops cryogenic haloes of dispersion, it is much more extensive than the first one. The formation of cryogenic haloes is due to the processes proceeding in a seasonally-thawing layer. Hence, all haloes developed in Middle Pleistocene and in younger covering formations of the cryolithozone, find themselves in this class. The scheme of classification of cryogenic haloes is shown in Fig. 7.

2) Availability of haloes for their discovering by geochemical surveys. Pre-glacial haloes, which were not affected by cryogenic processes in a seasonally-thawing layer, can be preserved only in a buried state. Otherwise, they should be inevitably transformed in haloes of a cryogenic class.

Among cryogenic haloes, open ones dominate, however, owing to the processes of solifluction and deflection, closed (buried) lithochemical anomalies are observed rather often (usually at the foot of slopes).

3) Type of the zone of oxidation of a deposit. Pre-glacial haloes have been developed in landscapes of an oxide type. Cryogenic haloes of dispersion are developed in landscapes of both oxide and sulphate types. A sulphate type prevails significantly, so cryogenic haloes distinguish, as a rule, by the abundance of mobile forms of many ore elements.

4) Type of freezing of covering formations. All pre-glacial haloes have been a subject of epigenetical freezing. The majority of covers of the cryolithozone is affected at present by epigenetic freezing and undergoes different physical-chemical and physical-mechanical alterations.

Solifluction-diluvium trains and young alluvium depositions underwent freezing in the course of their formation. Epigenetically frozen haloes (both open and buried) dominate in landscapes of oxide and sulphate types, but a certain portion of anomalies is characterised by syngenetic formation of ice.

5) Conformity of the composition of haloes and initial ores. Buried pre-glacial, open and closed cryogenic haloes, developing over outcrops of oxide oxidized ores, are characterised by strongly distorted relations of indicator elements, in comparison with initial ores. This inadequacy has been inherited from an old stage of hypergene alterations of ores.

Open and buried cryogenic dispersion haloes of sulphate oxidised ores underwent syngenetic freezing, they are presented only by the components of primary sulphides. In this case, the lack of correspondance in the composition of haloes and ore bodies is genetic, it is connected with the process of formation of haloes accompanied by simultaneous accumulation and freezing of host rocks. Open cryogenic haloes developed over sulphate oxidised ores in epigenetically frozen formations have the composition which is the closest to the composition of primary ores.

6) Relations between haloes and host unconsolidated formations. Pre-glacial buried haloes could be formed in both autochthonous and allochthonous covering formations. This means that both residual and superimposed pre-glacial buried lithochemical anomalies are possible. As to cryogenic haloes, residual anomalies prevail; only in allochthonous depositions, affected by syngenetic freezing, residual open and buried haloes could be formed over sulphate oxidised ores.
Fig. 7. Classification of cryogenic lithochemical secondary haloes of dispersion of ore deposits in the cryolithozone (a simplified scheme compared to the scheme proposed by Pitul'ko [23]).
7) Phase state of halo components. Residual pre-glacial haloes have been formed as a result of mechanical dispersion of ore components, stable under hypergene conditions. These haloes are located in dispersed formations of old crusts of weathering. Superimposed pre-glacial haloes have a salt origin.

Cryogenic haloes, located in autochthonous covering formations, are characterised by mixed phase states of components. Portions of mechanical and salt components depend on a type of the zone of oxidation of a deposit. Over oxide oxidised zones, mechanical haloes of dispersion of stable compounds are mainly formed. In residual cryogenic haloes of sulphate oxidised ores, the portions of mechanical and salt components of dispersion are commensurable. In all residual cryogenic haloes, the majority of elements occurs in mineral forms, due to the confinement of haloes to coarse-grained formations of contemporary crusts of weathering.

Superimposed cryogenic haloes were formed mainly as a result of salt dispersion of components of sulphate oxidised ores, they are located in dispersed covering formations.

8) Form of a halo in the section of covering formations. Residual pre-glacial haloes have in their section a flabellate (fan-shaped) form, superimposed haloes have more complicated contours. All cryogenic haloes have a mushroom-shaped form. Their dimensions are strongly increased in a seasonally-thawing layer. Sometimes, a mushroom-shaped form has no sufficient time to be formed (in watersheds, on steep slopes covered by coarse-fragmental formations); that is why the section of such haloes acquires a spotted character. The processes of displacement of a slope material distort a mushroom-shaped form of the section of an anomaly, so it becomes transformed into a train-shaped.

* * *

Analysis of specific features and systematization of lithochemical haloes of dispersion in landscapes of the cryolithzone leads to the following conclusions [23].

1) Polyelement composition of cryogenic haloes corresponds to the composition of ore outcrops; however, the coefficients of concentration of components may be essentially different in ores, their zones of oxidation, and in covering formations.

2) The width of haloes in a seasonally-thawing layer significantly exceeds the thickness of ore bodies.

3) The contrast index of haloes sharply increases with the depth of sampling; the haloes in non-violated soil profiles have a low degree of contrast.

4) Only a middle part of the horizon B1 of frozen soils and the surface of permafrost microrelief can be considered as representative for sampling.

5) The processes of dispersion of ore components are oriented to a relative enrichment of silt; the dimension of a representative fraction varies from 0.5–1 mm (mountain regions) to 0.1–0.25 mm (penevaluated territories).

6) Permafrost does not lay obstacles to the formation of salt haloes. A salt component is present in all cryogenic haloes of dispersion, it dominates always, to an even greater degree, in syngenetically frozen allochthonous covering depositions.

7) Lithochemical fluxes of dispersion of ore components in bottom sediments of contemporary channels characterise large ore-bearing areas, this means that they are of an integrated character.

4. Hydrochemical haloes and dispersion fluxes of ore deposits in the cryolithzone

4.1. Chemical composition of halo-forming groundwaters

In the cryolithzone, underground waters are disunited by permafrost into above-permafrost, inter-permafrost, and under-permafrost, or they are concentrated in a near-surface part of the hydrogeological section in taliks of different origins. Permafrost deteriorates the conditions of water exchange between deep (under-permafrost) water-bearing and surface horizons.

In accordance to the character of frozen grounds, water haloes and fluxes of dispersion are formed in different water-bearing horizons. In thick (up to 200–600 m and more) compact permafrost layers, a water phase is connected to above-permafrost and surface waters. Only at the sites of contrast newest tectonic movements and intense block tectonics, the so-called through taliks are widespread, so the discharge of underground waters proceeds along them.
On the most part of the territory of the cryolithozone, halo waters are located in the very upper water-bearing horizon – in a seasonally-thawing layer. Halo waters are clearly distinguished by their heightened mineralisation, sulphate-charged composition and anomalous amounts of indicator elements, against the background of weak-mineralised hydrocarbonate-calcium above-permafrost waters.

There are three major sources of the enrichment of above-permafrost waters in halo components: (1) halo waters of the sub-zone of cryogenesis of a polar cover association; (2) a salt component of lithochemical haloes, and (3) the products of contemporary oxidation of primary and secondary minerals of the sub-zone of hypergenesis of a polar cover association.

Halo waters of the sub-zone of cryogenesis of a polar cover association appear as a constant source of the formation of above-permafrost hydrochemical haloes. In winter, these waters reach the surface; in summer, the components introduced by them pass into the composition of lithochemical and hydrochemical haloes. During the summer time, a diffusion cathion-anion exchange between film waters of the sub-zone of the cryogenesis and above-permafrost waters takes place in lower parts of a seasonally-thawing layer.

Under the conditions of a hampered water exchange in frozen grounds, physically fixed water is enriched in many components, the following ones have the highest content: Ca, Mg, Fe$^{2+}$, Mn, Ti, V, Ni, Co, Cr, Cu, Pb, Zn, U, $\Sigma$Me and SO$_4$$^{2-}$. The lowest pH value is observed, as a rule, in samples taken from frozen rocks (for example, the samples of ice from the roof of permafrost), this is directly connected with the features of film water. It is known that specific electric conductivity of fixed water is significantly higher compared to free water, and it increases with lowering of humidity of the medium. The degree of dissociation of molecules in film waters is also higher, in comparison with free water. Dielectric constant of fixed water is essentially lowered as well. All these properties of fixed water determine higher solubility of compounds with covalence bounds in it, in particular, of many sulphides.

Components occurring at heightened quantities in waters of the sub-zone of cryogenesis are typical cryogenic migrants. Besides cryogenic migrants, there is another vast group of components migrating mainly in above-permafrost waters: Au, Ag, Bi, TR (REE), Zr, Nb, Th, K, Na, Ba, Sn, Fe$^{3+}$, In, Ga, Sh, As, Mo, B. The concentrations of these elements in halo above-permafrost waters are higher than in halo waters of the sub-zone of cryogenesis. When halo waters of the sub-zone of cryogenesis go into a seasonally-thawing layer, the content of cryogenic migrants and sulphate-ion drops sharply, and the pH value increases. Significant role in this is played by the dilution of halo waters by background waters washing cover formations hosting a lithochemical halo. As a result, mainly sulphate waters of the sub-zone of cryogenesis are transformed into hydrocarbonate waters with increased amounts of sulphate-ion.

The meaning of a salt component of lithochemical haloes in the formation of hydrochemical anomalies in above-permafrost waters is determined by its portion in the phase composition of a halo, the degree of fixation of elements in soils and covers, and the form of salt accumulations. The portion of a salt component of a lithochemical halo depends on geomorphological conditions of a given site.

Lithochemical haloes located in watersheds and on steep slopes, where fragmental covering formations are developed, are presented chiefly by a mechanical phase of dispersion. Above-permafrost waters drain intensively such sites, making them free of salt accumulations, so lithochemical haloes over there are practically deprived of a salt component, and its role in the formation of hydrochemical anomalies is quite insignificant. Major meaning is taken by dispersion in the form of suspensions and by contemporary oxidation of ore minerals in a seasonally-thawing layer. Insignificant amounts of dispersed materials and weak development of primitive soils stipulate free migration of ore elements in above-permafrost waters. Dimensions of hydrochemical haloes reach several hundreds meters (sulphate-ion), they are determined by the extension of slopes up to a thalweg of local water streams.

On more gentle slopes, a sorption-salt component of lithochemical haloes acquires its leading significance in the formation of hydrochemical anomalies. In landscapes of an oxide type, a salt component of dispersion is connected mainly with sorptive accumulations in clay matter and hydroxides of Fe and Mn, and also with carbonate minerals, and, to a smaller degree, sulphate hygpergene minerals. In landscapes of a sulphate type, sulphate minerals dominate. The degree of fixation of a salt component of lithochemical haloes is inversely proportional to the intensity of hydrochemical anomalies formed by this component. Hydrochemical anomalies are most intense in landscapes of a sulphate type.
Dimensions of hydrochemical anomalies in slope landscapes depend on the productivity of sources of mineralisation, their enrichment in mobile forms of ore components, migration properties of elements; these dimensions become reduced with the growth of a catchment basin. The presence of primary ore minerals (or their relics in landscapes of an oxide type) in cryogenic lithochemical haloes determines the role of these minerals as a constantly acting source of enrichment of above-permafrost waters in ore components.

In winter periods, the processes of atmospheric oxidation prevail, affecting mainly sulphur of monosulphides. In summer, dissolution of sulphide products of atmospheric oxidation proceeds, followed by further hydrogenic oxidation of sulphides with an efflux of the products of reactions. The rates of atmospheric and hydrogenic oxidations are in the proportion of 1:1000 [21], this appears as an important condition of long action of considered sources of the enrichment of halo waters, because during a whole year atmospheric oxidation, which is much slower, dominates.

Chemical weathering of ores promotes migration of released elements in a state of suspension. This migration is facilitated by intense physical destruction (reducing to very small fragments) of rocks in a seasonally-thawing layer. The formation of water haloes of hardly soluble elements (Sn, W, Au, Au-Ag and polymetallic ores).

Physical-chemical conditions of the development of near-surface zones of oxidation, including lithochemical haloes of deposits, differ essentially from the conditions of formation of corresponding weathering crusts. These differences are reflected in the intensity of migration of chemical elements in waters of halo landscapes; this migration is the most active in waters of a seasonally-thawing layer, it can be seen from Table 4. This table presents the coefficients of water migration calculated by the formula of Perel’man [18], its data are based on hydrochemical sampling of 18 deposits of North-East Russia (deposits of Sn, W, Au, Au-Ag and polymetallic ores).

In spite of high concentrations of halo components in waters of the sub-zone of cryogenesis, mobility of the majority of chemical elements in this sub-zone is significantly lower, than in a seasonally-thawing layer. Iron, manganese, silicium, and titanium make an exception, because their high mobility is due to sharply acid reaction in halo film waters. In addition, migration of Fe and Mn is amplified by the influence of reducing environment in frozen grounds.

**Table 4. Coefficients of water migration of chemical elements at the sites of lithochemical haloes of dispersion in landscapes of the cryolithzone [23]**

<table>
<thead>
<tr>
<th>Elements</th>
<th>Sub-zones of a halo</th>
<th>Background above-permafrost waters</th>
<th>Elements</th>
<th>Sub-zones of a halo</th>
<th>Background above-permafrost waters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thawing</td>
<td>Frozen</td>
<td>50–200</td>
<td>Fe</td>
<td>0.3</td>
</tr>
<tr>
<td>S</td>
<td>600</td>
<td>160</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>1–20</td>
<td>20</td>
<td>2–12</td>
<td>V</td>
<td>0.1</td>
</tr>
<tr>
<td>Mg</td>
<td>1–10</td>
<td>10</td>
<td>2–12</td>
<td>Zr</td>
<td>0.2</td>
</tr>
<tr>
<td>Sb</td>
<td>1.5</td>
<td>1</td>
<td>1–7</td>
<td>Bi</td>
<td>0.1</td>
</tr>
<tr>
<td>Zn</td>
<td>0.8–4</td>
<td>1</td>
<td>10–40</td>
<td>In</td>
<td>0.4</td>
</tr>
<tr>
<td>Cu</td>
<td>0.6–8</td>
<td>5</td>
<td>1–6</td>
<td>Sn</td>
<td>0.15</td>
</tr>
<tr>
<td>Pb</td>
<td>0.2–4</td>
<td>0.12</td>
<td>0.1–0.3</td>
<td>Y</td>
<td>0.15</td>
</tr>
<tr>
<td>Ag</td>
<td>0.4–2</td>
<td>0.7</td>
<td>5–8</td>
<td>Mo</td>
<td>0.06</td>
</tr>
<tr>
<td>Ba</td>
<td>0.2–8</td>
<td>0.3</td>
<td>0.1–0.2</td>
<td>As</td>
<td>0.06</td>
</tr>
<tr>
<td>Cr</td>
<td>0.5–3</td>
<td>0.5</td>
<td>0.2–0.5</td>
<td>Nb</td>
<td>0.03</td>
</tr>
<tr>
<td>Ni</td>
<td>0.3–3</td>
<td>0.6</td>
<td>0.8–2</td>
<td>Si</td>
<td>0.07</td>
</tr>
<tr>
<td>Mn</td>
<td>0.1–2</td>
<td>0.5–3</td>
<td>0.1–0.6</td>
<td>Ti</td>
<td>0.01</td>
</tr>
<tr>
<td>Co</td>
<td>0.1–2</td>
<td>0.08–1</td>
<td>0.1–0.3</td>
<td>Au</td>
<td>0.01</td>
</tr>
</tbody>
</table>

The comparison of the intensity of migration of chemical elements in halo waters and in background above-permafrost waters shows that a large group of ore components has a heightened
The acidity of solutions is important in halo waters, where the concentrations of components are high. The range of salts from solutions when the pH value of a medium is increased; in addition, the process of precipitation is accompanied by further metamorphization of their composition. This is caused by precipitation of a polysulphuric compound and mobile fulvate humus.

The degree of intensity of water migration of ore components is reflected in dimensions and composition of hydrochemical anomalies. The most extensive water haloes and dispersion fluxes are formed by the elements of the second group, and also by some elements of the first group which have high coefficients of water migration.

The question concerning migration of elements in halo above-permafrost waters is practically not investigated. There are some indications that many elements (including Mn, As, Zr, Mo, Ti, V, Cr, Pb, Th, Cu, Zn, Ni, Co, Sn) migrate in these waters in the form of colloids [29].

Geochemical environment in cryogenic zones of oxidation and in cryogenic lithochemical haloes of dispersion determines wide spreading of the sulphate type of ionic forms migration of ore components in halo waters of landscapes. At the same time, in acid waters, there are conditions which are favourable for the formation of numerous complexes, owing to the abundance of different polysulphuric compounds and mobile fulvate humus.

Specific features of a phase state of the components of lithochemical haloes (mainly, of a salt component) and a successive change of leading sources of the enrichment of halo waters in warm periods (waters of the sub-zone of hypergenesis, oxidation of ore substances, dissolution of salt accumulations) stipulate an inconstancy of intensity and contours of hydrochemical anomalies. The form of occurrence of halo components in above-permafrost waters seems to be inconstant as well.

4.2. Relationships between ore bodies and hydrochemical anomalies

Water in the zones of oxidation of northern deposits occurs mainly in a fixed state. Free waters are present only in through-talik "windows" confined to the zones of increased permeability. Such conditions are typical for regions with interrupted spreading of frozen grounds: the Polar Urals, Aldan Highland, East Trans-Baikal region (Russia), many regions in Canada. In the regions of continuous permafrost, free water appears in the zones of oxidation, as a result of infiltration of waters of a seasonally-thawing layer and thawing out of ice inclusions induced by a violation of the temperature regime around mine workings. Active interaction of mine waters with oxidized and half-oxidized ore causes strong metamorphization of their composition.

Depending on mineral background of the zone of oxidation, high-mineralised mine waters arise. Mine waters of sulphate zones of oxidation possess strong acidic properties. Halo waters of the sub-zone of cryogenesis, by their composition, are close to mine waters [23]. They reflect clearly specific features of the composition of a given kind of mineralisation. In a seasonally-thawing layer, owing to, firstly, the mixing of waters of the sub-zone of cryogenesis with background above-permafrost waters, and secondly, the changes of thermodynamic conditions, specific features of halo waters become, in a large measure, levelled. Sulphate-ferriferrous, sulphate-nickel, sulphate-copper-zinc and other peculiar waters are transformed into hydrocarbonate-calcium (or magnesium) ones, with increased amounts of sulphate-ion. A set of ore components in these waters is widened, at the extent of elements released by further near-surface oxidation of ore minerals. Thus, halo above-permafrost waters of any deposit of the cryolithozone, having a cryogenic zone of oxidation, includes obligatory a full spectrum of ore components; even if the concentration of sulphides in ores is low, these waters are characterised by sulphate composition.

The movement of halo waters towards the zones of discharge (surface water streams) is accompanied by further metamorphization of their composition. This is caused by precipitation of a range of salts from solutions when the pH value of a medium is increased; in addition, the process of sorption by mineral and organic substances takes place. In the course of longitudinal and transversal dispersion of microcomponents (trace elements), their concentrations decrease regularly. As a result, in dispersion fluxes coupled with the drainage of hydrochemical haloes of ore bodies, only few elements (reflecting mainly a sulphate component of primary ores) can be fixed. The set of these
elements includes S (in the form of SO$_4^{2-}$), Zn, Ag, Ni, U, ΣMe, and if the sensitivity of analysis is sufficient, Sb and As. At the same time, if ore bodies are located near by river-beds of surface water streams, the set of indicator elements in the composition of anomalous waters corresponds to primary ores.

The following elements appear as universal hydrogeochemical indicators of practically any ore deposit of hydrothermal genesis in the cryolithzone: SO$_4^{2-}$, Zn, Ag, ΣMe, often Cu. Specialisation of anomalous waters of a concrete deposit is determined by a set of additional elements.

Any hydrochemical field should be considered as an aggregate of water haloes and dispersion fluxes of ore bodies; every hydrochemical anomaly should be interpreted at first as a flux of dispersion, and then – as a hydrochemical halo.

5. Biogeochemical haloes and dispersion fluxes of ore deposits in the cryolithzone

Biogeochemical halo of dispersion is presented by an area of anomalous concentrations of ore components in vegetation of a contemporary landscape which sides directly with ore outcrops or with the zone of a secondary lithochemical halo. Biogeochemical fluxes are developed on the ways of transit of solid and liquid run-off of ore components, fixing local sites of their episodic or prolonged accumulations.

5.1. Composition of biogeochemical anomalies

The patterns of biogeochemical anomalies in the cryolithzone are determined, in a large measure, by the composition of halo waters (at least, for vegetation of eluvial landscapes). The leading role is played by the composition of above-permafrost waters. Halo above-permafrost waters enrich plants in the most mobile ore components, especially if concentrations of these components are high. At deposits with cryogenic zones of oxidation, within the limits of ore outcrops and at the centres of secondary lithochemical haloes, such conditions are always available. Even if the content of sulphides in a primary source is low, the concentration of mobile compounds in film waters of a polar covering association are rather high. this provides a supply of plants with many sulphide components.

Landscapes with a sulphide type of migration of chemical elements are distinguished by the abundance of mobile forms of ore components which are of easy access to plants. In sulphate landscapes, at the expense of the extraction of components of halo waters, biogeochemical haloes of the following elements are developed: Zn, Ni, Ag, Mo, Cu, Pb; sometimes Cr, Mn, Sn as well [23]. In landscapes of this type, these elements appear as universal biogeochemical indicators of tin, gold, and polymetallic mineralisations. In landscapes of an oxide type, biogeochemical haloes of dispersion of above-mentioned elements are practically not developed.

Biological absorption of mineral components has a selective character. Nevertheless, the composition of cellular sap of plants corresponds, in general, to the composition of soil solutions. Specific features of nutrition of plants in permafrost landscapes lead to high concentrations of a range of trace elements in soil and cellular solutions, these concentrations are often so high that they can not be assimilated by produced organic substances. Hence, in vegetation of northern landscapes, weakly-fixed forms of chemical elements can be present. Pitul'ko proposes to call them "mobile components" of plants, and the forms which are in the composition of organic matter – "ash components" [23].The composition and quantity of mobile components depend on the providing of a landscape by soluble compounds and on the value of a physiological barrier of absorption. Mobile elements easily pass to a water extraction, this property of halo plants was used in order to carry out a special express-florometric method of prospecting of ore deposits [20]. This method is based on the use of water extractions of water-soluble fractions of heavy metals from a plant material. Anomalies revealed by this method are more contrast and localized, in comparison with biogenic haloes registered by a gross content of ore components. Fig. 8 shows informative possibilities of express-florometric, biogeochemical, and lithochemical anomalies. Using express-florometric anomalies, even ore bodies of low thickness become manifested. This confirms tight coupling of a liquid phase of plants with halo above-permafrost waters and also – with waters of the sub-zone of cryogenesis.
Fig. 8. Comparative contrastness of express florometric (Zn-mob), biogeochemical (Zn-phyto), and lithochemical (Zn-litho) anomalies (deposit Baryllyellah, Yakutia) [23].

It is worth noting that many details of the composition of biogeochemical anomalies may be examined, using instrumental neutron activation analysis (INAA). With its high sensitivity and the possibility to determine many trace elements, INAA appears as a powerful tool of investigation of biogeochemical haloes formed by ore components and their satellites in plants of the cryolithozone. Fig. 9 illustrates the application of INAA for the study of biogeochemical haloes in Yakutia, it presents the profiles of concentrations of several chemical elements in the samples of moss over a small body of cinnabar [36].

Fig. 9. Scheme of a section showing the location of a cinnabar body and the profiles of Hg, Fe, Sc, Cr, Co, Ce, and Eu in the samples of moss (mm – points of sampling).
5.2. Major features of the formation of biogeochemical anomalies

In accordance with regularities of the changes of composition of halo waters, and in dependence on relief, biogenic haloes of mobile ore components become less contrast from a watershed to valleys. Beside passive accumulations of mobile components which are present in excessive amounts in halo waters, plants actively assimilate also weak-mobile elements of soils, this is a direct consequence of contemporary biogeochemical weathering.

Among biochemical processes, the most important in this respect is ferment activity of root hairs, and an increase of acidity of a medium around them. Active biochemical decomposition of a mineral substratum can be realized only with the aid of ferments, which are high molecular catalysts [16]. An acidic medium around root hairs is created as a result of the secretion of carbon-acid gas, ions of hydrogen and organic acids by plants. Some organic acids generate different complexes, which are capable to transfer hardly soluble elements into solutions.

Intensity of biochemical weathering does not depend on the type of an ore landscape. It is determined by the quantity of living matter, species differences, and general landscape conditions. That is why even in landscapes of an oxide type, biogenic haloes of dispersion of Sn, B, Au, in many cases also Ag and Cu are formed.

It is well known that vegetation of permafrost landscapes executes a function of a biological barrier which lays obstacles to an efflux of ore components. The most demonstrative in this respect is the formation of biogenic haloes of dispersion at the sites of discharge of halo above-permafrost waters and within litochemical haloes of dispersion.

Biogeochemical haloes are formed not only in the connection with indigenous sources of mineralisation, but also over exogenous deposits. For example, biogenic haloes of dispersion of Zn, Ag, Cu, Mo, Ni, Co, Sn, Pb, Mn and B were observed over cassiterite and gold placers [Pitul'ko, 1977]. All investigated placers are characterised by not deep bedding of an ore body (about 10 m) and combined concentration of an ore component with sulphides. The formation of biogenic haloes has been induced not only by the processes of biogeochemical weathering of ore minerals, but also by waters of the sub-zone of cryogenesis (migration of these waters towards the day surface promotes continuous enrichment of a root-bearing sphere in ore components).

Within the limits of ore fields, a direct dependence between the quantities of elements in plants and in a substratum is preserved only for components having no physiological barriers of absorption by plants [13, 14]. The existence of such barriers is one of the most important factors of lowering of contrastness of biogeochemical haloes. Under the conditions of the cryolithozone, the number of barrierless elements is restricted, it includes Sn, Pb, Mo.

All data regarding physiological barriers of absorption concern only wood parts of plants (branches), because the composition of green parts (leaves, needles) is extremely inconstant [15]. Intensity of biogeochemical anomalies depends on the phase of vegetation of plants (the other conditions being equal). Maximum concentrations of the majority of indicator elements in plants studied are observed in autumn.

6. Generic features of cycling of ore elements in periglacial regions

6.1. Active, mobile, weakly mobile migrants and inert elements

As it was shown in 2.2, the five groups of chemical elements can be identified, according to their intensity of migration in above-permafrost waters: very mobile, easily mobile, mobile, weakly mobile, and very weakly mobile (this intensity is described in terms of the values of coefficient of water migration calculated with the aid of Perel'man formula). Summarisation of the studies of general mobility of elements in different cryogenic environments leads to the following groups [23]:

1) Active migrants……………….. S, Ca, Mg, U, Fe, Mn, Zn
2) Mobile migrants ………………As, Cu, Mo, Ag, Ni, Co, B
3) Weakly mobile migrants ………K, Na, Si, Al, Se, Pb, Au, Sn, Ti
4) Inert elements ………………..P, Th, TR, Nb, Zr, Ta.

This grouping, which reflects the most important features of the behaviour of elements in the zone of hypergenesis of periglacial regions, coincides, roughly speaking, with the grouping of elements based on their peculiarities of their water migration. Below is given a short description the behaviour in the cryolithozone of each chemical element of the above-indicated groups.
1) Group of active migrants.

*Sulphur.* Sulphur is the most active and polymorphous migrant in cryogenic zones of oxidation. Its migration takes place at all stages of the development of a zone of oxidation. Intensive migration of sulphur proceeds in contemporary sulphate landscapes. Sulphate ion, being a necessary ingredient of mineralisation of fixed waters, plays an important role in the differentiation of physical-chemical conditions in cryogenic zones of oxidation. In particular, this differentiation promotes the development of electrochemical processes in frozen ores.

Plurality of the forms of occurrence of S in outcrops of cryogenically altered ores is a basic factor of intense salt dispersion of a wide range of ore components in sulphate landscapes (including such hardly mobile elements as gold). In oxide zones of oxidation, sulphur is re-distributed along the section of ore bodies and in host rocks, where releases of gypsum and jarosite can be observed. In the fibroferrite sub-zone, sulphur is a subject of various transformations, it migrates intensively. Oxidation of sulphides and sulphates of ferrous oxide releases significant amounts of native S. In many sites of this sub-zone, sulphur acid is formed.

In the composition of disulphide-melanterite ores, sulphur is present basically in hypogenic sulphides. Some portions of sulphur are in a native state and in the composition of secondary sulphides of Cu and Fe. And only near the upper border of the melanterite sub-zone, up to 10–20% of the total quantity of S occurs in the form of sulphates.

Deep erosion of the majority of deposits of the cryolithozone conditioned the presence of appreciable quantities of sulphide sulphur in outcrops of oxidized ores (in the composition of primary sulphides). Cryogenic sulphatization of old zones of oxidation generated the appearance of different sulphate minerals at the surface. However, their role in contemporary migration is small, waters of cryogenic oxide landscapes contain very low amounts of sulphate ion.

*Calcium.* The behaviour of Ca is illustrated by the distribution of secondary carbonates and gypsum. Within the limits of fibroferrite ores in sulphate zones of oxidation, calcium is bound by sulphate-ion, some portion of it is carried out into lateral rocks, where gypsum is deposited. In sulphate-oxide and oxide zones of oxidation, calcium migrates at much more scales.

In contemporary landscapes, Ca continues to be intensively dispersed, it is accumulated in subordinate landscapes. However, its efflux from near-surface parts of oxidized ores is slowed down, owing to the existence of stable secondary carbonates which are resistant to hypergene influences.

*Magnesium.* Magnesium migrates actively in upper sub-zones of sulphate zones of oxidation. It is a subject of very intense efflux from limonite-jarosite formations. In sulphate-oxide zones of oxidation, Mg, as Ca, is strongly re-distributed within the section of ore bodies. In upper horizons of oxide zones of oxidation, Mg occurs mainly in clay minerals. The efflux of Mg from the products of weathering of carbonatites, kimberlites and other rocks rich in this element is widely revealed. In contrast to calcium, which undergoes biogenic fixation in soils, magnesium is dispersed rather easily in landscapes of taiga and tundra.

*Uranium.* Uranium, if it is present in ores in the form of pitchblende, is actively re-distributed in oxide zones of oxidation. In contemporary landscapes, uranium is intensively dispersed by both mechanical and salt modes.

*Iron.* In the course of formation of sulphate zones of oxidation, iron basically stayed at its place, in contrast to pre-permafrost environments where it migrated more actively, passing into lateral rocks. In cryogenic landscapes, analogous conditions exist only near the surface. In the oxidation environment, re-deposited minerals (limonite, jarosite, fibroferrite) and ferri-silicate minerals are precipitated over there from acidic sulphide solutions.

In contemporary cryogenic landscapes, under a wide spreading of the reducing environment in a polar cover association, iron becomes one of mobile elements. Its migration is observed in the zone of cryogenesis and in lower parts of a seasonally-thawing layer. Iron is accumulated only near the day surface. The most intense migration of Fe is observed in sulphate cryogenic landscapes. Together with Ca and Mg, iron is accumulated in subordinate landscapes.

*Manganese.* The behaviour of Mn is similar, in many details, to the behaviour of iron. However, insignificant amounts of sulphide Mn in ores make the re-distribution of this element in sulphate zones of oxidation imperceptible. More visible are the traces of migration of Mn in the section of sulphate-oxide zones of oxidation.
The most intense migration of Mn is observed in the section of sulphate landscapes, in the limonite-jarosite sub-zone. Its leaching is hampered by the processes of oxidation, touching upper parts of a seasonally-thawing layer. Contemporary cryogenic landscapes are characterised by increased migration of Mn. During the development of gleying, manganese is concentrated in the formations of "iron hats", it is involved actively in the cycle of salt dispersion. This kind of dispersion is one of basic mechanisms of the formation of hydrochemical and biogeochemical haloes of Mn.

**Zinc.** Zinc represents major products of anode dissolution of sulphides, its subsequent migration is directed upwards. In the course of development of oxide oxidation, Zn is a subject of very intense efflux.

Under near-surface conditions, zinc migrates intensively. It is always present in the composition of re-deposited generations of sulphates of Fe, Cu, and Mg, these elements often form isomorphous mixtures with Zn. However, the process of efflux of Zn prevails over there. Leaching of Zn from ore outcrops leads to a sharp increase of its concentration, in comparison with primary ores.

In contemporary landscapes, migration of Zn envelops all natural bodies of the zone of hypergenesis. High migration ability of Zn is a cause of its accumulation in subordinate landscapes.

2) Group of mobile. migrants.

**Arsenic.** Arsenic, being a mobile element, is carried out only within the limits of the limonite-jarosite sub-zone of sulphate zones of oxidation, where re-deposited generations of arsenates (scorodite, annabergite, symplectite, etc) are widely spread. In the fibroferrite sub-zone, metasomatic differences of scorodite already prevail. Tight paragenesis of arsenates and limonite indicates the participation of solutions in re-distribution of As and its weak migration within frozen grounds.

In sulphate-oxide zones of oxidation, arsenates are located, as before, near the surface. However, their segregations can be sometimes traced up to significant depths, if the sites have sufficient permeability. In oxide zones of oxidation, As is also mobile, this is indicated by the presence of scorodite in lateral rocks having no links with primary sulphides. In the sub-zone of hypergenesis of a polar cover association, As can be easily leached from ore outcrops, it becomes re-distributed by above-permafrost waters.

**Copper.** In the most part of a sulphate zone of oxidation, Cu is not very mobile. Only in fibroferrite and limonite-jarosite ores, where free water episodically appears, migration of Cu becomes noticeable; it is indicated by re-deposited generations of different copper sulphates, and, if neutralisation of acid solutions takes place, by segregations of sulphates of Mg or carbonate complexes of Cu. In cathode parts of ore bodies, secondary sulphides of Cu and native copper are formed, later they are transformed into oxides.

In sulphate-oxide zones of oxidation, re-distribution of Cu affects deep horizons of ore bodies. An alteration of the regimes of infiltration and freezing often yields an appearance of unusual paragenetic associations of secondary ore minerals and the penetration of carbonates of Cu into ores. Oxide zones of oxidation intensively get free of Cu if host rocks are not carbonate.

Copper is actively leached from surface outcrops under contemporary conditions. However, its efflux is strongly hampered by the processes of sorption developing in frozen soils.

**Molybdenum.** In sulphate zones of oxidation, the distribution of Mo follows, in many details, the distribution of arsenic. The traces of its migration are manifested mainly in near-surface environments, where a significant efflux of molybdenum takes place. More intensively migration of Mo proceeds in the section of sulphate-oxide zones of oxidation.

Molybdenum is very stable in water solutions, in wide diapasons of pH and Eh. Soluble compounds of Mo are formed only in oxidizing alkaline solutions; it means that re-distribution of Mo is realized only in low-sulphide ores or in upper horizons of strongly oxidized ores. That is why in the section of oxide oxidized ores, sulphide and oxide molybdenum are distributed comparatively evenly.

Molybdenum actively migrates in the course of formation of contemporary landscapes. Molybdenum ochres can be easily destructed, dissolved, and carried out.

**Silver.** Migration of Ag in cryogenic zones of oxidation is coupled with its release by the influence of anode dissolution of electro-negative sulphides. In a cathode area, silver is precipitated as a native metal.

If the quantity of a liquid phase in near-surface layers is sufficient, Ag is capable to migrate in the form of sulphates. This leads to its significant concentrations in limonite-jarosite segregations.

All oxide zones of oxidation are characterised by accumulations of Ag. In contemporary landscapes, Ag is dispersed by mechanical, water, and biogenic modes.
**Nickel and Cobalt.** These metals are mobile in upper horizons of cryogenic zones of oxidation. In oxide zones, the re-distribution of Ni differs from the behaviour of Co. Owing to its instability in solutions when their pH values are increased, and due to its sorption by clay minerals, Ni is less mobile. In upper horizons of oxidized ores, Ni and Co are actively absorbed by hydroxides of Fe and Mn.

In contemporary oxide landscapes, Ni and Co represent few elements which are subjects of salt dispersion. Sometimes, they are accumulated in subordinate landscapes. Migration of Ni and Co in sulphate cryogenic landscapes is much more intensive.

**Boron.** If tourmaline is present in ores, boron is accumulated in upper horizons of cryogenic zones of oxidation. Boron occurring in silicates is more mobile. Under exogenous conditions, only salts of polyboracic acids are formed. Such elements as Al, Fe, Ca, and Mg are precipitated with B. The medium of zones of oxidation is usually enriched in these elements, this lays obstacles to active efflux of B. Only in contemporary landscapes, in cold waters of a seasonally-thawing layer, saturated with free carbon dioxide, boron becomes extremely mobile and intensively dispersed. It is involved in cycles of water, biogenic, and mechanical migration.

3) **Group of weakly mobile migrants.**

**Potassium and Sodium.** Migration of these elements occurs mainly near the day surface (sulphate zones of oxidation). In sulphate-oxide zones of oxidation, their re-distribution affects deeper layers.

In contemporary cryogenic ore landscapes, migration abilities of K and Na becomes balanced; this is a result of their common participation in the formation of jarosite, which is one of major minerals of ore outcrops, and it is rather stable in the zone of hypergenesis.

**Silicium.** In oxide zones of oxidation, the traces of intensive migration of Si are not preserved. Though silicate minerals can be easily dissolved in sulphate and hydrocarbonate media, there are several obstacles to migration of Si. These obstacles envelop reactions of monosilicic acid with cations of solutions, polymerization of this acid, and also polymerization and coagulation of colloids induced by neutralization of acidic solutions.

In cryogenic zones of oxidation, Si is mobile in near-surface horizons, because neutralization of sulphate solutions is slowed down there. Sometimes, the same conditions are developed in sulphate-oxide zones of oxidation as well. In contemporary landscapes, migration of Si takes place not only within an ore material, but also in a crust of weathering of host rocks, where newly-formed silicates and hypergene quartz are developed.

**Aluminium.** The behaviour of Al in many respects is similar to the behaviour of silicium. In cryogenic zones of oxidation, Al is only partially re-distributed into lateral rocks.

**Selenium.** Solutions of any zone of oxidation are not favourable for migration of Se, owing to the presence of substances creating the reducing environment. Only in the oxidizing environment, in upper parts of a seasonally-thawing layer, Se is a subject of active dispersion. It is capable to be accumulated in subordinate landscapes.

**Titanium.** Re-distribution of Ti is linked mainly with the weathering of rock-forming silicates. It is known that Ti is mobile in media with pH-values below 3 [17]. Such conditions existed in oxide zones of oxidation. In sulphate-oxide zones, they appeared locally and were induced by the warming of climate. Also, such conditions are realized in near-surface horizons of sulphate zones of oxidation. However, migration of Ti is restricted in all zones of oxidation, due to a strong aptitude of its compounds to hydrolysis.

In contemporary landscapes, Ti is mobile in the sub-zone of cryogenesis, this is connected with specific physical-chemical conditions in films of fixed water. First of all, it concerns the difficulties of ions of Ti$^{4+}$ to be subjected to hydrolysis. In this sub-zone, complex compounds, such as TiO$^{2+}$, with increased mobility can be formed as well. On the other hand, in a seasonally-thawing layer, Ti acquires again the properties of a hardly-mobile element, so it is accumulated in landscapes.

**Lead.** In both cryogenic and pre-glacial zones of oxidation, lead occurred in a hard-mobile state. Ions of Pb find themselves in fixed and free waters, when such minerals as anglesite (leadspar) become dissolved, or electrochemical dissolution of galenite occurs. Total efflux of Pb from all horizons of the zone of oxidation is not significant, so against a background of intensive leaching of other elements in near-surface layers, lead trends to be accumulated.

In contemporary landscapes, lead is dispersed chiefly by a mechanical way.
**Gold.** The physical-chemical environment of near-surface horizons of cryogenic zones of oxidation is extremely favourable for re-distribution of Au. Concentrated sulphate solutions promote the formation of complex compounds of gold and its transition to solutions. Rather often, the formation of secondary accumulations of Au was possible, at the expense of the transfer of a metal from ore outcrops downwards.

The major condition of migration of Au in oxide zones of oxidation was a richness of primary ores in sulphides, which caused the development of concentrated sulphate-ferriferous solutions. That is why secondary accumulations of gold occurred only at gold-sulphide deposits. The development of oxide zones of oxidation at gold-quartz deposits was not accompanied by the formation of the sub-zone with a noticeable secondary enrichment in Au.

In all zones of oxidation, Au (as Ag and Cu) is capable to be reduced to a native form. This increases the scales of secondary enrichment of cryogenically-altered ores in gold.

In contemporary landscapes, water migration of Au is rather active, in this process gold occurs in both mechanical forms and the forms of different complexes. Fulvate character of humus of permafrost soils is very favourable for re-distribution of Au in northern landscapes. Migration of Au in the form of thiosulphate complexes also takes place. Acidic reaction of surface waters provides stability of thiosulphate ions.

However, the rate of efflux of gold from halo landscapes is inferior compared to the rate of dispersion of the elements of the first and second groups, this yields a residual accumulation of Au in lithochemical haloes. The concentration of gold in these haloes can be two times higher than its concentrations in ore outcrops.

**Tin.** The behaviour of tin in cryogenic zones of oxidation is determined by the relationship between sulphide and oxide Sn in primary ores. Near-surface horizons are distinctly enriched in cassiterite and depleted in stannite.

In sulphate zones of oxidation, during the periods of warming, mechanical re-distribution of cassiterite from limonite-jarosite into fibroferrite compounds took place. In sulphate-oxide zones, only near-surface enrichment of ores in Sn is manifested. The development of oxide zones of oxidation was also accompanied by a residual enrichment of oxidized ores in cassiterite.

In contemporary landscapes, mechanical re-distribution of Sn proceeds. In the basement of a seasonally-thawing layer, an additional enrichment of a halo material in Sn is possible, owing to the gravitational sorting of particles and removal of soluble products of weathering.

4) Group of inert elements.

**Phosphorus.** At the expense of accumulation of accessory apatite, phosphorus was accumulated near the surface in sulphate zones of oxidation. Its fate in sulphate-oxide zones of oxidation is similar. However, in these zones, segregations of phosphates of Fe and Al among fresh ores are sometimes observed at significant depths. It seems that the Clarke quantities of P in mine waters served as their sources; cryogenic accumulations in the course of repeated freezing of ores promoted an increase of primary quantities.

In oxide zones of oxidation, residual accumulations of P also took place. Only if abundant hypogene phosphate mineralisation occurred, migration of phosphorus could become more or less significant.

Phosphorus is hard-mobile in cryogenic landscapes, it is necessary to take into account its important biogenic role.

**Thorium, Rare-Earth Elements, Niobium, Tantalum, Zirconium.** All these elements are characterised by their residual accumulation in all zones of oxidation. This is a result of the accumulation of their mineral-concentrators: thorite, xenotime, pyrochlore, columbite, baddeleyite, etc. Residual accumulations are most typical for oxide oxidized zones which underwent deep hypogene alterations.

In contemporary landscapes, against a background of mechanical dispersion, further accumulations of these elements occur.

### 6.2. Cycles of geochemical migration of ore elements in the cryolithozone

The studies of the properties of halo landscapes allow to reconstruct the cycles of geochemical migration of ore components which have begun in the remote past. Fig. 10 offers, in a generalized manner, the cycles of migration of elements in cryogenic landscapes. Its right side reflects specific features of migration of a wide range of chemical elements within halo landscapes, its left side illustrates their behaviour in authonomous and subordinate landscapes, within oreless areas.
Fig. 10. Cycles of migration of ore elements in cryogenic landscapes [23].
CD – covering depositions; S – soils; W – water; F – flora; OO – ore outcrops; + – accumulation; ++ – intense accumulation; ≈ – re-distribution; — — efflux; — — — intense efflux; n.o. – not observed; ? – not investigated.

The diagram shows that the pattern of migration of the majority of ore components in halo landscapes is practically the same. However, migration ability of proper ore elements (including the components of sulphides) is significantly higher in landscapes of the sulphate type. This is revealed mostly in the features of water migration of such elements, and in an essential expansion of the spectrum of biogenic accumulation.

Within oreless areas, conjugate landscapes of the cryolithozone are characterised by a certain constancy of the conditions of migration of considered components. Nevertheless, in subordinate landscapes, there is a tendency to slow down an efflux of mobile elements. Against a background of the conservation of the intensity of water migration in vegetation and soils of subordinate landscapes, more active accumulation of the majority of chemical elements arises, in comparison with autonominous landscapes.

The conjugation of oxide landscapes with background ones leads to the formation of weak-contrast water haloes of dispersion of Ca, Mg, Mn, Ni, Co, Ti and B, which already can not give rise to anomalous concentrations when these waters come to surface-stream flows. The possibilities of water migration of other elements are restricted.

Oxide landscapes are characterised by the prevalence of narrowed weak-contrast lithochemical and biogeochemical haloes, among them the haloes of Sn, Au, Ag, Pb and B are mostly developed.

In sulphate landscapes, the parameters of biogeochemical and lithochemical haloes are more diverse; besides narrow and weak-contrast haloes of Ca, Mg, Mn, Ti, Ni, Co, and As, the following features are observed: (1) wide (but weak-contrast) haloes Zn, Cu, and Mo; (2) sufficiently wide and contrast haloes of Ag, Au, Sn, and B; (3) narrow contrast haloes of Pb and W. Among biogeochemical haloes, wide and contrast haloes Ag, Ni, B, Pb and Sn are fixed distinctly.

When sulphate halo landscapes conjugate with background sites, the pattern of water migration of many ore components remains invariable, so wide hydrochemical haloes and fluxes of dispersion are formed over there; however, hydrochemical haloes of Fe, Mn, Ti, Mo, As and Sn are less extensive.

<table>
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<tr>
<th>Elements</th>
<th>Autonomous landscape</th>
<th>Subordinate landscape</th>
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<th>Sulphate type of landscape</th>
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7. Frozen grounds as possible media for radioactive waste disposal (pro and con)

7.1. Mean features of the cryolithozone in the light of its use for waste disposal

Several distinct features characterise permafrost terrains which is important in the light of its use for waste disposal, they are as follows.

- Soils, other artificial deposits and bedrocks that are perenniially frozen contain a low-temperature mineral – ice – as interstitial cement, lenses and massive bodies. The ice content varies with fluctuations in climate, landscape properties, and surface processes, of both natural and human-induced origin.
- Permafrost terrains are subject to yearly thawing from the surface down, resulting in the formation of a seasonally thawed (active) layer. On the other hand, normally unfrozen ground layers (taliks) may freeze seasonally from the surface. The formation of seasonally frozen and unfrozen layers may be accompanied by a range of processes and phenomena such as weathering, sliding and slumping, sorting, lenses of saline groundwater, gelification, icings, mobile rock "streams" (kurums) and rock glaciers, frost heaving and cracking, thermokarst subsidence, and thermal erosion (the erosion of ice-rich permafrost by the combined thermal and mechanical action
- Freezing and formation of massive ice and ice-saturated deposits cause profound changes in various properties (especially, in physical ones) of permafrost terrains. This may involve an increase in the rates of processes, loss of surface stability, and the formation of many relief and landform characteristics of the cryolithozone.
- Fluctuations in air temperature determine the ground temperature regime, freezing and thawing, and the state of frozen grounds, the dynamics of cryogenic processes and the formation of such phenomena as ice wedges, massive ice, and bodies of saline water. Permafrost characteristics are thus tightly linked with climatic and environmental changes.

The cryolithozone is usually divided into a northern zone of continuous permafrost and a southern zone where permafrost is discontinuous or concentrated into smaller "islands".

Several Russian enterprises already use perenniially frozen terrains for disposal of ecologically dangerous wastes. From the beginning of the 80s, Russian research-industrial unit "Jakutalrez" conducts swinging its technogenic salt (non-radioactive) brines into carbonate frozen layers in the district of Mirninsky (Jakutiya). Another industrial enterprise – “Podzemgazprom" works on the problem of disposal of the wastes after drilling (non-radioactive) and storage of hydrocarbons in permafrost rocks of the Yamal peninsula and Western Siberia. From the close of the 80s, Russian research institute " Promtechnologiya" carries out scientific and designing works concerning disposal of radioactive waste in rocky perenniially frozen terrains [10]. Intensive studies in this field are conducted at the Department of Geocryology of Moscow State University [6-10].

Disposal of ecologically dangerous wastes in the cryolithozone appears to reveal the following advantages [10].

- Frozen rocky and dispersed layers are characterised by an essentially reduced rate of different chemical reactions and by sharply raised insulating properties, in comparison with unfrozen rocks. Frozen rocks practically do not filter, they have good sorption properties and low velocities of migration of unfrozen water, ions of stable salts, and chemical elements.
- Frozen grounds, even presented by such rocks as sands and clays, demonstrate rather high properties of solidity and strength, compared with thawing rocks; this provides good conditions for construction of underground repositories without timbering their walls, making this construction much cheaper.
- Perenniially frozen grounds remain comparatively immutable during several dozens and even hundreds of thousands years, and today there is no reason to suppose their disappearance within next milleniums. The state of contemporary geocryology allows to assess and forecast the development of permafrost rocks and the surface of the cryolithozone, taking into account both natural-historical dynamics of the environment and the influence of antropogenic activities.
- Perenniially frozen grounds are sufficiently disseminated, they cover more than 25% of the Earth land; in Russia they occupy more than 2/3 of its territory. Their thickness is always large – from one hundred meters up to one km from the surface down.
Permafrost rocks are usually confined to the Extreme North, i.e. to circumpolar regions, where the density of population is very low, this factor is ecologically important.

*Several issues regarding disposal of high-level radioactive waste in permafrost terrains have to be studied. The most important problems to be solved are as follows.*

- Assessment of mechanical stability of ground walls of a repository in frozen rocks.
- Investigation in detail of the influence of residual heat discharge and radiation of waste upon mechanical and insulating properties of host media.
- Assessment of different insulating characteristics of frozen grounds concerning filtration, ion migration, gas penetration, sorption, corrosion, etc, and the forecast of the interaction of these grounds with radioactive waste.
- Long-term geocryological prognosis, taking into account both natural and anthropogenic phenomena and processes.

**7.2. Assessment of mechanical stability of ground walls of a repository in frozen rocks**

In the cryolithozone, construction of repositories of waste without heat discharge can be accomplished by mine, adit, or other modes without timbering of walls. In Russia, a significant experience of building and exploitation of such installations has already accumulated. Such installations include mining galleries and drifts, underground refrigerators and storehouses, laboratories, etc. Mine working are divided into storage chambers, ventilation premises, and unsealing sections connecting underground rooms with the surface (see Fig. 11).

![Diagram of underground refrigerators](image)

*Fig. 11. Underground refrigerators of mine (shaft) (a) and adit (c) types and scheme of disposal of chambers (b) [10].*
For example, in large underground repositories in Siberia made in fine-ground dispersed frozen rocks at depth between 6 and 14 m, the volume of underground workings is as much as 13 000 m$^3$, and their length is about 1000 m. The chambers have bays from 2 to 5 meters long, with half-circular arches without timbering. Such installations are in operation during more than 20 years, and, practically, there were no incidents of the collapse of roofing. As rough calculations show, a limit value of a bay for non-timbered mine workings depends on the composition of frozen rocks, their ice content, cryogenic texture and temperature; these values range from 20–25 to 2–2.5 m [7].

High mechanical stability of walls and roofing without timbering is caused by the fact that strength of frozen sandy and clayey rocks is several times higher than strength of unfrozen rocks, and it increases with a temperature fall. Rocky layers usually have good strength characteristics, but their use makes the construction much more expensive.

Mechanical stability of frozen or thawed rocky layers around a repository of waste with heat discharge, in cases of well, pit-stem or adit modes of disposal does not excite any apprehension. However, special calculations are necessary designed for assessment of changes of carrying ability and limits of admissible deformations of frozen rocks, because at the expense of their transition into a thawed state during the formation of thawing haloes, the strength of rocks decreases, the ability of being deformed increases, and the action of forces of freezing of a ground with a material of external contour of a repository is stopped.

7.3. Investigation of the influence of residual heat discharge and radiation of waste upon mechanical and insulating properties of host media

The forecast of the interaction of heat discharged with host permafrost rocks is very important, because this interaction leads to development of the processes of thawing and subsequent re-freezing, migration of moisture and chemical elements to the front of "freezing-thawing", etc. The radii of haloes of thawing and temperatures of rocks near repositories depend on many factors: initial volume density of the discharge of energy of radioactive waste, the period of their decay, the volume of a repository, heat conductivity, heat capacity, the content of ice (the expenses of heat for phase changes), and the temperature of host permafrost rocks.

The temperature regime and parameters of thawing haloes can be calculated for any time, using the problem of Stephan. Numerical modeling of the dynamics of the formation of a temperature field of rocks in the zone of influence of a repository of high-level radioactive waste has shown that the radii of thawing haloes of permafrost rocks can range from several meters up to tens or even hundreds of meters, depending on the combination of above-mentioned factors [7]. Maximum haloes of thawing are typical for rocky terrains having rather low content of ice but high negative temperatures, whereas minimum haloes are displayed in low-temperature sandy-loamy with high content of ice (see Fig. 12).

![Fig. 12. Dependence of the thawing radius of rocks (R) around a well-type repository of radioactive waste for the 10th year of its exploitation: a – on initial heat discharge (q) at the rock temperature t = – 3°C (1 – q = 0.32 kWt/m$^3$, 2 – q = 1.0 kWt/m$^3$); b – on the temperature of host rocks at q = 0.35 kWt/m$^3$ (3 – t = – 0.5°C, 4 – t = – 2°C); I – loam, II – granite.](image-url)

1 – tambours, 2 – chambers, 3 – ventilation premise, 4 – strong hydroisolation, 5 – traps,
6 – seasonally thawing ground, 7 – permafrost ground, 8 – loading pit. All dimensions are in cm.
The absence of underground water (at temperatures below 0°C, all free water is transformed into ice). In considering insulating properties of frozen grounds, it is necessary, first of all, to take into account the presence of ice. Radiation upon the properties of frozen grounds are diverse and numerous, they demand further studies.

Irradiation may also provoke the processes of radiolysis of water formed by thawing of frozen grounds. This process of re-freezing in any closed system involves usually the development of deformations and strengths of heaving of rocks (especially of clay composition), and under certain conditions it may provoke deforming and crumpling of repository wells. Negative effects of re-freezing can be eliminated or minimized by such measures as a decrease of the content of radionuclides in a volume unit, an increase of the distance between containers, etc.

The formation of significant thawing haloes in rocky layers that can have a diameter of 50 m and more, generates the problem of assessing parameters of their jointing and possible loss of anti-filtering properties by a whole rocky block. In addition, a weak content of ice can lead to very significant increases of a depth of thawing from the surface, in case of global climate warming. Calculations show that in the course of 150–200 years, this depth may reach a value of 60–70 meters. Then the whole of repository will find itself in a thawed zone of filtering rocky layers. In this respect, fine-grained dispersed permafrost rocks with a high or moderate content of ice appear as more reliable. Firstly, their highest possible depths of thawing from the surface will scarcely exceed 15–20 m during 100 years (even if global warming takes place), and second, thawing haloes of ice-bearing clayey rocks around a repository will not exceed several tens of meters. So, there will be only the problem of choice of an optimum depth of disposal of high-level radioactive waste. This is rather easy to make, performing mathematical prognostic modeling, taking into account an initial content of ice, temperatures of permafrost rocks, and their thickness. However, in any case, the depth of laying of an adit, well or adit-well repository should be no less than 50–60 m. Calculations show that insulating and screening properties of fine-grained dispersed rocks, both frozen and thawed, provide in their thawing haloes reliable isolation of high-level radioactive wastes from their release into the biosphere during the next 1000 years (see below about the assessment of insulating properties of perennially frozen grounds).

Another important issue which can not be ignored in design of a repository and assessment of its safety, is the action of radiation upon a medium hosting radioactive wastes. The changes induced by irradiation in the material of containers and repository walls may affect physical and chemical properties of substances, this will lead, in particular, to an increase of their rate of dissolution. Irradiation may also provoke the processes of radiolysis of water formed by thawing of frozen grounds, this should reinforce solubility of solid substances as well. These processes generate the appearance of free oxygen, hydrogen peroxide, and free radicals in the solution, so underground waters will become aggressive, with even more increased ability to dissolve. Details of the action of radiation upon the properties of frozen grounds are diverse and numerous, they demand further studies.

### 7.4. Assessment of insulating characteristics of frozen grounds

In considering insulating properties of frozen grounds, it is necessary, first of all, to take into account the absence of underground water (at temperatures below 0°C, all free water is transformed into ice). This excludes the possibility of migration of radionuclides, toxic chemical elements and other ecologically hazardous substances beyond the limits of a repository by filtrating waters. It is clear that perennially frozen terrains with cryopegs should be excluded from the list of sites-candidates for underground disposal (cryopegs are layers and lenses of ground perennially below 0°C, but unfrozen (cryotic) because of saline pore water, they can change in vertical position, volume, temperature, and salinity with short-term (several years) climatic fluctuations). Thus, even if there is some partial thawing of frozen rocks around underground repositories of wastes with heat discharge, free water formed at the expense of thawing of rock ice will occur only within the limits of a halo of...
thawing which will be encircled by frozen non-filtering rocks. One can say that ice-bearing rocks, with their ability to eliminate the possibility of filtration of underground waters, work as a natural geological barrier of long duration. However, it is necessary to assess separately anti-freezing properties of a potentially dangerous group of rocks (such as fractured and weathered rocky, sandy and coarse-fragmented ones) and properties of a group of practically non-filtering rocks (both in a frozen and thawed state) having sandy-loamy or clayey composition. The reasons are as follows.

Firstly, rocks of the first group used as a hosting medium for repositories should have a maximum coefficient of filling of their pores, cavities, and fractures by ice ($G = 1$). Otherwise, even in a frozen state, there is a risk of inundation of mine openings and repositories caused by natural or human-induced processes (such as uplift of water-table, rise of head filtration, flooding of territories, sea transgression, etc). Secondly, thawing of massifs of this group (even if filling of pores and fractures by ice is complete) is inadmissible in principle, due to their high filtration permeability at the state of thawing.

Fine-grained dispersed rocks of the second group at the state of freezing, even with their coefficients of filling of pores by ice $G = 0.4–0.5$ (this always takes place under natural conditions), are practically non-filtering. But even after the transition of these rocks into a thawed state, their filtration ability is of several orders of magnitude lower compared with rocks of the first group. Thus, it is obvious that frozen grounds with sandy-loamy and clayey composition appear as incomparably more reliable natural screens, practically preventing completely the release of radionuclides, toxic chemical elements, liquid brines and solutions into the biosphere by the way of convection (by filtering waters).

The same can be said about gas- and air-permeability of frozen grounds, in respect of the role of convection. Special experiments have shown, for example, that even frozen sandy-clayey rocks are characterised by coefficients of gas permeability which are of one order of magnitude lower in comparison with thawed rocks [7].

However, it is necessary to take into account that, besides filtration (convective) mechanism, another one – migration (diffusive) mechanism can result in the release of radionuclides and toxic elements into the biosphere. Though the rates of such processes in frozen rocks are low, nevertheless their assessment and prognosis should be performed for any concrete case, because very long-terms (up to 10 000 years) of disposal are planned. Thus issue has been investigated very weakly in both field and laboratory conditions. The results of experiments conducted at the Department of Geocryology of Moscow University show the following [10] Coefficients of diffusion of ions and chemical elements on frozen fine-grained dispersed rocks vary within the limits of one order of magnitude, they become essentially lower with a fall of negative temperature (see Table 5).

### Table 5. Coefficients of diffusion of ions of chemical elements in frozen rocks and ice [10]

<table>
<thead>
<tr>
<th>Rocks</th>
<th>Experimental conditions</th>
<th>Concentration of a frozen solution</th>
<th>Ions</th>
<th>Coefficient of diffusion, cm²/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experiment duration, months</td>
<td>Temperature of experiment, °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>3</td>
<td>–6</td>
<td>0.1N</td>
<td>Sr</td>
</tr>
<tr>
<td>Loam</td>
<td>3</td>
<td>–6</td>
<td>0.1N</td>
<td>Sr</td>
</tr>
<tr>
<td>Kaolinite clay</td>
<td>1</td>
<td>–6</td>
<td>0.1N</td>
<td>Sr</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>–2</td>
<td>0.1N</td>
<td>Sr</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>–20</td>
<td>0.1N</td>
<td>Sr</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>–6</td>
<td>0.1N–0.6N</td>
<td>Co</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>–6</td>
<td>0.1N</td>
<td>Sr</td>
</tr>
<tr>
<td>Ice</td>
<td>0.5</td>
<td>–6</td>
<td>0.1N</td>
<td>Sr</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>–6</td>
<td>0.1N</td>
<td>Zn</td>
</tr>
</tbody>
</table>

For the samples of massive ice, the values of coefficients are of almost one order of magnitude higher than for frozen rocks studied. From this, one can suggest that in frozen rocks, ice and thin films of unfrozen water may serve as a conducting medium. Ice is presented either as an isolated matter in rock pores or as numerous, but separated interlayers, veins, and schlieren, so there is no dissoluble ice way in a rock, and the mechanism of migration of ions and elements appear to be excluded. However, this does not concern massifs of underground ice because migration rates in ice are essentially greater.
Based on regularities of migration of ions and elements in loamy-sandy frozen rocks composed by montmorillonite and hydromicas, which have been identified in the course of laboratory experiments, it is possible to assess, in the first approximation, the dynamics of development of haloes of ion migration. Rough calculations show that radii of migration of radionuclides and chemical elements around a repository may be as much as tens of meters per millenium. Nevertheless, such results need additional checks and new special studies. Even if thawing of loamy-sandy rocks hosting an underground repository is complete, the rate of an increase of a halo of migration of ions, chemical elements and radionuclides not only remains, but even decreases. This is induced by two reasons: first, the coefficients of diffusion in thawed fine-grained rocks are lower compared to frozen rocks, and second, sorption ability of fine-grained rocks sharply increases when they are transformed from a frozen state into a thawed one.

By assessing insulating properties of frozen clayey rocks in general, one should note their high adsorption ability, in comparison with rocky layers, together with weak corrosion activity and lowered rates of all chemical reactions, which is connected to the absence of free water under negative temperatures of rocks. On the other hand, a range of issues regarding underground disposal of radioactive and toxic wastes in the cryolithozone, requires serious research. In geocryology of today, there are many unsettled questions, such as the features of chemical reactions (dissolution, hydrolysis, ion exchange, oxidation-reduction, etc) in frozen rocks with different composition, structure, and properties.

7.5. Long-term geocryological prognosis

Firstly, it is necessary to consider natural phenomena and processes responsible for the behavior of the cryolithozone in the distant future. Long-term forecast of the changes of air temperature for mid-latitude areas of the Russian Platform has been performed at the Department of Geocryology of Moscow State University [10]. The analysis based on paleoclimatic and paleotemperature data has shown that within the next 6-10 thousands years a new global fall of temperature has to be expected. So, the area of spreading of perennially frozen grounds will not only be conserved, but should be expanded. Local deviations of average annual temperatures from the values forecasted for 100–200 years due to natural climate dynamics will not exceed 1–2°C. Thus, there will be no essential changes in the conditions of the cryolithozone, and, from this point of view, underground repository will be intact even in a rather long-term perspective.

![Fig. 13. Forecasted values of the rise of average annual air temperatures by 2100 owing to an increase](image)
of the concentration of green-house gases in the atmosphere (according to the IGKE scenario [2]).

Obviously, much more important changes of the temperature regime of frozen rocks can be induced by possible global warming owing to raised amounts of green-house gases in the atmosphere. Several scenarios of such global climate warming have been suggested (see, for example, [6]). E.D. Ershov et al. have used the so-called IGKE scenario proposed in 1993 by a group of Russian scientists [2]. The calculation of the values of a temperature rise by 2100 due to an increase of the concentration of green-house gases in the atmosphere was based on the use of numerical solution of the problem of Stephan, the results are presented in Fig 13. The calculation analysis shows that by 2100, the southern boundary of permafrost terrains, occurring from the surface, will be removed towards the north – by 500–700 km within Western Siberia and by 1000 km or more within Middle Siberia and north-east Russia. On the territory of European north of Russia, there will be no frozen grounds occurring from the surface at all.

The calculation results allowed to draw a forecasting geocryological map of Russia for 2100 which is presented in Fig. 14 [10].

Fig. 14. Prognostic geocryological map of Russia for 2100 based on possible global warming [10] according to the IGKE scenario [2].

1 – zone of thawed by 2100 perennially frozen grounds; 2 – zone of perennially frozen grounds without pouring out, having the depth of occurrence from 5 to 20 m (relict permafrost rocks occurring at the depth of 50 m or more are not shown in this map), average annual temperature of rocks \( t_0 \) is between 0° and 3°C; 3 – zone of insular (50–90%) propagation of perennially frozen grounds with \( t_0 \) from 0.5°C to −2°C; 4–6 – zones of continuous (compact) propagation of perennially frozen grounds: 4 – with \( t_0 \) from −1°C to −5°C, 5 – with \( t_0 \) from −5°C to −6°C, 6 – with \( t_0 \) from −6°C to −8°C; boundaries: 7 – of perennially frozen grounds without pouring out, 8 – of insular perennially frozen grounds, 9 – of continuous perennially frozen grounds, 10 – contemporary southern boundary of permafrost rocks.

There are several zones with different geocryological conditions on the map given in Fig. 6. The first zone covers the territory where perennially frozen grounds which have today a thickness up
to 15 m will be practically completely thawed during the period of time considered. Average annual temperature over here will be positive along all the section. Only in winters, the layers will be frozen in some extent, their depth will be determined by concrete climate and landscape characteristics, by the composition and properties of an upper horizon of rocks.

The second zone includes territories where frozen grounds will be thawed down from the surface. Depending on the composition, structure, and properties of rocks, their initial average annual temperature, the thickness of a thawed out horizon will be between 5 and 20 m. So, there will be two horizons of rocks: the horizon of thawed layers with average annual temperature from 0°C till +2°C, and the horizon of underlying permafrost rocks having the temperature from from 0°C till −0.5°C. This zone will be characterised also by seasonal freezing of rocks.

The third is the zone where perennially frozen rocks with average annual temperatures up to −2°C predominate. However, in some localities, the sites can be observed where thawing from the surface (which is typical for the second zone) will begin. The sites of permafrost grounds will be affected by seasonal thaw, whereas the sites with taliks will be touched by seasonal freeze.

The fourth is the zone of continuous spreading of perennially frozen rocks. Their average annual temperatures will be negative (with the exception of talik zones under large lakes and rivers), but by 4–6°C higher than today.

In all these zones, both thawing and frozen rocks will be characterised by non-stationary temperature regime. Their temperatures along the section, the values of a depth of seasonal freeze, seasonal and permafrost thaw will vary in time during all the forecasted period.

The forecasted time of the beginning of thawing depends on the contemporary average annual temperatures of permafrost rocks and on the expected tendency of temperature rise in each given region. The rate of thawing is determined not only by initial conditions of rocks and a forecasted temperature rise, but by the composition and properties of rocks as well. This can be seen from the comparison of calculation results for different regions of Russia presented in Fig. 15.

It is clear that under the same conditions, the surface and initial rock temperatures, the depth of thawing of rocky layers (for example, granites) will be 3–5 times more than in case of iced clayey rocks [9].

Using basic classification indications (large morphostructures, composition of permafrost rocks, their ice content, average annual temperature, thickness, seismicity), several types of perennially frozen terrains and regions of their propagation have been identified by E.D.Ershov et al [9,10]. The conditions of these regions were assessed according to their ability of being favourable for the construction of underground repositories. As a result, a survey map (the scale of 1:25 000 000) of zoning of the territory of Russia has been composed. This map is presented in Fig. 16, it reflects the conditions of underground disposal of ecologically dangerous wastes (without heat discharge). The

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Fig. 15. Geological structure (b) and dynamics of thawing of permafrost rocks owing to global warming (a) for several points within the cryolithozone of Russia [10].

following types of regions are shown: very favorable, favorable, conditionally favorable, unfavorable, and very unfavorable.

Fig. 16. The map of zoning of the territory of Russia according to the conditions of underground disposal of ecologically dangerous wastes without heat discharge [10].

1–6 – regional conditions for disposal of repositories (1 – very favorable, 2 – favorable, 3 – conditionally favorable, 4 – unfavorable, 5 – very unfavorable in fine-grained rocks, but conditionally favorable in coarse-grained rocks, 6 – favorable in fine-grained rocks, but unfavorable in coarse-grained rocks), 7 – boundaries of regions (a), areas (b), temperature zones (c), 8 – southern boundary of propagation of permafrost rocks, 9 – regions with seismicity > 7 points.

There are very favorable conditions for disposal of repositories in localities where rocks possess high insulating properties (strong adsorption capacity and weak ability for filtration) even in the state of their thawing, together with high heat stability, and can demonstrate moderate mechanical steadiness. In such regions, an entering of cold air in winter into an underground repository will be sufficient to compensate the expenses of cold due to the load of containers. In order to avoid thermokarst caused by thawing of layers with a high content of ice, having repeated ice veins or ice beds, the construction of superficial buildings necessary for the maintenance of a repository should be accompanied by land-improvement measures.

Naturally, the more favorable are regional conditions, the more reliable are safety and durability of a repository, and the lesser are capital and exploitation expenditures.
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