Earth's Cryosphere, 2016, vol. XX, No. 2, pp. 23–28 **http://earthcryosphere.ru/**

SYNCRYOGENIC MINERALS IN THE NORTHEAST OF RUSSIA

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Formation and development of the permafrost zone in the northeast of Russia resulted in the emergence of new types of minerals, named syncryogenic by the authors. Among them there are fossil coals partially oxidized due to oxygen and water deficits in the permafrost formations; placer gold formed during seasonal freezing and thawing, and peat accumulated at the near-surface cryogenic aquifuge.

Northeast of Russia, permafrost, cryosophy, syncryogenic minerals, oxidized fossil coal, placer gold, peat

INTRODUCTION

Over the recent years, a new science of *cryosophy* is being formed within the entire complex of sciences dealing with the cryosphere, in the framework of which *cryodiversity* is being studied, which is a totality of objects and phenomena related to cold and phase changes of water [*Melnikov et al., 2013*]. A component of cryodiversity is the *cryogenic resource,* a source of new types of raw materials for manufacturing useful products, for nanotechnologies, new ways of gas storage and transportation, utilization of greenhouse gases, etc. [*Melnikov and Gennadinik, 2011; Melnikov, 2012, 2014*].

The objective of this study is to demonstrate that in the northeast (NE) of Russia there are such elements of the cryogenic resource (mineral deposits), the conditions of the formation of which and whose properties are caused by the plurality of the processes and phenomena related to seasonal and permafrost freezing and thawing of the permafrost mass and to omnipresent near-surface cryogenic aquifuge.

The materials used for the study were obtained during many years' field, laboratory and office work of the authors in the northeast of Russia. The works by the geologists and hydrogeologists of the former Sevvostokgeologiya geophysical production company were also used. Some of them have been partly published, and some are kept as manuscript reports in the Magadan branch of the Territorial Fund for Geological Information.

RESULTS AND DISCUSSION

Analysis and summarization of the results of the geological works performed in the northeast of Russia over the recent 80 years allowed identification of mineral deposits the formation of which occurred at the time of emergence and development of permafrost in the Quaternary time. This allows us to consider such mineral deposits syncryogenic (*Greek syn – with, together with*). Among these, we consider fossil coals transformed in the permafrost or placer gold and peat accumulations formed (Fig. 1).

Syncryogenic oxidized coals. Identification of fossil coals oxidized in permafrost as an independent type of a mineral deposit was based on the works by *O.B. Maksimov* [*1948, 1949*]. Maximov was the first to notice that, resulting from weathering of permafrost coals in their natural bedding, they become enriched with low-molecular weight organic acids (LOA): acetic benzene carbonic acid, oxalic acid, etc. and regenerated humic acids (RHA). Over the subsequent years, the other researchers showed that oxidation (or weathering) of coal in the permafrost zone is widespread and stretches to the depth of 50–60 m, rarer reaching 100 m [*Karavayev et al., 1965*]. The mechanism of oxygen penetration into icy formations of coal is scarcely studied; however, the fact of coal oxidation in the frozen state is not subject to any doubts and is proven by the presence of copperas ($Fe_2SO_4 \cdot 7H_2O$) and of free organic acids in them. In case of oxygen deficit and in the absence of gravity water, the process of oxidation of frozen coal, according to *Maksimov* [*1948*], is described by the formula

$$C_{org} + O_2 + H_2O \rightarrow LOA + RHA,$$

where C_{org} is the organic mass of coal.

The percentage of LOA, which are a mixture of oxy- and keto acids, reaches 10 %, including benzene carbonic acids – up to 3.5 %, acetic acid – up to 1.5 %, RHA – up to 75 %. At the same time, coals oxidized in permafrost decrease their quality as an energy source by nearly 50 % [*Popov, 1962*]. Therefore, during coal production the greater amount of such coal becomes dumped, contributing to contamination of the atmosphere and of the hydrosphere. At the same time, syncryogenic oxidized coal is a raw material for producing low-molecular-weight organic and regenerated humic acids. The idea of extracting LOA from oxidized frozen coals and of using them in the chemical industry belongs to *O.B. Maksimov* [*1949*].

Modern researchers have shown that the complex of oxy- and keto acids and of RHA coals is referred to biologically active agents, which are used in spa treatment, including medical treatment of tumors, in processing oil products, in extracting gold

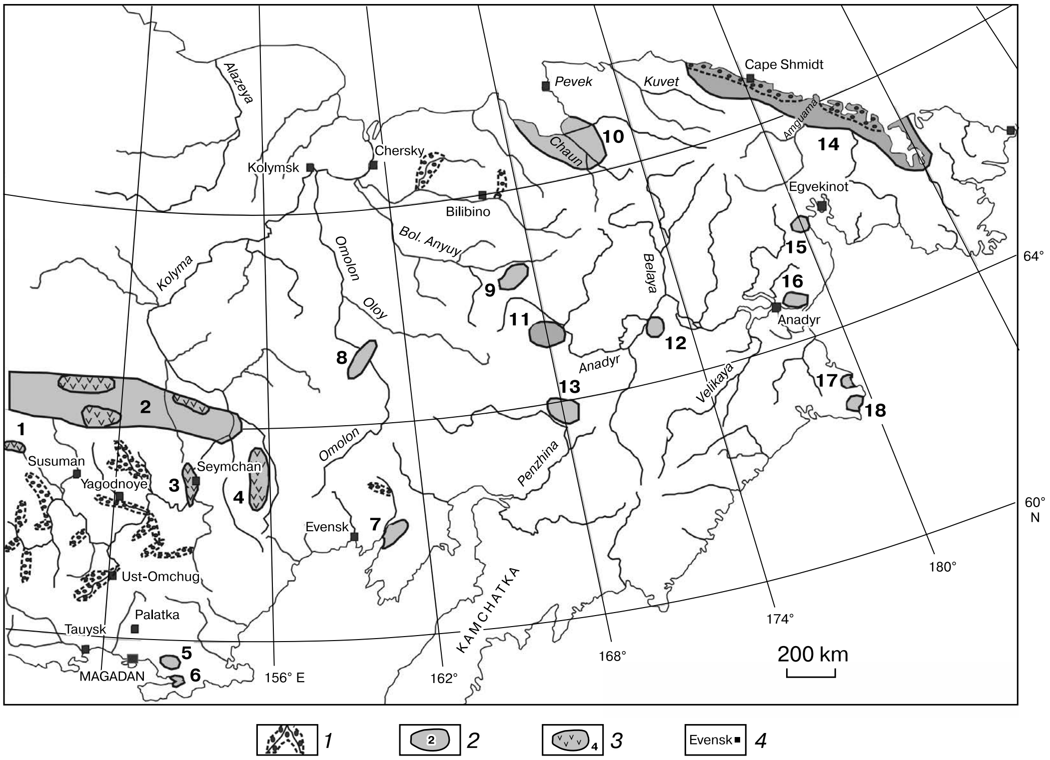

Fig. 1. Occurrence of the deposits of syncryogenically oxidized coal and of syncryogenic placer gold deposits:

1 – river valleys and littoral regions with manifestations of syncryogenic placer minerals; *2* – coal-bearing basins perspective in terms of deposits of syncryogenically oxidized coals, including: **1** – Arkagalinsky coal basin; **2** – Indigiro-Zyryansky coal basin, **3** – Elgensky coal basin, **4** – Omsukchansky coal basin, **5** – Lankovsky coal basin, **6** – Melkovodnensky coal basin, **7** – Avekovsky coal basin, **8** – Omolonsky coal basin, **9** – Anyusky coal basin, **10** – Chaunsky coal basin, **11** – Markovsky coal basin, **12** – Eldenyrsky coal basin, **13** – Penzhinsky coal basin, **14** – Vankaremsky coal basin, **15** – Egvekinotsky coal basin, **16** – Anadyrsky coal basin, **17** – Beringovsky coal basin, **18** – Amaamsky coal basin; *3* – areas of the coal-bearing basins with confirmed development of syncryogenically oxidized coals; *4* – the main settlements.

and ore at gold refineries, etc. [*Perminova, 2008; Application..., 2012*].

Syncryogenic placer gold. This type of the mineral deposit was identified based on the actual facts of recovery of mined out placer gold deposits within 15–20 years, including geologically inexplicable double or triple production of gold from the deposits, compared to its explored reserve. Such cases occurred in the basins of the Orotukan River (Zagadka Creek), of the Laryukovaya and Gerba Rivers (Solnechny, Zhurba, and Kazak Creeks), from which gold has been produced for over 80 years. Stability of the mass of gold produced over a long period of time from the many times washed technogenic deposits cannot be attributed only to the defects or errors of geological calculations or production [*Shilo, 2000; Flerov, 2003*]. The best-known cryogenic process of enrichment of the technogenic gold deposits is disintegration of aggregations of gold grains with other minerals at seasonal freezing-thawing cycles of the beneficiation tailings. However, continuous recovery of the resources of placer gold takes place primarily due to cryogenic processes. The find by A.V. Alshevsky (Shilo Northeastern Research Institute, Russian Academy of Sciences) in August 1979 of a "gold spade" in the floodplain of the Sentyabrsky Creek (the basin of the Tenka River) in the dump on the area of the gold deposit mined out by the gold diggers in the mid-1960s is the direct proof of such processes of accumulation of the mass of gold in the dumps. A fragment of the spade is kept in the museum of the Northeastern Research Institute. Gold grains several millimeters in diameter were removed but gold films are well preserved there – the places of the grains' contact with the steel surface of the spade.

Rather numerous are the facts of gold migration in suprapermafrost waters and of accumulation of this metal by iron hydroxides, by algae, and its presence in the sulfate salts collected from the surface of sulfurized minerals (Table 1).

The processes of gold transition to an aqueous solution were first studied by *S.S. Smirnov* [*1951*],

Table 1. **The content of gold in different bodies related to suprapermafrost waters***

No.	Samples: place and date of sampling	Chemical composition of water, formula	Gold content, g/t
1	Rust [$Fe_2O_3{\cdot}nH_2O$; $FeO(OH)$; $Fe(OH)_3$] from the surface of a pipe on the left bank of the Uval Creek (the basin of the Omchak River); 20.08.2001	$M0.08\ \frac{SO_4 69 HCO_3 30}{(Na+K)48Ca30Mg21}$ pH 6.8	0.75
2	A layer of $Fe(OH)_3$ at the bottom of the water leak from pyritized mud shale (T_3n) at the foot of the slope of the Gerba River plain; 15.08.2001	$M0.05\ \frac{SO_4 60 HCO_3 36}{(Na+K)73Mg15Ca12}$ pH 6.8	0.4
3	Accumulations of filamentous algae in the channel of the downstream of the Kazak Creek; 04.08.2001	$M0.2\ \frac{HCO_3 52 SO_4 27Cl21}{Ca48(Na+K)25Mg25}$ pH 6.5	0.4
4	A layer of $Fe(OH)_3$ near the water outlet on the slope of Goltsovy Creek (the basin of the Maly At-Uryakh River)	$M0.76\ \frac{SO_4 61 HCO_3 38}{Ca63Mg37}$ pH 7.4	1.03
5	Salt bloom at the foot of the beneficiation tailings in the valley of the Zagadka Creek; 02.09.2001	–	0.12
6	Springs of suprapermafrost waters in the valley of the Pavlik Creek (the area of a gold ore deposit); 21.08.2001	$M0.11\ \frac{SO_4 62 HCO_3 37}{(Na+K)40Ca31Mg29}$ pH 6.2	0.09 μg/dm^3

* The tests were conducted at the Shilo Northeastern Research Institute of the Far Eastern Branch of the Russian Academy of Sciences, including the hydrochemical tests performed by analyst D.S. Krotova, and nuclear-absorption tests performed by analyst V.P. Kolesova.

who showed that gold could get dissolved, transferred and accumulated under conditions of the oxidation zone of sulfide deposits. His ideas were developed by other researchers, who also experimentally proved dissolution of gold in water, especially in the presence of the salts of iron oxides in water [*Godovikov, 1975; Plusnin and Pogrebnyak, 1979; Varshal et al., 1984*].

In the modern cryogenic region, the chemical agents of gold migration may be activated by the processes of seasonal freezing-thawing of water-saturated surface layer of permafrost, including the anomalous properties of thawed water, emergence of natural electric fields, and the cryogenic metamorphism of ground waters. The placer deposit role of thawed water was revealed experimentally by using an isotope ^{195}Au [*Mitrofanov et al., 1981*]. It was found that after thawing, distilled water desorbs gold from the solid phase, which is accounted for by the increase of the geochemical activity of thawed water. During half a day, this property disappears, and gold from the solution precipitates or gets absorbed. This process can take place under natural conditions at thawing of the seasonally thawed layer (STL) on the slopes of mountain valleys. Gold absorbed on loose slope sediments passes into water and migrates to the bottom of the river valley, where it precipitates on the gold grains.

Manifestations of the anomalous properties of thawed water may be reinforced by natural cathode phenomena arising during freezing–thawing. The natural potential difference on the border of thawed and thawing soils in the Anadyr plain in some cases reached 1055 mV [*Glotov, 1989*]. Discharge currents contributing to migration and accumulation of gold arise at freezing of water [*Workman, 1954; Shavlov, 1996*]. Due to these cathode phenomena, gold compounds, which are stable in a water-soluble state, get destroyed to form native nanoparticles. They are deposited on the available gold grains and form films on ice crystals. Such films were first described by *S.L. Shvartsev* [*1976*].

We can suppose that cryogenic metamorphization of the chemical composition of the natural waters is an important process which controls accumulation of gold in placer deposits. The percentage of gold in STL waters by the end of the warm period of the year varies within $(0.5–1){\cdot}10^{-3}$ mg/dm^3. When water-bearing layers get frozen, the total mineralization of water and the gold content increase several times, sometimes dozens of times. The hydrogeochemical role and significance of this process are practically unknown; yet, they attract the attention of many researchers. We can suppose that cryogenic increase of the percentage of water-dissolved gold results in its adsorption on the surface of gold grains or of iron oxides. In all the cases, the zones of hydrothermal mineralization, gold ore objects and syngenetic pyrite in clayey and sandy-clayey shale of the Perm-Jurassic age serve as sources of the noble metal in the water solutions. The content of gold in pyrite from sedimentary strata is 37–60 mg/t, and that in the pyrite of quartz veins is 75–100 mg/t [*Voroshin, 1992; Sidorov and Thomson, 2000*]. The existence of the sources of gold, of natural processes of its migration in water solutions, its precipitation or sorption on the surface of mineral particles allowed the researchers to substantiate formation of “hydrogenic placer gold” [*Roslyakov, 1981; Tausson et al., 1989; Abramov et al., 2003; Dutova et al., 2006*]. Analysis of the above studies suggests that the “hydrogenic placer gold” is associated with the permafrost region within its borders in the extreme cold cryochrons of the Pleistocene, according to *S.M. Fotiev* [*2013*]. Thus, it is possible to refer syncryogenic placer gold to genetic types developed in this region. The plurality of the accumulated facts relating to manifestations of placer gold-generating cryogenic processes allows us to state the problem of technogenic control of these processes and of recovery of anthropogenic placer gold deposits.

Syncryogenic peat accumulations. Compared to peat deposits in non-permafrost regions, these deposits are different by the occurrence of peat-forming plants, the geomorphological variety of areas with peat accumulations, and by the peat-generating processes. The permafrost zone is characterized by poor species diversity of peat forming plants, related to the character of their mineral nutrition. This is accounted for by the low mineral content (less than 100 mg/dm^3) of natural waters feeding the bogs. In the areas of annual discharge of mineralized subpermafrost waters, aufeis destroying vegetation develops in the winter period [*Tolstikhin, 1974*]. Peat forming plants are primarily oligotrophic; therefore, it is difficult to divide syncryogenic deposits into the commonly known lowland, transitional, and highland deposits [*Lazarev and Korchunov, 1982*]. Among the peat accumulations, forest and forest-marsh types are absent. Usually peat deposits are of the marsh grass-moss and moss types.

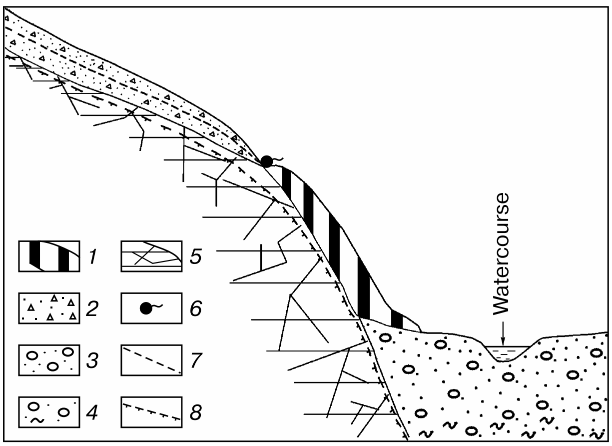

Fig. 2. Formation of peat accumulations on a montane slope:

1 – peat; *2* – rubble-gruss slope deposits; *3* – alluvial sand-gravel-pebble deposits; *4* – the same, with admixture of clayey particles; *5* – hypergenically crevassed rocks; *6* – STL ground water outlets; *7* – groundwater level in the seasonally thawed layer; *8* – permafrost top.

The geomorphology of these deposits is attributed to the fact that under harsh climatic conditions of the northeast of RF, the size of plant litter in all the ecosystems prevails over its decomposition rate. This results in accumulation of vegetation substances both on excessively wet and on the drained areas of all the elements of the terrain. In the absence of excessive moisture, the process of “dry” peat accumulation takes place. The thickness of “dry” peat varies from 26 cm in thin larch forests to 33 cm in thin lichen-moss Arctic forests [*Berman et al., 1972*]. The accumulated “dry” peat absorbs moisture, causing appearance of peat-forming plants and accumulations of common moss peat on its surface.

Peat accumulations on the crowns of mountain slopes have interesting genesis. In this region, due to the near-surface cryogenic aquifuge, linear beds of seasonally thawed layer (STL) groundwater discharge are formed, resulting in excessive moisture and bogging of the slope below the groundwater discharge bed. “Hanging peatland is formed up to 0.7–1.0 m thick, composed of mossy peat with a low degree of decomposition and the volume reaching the first tens of thousands of cubic meters (Fig. 2).

The largest peat deposits have been found on plains and in intermontane depressions (Fig. 3). They are most often associated with overgrown hollows of drained off thermokarst lakes, which serve as the local sources of concentration of suprapermafrost water runoff to plains and lowlands (Anadyrsko-Penzhinskaya, Vostochno-Sibirskaya, Indigiro-Zyryanskaya, etc.). Depressions between boulder trains and runoff tracks on the tundra surface serve as accumulators of the ground waters of STL.

We estimate the total geological peat deposits of northeastern Russia to be 2 billion ton in a frozen-air state [*Glotov et al., 2003*].

Another difference observed between the peat generating processes in the permafrost zone and in non-permafrost regions is that seasonal thawing in the peat deposits does not normally exceed 0.5 m (within the peat generation layer) [*Tyuremnov, 1976*], i.e., weakly decomposed peat gets frozen syngenetically. In fact, medium- or strongly decomposed peat forms the foundations of the explored peat deposits, with humic substances content reaching 50 %. In our

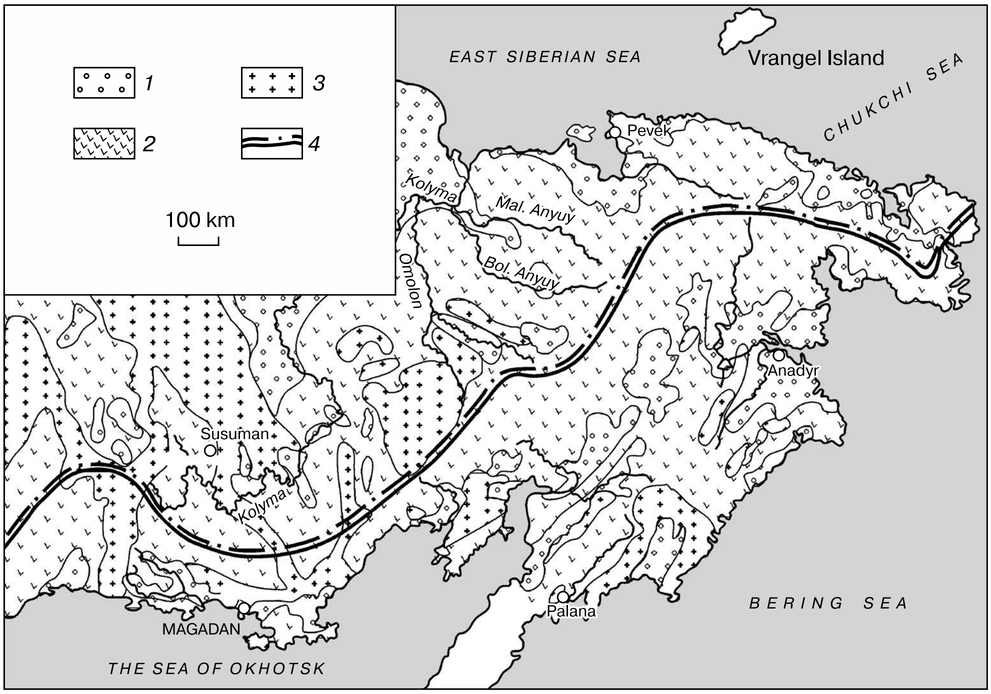

Fig. 3. Peat-bearing regions of the northeast of Russia:

1 – highly promising (depressions); *2* – promising deposits are likely to occur everywhere except the goltsy altitudinal belt (smoothened low hills with flattened watersheds); *3* – deposits of little promise are possible to occur on the slope bends and at the bottoms of river valleys (dissected mountains); *4* – the main divide of the Earth.

opinion, this indicates development of a poorly studied process of incomplete oxidation of organic substances in a frozen condition, similar to that revealed in frozen coals. This process results in enrichment of frozen peat with humic and low-molecular-weight organic acids. We verified the presence of these acids in the peat when studying the seasonally thawed layer in the Anadyrskaya and Khatyrskaya lowlands [*Glotov and Shcherban, 1989*]. It is to be noted that the peat generating phenomena of seasonal gas-geochemical activity in STL in peat masses are poorly studied [*Glotov, 1992*]. This cyclic nature is manifested in the seasonal change of the oxidation setting to reduction setting with respective transformation of the entire complex of biogeochemical reactions. Gas geochemical consequences of these processes were identified, and accumulation of phenol compounds in the peat in the cold period of the year was found.

In total, the collected information on the specific features of formation of peat accumulations in the northeast of Russia related to the spread of near-surface cryogenic aquifuge and the originality of peat forming processes allow a special genetic type of peat, the syncryogenic type, to be identified. It is different from the peat of non-permafrost regions by a number of characteristics of higher quality, including the absence of wood remains, significant bituminity, abnormally high sorption properties of the mossy types of poorly decomposed peat, etc. These properties allow peat to be used in production of plant protein and animal feeds, in manufacture of peat insulation slabs and peat turf mats and other products, which may be in demand in the exploration of Arctic and subarctic regions.

CONCLUSIONS

The above information indicates that the processes of seasonal and perennial phase changes of water cause emergence of new properties, including consumer properties, in the known minerals, named syncryogenic by the authors. They include fossil coals partially oxidized in the permafrost formations; peat deposits accumulated in the humid cold climate due to cryogenic aquifuge and the specific features of peat generation, which occur both in the seasonally thawed and frozen peat. Repeated regeneration of placer gold in the anthropogenic deposits is also related to cryogenesis. The authors refer such gold also to syncryogenic minerals. This fully agrees with the general theoretical ideas of the variety of geological effects of cryogenesis [*Melnikov et al., 2013*].

The processes of cryogenesis and of precipitation of metals from aqueous solutions may be technically controlled. Therefore it is likely that artificial resources can be created, for example, syncryogenic oxidized coals and peat, for them to be enriched with bioactive substances, so that they could be further used in the spa industry. There are actual prerequisites for the formation of anthropogenic placer gold deposits, and possibly other metals (uranium, copper, and rare earth metals), as well.

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Received May 14, 2015