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CHRONICLE

CONTRIBUTION OF YAKUTIAN RESEARCHERS TO THE ADVANCEMENT OF GEOCRYOLOGY (ON THE 300th ANNIVERSARY OF THE RUSSIAN ACADEMY OF SCIENCES)

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The main stages in the development of geocryology in the 20th–21st centuries are highlighted. The major research achievements are presented in the fields of permafrost science including general, engineering, historical and regional geocryology. The most important scientific results of the Order of the Red Banner of Labor Melnikov Permafrost Institute, Siberian Brunch, Russian Academy of Sciences, are presented.

Keywords*: geocryology, permafrost, cryogenic resources, Arctic shelf, geothermics, hydrogeology, permafrost geochemistry and ecology.*

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INTRODUCTION

The year 2024 marks the 300th anniversary of the Russian Academy of Sciences, which gave the world many glorious discoveries and names – Mikhail Lomonosov, Dmitry Mendeleev, Nikolai Pirogov, Nikolai Lobachevsky, Konstantin Tsiolkovsky, Nobel laureates Ivan Pavlov, Ilya Mechnikov, Lev Landau, Nikolai Basov, Peter Kapitsa, Zhores Alferov and others.

Permafrost science (geocryology) as an independent branch of knowledge was formed in the 1930s of the 20th century. It is a rather young science, the practical importance of which in the national economy was realized only at the end of the century. Nowadays, no Earth science conducting research in permafrost and no branch of national economy within the northern territories can do without the scientific products of the permafrost science.

In 1939, the expedition of the Council for the Study of Productive Forces, headed by Professor M.I. Sumgin, the founder of permafrost science, started its work in Yakutsk. In 1941, on the basis of this expedition, the Decree of the USSR Council of People's Commissars decided to organize the Yakutsk Research Permafrost Station of the Obruchev Institute of Permafrost Science, Siberian Branch, USSR Academy of Sciences.

Later on, the scale of the research of the Yakutsk Research Permafrost Station increased so much that in 1956 it was transformed into the Northeastern Branch of the Obruchev Institute of Permafrost Science. In 1960, the Institute of Permafrost Science, Siberian Branch, USSR Academy of Sciences, first in Eastern Siberia and the only in the world, was established on the basis of Yakutsk Research Permafrost Station of the Obruchev Institute of Permafrost Science (Fig. 1).

Since 1960 and for the next almost 50 years, the scientific and organizational management of this institution was carried out by Academician P.I. Melnikov. Through his efforts and the work of the subsequent directors (Dr. R.M. Kamenskiy, Dr. R.V. Zhang, and Corresponding Member of the Russian Academy of Sciences, Dr. M.N. Zheleznyak) permafrost scientists in Siberia gave the wide recognition and well-deserved authority in the country and abroad.

Today, the Order of the Red Banner of Labor Melnikov Permafrost Institute, Siberian Branch, Russian Academy of Sciences (hereinafter referred to as the Institute) develops geocryological (permafrost) research, the important direction for the Russian Federation [*Zheleznyak et al., 2021*]. The relevance of the research is determined by the fact that the object of these studies – permafrost – occupies 65% of the territory of Russia and almost entire Eastern Siberia. The Institute has an extensive monitoring network (research stations, laboratories, test

Fig. 1. The staff of the newly formed Institute of Permafrost Science of the Siberian Branch of the USSR Academy of Sciences.

In the center of the second row is the Institute Director, future Academician P.I. Melnikov (Yakutsk, 1962).

sites) and conducts research in Yakutia, Magadan Oblast, Krasnoyarsk Krai, and the Kazakhstan mountains.

According to the Charter, the main goal of the Institute is to carry out the fundamental, prospecting and applied scientific research in the field of geocryology (permafrost science), to develop the scientific bases for rational nature management in permafrost, as well as to solve the applied engineering and geocryological problems and tasks. At present, the Institute staff is working on six research projects in accordance with the State "Program of Fundamental Scientific Research in the Russian Federation for a Long-Term Period (2021–2030)". The work is carried out according to the priority direction 1.5.10.7. "Earth's Cryosphere and Spatial and Temporal Evolution of its Material and Energy Resources" (Russian Federation Government Order N 966-r dated April 21, 2022). Since 2021, the Institute has been the main executor of the technological project no. 2 "Stability of Permafrost Ecosystems under Climate Change and Anthropogenic Impacts" in the Scientific and Educational Center "North: Territory of Sustainable Development". The Institute employs 205 people, including 86 researchers, 18 doctors and 37 candidates of sciences.

The Yakutian permafrost scientists are world-renowned for their achievements in the fields of general and engineering permafrost science, geothermics, hydrogeology, geochemistry and ecology of the permafrost zone, permafrost forecasting, reclamation of frozen soils, thermophysics of cryogenic processes, cryolithology, permafrost landscape science and mapping.

Yakutia: A Starting Point in the Systematic Study of Permafrost (1941–1960)

As it was noted above, the systematic study of permafrost began at the Yakutsk Research Permafrost Station of the Obruchev Institute of Permafrost Science in 1941. In 1949–1953, geocryological research was carried out in two directions: engineering and regional [*Safronov, 2009*]. The staff of the station studied the composition, structure and physical and mechanical properties of permafrost deposits, generalized the available construction experience, and conducted numerous experiments in laboratory and natural conditions. The obtained materials have allowed us to conclude that, the principle of preserving soils at the frozen state at the bases of industrial and residential buildings is the main one in the severe continental climate of Central Yakutia. According to this

principle, all buildings were recommended to be built with ventilated cellars or ventilation ducts and channels.

To ensure water supply in Yakutsk, the station staff in cooperation with the Yakutsk geological and prospecting drilling company drilled and sampled the first in Yakutia exploration and production well for subpermafrost water. The results of the work were presented by P.I. Melnikov, A.I. Efimov and P.A. Solov'ev in the special scientific and technical report, which was highly appreciated by professionals and was awarded a prize by the Department of Geological and Geographical Sciences of the USSR Academy of Sciences. These studies opened the era of the wide use of artesian subpermafrost waters in Yakutia for drinking and household water supply.

Regional geocryological studies covered an extensive territory of the Republic and included the study of the conditions of the distribution and development of permafrost, groundwater, giant aufeises and "fossil" ice. The studies were conducted together with leading scientists from the Moscow Obruchev Institute of Permafrost Science of the USSR Academy of Sciences, the Lomonosov Moscow State University, the All-Union Geological Institute, the Leningrad Mining Institute and others.

In 1952–1953, Yakutian permafrost scientists carried out the most detailed year-round expeditionary work within the Yana–Indigirka Lowland. New data were obtained on the composition, structure and distribution of permafrost rocks; classic outcrops of ground ice were surveyed on the coast of the Dmitry Laptev Strait in the Arctic zone of Yakutia.

During the same period, the thermophysical field began to develop intensively. This occurred due to the need for the thorough study of the processes of freezing and thawing of rocks, formation of permafrost temperature and thickness. During these years, the serious study of heat and mass exchange processes and thermophysical properties of frozen rocks began. The basis for creating the databases of thermophysical properties of frozen rocks has been laid. Unique facilities were developed for physical modeling of freezing-thawing processes in the upper horizons of the permafrost, as well as for the possible application of geophysical methods for contouring of frozen and thawed rocks.

A large amount of factual material, obtained by the station staff during expedition and experimental studies, was summarized in the two-volume monograph of the team of authors "Permafrost Zone of the Lithosphere in Yakutian ASSR within the Lena River Basin" [*Melnikov et al., 1955*].

Fundamental Scientific Results of Yakutian Scientists from the Middle to the End of the 20th Century (1961–2000)

During this period, large-scale comprehensive expeditionary works were carried out not only in different regions of Yakutia, but also far beyond its borders. For example, such large expeditions as the Verkhoyanskaya (1958–1959), Vilyuyskaya (1958–1960), Ust'-Vilyuyskaya (1960–1963), Udokanskaya (1961–1965), Severnaya (1962–1965), Central-Yakutskaya (1965–1967), Soviet–Mongolian (1967–1983), Severo-Yeniseiskaya (1970–1974), Baikalo-Amurskaya (1975–1983), Arctic (1985–1989) and others were organized. The huge factual material, obtained as a result of comprehensive expeditionary works, formed the basis for the compilation of unique monographs and large cartographic generalizations. Thus, the materials of the Verkhoyanskaya Expedition, which worked according the program of the International Geophysical Year in Eastern Yakutia, were summarized in the large collective monograph "Ground Freezing and Glaciation in the Suntar-Khayata Radge, Eastern Yakutia", published in 1964 [*Grave et al., 1964*] and later used in writing the book "Last Glaciation and Permafrost in the Southern Verkhoyansk Range" [*Nekrasov et al., 1973*].

Based on the materials of the Udokanskaya Expedition of the Institute, the large generalized monograph "Perennially Frozen rocks of the Stanovoi Highland and Vitim Tableland" was written and published [*Nekrasov et al., 1967*]. The results of the Severnaya Expedition were summarized in the book "Permafrost in the Coastal areas of Yakutia" [*Grigoriev, 1966*]. The materials of the Soviet–Mongolian Expedition of the Institute are presented on the geocryological map of the Mongolian People's Republic at a scale of 1:500 000 [*Gravis, 1971*] and in the fundamental monograph "Geocryological Conditions in the People's Republic of Mongolia" [*Gravis, 1974*]. The huge factual material obtained by the field teams of the Baikalo-Amurskaya Expedition of the Institute is summarized in three major monographs [*Nekrasov et al., 1973; Solov'eva, 1976; Ahn et al., 1984*] and the 1:2 500 000 scale geocryological map "Baikal-Amur Railway" [*Nekrasov, 1979*].

From 1958 to 1988, more than 50 scientific geocryological stations were established, including about 20 with a year-round cycle of daily observations. Huge and unique factual material was obtained at the research stations, where the processes of heat exchange in the system "lithosphere–soil–atmosphere" were studied in different natural landscape zones of Siberia, the Far East, Central Asia and Mongolia, as well as at the sites with different types of anthropogenic disturbance of the surface conditions. Actinometric and gradient observations of total scattered and absorbed radiation, radiation balance, air temperature and humidity were carried out at all thermal-balance stations of the Institute according to the unified methodology and in full. Temperature and heat fluxes at different depths, humidity and moisture balance were measured in a topsoil layer. Systemati-

zation and analysis of the data, accumulated at the thermal balance stations of the Institute, were presented in fundamental monographs [*Pavlov, 1975, 1979, 1984; Gavrilova, 1963, 1978, 1981*], as well as in other generalizing works and practical recommendations of the Institute staff.

Geothermal studies, focused on studying the conditions of the formation of a negative temperature field and processes of deep freezing of the Earth's crust, were widely developed during this period [*Balobaev et al., 1977, 1983; Balobaev, 1991*]. Methods and equipment for measuring temperature and thermophysical properties of rocks were developed. Thanks to this, it became possible to study thermal fields in rocks in any hard-to-reach area.

Permafrost scientists-hydrogeologists made a significant contribution to the development of the concepts about the specific features of the development of the Siberian permafrost. It was during these years that completely new scientific fields in the study of permafrost-hydrogeological conditions in Siberia began to develop, prospecting studies were carried out, and methods for studying the regime of aufeis and aufeis-forming groundwater sources were developed. In cooperation with hydrogeologists from the Central Geological Survey Expedition of the Yakutsk Territorial Geological Department, the staff of the Groundwater Laboratory of the Institute participated in compiling the first "Hydrogeological Map of Yakutia at a scale of 1:2 500 000" [*Hydrogeological Map..., 1967*] and in writing two volumes of the monograph "Hydrogeology of the USSR" [*Tolstikhin, 1970; Glotov, 1972*], devoted to the description of the permafrost-hydrogeological conditions of Yakutia and the North-East of the USSR.

The results of long-term unique hydrogeological observations on groundwater sources Ulakhan-Taryn, Buluus and Mugur-Taryn (Central Yakutia), Taryn-Yuryakh, Tikhon-Yuryakh and others (Eastern Yakutia) were generalized [*Shepelev, 1987*]. The first practical recommendations on the use of groundwater in Yakutia for water supply purposes and the use of a heating cable in the operation of water intake wells under conditions of the permafrost were prepared and published.

Long-term expeditionary, stationary and experimental hydrogeological studies of the changes in the chemical composition of groundwater under the influence of cryogenesis were carried out. As a result of the generalization and analysis of the obtained materials, a new scientific field in geocryology – cryohydrogeochemistry – was created [*Anisimova, 1981*].

In 1969, the genetic classification of cryogenic textures was completed, distinguishing the basic textures characterizing the main types of freezing – subaqual and subaerial cryolithogenesis [*Katasonov et al., 1979; Katasonov, 2009*].

The problem of global climate warming and its impact on permafrost has been comprehensively studied.

Systematic observations of temperature of frozen soils and its seasonal thawing in different regions and landscapes in Yakutia and the Tien Shan Mountains have been made. The main patterns of the distribution, structure and temperature regime of seasonally frozen rocks in different landscape-facial mountain conditions of Kazakhstan were revealed. The basic patterns of the distribution, morphology, dynamics of cryogenic processes and phenomena in the mountains of South-Eastern Kazakhstan and Central Asia were established. All cryogenic phenomena were systematized by the main relief-forming factors. The results of long-term geocryological research of the Kazakhstan High Mountain Geocryological Laboratory of the Institute were recognized worldwide and were used in the compilation of the "Atlas of Snow and Ice Resources of the World" [*Kotlyakov, 1997*], the "Circumpolar Map of Permafrost and Rock Ice Content" and the geocryological map and monograph for the National Atlas of the Republic of Kazakhstan [*Gorbunov, Seversky, 2010*].

A two-dimensional physical-mathematical model of thermodynamic processes in the subpermafrost zone under long-period fluctuations of the Earth's climate (40 thousand years), which are the cause of the change of warm and cold epochs in the Pleistocene, was constructed and realized. The manifestation of the vacuum-piston effect under the permafrost, associated with significant drops of hydrostatic pressure in a weakly open system, was noted. At a phase boundary, the pressure can drop to zero during thawing from below. In this case, a compensatory process of intrapore water evaporation and a powerful suction effect occurs. During freezing, the hydrostatic pressure reaches the rock strength limit, resulting in the appearance of cracks of all-round compaction and in the formation of ice structures in the sequence of frozen rocks. These processes cause the formation of fresh subpermafrost waters at great depths.

The most significant regional geocryological studies were carried out under joint programs with Japanese, German and American scientists and with their supporting of expedition work. Using the latest equipment, the conditions of the formation of the ice complex of the Arctic lowlands and the intensity of its destruction in the modern period were studied in detail; the chronology of sediments was established, including the rocks at the bottom of the ice complex, the age of which is estimated at 94–14 ka. Accumulation of the ice complex ended 12–10 ka ago. Sedimentation continued all this time under the conditions of open permafrost landscapes with embryonic glaciation in the form of snowfields.

Thermokarst, thermoerosion, thermoabrasion and cryosolifluction are involved in the modern destruction of the ice complex. The mean multiannual rate of destruction of ice-covered shores is 2.2–2.5 m/year, and the maximum rate reaches 20 m/year. As a result, the volume of sediment entering the sea is comparable to its removal by large rivers and amounts to about 49 million tons per year. Long-term field and analytical studies conducted in Central and Northeastern Siberia and on Arctic islands have made it possible to estimate the geologic time of accumulation of most of these rocks and to determine their place among continental sediments of the last epoch of continental glaciation. The nival hypothesis of the origin of the ice complex rocks was put forward, based on the fact that fossil ice was formed from melt water during its burial and freezing in frost cracks of an active layer of nival landscapes. The materials of the studies of the ice complex are presented in two monographs [*Kunitsky, 1989; Grigoriev, 1993*]. These works reveal the specific features of the formation of continental sedimentary rocks under conditions of the interaction of permanent and seasonal drifted snowfields with other components of the permafrost landscape (Fig. 2).

The specific features of the formation and distribution of frozen rocks within the Aldan anteclise were studied. The leading role in the formation of their temperature and thickness is played by the geological and geomorphologic structure of the region [*Zheleznyak, 1998*].

The variability of cryolandscapes in Central Yakutia was assessed over 60 years on the basis of the relationships between air and soil temperature, precipitation, depth of an active layer, and biota productivity. An eco-coefficient, indicated the predisposition of the natural environment to the activation of cryogenic processes, was calculated. Landscape-thermal-physical differentiation of the main natural-territorial complexes was carried out. The methodology for retrospective and forecast mapping of the dynamics of permafrost landscapes of taiga was developed on the basis of the interpretation of multi-temporal aerial photographs and the study of the variability of geocryological conditions [*Fedorov, 1991*]. Quantitative indicators of the formation of suprapermafrost waters due to infiltration of atmospheric precipitation, thawing of ground ice, and moisture condensation in the aeration zone were established. The presence of these waters in an active layer is a factor in the increase in the mean annual temperature of frozen rocks and the formation of taliks [*Shepelev, 1995*].

The role of the water phase transitions in the formation of natural water exchange cycles was clarified. Four types of water exchange were identified: climatic, biological, geological, and technological. The energy and intensity of the global annual water exchange were calculated.

The dynamics of anthropogenic salinity of rocks of the active layer has been studied. The degree of salinity increases in the direction of a phase boundary, which causes the formation of cryopegs and their movement into the depth. Dependences of their hydrochemical regime on runoff conditions and seasons of a year were established. Anthropogenic cryopegs are one of the main threats to the integrity of engineering infrastructure in settlements of the North.

Fig. 2. Study and sampling of polygonal wedge ice of the yedoma formation (Central Yakutia).

Factual material on frost resistance of rocks was generalized; some aspects of the theory of cryogenic weathering were developed; the influence of energy exchange cycles on changes in the structure of permafrost rocks was revealed. The impact of cryogenic weathering on cryolithologic and physical-technical properties of rocks was established. The methodology of forecast and assessment of the influence of cryogenic weathering on the change in physical and technical properties of hard rocks and coarse clastic rocks was developed.

In total, from 1961 to 2000, the Institute's staff published 218 publications in the form of monographs, textbooks, brochures, recommendations, collections of scientific papers, etc. [*Kamenskiy, Shepelev, 2003*].

At the end of the 20th century, Russian permafrost scientists published the brochure "Development of the Basics of Cryogenesis (Study of the Earth's Permafrost. Forecast)", in which they made a conclusion about the cryogenesis of the Earth's permafrost [*1988*]. They concluded that the results of geocryological studies, obtained by large teams of scientists and professionals, provided the design and construction of the most important national economic facilities in Eastern Siberia and determined the leading position of Russian geocryology.

Development of Permafrost Science (Geocryology) in the 21st Century

During this period, the Institute has developed fundamental problems of geocryological science, has continued to carry out the advanced studies of the geocryological conditions in the areas of the industrial development of permafrost and has participated in various international, federal and regional scientific programs, Russian Foundation for Basic Research and other scientific foundations [*Research priorities..., 2012*].

The Institute has conducted the integrated geocryological studies for scientific support of the federal megaprojects being implemented in the Republic of Sakha (Yakutia), such as the South Yakutia hydropower complex, Talakan oil and gas condensate field, Elkonskoye uranium deposit; iron ore and coal deposits of South Yakutia, "Mir", "Aikhal" and "Udachny" diamond-bearing mines; "Eastern Siberia–Pacific Ocean" oil pipeline; "Power of Siberia" gas pipeline (Fig. 3), "Ulak–Elga" and "Tommot–Fondakh" railroads [*Research priorities...., 2012*].

The patterns of the formation, distribution, regime and resources of different types of groundwater in the permafrost, specifics of their use, protection from depletion and pollution were studied.

Fig. 3. The staff of the institute – participants of the expedition "Power of Siberia" (2019).

The natural factors causing the emergence and existence of radiation-thermal suprapermafrost taliks in the continuous cryolithozone of Central Yakutia were revealed; the statistical dependence between groundwater resources of interpermafrost taliks and the sum of atmospheric precipitation was established; the long-term variability of the flow rate of known groundwater sources confined to the foot of the Bestyakh terrace of the Lena River was assessed; the influence of microorganisms' activity on the temperature and chemical regime of water-bearing rocks was evaluated.

Materials of the long-term research on groundwater in permafrost of Central Yakutia were systematized and generalized: a legend was developed and a model of the Hydrogeological map of Central Yakutia at a scale of 1:1 000 000 was made, the fundamental monograph "Groundwater of Central Yakutia and prospects for its use" was written [*Balobaev et al., 2003*].

Cryogenic processes and phenomena in Arctic were most actively studied by annual expeditions. An important step was made in solving the fundamental problem of the distribution and evolution of submarine permafrost on the Arctic shelf. Data on its parameters in the western coastal-shelf zone of the Laptev Sea were obtained for the first time. Anomalously high, gradient-free temperatures in boreholes call into question the generally accepted thesis about the widespread distribution of subaquatic permafrost and its large thickness (up to 600 m) on the shelf of this region [*Grigoriev et al., 2003*].

Stationary observations of anthropogenic disturbances in the permafrost allowed us to find out the specific features of the cryogenic landscape restoration in the initial successional stages. The cryoecological features of agrolandscapes in Central Yakutia were assessed. The methodology of their cryoecological zoning was developed and the criteria of cryogenic processes activation under anthropogenic impacts and changes in modern climate were determined. The main patterns of interrelations between permafrost and climate of cold regions of the Earth were established. A series of forecast maps of climate change was compiled [*Gavrilyev et al., 2001*].

The paleoreconstruction of spatial and temporal variability of permafrost thickness in different geomorphologic areas of the southeastern part of the Siberian Platform in the period from the end of the Middle Neopleistocene to our time has been performed. It was found out that 125 ka ago permafrost rocks occupied less than 58% of the investigated territory.

On the basis of geothermal studies in the reference areas of the southeast of the Siberian Platform, the temperature of rocks to a depth of 3000 m was calculated and a series of permafrost-geothermal sections was constructed. Data on thermophysical properties of rocks in the central and northern regions of the Siberian Platform were collected and systematized along geotemperature sections across the Putorana Plateau–Dolganskaya–Yraas and along a strike of the Yenisei–Khatanga Trough. As a result of these works, regional and local features of the geocryological conditions of the studied territories were revealed. Geocryological, permafrost-landscape and ecological maps of different scales have been compiled, catalogs and databases of geocryological data have been created, which are the basis for design decisions and forecasting the stability of complexes of constructions [*Zheleznyak, 2005*].

The beginnings of engineering cryolithology have been developed on the basis of the studies of the formation and properties of permafrost soils under the influence of temperature, climatic and tectonic factors. Cryolithology is a science at the interface of lithology and engineering geology, which studies the laws of the formation, transformation, structure and mechanical properties of permafrost rocks, as well as the factors and conditions that predetermine the extreme characteristics of these properties [*Guryanov, 2009*].

In V.R. Alekseev's works, many questions of land hydrology, geobotany, glaciology, permafrost science, geoecology, periglacial morphology, and the history of geographic research in Siberia and the Far East were solved. The main works are devoted to the study of especially dangerous cryogenic phenomena – snow avalanches, aufeis, permafrost and seasonal permafrost [*Alekseev, 2004; Alekseev, Zhang, 2011*].

The use of cryogenic resources of the Earth in the engineering practice was theoretically proved and experimentally confirmed in the natural conditions of Yakutsk. A new technology was developed and patented to control the temperature regime of underground structures built in the layer of annual heat turnover in permafrost. It is based on the phase shift of temperature fluctuations in frozen soils. For the first time in the world practice, a cryoreservoir for plant seeds has been built and operated (Fig. 4). The possibility of the practical use of heat of water phase transition for heating some types of production facilities in winter time was established [*Kuzmin, 2002*].

In the field of hydraulic construction in permafrost, the formation of the heat and moisture state of ground dams and their foundations has been actively studied [*Kamenskiy, 1977; Olovin, Medvedev, 1980; Olovin, 1993; Zhang, 2000, 2002; Zhang et al., 2012*], as well as the thermal and mechanical interaction of reservoirs with the environment [*Konstantinov, Sukhodrovskiy, 1977*]. These studies revealed the complexity of processes occurring in the structures during their operation. They have shown that in dams, made of rock fill, there is a periodic change in the thermal state (freezing–thawing) of the body and foundation soils, that is, a structure exists in the un-

Fig. 4. The staff of the Melnikov Permafrost Institute, Siberian Branch of the Russian Academy of Sciences at the opening of the Federal Cryoreservoir of Plant Seeds (Yakutsk, 2012).

steady heat-moisture regime. The obtained data formed the basis for the first forecast models. The results of design, development, technological and research works, survey materials, as well as the experience of construction and operation of hydraulic structures in Yakutia and adjacent territories were generalized. The experience of construction and operation of a number of hydraulic structures in Yakutia with frozen and thawed type of dams in the permafrost was summarized. In 2019, the monograph "EmbankmentDams in the Russian Permafrost Zone" [*Zhang et al., 2019*] was published. In addition to the generalization of experience, the monograph presents own results of field studies of the formation of cryogenic-temperature regime of hydroelectric power and water management facilities, which is the basis for static and filtration stability of the hydraulic structures. The monograph also shows the role of the geocryological monitoring and a system of its arrangement using geophysical methods and gives a modern idea of the operation of earth dams under conditions of changing climate on Earth.

The specific features of geoelectric, seismic, temperature sections and dynamics of the main parameters reflecting the interaction of engineering structures with the surrounding geocryological environment were studied. Modern high-tech automated technical means of the surface and borehole geophysical surveys, including geoelectric tomography, interborehole radio-wave interrogation, high-precision logger temperature measurements, etc. were introduced, allowing to significantly increase the productivity and informativeness of geophysical methods to control the stability of hydraulic structures in the permafrost [*Alekseeva, Kut', 2022*].

Long-term geocryological studies, carried out by the Yakutian researchers in the permafrost of Russia, in Murmansk, Norilsk, Krasnoyarsk, Igarka and Yakutsk, allowed to generalize and formulate the most significant scientific conclusions and practical recommendations [*Goncharov, 1988, 2016; Rastegaev et al., 2009*].

The theoretical basis for the design of new generation devices for measuring the surface temperatures in engineering mining (boreholes, mines, adits) was developed. The methodology of experimental laboratory studies of frost heave of the coarse-grained soil systems was proposed. Engineering-geocryological zoning of permafrost of Southern Transbaikalia was carried out. Scientific and methodological bases of the studies of thermal and mechanical interaction of bases and foundations during the degradation of permafrost were developed. The main patterns of thermomechanical interaction of pile foundations

with thawing permafrost soils were established [*Shesternev, 2001, 2012*].

The Institute actively participated in the discussion and work on the Law "On Permafrost Protection in the Republic of Sakha (Yakutia)" adopted on May 22, 2018 N 2006-Z N 1571-V. The law presents the modern regulatory legal framework in the field of environmental protection and nature management in the form of 21 articles of the law regulating various aspects of the permafrost protection. The following articles of the law are related to the field of construction: 15. "Permafrost monitoring" – integrated observations of the state of permafrost rocks, processes and phenomena occurring in them; 16. "Geotechnical monitoring of permafrost" – a set of works based on field observations of the state of the foundation soils (temperature regime), hydrogeological regime, movement of foundations of newly erected, reconstructed and operated structures [*Alekseeva, 2022*].

In the period from 2001 to 2023, the Institute's staff published 210 monographs, textbooks, brochures, recommendations, collections of scientific papers, etc.

CONCLUSIONS

The outstanding achievements of the Yakutian permafrost scientists in the 20th and early 21st centuries are as follows.

1. New scientific fields were founded and developed at the interface of geocryology and other sciences:

– cryohydrogeochemistry is the science about the formation features of the chemical composition of groundwater in permafrost, the dependence of their hydrochemical regime on the amount of freezing, the water exchange conditions, as well as about the lithologic composition of the constituent rocks, geomorphology of the area and other factors;

– cryolithology is the special section of lithology, which studies the composition and cryogenic structure of frozen sedimentary sequences depending on the conditions of their accumulation and freezing and establishes the patterns of the ice content distribution in sediments on the basis of permafrost-facial analysis. The basics of engineering cryolithology are formulated;

– geothermics of the frozen zone of the lithosphere is a scientific field that studies the main natural factors leading to the formation and development of frozen rocks and reveals the relationship between the permafrost thickness and geotectonics, geodynamics and the thermal state of the Earth's deep interior;

– thermoreology of frozen soils is a new field in geocryology, which studies the thermoreological properties of frozen soils and ice on the basis of their structural transformations, physical and mechanical properties, etc.;

– thermophysics of landscapes is a scientific field that reveals the relationship between individual landscape components, including permafrost, and studies landscape complexes using thermophysical methods;

– landscape permafrost science, the main purposes of which are to study the patterns of the spatial differentiation and dynamics of permafrost landscapes, to develop criteria to assess their stability and to forecast their development;

– theory of heat and mass transfer in frozen, thawing and freezing soils, forming the structure, properties and dynamics of an active layer;

– theory of physical and chemical processes in the natural environment with the participation of a solid phase of water (ice) and unfrozen liquid films of water.

2. Fundamental hydrogeological studies of the permafrost were carried out: the Yakutsk artesian basin of subpermafrost waters was discovered; the Map of permafrost-hydrogeological zoning of Eastern Siberia, the Hydrogeological Map of Yakutia, the Map of suprapermafrost waters of Yakutia, fundamental monographs on the hydrogeological conditions of the permafrost were compiled and published.

3. The conditions of the formation, distribution and destruction of the modern ice complex – the surface sequence of soils with the excessive ice content in the form of ice wedge formations were studied.

4. The complex geocryological substantiation of "construction sites of the century" (BAM, AYAM zones, diamond, gold, tin deposits, etc.) was carried out. Recommendations were developed to reduce the consequences of anthropogenic transformation of northern geosystems.

5. The main patterns and quantitative indicators of physical and mechanical properties of frozen soils depending on changes in the environmental conditions were established: classification of the main varieties of soils in Yakutia by the phase composition of water depending on temperature was developed; formulas for determining physical characteristics of frozen soils were proposed; design characteristics of bearing capacity of pile foundations were determined.

6. The following ways and methods of the construction of buildings and structures under conditions of permafrost were developed and put into practice:

– pile foundations with vented under-floor space;

– pile foundations with "cold piles" – reinforced concrete piles with built-in cooling devices;

– pile foundations with cast-in-situ bored piles;

– surface foundations (shell foundations, structural foundations and flat foundation slabs with honeycomb filler);

– underground method of pipeline laying;

– method of construction of underground tanks (cold accumulators, storage tanks for various products, gases and fuels and lubricants);

– method of providing filtration and static stability of frozen dams;

– method of preserving frozen foundations of engineering structures by means of seasonal cooling systems;

– method of preserving frozen foundations of engineering structures by the use of heat pumps.

7. The main spatial and temporal patterns of the relationship "climate–permafrost" were revealed: for the first time these relationships were typified in detail depending on a rank of the climate formation (from space to intra-terrestrial) was made; the specific features of climate and the permafrost distribution on the Eurasian and North American continents were determined). The forecast of changes in the climatic conditions in Yakutia up to the middle of the 21st century and the response of permafrost to possible climate change are made.

8. Long-term monitoring of dynamics of thermoabrasian damage of the Arctic lowland seashores, composed of ice complex, was carried out. The forecast of the retreat rate of the Arctic seashore was made.

Owing to the extreme importance of assessing the permafrost response to the ongoing global climate warming, the strategic goals of the Institute's activities are the following top-priority directions of the development of geocryological research.

1. Assessment of dynamics of permafrost in different natural and natural-technogenic geosystems.

For the successful development of this scientific field, it is important to create a monitoring network as an informational geocryological system, with increased accuracy and informativeness of obtained data, using a remote observation system. The most urgent issues are the study of subaquatic permafrost evolution on the shelf of the Arctic seas of Yakutia, the study of trends and magnitude of changes in parameters of the permafrost sequences in the urbanized areas, as well as in the areas of construction of large linear (oil and gas pipelines, roads and railways) and hydraulic structures.

2. The geothermal, geothermophysical and geochemical state of permafrost of Siberia.

Research in this scientific field includes the further development of the theory of the thermal state of permafrost, modeling of geothermal and thermophysical processes in permafrost, improvement of paleoreconstruction methods of the subsurface permafrost temperature and thickness, study of patterns of migration and concentration of chemical elements in permafrost.

3. Study of the main trends in the transformation of cryogenic landscapes under climate change and anthropogenic impacts.

This scientific direction should include the development of the forecast modeling of cryogenic landscapes, quantitative assessment of the consequences of their transformation under different scenarios of climate change, determination of criteria of stability to climatic fluctuations and anthropogenic impacts.

4. Study of the patterns and tendencies of change in regime and resources of different types of groundwater in permafrost, specifics of their use and protection.

Development of this scientific field should be based on more detailed study of groundwater interaction with permafrost and surface waters. Improvement of scientific and methodological bases of the permafrost-hydrogeological mapping and zoning of different scales and purposes should be referred to important issues.

5. Development of the theory of reliability of operation of geotechnical systems in permafrost.

Research in this very important and relevant scientific field should include the solution of such issues as the development of a new theory of transformation of material composition, structure and properties of rocks in the permafrost taking into consideration climate changes and anthropogenic loads, the improvement of methods for determining the strength characteristics of frozen soils, the creation of new technologies for construction and foundation structures, the improvement of methods for engineering protection of territories and individual structures from negative processes and phenomena (waterlogging by suprapermafrost waters, frost heave, thermokarst, etc.).

References

Ahn V.V., Lyubomirov A.L., Solov'eva L.N., 1984. *Geocryological Conditions of the Baikal-Stanovoy Part of the BAM Zone*. Novosibirsk, Nauka, 152 p. (in Russian)

Alekseev V.R., 2004. *Frozen Ground Engineering, Glaciology and Ice engineering: Fundamental Information Sources in Russian*. Yakutsk, Melnikov Permafrost Institute SB RAS, 186 p. (in Russian)

Alekseev V.R., Zhang R.V., 2011. *Cryogenic Building Materials: Concept Development, Classification, State of the Art*. Yakutsk, Melnikov Permafrost Institute SB RAS, 66 p. (in Russian).

Alekseeva O.I., 2022. *Engineering Structures on Frozen Ground*. Yakutsk, Melnikov Permafrost Institute SB RAS, 183 p. (in Russian)

Alekseeva O.I., Kut' A.A., 2022. *Main Results of the Melnikov Permafrost Institute SB RAS in 2021. Annual Report*. Yakutsk, Melnikov Permafrost Institute SB RAS, 212 p. (in Russian).

Anisimova N.P., 1981. *Cryohydrogeochemistry of the Frozen Zone*. Novosibirsk, Nauka, 153 p. (in Russian)

Balobaev V.T., 1991. *Geothermics of the Frozen Zone of the Lithosphere in Northern Asia*. Novosibirsk, Nauka, 191 p. (in Russian)

Balobaev V.T., Ivanova L.D., Nikitina N.M. et al., 2003. *Groundwater of Central Yakutia and Prospects for Its Use*. Novosibirsk, Acad. Publ. House "Geo", 137 p. (in Russian)

Balobaev V.T., Pavlov A.V., Perl'shteyn G.Z., 1983. *Thermophysical Investigations of Siberian Permafrost*. Novosibirsk, Nauka, 215 p. (in Russian)

Balobaev V.T., Volod'ko B.V., Devyatkin V.N., Levchenko A.I., 1977. *Manual on Calibration and Use of Thermistors in Geo-*

thermal Measurements. Yakutsk, Inst. Merzlotoved. Sib. Otd. Akad. Nauk SSSR, 77 p. (in Russian)

Earth Cryology Council., 1988. *Development of the Basics of Cryogenesis (Study of the Earth' Permafrost. Forecast)*. Yakutsk, Inst. Merzlotoved. Sib. Otd. Akad. Nauk SSSR, 23 p. (in Russian)

Fedorov A.N., 1991. *Permafrost Landscapes in Yakutia: Identification and Mapping*. Yakutsk, Inst. Merzlotoved. Sib. Otd. Akad. Nauk SSSR, 140 p. (in Russian).

Gavrilova M.K., 1963. *Radiation Climate of the Arctic*. Leningrad, Gidrometeoizdat, 255 p. (in Russian)

Gavrilova M.K., 1978. *Climate and Longterm Ground Freezing*. Novosibirsk, Nauka, 213 p. (in Russian)

Gavrilova M.K., 1981. *Modern Climate and Permafrost on the Continents*. Novosibirsk, Nauka, 112 p. (in Russian)

Gavrilyev P.P., Ugarov I.S., Efremov P.V., 2001. *Permafrost-Ecological Characteristics of Taiga Agrolandscapes*. Yakutsk, Melnikov Permafrost Institute SB RAS, 196 p. (in Russian)

Glotov V.E. (Ed.), 1972. *Hydrogeology of the USSR, vol. XXVI, Northeast of the USSR*. Moscow, Nedra, 297 p. (in Russian)

Goncharov Yu.M., 1988. *Effective Foundation Designs for Permafrost Areas*. Novosibirsk, Nauka, 192 p. (in Russian)

Goncharov Yu.M., 2016. *Foundations and Supporting Soils in Permafrost*. Yakutsk, Permafrost Institute SB RAS, 406 p. (in Russian)

Gorbunov A.P., Seversky A.V., 2010. Geocryological Map, 1:5 000 000 scale. In: *The National Atlas of the Republic of Kazakhstan, vol. 1, Environmental Conditions and Resources*. Almaty, 2010, p. 92–93. (in Russian)

Grave N.A., Gavrilova M.K., Gravis G.F. et al., 1964. *Ground Freezing and Glaciation in the Suntar-Khayata Range, Eastern Yakutia*. Moscow, Nauka, 143 p. (in Russian)

Gravis G.F. (Ed.), 1971. *Geocryological Map of the People's Republic of Mongolia, Scale 1:500,000*. Yakutsk, 8 sheets. (in Russian)

Gravis G.F. (Ed.), 1974. *Geocryological Conditions in the People's Republic of Mongolia*. Moscow, Nauka, 200 p. (in Russian)

Grigoriev M.N., 1993. *Cryomorphogenesis of the Lena River mouth area*. Yakutsk, IMZ SO RAN, 182 p. (in Russian)

Grigoriev M.N., Rachold V., Schirrmeister L., 2003. Russian–German cooperation SYSTEM LAPTEV SEA, the Expedition Lena 2002. *Rep. Polar Marine Res*. 466, 341 p.

Grigoriev N.F., 1966. *Permafrost in the Coastal Areas of Yakutia*. Moscow, Nauka, 180 p. (in Russian)

Guryanov I.E., 2009. *Engineering Cryolithology: Strength of Perennially Frozen Soils*. Novosibirsk, Acad. Publ. House "Geo", 139 p. (in Russian)

Hydrogeological Map of the Yakutian ASSR. Scale 1:2500 000, 1967. Compiled by N.N. Indoleva et al., Yakutsk, Permafrost Institute, Yakutsk Geological Bureau of USSR Ministry of Geology, 4 sheets. (in Russian)

Kamenskiy R.M., 1977. *Thermal Regime of the Dam and Water Reservoir, Vilyui Hydro*. Yakutsk, Inst. Merzlotoved. Sib. Otd. Akad. Nauk SSSR, 92 p. (in Russian)

Kamenskiy R.M., Shepelev V.V. (Eds.), 2003. *Results of geocryological investigations in Yakutia in the 20th century and future prospects*. Yakutsk, Melnikov Permafrost Institute SB RAS, 204 p. (in Russian)

Katasonov E.M., 2009. *Lithology of Frozen Quaternary Deposits (Cryolithology) in the Yana Coastal Lowland*. Moscow, OAO PNIIIS, and Melnikov Permafrost Institute, 176 p. (in Russian)

Katasonov E.M., Ivanov M.S., Pudov G.G. et al., 1979. *Structure and Absolute Geochronology of Alas Deposits in Central Yakutia*. Novosibirsk, Nauka, 95 p. (in Russian)

Konstantinov I.P., Sukhodrovskiy V.L., 1977. On shoreline development in permafrost regions (a case study of the Vilyui Reservoir). In: *Investigations of Siberian Reservoir Shores*. Novosibirsk, Nauka, p. 62–72. (in Russian)

Kotlyakov V.M. (Ed.), 1997. *Atlas of Snow and Ice Resources of the World*. Moscow, NPP Kartografiya, 392 p. (in Russian)

Kunitsky V.V., 1989. *Cryolithology of the Lower Lena Area*. Yakutsk, Inst. Merzlotoved. Sib. Otd. Akad. Nauk SSSR, 163 p. (in Russian)

Kuzmin G.P., 2002. *Underground Structures in Permafrost*. Novosibirsk, Nauka, 176 p. (in Russian)

Melnikov P.I., Efimov A.I., Solov'ev P.A. et al., 1955. *Permafrost Zone of the Lithosphere in Yakutian ASSR within the Lena River Basin*. Manuscript. Yakutsk, Melnikov Permafrost Institute SB RAS Unpublished Materials, No. 813, 853 p. (in Russian)

Nekrasov I.A. (Ed.), 1979. *Baykal–Amur Railway: Geocryological Map*. Moscow, GUGK, 2 sheets. (in Russian)

Nekrasov I.A., Maksimov E.V., Klimovskiy I.V., 1973. *Last Glaciation and Permafrost in the Southern Verkhoyansk Range*. Yakutsk, Yakutsk Publ. House, 150 p. (in Russian)

Nekrasov I.A., Zabolotnik S.I., Klimovskiy I.V., Shastkevich Yu.G., 1967. *Permafrost on the Stanovoy Upland and Vitim Plateau*. Moscow, Nauka, 168 p. (in Russian)

Olovin B.A., 1993. *Permeability of Permafrost*. Novosibirsk, Nauka, 257 p. (in Russian)

Olovin B.A., Medvedev B.A., 1980. *Temperature Field Dynamics in the Vilyui Hydro Dam*. Novosibirsk, Nauka, 48 p. (in Russian)

Pavlov A.V., 1975. *Heat Exchange between the Soil and Atmosphere in Northern and Temperate Latitudes of the USSR*. Yakutsk, Yakutsk Publ. House, 302 p. (in Russian)

Pavlov A.V., 1979. *Thermal Physics of Landscapes*. Novosibirsk, Nauka, 285 p. (in Russian)

Pavlov A.V. (Ed.), 1984. *Energy Exchange in the Landscape Sphere of the Earth*. Novosibirsk, Nauka, 256 p. (in Russian)

Rastegaev I.K., Baksheev D.S., Kamenskiy R.M., 2009. *Pile foundation engineering in permafrost areas*. Novosibirsk, Acad. Publ. House "Geo", 279 p. (in Russian)

Research priorities of the Melnikov Permafrost Institute for 2012–2022: brochure by the Scientific Council., Yakutsk, Melnikov Permafrost Institute SB RAS, 2012, 18 p. (in Russian)

Safronov A.F. (Ed.), 2009. *Academic Science in Yakutia (1949–2009)*. Novosibirsk, Acad. Publ. House "Geo", 219 p. (in Russian)

Shepelev V.V., 1987. *Spring Waters of Yakutia*. Yakutsk, Yakutsk Publ. House, 128 p. (in Russian)

Shepelev V.V., 1995. *Suprapermafrost Water: Formation and Distribution Patterns*. Yakutsk, Melnikov Permafrost Inst. SB RAS, 48 p. (in Russian)

Shesternev D.M., 2001. *Cryosupergenesis and Geotechnical Properties of Rocks in the Permafrost Zone*. Novosibirsk, Izd. Sib. Otd. Ross. Akad. Nauk, 266 p. (in Russian)

Shesternev D.M., 2012. *Soil Heaving under Conditions of Permafrost Degradation*. Yakutsk, Permafrost Inst. SB RAS, 194 p. (in Russian)

Solov'eva L.N., 1976. *Permafrost Morphology in the Sayan-Baykal Region, Buryat ASSR*. Novosibirsk, Nauka, 126 p. (in Russian)

Tolstikhin O.N. (Ed.), 1970. *Hydrogeology of the USSR, vol. XX, Yakutian ASSR.* Moscow, Nedra, 383 p. (in Russian)

Zhang R.V., 2000. *Design, Construction, Operation and Maintenance of Small Dams in Permafrost Areas (Examples from Yakutia)*. Yakutsk, Melnikov Permafrost Inst. SB RAS, 160 p. (in Russian)

Zhang R.V., 2002. *Temperature Regime and Stability of Small Dams and Canals on Permafrost*. Yakutsk, Melnikov Permafrost Inst. SB RAS, 207 p. (in Russian)

Zhang R.V., Kuznetsov G.I., Shepelev V.V., Kuz'min G.P., Shesternev D.M., Biyanov G.F., Koz'min B.M., Alekseeva O.I., Velikin S.A., Melkozerov G.V., 2012. *Small Dams on Permafrost in Yakutia: Guidelines for Design and Construction.* Yakutsk, Melnikov Permafrost Inst. SB RAS, 124 p. (in Russian)

Zhang R.V., Velikin S.A., Kuznetsov G.I., Kruk N.V., 2019. *Embankment Dams in the Russian Permafrost Zone*. Novosibirsk, Acad. Publ. House "Geo", 427 p. (in Russian)

Zheleznyak M.N., 1998. *Geothermal Conditions of Permafrost in the Western Portion of the Aldan Basin*. Yakutsk, SB RAS, 92 p. (in Russian)

Zheleznyak M.N., 2005. *The Ground Temperature Field and Permafrost in the Southeastern Part of the Siberian Platform*. Novosibirsk, Nauka, 227 p. (in Russian)

Zheleznyak M.N., Zhang R.V., Shepelev V.V., Grigoriev M.N., Fedorov A.N., Alekseeva O.I., 2021. The Melnikov Permafrost Institute, Siberian Branch, Russian Academy of Sciences at the turn of its 60th anniversary. *Earth's Cryosphere* XXV (1), 48–60.

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