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ECOLOGICAL PROBLEMS OF EARTH'S CRYOLOGY

ENVIRONMENTAL PROBLEMS OF OIL AND GAS EXPLORATION AND DEVELOPMENT IN THE RUSSIAN ARCTIC

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Permanent frozen ground poises a core environmental issue for exploitation of natural resources in the Arctic and sub-Arctic. Different technogenic impacts are capable of triggering new geocryological processes or essentially enhance natural changes in permafrost conditions, to the extent that they become hazardous or even catastrophic. The active advancement of oil and gas operations into the northern territories and further to the continental shelf requires introducing new safety policies ensuring geo-ecological security of the permafrost regions. A specialized state geocryological observational network comprising polygons, stationaries and sites for periodic observations will provide monitoring of natural dynamics of the geosystems at various level of detail and their interactions with engineering activities, which will ultimately allow to optimize the process of executive decision-making, strengthening thereby responsibility of subsoil users and related state agencies.

Natural and technogenic changes, permafrost zone, geocryological processes, environmental safety, state geocryological polygons, Arctic

INTRODUCTION

The ninth of Russia's gross national product and nearly a quarter of the total exports come from the Arctic regions, which produce over 90 % of nickel, cobalt and platinum group metals, about 80 % of natural gas and 60 % of crude oil [*Pavlenko, 2013*]. Therefore, effective and sustainable development of the region is one of the key national priorities of Russia, despite the fact that the population density and total labor pool are extremely low there. Geographically, the Russian Arctic and sub-Arctic sectors approximately coincide with the extent of the permafrost zone (cryolithozone), slightly going beyond its limits in the European North, whereas the presence of permanent frozen deposits ground implies the heart of many problems rather than the region's specificity alone, and does provide additional challenges to both subsoil use and ecological situation in the Arctic.

The permafrost zone with the environmental situation largely dictated by natural disasters and technogenic impact (technogenesis) occupies about two-thirds of Russia's territory and is characterized by a host of vicissitudes of a continental climate, lack of modern transport communications infrastructure, low density of population, and a great number of large national nature reserves and specially protected areas. In this context, permafrost represents a key factor shaping the environmental conditions of the North. A multitude of natural exogenous processes, facilitated by global climate fluctuations have triggered active transformations in the Arctic and sub-Arctic landscapes and in the aquatic environment. The cumulative geo-ecological effects of these processes are generally found to be adverse, as is evidenced from: the surface deformations [*Khomutov and Leibman, 2014*], imminent destruction of entire ecosystems [*Moskalenko, 2012*], changing configurations of coastlines (Fig. 1) with their retreat rate reaching tens of meters a year, in some areas [*Vasiliev et al., 2001; Lantuit et al., 2012; Kritsuk et al., 2014*].

The integrated studies and predictions of permafrost behavior must be given first priority to when developing strategies for extensive economic development of these regions. Many challenges facing the subsoil use and resource management in the permafrost zone stem from the insufficient level of its engineering-geocryological and hydrogeological study [*Pavlov and Dubrovin, 2000; Bryukhovetskii et al., 2014*].

Ignoring environmental threats and risks (facing and potential) caused by global climate change and technogenesis will only aggravate these problems.

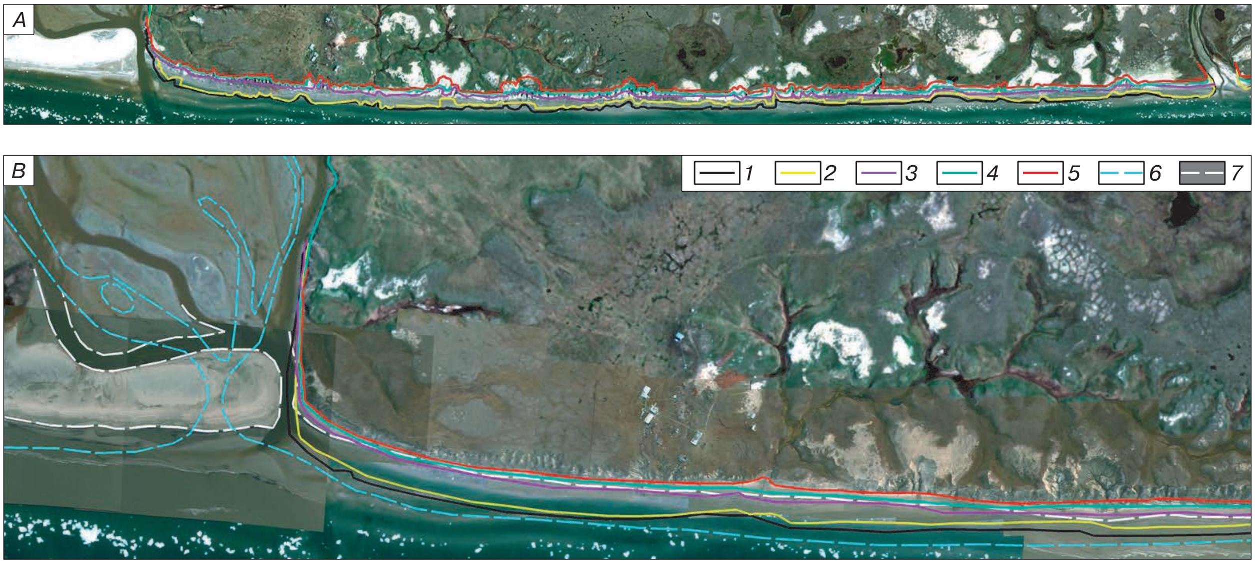


Fig. 1. Coastal dynamics of the Kara Sea in the vicinity of the Marre-Sale stationary over a 44-year period (1969–2013), interfluve area of the Marreyakha–Yavaryakha rivers:

A – coastal berm, 4.5 km long; *B* – foot of slope 2 km long (*1* – 1969; *2* – 1978; *3* –1999; *4* – 2009; *5* – 2013); *6*, *7* – shoreline in 1969 and in 2013, respectively.

Given that the economic development of the area underlain by permafrost considerably outpaces the ongoing geo-ecological and geocryological research aiming to provide a substantiation of rational and environmentally safe use of the subsoil, the absence of a full-fledged strategy for regional studies and permafrost monitoring has thus far been a critical issue [*Dubrovin and Kritsuk, 2014*]. The implications are that gaps in such knowledge have already resulted in inadequate engineering solutions (Fig. 2).

Although the environmental changes occurred during the period of oil and gas fields development in

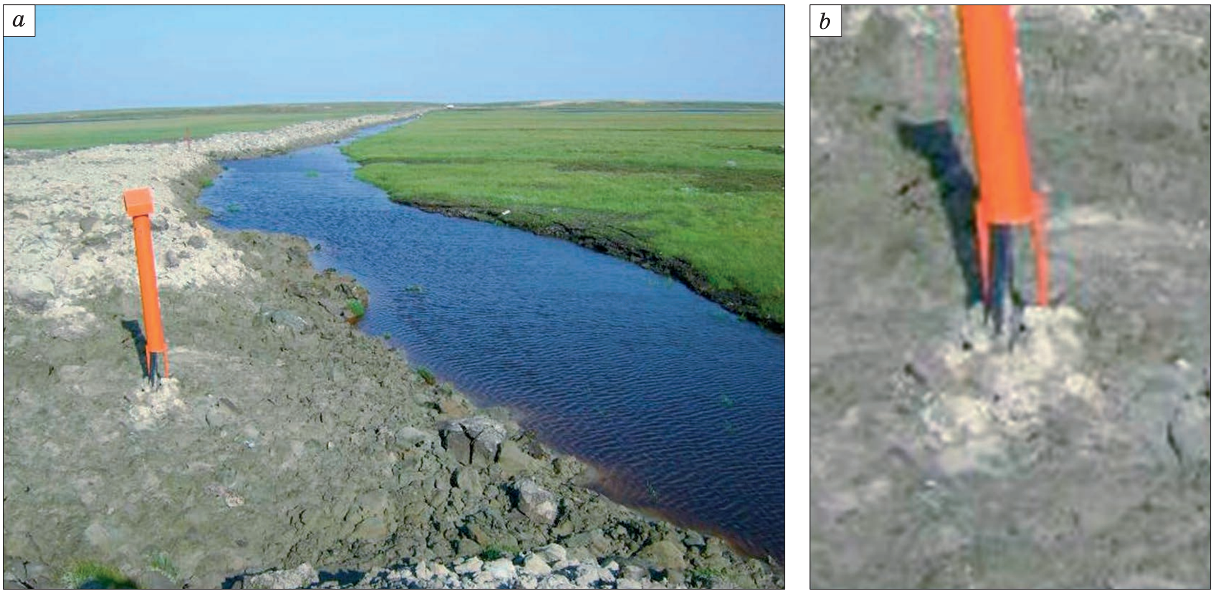


Fig. 2. Formation of extended technogenic thermokarst lake resulted from the area flooding through the crowning of the buried pipeline (*a*).

b – a post of measuring block of the technical control system of the gas pipeline (cables are exposed due to the crowning settlement). Photograph from a monitoring agency.

Western Siberia spanning 40 years are found to be unparalleled, there still remain some basic needs to address to and provide for: a scientifically grounded complex geo-ecological assessment that would also measure both environmental and human-caused impacts; forecasts for medium and long term permafrost dynamics; predictions of exogenous and endogenous geological processes induced by huge amounts of fluids withdrawn from or injected into the subsurface. These are not the least important factors in terms of geo-ecological effects and choice of technologies, ignoring which have already resulted in numerous cases of maloperations, like for example, in the Middle Ob area, where over 3.5 thousand of oil-wells casings either got broken down or collapsed caused by horizontal shear displacement of rock-mass. This is also the case with the maintaining artificial reservoir pressure (which sometimes requires including chemical reagents) that undermines the water-bearing system of the permafrost zone causing ingress of oil and brines into aquifers and onto the surface. The injection of superheated water and steam into the reservoir induce changes of geothermal and geochemical fields [*Dubrovin and Kritsuk, 2014*].

CARTOGRAPHIC MODELING AS A BASIS FOR PERMAFROST MONITORING

The most important attributes of the forming trends in the environmental dynamics of the northern regions of Russia are derived from the present-day conditions and dynamics of natural and technogenic geosystems of the permafrost zone. These are determined by the interplay between geological environment (geosphere) and other spheres – external relative to it: the atmosphere, hydrosphere, biosphere, on the one hand, and man-made technical systems, on the other hand. The spatio-temporal parameters of these interactions can be assessed through the system of cartographic and information models realized as digital maps with their respective databases, in particular, zoning maps. A spatial cartographic model serves to solve the problem of information representation and extrapolation whose reliability depends on the available data. The statistical criteria allow to numerically assess the validity of data transfer with a required probability. A cartographic model integrated into the environmental monitoring system is designed to provide information on the existing natural and technogenic conditions (both background and current) with a required accuracy and reliability, simultaneously serving as the basis for prediction of changes in geocryological parameters of geosystems, specifically, for obtaining *in situ* and predicted permafrost and geo-ecological parameters [*Drozdov, 2004*].

Economic management in the northern latitudes necessitates the need to address a number of problems, intrinsically geo-environmental, to generally assess threats and risks of exploiting natural resources in the Arctic region. These are primarily associated with the interplay of the two factors having critical impact on the geological environment and permafrost conditions – climate fluctuations and technogenesis. The way of these problems solution basically consists in the ***creation of permafrost monitoring system*** comprising both the data on natural geosystems and those resulted from observations of the technogenesis effects at the operating facilities [*Dubrovin, 2003*]. The ultimate goal of this research is to obtain reliable time-sensitive information on the ongoing changes derived from the permanent conceptual and cartographic geo-ecological models of the region. This system should integrate and synthesize the information flows from monitoring observations at geological and geotechnical objects.

The emerging issue is primarily concerned with spatial coverage of such models, and secondly the level of detail of the information existing, obtained and continuously updated in the course of monitoring. It is obvious that the anticipated results – quite accurate and economically feasible for the projected design – can be obtained only for a limited area. Estimates for more extensive planning can be obtained for an area of production facility or industrial complex. The country- or region-wide perspective evaluation requires a thorough grounding in general laws of spatio-temporal distribution of the environmental parameters. It is therefore necessary to particularize hierarchy of cartographic models, objects and systems for environmental monitoring in general and, specifically, for the permafrost zone.

This, in turn, is consistent with the goals, tasks and capabilities of multiscale cartographic representations of the developed area underlain by permafrost, and requires improvement of principles of geocryological classification and zoning [*Dubrovin, 2011*]. In this case we can define two types of information flows between the various-level models: the one "from bottom up (ascending)" based on generalization of more detailed information, contributing to the cartographic model of higher level; while the model "from top down (discending)" directs information about the objects relatedness to major geological, landscape, other classification units, hydrometeorological data, etc., to the lower level.

The environmental safety during development and exploration of mineral resources in the Arctic cryolithozone thus requires either revisiting the problems at hand or decisions to be taken on major new scientific-methodical, organizational and technical issues, associated with the principles of integration factored into regional (areal) and stationary (monitoring) research methods. The practical steps of implementation thereof are to be focused on: location and architecture of monitoring networks; unification of observations based on the state-of-the-art automated and remote sensing technologies; multivariate processes modeling which incorporate risks aspects of future resource development in the area; legislative basis for assessment of potential geo-environmental impacts from oil and gas production operations in the onshore and offshore areas.

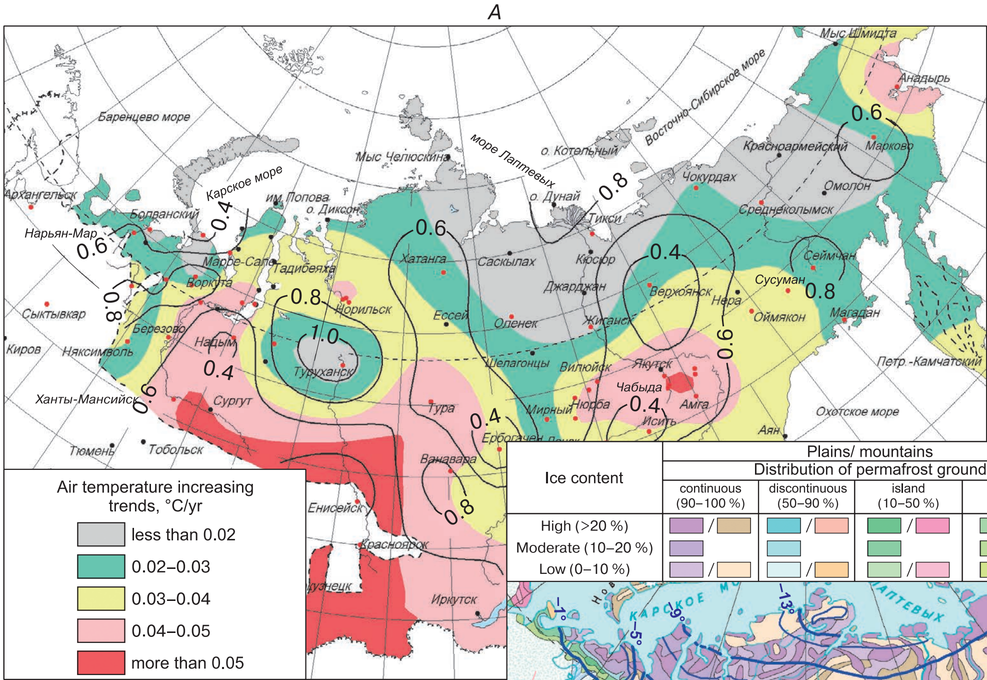
A lack of comprehensive permafrost and hydrogeological studies and pilot industrial experiments in advance of the front end engineering results primarily in low efficiency of the project design solutions. For example, such seminal documents as "The Program for Complex Development of Oil and Gas Fields in Yamal-Nenets Autonomous District and Northern Areas of Krasnoyarsk Krai" [*On the Program..., 2010*], and other key instruments somehow contain no sections for hydrogeological studies of the area [*Dubrovin and Kritsuk, 2014*], which plays a causative role in geo-ecological side effects and economic losses. Despite the long history of data acquisition, there are still critical limitations in obtaining new geocryological field data in the context of modern conditions, so the topicality of ultimate use of all the previously stored data is increasing, which can be facilitated by maintaining the geocryological data base and using GIS-technologies [*Drozdov et al., 2007*].

Regarding the spatial coverage, the permafrost data should be GIS-based and correlate with the cartographic models at global, regional, local and elementary (object) levels.

Global GIS are the overview representations depicting the Earth's hemispheres, continents or their large parts, which can be exemplified by thematic circumpolar maps and maps of the USSR and Russia. The informative part is contained in the legends (system of conventional signs), explications and summary tables for these maps (e.g., "Geocryological map of the USSR" [*Yershov, 1991*]).

Regional GIS databases are maintained for major natural regions and units of administrative divisions and are based on digital zoning maps supplemented with databases containing generalized landscape-geological, geocryological and geoecological information (e.g. Atlas of Tyumen Region [*1971*] GIS "Geocryology of Yakutia" [*Zheleznyak, 2011*], and database on natural reserves areas of the Yamal Peninsula [*Korostelev and Aleksandrov, 1997*]).

It should be noted that the needs of geocryology are rather sufficiently provided for with climatic and meteorological data for construction of functional de-



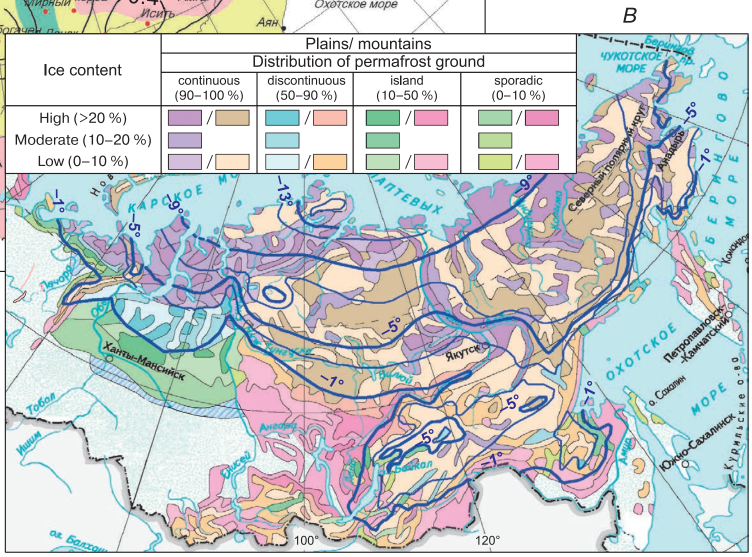


Fig. 3. Climate trends and changes in the cryolithozone.

A – cryolithozone susceptibility to climate changes [*Malkova et al., 2011; Second... report..., 2014*]; isolines – trend showing relation between ground temperature and air temperature; *B* – schematic map of the Russian cryolithozone as of 2000, after E.S. Melmikov, K.A. Kondratieva, and G.F. Graves [*Melnikov and Drozdov, 2006*]; isolines – ground temperature at depth of zero seasonal amplitudes.

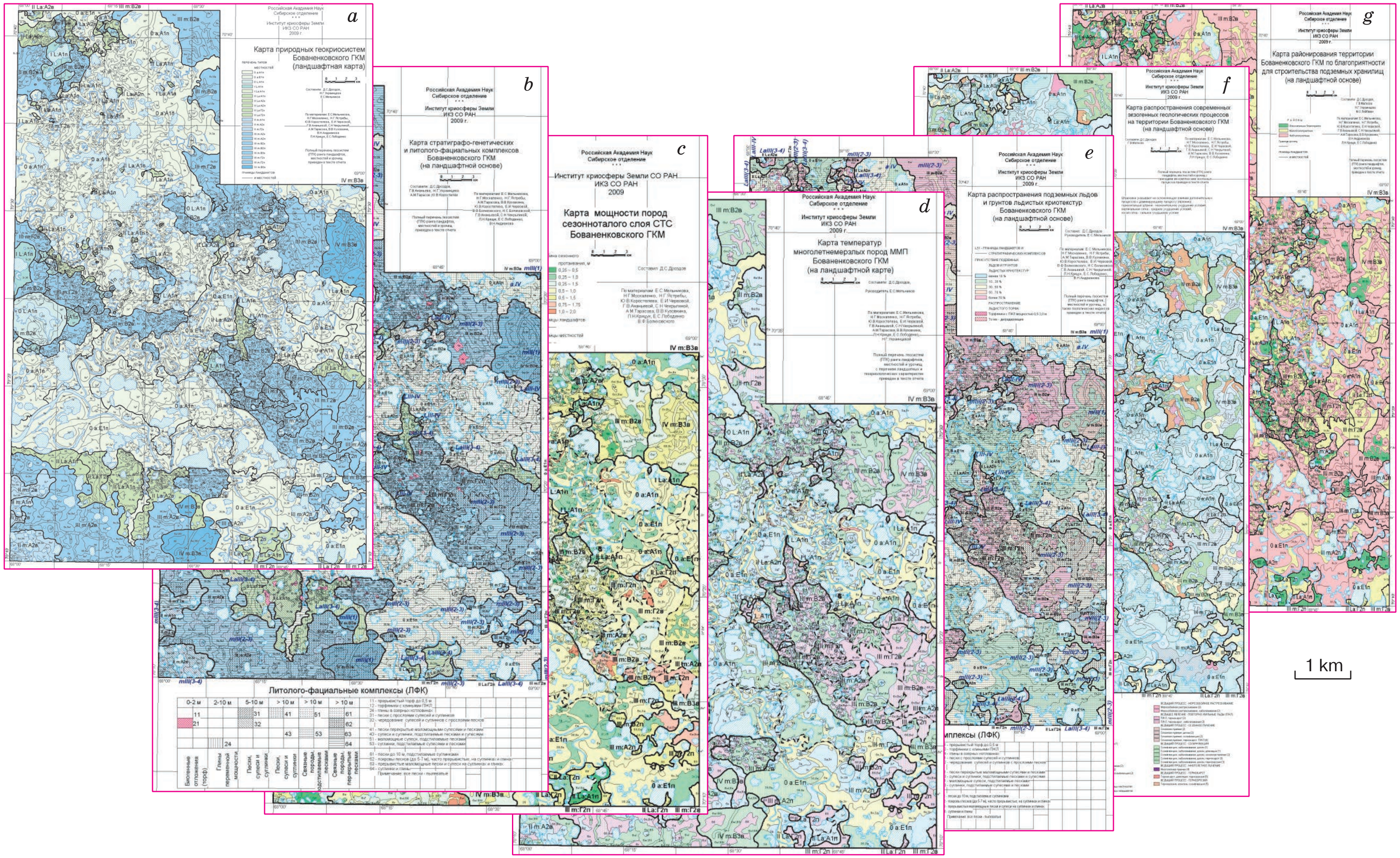


Fig. 4. An example of a set of GIS-maps for the Bovanenkovo gasfield, Yamal [*Drozdov et al., 2001*] showing:

a – landscapes; *b* – geology; *c* – seasonal thaw; *d* – ground temperature; *e* – ice content; *f* – exogenous geological processes; *g* – geo-environmental opportuneness for engineering works.

pendencies and correlations only at the global level and, partly, at regional level. These levels of detail however indicate that the climatic, relations between meteorological and permafrost parameters vary greatly in different sectors and regions of the permafrost zone of Russian Arctic (Fig. 3). Accordingly, the trends in the air and permafrost temperature variations show different correlations for different regions. It therefore stands to reason that transfer of experiences in oil/gas fields development from one region to another technically won't work.

Local databases and GIS contain basic information for the areas of major economic infrastructures. For example, descriptions of the observation points (wells, test points, etc.) are required for gas production sites, industrial areas, etc. The primary cartographic information (factual material) is derived from digital GIS-maps and derivative geological, geo-ecological and other maps. Thus, the GIS for Bovanenkovo oil and gas condensate field in Central Yamalthat includes a set of environmental and nature conservation maps has been actively used since 1999, under the implementation of 11 resource development projects (Fig. 4) [*Drozdov et al., 2001; Drozdov, 2004*].

Elementary (object-wise) databases contain primary information on site (geotechnical) investigations, monitoring and stationary observations, and inspection tests.

GEOCRYOLOGICAL POLYGONS AND STATIONARIES

Whereas the considered hierarchy is represented only in the form of separate implementations, it is all but impossible to ensure quality data coverage either of the permafrost zone alone or the entire Arctic. Depiction of the permafrost zone with deployment of the state geotechnical (engineering geocryological) surveys constitutes only few percent. The more so, the northern West Siberia region is covered only by thematic representations scaled accordingly, regardless of the key role it plays in Russia's energy resource and raw material base. The biggest concern, though, is that there has thus far not been reached general consensus on monitoring the natural and technogenic changes in the Arctic and permafrost area taken as a whole. In particular, the issue of zoning remains unresolved, although it is essential for representability of the monitoring results. These issues necessitate both landscape and geological substantiations, and organizational basis.

The latter could be instrumental in solving zoning issues and provide for monitoring of technogenic impacts and environmental responses through a specialized state program "Cryolithozone of Russia", which can be implemented as a structural part of the Federal Target Program (FTP) within the Strategy for the "Development of the Arctic Zone of the Russian Federation and National Security Efforts for the period up to 2020" [*The … strategy…, 2015*]. The "Cryolithozone of Russia" program should outline the conceptual approach to and strategy for the integrated regional and geo-ecological (hydrogeological, geotechnical, geocryological) monitoring studies of the permafrost zone to be utilized for the purposes of mineral resource development in the areas in the near and medium-term perspectives. The program is also expected to include the required volumes and stages of regional and monitoring surveys in the newly developed and largely understudied or fragmentaly studied regions of the permafrost zone, including the Arctic seas shelf.

The new concept of the permafrost zone monitoring developed by VSEGINGEO [*Pavlov and Dubrovin, 2000; Dubrovin, 2003, 2011; Kritsuk et al., 2014*] is prioritized to conduct a full range of the preemptive regional and monitoring activities, as part of creation of the system of ***state geocryological (geo-ecological) polygons*** representing large areas potential for development (Fig. 5). The concept is elaborated so as to be completely integrated into the existing since 2001 the State Monitoring of the State of the Subsurface and Mineral Resources (SMSSMR), as a geocryological block. The SMSSMR framework includes subdivisions of the background and object monitoring, with background monitoring carried out by the organizations of Russian Ministry of Natural Resources, while object monitoring is the responsibility of subsoil users under appropriate license agreements [*Dubrovin, 2011*].

The purpose of establishing polygons is to provide the government authorities at various levels and subsoil users with scientific and informational support on the current status of the environment and its projected changes in the Arctic and sub-Arctic cryolithozone driven by both natural forcings and technogenic factors, and to create the system of environmental security for the Arctic regions under development.

The ***State geocryological (geo-ecological) polygon*** (acting as the largest observation unit within the SMSSMR activities), territorially, is subsumed into the landscape (sub)provinces. These are the parts of areas of main regional I–II order structures (within hydrogeological basin or its part, geocryological subzone or part thereof; mountain-folded region, etc.), located in one natural and climatic subzone (more rarely – in two sub-zones) and characterized by common features of geological structures, permafrost conditions, and the regime of cryogenic processes. Such areas (landscape subprovinces) allocated in the Arctic and Subarctic total up to about 40, of which 8–12 being intensely developed, and the prospects for future development are good for as many as 10 of them.

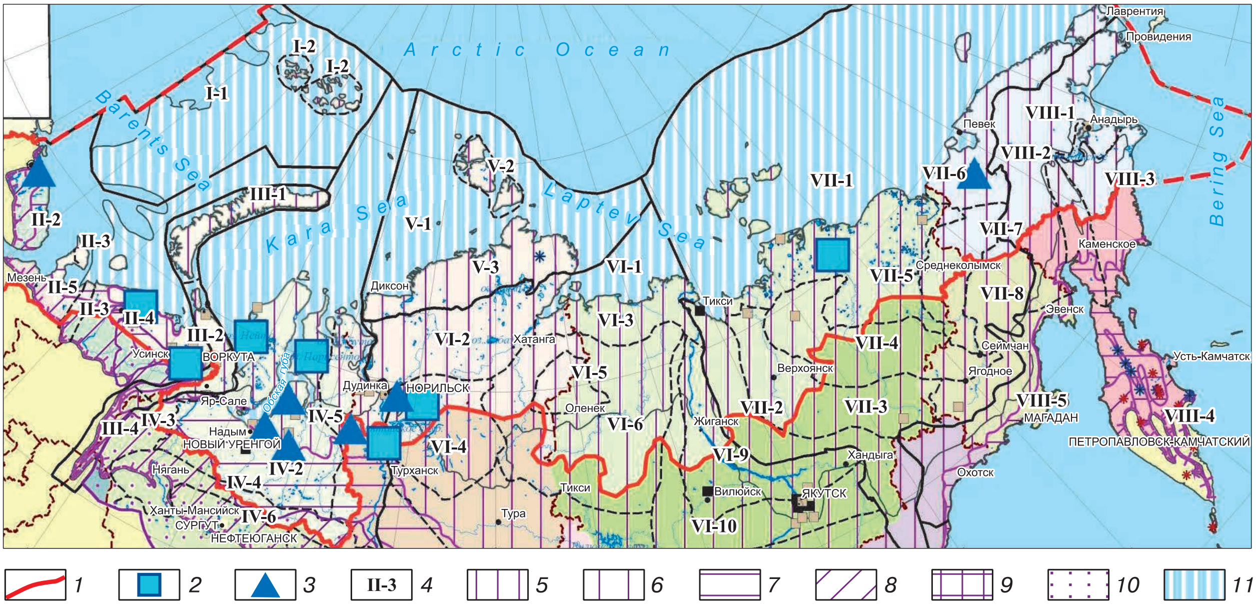


Fig. 5. Zonation of the Arctic zone (*1*) and northern part of the cryolithozone of Russia with allocation of geologic-structural regions and notations for prospective state geocryological (geo-ecological) polygons (*2*) and stationaries for background monitoring (*3*) [*Dubrovin, 2011*].

Administrative units are color marked. *4* – numbered regions of I and II orders. Distribution and temperature of permafrost: *5* – continuous ($t < -5$ °C); *6* – continuous ($t = -1...-5$ °C); *7* – discontinuous; *8* – isolated patches; *9* – continuous and discontinuous in the mountains; *10* – relict permafrost; *11* – subaquatic permafrost.

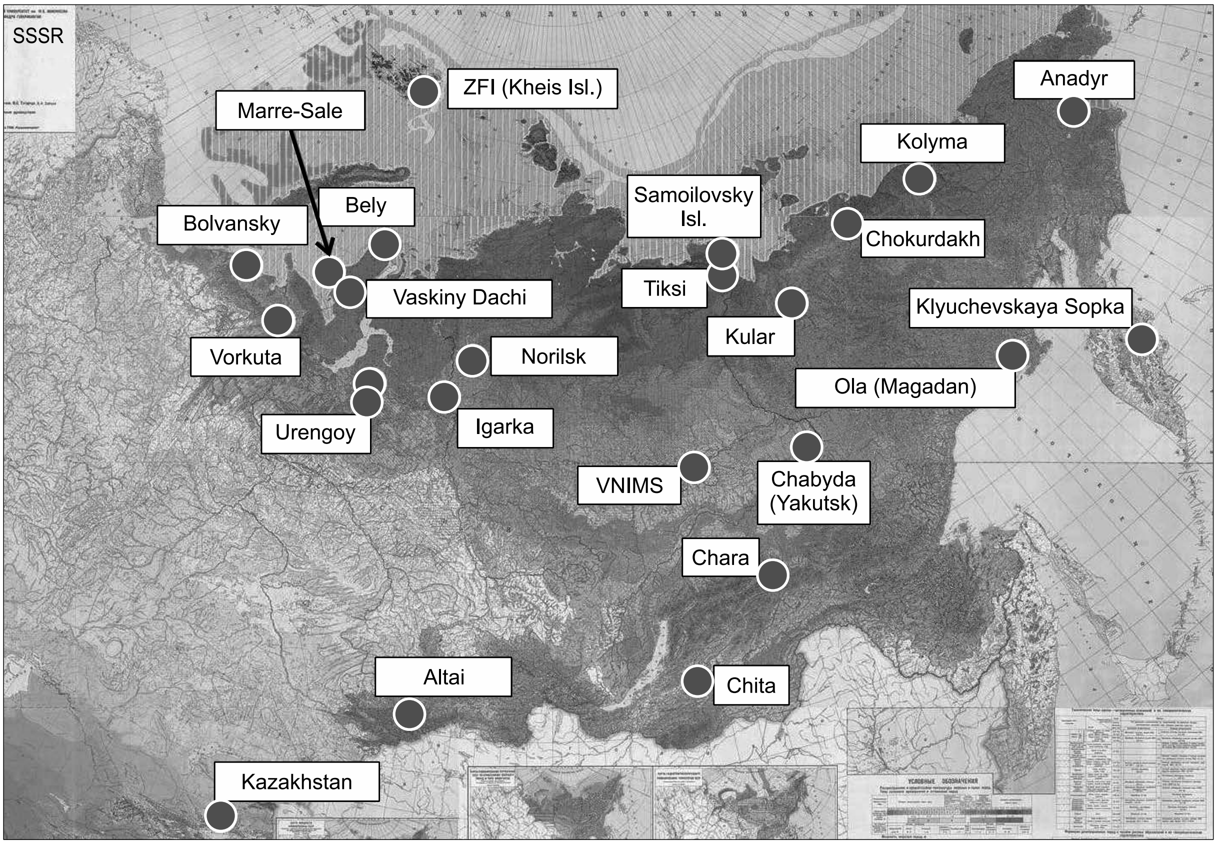


Fig. 6. Map of active geocryological stationaries and sites for periodic observations (with [*Yershov, 1991*] as a support sheet).

Within the SMSSMR polygon, a complex of specialized monitoring observations has been launched with focus on basic components of the environment both undisturbed and impacted, to identify qualitative and quantitative trends in variations of regional parameters of the main aspects of the geological environment: hydrogeological, hydrogeodynamic, geotechnical and permafrost. The total area of the polygons comprises tens of thousands of square kilometers (sheets 1–2 of the 1:500 000 map).

The SMSSMR polygons should represent by themselves the highest form in the hierarchy of the monitoring network and become the objects of generalization of the data on geocryological and hydrogeological conditions at ***regional level***, with the data obtained from ***background monitoring stationaries*** located in the vicinity and other monitoring sites being the source of information. Confined to large objects of resource development or economic infrastructure, they were established so as to be representative and to fulfil the task of information generalization ***at the local level***. Given the availability of landscape and geological extrapolation criteria for the testing and experimental data, they successfully perform this function. The area of stationaries being small in size, they provide for the data generalization within them only ***at the elementary level***. Presently, however, out of 25 stationaries and 45 sites for periodic observations functioning back in the 1980s and belonging to different governmental departments, only 15 continue to operate (Fig. 6), which is far too insufficient to answer the facing challenges.

MONITORING OF NATURAL ENVIRONMENTAL CHANGES

Monitoring of natural changes is primarily concentrated at the stationaries and sites for periodic inspection, with the results extrapolated and interpolated within the polygon on the basis of landscape (geosystem) method and remote sensing methods.

Despite being few in number, monitoring stationaries and sites allow to compare peculiarities of latitudinal and sectoral variability of the permafrost conditions and to estimate patterns of their time-dependent variability over the past decade. Thus, the Bolvansky (European North) and Urengoy (northern West Siberia) stationaries, located in the southern tundra, show similar geological, geomorphological and landscape conditions. Climatic factors affecting the ground temperature regime at both stationaries also appear similar, as well as average summer air temperature and snow accumulation. Therefore, the seasonal thaw depth controlled primarily by average summer air temperature is the same for both regions. Over the last 10–12 years, the seasonal thaw depth in southern tundra areas increased in the drained sites. In case of a longer period (~40 years) the increasing trend in the seasonal thaw depth is not articulated.

At the same time, the mean annual air temperature dictated by more severe winter conditions in the northern West Siberia is lower by almost 4 °C, than in the European North and temperature of frozen ground is much lower, accordingly [*Drozdov et al., 2012*]. The low mean annual and winter temperature in Western Siberia largely control the harsh geocryological conditions in the tundra landscape with permafrost temperatures −4...−5 °C (Fig. 7), while in the European North, they range between −1 and −2 °C. The differences are distinctly visible against the background of a general rise in the permafrost temperature over the past 40 years. Exception is the azonal-warm landscape conditions, controlled by accumulation of deep snow cover (Fig. 7).

Interestingly, these regions differ in gradients of climatic and geocryological trends. The climate warming trend has shown 0.06...0.07 °C/year air temperature rise in the last three decades. At this, in the European North, the ground temperature trends under the natural landscape conditions are 2–7 times less than the air temperature gradient trends, while in Western Siberia such trends show only a 1.5–2.5-fold-decrease. Moreover, there emerged a short-lived thermal maximum attributed to the late 1990s in Western Siberia and was characterized by the appearance of woody vegetation which subsequently disappeared in the southern tundra landscapes.

It appears both natural and predictable that the permafrost response to climate warming manifested itself in the greatest rate of increase in average annual permafrost temperature characteristic of the low-temperature landscape, while the frozen ground "warmed" at the lowest rates in high-temperature landscapes. The latter are also characterized by lowering the permafrost table and the formation of supra-permafrost taliks [*Drozdov et al., 2010, 2012*]. How-

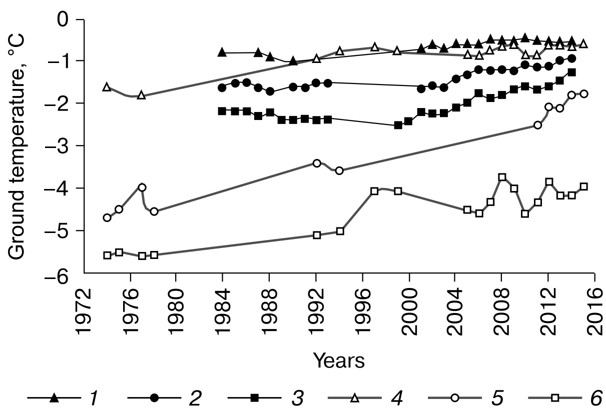


Fig. 7. Ground temperature rise under different landscape conditions of plain southern tundra in the European North (*1–3*) [*Malkova et al., 2015*] and in Western Siberia (*4–6*) [*Drozdov et al., 2015*]:

1, *4* – azonal anomalously warm conditions; *2*, *5* – typical tundra on a gentle slope; *3*, *6* – hill summits covered by drained tundra.

ever, the real growth and the ratios of these changes can be estimated only from the monitoring results which provide control and verification of the standard thermophysical predicting models, and the geoecological forecasts derived from them.

TECHNOGENIC INFLUENCES

In addition to natural changes causing ground temperature to rise, there is a variety of technogenic disturbances of the surface, and the warming effect from engineering infrastructure facilities. Direct interactions between the latter and soils are controlled by technological monitoring, covering, however, a limited extent of the geological environment.Instrumental observations complemented by descriptions of a wide diversity of processes and the scale of the related effects are used for generalized characteristizion of technogenesis.

For example, ground temperature showed an additional increase of 1...2 °C in the immediate vicinity of buildings within the Urengoy field (Western Siberia), while it reaches positive values in forested areas and is approaching 0...–2 °C in the tundra and peatland areas. A marked increase in ground temperature observed in open pit mines, around the pipelines, along the embankments, in the marginal parts of gas wells pads, i.e. where there are favorable conditions for snow accumulation. Permafrost temperature within the road fillings and well pad sites proved to differ little from the background temperatures. Ground temperatures of embankments laid through marshes and flat tundra areas appear almost equal to the background temperatures.

A substantial increase in the seasonal thaw depth is observed within engineering infrastructure facilities and in their vicinity, at times complemented by the appearance of bowl-shaped thaws caused by technogenic influences. In the context of the southern tundra forest, thaw depth reaches 3–4 meters within the extent of mine pits, along the (winter) roads and pipelines, and on embankments, with bowl-shaped thaw up to 8–9 m deep forming under the buildings in the area of gas operations [*Drozdov and Chekrygina, 1998*].

The subsequent observations revealed that the economic infrastructure operations in the territory of the Urengoy field triggered a number of geo-engineering processes including deflation, erosion and thermal erosion, thermokarst, waterlogging, underflooding and flooding. Their activation was mainly due to the disturbances of natural covers, deviated runoff and groundwater flow paths, and changing terrain.

Technogenic deflation received the greatest development in the territory of the Urengoy gasfield, showing most recent sand blowouts 0.1–6 km in size, attributed mostly to quarries, roads and well pads. Next in intensity are the effects of human activities that have brought about waterlogging and flooding. Road embankment and pipe crowning intercept surface and groundwater runoff even in minor, morphologically not pronounced depressions, leading to the formation of marshes (bogs) and narrow elongated lakes. In turn, all embankments tend to be subjected to severe erosion and need regular remedial works. Disturbance of heat exchange conditions due to the removal of land cover tends to be actively promote thermokarst processes, with their activation centers developing beneath the off-road vehicle tracks, winter roads, transmission tower footing, trenches, and so on.

The dramatic intensification of erosion is also associated with building roads, including winter roads, pipelines, and open pit mining. It is manifested mainly in the emergence and rapid growth of young gullies in marginal parts of terraces and in the sides of small rivers valleys at the expense of concentration of surface runoff. The latter is primarily attributed to the polygonal peatland areas, with the ice wedges thawing quickly and causing extensive erosion processes. In this case, the process is activated even on surfaces with low inclinations, no matter how great is the distance from the erosion base level [*Drozdov and Checrygina, 1998*].

In a similar vein, the technogenic effects-driven activation of thermokarst and thermal erosion processes in ice-rich sediments of the Yamal peninsula threaten to become catastrophic.

Constant technological monitoring, conducted by oil/gas operators, benefit the accumulation of a huge amount of information about various processes, deformations of structures and terrain surface, temperature variations, and on the state and properties of ground basements. Relying on these, the engineering solutions are made at the lowest, elementary level. However, this information is rarely used for general analysis of the situation, inventory errors and miscalculations, and for innovative scientific and technological solutions. In addition, technological monitoring is focused almost solely on engineering objects, without covering technogenesis-driven changes taking place at some distance from economic infrastructures. Therefore, the data resulting from technological monitoring processes should be considered as a tremendous informational resource readily available for state permafrost polygons and bridging the gap in their coverage of technogenic impacts, which will require establishing direct channels of data exchange between businesses (including subsoil users), and the system of state monitoring of the subsurface condition.

CONCLUSION

Despite the deficit in the monitoring-based permafrost research works funding, the observational data obtained at permafrost stationaries (not always on regular basis) and at the sites for periodic observation provide information critical for estimations of permafrost degradation driven by climatic fluctuations and technogenesis. Research works addressing these issues should therefore be continued. Creation of the permafrost zone monitoring system will provide a scientific substantiation of standardization of resource management practices in the cryolithozone, and benefit improvement of methods for data obtaining, processing, compilation and interpretation by applying a unified concept, underpinned by the system of cartographic models ranging from global and regional, to local and elementary (object) level.

The permafrost zone monitoring system, consisting of the cluster of state geocryological polygons with each represented by a network of stationaries and sites for periodic observations serves as a basis for observation of the cryolithozone within the SMS-SMR framework.

Given that works for permafrost mapping are costly, the regional permafrost studies are intended to be limited to mapping the corresponding polygon(s) at a scale of 1:500 000 on the basis of the existing database adjusted according to interpretations of the existing aerial and satellite imageries from different years and using *in situ* data from monitoring observations at permafrost stationaries, which does not require involving special regional expeditions.

The next step and level of geogryological study and mapping of the areas of state geocryological (geoecological) polygons represent local – a lower – scale of generalization of the information, corresponding to the scale of 1:100 000. Given the research is carried out at key sites, some gauge holes drilled into the permafrost are to be adequately equipped for monitoring observations.

The stationaries areas should be considered as elementary level of the object monitoring. The observations must encompass a period of at least 25–35 years to establish a trend and, if possible, a variability constituent of the geocryological and hydrogeological conditions. The objects of study within a geocryological stationary are targeted on boreholes and observational sites (with focus on cryogenic processes). The large-scale maps (1:25 000...1:10 000) for geocryological zoning may, inter alia, underpin the thermal and geoecological modeling of the stationary areas. A technique for compilation of maps of this kind was developed by VSEGINGEO and tested several times in different regions of the permafrost zone [*Melnikov, 1978, 1983; Kritsuk and Dubrovin, 2003; Kritsuk et al., 2014*].

The LPC standalone universal measuring complex could be used as a basic autonomous measuring system for monitoring observations, which proved feasible in multiyear tests at permafrost stationaries at the Yamal and Gydan peninsulas and production and environmental monitoring facilities of the gas industry in different regions. The instrument is currently widely and effectively used in different regions of the permafrost zone and beyond its extent [*Dubrovin and Kritsuk, 2011*].

Recognizing the need to re-establish hierarchy of cartographic models on a new base along with creation of the monitoring observations system targeted at basic parameters of permafrost at special stationaries and polygons in the Arctic and sub-Arctic regions would thus constitute important prerequisites for effective resource management within the cryolithozone [*Melnikov, 1978; Drozdov, 2004*] Total number of such complex observational objects (polygons) should not exceed 8–12 in the perspective of 2020. VSEGINGEO generated the "Map of geocryological zoning of Russian permafrost zone for selection of monitoring objects and substantiation of observational networks" (scaled 1:8 000 000) [*Dubrovin et al., 2011*].

The proposed system of geo-ecological informational provision and its practical implementation in parallel with economic development of the permafrost regions can be achieved through the creation of the state permafrost polygons as specially protected natural areas, which will fundamentally improve the environmental policies in the Arctic and sub-Arctic sector, secured by strengthening responsibility of subsoil users and the role of the state and the subjects of the federation in solving the environmental issues inherent to the objects of subsoil use under the unparalleled conditions of the permafrost zone.

Application of the unified set of instruments and methods along with creation of unified standards for the background and object, SMSS-integrated observations within the geocryological polygons will benefit information content and cost-effectiveness of the monitoring data, allowing to establish control for the terms and conditions of license agreements to be strictly followed, and, ultimately, to minimize the risk of geo-ecological disasters and accidents in the course of the resource exploration and development operations in the permafrost zone [*Dubrovin and Kritsuk, 2014; Drozdov and Dubrovin, 2015*].

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