Geo-Mar Lett (2005) 25: 81–88
DOI 10.1007/s00367-004-0189-7

ORIGINAL

D. S. Drozdov · F. M. Rivkin · V. Rachold
G. V. Ananjeva-Malkova · N. V. Ivanova
I. V. Chehina · M. M. Koreisha · Yu. V. Korostelev
E. S. Melnikov

Electronic atlas of the Russian Arctic coastal zone

Received: 9 December 2003 / Accepted: 2 August 2004 / Published online: 9 March 2005

Abstract A set of digital maps including geology, Quaternary sediments, landscapes, engineering-geological, vegetation, geocryological and the series of regional sources have been selected to characterize the Russian Arctic coast. Based on this data, new maps of engineering geocryological zoning and zoning of the coast with respect to the intensity of exogenous geological processes and risk of technogenic impacts have been generated at the scales of 1:4,000,000–1:8,000,000. These maps are a tool to assess the impact of industry on the Arctic coast of the country.

Introduction

The Arctic coast is characterized by a diversity of geological-geomorphological structures, which are expected to respond differently to changes in the natural environment and in anthropogenic impacts. The prediction of the dynamics of the coast is one of the major targets of the coastal engineering project program supported by the Russian Federal Committee on construction. This program has both a fundamental scientific significance and the applied socio-economic aim of predicting the development of Arctic coasts, which are vulnerable to changes in natural conditions and are of importance since the coastal zone is the region inhabited by northern populations. At present, oil fields are prospected and developed and permanent and temporary berths are constructed in this region. The latter necessitates the development of natural conservation measures in the coastal zone of the Arctic seas, based on data on the dynamics and development of seacoasts.

Industrial impacts on the Arctic coastal zone will inevitably increase as oil and gas fields are developed on the Arctic shelf and coast and as oil and gas terminals and pipelines are constructed. First of all, these impacts will be manifested as thermal and mechanical changes in frozen rocks in the coastal zone.

Geo information system (GIS) technology (using digital maps of territories and water areas with corresponding digital databases on geomorphology, landscapes, lithology, soil properties, geocryological conditions, coastal bathymetry, etc.) is one of the most effective methods for assessing the state of the Arctic environment and for accumulating available data (Melnikov and Minkin 1998; Rachold et al. 2002, 2003). A synthesis of information from databases and a reconstruction of thematic digital maps make it possible to reflect the present-day state, trend, and dynamics of coastal processes.

To assess larger-scale regularities and patterns in the spatial distribution of geo-environmental parameters in the coastal zone of the Russian Arctic region, it is optimal to use a set of GIS maps, constructed at scales of 1:4,000,000–1:8,000,000, in order to reflect in detail the features to be mapped. The set should include maps of landscapes, Quaternary sediments, and engineering geocryological zoning, as well as specialized zoning maps of the coast with respect to an intensity of exogenous geological processes and a risk of technogenic impact. These maps are in turn the basis for describing the coastal zone at scales of 1:1,000,000–1:2,500,000 in

D. S. Drozdov (✉) · G. V. Ananjeva-Malkova
Y. V. Korostelev · E. S. Melnikov
Earth Cryosphere Institute, SB RAS,
Vavilova 30/6, Moscow, 117982, Russia
E-mail: ds_drozdov@mail.ru
Tel.: +7-095-1359920
Fax: +7-095-1356582

F. M. Rivkin · N. V. Ivanova · I. V. Chehina · M. M. Koreisha
Industrial and Research Institute of Engineering
Survey for Construction, Moscow, Russia

V. Rachold
Alfred Wegener Institute for Polar and Marine Research,
Potsdam, Germany

more detail and for dividing this zone into quasi-uniform segments.

Research area and methods

The area characterized in this work includes the 200-km-wide band along the entire Russian Arctic coast from the Norwegian boundary in the west to the Bering Strait in the east. Norwegian scientists study the Norwegian Arctic coast within the scope of the INTAS project 01-2332.

Methods included collection of the majority of available hard copies of cartographic materials and their digital formats and transformation of these materials into a uniform digital graphic format to be used by differently oriented specialists in various organizations. As the uniform graphic basis, we have used the digital map of the coast and of the hydrographic network north of 60°N in the Lambert Azimuthal projection with the axial meridian 100°E (major axis 6,370,997 m). This projection makes it convenient to observe the entire Russian coastal zone.

As a software system, we have used the GEODRAW/GEOGRAPH GIS package, which makes it possible to perform a quick vectorization of thematic layers of digital maps, to correct and edit vector layers, to transform half-tone images (aerial and satellite-borne photographs, sheets of different maps, etc.), and to adjust them to the working projection (GeoGraph 1996). The package makes it possible to rapidly move data to other GIS programs (ArcInfo, MapInfo, etc.).

The main technological stages for constructing digital maps are as follows:

– Adjustment of half-tone images of remote observations and source maps of different scales and orientation to the working cartographic projection. While processing the images and maps, the graphics of non-digital sources were corrected because they were drawn up without computer and had many mistakes. The different geologic sources are reinterpreted according to modern geological hypotheses.
– Vectorization (manual or automatic) of source maps and retrieval or definition of thematic layers: landscapes, geological complexes, types of vegetation, geomorphological structures where natural and technogenic processes are observed, etc.
– Importation of digital layers of available digital maps.
– Combination of thematic layers of the same content but obtained from different sources in common digital envelopes. In addition to graphical superposition, the boundaries and contours are corrected at this stage according to the reliability of a specific source and to some accepted scientific paradigm (for example, marine or glacial origin of sediments, syngenesis or epigenesis of ground ice, etc.).
– Joint editing of adjacent thematic layers (for example, of the maps of landscapes and Quaternary sediments) in order to superpose boundaries of mapped zones in case the information presented by different layers is correlated.
– Editing of thematic layers (digital maps of different content) according remotely sensed data (for example, according to satellite images).
– Improvement and adjustment of digital maps to landscape, geological, geocryological, and other databases and generation of corresponding map legends.
– Compilation of electronic and hard copies of thematic layers, using information and the graphical possibilities of the GIS programs (Fig. 1).

At all listed stages, except for the first two, the work is performed in an iteration regime. This means that contradictions between different information elements that appear at each subsequent stage cause one to re-edit the maps, digital layers, databases, etc., constructed at previous stages. The maps presented in this work were constructed using 4–5 iteration cycles.

The first iteration procedures were performed in 1999–2001 during the construction of the circumpolar Arctic vegetation map within the scope of the CAVM international program (Walker et al. 2002). The CAVM researchers began using the main hard and electronic copies of the source maps to characterize the coastal zone of the Russian Arctic regions (Fig. 1). The available detailed maps and data for different regions were used also.

Landscape and surface geology maps

The digital landscape and surface geology maps are the graphical and data basis for the majority of different derived geological, environmental, etc. maps. The reliability of landscape and surface geology maps is improved by the mutual confirmation of numerous source maps. The main source maps are the following:

– A bedrock geology map at a scale of 1:5,000,000 (Nalivkin 1966) contains the most important information on the composition and age of hard rocks and makes it possible to distinguish regions with karst-susceptible rock. This is of special interest for areas without a thick cover of non-consolidated Quaternary sediments.
– The map of the Quaternary (surface) geology at a scale of 1:2,500,000 (Ganeshin and Adamenko 1976) shows a detailed stratigraphy of non-consolidated surface soils. It is of prime importance that this map characterizes in detail the genesis of the sedimentary cover in the mountain regions. However, it is difficult to characterize the northeastern regions of European Russia and Western Siberia with the help of this map since it represents most of the Quaternary sediments as glacial (rather than marine) formations in these regions, which causes many conflicts.
– A landscape map of the USSR at a scale of 1:2,500,000 (Gudilin 1980) characterizes morphology,

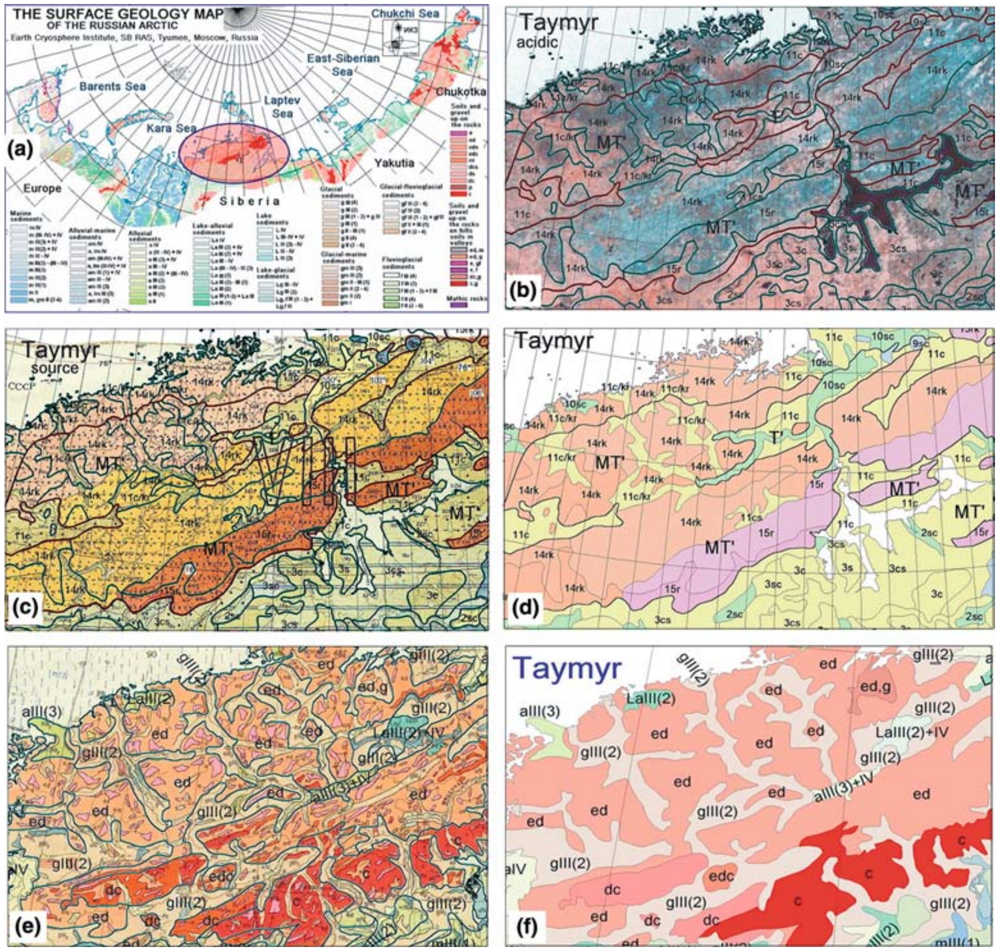

Fig. 1 Common processing of different source images and maps: **a** landscape and surface geology maps as the main source of the Arctic sea coastal zone segmentation on the base of on-shore data, **b** processing of satellite images (AVHRR), **c** source landscape map (Gudilin1980), **d** digital landscape layer, **e** source surface geology map (Ganeshin and Adamenko1976), and **f** digital surface geology layer

landscape zonality, and lithology in a complicated fashion but has the same disadvantages as the previous map.

- The Engineering-geological map of the USSR at scale 1:2,500,000 (Churinov 1972) generalizes geological and surface geological information and displays lithology, petrography and properties of soils and rocks. The data are rather old.
- The vegetation map of the USSR at a scale of 1:4,000,000 (Belov et al. 1990) helps to refine climatic zone boundaries.
- The geocryological map of the USSR at a scale of 1:2,500,000 (Ershov and Kondratjeva 1991) supplies all kinds of geocryological data.
- General digital information on landscapes and permafrost with respect to a geosystem approach is presented in a landscape map of Russian permafrost at a scale of 1:4,000,000 (Melnikov 1999) and the Circum-Arctic map of permafrost and ground ice conditions (Brown et al. 1999).
- The series of regional maps at scales of 1:1,000,000–1:2,500,000 specifies information for the northern European regions (Map of geomorphological and neotectonic zonation 1983), Western Siberia (Melnikov et al. 1991; Sergeev 1972), and Yakutia (Melnikov 1988).

Thus, the digital map of Quaternary sediments synthesizes many global and regional maps constructed by different researchers at various scales and coordinated based on recently published and our own data on landscape, geological and geocryological conditions in different parts of the Russian Arctic regions (Fig. 2). As the authors of the article follow the geosystem approach, the map of Quaternary sediments showed itself to be the most useful graphical basis for drawing up landscape polygons and generating different thematic layers.

The map of surface geology reflects more than one hundred simple and complicated stratigraphic-genetic Quaternary sediment complexes. Recent biogenic sediments (peat) have not been indicated on the map of Quaternary sediments since they often occur in the form of a vast continuous thin cover in the northern regions. This map also shows outcrops of bedrock or areas where this rock occurs close to the surface. Different colors and tints of one color are used to show the genesis and age of the surface rocks, respectively. The legend to this map is given in the form of a simple list of all types of encountered Quaternary sediments (from younger to older sediments) grouped according to their genesis (Drozdov et al. 2003; Drozdov and Korostelev 2003).

The landscape map displays the longitude and altitude zonality, morphology, lithology, and vegetation. It

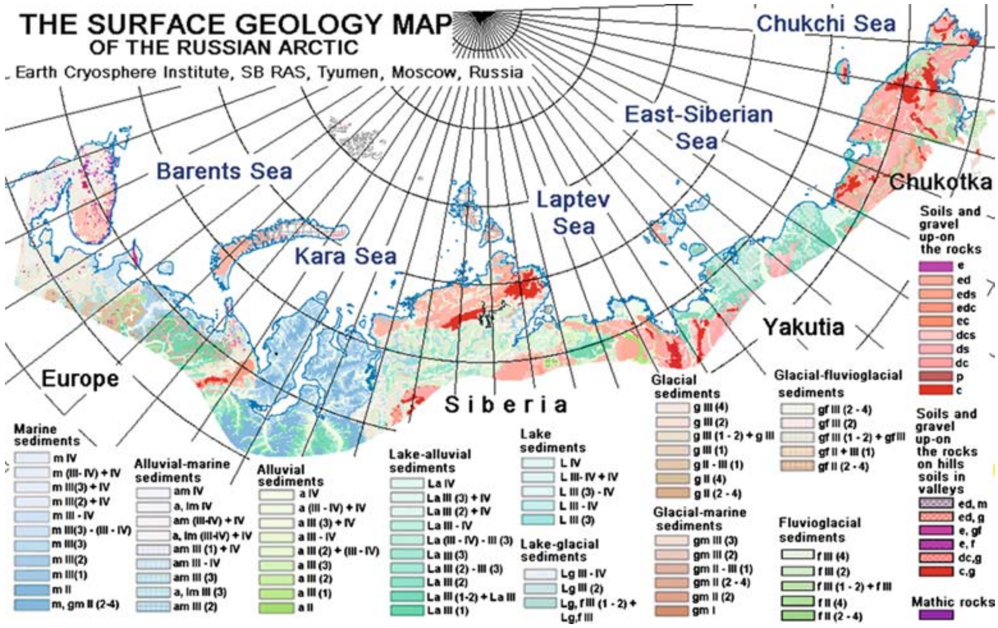

Fig. 2 Sketch of the surface geology map of the Russian Arctic

is used as the general map, i.e. the source and the contour base for resultant maps. The landscape structure was detailed according to the hierarchic principle of geological systems based on the taxonomy of natural complexes developed by Russian scientists (Melnikov et al. 1991). This map shows the largest landscape units: provinces, sub-provinces, regions, and landscapes (landscape groups). The boundaries of the regions and landscapes have been drawn using our digital map of Quaternary sediments. Data on the lithology of the surface rocks are shown within landscapes based on results of our fieldwork performed in different Russian Arctic regions.

Lines of differing thickness show the boundaries between different-rank taxonomic units on the digital landscape map. Special letters indicate the types of landscape provinces and sub-provinces. The color reflects the diversity of landscapes encountered on the Arctic coast. The lithology of the surface rocks (including that of biogenic formations) within different types of landscapes is characterized by text indices (Fig. 3).

Zoning of the Russian Arctic coast

From the viewpoint of geology, geomorphology, and geocryology, the Arctic coast is a complicated and dynamic transient cryogenic zone composed of soils and hard rocks of platform regions and mountain structures. The coast is mostly located in the zone of permafrost. In the eastern sector (behind the Urals), the rocks are almost always solidly frozen. Saline cooled sediments with brines (cryopegs) and negative temperatures are often encountered in the European north.

Geo information system of the Russian Arctic coasts also have a hierarchic structure. The main taxa on the map of engineering geocryological zoning of the Arctic coast correspond to the main genetic types of the coastal zone (abrasion, accumulative, and stable areas) according to the morphogenetic classification of Eurasian coasts developed within the scope of this project (Nikiforov et al. 2004).

The specificity of the industrial impact is complicated by the diversity of this impact and by the complex thermal-mechanical effect on frozen rocks superposed on the unstable and dynamic geocryological conditions of the coast. The latter should be considered independently for:

- Abrasion coasts composed of hard rocks.
- Abrasion coasts composed of dispersed continuous permafrost.
- Accumulative coasts (including shoal, beach, and laida—Holocene marine terrace) composed of dispersed discontinuous isolated permafrost.

The zoning of the Arctic coast is methodologically based on the generalization of the main coastal types, distinguished according to morphogenetic classification, and their correlation with present-day engineering geocryological conditions on the Arctic coast and with the detailed segmentation of the Arctic coast using data obtained from the digital landscape map (Rivkin et al. 2003).

The map of Arctic coastal zoning has been compiled in the form of a narrow band extended along the coastline. The real width of this band depends on the present-day geomorphological, geocryological, and landscape conditions, exogenous geological processes, and the geological evolution of the coast itself and the adjacent area influence the coast. So the real width of this band ranges from several hundred meters at the rocky Kola Peninsula to several tens of kilometers at the Laptev Sea coast, composed of icy Quaternary sedi-

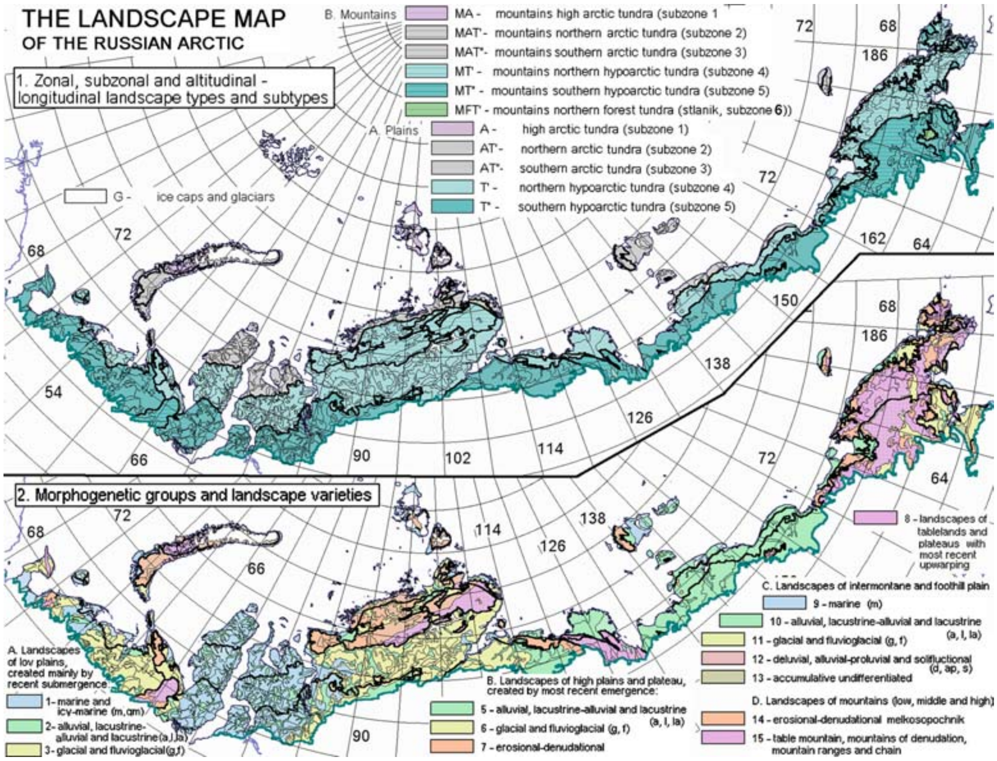

Fig. 3 Sketch of the landscape map of the Russian Arctic

ments where the annual recession reaches 20 m and more. In both cases, this band is derived from the 1:8,000,000 scale map. Therefore, some conventional coastal zone width is shown that makes it possible to display the main natural conditions characterizing the coast.

Industrial impacts on frozen rocks of the Arctic coast have been estimated based on an analysis of the engineering-geocryological conditions and exogenous processes in the coastal zone and on their natural dynamics. Taking into account changes in the trend and dynamics of exogenous processes, we have assessed the risk of industrial impact on the Arctic coast. It is of importance to take into account the specificity of the industrial impact, including both thermal (of different sign) and mechanical effects on frozen rocks. The method for assessing consequences of the industrial impact is based on the assessment of changes in the dynamics of exogenous geological processes caused by the construction of structures and the exploitation of engineering facilities.

Results and conclusions

The engineering-geocryological zoning of the Russian Arctic coast, based on an analysis of geotechnical and geocryological conditions in the areas adjacent to the coastal band (Rivkin et al. 2003), was performed using the morphogenetic classification of coasts. Engineering-geocryological conditions and the map legend were analyzed using a matrix table (Table 1), which makes it possible to relate different types of coasts to the rock and soil varieties composing these coasts. Since the zoning was performed for the small-scale map (1:8,000,000), the morphogenetic subtypes of coasts were combined in three main groups: abrasion (thermoabrasion in the areas with permafrost), accumulative, and stable coasts (Table 1). Since most of the coast is composed of scattered frozen rocks and since their transformation under the action of the sea and exogenous geological processes depends substantially on the ice content of these rocks, the latter have been differentiated with respect to their ice content (rocks with low, high, and very high ice content). We have distinguished 26 engineering-geological regions. The matrix table is, in fact, the main element of the legend to the map of engineering and geocryological zones of the Arctic coast at a scale of 1:8,000,000 (Fig. 4). The distribution of thermoabrasion and abrasion, accumulative, and stable coasts is 56, 20, and 24%, respectively. Permafrost distribution is indicated on the map by hatching (Table 2). The engineering-geological regions, distinguished from one another by the complex of natural conditions, are represented as a colored and not-to-scale band extended along the coastline. All information shown within this band corresponds only to the coast.

Based on an analysis of the effect of exogenous geological processes on the coast, we have combined the destructive coastal processes into six groups with respect to their intensity within the distinguished 26 regions: groups of low, insignificant, medium, considerable, high, and very high intensity (Table 3). This information is

Table 1 Engineering-geological units of the Arctic coasts (legend to Figs. 4, 5, 6)

Coasts	Rocks and sediments comprising the coast							
	Rocks	Unfrozen ground	Frozen grounds			Combination of rocks and grounds		Ice
			Low ice content	Ice content (medium ice content)	High ice content	Unfrozen ground	Low ice content frozen ground	
Abrasion	No. of the engineering-geological units							
Abrasion	1							
Thermal abrasion			2	3	4			
Coastal ice								5
Thermal-denudation			6	7	8		9	
Abrasion-accumulative		10	11	12	13		14	
Accumulative								
Lagoon			15	16				
Laida[a]		17	18	19				
Deltas		20	21	22	23			
Stable								
Fault, fiord	24					25	26	

[a]Broad tundra lowland along the Arctic coastline, which is periodically flooded during high tides

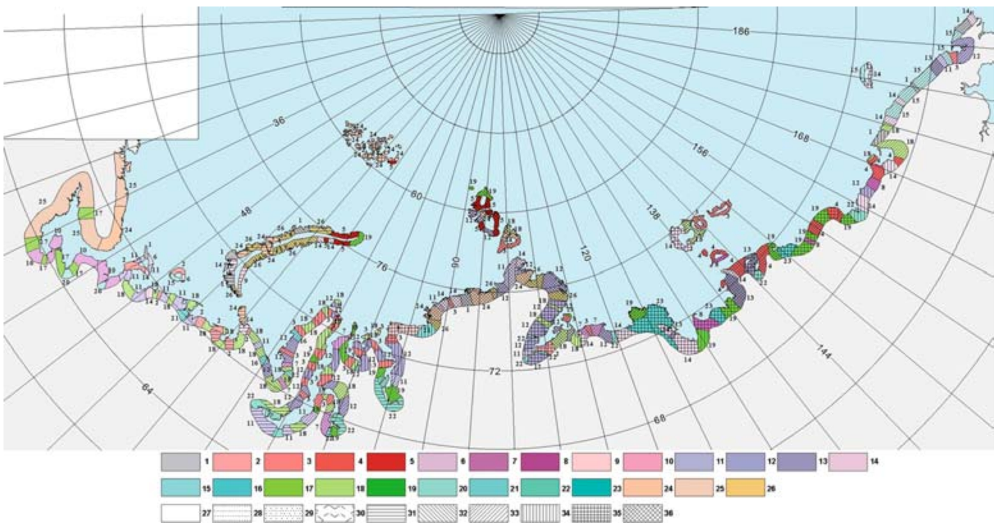

Fig. 4 Engineering-geological map of the Arctic coast, base scale 1:8,000,000. *1–26*engineering-geological units (see Table 1), *27–36*permafrost conditions (see Table 2)

Table 2 Permafrost conditions (legend to Figs. 4, 5, 6)

Permafrost distribution	Ground temperature , °C									
	> 0	0 to -0.5	-0.3 to -1.0	-0.5 to -2.0	-1.0 to -4.0	-3.0 to -6.0	-5.0 to -7.0	-7.0 to -9.0	-9.0 to -11	< -11
Thawed grounds	27	28								
Island (<20%)			29							
Massive Island (20-50%)				30						
Discontinuous (50- 80%)					31	32	33	34	35	36
Continuous (> 80%)										

Table 3 Intensity of destructive coastal processes (legend to Fig. 5)

1.		Low intensity
2.		Insignificant intensity
3.		Moderate intensity
4.		Considerable intensity
5.		High intensity
6.		Very high intensity

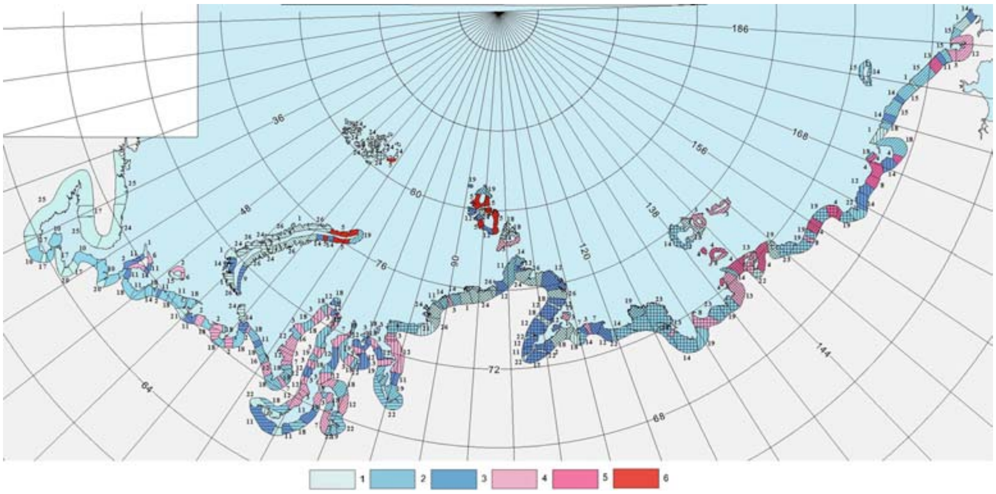

Fig. 5 Map illustrating the intensity of destructive coastal processes, base scale 1:8,000,000. *1–6* intensity of destructive coastal processes (see Table 3), for other legends (engineering-geological units and permafrost conditions) see Tables 1 and 2

presented as a map of destructive coastal process intensity (Fig. 5).

While carrying out such analysis it is necessary to take into account that there can be some confusion between actual impacts, which should be characterized by certain features, e.g., coast recession, and coastal vulnerability, that is, the measure of the cost sensitivity to various kinds of possible disturbances and future problems.

On this basis, we have assessed the industrial impact on the Arctic coast (Fig. 6). Impact assessment has been performed differently for each engineering-geocryological region distinguished on the coast, taking into account technological features of construction and engineering facilities: aerial construction; highways and airdromes; underground (with positive and negative pipe temperatures) and surface pipelines; and quarries. The total assessment has been performed for the most hazardous manifestation of the effect, assuming that the effect of the most destructive technogenic factor will be larger than that of the remaining factors (Table 4).

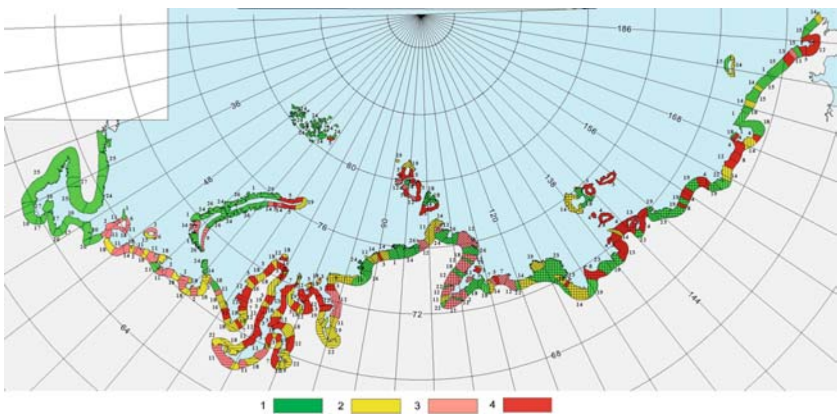

Fig. 6 Map illustrating estimates of industrial impact on the Arctic coast, base scale 1:8,000,000. *1–4* estimates of industrial impact (see Table 4), for other legends (engineering-geological units and permafrost conditions) see Tables 1 and 2

Table 4 Industrial impact assessment (legend to Fig. 6)

No. in the legend	Degree of danger	Possible impact on exogenous geological processes as a result of industrial influence
1	Non-hazardous	Present exogenous geological processes are not intensified; new processes are not initiated
2	Slightly hazardous	Initiation or intensification of exogenous geological processes are hardly probable; changes in geocryological and/or surface conditions are reversible; conditions close to initial are recovered after the termination of industrial impact
3	Hazardous	Initiation or intensification of exogenous geological processes are probable; processes develop intensely but from back
4	Very hazardous	Present processes are intensified; new exogenous geological processes are initiated; processes are accelerated and cause irreversible changes in the natural environment

Based on the map of the engineering-geocryological zones, we have constructed an industrial impact risk assessment map for the Russian Arctic coast at a scale of 1:8,000,000, where each coastal region is shown according to the above gradations in the form of a narrow colored band extended along the coastline.

Acknowledgements This work was supported by INTAS (grant 01–2332), the Russian Foundation for Basic Research (grant 01-05-64256), and the Tyumen Regional Academy, and was performed according to the scientific plan of the Russian Federal Committee on Construction for developing the Russian coastal engineering protection program.

References

Belov VA, Gribova SA, Kotova TV (eds) (1990) Vegetation map of USSR at scale 1:4 000 000 (in Russian). Moscow, GUGK

Brown J, Fenians OJ, Heginbottom JA Jr, Melnikov ES (1999) Circum-Arctic map of permafrost and ground ice conditions. International Permafrost Association and United States Geological Survey

Churinov MV (ed) (1972) The engineering-geological map of the USSR at scale 1:2 500 000 (in Russian). Moscow, GUGK

Drozdov DS, Korostelev YuV (2003) Environmental maps of the Russian Arctic as a base for the segmentation of the coastline and the analyses of coastal dynamics. In: Extended abstracts, 8th international conference on Permafrost, vol 1, 21–25 July 2003, Zurich. A.A. Balkema Publishers, pp 27–28

Drozdov DS, Korostelev YuV, Malkova GV, Melnikov ES (2003) The set of eco-geologic digital maps of the Timan-Pechora province. In: Proceedings of the 8th international conference on Permafrost, 21–25 July 2003, Zurich, pp 205–210

Ershov ED, Kondratjeva KA (eds) (1991) The geocryological map of the USSR at scale 1:2 500 000. Moscow, GUGK

Ganeshin GS, Adamenko OM (eds) (1976) The map of the Quaternary (surface) Geology at scale 1:2 500 000 (in Russian). Moscow, GUGK

GeoGraph for Windows (1996) User manual. Version 1.5 (in Russian). Moscow, IG PAS

Gudilin IS (ed) (1980) Landscape map of USSR at scale 1:2 500 000 (in Russian). Moscow, GUGK

Map of geomorphological and neotectonic zonations (1983) Complete set of maps of European part of RSFSR (in Russian). Moscow, MSU

Melnikov ES, Kritsuk LN, Moskalenko NG (1991) Explanatory note to the map of natural complexes of the North of Western Siberia for the purposes of the geocryological forecast and planning of nature protection actions at large-scale construction (in Russian). Moscow, VSEGINGEO, p 36

Melnikov ES, Minkin MA (1998) About strategy of development of electronic geo information systems (GIS) and databases in geocryology (in Russian). Earth Cryosphere 3(2):70–76

Melnikov ES (ed) (1999) Landscape map of Russian permafrost at scale 1:4 000 000 (in Russian). Earth Cryosphere Institute SB RAS, Tyumen

Melnikov PI (ed) (1988) Permafrost and landscape map of Yakutia at scale 1:2 500 000 (in Russian). Melnikov Permafrost Institute, Novosibirsk

Nalivkin DS (ed) (1966) Bedrock geology map at scale 1:5 000 000 (in Russian). Moscow, GUGK

Nikiforov SL, Pavlidis YuA, Rachold V, Grigoryev MN, Rivkin FM, Ivanova NV, Koreisha MM (2004) Morphogenetic classification of the Arctic coastal zone

Rachold V, Brown J, Solomon S (2002) Arctic coastal dynamics—report of an international workshop, Potsdam, 26–30 November 2001. Rep Polar Res 413:103

Rachold V, Lack M, Grigoriev MN (2003) A geo information system (GIS) for circum Arctic coastal dynamics. In: Proceedings of the 8th international conference on Permafrost, vol 2, 21–25 July 2003, Zurich. A.A. Balkema Publishers, pp 923–927

Rivkin FM, Koreisha MM, Ivanova NV (2003) The engineering-geocryological zoning of the Russian Arctic coast for the estimation of hazard caused by the industrial impact. In: Proceedings of the 8th international conference on Permafrost, vol 2, 21–25 July 2003, Zurich. A.A. Balkema Publishers, pp 959–963

Sergeev EM (ed) (1972) The engineering-geological map of the Western Siberian plate at scale 1:1 500 000. Moscow University

Walker DA, Gould WA, Maier HA, Raynolds MK (2002) The circumpolar Arctic vegetation map: AVHRR-derived base maps, environmental control, and integrated mapping procedures. Int J Remote Sens 23(21):4551–4570