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Cryogenic Processes of Arctic Land-Ocean Interactions

By Felix E. Are[1], Erk Reimnitz[2] and Heidemarie Kassens[2]

THEME 12: Gashydrates and Permafrost, Onshore and Offshore

Summary: Geodynamic processes on Arctic margins of Eurasia are caused largely by diverse and extremely dynamic Land-Ocean interactions. All processes of interaction, except tectonic movements, are cryogenic. They play an important role in the evolution of Arctic environments. Among these processes belong the formation and degradation of permafrost, sea ice activities and the formation and degradation of gas hydrates. The formation of permafrost on the exposed shelf during the last Glaciation and its partial degradation in post glacial time led to dramatic changes of the Arctic environments.

At present, ice bonded permafrost is widespread on the Arctic shelf. In some places, frozen sediments or pure ice are observed 30 cm below the sea floor. Offshore permafrost is poorly known and therefore predictive permafrost maps are compiled by means of mathematical modelling. Paleogeographical information on climate change during last 100 000 years may be obtained by means of geothermal investigations of modern permafrost and subsequent mathematical modelling.

The geological interpretation of seismograms obtained in Arctic seas of Eurasia is complicated, because cryogenic factors mask real geological structure. On the other hand, interpretation of such seismograms gives valuable geocryological information. Shore erosion with comparatively stable sea level started in the middle of the Holocene and continuous now at rates of between 2-6 m/year. Therefore tens of square kilometres of Arctic land are consumed every year and the total retreat of shores at constant sea level is locally as large as 50 km. The input of shore erosion products to the sediment balance of Arctic seas is comparable to that of the rivers, and very likely exceeds these.

Large amounts of hypogene gas and gas hydrates are present in permafrost beginning at depths of some metres below the bottom. The permafrost formation preserves upward fluxes of gas. The degradation leads to resumption of free gas migration and decomposition of hydrates. Sea ice, completely protecting shore and shoreface against the hydromechanical influence of sea in winter, accomplishes much work toward bottom erosion, mobilisation and transportation of bottom sediments throughout the year. Frazil ice activity plays an extremely important part in shore retreat, favouring suspension of bottom sediments during late fall storms.

INTRODUCTION

Geodynamic processes on Arctic margins are caused largely by diverse and extremely dynamic Land-Ocean interactions, which in the upper Pleistocene and Holocene took place on the modern shelf and coast in areas as wide as 600 km and ranging in altitude up to 200 m. Such extensive areas of interactions are conditioned by glacial/interglacial alternations caused by climate changes and corresponding glacio-eustatic sea-level fluctuations accompanied by glacio-isostatic and tectonic movements of the earth's crust. All these global large-scale processes, except tectonic movements, are caused by or connected with freezing of water and thawing of ice and are called cryogenic.

The area of Land-Ocean interactions in the Arctic is characterised by the presence of permafrost. In September 1994 the European Conference on Grand Challenges in Ocean and Polar Science took place in Bremen. For three days the best European experts were lecturing on the main problems of Polar Science. But permafrost was not included among the problems to be addressed. During the following four years the attitude towards the role of permafrost in polar environments changed considerably, at least in Germany. In particular this change is indicated by the first appearance of permafrost among the topics of the ICAM conferences.

Permafrost, a product of severe climate, is an integral and very sensitive part of polar environments. It plays an important role in Arctic Land-Ocean interactions. To understand and evaluate this role as a whole we must consider not only permafrost itself but a vast complex of interrelated cryogenic phenomena and processes. The most important of them are given in Table 1.

A. Permafrost
  I Main topic
    Formation and degradation of permafrost
  II Sub-topics
    - Accumulation of large underground bodies in the form of ice wedges, segregated, injected and buried ice,
    - thermokarst,
    - thaw settlement of frozen unconsolidated sediments,
    - coastal erosion
B. Sea ice
    - direct and enhanced erosion of shores and sea bottom by drift ice,
    - Erosion of sea bottom by anchor ice,
    - Entrainment of sudpended sediments into drift ice by anchor ice and frazil ice,
    - Intensification of hydraulic transport of suspended sediments by frazil ice,
    - Transport of sediments by drift ice
C. Gas hydrates
    Formation and decomposition of gas hydrates

Tab. 1: Cryogenic processes of Land-Ocean interactions in the Arctic.

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[1] Petersburg State University of Means of Communications, Russia P.O. Box 210, 195220 St.-Petersburg, Russia, <but@peterlink.ru>

[2] GEOMAR Research Centre for Marine Geosciences, University of Kiel, Wischhofstrasse 1-3, D-24148 Kiel, <hkassens@geomar.de>

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Formation and degradation of gas hydrates is much more complicated than freezing of water and thawing of ice, but it is also connected with a phase change and accompanied by release or absorption of latent heat. Therefore gas hydrates belong to the cryogenic phenomena. They are present in the Arctic Land-Ocean interaction zone and shouldn't be neglected.

The goal of this paper is to turn the attention of the readers to the role and importance of cryogenic processes in the evolution of Arctic environments, to show that these processes are poorly studied and represent a vast area for future investigations.

FORMATION AND DEGRADATION OF PERMAFROST

The formation of permafrost on the emerged Arctic shelf during the sea regression and its total or partial degradation during the transgression is the largest-scale cryogenic process of the Arctic Land-Ocean interactions. The movement of the shore line during a regression doesn't cause any significant changes of emerging sea floor relief. This is confirmed in particular by observations of the modern regression in the Caspian Sea.

During the late Pleistocene Glaciation, permafrost formed on the emerged shelf. But it was not only downward freezing of sediments and rocks. Accretion and syngenetic freezing of ice complex - terrestrial fine-grained deposits reaching thicknesses of as large as 50 m and having ice content by volume as large as 95 %, occurred on the unglaciated parts of the shelf. Unique dry tundra-steppe landscapes populated with mammoth fauna developed (Sher 1997).

The Ice complex, very sensitive to heat influence, underwent submergence during the last transgression. A strongly ice-dominated ocean and low water temperatures at the beginning of the transgression increased the capacity of ice complex to resist the action of the sea. Very gentle slopes of shelf lowlands, especially in the Laptev and East-Siberian Seas, led to enormous speeds of shore-line movement which in places could reach 1000 m/year or more. As a consequence, submergence of the ice complex took place without extensive thawing and erosion. Therefore remnants of ice complex probably are preserved till now under the sea floor. For example, such a remnant of unknown thickness is revealed by drilling under the deltaic sediments in Lena River delta (Galabala 1987).

A relatively stable sea level became established by the middle of the Holocene about five thousand years ago. The previously prevailing fast submergence of the shelf changed to stable conditions, leading to the formation of an equilibrium profile in the shore zone and equilibrium relief of the shallow sea floor corresponding to this constant sea level. Submergence of the shelf led to a sharp increase of the mean annual shallow sea floor temperature, which with time led to the onset of permafrost degradation from below on the entire area of submergence.

The dynamics of the upper boundary of the newly submerged permafrost was much more complicated, mainly because of an uneven temperature distribution at the surface of the submerged shelf. On the outer shelf at depths exceeding ~20 m, the mean annual temperatures have become negative, which favours frozen state of inundated terrestrial fresh water sediments. In areas of river water outflow, in water depths less than 10 m, the mean annual temperatures of the sea floor are positive and therefore permafrost is degrading from above. Positive mean annual temperatures are also observed outside of areas of river water inflow where water depths are less than 2-8 m (Zigarev 1997). The modern position of the upper boundary of permafrost on the Eurasian shelf depends not only on temperature but also on the salinity of sediments, the glacial history and glacio-isostatic and tectonic movements.

The permafrost on the Eurasia shelf is very poorly known. A short review of the drilling evidence on the ice bonded permafrost distribution is presented in Table 2. The locations of boreholes are shown in Figure 1. The limited information given in Table 2 gives clear evidence that ice bonded permafrost is widespread on the Eurasian shelf not only near the shore but in the open sea. The frost table (the upper boundary of frozen sediments) is situated usually at some tens of metres under the sea floor. But in some places it is observed at a depth of no more than 30 cm.

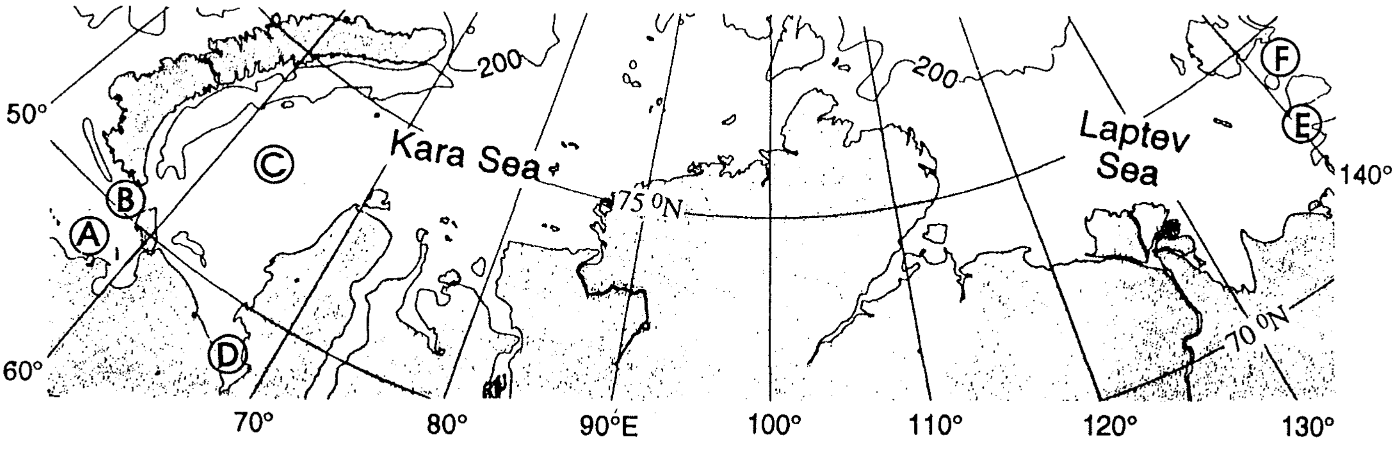

Fig. 1: Locations of boreholes presented in Table 2.

Borehole number	Borehole depths	Water depth	km from shore	upper/lower surface of permafrost	Refe-rences
		Pechora Sea			
				23-63/53-163	(1)
		A			
383	109.5	15.5	8	63.0/109.5	(1)
384	90.0	21.0	54	23.5/44.0	-’’-
385	87.5	28.0	15	41.0/71.5	-’’-
				22-43/ -	(2)
		B			
no. of holes 2	16-25			0.3-14/ -	(4)
480	100	47		0.3/>100	(4)
481	50			19/>50	(4)
		Kara Sea			
		C			
253	50	114	150	13.5/>50	(1)
254	20	109	150	8.4/>20	-’’-
206	20	80	100	17.0/>20	-’’-
		60-115		8-13/ -	(2)
		D			
1249, 1250		13.6	12	13.2-16.4/ -	(1)
867		16.0	20	28.8/ -	-’’-
240	78	14.0	12	17.0/>78	-’’-
		14-16		14-28/ -	(2)
240	80	13		15/>80	-’’-
		Laptev Sea			
		E			
17	193	14	26	23/ -	(3)
7-14	149	13	25	7/ -	-’’-
38-12	152	14	15	10/>152	-’’-
no. of holes 42	44-216	3-19	up to 32	2-28/ -	-’’-
		F			
no. of holes 7	22-77	up to 28	up to 32	none	(3)

Tab. 2: Ice bonded Permafrost on Eurasian Shelf (Drilling Evidence, depth in m). (1) MELNIKOV & SPESIVTSEV 1995; (2) GRITSENKO & BONDAREV 1994; (3) FARTYSHEV 1993; (4) MELNIKOV et al. 1997.

No drilling was carried out in the central part of the Laptev Sea till now, but in some places ice crystals and frozen sediments were observed in sediment cores. Fig. 2 shows a core section of silty clay obtained in 1993 at 73°27.98’N, 131°38.59’E, at a water depth 24 m. The length of the core was 85 cm; temperature -1.5 °C at the surface and -1.3 °C at 85 cm. Separate ice crystals gradually coarsening downward were observed beginning from the 18 cm level. Below the 61 cm level ice pieces as large as 3 cm were abundant (KASSENS & KARPIY 1994). Limited core recovery in general may be caused by the presence of ice-bonded permafrost near the surface (MOLOCHUSHKIN 1973, KASSENS 1994, KASSENS & KARPIY 1994, NEBEN et al. 1998). Most seismograms in the Laptev Sea show sub-horizontal boundaries at depths less than 10 m, which are interpreted as the upper surface of ice bonded sediments (ROMANOVSKY et. al. 1997, HINZ et al. 1998, NEBEN et al. 1998).

Lack of factual evidence on the distribution and parameters of the cryolithozone on the Arctic shelf forces investigators to use mathematical modelling for compiling predictive permafrost maps, based on what is known about sea level history and shelf relief. Such maps give the most probable, generalised idea of the shelf cryolithozone. But even the scant information available till now from direct field investigations, shows that modern procedures of modelling can not reproduce the real diversity of the shelf cryolithozone, which sometimes appears anomalous. For example, along the thoroughly surveyed 70 km gas pipeline route crossing the up to 20-m-deep Baydaratskaya Bay, Kara Sea, 30 m deep boreholes penetrated unfrozen loams with negative temperatures of between 0.5-0.2 °C at all but one section. Here the same loams were frozen with temperatures of between 1.8-2.2 °C below zero (Fig. 3). This section lies 12-20 km from the coast of the Yamal Peninsula at a water depth of

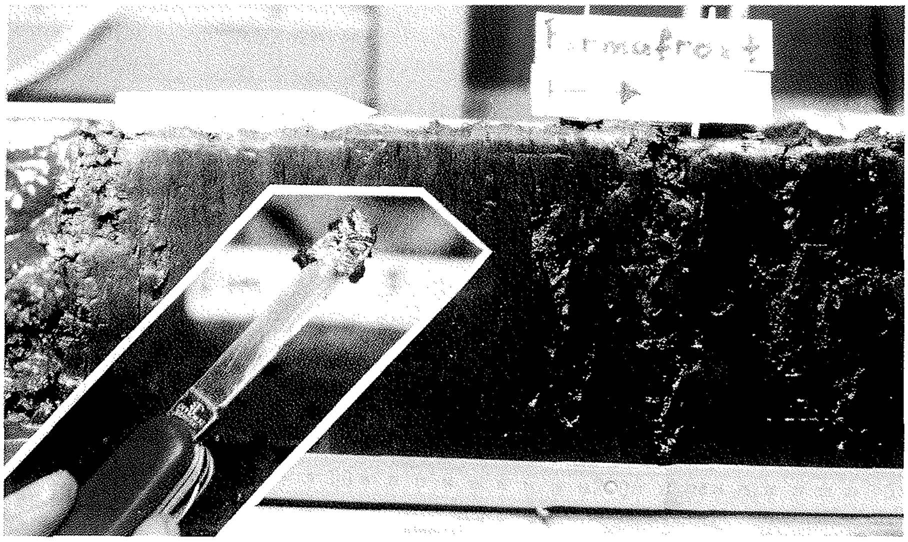

Fig. 2: Frozen sediments in the core and ice agregate from this core taken in the Laptev Sea, 1993, 73° 27,98'N, 131° 38.59'E, water depth 24 m.

14-16 m. The table of ice bonded sediments is 13-29 m below the sea floor. Borehole #240 reaching to 78 m did not penetrate any unfrozen sediments. In the interval 19-29 m below the sea floor this borehole penetrated alternation of ice and loam with basal structure (ice containing dispersed particles) (MELNIKOV & SPESIVTSEV 1995). There is no reliable explanation for the presence of ice-rich frozen sediments in this section of the pipeline route. Inverse to the above approach of predicting offshore permafrost distribution from paleogeographical knowledge is that of using geothermal data from modern permafrost to hindcast paleogeography (LACHENBRUCH 1957, ARE & TOLSTYAKOV 1970, ARE 1988, NELSON et al. 1993). The temperature field of permafrost may retain information on surface temperature alterations for several centuries, while the thickness of ice bonded permafrost and position of its upper and lower boundaries retains such information for the last 100 thousand years. This information may be extracted by means of geothermal measurements and subsequent mathematical modelling. Unfortunately this possibility was almost not used till now. Such approach is especially promising for reconstructing the transgression-regression history of Arctic seas at depths over 2 m. Here, lacking the complexities introduced by a changing snow and vegetation cover, seasonal thawing of bottom sediments does not occur and the mean annual bottom-water temperature and sediments are nearly equal. This simplifies considerably the geothermal monitoring and modelling.

Analyses of the large amount of seismo-acoustic data, obtained in Arctic seas of Eurasia, showed that in the presence of ice bonded permafrost cryogenic factors often mask real geologi-

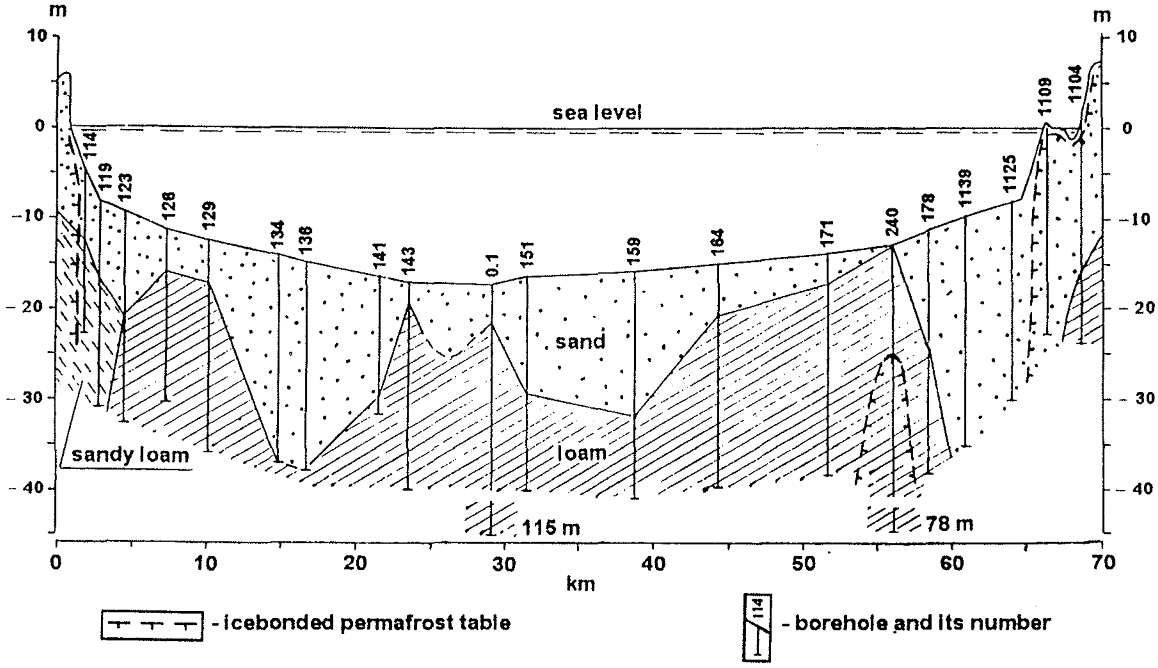

Fig. 3: Simplified geological cross section along the gas pipeline route across Baydaratskaya bay, Kara Sea (MELNIKOV & SPESIVTSEV 1995).

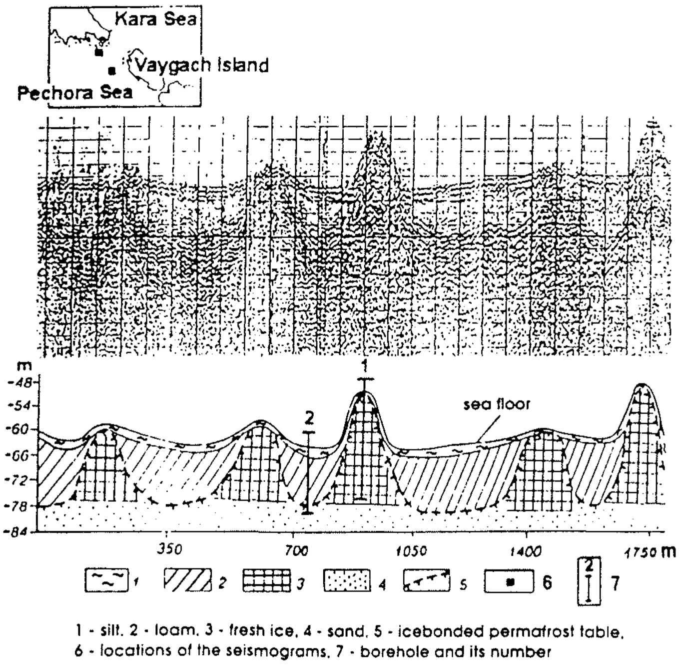

Fig. 4: Seismogram from Pechora Sea floor (area B in Fig. 1) and its geological interpretation (MELNIKOV et al. 1997).

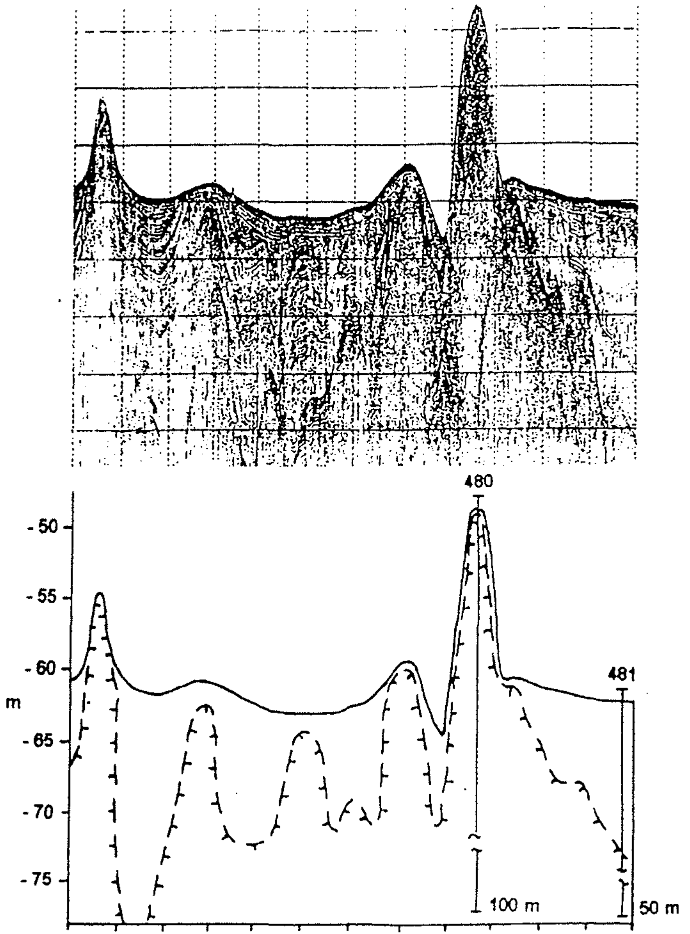

Fig. 5: Seismogram from Pechora Sea floor (area B in Fig. 1) and its geological interpretation (MELNIKOV & SPESIVTSEV 1995, simplified)

cal structure. On the other hand, interpretation of such seismograms gives valuable geocryological information, allowing to distinguish ice bonded permafrost, ice bodies and probably gas hydrates under the sea floor (MELNIKOV & SPESIVTSEV 1995, HINZ et al. 1998). For example, numerous seismograms with peculiar patterns shown in Figure 4, were obtained in the Barents, Pechora and Laptev Seas (MELNIKOV & SPESIVTSEV 1995, PAVLIDIS & POLYAKOVA 1997, MELNIKOV et al. 1997, ROMANOVSKY et al. 1997). The hills visible in Figure 4 are conical, 12-17 m high with a 100-300 m wide base. In 1995, borehole 1 was drilled on top of one of the hills. It penetrated pure freshwater ice 0.3 m below the floor and did not reach its base at 25 m depth. Borehole 2 in a depression between hills met ice bonded sand at 14 m depth.

Another example, also from Pechora Sea, is given in Fig. 5. The 100-m-deep borehole #480 drilled on top of a hill penetrated frozen clay with an ice content of up to 70 % by volume near the surface and did not reach its base. Borehole 481 in sands met the ice bonded permafrost table at 22 m. At 28 m this borehole entered the same clays penetrated in borehole 480. Extensive gas emission from the drill core was observed. At 50 m depth a powerful gas blow-out occurred. The height of water-gas fountain reached 10 m above the deck of the drilling ship. The ship withdrew immediately (MELNIKOV et al. 1997). The described drilling evidence enabled reliable geocryological interpretation of the seismograms, presented in Figures 4 and 5.

PROCESSES ACCOMPANYING AND INFLUENCING PERMAFROST EVOLUTION

The freezing of pore water and formation of large underground ice bodies in permafrost lead to the increase of total sediment volume. As far as we know, nobody measured the uplift of earth surface caused by this process. But the decrease of the sediment volume due to its thawing has been studied for a long time because (1) - thaw subsidence of frozen grounds is of great importance for engineering and (2) - local thawing of ice-rich sediments creates a unique lake-thermokarst relief and corresponding environment, wide spread on the Arctic lowlands. The depth of thermocarst lake depressions in the Arctic reaches 20 m. Correspondingly the degradation of inundated ice complex on the shelf will lead to the equally large subsidence of the sea floor.

Thousands of kilometres of Arctic sea coasts retreat at rates of between 2-6 m/year under the action of coastal erosion (ARE 1985, BARNES et al. 1991), consuming tens of square kilometres of Arctic land every year. This is a special kind of sea transgression occurring with a constant sea level. Clearly this process has to be considered by various economic activities on the coast. It also plays an important role in the evolution of the Arctic coastal environment. Sea level has risen during the past century and is expected to continue rising, reaching most probably 50 cm above the present level by the year 2100 (Climate change 1995, 1996). Therefore, the rate of erosion may accelerate considerably in future.

Sediment discharge by rivers in the past has been considered the main terrestrial input to the marine sediment balance. However, we now realise that the products of coastal erosion may equal or exceed river input, as shown for the Laptev Sea in a study by ARE (1998). A comparison in the Alaskan part of the Beaufort Sea, done conservatively by setting the depth limit of erosion at 2 m, also showed the dominance of shore erosion over river input by a factor of seven (REIMNITZ et al. 1988).

SEA ICE ACTIVITIES

Sea ice, completely protecting shores and the upper part of the shoreface against the hydromechanical influence of the sea in winter, accomplishes much work toward bottom erosion, and mobilisation and transportation of bottom sediments throughout the year.

Probably the most important kind of sea ice activities accomplishes frazil and anchor ice, which are formed during strong fall storms in super-cooled water with negative air temperature. Rising ice particles and aggregates bring bottom- and suspended sediments to the sea surface where they are incorporated into the new ice cover after the storm. In some winters the ice cover in parts of the Beaufort Sea carries as much as 1000 m^3/km^2 of sediments and the total amount of sediments in the ice cover along the Alaska coast can be an order of magnitude higher than the sediment input of all rivers draining into the same area (KEMPEMA et al. 1989, REIMNITZ et al. 1993). Drift of turbid ice transports sediments over very large distances. The role of frazil ice is not limited to uplifting of sediments to the ice cover. Frazil ice increases the turbidity of sea water during storms considerably, and therefore hydraulic transport of sediments by wind-driven currents is greatly increased.

Another important kind of sea ice activity is the sea-floor gouging by drift ice, which creates trenches with parallel flanking ridges to at least the shelf edge at 65 m (BARNES et al. 1984). Gouging bulldozes bottom sediments in the direction of ice drift. In the extremely ice-gouged Chukchi Sea near Point Barrow the amount of bottom sediments bulldozed across the 8-m isobath during a particular year is calculated as large as 1.5-2.0 m^3/m (REIMNITZ et al. 1990). Creation of trenches increases hydraulic roughness of the sea floor, favouring the transport of both suspended- and bedload. The role of sea ice in erosion and transportation of sediments is not exhausted with what is told above but could not be described completely in this short paper.

The major coastal depocenters along Arctic margins are river deltas, with their mode of construction and unique shape controlled by cryogenic processes. Even at the onset of summer, when large rivers start flowing, 2-m thick fast ice from the previous winter still covers the sea, strongly influencing the spreading of discharged waters and sediments. A 20-km-wide, <2-m-shallow platform surrounding large ice stressed deltas, makes them stand in strong contrast to delta-front profiles from non-Arctic areas and still requires an explanation. Seasonally the frost table here lies directly at the seafloor. Eight-m-deep craters forming from the drainage of river water through fast ice present the most severe, single design constraint for pipeline construction along Arctic margins.

FORMATION AND DEGRADATION OF GAS HYDRATES

The cryogenic processes of land-ocean interaction in the Arctic strongly influence the underground gas emission into the atmosphere. Perennially frozen, ice saturated sediments have very low permeability (ANANYAN et al. 1972, AGUIRRE-PUENTE & GRUSON 1983). Therefore the formation of permafrost preserves gases present in these deposits. As this takes place, the gases may stay in a free state or transform into hydrates in correspondence with new temperature-pressure conditions. The gas content in frozen deposits is being investigated intensively during recent years (YAKUSHEV 1989, ARE & MAMZELEV 1992, GRITSENKO & BONDAREV 1994, GUBIN & SAMARKIN 1996, RIVKINA et al. 1996, GALYAVICH et al. 1997, RIVKIN 1997, SKOROBOGATOV et al. 1998, ZIMOV et al. 1998). Research shows that in many areas the gas content exceeds the productivity of biological processes, both modern and those which developed during accumulation of deposits. The majority of investigators explain this fact with migration of hypogene gases (GLOTOV 1992, CRANSTON et al. 1994, ERMAKOV et al. 1995, KUZIN & YAKOLEV 1996, MONASTERSKY 1996). Therefore the formation of permafrost preserves upward fluxes of gas. Noteworthy is the fact that part of the gas is in the hydrate state in the upper <100 m, where geostatic pressure is less than needed for their existence (YAKUSHEV 1989, ERSHOV et al. 1990, RIVKINA et al. 1995, 1997, MELNIKOV et al. 1997).

The degradation of permafrost strongly increases permeability of sediments and creates conditions for resumption of free gas migration, decomposition of hydrates and emission of gases into the atmosphere. Permafrost may degrade not only due to climate warming, but also along the retreating Arctic shores.

On initiative of the U.S. Geological Survey, investigations of gas hydrate decomposition and emission of gases into the air along the retreating Arctic shores, and the influence of this process on the Earth climate warming were included in the World Ocean Agreement between the United States and the Soviet Union, which was signed in 1990. Nothing was done to fulfil this agreement, and the problem continues to exists. Data available suggest that emission of gases into the atmosphere due to permafrost degradation by climate warming and Arctic coastal retreat may dramatically favour the greenhouse effect development.

CONCLUSIONS

Most processes of Arctic Land-Ocean interaction are cryogenic. To these processes belong formation and degradation of shelf and coast permafrost with several accompanying processes, various kinds of sea ice activities, and gas hydrate formation and decomposition. The cryogenic processes play an important role in the evolution of Arctic environments. They are poorly understood and therefore often neglected. The goal of this paper is to turn attention of students of geodynamics on Arctic continental margins to the cryogenic processes. A short review of factual evidence available shows the complexity of Arctic Land-Ocean interactions and the existence of a vast field for future investigations needed for understanding of the evolution of Arctic environments.

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