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Shoreface of the Arctic seas – a natural laboratory for subsea permafrost dynamics

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ABSTRACT: Subsea permafrost on the Arctic shelf occupies some 13 million km^2, but is poorly understood. Mathematical modeling, based on the differential equation of heat conduction, is widely used for the compilation of predictive permafrost maps. Realistic geocryological conditions on the Arctic shelf cannot however be explained simply by heat conduction. Laboratory and field investigations show that heat convection and mass transfer play an important role in marine permafrost dynamics. Correspondingly, mathematical models are not yet developed, not only because of the complexity of the problem, but due to a limited understanding of subsea permafrost properties. Comprehensive experimental investigations of subsea permafrost are therefore required. The shoreface of erosional coasts are ideal locations for field investigations, as the distance from the retreating shore seaward represents a time scale, and degradation of the submerged permafrost may be traced from its inception.

1 INTRODUCTION

Subsea permafrost on the Arctic shelf occupies an area of 13 million km^2 (Zhigarev, 1997). Whilst rich in natural resources, limited research has been conducted on subsea permafrost, particularly in Eurasia. Large-scale geocryological investigations on the shelf are required for the successful utilisation of natural resources, for paleogeographical reconstructions and for the prediction of future environmental changes. Severe climate and high costs hamper these investigations however. Mathematical modelling of subsea permafrost dynamics is therefore widely used for the compilation of predictive permafrost maps (Molochushkin, 1970; Antipina et al., 1978; Fartyshev & Antipina, 1982; Solovyev et al., 1987; Osterkamp & Fei, 1993; Romanovsky et al., 1997; Danilov et al., 2000). These models are based on the differential equation of heat conduction and account for the dependence of the freezing point on the salinity of seawater and pore water solution. Results of this modelling cannot be verified in most regions because of the absence of boreholes on the shelf. Nevertheless, the limited drilling data available indicates that geocryological conditions on the shelf are highly variable and often cannot be explained by heat conduction alone (Iskandar et al., 1978; Swift et al., 1983; Are et al., 2000). Other processes of heat exchange and mass transfer apparently play an important role in subsea permafrost dynamics (Table 1).

Table 1. Processes of heat exchange and mass transfer.

Process	Cause
Heat exchange	
Conduction	Temperature gradient
Pore water convection	
A. Free	Density gradient
B. Forced	Pressure gradient caused by (1) Near bottom currents (2) Wave disturbance (3) Cryogenic pressure
Mass transfer	
Moisture migration	Temperature gradient
Ion diffusion	Salinity gradient
Free convection of ions	Salinity gradient
Forced convection of ions	Pore water freezing

2 HEAT EXCHANGE AND MASS TRANSFER PROCESSES OVERVIEW

2.1 *Free convection of the pore water*

Investigations of the shores of Vilyuy Hydroelectric power station water reservoir (East Siberia) showed that free convection may cause a fast thawing of perennially frozen coarse-fragmental rocks in the coastal zone (Are & Burlakov, 1984; Are, 1985) (Fig. 1). This type of heat exchange is of little importance in sands and fine-grained sediments however (Chudnovsky, 1954; Payne et al., 1988; Ershov, 1995).

2.2 *Forced convection of the pore water*

Sea water and pore water in bottom sediments represent a single hydraulic system. Near bottom currents therefore cause filtration of pore water in a downstream direction. Reciprocating movement of near bottom water caused by waves also initiates a corresponding movement of pore water (Fig. 2).

The influence of forced convection of this kind on the heat exchange between sea water and bottom sediments depends on a sediments permeability. In clays this is insignificant. In sediments with higher permeability the thermal role of filtration fluxes may be important.

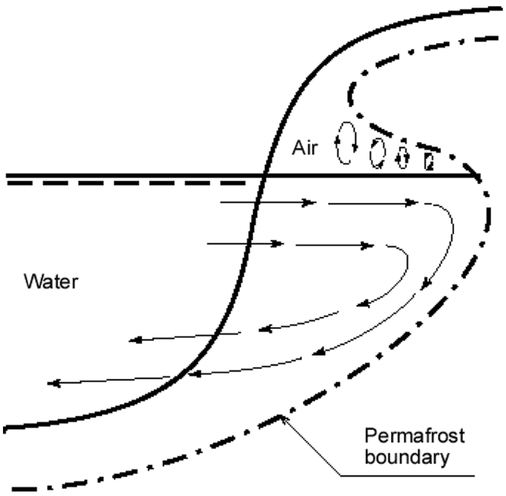

Figure 1. Free convection of water and air creates a talik in perennially frozen coarse-fragmental rocks outside of Vilyuy Hydroelectric power station reservoir (Are, 1985).

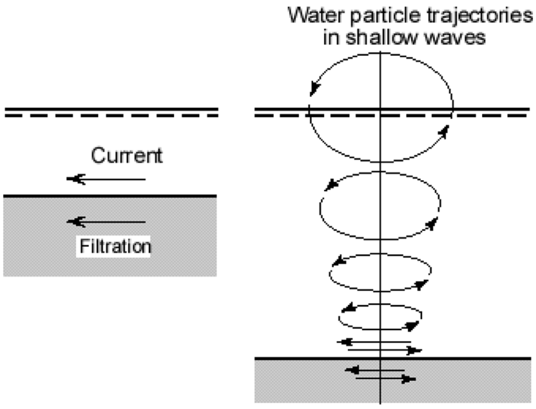

Figure 2. A schematic diagram of pore water forced convection.

For example, vast taliks are widespread beneath the river flood plains of northeast Siberia. These taliks develop because of intensive heat exchange between river underflow and perennially frozen sediments (Mikhaylov, 1993). Hydraulic conductivity of the flood plain deposits of these rivers averages several hundred m/day (Mikhailov, 1993), typical for gravel and coarse sand with pebbles (Priklonsky, 1955; Maslov, 1982).

According to Swift et al. (1983) and Harrison et al. (1983) the movement of pore water caused by sea waves may significantly influence the salt transport into coarse sands.

The sea ice cover adfreezes to the seabed during the winter in coastal shallows up to the 2 m isobath, which is situated up to 20 km from the coast. The bottom sediments under the adfrozen ice undergo seasonal freezing. In this process, the pore water pressure between the seasonally frozen layer and the underlying perennially frozen sediments rises due to volumetric expansion of the freezing water and water expulsion from the freezing zone. The differences in pore water pressure of the unfrozen sediments under the ice and the sediments outside the 2 m isobath initiates pore water filtration (forced convection) in an off-shore direction (Fig. 3).

2.3 *Moisture migration*

Pore moisture migration towards areas of low temperature is well known. This process creates an additional convective heat inflow to the freezing zone of sediments. In clays this comprises 20% of the total inflow and slows the freezing process (Ershov, 1995). In thawing sediments the moisture migrates to the freezing zone, accelerating thawing.

2.4 *Ion diffusion and free convection*

In saline sediments, migration of pore moisture is accompanied by the migration of salt ions, chemical elements and mineral components. As a consequence, the heat exchange and mass transfer processes become coupled. Comprehensive laboratory investigations of mass transfer between fresh sediments, saline water and ice by negative temperatures were carried out at the Geocryology department of Moscow University (Ershov, 1995). It was found that with a zero temperature gradient, the ions and unfrozen water films migrate into frozen sediments in the direction of lowered salinity. The ion migration takes place both by means of molecule diffusion and convection in unfrozen water films. The role of convection is therefore significant. The effective ion diffusion coefficient in clays averages 10^{-5}–10^{-7} cm^2/s. The intensity of migration increases with a reduction of sediment grain size and in clays is 2–5 times more intensive than in silts.

2.5 *The forced convection of ions*

The forced convection of ions manifests itself particularly strongly in coastal shallows in the area of sea ice adfreezing to the bottom (Fig. 3). Adfreezing does not take place simultaneously at all locations because of variations in seabed relief and irregular increases in ice thickness. Closed water spaces (pockets) therefore appear between the ice and the seabed. During continuing freezing of water the expulsion of ions from the freezing zone occurs, and as a result the water salinity in the pockets increases. For example, according to Molochushkin (1969), in March 1966 near Muostakh Island, Laptev Sea the water salinity in a closed pocket 180 m from the shore was 74.18‰. In the open sea outside the 2 m isobath it was only 19–20‰.

Similar processes occur during active layer freezing in the near shore zone. Their annual repetition leads (1) to a general increase of pore water salinity compared with

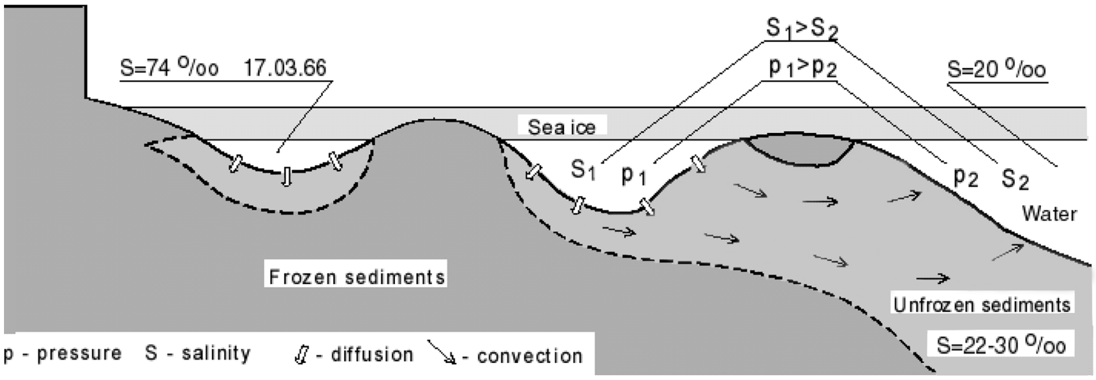

Figure 3. A schema of shoreface seasonal freezing, as observed on Muostakh Island, Laptev Sea in March 1966.

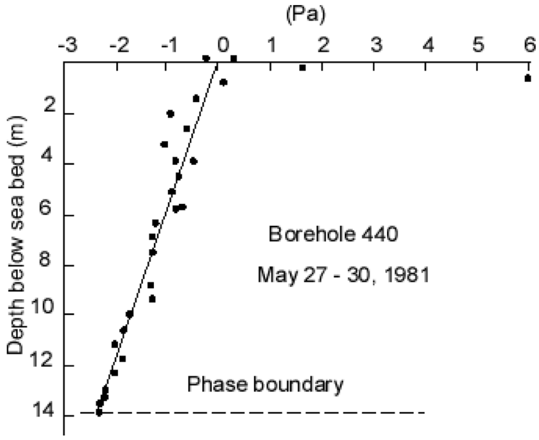

Figure 4. Measured pore water pressure minus calculated hydrostatic pressure, after Swift et al. (1983).

seawater salinity, and (2) to the formation of unfrozen cryopegs in bottom sediments (Iskandar et al., 1978).

Osterkamp and his colleagues have carried out several investigations of subsea permafrost dynamics in the Beaufort Sea during the last few decades. Their observations and *in situ* measurements convincingly testify that subsea permafrost is degrading at negative temperatures because of salt infiltration into fresh, frozen sediments (Iskandar et al., 1978; Osterkamp et al., 1989). The rate of degradation accounts for several cm/year, a figure too large to be the result of molecular diffusion of dissolved salts (Swift et al., 1983).

Measurements of pore water pressure indicate that it is lower than the calculated hydrostatic pressure. This difference between the measured and calculated pressure values increases linearly with depth. According to Swift et al. (1983) the loss of pressure with depth is caused by the free convection downwards of dissolved salts (Fig. 4).

3 DISCUSSION

Baker and Osterkamp (1988) visually observed the free convection of NaCl (sodium chloride) solution in a frozen medium sand, saturated with coloured fresh water in laboratory experiments. A layer of the same sand saturated with NaCl solution of 35‰ concentration was placed above the frozen sand sample. The frozen sand temperature during the experiment was −2°C, whilst the saline sand was at room temperature. Upward movement of pore water coloured fingers was recorded at 5.6 cm/hour up to 40-cm height. The hydraulic conductivity coefficient of sand in the unfrozen state was 17 m/day. Other experiments with downward freezing of saline sand showed that salt movement in the unfrozen zone is caused mainly by free convection, with the cryogenic expulsion from the freezing zone being unimportant (Baker et al., 1990).

The Laptev Sea bottom sediments are much more fine-grained compared to sediments from the Alaskan Beaufort Sea. The intensity of pore water convection should therefore be less in the Laptev Sea. Over 50 boreholes drilled around the Lyakhovskiye Islands in water depths of between 3–28 m and up to 32 km offshore reached ice-bonded permafrost at 2–28 m below the sea floor. Seven boreholes 22–77 m deep, drilled along a line crossing Sannikova Strait, did not reach permafrost (Fartyshev, 1993). During bilateral Russian-German ship-based expeditions in the Laptev Sea, carried out in 1993–2000, no ice was observed in the majority of several hundred sediment gravity cores. Only single ice crystals were present in some cores. The first ice bearing core of clay sediments 85 cm long was obtained in 1993 about 100 km from the Lena River delta at the 20 m isobath and 60 cm below the sea floor (Are et al., 2000). Drilling in the north-east part of the Laptev Sea in 2000 revealed ice-bonded permafrost in two boreholes at 6 and 9 m depth (Kassens et al., 2000; Bauch et al., 2002). Acoustic investigations on the same expedition suggest that the top 70 m of the Laptev Sea sediments are unfrozen or ice-bearing. Ice-bonded sediments only occur below this depth (Niessen et al., 2000; Drachev et al., 2002). The data cited indicates that the thawing of frozen bottom sediments at negative temperatures as a result of mass transfer processes may be considerable in the Laptev Sea.

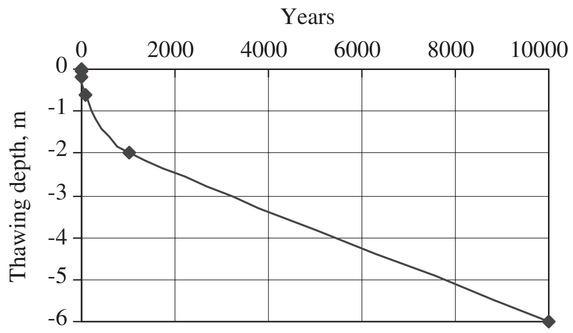

Figure 5. Fresh clayey subsea permafrost thawing under the negative temperature due to the action of molecule diffusion only, reproduced from data reported by Osterkamp (1975–1976).

Osterkamp (1975–1976) was probably the first to calculate the thawing rate of fresh sediments at negative temperatures due to the sole influence of salt molecule diffusion (Fig. 5). The diffusion coefficient of $1 \times 10^{-6}\,cm^2/s$, used in these calculations corresponds to clays (Ershov, 1995). The calculated thaw depth of 6 m during 10 ka provides an argument against the existence of ice-bonded permafrost on the floor of the Arctic seas, with the exception of areas of seabed erosion or localised sections with specific geocryological conditions.

According to Osterkamp (2001), poor knowledge of the physical and chemical processes occurring within subsea permafrost, in combination with a lack of factual data for the calibration of models, restricts the effective modelling of permafrost distribution on the shelf. Accurate predictions of its evolution are therefore limited. In general, the temperature field near a phase boundary at negative temperature should be anomalous, because a cooling mixture appears at the contact of freshwater ice and saline pore water. Under these conditions the thawing of ice can take place independent of the presence or absence of an external heat flux to the phase boundary. For example, if a contact of salt solution and ice occurs in a temperature field without a gradient, the ice will thaw as a consequence of the cooling of the surrounding sediment. The temperature of the sediment will therefore reduce, and opposing directed temperature gradients above and below the phase boundary will develop (Fig. 6). The main task is to evaluate the cooling effect *in situ* within the thawing zone and therefore its influence on the temperature field and subsea permafrost degradation.

The development of a mathematical model of subsea permafrost dynamics which takes into account all participating physical and chemical processes and boundary conditions is extremely difficult. Recent theoretical studies allow an understanding of some results from field investigations. These suggest various hypotheses, but certainly do not solve the problem completely.

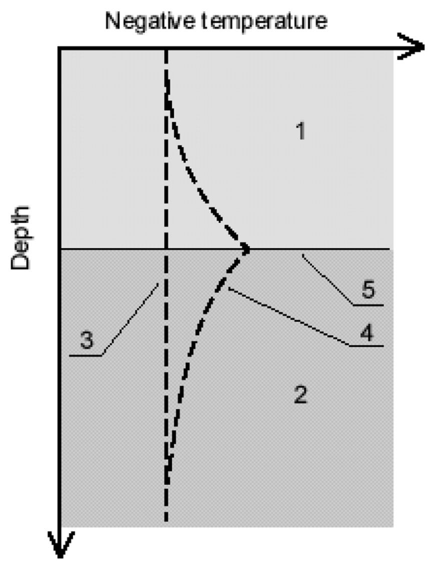

Figure 6. Sediment cooling during thawing by negative temperature. 1 – unfrozen saline sediments; 2 – frozen fresh sediments; 3 – initial temperature; 4 – temperature during thawing; 5 – phase boundary.

Difficulties arise not only because of the complexity of the problem but also as a consequence of an incomplete understanding of subsea permafrost properties and the physical and chemical processes of its evolution. It is therefore necessary to carry out comprehensive geocryological investigations *in situ*. The technical complexity and high cost of such investigations will require a united effort from the international permafrost community.

At the present time degradation is the dominant process influencing subsea permafrost dynamics. The retreating Arctic shoreface is the ideal location for investigations of this process. The last glacio-eustatic transgression of the sea ceased in the mid-Holocene and the relative sea level in several Arctic regions has remained stable during the last 5–6 ka. Prevailing rates of the Arctic lowland shore retreat currently range between 2 and 6 m/year. Based on this data, it can be estimated that the sea has inundated a strip of land at least 10–36 km wide during the second half of the Holocene. Coastal dynamics have been monitored during the last 50 years, with the highest mean annual retreat rate of 16 m/year being observed near Cape Halkett in the Beaufort Sea (Reimnitz et al., 1988), with a total retreat during this period of 800 m.

The position of the shore has been documented several times during the last 50 years in several sections of the Arctic coast. Over these sections the distance from the shore seaward up to several hundred meters represents a comparatively reliable time scale of inundation. It is therefore possible to study the evolution of subsea permafrost in time by means of investigations along the shoreface profile (Are, 1980; Are, 1988; Osterkamp et al., 1989). The results of these investigations will significantly improve our understanding of subsea permafrost dynamics. This knowledge can then be utilised for the calibration of existing mathematical models and for the development of new and more reliable models.

4 SUMMARY

Investigations of subsea permafrost dynamics are necessary to understand the history of the environment, to forecast its future evolution and to successfully utilise the natural resources of the Arctic shelf. Extremely complicated physical and chemical processes occur within subsea permafrost and govern its dynamics. The current understanding of these processes is insufficient to solve topical scientific and practical problems. In parallel with laboratory experiments, the *in situ* investigations of subsea permafrost dynamics are absolutely necessary. The best conditions for such investigations occur in the nearshore area of rapidly retreating coasts. The distance from the shore along these coasts represents a time scale, and degradation of permafrost may be observed from the initiation of this process.

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