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Destabilization of intrapermafrost gas hydrates by salt migration from cryopegs: experimental results

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Abstract. The migration of dissolved salts from natural saline solutions (cryopeg brines or seawater) into permafrost and its effect on the dissociation of intrapermafrost gas hydrates is studied in laboratory experiments. The experiments are applied to laboratory-made frozen sand samples saturated with methane hydrate and exposed to interaction with chemically different frozen saline solutions simulating cryopeg brines. The runs were performed at atmospheric pressure and a constant subzero temperature of approximately −6 °C, i.e., under the P-T conditions that can maintain self-preservation of metastable methane pore hydrates.

Variations in the NaCl/$MgCl_2$ concentration ratio in the solutions affect significantly the salt transport patterns and the salinity level critical for complete hydrate dissociation. Specifically, both salt migration and hydrate dissociation in frozen soils are faster at lower NaCl and higher $MgCl_2$ concentrations.

Phase transitions in the pore moisture of frozen hydrate-bearing sand samples interacting with frozen saline solutions are analyzed using low-field NMR relaxometry. According to the NMR data, the front of elevated liquid water content propagates along the salt flow direction, at a rate increasing with the mobility of salt ions in the series Na_2SO_4 – NaCl – $MgCl_2$.

The experimental results confirm that migration of natural saline solutions (e.g., cryopeg brines or seawater) driven by natural or production-related factors can destabilize intrapermafrost gas hydrates.

Keywords: Arctic, permafrost, natural gas hydrates, cryopegs, salt migration, gas hydrate dissociation, methane emission

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Introduction

The universally recognized enormous oil-and-gas potential of the Arctic region makes it highly attractive for exploration and production of hydrocarbons. However, petroleum production in the high latitudes is challenging due to the presence of permafrost. Permafrost is a complex multicomponent system that comprises an organic-mineral soil skeleton, ground ice, naturally cooled saline solutions, and accumulations of gas in free or hydrate forms. Gas hydrates are crystalline clathrate compounds mostly formed from methane and water molecules under specific pressure–temperature conditions (Makogon, 1974; Max, 2000). Gas hydrates are widespread in nature, and their ability to store up to 170 m³ of methane per 1 m³ of hydrate makes them a promising unconventional source of natural gas (Yakushev, 2009; Makogon, 2010). Gas hydrates may occur in both stable and metastable states, yet they are extremely sensitive to any environmental change (Chuvilin et al., 2018). The stability of gas hydrates depends on temperature, formation pressure, and effects of saline fluids, and their destabilization leads to intense gas emission as well as to changes in thermal and flow properties of the host sediments, and a loss of their mechanical strength (Chuvilin et al., 2019a, b; Shakhova et al., 2019; Dzyublo et al., 2020).

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Among other factors, gas-hydrate dissociation in permafrost can result from interaction with natural saline solutions, such as seawater or brines from cryopegs (Chuvilin et al., 2019b; Malakhova, 2020). Saline fluids, which trigger the dissociation process, migrated in the course of permafrost evolution and formation of subsea permafrost during Arctic-sea transgressions. Salt transport becomes especially critical when exploration and production drilling operations disturb cryopegs and induce seawater influx into permafrost.

Presently, the influence of salt migration on intrapermafrost gas hydrates remains poorly studied both theoretically and experimentally. The available experimental data on salt transport in frozen hydrate-bearing sediments (Chuvilin et al., 2019b, 2022a, 2023a, b) concern mainly pure salt solutions (e.g., NaCl, $MgCl_2$, KCl), whereas natural fluids contain diverse cations and anions. Cryopegs are lenses of highly saline pressurized negative-temperature brines in permafrost produced by cryogenic metamorphism, with a salinity up to 100 $g \cdot L^{-1}$ or higher. Cryopegs form as water-soluble salts are expelled from freezing sediments, become concentrated before the freezing front and entrapped within the frozen ground. The migration and accumulation of pore brines is promoted by repeated freezing–thawing cycles (Kiyashko, 2014; Sukhorukova, 2015; Streletskaya, 2016). Within permafrost, cryopegs occur at different depths as lenses of different sizes that lack hydraulic connection (Streletskaya, Leibman, 2002; Trofimov, Krasilova, 2017). According to the available data, cryopeg solutions in the Arctic, like seawater, exhibit a marine type major-ion chemistry (Table 1) are dominated by NaCl (up to 80–82 wt.%); magnesium salts rank second (up to 15 wt %), while the contents of potassium and calcium salts are usually limited to a few percent (Ivanova et al., 2008; Kiyashko, 2014; Shimanov et al., 2019; Aksenov, Gevorkyan, 2023).

At the time being, a wealth of experimental evidence is available on the interaction of pure salt solutions (NaCl) with frozen hydrate-bearing sediments (Chuvilin et al., 2022b, c; 2023b), but the effect of mixed saline fluids remains underexplored. There have been few attempts to incorporate this process into mathematical models (Malakhova, Eliseev, 2020; Kazakevich et al., 2022). Accordingly, special laboratory experiments are required to study how salt fluxes from cryopegs can destabilize intrapermafrost gas hydrates.

Methods

The experimental modeling of pore gas hydrate dissociation in frozen sediments associated with salt migration included several steps:

1) preparing laboratory-made samples saturated with methane hydrate in a high-pressure cell;

2) freezing hydrate-saturated samples in the high-pressure cell and bringing them into a metastable state by lowering the pressure to atmospheric while maintaining a fixed subzero temperature;

3) retrieval of frozen hydrate-saturated samples from the pressure cell;

4) juxtaposing the frozen samples with metastable pore methane hydrate against a frozen saline solution at a constant subzero temperature under atmospheric pressure (0.1 MPa).

The experiments were run in a sealed thermally insulated container, at a constant temperature of −6 °C (Figure 1) where the frozen hydrate-saturated samples physically contacted saline solutions under the conditions maintaining self-preservation of gas hydrate, at 0.1 MPa. The synthetic saline solutions of different compositions S-1 and S-2 (Table 2) simulated fluids from intrapermafrost cryopegs in the Arctic. The solutions mainly consisted of NaCl (up to 81%) and smaller amounts of other salts: magnesium and potassium chlorides, as well as magnesium and calcium sulfates. A solution of pure NaCl (hereafter S-3) was used for comparison.

The samples were compacted fine-grained silica sand (> 98% quartz), mostly of the 0.25–0.10 mm size fraction (80%), while silt and clay particles did not exceed 1%. The initial salinity did not exceed 0.01%; the specific active surface area was 0.6 g/m^2 (Table 3).

The cylindrical sand samples ($d = 3$ cm, $h = 9$ cm), with a density of $\rho = 1.85 \pm 0.02$ g/cm^3 and a porosity of ($\varphi = 39 \pm 1\%$), were saturated with water to the designed moisture content ($W = 12 \pm 1\%$) and then saturated with hydrate in 0.7 L a high-pressure cell (Figure 2), using cooled methane as a hydrate-forming gas. The high-pressure cell allowed gas pressures up to 8 MPa.

The prepared sand samples were frozen and uniformly saturated with methane hydrate to a content of 40–60% (Chuvilin, Gureva, 2009). Hydrate saturation began at a temperature about −6 °C under a flux of cooled methane pressurized to 6 MPa. The procedure prevented moisture redistribution during hydrate formation and thus ensured uniform distribution of gas hydrate throughout

NaCl	$MgCl_2$	$MgSO_4$	KCl	$CaSO_4$
77-82%	11-15%	4%	2%	5%

Table 1. Relative contents of different salts in cryopeg brines and seawater (in wt.%)

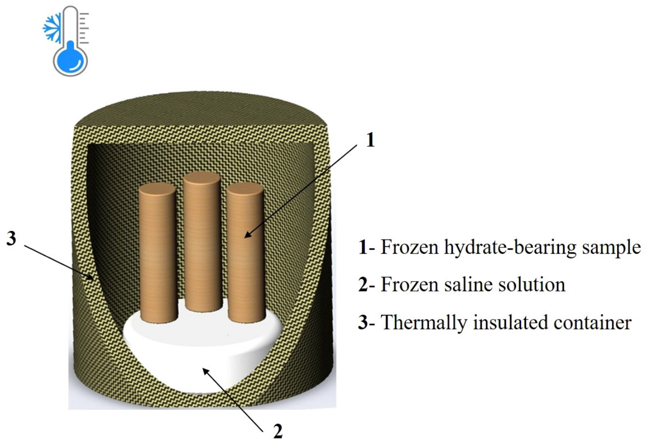

Figure 1. Experimental setup for interaction of frozen hydrate-bearing samples with a frozen saline solution at 0.1 MPa and −6 °C

Figure 2. High-pressure cell for hydrate saturation of samples (manufactured together by KryoLab LLC and FabLab & Machine Shop, Russia)

the sample. Further hydrate saturation was stimulated by cyclic freezing and thawing between −6 °C and +3 °C at methane pressures above the thermodynamic equilibrium. Overall, the hydrate-saturation process lasted at least two weeks.

Then the pressure cell with the frozen hydrate-saturated samples was cooled to −8 ± 1 °C to freeze out the residual moisture and the pressure was lowered to below equilibrium to set up the self-preservation regime for the pore hydrate. The pressure cell with the frozen samples containing metastable pore hydrate was then opened in a climate chamber. The resulting samples had a moisture content of W = 12 ± 1%, a density of ρ = 1.85 ± 0.02 g/cm³, a porosity of φ = 39 ± 1%, and a hydrate coefficient (fraction of pore water converted to hydrate) of $K_h \approx 0.47$. Atw the next step, the frozen hydrate-saturated sand samples were juxtaposed against a frozen 0.1 N saline solution. The experiments were run at atmospheric pressure and a constant temperature of −6 °C. The samples were removed at set time steps and sectioned at 0.8 ± 0.2 mm intervals. The maximum interaction time between the frozen hydrate-bearing sample and the frozen saline solution reached 6 h. Over that period, no more than 11% of the metastable pore hydrate dissociated.

The sectioned samples were analyzed to assess the distribution of moisture, gas content, hydrate coefficient, and salt content along the sample height. The amount of salt ions that diffused across the sample-solution interface was determined in water extracted from water-soluble salts, on a “MARK 603” conductivity meter (Russia). The calculated key parameters included hydrate coefficient, salt-ion flux density, and effective diffusion coefficient. The hydrate coefficient K_h was found using a coordination number of 5.9 as in (Davletshina and Chuvilin, 2020):

$$K_h = \frac{W_h}{W},$$

where W_h is the fraction of moisture converted to hydrate (relative to dry weight) and W is the initial moisture content (wt.%).

Solution	Salt content, wt.%				
	NaCl	$MgCl_2$	$MgSO_4$	KCl	$CaSO_4$
S-1	77	15	0	2	6
S-2	81	11	5	3	0

Table 2. Chemistry of saline solutions

Sample	Content of particles in each fraction, %						Mineralogy	Salinity, %
	1÷0.5	0.5÷0.25	0.25÷0.1	0.1÷0.05	0.05÷0.002	< 0.002		
Fine-grained sand	--	1.5	80.4	17.3	0.8	--	>98% quartz	0.01

Table 3. Main initial parameters of the samples

The flux of salt ions into the sample (*Js*, g/cm²·s) was calculated as

$$J_S = \frac{v}{S \cdot t},$$

where *S* is the cross-section area of the sample (cm²), *v* is the weight of salt (g), *t* is the interaction time (s).

The effective diffusion coefficient (D_{ef}, cm²/s) for salt migration is given by

$$D_{ef} = \frac{J_S}{gradC} \cdot 10^4,$$

where *Js* is the change in the salt-ion flux across the sample (g/cm²·s), and *gradC* is the concentration gradient (g/cm⁴).

Results

The experiments revealed the migration patterns of dissolved salts, as well as the ensuing dissociation of pore methane hydrate induced by the interaction of frozen hydrate-bearing samples with frozen saline solutions S-1 and S-2 compositionally similar to seawater. The diffusion of salt ions across the sample-solution interface caused almost no effect on moisture content, which remained within $W = 12 \pm 1.1\%$. The experimental results of this study were compared with our previous data (Chuvilin et al., 2022b) for frozen hydrate-bearing sand interacting with a frozen 100% NaCl solution (S-3). The interaction lasted from 75 to 295 minutes (Figure 3).

Salt ions penetrated progressively farther inward the samples with time (Figure 3a, solution S-2): the distance from the sample-solution contact increased from 2.7 cm for 75 minutes of interaction to 3.5 cm for 90 minutes, on to 5 cm for 130 minutes, and eventually 6.5 cm (almost all along the sample) at the end of the run (225 minutes). The salinity increased correspondingly and reached 0.83% at 225 min

The respective distances for solution S-1 (Figure 3b) increased in a similar way: 3.3 cm from the contact for 90 minutes of interaction, 5.1 cm for 145 minutes, and 6.1 cm for 295 minutes; the salinity at the end of the run, 295 minutes after its onset, was 0.75 %.

The amount of accumulated salt ions correlates with the distribution of methane hydrate over the samples. The hydrate content decreased systematically (Figure 4) away from the sample-solution interface relative to the initial $K_h = 47$ % prior to the sample-salt interaction.

The distribution of pore methane hydrate likewise depends on the duration of the sample-solution interaction. Specifically, gas hydrate dissociated completely at a distance of 1 cm from the contact for 75 minutes

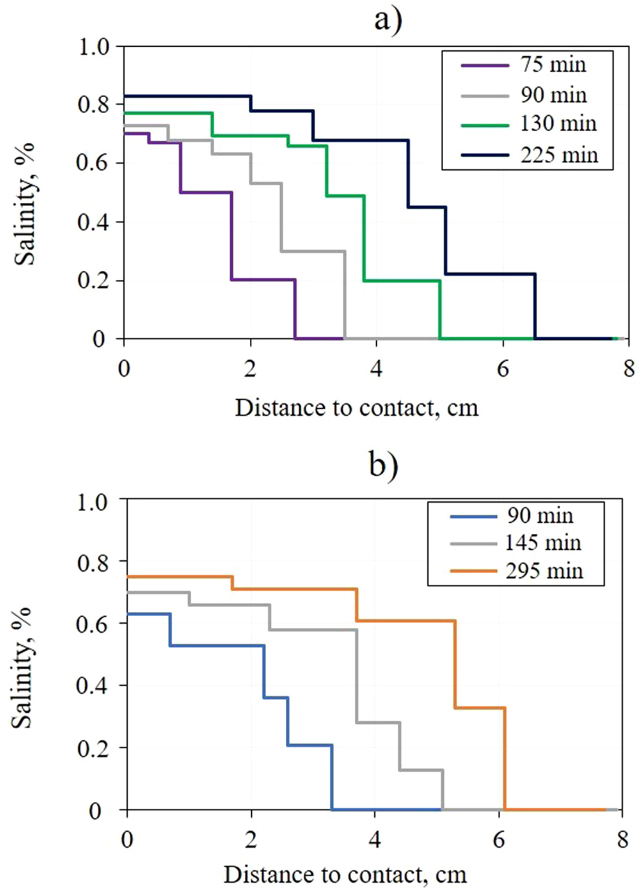

Figure 3. Time-dependent accumulation of salt ions along the hydrate-saturated sand samples ($W = 12 \pm 1.1\%$) interacting with frozen 0.1 N solutions a) S-2 and b) S-1 at 0.1 MPa and – 6 °C

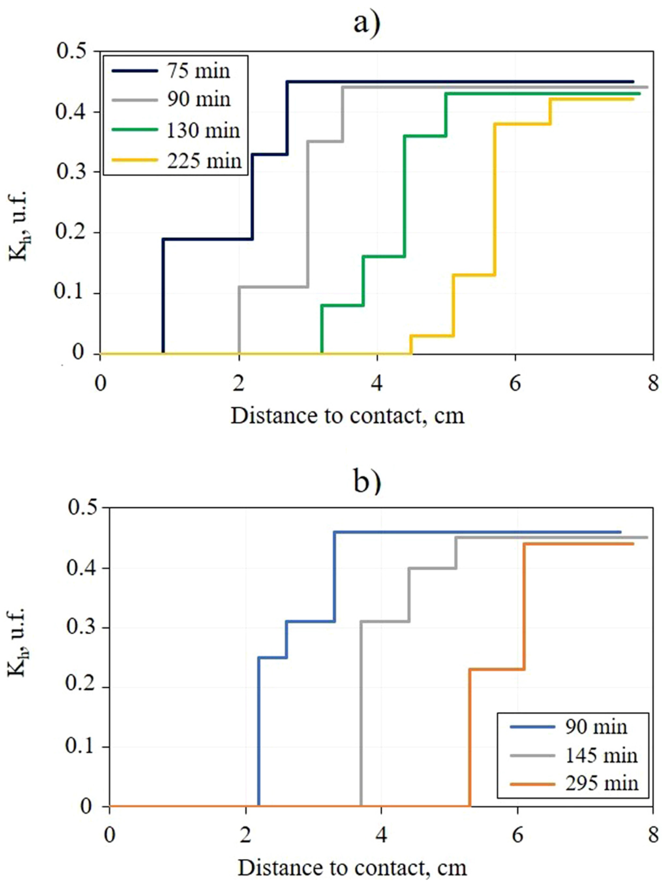

Figure 4. Time-dependent variations of hydrate coefficient K_h along a frozen hydrate-bearing sample ($W = 12 \pm 1.1\%$) interacting with frozen 0.1 N solutions a) S-2 and b) S-1 at 0.1 MPa and – 6 °C. Initial K_h before the run was 0.47

of interaction with solution S-2 (Figure 4a), and the distance increased with time to 2 cm in 90 minutes, 3.5 cm in 130 minutes, and 4.5 cm in 225 minutes (run end). The diffusion of salt ions reduced the hydrate percentage in the pore moisture (K_h) and formed a front of complete hydrate dissociation. The dissociation front propagated 2.2 cm far from the contact for 90 minutes of interaction with solution S-1 (Figure 4b), 3.7 cm for 145 minutes, and 5.3 cm for 295 minutes (run end).

The observed patterns of interaction between frozen sand and solutions compositionally similar to cryopeg fluids and seawater were compared with those for a pure NaCl solution (S-3). The patterns of salt diffusion into frozen hydrate-bearing sand at a constant negative temperature of –6 °C varied depending on chemistry of solutions S-1, S-2, and S-3 (Figure 5).

The rate of salt migration was the highest from solution S-1 (maximum distance of 6.5 cm from the contact) and the lowest from solution S-3 (4.3 cm); salt ions from solution S-2 penetrated to 6.2 cm from the contact (Figure 5a).

The faster transport of salt ions from solution S-1 into the sample led to faster hydrate dissociation (Figure 5b).

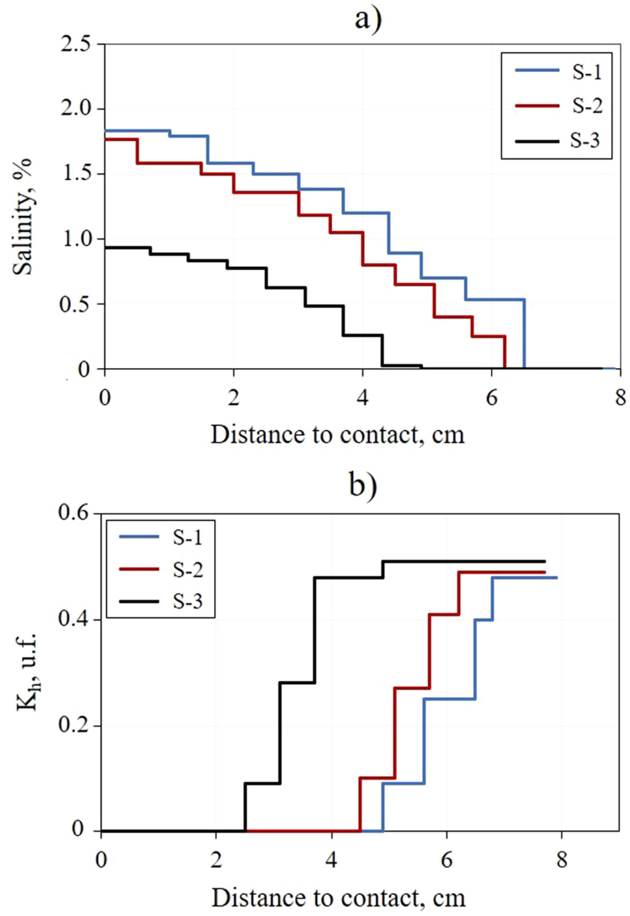

Figure 5. Effect of solution chemistry on salinity (a) and hydrate coefficient (b) patterns produced by interaction of frozen hydrate-bearing sand (W = 12±1.1%) with 0.1 N frozen saline solutions S-1, S-2, and S-3 for 3 hours, at 0.1 MPa and –6 °C

Depending on salt composition, the front of complete hydrate dissociation propagated to distances of 4.9 cm from the contact in the case of solution S-1, 4.5 cm for S-2, and only 2.5 cm for S-3 (Figure 5b).

The solution chemistry also had bearing on the critical salt concentration C_{cr} of the solutions required for complete hydrate dissociation for 3 hours of the sample-solution interaction (Table 4). The obtained critical salinity values were, respectively, 0.8% for S-3, 0.58% for S-2, and 0.47% for S-1.

Another parameter to correlate with solution chemistry is the density of ion flux into the samples (Figure 6).

The average density of ion flux from solution S-1 was notably higher than that from S-3 (Figure 6): $4.10 \cdot 10^{-9}$ g/(cm$^2 \cdot$s) against $2.97 \cdot 10^{-9}$ g/(cm$^2 \cdot$s), respectively, after 3 hours of interaction.

The experimental results were used to calculate coefficients of effective salt diffusion D_{ef} (Table 5), which showed a decrease from $4.0 \cdot 10^{-7}$ cm^2/s for S-1 to $3.8 \cdot 10^{-7}$ cm^2/s for S-2, and down to $1.7 \cdot 10^{-7}$ cm^2/s for S-3 (D_{ef} for S-1 was 2.3 times higher than for S-3), i.e., likewise depended on solution chemistry.

In general, the experiments revealed considerable variations in the rates of salt transport and hydrate dissociation in the frozen sand samples as a function of salt composition, especially the relative percentages of NaCl and $MgCl_2$. According to previous studies (Chuvilin et al., 2022b), the migration of salts becomes progressively faster in the series Na_2SO_4 – KCl – $CaCl_2$ – NaCl – $MgCl_2$ (Figure 7), while the critical salinity required for complete dissociation of pore gas hydrates increases correspondingly. Note that sulfate salts cause only minor influence on hydrate stability.

Processes in ice- and hydrate-bearing samples associated with salt transport: NMR constraints

Phase transitions in the ice-hydrate-water-gas-soil systems were studied using low-frequency low-field nuclear magnetic resonance (NMR) relaxometry on and Oxford Instruments Geospec 2-53 benchtop analyzer (UK). The Geospec 2-53 model, operated at a frequency of 2.28 MHz and a field of 0.05 T, features an additional set of gradient coils on each side of the magnet, which allow estimating the total volume of liquid pore water and plotting its 1D profile along the sample (Mukhametdinova et al., 2021).

The NMR measurements of gas- and hydrate-saturated samples were performed using a specially designed core holder made as a ~40 cm^3 high-pressure cell equipped with a gas pressure gage and a gas supply fitting (Bukhanov et al., 2022). The core holder is made of PEEK Zedex-324 highly durable plastic remarkable for its high resilience, resistance to a large range of temperatures (from –50 °C to +250 °C), low

Solution	Solution chemistry, %		C_{cr}, %
	NaCl	$MgCl_2$	
S-1	77	15	0,47
S-2	81	11	0,58
S-3	100	0	0,80

Table 4. Effect of solution chemistry (0.1 N solutions) on critical salt concentration sufficient for complete dissociation of pore gas hydrate in a frozen hydrate-bearing sample (W = 12 ± 1,1%), at–6 °C

Solution	Concentration of salt, %		D_{ef}, (cm^2/s)
	NaCl	$MgCl_2$	
S-1	77	15	$4.0 \cdot 10^{-7}$
S-2	81	11	$3.8 \cdot 10^{-7}$
S-3	100	0	$1.7 \cdot 10^{-7}$

Table 5. Effect of solution chemistry (0.1 N solutions) on diffusion of salt ions into frozen hydrate-bearing sample (W = 12 ± 1,1%), at 0.1 MPa and –6 °C

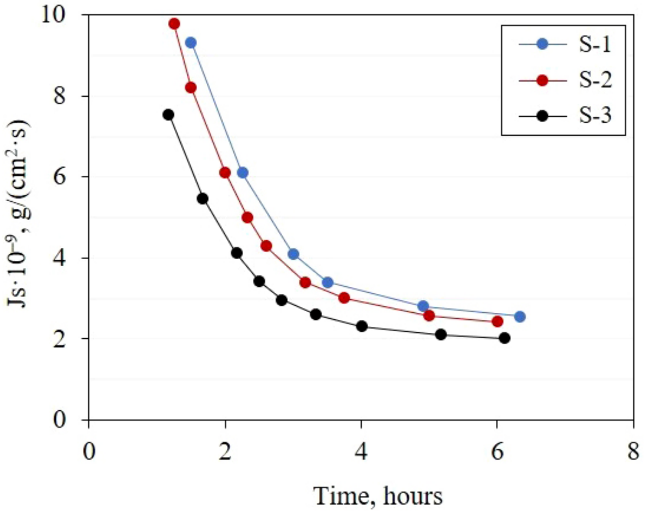

Figure 6. Effect of solution chemistry on average density of ion flux Js into a frozen hydrate-bearing sample (W = 12 ± 1.1%) from frozen 0.1 N saline solutions S-1, S-2, and S-3 at 0.1 MPa and –6 °C

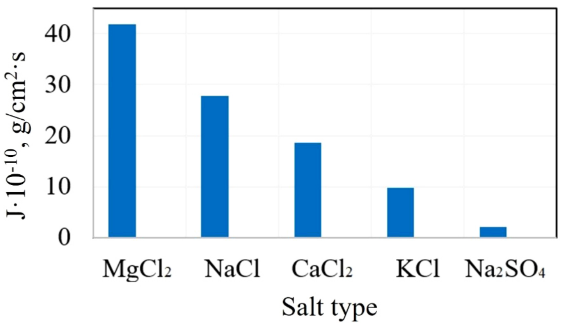

Figure 7. Effect of solution chemistry on the density of ion flux into a frozen hydrate-bearing sample (W = 12 ± 1.1%) from frozen 0.1 N saline solutions, 4 hours of interaction, 0.1 MPa, –6 °C (Chuvilin et al., 2022b)

thermal conductivity (~0.2 W/m·K), high strength, and noise much lower than the NMR signals. With these characteristics, the core holder allows analyzing the phase composition of pore moisture in porous media under a gas pressure up to 8.0 MPa and temperatures from –10°C to +25°C. The procedure of NMR measurements under the conditions of salt transport into ice- and hydrate-bearing samples was detailed in our previous publication (Bukhanov et al., 2024).

The NMR data revealed two features in the behavior of liquid pore water contents in frozen hydrate-bearing sand associated with diffusion of different salt ions into the samples: (i) the front of high liquid water contents propagated along the salt flux direction away from the sample-solution interface; (ii) the propagation rate depended on solution chemistry. The liquid water front advanced to distances of 3.1 cm from the interface for 1 hour (Figure 8a) and 4.4 cm for 2.5 hours (Figure 8b) of interaction with solution S-3. The propagation rate was about 25-30 % faster in the run with solution S-2, at the same pressure and temperature conditions: the front reached the opposite sample end 2.5 hours after the run onset (Figure 8b). Note that pore ice melted only partly in both runs, leaving the samples frozen all over the run duration despite the observed increase in the amount of liquid pore water under the effect of salt transport.

The observed profiles of liquid pore water contents are controlled by salt diffusion into sand, which causes partial melting of pore ice and induces dissociation of pore gas hydrate releasing non-equilibrium (supercooled but unfrozen) water. The faster propagation of the liquid water front in the case of solution S-2 compared to that for S-3 is due to higher mobility of some dissolved

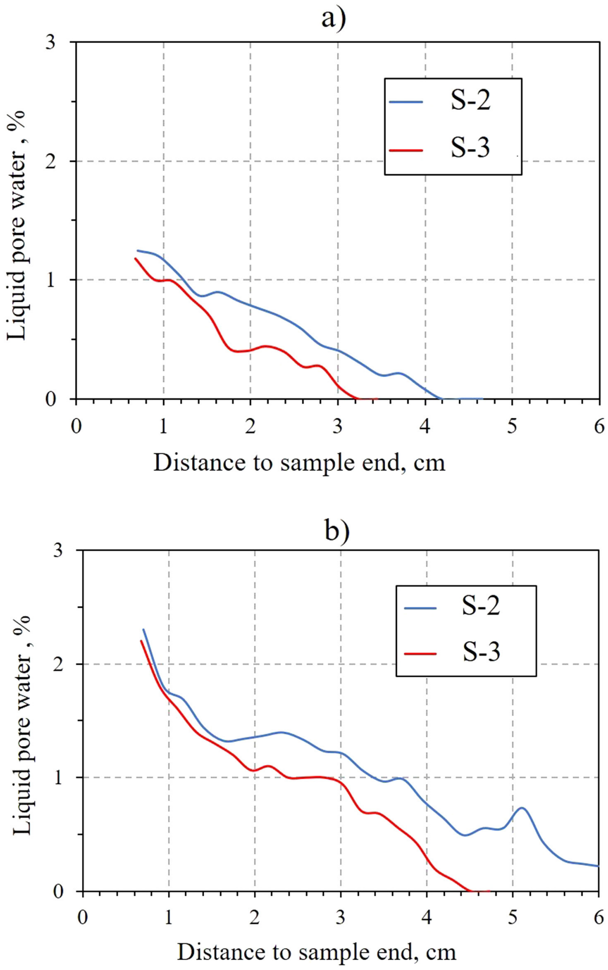

Figure 8. Distribution of liquid pore water contents along frozen hydrate-bearing samples interacting with frozen 0.1 N saline solutions S-2 and S-3 at –6°C and 0.1 MPa, 1 hour (a) and 2.5 hours (b) after the run onset

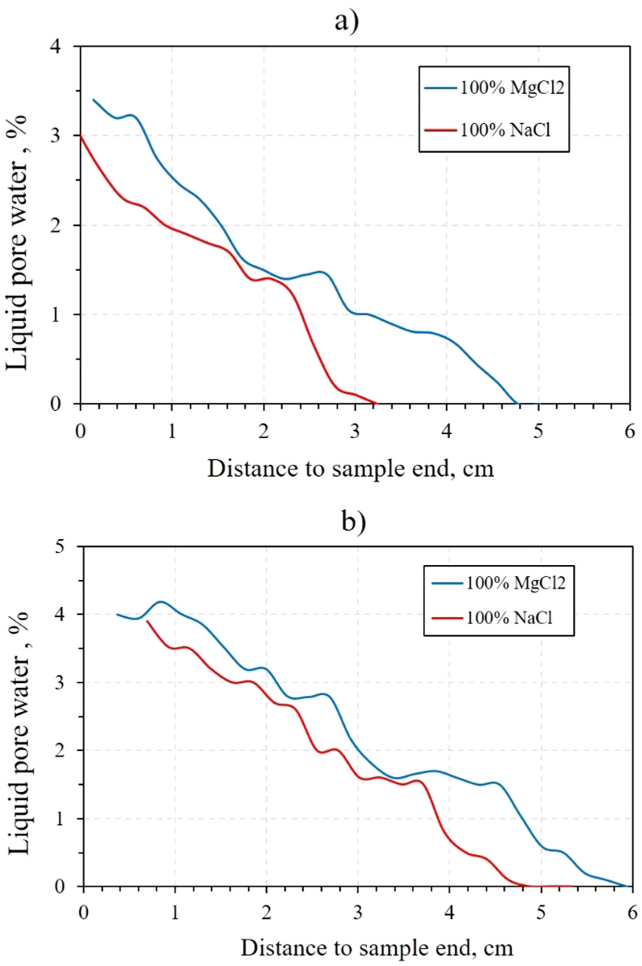

Figure 9. Distribution of liquid pore water along frozen hydrate-bearing samples interacting with frozen 0.1 N saline solutions S-2 and S-3 at –6°C and 0.1 MPa, 0.8 hour (a) and 2.2 hours (b) after the run onset

salts (especially $MgCl_2$). This inference is supported by experimental evidence that the front of high liquid water contents advanced 20-30 % faster in samples interacting with a 100% $MgCl_2$ solution than in the case of a100% NaCl solution, both 0.16 N (Figure 9).

The NMR data traced the propagation of the liquid water front (W_{liqud} = 1%) in the frozen hydrate-bearing samples receiving salt ions that migrated from different saline solutions (Figure 10). The estimated propagation rates differed depending on solution chemistry and were 26% higher in the case of the $MgCl_2$ solution and almost 3.5 times lower for the Na_2SO_4 solution relative to the respective value for the NaCl solution.

The NMR-derived pattern of liquid pore water front is consistent with the above data on migration of salt ions into the frozen hydrate-bearing samples at –6°C. The NMR data likewise show that the propagation rate of the liquid water front associated with salt transport increases in the series Na_2SO_4 – NaCl – $MgCl_2$.

Discussion

As demonstrated by the experimental results, the interaction of frozen hydrate-bearing sand samples with saline solutions simulating cryopeg fluids in permafrost can destabilize gas hydrates. Cryopegs occurring in the Arctic permafrost at depths from 20 m to 150 m (Shimanov et al., 2019) become channeled when disturbed by exploration or production drilling and thus can trigger dissociation of both intrapermafrost and subpermafrost gas hydrate accumulations. The data of laboratory modeling can be used to reconstruct the scenario of destabilization by salt migration from drilled cryopegs (Figure 11).

Gas hydrates in permafrost can be stable or metastable (Figure 11a) occurring in the zones of present and past hydrate stability, respectively. The metastable gas hydrates originated thousands to tens of thousands years ago under favorable thermodynamic conditions of the geological past, have survived till present due to

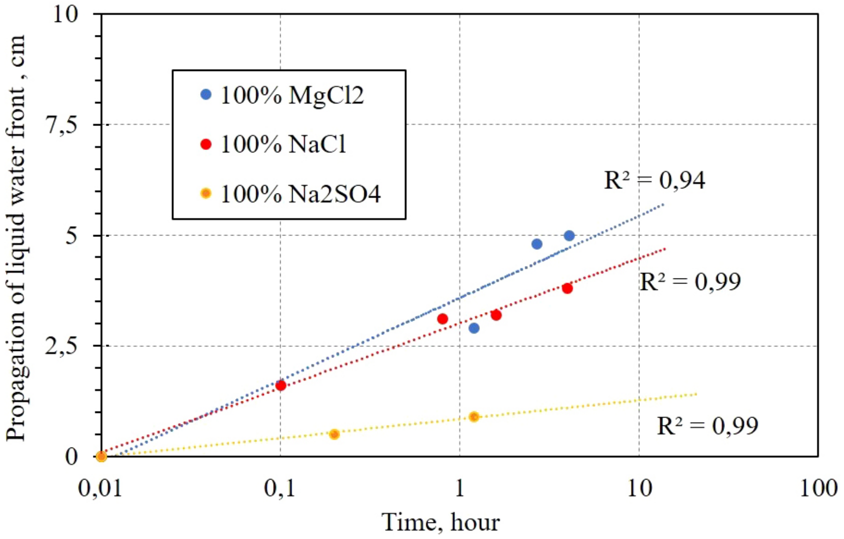

Figure 10. Propagation of the liquid pore water front (W_{liqud} = 1.0%) associated with salt transport into a frozen sand sample interacting with 0.1 N saline solutions of different compositions, at –6°C and 0.1 MPa

self-preservation (Chuvilin et al., 2018), and fell above the modern hydrate stability zone.

Drilling can perforate the isolated cryopeg lenses and let the brines, sometimes mixed with drilling mud, flow down the permafrost to reach the gas hydrate accumulations it stores (Figure 11b). The migration of dissolved salts into hydrate-bearing sediments destabilizes gas hydrates till complete dissociation as the solutions reach critical salinity. The critical salinity sufficient to break down metastable gas hydrates existing at pressures below the thermodynamic equilibrium is much lower (Chuvilin et al., 2023b) than for the stable hydrates pressurized to the above-equilibrium level (Figure 11c). On the other hand, salt migration into sediments bearing stable gas hydrates is much slower than into the zone of hydrate metastability (Figure 11c). Therefore, the metastable gas hydrates can dissociate completely before the partial dissociation of the stable hydrates. Methane released by dissociating gas hydrates either forms gas pockets in permeable permafrost or migrates upward along thaw aureoles around wells. Methane emission from wells under drilling or from the annular space behind producing wells was witnessed repeatedly in the oil and gas fields of northern West Siberia (Avetov, Yakushev, 2017; Avetov et al., 2018; Yakushev, 2019, 2023). Although the gas emission events disturb wellbore stability and pose emergency risks, these problems are commonly solved *ad hoc*, without clear theoretically grounded guidelines. Elaboration of workable regulations as to gas emission associated with salt migration and the ensuing dissociation of intrapermafrost gas hydrates is impossible without comprehensive research, with due regard for the geocryological structure of the area till the permafrost base.

Conclusions

Metastable and stable gas hydrates in the natural conditions of the Arctic permafrost are prone to dissociation under the effect of cryopeg brines or seawater. Dissolved salts can migrate into hydrate-bearing permafrost when isolated cryopeg lenses become perforated by drilling operations in oil and gas fields. The processes in frozen hydrate-bearing sand affected by salt fluxes from disturbed cryopegs were simulated in laboratory experiments using frozen saline solutions of different compositions (NaCl, $MgCl_2$, and Na_2SO_4 typical of permafrost fluids) at atmospheric pressure and a constant negative temperature of –6 °C.

The experiments showed that salt transport and the ensuing hydrate dissociation are largely controlled by solution chemistry, namely, relative contents of NaCl and $MgCl_2$: the migration and dissociation rates are higher at lower NaCl. The experimental results were used to estimate the average ion flux density, the effective diffusion coefficient, and the critical concentration of salts required for complete dissociation of pore gas hydrates. The density of ion flux and the diffusion coefficient are higher while the critical salinity is lower at lower percentages of NaCl and higher $MgCl_2$ in the solutions interacting with frozen hydrate-bearing samples.

Phase transitions in the pore moisture of frozen hydrate-bearing sand exposed to contact with saline solutions were studied by low-frequency low-field NMR relaxometry. The NMR data traced the propagation of liquid water front along the salt flow and the effect of solution chemistry on the propagation rate, which increased in the series Na_2SO_4 – NaCl – $MgCl_2$.

Thus, the dissolved salts migrating from disturbed intrapermafrost cryopegs during exploration and production in the Arctic oil and gas fields act as another destabilizing agent for gas hydrates in permafrost.

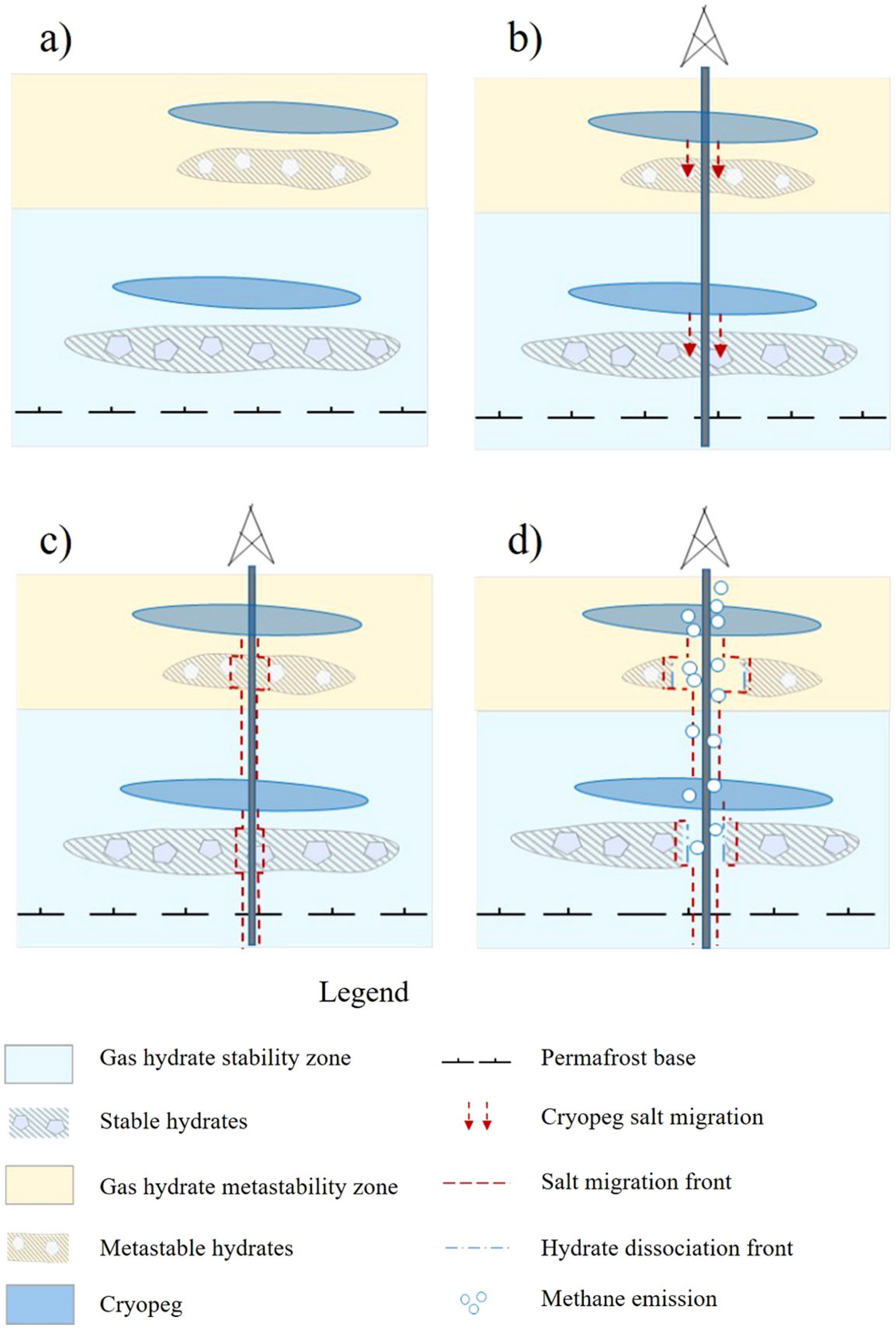

Figure 11. Intrapermafrost gas hydrates destabilized by saline solutions from drilled cryopegs

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IN RUSSIAN

Дестабилизация внутримерзлотных газогидратов при их взаимодействии с криопэгами. Результаты экспериментального моделирования

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В представленной работе на основе экспериментального моделирования рассмотрено влияние состава природных солевых растворов (криопэгов) на основные характеристики солепереноса и условия диссоциации поровых газогидратных образований в мерзлых породах. Исследования проводились на искусственно приготовленных мерзлых гидратонасыщенных песчаных грунтах, которые контактировали с замороженными солевыми растворами различного химического состава при атмосферном давлении и постоянной отрицательной температуре ~ –6 °C, т.е. в условиях проявления эффекта самоконсервации поровых гидратов метана.

В ходе экспериментального моделирования выявлено, что изменение соотношения содержания солей NaCl и $MgCl_2$ в контактном растворе значительно влияет на процессы солепереноса и критическую концентрацию, вызывающую диссоциацию порового гидрата метана. Так, с понижением содержания NaCl (и повышением $MgCl_2$ соответственно) в солевом растворе интенсивность солепереноса и процессов диссоциации газогидратов в мерзлом грунте увеличивается.

На основе метода ЯМР-релаксометрии проведена экспериментальная оценка фазовых превращений в мерзлых гидратосодержащих песчаных породах при их контакте с замороженными солевыми растворами. Полученные результаты указывают на закономерное продвижение во времени фронта повышенного содержания жидкой фазы воды в направлении миграционного потока соли. Как показывают ЯМР исследования, интенсивность продвижения фронта жидкой компоненты повышается в соответствии с увеличением миграционной способности ионов солей в ряду Na_2SO_4 – NaCl – $MgCl_2$.

Результаты экспериментального моделирования позволяют обосновать возможность дестабилизации внутримерзлотных газогидратных образований за счет перетоков и миграции различных природных солевых растворов (например, криопэгов или морской воды) вызванных как природными, так и техногенными причинами.

Ключевые слова: Арктика, многолетнемерзлые породы, природные газовые гидраты, криопэги, солеперенос, диссоциация газогидратов, эмиссия метана

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