geosciences

Editorial

Permafrost and Gas Hydrate Response to Ground Warming

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Citation: Chuvilin, E.; Sokolova, N. Permafrost and Gas Hydrate Response to Ground Warming. *Geosciences* **2023**, *13*, 281. https://doi.org/10.3390/geosciences13090281

Received: 3 August 2023
Accepted: 28 August 2023
Published: 18 September 2023

This Special Issue of *Geosciences* is a collection of fifteen original research and overview papers on the response of permafrost and gas hydrates to ground warming caused by natural climate trends and industrial loads. The issues considered include permafrost degradation and dissociation of gas hydrates induced by climate change; warming-related changes in the composition, structure, and properties of ice, frozen ground, and hydrate-bearing sediments; thermal interactions of engineering structures and facilities with frozen and hydrate-bearing foundation soils; gas emissions from permafrost in the Arctic shelf, etc.

Several of the contributions report on the results of laboratory [1–4] and numerical [5,6] experiments on the formation, stability, and dissociation of gas hydrates under various effects. The experiments in [1] investigated external and internal controls on dissociation and self-preservation of pore gas hydrates in sand-clay samples at negative temperatures. They were performed using special equipment for laboratory hydrate saturation at specified temperature and pressure ranges, and the saturation and dissociation rate of pore hydrates was estimated with the pressure–volume–temperature (PVT) analysis. The amount of residual unfrozen water in hydrate-bearing frozen samples during dissociation and subsequent self-preservation of gas hydrates was determined by means of nuclear magnetic resonance (NMR) measurements. The results show that pore gas hydrates in samples exposed to warming dissociate more rapidly and are worse preserved in cases of higher salinity and clay content at lower ice and gas saturation. Another conclusion is that pore gas hydrates dissociate more rapidly at non-equilibrium temperatures below the self-preservation range (about −50 °C) than at warmer negative temperatures that maintain self-preservation of partly dissociated gas hydrates. The laboratory measurements and calculations show that dissociation of pore gas hydrates in degrading permafrost under climate warming may release at least 16 m^3 of methane per 1 m^3 of rock, which poses risks to the Arctic infrastructure, especially at petroleum production sites.

Another experimental work [2] addressed the gas permeability of hydrate-bearing permafrost, with implications for the sequestration or production of natural greenhouse gases. It was found out that the formation and dissociation of pore gas hydrates change the permeability of frozen sand: samples with 40 to 60% initial ice saturation become at least twice less permeable as up to 40% of pore ice converts to hydrate. The processed experimental data provided the basis for a model simulating changes in the pore space of gas-saturated sediments, from the formation of gas hydrates to their dissociation under certain pressures and temperatures. The results may be useful in predicting the behavior of frozen hydrate-bearing gas reservoirs, as well as in the design of methods for decomposition of relict gas hydrates in permafrost.

Two papers by the same team of authors [3,4] focused on the migration of salt ions in hydrate-bearing frozen sediments. The experiments in [3] studied the effect of dissolved salts migrating from natural and industrial sources on the stability of intrapermafrost gas hydrates. The dissociation of pore gas hydrates in frozen samples in the presence of salt migration was shown to be sensitive to the ambient temperature and properties (concentration and composition) of saline solutions. The results can be used to model phase transitions in frozen hydrate-bearing rocks interacting with saline fluids in stable and metastable conditions, as well as to obtain an empirical temperature dependence of critical salinity required for complete dissociation of metastable pore gas hydrates.

The other experimental study [4] simulated the effect of fluid–rock salt migration on the dissociation of pore gas hydrates in permafrost interacting with saline fluids and related temperature effects. The modeling reproduced conditions typical of permafrost interacting with seawater (–6 °C and NaCl salinity) and showed that more saline hydrate-bearing rocks are prone to phase transitions of pore moisture and hydrate dissociation. In this case, the hydrate-bearing rocks cool down faster than their hydrate-free counterparts, with other conditions being the same, and require more time to recover the initial temperature, while the cooling effect is stronger at higher salt concentrations which increases the dissociation rate. The experimental results were used to model phase changes in the pore space associated with salt transport with implications for the causes of temperature changes.

The authors of [5] suggest a generalized model for gas release from frozen sediments containing gas-bearing ice and metastable pore gas hydrates under geodynamically caused decompression. The model uses the geothermal problem of gas spill over the horizontal reservoir top upon dissociation of metastable gas hydrate into gas and ice. The problem formulation was based on qualitative and quantitative characteristics of the processes depending on different parameters. The model is the extreme case of the previously published model [6], which provides an approximate analytical solution in a convenient self-similar formulation and ensures high accuracy at relatively high latent gas pressure in hydrates ≥ 1.1.

In paper [7], methane flow through porous materials with possible subsequent explosive emissions at a pore pressure exceeding the overburden pressure is simulated in physical and mathematical models. Gas blowout may occur when the increased flow of methane releases upon dissociation of buried gas hydrates through mechanically weak soft sediments. Both physical and mathematical models, with the applied assumptions, yield first-approximation solutions, and further work is required including the use of materials with different properties and system parameters in laboratory experiments and improvements to the mathematical model. However, even quite a simple problem formulation has demonstrated the possibility that the presumable methane emission mechanism is caused by an increased flow rate of gas released by dissociating gas hydrates from degrading shallow permafrost, as in the case of the Arctic permafrost.

Three papers [8–10] consider climate-induced changes in composition and properties in warming permafrost [8], which is critical for production operations [9,10]. The behavior of unfrozen pore water contents in the Arctic permafrost [8] is important as the latter may change considerably its mechanic, thermal, and other physical properties under ongoing warming. The authors [8] provide a historic background and a classification of methods for determining the phase composition of pore moisture and describe a new method based on water potential measurements. The water potential method was applied to estimate the amount of unfrozen pore water in typical samples from West Siberia and to study its sensitivity to particle size distribution, salinity, and organic carbon contents. The obtained patterns of temperature-dependent contents of unfrozen liquid water in shallow permafrost for the case of a typical permafrost area in the Yamal Peninsula provide a reference for predicting the permafrost response to climate warming.

Two other papers [9,10] investigate interactions of wells and piles with permafrost at petroleum production sites in the present climate conditions. In the first, the thermal interaction of a gas-producing well with ice-rich permafrost containing relict gas hydrates is modeled [9] in Ansys Fluent using the enthalpy formulation of the Stephan problem. The thermal parameters of permafrost are chosen with reference to laboratory- and field-experimental evidence from the Bovanenkovo gas-condensate field in the Yamal Peninsula. The modeling showed that methane emission upon dissociation of gas hydrates caused by permafrost thawing around wells can reach 400,000–500,000 m^3 of methane for thirty years of gas production from wells with non-insulated tubing. Meanwhile, heat insulation of tubing will keep the permafrost frozen over the whole well lifespan and prevent its degradation, as well as the ensuing dissociation of intrapermafrost gas hydrates and methane emission.

The other paper [10] possesses valuable practical results as it presents a new method to protect overdriven and bored precast piles from frost-heaving effects in the Arctic region caused by climate warming. It is suggested to insulate the piles with the OSPT Reline polymer heat-shrinkable jacket designed at the Mayak Plant for Polymer Technologies (Ozersk, Chelyabinsk region, Urals, Russia). The jacket can be factory-mounted or the piles can be coated in the field immediately before use. The interaction of heaving soil with a pile covered with the Reline jacket was modeled in the laboratory to estimate the uplift force and the related shear strength of frozen soil along the soil–pile adfreeze surface. The experiments were applied to silty sand and silty clay soils, which are widespread in the Arctic region, and cement–sand mortar, at temperatures −6 to −1 °C selected according to predicted warming scenarios. The decrease in the uplift force and its sensitivity to temperature are controlled by changes in the roughness of protected pile surfaces, soil particle sizes, presence or absence of unfrozen pore water, and temperature dependence of the total moisture content at the account of unfrozen pore water. Frost-heave uplift forces on Reline-protected piles are 52% to 85% lower than on uncovered steel piles, depending on soil type and temperature. Thus, the new insulation material can ensure strong durable protection of pile basements against heaving-related damage in the conditions of ongoing permafrost degradation.

Three contributions [11–13] report geophysical evidence of the permafrost structure and gas hydrate deposits. Geophysical surveys can image permafrost to its base, with vertical permeable zones, taliks, gas pockets, and accumulations of gas hydrates. The authors of [11] sketch the history of the permafrost in northern West Siberia and suggest its geological model to a depth of 500 m as a possible basis for further modeling. The geophysical surveys applicable to resolve permafrost features include synthetic seismograms, electric resistivity tomography (ERT), and transient electromagnetic (TEM) soundings. The TEM survey is especially efficient in this respect, in combination with ERT and seismic survey, though the choice of methods in each specific case depends on economic viability and field conditions.

Echo sounding is presented in [12] as a workable tool for estimating the sea bottom temperature in the East Siberian Shelf (Anadyr Gulf and shelves of the East Siberian and Laptev Seas), which is presumed to accommodate more than 80% of the world's predicted subsea permafrost and a large portion of related gas hydrates. Gas emissions from the subsea permafrost are controlled by its current thermal state which, in its turn, depends on environmental factors. In addition to the hardly feasible and sporadic direct measurements, the thermal state of subsea permafrost and phase transitions of its pore moisture can be estimated remotely by echo sounding using on-board sonar systems. This possibility has been proven by the reported field, laboratory, and theoretical data. The revealed correlation between the duration of seabed acoustic response (echo duration, Δ) and the temperature of shallow-marine bottom sediments provides the basis for high-frequency acoustic thermometry. The method is advantageous over the classical surveys that use source-receiver traveltimes as it does not require logging and thus yields immediate results without waiting for thermodynamic equilibration between the sensors and the ambient material. In all cases, the temperature estimation should begin with relating empirically the echo duration and the average sediment temperature within the target temperature range. Therefore, high-frequency acoustic thermometry has several applications: fast contouring of low-temperature zones; remote measurements of seabed surface temperature; estimating the thickness of frozen sediments near the bottom; contouring zones of gas hydrate stability in the Arctic shelf.

Another paper in this thread [13] deals with single-beam sonar measurements of methane emissions from the East Siberian Arctic shelf on the extension of Siberian tundra flooded during the Holocene transgression 7 to 15 kyr ago. This is an efficient tool for the mapping of seabed methane fluxes and monitoring of Arctic seabed permafrost seepage to detect unfrozen zones where intra- and sub-permafrost methane hydrate can lose stability. The sonar-based quantifying of methane bubble fluxes is challenging and can scarcely be modeled in the laboratory. The authors suggest an approach that combines theoretical calculations, laboratory experiments, and field observations to constrain the shape and size of bubbles, as well as the rate of their ascent, gas composition, water temperature, etc. The sonar is calibrated in the fast ice zone in order to relate the backscattering acoustic signal and the flux in rising methane bubbles in response to insonification, and the results are used to estimate natural methane fluxes.

Two more papers [14,15] discuss models of gas emission in the Arctic. The model of [14] explains explosive gas emissions from shallow permafrost with formation of craters, which is possible at a certain combination of cryological and geological conditions. These conditions are however restricted currently to a few areas in northern West Siberia, and the blowouts of this kind are uncommon in other areas of Arctic Eurasia and North America. Explosive gas emission is modeled for the case of the Yamal Peninsula, with regard to high gas contents in shallow permafrost which encloses ground ice, unfrozen intra-permafrost and sub-permafrost saline lenses (cryopegs), and hydrocarbon accumulations with related ascending gas–water fluids.

The other model [15] simulates geodynamic triggers of gas hydrate dissociation, methane emission, and breakup of Arctic and Antarctic ice sheets associated with tectonic wave deformation from nearby large earthquakes. Waves induced by lithospheric deformation processes can travel thousands of kilometers at ~100 km/yr and produce additional stress which can appear in the Arctic and Antarctic regions a few decades after large seismic events. The strain waves from earthquakes in subduction zones can affect gas hydrates and trigger methane emissions in Antarctica in the same way as in the Arctic shelf. In West Antarctica, this stress reduces the ice–rock cohesion and lets ice slide down into the sea, with the ensuing faulting, decompression of hydrate-bearing sub-ice rocks, dissociation of metastable gas hydrates, methane emissions, and warming in the southern polar areas. The suggested geodynamic model does not undermine the ideas of ice waning under the effect of warm sea currents, air flows, and related processes, but it predicts a further degradation in ice sheets and warming in Antarctica due to the frequency of large earthquakes in the southern Pacific that have increased in recent decades.

The model of gas emission in the Arctic shelf in [16] invokes Late Mesozoic-Cenozoic geodynamic conditions for the accumulation of inorganic methane. Abiogenic generation of hydrocarbons is possible by carbon transport from subduction zones to rifts and by serpentinization of rift ultramafic rocks, which is the case for the Laptev Sea and Gakkel Ridge areas. Most of abiotic hydrocarbon gases are released into water and air, while their amount in the lithosphere is too small to create large oil or gas accumulations. However, some gases (mainly methane) are buried in bottom sediments and become sequestered in gas hydrates forming large gas reservoirs. The possible destruction of such gas hydrate deposits can contribute to methane fluxes of mixed origin into the cold East Arctic seas. The study is mostly theoretical while the suggested mechanism of multi-stage cyclic transformations and transport of carbon through crust and mantle requires further investigation in terms of the global carbon budget.

Acknowledgments: The Guest Editor is grateful to all authors for the valuable contributions to the Special Issue and to anonymous reviewers for thoughtful comments and suggestions that helped in improving the manuscripts. The excellent job by the editors and all the staff of the *Geoscience* department is especially appreciated.

Conflicts of Interest: The author declares no conflict of interest.

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