geosciences

Editorial

Gas Emission and Formation of Craters in the Arctic Permafrost Synopsis

Evgeny Chuvilin * and Natalia Sokolova

Skolkovo Innovation Center, Skolkovo Institute of Science and Technology, 30, Build. 1, Bolshoi Boulevard, 121205 Moscow, Russia; n.sokolova@skoltech.ru
* Correspondence: e.chuviline@skoltech.ru

This Special Issue of Geosciences is a collection of twelve research and overview papers devoted to shallow Arctic permafrost as a natural reservoir that stores large amounts of bound gas, mainly methane. The gas occurring in both coastal and shelf permafrost can emit into air and produce positive or negative landforms on the surface. The key problems of gas saturation, permeability, and emanation discussed in the papers are especially relevant in the context of greenhouse gases and related global warming. The authors consider the generation, migration, accumulation, and emission of natural gas in the Arctic coast and shelf permafrost, gas sources, and craters produced by explosive emission, as well as the role of climate change and permafrost evolution in the dissociation of gas hydrates and its consequences.

The Special Issue begins with an overview by Chuvilin et al. [1] of ample published evidence on gas emission in the Russian Arctic coast and shelves. The information is summarized in a table and a map. The table shows location, signatures, and possible sources of gas, with the respective references. The gas emission events can be conventionally divided into natural and man-caused. Among the natural events, special focus is made on emission from Arctic lakes, as well as on gas explosions with formation of craters in tundra. The man-caused emission is mostly associated with drilling of geotechnical, exploratory, or production boreholes deep into gas-saturated permafrost. The drilling-related emission events have particular features and long duration. The reported data provide convincing evidence for the effect of permafrost on gas emission (explosive or not) and for its relation with large oil and gas fields.

Other papers of the collection provide details on various aspects concerning gas emission from onshore and offshore permafrost in the Russian Arctic, mostly in the Arctic coast of West Siberia [2–9], which has been under active development lately. Specifically, the Yamal Peninsula is an especially rapidly developing densely populated area, with much infrastructure for petroleum production and transportation.

Oblogov et al. [2] report data on methane contents in the active layer and uppermost permafrost in the tundra landscapes of the western Yamal coast (Marre-Sale area), as well as on gas emission into the atmosphere. The considerations are illustrated with a detailed map of main landscapes and vegetation of the area. The active layer is especially rich in methane in wetlands (peat bogs, floodplains, ephemeral streams, and lakes that occupy about 45% of the tundra), and the CH_4 concentrations increase with depth. This fact confirms the diffusive mechanism of methane transport in the active layer and emission. The uppermost permafrost (transition zone below the present active layer base) may store five times more methane than the active layer, and thus may be a potential source of greenhouse gases that begin releasing since the very onset of permafrost degradation.

The emission of greenhouse gases (CO_2 and CH_4) in biogeochemical cycles, upon degradation of permafrost in the Yamal Peninsula, is a subject of the paper by Semenov et al. [3]. The paper focuses on the distribution and genesis of methane and dissolved organic matter (DOM) in ground ice samples. The emission of CO_2 and CH_4 from thawing permafrost

check for updates

Citation: Chuvilin, E.; Sokolova, N. Gas Emission and Formation of Craters in the Arctic Permafrost Synopsis. *Geosciences* **2022**, *12*, 46. https://doi.org/10.3390/geosciences12020046

Received: 30 December 2021
Accepted: 31 December 2021
Published: 18 January 2022

begins with the liberation of CH_4 entrapped in ice and the generation of CO_2 in DOM. According to laboratory data, the distribution of parameters in different biogeochemical media is controlled mainly by the conditions of ground ice formation. Thus, the distribution of selected parameters can be used to rank representative ground ice samples of different types, with implications for gas emission patterns. Tabular ground ice has a greater potential for the emission of greenhouse gases than ice wedges, due to the presence of entrapped methane, DOM, and dissolved inorganic nitrogen. The chemical compounds in ice wedges are strongly variable. Special analysis of results made it possible to estimate qualitatively the heterogeneity of cryogenic landscapes in terms of greenhouse gas emission and permafrost properties.

In addition to methane emission, which is more or less rapid and voluminous in different Arctic landscapes, people have witnessed lately a new, almost unpredictable, way of methane release from permafrost: explosive events with formation of giant craters on the surface [4–8].

The evolution of a gas emission crater (GEC) in the Erkuta-Yakha River valley, Yamal Peninsula, is discussed by Chuvilin et al. [4]. The crater was discovered and sampled in June 2017, and the samples of soil and ice from the crater walls were analyzed in laboratory. The formation of the crater was preceded by one or two years of heaving detectable in aerial photographs. The crater walls are cut by cracks partly healed with ice, this being evidence of stress buildup and partial release in a freezing talik that existed in the place of the future crater. The carbon isotope composition of the gas component in ground ice corresponds to biogenic methane, while the presence of ethane and propane indicate a possible contribution of deep gas. The contents of CO_2 exceeding those of CH_4 in some samples prompt to cryoconcentration, which commonly occurs when taliks freeze up from all sides. The model based on the results predicts a combined effect of deep-seated and shallow causes on the GEC formation, as follows: deep gas fluxes and evolution of an oxbow lake associated with the freezing of a closed talik, respectively. The model simulates the multistage crater evolution from geological prerequisites to formation of a new lake.

Another study by the same authors [5] continues the modeling of conditions for accumulation and explosive emission of gas from the Arctic permafrost. Several suggested models describe gas accumulation and pressure buildup in a freezing closed talik in shallow permafrost, which may be responsible for the explosive gas emission and the formation of craters. The gas accumulation and overpressure may follow different scenarios, and several scenarios may develop simultaneously within a single talik zone. Gas inputs into taliks may have several sources, as follows: microbially mediated recycling of organic matter, dissociation of intrapermafrost gas hydrates, and migration of subpermafrost and deep gases through permeable zones in deformed crust. These processes can accelerate when permafrost degrades from above as a result of climate warming. Cryoconcentration of gas leads to pore pressure increase in the freezing gas-saturated talik, which may cause ductile deformation of the overlying permafrost and surface heaving. Once the pore pressure in the freezing talik exceeds the permafrost yield strength, the gas-water-soil mixture may erupt explosively to produce a crater in the place of the heave. However, the critical gas pressure cannot exceed the equilibrium pressure of hydrate formation for the predominant gas, i.e., 2.0–2.5 MPa for methane in the considered case.

Two Arctic field campaigns of 2017–2018 aimed at another GEC feature in the Yamal Peninsula, in the Seyakha River valley, which was studied using drone photography, echo sounding, and radar survey [6]. Processed radar data made basis for a 3D digital elevation model (DEM) of the crater and shallow sediments in the area. The studies revealed an intrapermafrost uplift possibly associated with the formation of a gas chamber. Long-term monitoring of continuous gas emission (mainly biogenic methane) in 2017 through 2019, along with other data, led Bogoyavlensky et al. [6] to infer that the Seyakha pingo-like feature (PLF) is growing by a gas-dynamic mechanism and that gas may release in a volcanic-like eruption. Proceeding from their experience, the authors suggest the following recommendations for future field research in the Arctic: geodynamic processes and landscape change can be monitored using drone aerial imagery.

During the Arctic campaign of 2020, evidence on one more giant gas-emission crater (GEC) in the central Yamal Peninsula was collected about two months after its formation [7]. The crater is identified as C17 in the geoinformation system (GIS) "Arctic and World Ocean" created by the Oil and Gas Research Institute (Moscow). Interpretation of satellite images placed constraints on the probable origin time of the crater, within three weeks in the latest spring–earliest summer of 2020. Detailed examination and sampling became possible because the crater was still well preserved and almost dry. Bogoyavlensky et al. [7] report data on the permafrost structure around the crater and on the composition of soil ejected by the explosion. Drone aerial photographs of the crater interior allowed modeling it in 3D and imaged the crater walls, as well as a large cave penetrating into the ground ice near the crater bottom. The description of the new crater and the related caves in ground ice turned attention to the origin of the gas, its migration pathways, and accumulation in shallow permafrost. The total volume of ground and ice mobilized by the crater formation amounts to 10,000 m^3, including ~7500 m^3 of the near-bottom cave. These estimates provide reference for calculating the volume of gas emitted into air during catastrophic explosions.

GEC features in northern West Siberia (Yamal and Gydan Peninsulas) can be detected and mapped using satellite data [8]. Analysis of satellite images shows that 5% of the territory in both peninsulas has undergone changes in vegetation, landscapes, and/or surface waters between 1984 and 2017. With a special algorithm used to detect the changes, Zolkos et al. identified seven craters known from previous publications and three new features. Two out of the three newly discovered craters are geomorphically similar to several GECs known from vicinities of the Bovanenkovo gas field and are located not far from the field. The GEC formation poses risks to people and infrastructure but is hard to predict. Mitigating the potential hazard and better understanding the regional-scale variability of landscape responses to climate change in the Arctic permafrost areas require upgrading the detection methods. In this respect, the suggested approach is an important step forward toward the monitoring of crater formation. The method can be improved and automated on the basis of additional GEC monitoring data.

The paper by Yakushev [9] focuses on gas emission associated with production drilling in West Siberian gas fields (Bovanenkovo and Yamburg). The events of gas emission from permafrost within operated gas fields occur quite often at different distances from the wellhead, as a result of permafrost thawing around producing wells. The isotope and molecular compositions of gas samples from well vicinities indicate that the gas is of microbial origin and can come from uppermost permafrost. It is free or clathrate interstitial gas that becomes liberated from pores and rises toward the ground surface, making its way through thawing permafrost. Prolonged operation of wells increases the thaw radius and induces further emission of entrapped gas. Biogenic gas can release in the immediate vicinity of operated wells or at some distance away, till the thaw boundaries, while the emission of thermogenic gas from deep reservoirs is of limited amount and appears only around casing strings.

Three other papers [10–12] deal with natural gas seeps in the Arctic shelf.

Chernykh et al. [10] overview the existing approaches to echo sounding of methane bubble fluxes from the sea bottom into the water and suggest a new technique for quantitative evaluation of methane seepage from the cross section area of a back scattering CH4 bubble plume. The method was successfully tested in single- and multi-beam acoustic surveys of a large seep in the Laptev shelf. The gas flux estimates obtained with the new method are comparable to those inferred from calibration against an engineered gas plume. The method is applicable to fast remote estimation of methane seeps, while the echo sounding survey has been a widely used efficient tool for the mapping of methane fluxes and the monitoring of subsea Arctic permafrost seepage. Gas seeps detected in the East Siberian Arctic shelf may guide to zones of permafrost degradation and related destabilization of gas hydrates.

Matveeva et al. [11] simulated various effects on the evolution of permafrost and on the zone of gas hydrate stability in the Laptev Sea, for two scenarios. The scenarios, with different durations of frost season and the respective temperature shifts, were compared to estimate their influence on the permafrost-hydrate system and to predict the pattern of the latter. The model accounts for the latent heat of ice and hydrate formation, thermal insulation properties of gas hydrates, as well as the effect of these properties on the geometry of relict subsea permafrost and gas hydrate stability zone (GHSZ). Unlike the previous models, where the thermal properties of sediments were assumed to be constant or locally changing, the suggested model implies a gradual change of thermal properties with depth while the sediments remain in the same phase state and an abrupt change in the case of phase transition. The modeling shows that the presence of gas hydrates retards permafrost thawing and prolongs the conditions for hydrate stability. The applied simulation approach provided constraints on the maximum and minimum parameter values and possible ranges, though the real values may lie between the predicted extremes.

The last paper in the collection [12] gives the following new outlook of the Arctic climate change: abrupt warming excursions may have seismic triggers associated with strong deformation at the lithosphere boundary. Seismic effects propagating quite slowly along the Arctic shelf and adjacent areas may induce emission of interstitial methane entrapped in permafrost and mobilize metastable gas hydrate particles surrounded by ice films. The suggested mechanism stems from correlation between a series of large earthquakes in the Aleutian island arc, which occurred in the beginning and middle of the 20th century, and two warming excursions in 1920 and 1980. Lobkovsky [12] presents global maps of large earthquakes from 1891 to 2020 and a curve of air temperature anomalies for the past 120 years. The author [12] is far from claiming that the seismic triggers alone would be responsible for the observed Arctic climate change and, especially, the global warming. However, the geodynamic climate forcing, which may have bearing on abrupt climate oscillations in the 20th and 21st centuries, may constitute an additional element in the existing climate models. The Earth's climate system is complicated and should be described by integrated models including interacting chemical, physical, and atmospheric agents.

To conclude this brief synopsis, it is pertinent to note that the discussed ideas, approaches, and research methods concerning natural gas emission in the Arctic will be of interest for people engaged in the Arctic research, as well as for a large scientific community. The Special Issue has brought together experts in different fields, which is beneficial for sharing and spreading scientific information.

Author Contributions: All authors contributed equally to this article. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Russian Foundation for Basic Research (grant 19-55-51001), the Russian Science Foundation (grant 21-77-10074).

Acknowledgments: 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 improving the manuscripts. The excellent job by editors and all stuff of the Geoscience department is specially appreciated.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Chuvilin, E.; Ekimova, V.; Davletshina, D.; Sokolova, N.; Bukhanov, B. Evidence of Gas Emissions from Permafrost in the Russian Arctic. *Geosciences* **2020**, *10*, 383. [CrossRef]
2. Oblogov, G.; Vasiliev, A.; Streletskaya, I.; Zadorozhnaya, N.; Kuznetsova, A.; Kanevskiy, M.; Semenov, P. Methane Content and Emission in the Permafrost Landscapes of Western Yamal, Russian Arctic. *Geosciences* **2020**, *10*, 412. [CrossRef]
3. Semenov, P.; Pismeniuk, A.; Malyshev, S.; Leibman, M.; Streletskaya, I.; Shatrova, E.; Kizyakov, A.; Vanshtein, B. Methane and Dissolved Organic Matter in the Ground Ice Samples from Central Yamal: Implications to Biogeochemical Cycling and Greenhouse Gas Emission. *Geosciences* **2020**, *10*, 450. [CrossRef]

4. Chuvilin, E.; Stanilovskaya, J.; Titovsky, A.; Sinitsky, A.; Sokolova, N.; Bukhanov, B.; Spasennykh, M.; Cheremisin, A.; Grebenkin, S.; Davletshina, D.; et al. A Gas-Emission Crater in the Erkuta River Valley, Yamal Peninsula: Characteristics and Potential Formation Model. *Geosciences* **2020**, *10*, 170. [CrossRef]
5. Chuvilin, E.; Sokolova, N.; Davletshina, D.; Bukhanov, B.; Stanilovskaya, J.; Badetz, C.; Spasennykh, M. Conceptual Models of Gas Accumulation in the Shallow Permafrost of Northern West Siberia and Conditions for Explosive Gas Emissions. *Geosciences* **2020**, *10*, 195. [CrossRef]
6. Bogoyavlensky, V.; Bogoyavlensky, I.; Nikonov, R.; Kishankov, A. Complex of Geophysical Studies of the Seyakha Catastrophic Gas Blowout Crater on the Yamal Peninsula, Russian Arctic. *Geosciences* **2020**, *10*, 215. [CrossRef]
7. Bogoyavlensky, V.; Bogoyavlensky, I.; Nikonov, R.; Kargina, T.; Chuvilin, E.; Bukhanov, B.; Umnikov, A. New Catastrophic Gas Blowout and Giant Crater on the Yamal Peninsula in 2020: Results of the Expedition and Data Processing. *Geosciences* **2021**, *11*, 71. [CrossRef]
8. Zolkos, S.; Fiske, G.; Windholz, T.; Duran, G.; Yang, Z.; Olenchenko, V.; Faguet, A.; Natali, S.M. Detecting and Mapping Gas Emission Craters on the Yamal and Gydan Peninsulas, Western Siberia. *Geosciences* **2021**, *11*, 21. [CrossRef]
9. Yakushev, V. Natural Gas Liberations around Production Wells at Russian Arctic Gas Fields. *Geosciences* **2020**, *10*, 184. [CrossRef]
10. Chernykh, D.; Yusupov, V.; Salomatin, A.; Kosmach, D.; Shakhova, N.; Gershelis, N.; Konstantinov, A.; Grinko, A.; Chuvilin, E.; Dudarev, O.; et al. Sonar Estimation of Methane Bubble Flux from Thawing Subsea Permafrost: A Case Study from the Laptev Sea Shelf. *Geosciences* **2020**, *10*, 411. [CrossRef]
11. Matveeva, T.; Kaminsky, V.; Semenova, A.; Shchur, N. Factors Affecting the Formation and Evolution of Permafrost and Stability Zone of Gas Hydrates: Case Study of the Laptev Sea. *Geosciences* **2020**, *10*, 504. [CrossRef]
12. Lobkovsky, L. Seismogenic Triggering Mechanism of Gas Emission Activizations on the Arctic Shelf and Associated Phases of Abrupt Warming. *Geosciences* **2020**, *10*, 428. [CrossRef]