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HYDRATE FORMATION

GENETIC TYPES OF HYDROCARBON GASES IN THE PERMAFROST STRATA

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The existing data on origins of intrapermafrost hydrocarbon gases have been summarized, with identification of specific features of biochemical (microbial), catagenic (thermogenic) and coalbed (shale) types of the intrapermafrost gas hydrates. Additionally, a schematic representation of different types of intrapermafrost gases distribution in the Russian territory is provided.

Methane, permafrost strata, genesis of intrapermafrost gas

INTRODUCTION

Much attention from climate scientists, geographers and geologists has been given lately to identifying the origin of methane and its distribution in the perennially frozen strata (permafrost interval), specifically, in their near-surface layers. Given that the related objectives are associated mostly with the estimation of potential contribution to a greenhouse effect due to methane and other greenhouse gases (GHG) emissions from the perennially frozen ground as it experiences progressive thawing, most studies focus, primarily, on the processes of shallow biochemical (or marsh) gas release.

However, the data from deep drilling into permafrost strata in different Arctic regions, including sub-sea permafrost in the Arctic offshore areas, suggest different genesis of methane and other hydrocarbon gases trapped in them. The origin of gas not only largely determines the volumes of the intrapermafrost gas accumulations, but it also predicates a potential threat to the industrial development of the Arctic oil, gas and gas condensate deposits overlain by the permafrost.

Encountering occurrences of intrapermafrost gas or gas-hydrates while drilling have always caused local gas liberations of different intensity, often with disastrous consequences for the drilling rig. In this contexts, identification and systematization of various sources and genetic types of hydrocarbon gases in the permafrost interval appear a matter of practical importance.

BIOCHEMICAL (MARSH) GAS

In the middle of the 20thcentury, before the intensive development of oil and gas resources in the area of continuous permafrost, the latter was viewed by many researchers as gas-impermeable layers of sedimentary rocks with the pore space totally or partly filled with segregated ice. This, specifically, allowed to assume that the permafrost strata may serve as regional seals for oil and gas pools accumulated directly beneath the lower boundary of the permafrost [*Vozhov, 1984*]. An exception was made for the near-surface (within the limits of the seasonally thawed, or active layer) small concentrations of marsh gas (methane) in wetland areas. In many regions with the presence of continuous permafrost, flammable (combustible) gas releases were pronouncedly manifested, during drilling the uppermost layers of the perennially frozen strata, when shallow wells penetrated them [*Are, 1998*].

Generation of gas there, as well as in the areas without continuous permafrost, was earlier and is now associated with the processes of biochemical reworking of organic matter buried during the sediment accumulation. There have been numerous evidences of intermittent but intensive releases of shallow occurring biochemical gas onto the surface, while drilling into the naturally occurring gas pockets, experiencing freezing [*Anthony et al., 2010*].

However, analysis of the carbon isotopic composition of methane released while drilling deeper (500 m) wells in the permafrost areas (northern West Siberia, northern Canada), showed that biochemical methane has a much greater depth of occurrence, than the active layer thickness, or that of the layer of zero annual temperatures amplitude (Table 1).

Notably, distribution of biochemical methane was observed in the sections of the perennially frozen strata of both epigenetic and syngenetic type of permafrost aggradation. However, in some areas [*Kraev* *et al., 2013*] high concentrations of methane were documented only in the epigenetic permafrost layers, whereas it proved almost totally absent from the perennially frozen layers of syngenetic type.

Some studies have shown, that biochemical methane accumulates more extensively in the shallow active bayer, than in the perrennially frozen strata [*Rivkina et al., 1998; Brouchkov and Fukuda, 2002*]. Accumulations of biochemical methane often form beneath the canopy of the seasonal ice cover of lakes and deep marshes [*Anthony et al., 2010*]. This type of methane can occur both in dispersed state, and in the form of fairly large concentrations, particularly, during its conversion into the methane hydrate under the permafrost conditions [*Rivkin and Levantovskaya, 2002*].

Methane is widely distributed within the frozen sedimentary strata extending over large areas and presents by itself, on the one hand, a threat of sudden blowouts in drilling deep wells, and a potential local source of energy supply for small settlements located in the hinterland areas, away from the regional power supply systems, on the other hand [*Yakushev and Chuvilin, 2000*]. Furthermore, it has been viewed as a major greenhouse gas contributed to the atmosphere from the polar regions [*Walter et al., 2008; Wille et al., 2008*].

CATAGENETIC (THERMOGENIC) GAS

The possibility of existence of large natural gas occurrences in the permafrost interval has thus far been disputable. However, already the pioneering deep drilling operations deployed back in the 1940–1950s in the oil-and-gas bearing area on the Laptev Sea coast revealed, that oil and gas-containing layers were identifiable in the permafrost strata [*Kalinko, 1959*]. It has been also established, that the formations, predominantly, of Permian and Triassic age occurring in the permafrost are most likely to be oil and gas-bearing.

Gas seeps from these formations onto the day surface were justifiably attributed to the well-developed folded area and a significant tectonic fragmentation of the sedimentary cover. Seepages of crude oil and natural gas were confined to sandstones, at times saturated with oil, whereas gas seeps alone were detectable on the day surface (mainly, in shallow lakes), and in the exploration wells.

In the Anabar-Khatanga interfluve area, gas shows from Middle and Upper Triassic tuffites and sandstones at depths of 70–120 m were reported from wells R-41 and K-426. Based on the results of testing the 112–113 m interval of well R-41, it was established that the gas flow rates can be appreciable, reaching 11 500 m^3/day. Alternatively, when the formation was tested by well K-426 at a depth of 95 m, the estimated gas flow rate was not greater than 120 m^3/day [*Kalinko, 1959*]. It stands to reason, that it's not biochemical, but catagenetic gas that is emplaced next to oil.

Table 1. **Carbon isotopic composition of methane in intrapermafrost gas in northern West Siberia and in Canada**

Well No.	Age of sediments	Depth of gas release, m	$\delta^{13}C$, ‰
The Mackenzie Delta [*Dallimore and Collett, 1995*]			
92GSCTaglu	Neogene	57.0	–89.9
	Neogene	119.4	–78.8
	Neogene	167.5	–79.9
	Neogene	326.0	–78.0
	Neogene	354.0	–79.8
Yamal Peninsula, Bovanenkovo OGC field [*Yakushev and Chuvilin, 2000*]			
51-R-1	Qm_3	28–33	–73.9
51-R-1	Qm_2	59–64	–74.6
52-R-2	Qm_2	114–120	–70.4

The occurrences are confined to the sandstone intervals with fairly good reservoir properties, i.e. the perennial freezing proceeded in conventional oil and gas-bearing deposits. The latter, having formed in the previous geological epochs along with the source rock formations were subsequently subject to multi-year epigenetic freezing. In this case, the accumulations with complex composition of hydrocarbons can be featured by the processes of heavy hydrocarbon precipitating into liquid phase, while the gas phase becomes lighter in composition, with methane with small admixture of its homologues being a major component. The processes of hydrate formation also take place here. Another mechanism for catagenetic gas appearing in the permafrost strata is its migration through permeable zones (faults) or lithological windows. *F.E. Are* [*1998*] introduced the following possible scenario for deep gases emission into the atmosphere. Prior to the formation of the cryogenic zone, deep-buried gas occurrences discharged locally into the hydro- and atmosphere through the subvertical fractured zones and the overlying unconsolidated Quaternary sediments.

Given that the permafrost aggradation precluded upward migration of gas, the voids formed in the perennially frozen ground were gradually filled with free-gas or gas-hydrate. These cavities will concentrate mainly along the former discharge areas, for example, in the conjugate fault and talik zones.

Such inferred mechanism of hydrocarbon migration to the permafrost interval from the underlying oil-gas-condensate deposits appears by far possible. On Alaska's North Slope, in the areas of the Kuparuk River and Prudhoe Bay oil fields, where dedicated exploration works for terrestrial hydrate-saturated deposits were carried out, at least two major deep faults are known, which are likely to serve as conduits for the upward migration of hydrocarbons to the gas hydrate stability zone (GHSZ) and into the permafrost strata. According to the isotope analysis, gases derived from the chydrate-bearing layers contain both biochemical and deep catagenetic gas in their composition. Catagenetic gas from the gas cap of oil deposits may have migrated along the fault zones to GHSZ, to be mixed there with biochemical gas released during the organic matter decomposition, and then, reaching sufficiently high concentrations, changed into hydrate state. Another scenario suggests, that both catagenetic and biochemical gases were, originally, mixed and concentrated outside the GHSZ interval [*Collett, 1993*].

The subsequent cooling of sedimentary rocks induced by climatic changes, created favorable conditions for the formation of gas hydrates [*Collett, 1993*]. As the permafrost aggradation proceeded, part of gas hydrate intervals were subsumed into the frozen strata.

Deep catagenetic gas may be encountered in the permafrost strata as a result of human activity, percolating through the leaking killed wells. From this perspective, it does make sense to learn from the experience of plugging exploration well No. 118 in the central part of the Bovanenkovo oil-gas-condensate field on the Yamal Peninsula, in 1984–1988 [*Yakushev, 2009*]. For many years, natural gas blowout persisted via borehole annulus of the killed well, prompting high concentrations of gas around it, specifically, in the permafrost zone. At this, gas discharged through a giant crater that has formed around the wellhead. Gas liberations from the permafrost were observed to a distance of 1 km away.

A few days after the accident happened, in July 1984, gas began to penetrate into the permafrost, saturating all the overlying permeable formations, especially in the upper part of the section, beneath the 40–50-meter-thick impermeable ice-rich Quaternary deposits. Major secondary gas occurrences formed in the permeable layers at the 40–60 and 100–120 m depth intervals within the permafrost zone.

As the saturation pressure intensified, gas spread laterally throughout the area, depending on the frozen sediments permeability, and reached the nearby lake and river-valley areas featured by thin permafrost strata and taliks, where it began to discharge onto the day surface with varying intensity. Since then, secondary gas occurrences may have ceased to spread throughout the area due to the gas discharging from them actively onto the day surface.

From the above cited example it follows, that secondary gas occurrences are located mainly at depths of 40–60 and 100–120 m, which all in all correspond to the depths of the most intense blowouts of biochemical gas from the permafrost interval, identified by subsequent drilling the appraisal wells into the permafrost in different parts of the Bovanenkovo oil-gas-condensate (OGC) field [*Yakushev, 2009*].

Intrapermafrost layers with reservoir properties are presumably confined to the intervals with the same depth. The relief wells drilled later confirmed active migration of gas to the day surface, particularly, from depths greater than 50 m. At depths of 40–60 m gas liberations were relatively weak, while at 100–120 m, their nature could be likened to a breakthrough from greater depths (probably, from Cenomanian deposits). Judging from this case, determining origin of the bulk of gas (whether it is biochemical or deep catagenetic) occurring within the perennially frozen sediments in the vicinity of the killed well appears challenging. The presence of jet-type migration of gas in the ice-poor sediments at depths of 100–120 m is not doubted, though.

Thus, the assumption that ice-rich overburden sediments (for instance, the uppermost 40–50 m in the Bovanenkovo OGC field) are practically impermeable to gas, has proven true. This partly confirms the hypothesis on the surface layer of ice-rich permafrost strata acting as regionally extending impermeable overburden and traps the gas migrating upward. However, the underlying layers of the permafrost interval, having a lower ice content and comprising permeable sand interlayers, do not hinder the lateral migration of gas to the permafrost strata. It is obvious, that this accident has ultimately led to the formation of technogenic accumulations of Cenomanian gas in the permafrost strata.

COALBED OR SHALE METHANE

A special case of intrapermafrost gas accumulations is concentrations of coalbed gases or shale gases. They are observed in areas of distribution of coal- and shale-bearing basins, where the aggrading permafrost stratum prevents the weathering of the upper interval of the deposits (Fig. 1). The paper by [*Khvorostina, 1985*] offers an illustration of gas liberation from the coal seams their and gas content within the permafrost interval of the South Yakutian coal basin. The presence of nitrogen, carbon dioxide and hydrogen in gas (other than methane) should be marked among specific features of gas-generation within the cryogenic zone of coal-bearing basins.

At this, the concentration of hydrogen may reach 34 %, given the normal background of 1–5 %. Methane zones tend to occur, starting already at depths <100 m, unlike coal basins outside the permafrost area, where its inception occurs from depths of 500–600 m. The content of carbon dioxide typically does not exceed 5 %, but sometimes its share accounts for 20 %. Nitrogen is present practically ubiquitously, ranging from 2 % (at depths greater than 200 m) to 92 % (5–20 m).

Similar studies given to Arkagalinskaya area in the Zyryanka basin in NE of Russia have also shown that the presence of the permafrost strata dramatically reduces the methane weathered zone, while the uppermost layers of the permafrost interval contain elevated amounts of methane [*Khryukin, 1978*]. Similar accumulations of gas may form during the freezing of gas-bearing shale strata, but no detailed analysis of this phenomenon has hitherto been offered.

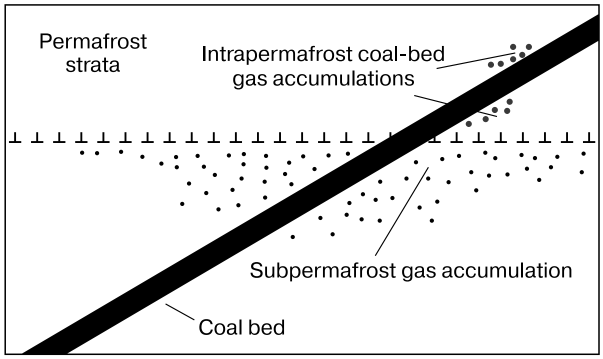

Fig. 1. Accumulations of coal-bed gas in the area of distribution of perennially frozen sediments.

DISTRIBITION OF HYDROCARBON GASES OF DIFFERENT ORIGIN IN THE PERMAFROST STRATA IN THE RUSSIAN TERRITORY

In order to carry out the zoning of areal distribution of the permafrost strata in the Russian territory based on the origin of gas in the intrapermafrost gaseous and gas-hydrate occurrences, the schematics of oil- and gas- and coal-bearing basins was superimposed onto the Russian cryosphere maps. The rest of the territory is subsumed either into plains with the Quaternary sedimentary cover, where intrapermafrost biochemical gas is encountered, or into orogenic belts where biochemical gas accumulations may occur in unconsolidated sediments of the intermountain basins. The work resulted in the creation of a scheme outlining distribution of intrapermafrost gases of different origin (Fig. 2) [*Yakushev et al., 2007*].

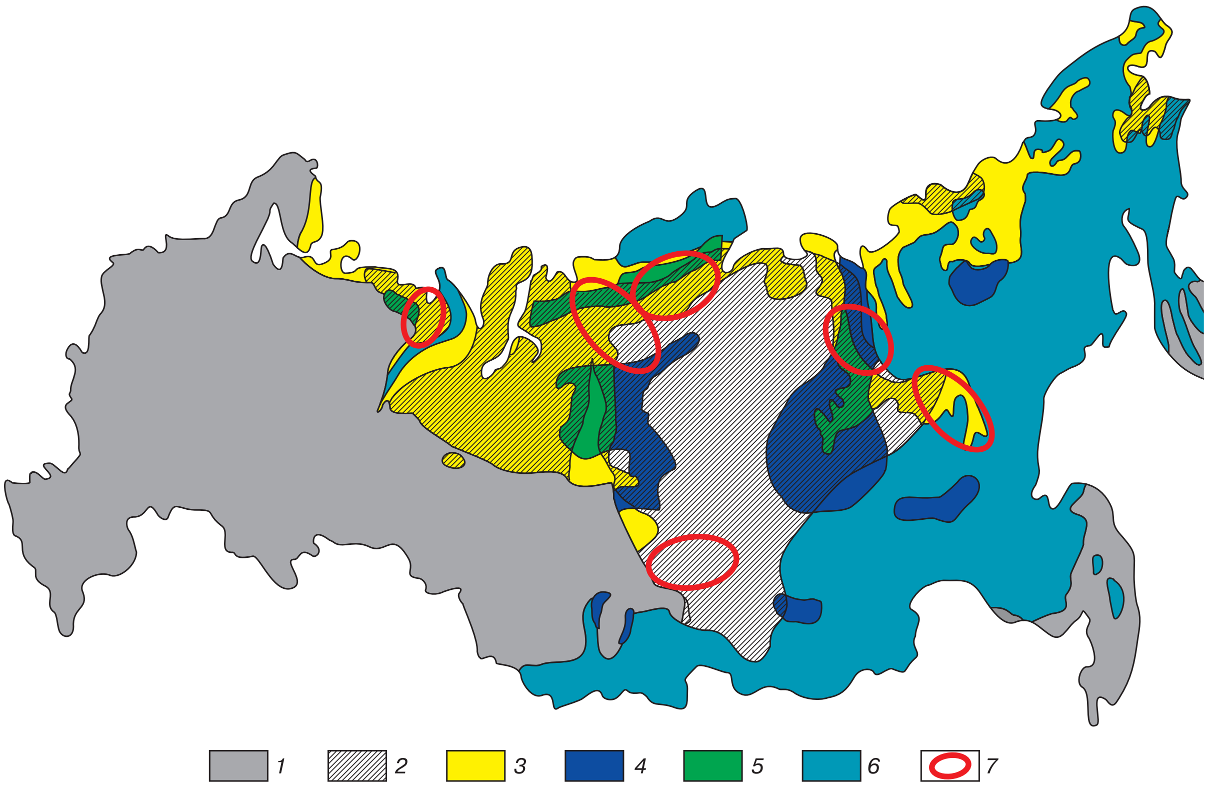

Fig. 2. Schematic representation of the intrapermafrost gases of different origin distribution in the Russian territory (from [*Yakushev et al., 2007*], with updates).

1 – the area of missing perennially frozen soils; *2* – area of distribution of deep catagenic gas; *3* – area of distribution of biochemical gas within the extent of the Arctic plains; *4* – area of coal-bed gas distribution; *5* – area of shared distribution of coal-bed and biochemical gases; *6* – area of biochemical gas distribution in the intermountain troughs; *7* – inferred area of shale gas distribution.

CONCLUSIONS

Our studies, with their focus on genesis, conditions of migration and accumulation of intrapermafrost gases have allowed the following conclusions:

1. Methane of biochemical origin appears to be a major gas encountered in the permafrost strata. Its formation is associated with microbial reworking of organic matter within the active layer during the summer, and with a slower processing of deep-buried organic matter within the perennially frozen sediment layer. Methane accumulating into individual occurrences may be the result of the gas-bearing sediments freezing and subsequent expulsion of water-gas mixture into the permeable thawed and frozen interlayers or into hydro-fractures caused by the pressure of confining freezing. When volume freezing proceeds inside the closed "gas pockets", there can develop pressures exceeding the pressure of hydrate formation, which, partially, forces gas change into gas-hydrate state. The formation of occurrences of biochemical gas is favored by salinity of the perennially frozen sediment, which increases the mobility of water and creates more favorable conditions for its displacing by gas. However, most of the occurrences of biochemical methane are relatively small, but numerous, and scattered over a large area.

2. In the areas of oil- and gas-bearing basins distribution, deep catagenetic hydrocarbon gases may be encountered in the permafrost strata. The origin of these gases may have resulted from:

a) epigenetic freezing of rock massifs hosting conventional oil and gas pools;

b) gas migration from the bottom upward through the permeable zones (faults, lithological windows, taliks) and the formation of accumulations in the permeable layers of the perennially frozen strata;

c) the formation of technogenic occurrences within the permafrost interval due to natural gas overflows in the wellbores of killed wells. This gas can mix with or even replace the biochemical gas in the reservoirs emplaced within the permafrost strata.

3. Coal-bed or shale gas occurrences formed either prior to the freezing of the cross-section, or following it, can be encountered in the areas of coal and shale sequences distribution within the permafrost interval. In the latter case, the formation of ice-rich gas cap for these strata overlaps the weathered zone, prompting the formation of gas accumulations at a depth from a few first tens of meters.

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