A new cryogenic-clathrate-explosive genetic model of modern circular structures in Siberia

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Summary

The paper considers some morphological and geological peculiarities of modern circular structures located in the Patom Mountains, Yamal and Taimyr Peninsulas. Detailed geological and geophysical studies of these structures let us determine that the leading process of their formation was the process of phase transformation of methane hydrates to gas and its subsequent explosion in the permafrost zone. The cryogenic-clathrate-explosive model of the «Patom crater» origin has been proposed. The sequence of the «crater» formation was following: methane migration from carbonaceous shale horizons occurring at the depths up to several kilometers, accumulation of gas in clathrate form in porous limestone beneath the permafrost screen during the Little Ice Age, phase transformation of methane hydrates to gas and water with a huge increase in methane volume during the warming period, underground gas explosion and excavation of limestone blocks onto the surface, their subsidence due to hydrolaccolith ice core melting and the formation of the central mound. The youngest funnel-shaped structures have abnormally high concentrations of methane in the air. Their formation may also be a result of underground gas explosion. The source of this gas is methane clathrates accumulated in the arctic permafrost zone in hydrocarbons migrating from parent petroleum reservoirs.

Main objectives:
Circular structures, «Patom crater», Yamal and Taimyr funnels, permafrost, methane clathrate, underground explosion.

New aspects covered:

A new cryogenic-clathrate-explosive model of the «Patom crater», Yamal and Taimyr Peninsulas funnels origin has been proposed on the basis of detailed geological and geophysical studies.

Topic:
2.20 Source Rocks and Petroleum Systems
5.01 Environmental and Hydrological Issues Related to Unconventional Resource Exploitation

Introduction

There are a number of local circular structures of volcano-like (figure 1c) or funnel types (figure 1b) in Siberia. Their size varies from a few meters up to 80-100 meters. Funnel-shaped structures found in the summer of 2014 in Yamal and Taimyr peninsulas have the age of no more than a few months. Conical, volcano-like "Patom crater" and its satellites were formed at least 500 years ago. All these structures are located in sedimentary (or weakly metamorphosed) rocks in the permafrost zone. There is no agreement about the genesis of these structures. Different versions of their technogenic, impact, volcanic or cryogenic origin are being discussed in scientific literature. Recent studies allow exclude anthropogenic and cosmogenic model of their genesis which may be a combination of cryovolcanic [Gladkochub et al. 2011] and gas volcanic [Isaev et al. 2012] events. They are likely to form by underground explosion of gases accumulated in the permafrost. The study of such structures is necessary to understand the mechanisms of their formation because it is important to predict adverse events near oil and gas fields.

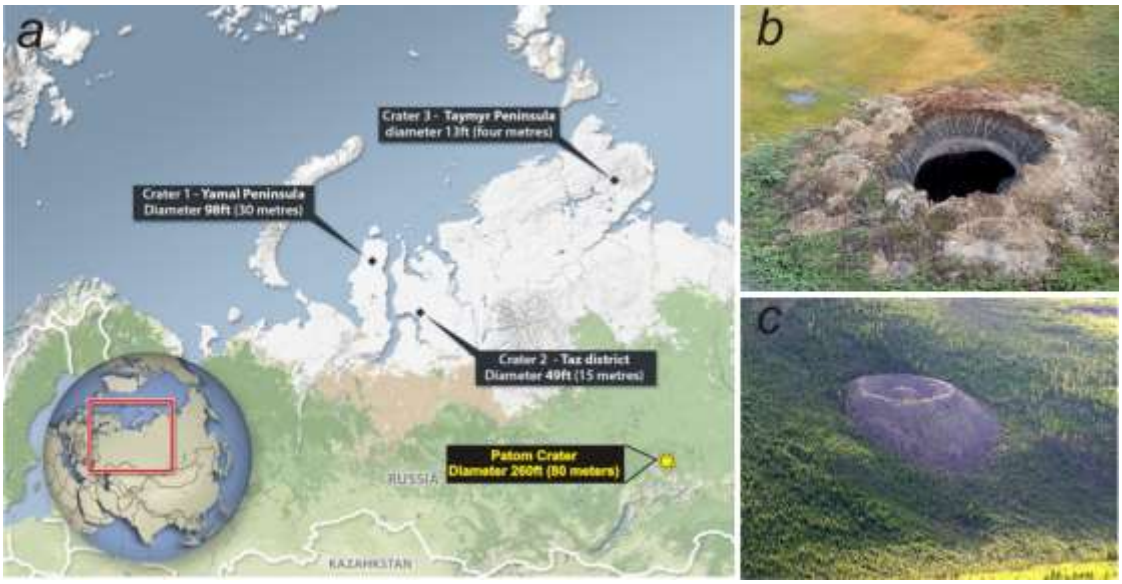

Figure 1. Geographical location of circular structures with cryogenic-clathrate-explosive genesis (a), and the general appearance of funnel-like (b, Yamal peninsula) and volcano-like (c, Patom Highlands) structures.

Gas clathrates in permafrost overview

This paper considers a new model of such structures formation. According to the authors, phase transformation of continental clathrates - gas hydrates (primarily methane) - occurring in the cryolitic zone is a leading factor of their formation processes [Savichev 2011, Savichev and Ermolin 2012]. Gas clathrates are non-stoichiometric crystalline solids composed of hydrocarbon gases trapped within the cavities of a rigid "cage-like" lattice of water molecules. These compounds contain clusters (two or more) of gas-trapping polyhedra formed by pentagonally and hexagonally arranged hydrogen-bonded water molecules. It is known that the unit volume of gas hydrate is stable at low temperatures at depths of several hundred meters in the permafrost and may hold up to 160-180 volumes of pure gas and the release of this gas can lead to subsequent explosive processes. The possible presence of methane in hydrate form in the permafrost is known for quite some time. Figure 2 shows methane hydrate stability fields in the continental and oceanic conditions. Typically, methane hydrates may be present in a metastable form and at lower levels (<200 m) due to the effect of self-preservation [Istomin et al. 2006]. All considered circular structures are located in the permafrost zone among the rocks that are potential hydrocarbons reservoirs. The presence of increased methane concentrations in the air near the ground has been determined instrumentally. Therefore, the major role in identifying the genesis of these structures should be given to the processes of phase transformation of methane clathrates.

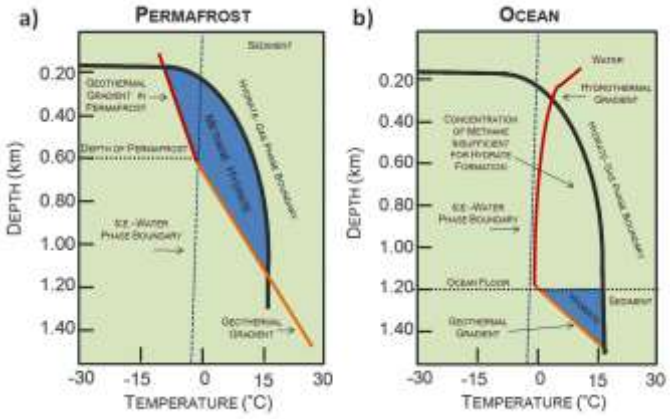

Figure 2. Methane hydrate stability zones (blue) for (a) permafrost and (b) oceanic environment, according K.A. Kvenvolden [1993].

Origin of enigmatic Patom crater and it analogies

At present, the "Patom crater" which is located in the northeast of the eponymous highlands is the most studied structure (Fig. 1c). It is a volcano-like building composed of blocks of Neoproterozoic graphitized limestone. It has a diameter of 80 m, a height of 35 m and the age at least of 500 years [Antipin et al. 2008; Savichev 2011]. Despite the more ancient age of this structure, a model of its formation may well be related to some craters in the Yamal and Taimyr found in 2014 [Bogoyavlensky, 2014]. There are no both the signs of impact events on the surrounding limestone and the traces of human activity in the vicinity of the "crater", so cosmogenic or antropogenic models of its formation are excluded. The "Patom crater" is located more than 150 km from the modern areas of volcanic activity. Geochemical studies have shown that there is no reliable evidence of modern juvenile fluids participation in its formation. Hydrothermal mineralization discovered in the "crater" has the age of about 360 million years [Savichev et al. 2012]. The "Patom crater" is closely related to cryogenic relief forms (hydrolaccoliths) on its morphology (Fig. 3). They have a regional name "Pingo" in Canada, "Bulgunnyah" in Yakutia, and were formed as a result of segregative or injection ice formation. Pingoes have the ice core which melts to form a central depression which finally fills with water in the phase of warming (Fig. 3c). Hydrolaccolites may have a zonal structure and represent conical constructions due to periodic freezing of new portions of pressure water (Fig. 3b, d). The "Patom crater" differs from segregative pingoes primary in its location on a steep (~ 30º) slope. This position is possible only for injection hydrolaccolites.

Figure 3. Cryogenic circular structures in the permafrost zone: a - "Patom crater", Eastern Siberia, b – «Bulgunnyah», Yakutia, c – «Pingo», Canada, g – zoned hydrolaccolite, Mars.

Integrated geological and geophysical (audiomagnetotelluric sounding and magnetovariaton profiling) studies of the "Patom crater" during the expedition of 2010 allowed us to propose a genetic model that considers this phenomenon as a result of sequential geological processes. The "Patom crater" is located in a 600 m wide graben (between two NW-faults) where preserved from erosion limestone occurs and their thickness is comparable to the depth of the permafrost in the Patom Highlands (black dotted line on figure 4). Neoproterozoic sedimentary rocks are present in the geological cross-section of the studied area, and some folded carbonaceous shale horizons are distinguished among them according to their abnormally low resistivity values [Ingerov and Ermolin, 2011]. Low-grade metamorphic conversion makes it possible to assume the presence of gaseous hydrocarbons capable of their rising migration through weakened fault zones (fig. 4).

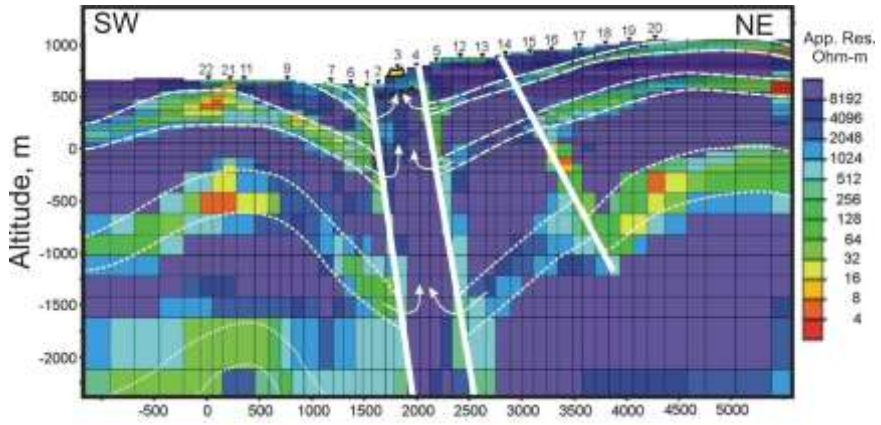

Figure 4. The geoelectric cross-section through "Patom crater" [Ingerov and Ermolin, 2011] with elements of its geological and genetic interpretation. Thick white lines indicate faults, thin dashed - carbonaceous shale horizons, arrows - the possible ways of migration of methane. "Patom crater" shows as yellow cone

We propose the following genetic model of the "Patom crater". Probably the accumulation of methane occurred in porous carbonate rocks (may be in caverns) under the permafrost screen for a long time. It is known that the thickness of the permafrost zone in the neighboring districts of Yakutia is no more than 250-350 m, hence there were some conditions necessary for the formation of gas hydrates. Annual average temperature increasing which began at the turn of XVII-XVIII centuries after the "Little Ice Age" and coincided with the beginning of the crater formation was determined by dendrochronology and may have caused a phase transformation of gas hydrates. Their dissociation resulted in an abnormally high porosity and release of large amounts of water as well as the release of volatile methane. So, there are two different versions of limestone blocks excavation onto the surface: 1) released pressure water climb up the weakened zone, froze and it led to the formation of injection hydrolaccolith and turned blocks of limestone on the surface to form a gravel heap, 2) there was an underground explosion of methane. Such explosive origin seems to be more possible owing to the presence of limestone fragments in the bark of larch on the periphery of the "Patom crater". The modern shape of the "crater" began to form since the XVIII century when the "ice plug" began to melt under the "Patom crater" causing a sinking of the top of the large cone to form a central hill. V.I. Voronin studied tree rings and fixed a catastrophic event in 1841-1842 but a powerful shifting of the soil in these years caused the violation of tree root systems may be considered the cause of the effect on the trees in the vicinity of the crater [Antipin et al. 2008]. It is possible that the melting of the hydrolaccolite ice core occurred not only in the roof, but also at the bottom of the permafrost zone due to endogenic heat. Satellite imageries show that the "Patom crater" is not the only structure of this type in the Patom Highlands. Characteristically, all these circular structures occur within the Davansky deep fault zone extension.

The youngest structures formed and discovered in 2014 in the Yamal and Taimyr are funnels with a diameter from 4 to 40 m (Fig. 4) [Bogoyavlensky 2014]. Their craters are hollow; they gradually fill with water, and the edgings consisted of thrown surrounding rock are observed around the craters to a distance of 120 m. Explosive nature of their origin is not in doubt. The funnels under consideration are still studied poorly, but now there are the preliminary data on the anomalously high (up 9.6%) explosive hazardous concentrations of methane in the air at the bottom of the craters

(http://www.vesti.ru/doc.html?id=1859773&cid=2161). The presence of methane is expected to be in hydrated form at the depth, and its conversion into the gas phase is thought to be a factor of funnel formation. According to I.N. Eltsov (http://nsk.kp.ru/daily/26304/3182758/) the largest crater found in the area of the Bovanenkovo gas field in Yamal Peninsula is located within the intersection of major faults.

Conclusions

The formation of circular structures in the permafrost of Siberia results in transformation of gas clathrates. Some thermal effects on their deposits within the permafrost may be caused by endogenous factors. The proposed model is similar to those for gas hydrates of oceanic funnels (Serie et al, 2012). A number of pingo-like structures arising from the destruction of methane hydrate are identified on the shelf of the Laptev Sea, the North Sea and the Gulf of Mexico.

Acknowledgements

The work is supported by the Russian Ministry of Education as a part of the state task in the field of scientific activity № 5.2115.2014 / K in the 2014-2016.

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