EXPLOSIVE GAS EMISSION CRATERS ON EARTH: POSSIBLE ANALOG FOR RAISED RIM LAKES ON TITAN. L. R. Schurmeier[1], G. E. Brouwer[1], S. A. Fagents[1], [1]Hawai‘i Institute of Geophysics and Planetology, University of Hawai‘i at Mānoa, Honolulu, HI 96822 (lschurme@hawaii.edu).

Introduction: The Earth's warming climate has begun to dramatically change the landscape in extreme and unexpected ways. In recent years, large explosion craters have suddenly appeared in the Siberian Yamal and Gydan peninsulas (Fig. 1) [1, 2, 3]. The explosions are due the sudden release of a shallow buildup of gas within the warming permafrost. Offshore, clusters of hundreds of large craters and mounds were also recently identified on the shallow seafloor (Fig. 2) [4]. They are within the shallow arctic continental shelves where relict methane clathrate hydrate layers exist below permafrost. Methane clathrate hydrate is a form of ice that contains methane gas trapped within the ice lattice cages. These methane clathrate layers are potentially large methane reservoirs that exist on and offshore. Likewise, arctic permafrost may also represent significant methane storage from decaying matter and microbial activity. Either source of methane can be implicated in the explosive formation of GECs.

On Saturn's moon Titan, a subset of lakes and depressions in polar regions (Fig. 3) have recently been suggested to have formed as maar eruptions, due to the sudden explosive vaporization of near surface aquifer fluids [5, 6]. Here, we suggest that these raised rim lakes could have formed via gas accumulation and explosive release in a manner directly analogous to the formation of gas emission craters (GEC) on Earth.

Figure 1: Areal image of a gas emission crater (GEC) located in the Yamal Peninsula on 7/15/15 (photo credit: R. Amanzhurov) and satellite imagery of a mound (~55 m wide) caused by pressurized gas trapped in the subsurface before the explosion (a) and the GEC (~20 m wide hole with ~5-10 m wide parapet) after the explosion (b). Figure from [1].

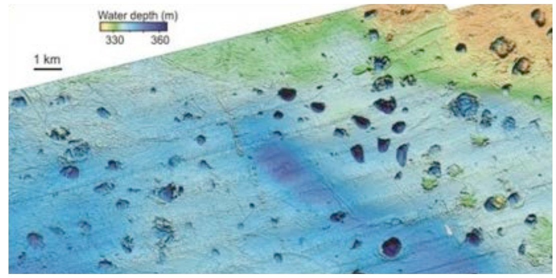

Figure 2: Gas emission craters (GEC) and mounds on the seafloor of Bjørnøyrenna in the Barents Sea. Colors indicate water depth. Figure from [4].

Titan's icy crust is similar to Earth's arctic crust in many ways. The near-surface is likely an aquifer composed of porous water ice or methane clathrate hydrate [7] and filled with aquifer fluids of liquid methane, ethane and nitrogen [8]. We compare different scenarios that could lead to explosive eruptions on Titan and consider what this means for Titan's changing climate and surface exchange processes.

Observations: We observe similar morphologies for GECs on Earth and raised rim lakes on Titan.

GEC Observations on Earth: Land. The craters are ~20 to 90 m diameter, surrounded by ejecta ramparts ~5 to 10 m wide and include large ejected icy blocks The craters are funnel-shaped near the surface (but can later collapse) and have cylindrical interiors extending to depths of ~15 m to over 50 m [1, 2, 3]. The precursor mounds are ~20 to 55 m in diameter and ~2 to 6 m tall [1]. Methane gas is observed within the ice and emanating from the crater and lake.

GEC Observations on Earth: Seafloor. Craters are ~300 m to 1 km in diameter and up to 30 m deep [4].

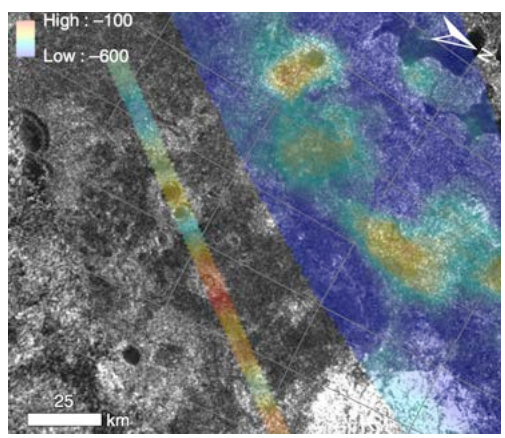

Figure 3: Cassini SAR images of sharp-edged depressions on Titan in the north. Many are circular and have raised ramparts. Colors indicate topographic elevation. Figure from [5], NASA.

Many have steep interior walls, with gradients up to 50°, and lack surrounding ramparts. Others have more complex morphologies with gently dipping exterior slopes. Many craters have large pingo-like mounds at or near their edges and smaller mounds within the depression. Methane gas has been detected escaping from the craters and their mounds [4].

Observations on Titan. Titan's north polar region hosts numerous sharp-edged depression (SED) lakes. A subset of the SED lakes are generally circular in planform, or composed of nested or overlapping circular depressions, and have raised rims and radar bright ramparts (Fig 3). The crater diameters are ~3 to 11 km [6] and ramparts extend another ~2 to 6 km beyond the crater rim. Many appear surprisingly fresh and are similar in morphology to fresh GEC on Earth.

GEC Formation Mechanisms on Earth:

On Land: 1) An ephemeral lake forms above permafrost. 2) The lake insulates the ground eventually causing melting of permafrost, forming a talik (unfrozen ground). 3) Gases migrate upwards from underlying destabilizing clathrate hydrates or methane-rich sediments and accumulate within the talik. Meanwhile, microbial life within the talik or sediments can produce additional methane and carbon dioxide gases. 4) Changing environmental or landscape conditions lead to the removal of the lake. 5) The talik freezes inwards, the ground surface swells into a mound and gases concentrate in the center. 6) The pressure under the mound exceeds the strength of the permafrost and the gas expands explosively upwards, creating a cylindrical conduit and a funneled crater with ejected material forming blocky icy ramparts 7) The crater fills with water.

Offshore: 1) Methane clathrate hydrate is stable within a defined depth range under arctic permafrost in the seafloor. 2) Ocean temperature increase and sea level fluctuations cause the clathrate hydrate stability region to shrink; clathrates begin to destabilize and release methane gas. 3) Methane gas migrates upward. Some gas slowly seeps out, while significant quantities remain trapped within the sedimentary layers. 4) Mounds form from the over-pressurization of trapped gas. 5) The pressure exceeds the strength of the overlying ground and the resulting explosion forms a crater. 6) Subsequent gas seepage could create mounds around or within the crater.

Possible GEC Formation Mechanisms on Titan: We suggest that the raised rim crater lakes with ramparts on Titan formed in a similar manner to that of onshore and offshore GECs on Earth. We assess the plausibility of the following scenarios that could lead to explosive eruptions on Titan:

1) A colder past climate enabled the formation of nitrogen-rich aquifer fluids. As the climate warms the liquid is vaporized, pressurized, and erupted in a maar-like explosion [5].

2) Liquid methane and ethane mixtures in an aquifer in contact with a heat source (e.g. cryomagma) is vaporized, pressurized, and erupted in a maar-like explosion [6].

3) Destabilization of methane clathrate at depth due to a thermal anomaly (e.g. cryomagma or warm upwelling ice) releases methane gas which rises, collects and pressurizes in the near-surface until it explodes.

4) Cryomagma intrusion stalls the upper crust (where it possibly destabilizes adjacent clathrates and collects methane gas within the intrusion), then freezes and expands, over-pressurizes, and explodes [8, 9].

Discussion: Gas emission craters on Earth are an alarming sign of the consequences of climate warming. The persistent warming of the Arctic [10] has increased our awareness of the dangers of future destabilization of shallow subsurface reservoirs of methane, a strong greenhouse gas. Its release from warming permafrost and methane clathrate hydrates could be a dangerous positive feedback of climate warming. Thus, understanding the cause and consequences of GECs is essential to understanding our climate future. If an analogous processes of GEC formation are occurring on Titan, these lakes may be a sign of climate change and/or cryomagmatism. Studying the mechanisms of explosive gas release can provide insight into Titan's changing climate and exchange processes between its interior, surface and atmosphere.

Future Work: We will use the extents of the bright ramparts (the assumed ejecta) around raised rim lakes observed in Cassini SAR images, along with plausible characteristics of the crustal material and erupting gas, to estimate the conditions necessary to form these features. Our aim is to provide volume estimates of released gases and to discriminate between formation hypotheses.

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