MODELING TERRESTRIAL GAS EMISSION CRATERS AS ANALOGS FOR TITAN'S RAISED-RIM DEPRESSIONS. G. E. Brouwer[1], L. R. Schurmeier[1], S. A. Fagents[1], [1]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Mānoa, Honolulu, Hawai'i 96822, USA (*gbrouwer@hawaii.edu).

Introduction: Raised-rim depressions are a class of lakes and depressions in Titan's north polar region. These depressions are characterized by their raised rims, circular planform shapes, and radar-bright halos. Previous studies have proposed that raised-rim depressions form via vapor explosions analogous to terrestrial maar explosions [1, 2, 3]. Here, we test the hypothesis that these features form in a manner analogous to cryospheric explosions that form gas emission craters (GECs) in permafrost regions on Earth.

Since 2014, many GECs have been found in Siberia on the Yamal and Gydan peninsulas [4]. Terrestrial GECs are characterized by cylindrical craters with funne-shaped radial ramparts constructed from what is interpreted as material ejected via the explosion of gases that accumulated and pressurized within the permafrost [4, 5]. Terrestrial GECs are 10 – 90 m in diameter while Titan's raised rim depressions range from 3 – 11 km wide. They display similar morphological attributes; circular shape, raised rims, a funnel-like interior, and ejecta-like ramparts [3]. These terrestrial examples provide a high-resolution and ground-truthed data set with which to test a model of their formation for application to Titan.

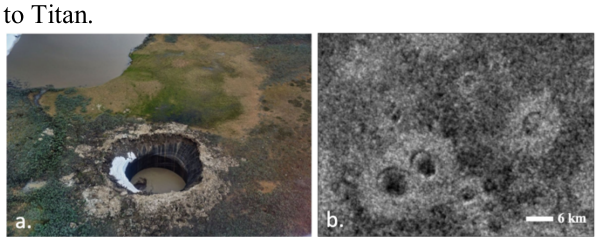

Figure 1. *Gas emission crater (GEC) called Yamal Crater (photographed by Ruslan Amanzhurov) measuring ~20 m in diameter. Figure adapted from Buldovicz et al. (2018). (b) Cassini SAR image of raised-rim lakes and depressions in Titan's north pole with diameters ~ 3 – 5 km.*

Formation of terrestrial GECs is thought to be due to the explosive release of pressurized gas trapped in the ice-rich subsurface. The gas may originate from microbes, the decay of organic matter, migration of deeper methane, or by dissociation of gas clathrate hydrates [5]. GECs are believed to form via gas explosions for several reasons: before the explosion there are similar-scale mounds (interpreted as pressurized gas mounds), the upper funneled interior morphology and raised ramparts are reminiscent of maar-like explosions, the deep cylindrical interior is unlike an impact crater, and after formation, GECs show elevated methane emission [6].

Titan's upper ice shell is thought to contain methane clathrates [7, 8] and previous studies have shown that release of methane gas due to destabilization of clathrates is possible in Titan's upper ice shell in response to a thermal perturbation and contact with ammonia-rich liquids, which lower the destabilization temperature of methane clathrates [3, 9]. We hypothesize that gases released from destabilized clathrates could accumulate in the shallow subsurface, pressurize, and explode.

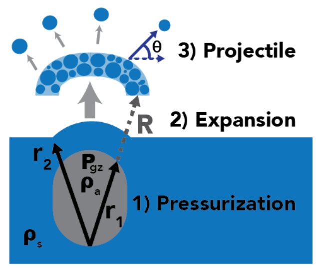

Figure 2. *Pressurization reaches the point of explosion in the gas chamber (grey), the retaining cap (blue) has thickness $r_{21} = r_2 – r_1$. Expansion phase of the explosion, the fragmented cap blocks (blue) are launched into the gas.*

Model: The explosion model is based on the work of [10] for volcanic explosions on Venus and Earth. Gas accumulates and pressurizes in a cylindrical region underlying impermeable caprock (permafrost or ice/clathrate) until the pressure exceeds the overburden and tensile strength of the overlying cap and explodes. The gas expands out of the vent, accelerates the retaining cap and displaces the atmospheric gas above the explosion site. The equation of motion is

$$\frac{dr^2}{dt^2} = \frac{3r^2\left[P_{gz}\left(\frac{r_1}{r}\right)^{3\gamma} - P_a\right]}{\{\rho_s({r_2}^3 - {r_1}^3) + \rho_a[(r_2 - r_1)^3 - {r_2}^3]\}} \quad (1)$$

where r is the radial position at any time t, r_1 is the gas region radius, $r_{21} = r_2 - r_1$ is the cap thickness, P_{gz} is the initial gas overpressure, P_a is the atmospheric pressure, ρ_s is the density of the solid, and ρ_a is the density of the atmosphere. Integration of the equation of motion using a finite differences method yields the time t_0 and position R_0 at which the maximum velocity u_0 is reached. Once the maximum velocity u_0 is reached, the gas velocity u begins to decay and the retaining cap (which is now a collection of blocks) is launched into the moving gas. The gas velocity decays with time t as

$$u = u_0\left(\frac{R_0}{R}\right)^2 \exp\left(-{t}/{\tau}\right) \quad (2)$$

where the time constant τ is $\tau = t' - t_0$ and t' is the total duration of the gas expansion phase. The trajectories of the blocks are then described as projectile motion with drag. We track the position and velocity of projectiles using an adaptive 4th order Runge-Kutta routine in Matlab. We use observations of crater and ejected material size and extent to find the initial gas pressure given assumptions about gas chamber size.

Model Constraints. Field work in the Yamal and Gydan peninsulas [1, 11] helps constrain the parameter space for Earth GECs. Mapping of secondary projectile craters formed in the explosion of Yamal Crater [11] provide estimates of ejecta block sizes (6 cm – 4 m) and distances (20 – 100 m). The gas region is constrained by measurements of diameters and depths of GECs: 25-37 m and 10-50 m, respectively [12].

We map Titan's raised-rim depressions using Cassini SAR (Synthetic Aperture Radar) images and SAR-Topo data to determine depression size and extent of ejecta deposit. We utilize the Crater helper tool in ArcGIS to digitize the raised-rim depressions and organize feature attributes. Our model allows us to constrain pre-explosion conditions given measurements of crater size and ejecta extent.

Preliminary Results: We first model the formation of terrestrial GECs. We consider four initial gas volumes estimated from observations made before and after crater formation. A minimum gas volume, 3900 m^3, is estimated using a digital elevation model of the precursor mound [13] above the background terrain. The mound volume and radius of the crater yield a gas region thickness r_1 of 22 m. The cap thickness r_{21} is taken to be 8 m, the depth of the funnel shape region, and the assumed cap thickness of previous studies [14]. The total depth r_2 is thus 30 m.

Assuming ejecta only originated from the cap directly above the explosion site, we estimate an alternative cap thickness of 11.3 m, using the minimum volume of ejecta, ~2000 m^3 [13,15]. The thickest cap explored is 26 m, the depth to the grotto observed at the base of the cylindrical cavity [13]. We take 50 m as an alternative depth estimate, as this was the depth of the cylinder when the GEC was first surveyed, before collapse.

Results for projectiles of 1500 kg/m^3 are shown in Figure 3 for the three cap thicknesses explored. The tensile strength of permafrost is not well constrained, so we assume that values within the 0.3 – 2.5 MPa range are plausible. Adding the lithostatic pressure to the tensile strength of the permafrost, crater forming explosions are possible for initial conditions that result in gas pressures in the 0.42 – 2.88 MPa range. Two of the three successful model runs were for a cap thickness of 8 m. The greater gas volume, 7422 m^3 vs. 3869 m^3, allowed by a greater maximum depth requires smaller gas pressures, 1.02 MPa vs. 2.4 MPa. The third successful run was for a thicker cap, 11.3 m. Despite the thick cap, the large gas volume allowed by the greater chamber depth promoted explosion. This indicates that as the cap thickness increases a greater volume of trapped gas is required for GEC formation.

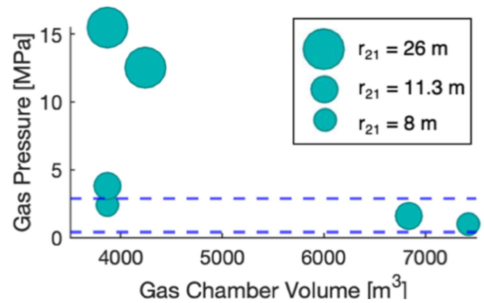

Figure 3*. Gas pressures required to launch the blocks observed at the maximum distance from Yamal crater (0.2 m diameter block at 120 m distance) as a function of gas chamber volume estimates. The different marker sizes correspond to the cap thickness r_{21}. Gas pressure values that lie within the blue dashed lines are within expected range.*

Discussion: Our findings show that that we can estimate plausible pre-explosion conditions for Yamal Crater using our explosion model. We find the parameter that most effects the model results is the cap thickness and gas volume. If the cap is thick, the gas volume must be substantially larger to produce an explosion.

Placing constraints on the gas region size for Titan conditions will be a greater challenge, given that we lack field observations. However, we can begin to constrain an upper bound on the pressure of the gas in the reservoir: the tensile strength of ice, 0.1–2.5 MPa [16] plus the lithostatic pressure, which depends on the cap thickness. Titan's crust likely consists of a 3–5 km thick layer of methane clathrates [8], which gives us an upper bound on the maximum depth r_2. Future work will explore plausible gas chamber sizes for implementation in the explosion model. We aim to estimate the amount of methane released by such gas-rich explosions and hence evaluate whether the formation of raised-rim depressions could have contributed significant methane to Titan's atmosphere.

References: [1] Mitri G et al. (2019) Nature Geosci, 791-796, 12(10) [2] Wood C and Radebaugh J (2020) JGR: Planets 125(8). [3] Schurmeier L et al. (2021), LPSC, #1785. [4] Bogoyavlensky V (2020) Geosci, 10(6). [5] Chuvilin E (2020) Geosci, 10(5). [6] (2019) Dvornikov YA et al. (2019) Permafrost Periglac Proc, 30, 146– 162. [7] Mitri G Showman A (2008) Icarus, 387-396, 193(2). [8] Choukroun M and Sotin C (2012) Geophys Res Lett, 39(4). [9] Choukroun M (2010) Icarus, 581-592, 205. [10] Fagents S and Wilson L (1995) Geophys J Int, 359-370,113. [11] Kizyakov A (2018) Rem Sens, 10(5). [12] Kizyakov A (2020) Rem Sens, 12(14). [13] Kizyakov A et al. (2015) The Earth Cryosphere (Kriosfera Zemli), XIX(2). [14] Buldovicz SN et al. (2018), Sci Rep, 8(1), p.1-6. [15] Liebman MO et al. (2014) Geogr Environ Sustain, 7(4), 68-79. [16] Litwin K (2012) JGR: Planets, 117(E8).