Possible explosion crater origin of small lake basins with raised rims on Titan

Giuseppe Mitri^{1,2*}, Jonathan I. Lunine^{3,4}, Marco Mastrogiuseppe⁵ and Valerio Poggiali³

The Cassini mission discovered lakes and seas comprising mostly methane in the polar regions of Titan. Lakes of liquid nitrogen may have existed during the epochs of Titan's past in which methane was photochemically depleted, leaving a nearly pure molecular nitrogen atmosphere and, thus, far colder temperatures. The modern-day small lake basins with sharp edges have been suggested to originate from dissolution processes, due to their morphological similarity to terrestrial karstic lakes. Here we analyse the morphology of the small lake basins that feature raised rims to elucidate their origin, using delay-Doppler processed altimetric and bathymetric data acquired during the last close flyby of Titan by the Cassini spacecraft. We find that the morphology of the raised-rim basins is analogous to that of explosion craters from magma-water interaction on Earth and therefore propose that these basins are from near-surface vapour explosions, rather than karstic. We calculate that the phase transition of liquid nitrogen in the near subsurface during a warming event can generate explosions sufficient to form the basins. Hence, we suggest that raised-rim basins are evidence for one or more warming events terminating a nitrogen-dominated cold episode on Titan.

Titan is the lone extraterrestrial body in our Solar System with persistent lakes and seas on its surface¹. Approximately 650 lacustrine features are found throughout the polar regions, with most lakes and seas found in the northern hemisphere^{1–3}. The south polar regions possess few filled lakes and a larger percentage of dry lakes and palaeolakes^{4,5}. Titan's lakes and seas are filled with liquid hydrocarbons, mostly methane with dissolved nitrogen^{6,7} and participate in an alkanological cycle similar to the terrestrial hydrological cycle³. This alkanological cycle is possible as the conditions on Titan (surface temperature of ~93 K) allow methane to be close to its triple point and to be present in liquid, gas and solid phases⁸. The formation of liquids within the lakes is probably the result of a complex hydrology including precipitation, surface runoff and subsurface aquifers in the icy crust³. The surfaces of the lakes on Titan's north pole are on the same equipotential surface⁹, demonstrating intercrustal flows of liquids and the presence of liquid hydrocarbon aquifers^{3,9}.

Sharp-edge depressions with raised rims

We used delay-Doppler processed altimetric and bathymetric data acquired during the last close flyby (T126; 22 April 2017) of Titan by the Cassini spacecraft^{7,10} in conjunction with a morphological analysis to elucidate the origin of small lake basins featuring raised rims. Figure 1 shows the altimetry (solid line) and the bathymetry (dotted line) of the lake named Winnipeg Lacus (78°N, 155°W) and the altimetric track overlying the Cassini synthetic aperture radar (SAR) images. The altimetric data (solid line) of Winnipeg Lacus depicts a rim (~300 m high) adjacent to a rampart-like structure surrounding the lake. The bathymetric profile shows a maximum lacustrine depression depth of ~100 m (ref. ⁷). The morphology of the seas and lakes of Titan can be described as broad and sharp-edge depressions (SEDs)^{9,11–13}. Broad depressions typify the hydrocarbon seas and some larger lakes with typical diameters of a few hundred kilometres. The smaller lakes (median diameter = 77 ± 20 km (± 1 s.d.))

are SEDs with a circular or irregular shape that are liquid filled to varying degrees^{3,9,11,12}. Recent analysis of Cassini Radar SAR data of SEDs in Titan's north pole found that 75% have observable rims where those with lake areas >750 km² had a higher probability of presenting an observable rim^{9,13}.

The irregular shape of most SEDs is not consistent with the planform morphology of impact craters. Due to similar planform morphology with terrestrial karst lakes, a karstic dissolution origin of the lake basins has been suggested^{14,15}. However, water ice is insoluble in liquid hydrocarbons¹⁶ and theoretical modelling of the materials expected to be on Titan's crust indicates that for the present environmental conditions a limited number of materials are capable of producing dissolution¹⁵. Further, deposition of photochemical products via precipitation¹⁷ to the poles is insufficient to produce an erodible organic sedimentary layer that can produce the depth of the SED basins⁹. The presence of raised rims in SED basins^{9,11–13} undermines the karst lake model for SEDs with raised rims. According to the karst model, the lake basins on Titan should be produced as dolines formed by collapse, dissolution or subsidence of the terrain; such processes do not produce rims. While SEDs with raised rims are not formed by a karstic process, their presence in a karstic-like environment is not excluded.

SEDs with raised rims as explosive craters

We propose that SEDs with raised rims are craters that are successively filled with hydrocarbon liquid and result from explosive eruptions probably due to phase transitions of liquid molecular nitrogen in the shallow subsurface during a colder period in Titan's past¹⁸. Examples of morphologies produced by explosive eruptions on Earth are maar craters, tuff rings and tuff cones produced during phreatic or phreatomagmatic eruptions. Maar craters are the result of shallow subsurface interactions and have floors that are below the surrounding topography; tuff rings and tuff cones are the result of interactions with liquid just below or at the surface¹⁹.

¹International Research School of Planetary Sciences, Università d'Annunzio, Pescara, Italy. ²Dipartimento di Ingegneria e Geologia, Università d'Annunzio, Pescara, Italy. ³Cornell Center for Astrophysics and Planetary Science, Cornell University, Ithaca, USA. ⁴Carl Sagan Institute, Cornell University, Ithaca, USA. ⁵Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, USA. *e-mail: giuseppe.mitri@unich.it

Fig. 1 | Winnipeg Lacus and surrounding lakes. **a**, Large-scale image of Winnipeg Lacus (78° N, 155° W) and surrounding lakes with altimetric track overlying the Cassini SAR image (T92 flyby). **b**, Small-scale image focused on Winnipeg Lacus. **c**, Cassini RADAR altimetric profile (solid line) showing the rim adjacent to a rampart-like structure and the surface of Winnipeg Lacus; bathymetric profile in dotted line (the zero in ordinate indicates the mean radius of Titan). Credit: NASA/JPL/CalTech

Explosive crater morphology of relatively flat floors, raised rims and typically rampart-like borders is a match for the morphology of SED basins with raised rims with and without rampart-like borders.

Terrestrial maars have circular and irregular shapes and often have composite or coalesced forms^{19,20}. Maar irregularity can be due to closely spaced explosive vents, which can erupt in a single complex

Fig. 2 | SED lakes. **a**, Examples of SED lakes in Titan's north polar region, several of which are broadly circular. **b**, These SED lakes have a rampart-like topography that appears radar-bright on their border. Credit: NASA/PDS

event or separately over time²⁰. Maars are typically the result of multiple explosions that can vertically and laterally shift with a range of explosive energies and depths^{20,21}. The spatial relationship between explosion epicentres can result in either a circular or irregular crater^{20,21} (for example, Devil Mountain maar, USA²² and Nejapa maar, Nicaragua²³). For a given explosion energy and material substrate strength, the explosion depth is a controlling factor in determining whether a crater and ejecta are produced or whether the energy is contained in the subsurface, at which point the containment depth is reached²⁴. Explosion energies and depths for Titan differ due to the lower material strength of water ice compared with rock and are discussed later.

Crater shape and size are influenced by other factors such as subsidence, collapse and erosion^{19,25}. Analysis of maars and similar landforms in the West Eifel Volcanic Field (Germany) found that maars affected by fluvial erosion lose their original shape and often have an irregular shape²⁶. Analyses of maars in the Hopi Buttes Volcanic Field (USA) demonstrate the complex morphology that can result from fluvial erosion, including 'concave-lakeward' and 'tongue-like' morphology found in the Teshim and Morale Claim Butte maars²⁷. Elongated, irregular terrestrial maars influenced by multiple eruptive events and erosion may reflect processes that formed Winnipeg Lacus as well as SEDs with raised rims featuring irregularities, including elongation, protrusions and other complex morphology (Fig. 1).

While fluvial erosion may be a secondary force in transforming Titan's surface²⁸, it is possible that it could have been more significant in a colder, nitrogen-dominated Titan. Since the density of liquid nitrogen is near water ice compared with liquid methane, nitrogen liquid would have a greater ability than methane liquid to erode Titan's surface²⁹.

Many maars are surrounded by ejected deposits known as a tephra ring; tephra refers to ejecta material of the maar. Tephra is a heterogeneous mix of surface and subsurface material and is found in both the crater and the surrounding ring. Tephra volume is controlled by the explosion depth as a function of explosive energy and material substrate; the closer the explosion depth is to the containment depth, the smaller the volume of tephra ejected will be^{24,30}. Tephra deposition is determined by the angle of the jets coming from the explosion vent; wider jets produce greater deposits whereas more vertically focused jets result in fallback of tephra into the crater³⁰. Cassini spectral and radar analysis of SEDs with raised rims on Titan found that some (<10) are surrounded by rampart-like radar bright ring structures, including Winnipeg Lacus (Fig. 1) and the lakes featured in Fig. 2 that are suggestive of tephra rings³¹.

Analysis of Cassini RADAR backscatter indicated that Titan's north polar empty lake basins have a heterogeneous composition and differ compositionally from their surroundings³². Cassini Visible and Infrared Mapping Spectrometer (VIMS) spectral analysis of empty lake basins and ramparts found they share the same composition³⁰. Eruptive jets, depending on their placement in the crater, can produce laterally focused directional jets, which can result in asymmetric ejecta deposition^{20,30}. Pre-eruptive surface topography can affect ejecta deposition, for example, creating a partial tephra ring at the Barombi Mbo amalgamated maar, Cameroon³³. Material substrate affects tephra formation; in highly permeable water-saturated substrates, a maar crater cannot form, rather a tephra ring or cone (for example, tuff ring and cone) forms at the surface (for example, Diamond Head tuff cone, USA). In this environment, the tephra may be water saturated and thus have a smaller ejecta angle¹⁹. Collapse and erosion can play important roles in the presence or absence of a tephra ring^{19,30,33}. The apparent lack of more rampart structures around SEDs constrains the explosive origin model; however, the paucity of ramparts could be due to explosion depth, material properties, and fluvial erosion and precipitation, both probably more substantial in a cold nitrogen-dominated Titan²⁹.

Warming events in a past nitrogen-dominated atmosphere

The photochemical lifetime of methane in Titan's atmosphere is several tens of million years, and the value of $^{12}\text{C}/^{13}\text{C}$ in Titan's atmosphere indicates that the current atmospheric inventory of methane probably outgassed $\sim 10^7$ – 10^8 yr ago³⁴. Evolution models suggest that Titan's crust is composed of water ice and clathrate hydrate, with mostly methane as primary guest species, and that episodic methane outgassing could be a cause for the continued presence of methane in the atmosphere³⁵. However, in the absence of continuous or frequent outgassing from the crust or deeper methane sources, Titan's atmosphere in the past may have been episodically methane depleted. Under such conditions, the greenhouse effect would have been limited to the collision-induced absorption of N_2 – N_2 , resulting in a Titan that was colder than at present, with a mean surface temperature lower than 81 K (refs. ^{18,29}).

Under the hypothesis that the interval between methane outgassing events was so infrequent that the atmosphere would be depleted, Titan's surface may have been characterized by the presence of liquid nitrogen lakes and of liquid nitrogen aquifers at the poles within the crust. If the temperature was low enough—81 K on the basis of the vapour pressure of pure molecular nitrogen—liquid nitrogen might have been stable on the surface and subsurface,

participating in a cycle similar to the present methane cycle^{18,29}. During this period, the molecular nitrogen liquid at and near the surface could have been close to the equilibrium vapour pressure at the high latitudes¹⁸ such that a small temperature variation produced by an exothermic or endothermic warming event could result in an extremely rapid rise in the vapour pressure of liquid within the nitrogen-dominated aquifers. The phase transition from liquid to vapour and the subsequent pressurization of subsurface N₂ gas could have resulted in an explosive eruption. The surface on a nitrogen-dominated Titan would have been able to absorb about five times the insolation compared with the current methane-dominated Titan²⁹. On Titan, increasing the molar fraction of methane in a liquid methane–nitrogen mixture results in an increase of the equilibrium vapour pressure (Fig. 3), resulting in a less volatile mixture. This potentially explosive process, depending on the amount of methane present in the liquid nitrogen solution, would have been limited to shorter-term warming events or would have only occurred at the beginning of a global warming scenario.

A similar phase transition process probably occurred during at least two geyser-like eruptions captured by Voyager 2 during its flyby of Neptune's largest moon, Triton³⁶. Models suggest that an exothermic warming event, probably insolation during Triton's southern spring/summer, caused sunlight to be absorbed by organic particles within the nitrogen-dominated icy crust, prompting a greenhouse effect and raising the temperature therein; this resulted in a subliming phase transition and subsequent increasing pressurization of N₂ gas in the subsurface, which produced venting of nitrogen, organic gas and particles^{36,37}. Geothermal heating may also have played a role in these events³⁸. Between 1989 and 1998, Triton experienced a ~2 K increase in temperature³⁹ and an increase in atmospheric pressure probably due to an increase of N₂ in the atmosphere³⁹. Streaks seen by Voyager 2 on Triton's surface and anomalous 'reddening' events recorded between 1997 and 2000 that appeared to correspond with variation in methane absorption band strength may have been evidence of venting caused by global warming^{40,41}.

We have investigated whether warming events in a past nitrogen-dominated atmosphere of a cold Titan could have produced explosions in the external crustal layer due to a phase transition occurring in the nitrogen-dominated aquifers. Figure 3 shows the vapour pressure of a solution composed of methane, ethane and nitrogen as measured for Winnipeg Lacus and Ligeia Mare (72% of CH₄, 11% C₂H₆, 16% N₂ molar fraction⁷) (red solid line) with Cassini RADAR altimetry data. For comparison, a model for the vapour pressure of a nitrogen-dominated solution (20% of CH₄, 80% N₂ molar fraction) is shown (red dashed line). Figure 3 shows the vapour pressure of molecular nitrogen (red dotted line) and methane (grey dashed line). We used the Antoine equation to describe the relation between the vapour pressure and temperature for pure methane, ethane and molecular nitrogen. The vapour pressure of the methane, ethane and molecular nitrogen solution is determined using Raoult's equation. We display the methane clathrates dissociation curve (solid brown line). The dissociation pressure as a function of temperature of methane clathrates is computed⁴². The temperature profile for a cold Titan with a surface temperature of 80 K at the north pole is indicated by the blue dotted line, and the temperature profile for the present recorded surface temperature of 91 K at the north pole is indicated by the blue solid line. The temperature profile for a model with a surface temperature of 87 K is shown. The model presented in Fig. 3 is for an internal heat flux of 0.007 W m⁻², a thermal conductivity of 3.5 W m⁻¹ K⁻¹ (pure water ice) and an atmospheric pressure of 0.15 MPa.

The comparison of the saturation vapour pressure with the expected temperature profile within the ice shell allows an evaluation of whether methane, nitrogen and their mixture are in liquid or vapour phases at the surface and within the crust. For the current conditions, CH₄–C₂H₆–N₂ liquid is thermodynamically stable on

Fig. 3 | Stability of methane, ethane, nitrogen and clathrates on the surface and within subsurface aquifers. Vapour pressure of a solution of methane, ethane and nitrogen as measured for Winnipeg Lacus and Ligeia Mare (72% CH₄, 11% C₂H₆, 16% N₂ molar fraction⁷) (red solid line); vapour pressure of molecular nitrogen (red dotted line) and methane (grey dashed line); vapour pressure for a nitrogen-dominated atmosphere (20% CH₄, 80% N₂ molar fraction) (red dashed line); methane clathrates dissociation curve (solid brown line). Temperature profile for a cold Titan with a surface temperature of 80 K (blue dotted line) and at present recorded temperature of 91 K at the north pole (blue solid line). The temperature profile for a surface temperature of 87 K (blue dashed line) is also shown. The temperature profile is calculated using a heat flux of 0.007 W m⁻² and a thermal conductivity of 3.5 W m⁻¹ K⁻¹ (pure water ice).

the surface and within subsurface aquifers (compare red solid line with the vapour pressure of the liquid solution with the expected current temperature profile in blue solid line). In a cold Titan with a nitrogen-dominated atmosphere, liquid N₂ is stable at the surface and within aquifers. Because nitrogen exists close to its equilibrium vapour pressure during this cold period on Titan, its vapour pressure increases rapidly with increasing temperature; thus, small temperature changes can produce the transition phase from liquid to vapour both on the surface and within the crust (compare red dotted line with blue dotted line). Molecular nitrogen efficiently dissolves methane. An aquifer with pure liquid nitrogen or with a small molar fraction of dissolved methane can react to temperature changes, producing a phase transition from liquid to vapour. The presence of methane makes any solution with nitrogen more thermodynamically stable such that an increasing amount of methane would probably halt the phase transition process.

The ability of an underground explosion to form craters and subsequently ejecta is a function of the explosive energy, explosion depth and material substrate properties. We used the scaling law of explosion crater according to experimental and test results from chemical and nuclear explosions⁴³ to model the craterization processes, adopting the cube root scaling law^{24,43} that is consistent with field results⁴⁴. The craterization process for a given explosion energy is dominated by tensile strength of the material substrate with respect to gravity and other variables such as atmospheric pressure⁴³. The scaled depth of subsurface explosions is $d_{sc} = dE^{-1/3}$ (refs. ^{24,44}). Under terrestrial conditions, the scaled crater diameter reaches a maximum (0.014 m J^{-1/3}) when the scaled depth is 0.004 m J^{-1/3} (refs. ^{24,44}). Explosion depths less than the optimal scaled depth will allow the release of enough energy to produce craters and ejecta while explosion depths greater than the scaled depth will have their explosive energy progressively confined to the subsurface until the containment depth, 0.008 m J^{-1/3} (refs. ^{24,44}), is reached and all explosive energy is maintained in the subsurface^{24,45}.

The laboratory-measured tensile strength (Y) of water ice is ~10⁶ Pa; however, the measured tensile strength of the ice of the

Ross Ice Shelf (Antarctica) is $\sim 10^5$ Pa (ref. 46). Experimental work has shown that the water-ice tensile strength on Titan may be higher than previously thought, and the tensile strength increases with decreasing temperature⁴⁷. Our model includes a tensile strength range from 0.1 MPa to 2.2 MPa. Given that the strength of Titan's crustal material is lower than that for Earth (15 MPa for basaltic rocks), for similar explosive energy the explosion depth can be deeper and result from a smaller liquid deposit but still erupt (Supplementary Information and Methods).

We have determined the required volume of nitrogen deposits to produce explosion craters. The latent heat of vapourization of N_2 is 200 kJ kg^{-1} . The density of liquid nitrogen at 80 K is 793 kg m^{-3} . We assume that the entire energy produced by the phase transition is converted to explosive energy. Under this assumption, an explosion containment depth of 100 m requires a liquid nitrogen deposit with a volume of $80\text{--}1,700 \text{ m}^3$, corresponding to tensile stresses of $Y = 0.1\text{--}2.2 \text{ MPa}$ (Supplementary Information). The phase transition of liquid nitrogen deposits is an efficient mechanism to produce explosions.

We interpret the morphological characteristics of the SEDs with raised rims as evidence of their explosive eruptive origin, suggesting that these SED basins were formed due to the phase transition of liquid nitrogen in the near subsurface during a warming event or events on a cold nitrogen-dominated Titan that may have existed at various times during Titan's past. These climatic conditions caused N_2 to exist near its equilibrium vapour pressure at high latitudes, making the vapour pressure of N_2 a steep function of increasing temperature. This resulted in pressurization of N_2 in the subsurface and a probable explosive release resulting in a crater where the rim is formed by the ejected material from the crater interior. This explosive process may or may not release methane as part of the process.

The presence of explosive eruption craters forming the SED basins therefore is evidence that Titan has experienced cold nitrogen-dominated epochs followed by rewarming to conditions more like those today. On Triton, the venting of nitrogen and possibly methane and an increase of atmospheric pressure are probably due to warming events that may mirror processes that happened in Titan's nitrogen-dominated past. The morphology of SEDs with raised rims is analogous to the morphology associated with terrestrial phreatic and phreatomagmatic explosions.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of code and data availability and associated accession codes are available at <https://doi.org/10.1038/s41561-019-0429-0>.

Received: 4 January 2019; Accepted: 15 July 2019;

Published online: 9 September 2019

References

- Stofan, E. R. et al. The lakes of Titan. *Nature* **445**, 61–64 (2007).
- Lopes, R. M. et al. The lakes and seas of Titan. *EOS Trans. Am. Geophys. Union* **88**, 569–570 (2007).
- Hayes, A. et al. Hydrocarbon lakes on Titan: distribution and interaction with a porous regolith. *Geophys. Res. Lett.* **35**, L09204 (2008).
- Aharonson, O. et al. An asymmetric distribution of lakes on Titan as a possible consequence of orbital forcing. *Nat. Geosci.* **2**, 851–854 (2009).
- Hayes, A. G. et al. Transient surface liquid in Titan's polar regions from Cassini. *Icarus* **211**, 655–671 (2011).
- Mastrogiuseppe, M. et al. The bathymetry of a Titan sea. *Geophys. Res. Lett.* **41**, 1432–1437 (2014).
- Mastrogiuseppe, M. et al. Deep and methane-rich lakes on Titan. *Nat. Astron.* **3**, 535–542 (2019).
- Yung, Y. L., Allen, M. & Pinto, J. P. Photochemistry of the atmosphere of Titan: comparison between model and observations. *Astrophys. J. Suppl. Ser.* **55**, 465–506 (1984).
- Hayes, A. G. et al. Topographic constraints on the evolution and connectivity of Titan's lacustrine basins. *Geophys. Res. Lett.* **44**, 11745–11753 (2017).
- Poggiali, V. et al. High-resolution topography of Titan adapting the delay/Doppler algorithm to the Cassini RADAR altimeter data. *IEEE Trans. Geosci. Remote Sens.* <https://doi.org/10.1109/TGRS.2019.2912575> (2019).
- Hayes, A. G. The lakes and seas of Titan. *Annu. Rev. Earth Planet. Sci.* **44**, 57–83 (2016).
- Birch, S. P. D. et al. Geomorphologic mapping of Titan's polar terrains: constraining surface processes and landscape evolution. *Icarus* **282**, 214–236 (2017).
- Birch, S. P. D. et al. Raised rims around Titan's sharp-edged depressions. *Geophys. Res. Lett.* **46**, 5846–5854 (2018).
- Malaska, M. et al. Identification of karst-like terrain on Titan from valley analysis. In *Proc. 41st Lunar Planet. Sci. Conf.* 1544 (USRA, 2010).
- Cornet, T. et al. Dissolution on Titan and on Earth: toward the age of Titan's karstic landscapes. *J. Geophys. Res. Planets* **120**, 1044–1074 (2015).
- Perron, J. T. et al. Valley formation and methane precipitation rates on Titan. *J. Geophys. Res. Planets* **111**, E11001 (2006).
- Krasnopolsky, V. A. A photochemical model of Titan's atmosphere and ionosphere. *Icarus* **201**, 226–256 (2009).
- Lorenz, R. D., McKay, C. P. & Lunine, J. I. Photochemically-driven collapse of Titan's atmosphere. *Science* **275**, 642–644 (1997).
- Lorenz, V. Maar-diatreme volcanoes, their formation, and their setting in hard-rock or soft-rock environments. *Geolines* **15**, 72–83 (2003).
- Graetinger, A. H. Trends in maar crater size and shape using the global Maar Volcano Location and Shape (MaarVLS) database. *J. Volcanol. Geotherm. Res.* **357**, 1–13 (2018).
- Valentine, G. A. et al. Experiments with vertically- and laterally-migrating subsurface explosions with applications to the geology of phreatomagmatic and hydrothermal explosion craters and diatremes. *Bull. Volcanol.* **77**, 15 (2015).
- Beget, J. E., Hopkins, D. M. & Charron, S. D. The largest known maars on Earth, Seward Peninsula, northwest Alaska. *Arctic* **49**, 62–69 (1996).
- Avellán, D. R., Macías, J. L., Pardo, N., Scolamacchia, T. & Rodríguez, D. Stratigraphy, geomorphology, geochemistry and hazard implications of the Nejapa Volcanic Field, western Managua, Nicaragua. *J. Volcanol. Geotherm. Res.* **213–214**, 51–71 (2012).
- Valentine, G. A., Graetinger, A. H. & Sonder, I. Explosion depths for phreatomagmatic eruptions. *Geophys. Res. Lett.* **41**, 3045–3051 (2014).
- Ross, P.-S. et al. Experimental birth of a maar-diatreme volcano. *J. Volcanol. Geotherm. Res.* **260**, 1–12 (2013).
- Seib, N., Kley, J. & Büchel, G. Identification of maars and similar volcanic landforms in the West Eifel Volcanic Field through image processing of DTM data: efficiency of different methods depending on preservation state. *Int. J. Earth Sci.* **102**, 875–901 (2013).
- White, J. D. L. Pliocene subaqueous fans and Gilbert-type deltas in maar crater lakes, Hopi Buttes, Navajo Nation (Arizona), USA. *Sedimentology* **39**, 931–946 (1992).
- Black, B. A., Perron, J. T., Burr, D. M. & Drummond, S. A. Estimating erosional exhumation on Titan from drainage network morphology. *J. Geophys. Res. Planets* **117**, E08006 (2012).
- Charnay, B., Forget, F., Tobie, G., Sotin, C. & Wordsworth, R. Titan's past and future: 3D modeling of a pure nitrogen atmosphere and geological implications. *Icarus* **241**, 269–279 (2014).
- Valentine, G. A. et al. Tephra ring interpretation in light of evolving maar-diatreme concepts: Stracciaccappa maar (central Italy). *J. Volcanol. Geotherm. Res.* **308**, 19–29 (2015).
- Solomonidou, A. et al. Spectral and emissivity analysis of the raised ramparts around Titan's northern lakes. *Icarus* <https://doi.org/10.1016/j.icarus.2019.05.040> (2019).
- Michaelides, R. J. et al. Constraining the physical properties of Titan's empty lake basins using nadir and off-nadir Cassini RADAR backscatter. *Icarus* **270**, 57–66 (2016).
- Tchamabé, B. C. et al. Towards the reconstruction of the shallow plumbing system of the Barombi Mbo Maar (Cameroon) implications for diatreme growth processes of a polygenetic maar volcano. *J. Volcanol. Geotherm. Res.* **301**, 293–313 (2015).
- Hörst, S. M. Titan's atmosphere and climate. *J. Geophys. Res. Planets* **122**, 432–482 (2017).
- Tobie, G., Lunine, J. I. & Sotin, C. Episodic outgassing as the origin of atmospheric methane on Titan. *Nature* **440**, 61–64 (2006).
- Smith, B. A. et al. Voyager 2 at Neptune: imaging science results. *Science* **246**, 1422–1449 (1989).
- Soderblom, L. A. et al. Triton's geyser-like plumes: discovery and basic characterization. *Science* **250**, 410–415 (1990).
- Duxbury, N. S. & Brown, R. H. The role of an internal heat source for the eruptive plumes on Triton. *Icarus* **125**, 83–93 (1997).
- Elliot, J. Letal Global warming on Triton. *Nature* **393**, 765–767 (1998).
- Buratti, B. J., Hicks, M. D. & Newburn, R. L. Jr Does global warming make Triton blush? *Nature* **397**, 219 (1999).
- Hicks, M. D. & Buratti, B. J. The spectral variability of Triton from 1997–2000. *Icarus* **171**, 210–218 (2004).

42. Sloan, E. D. & Koh, C. *Clathrate Hydrates of Natural Gases* 3rd edn (CRC, 2008).
43. Holsapple, K. A. & Schmidt, R. M. On the scaling of crater dimensions: 1. Explosive processes. *J. Geophys. Res. Solid Earth* **85**, 7247–7256 (1980).
44. Goto, A., Taniguchi, H., Yoshida, M., Ohba, T. & Oshima, H. Effects of explosion energy and depth to the formation of blast wave and crater: field explosion experiment for the understanding of volcanic explosion. *Geophys. Res. Lett.* **28**, 4287–4290 (2001).
45. Valentine, G. A. et al. Experimental craters formed by single and multiple buried explosions and implications for volcanic craters with emphasis on maars. *Geophys. Res. Lett.* **39**, L20301 (2012).
46. Kehle, R. O. Deformation of the Ross Ice Shelf, Antarctica. *Geol. Soc. Am. Bull.* **75**, 259–286 (1964).
47. Litwin, K. L., Zygielbaum, B. R., Polito, P. J., Sklar, L. S. & Collins, G. C. Influence of temperature, composition, and grain size on the tensile failure of water ice: implications for erosion on Titan. *J. Geophys. Res. Planets* **117**, E08013 (2012).

Acknowledgements

The authors thank A. H. Graettinger and J. Radebaugh for useful comments. We thank A. Hayes for his constructive comments on the manuscript. G.M. expresses appreciation to A. Solomonidou for sharing her results. J.I.L. acknowledges support from the Cassini

project, subcontract 1437803. V.P. acknowledges funding for this work from the NASA PDART programme grant number 80NSSC18K0513.

Author contributions

G.M. performed the data and morphological analysis, developed the geophysical models and wrote the manuscript. J.I.L. contributed to the interpretation of the data and contributed to the writing of the manuscript. M.M. and V.P. performed the data analysis (altimetric, bathymetric and SAR data) and contributed to the writing of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at <https://doi.org/10.1038/s41561-019-0429-0>.

Reprints and permissions information is available at www.nature.com/reprints.

Correspondence and requests for materials should be addressed to G.M.

Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s), under exclusive licence to Springer Nature Limited 2019

Methods

Explosion craters. We provide a first-order estimate of the required energy of an underground explosion necessary to produce Titan's SED basins with raised rims. We used a scaling law of explosion craters derived using experimental and test results from chemical and nuclear explosions⁴³. In a general form, the crater volume produced by a subsurface explosion is written as⁴³:

$$V \propto E^a g^{3(a-1)} Q_v^{3-4a+b} Y^{-b} \quad (1)$$

where E is the total explosive energy, g is the gravity, Q_v is the specific energy of the explosion, and Y is the medium strength; a and b are constants that depend on the adopted model. Assuming the crater volume does not depend on the specific energy of the explosion, the resulting scaling rule for the crater volume is⁴³:

$$V \propto E^a g^{3(a-1)} Y^{3-4a} \quad (2)$$

with $3/4 \leq a \leq 1$ and $b = 4a - 3$. If $a = 1$ then it is called the cube root scaling law, where the dimensions of the crater are proportional to the cube root of the energy and the crater volume is proportional to the total energy. If $a = 3/4$ then it is called the quarter root scaling law, where the linear dimensions of the craters are proportional to one-fourth of the total energy. Several studies have investigated whether the cube root scaling law or the quarter root scaling law best explains the experimental and test results of underground explosive processes^{43,48}.

Following previous analyses²⁴ that have modelled the explosion depths for phreatomagmatic eruptions, we adopt the cube root scaling law ($a = 1$). We assume that the cube root scaling law implies that the medium strength dominates the craterization processes. The assumption of a cube root scaling law is consistent with the experimental field explosion results pertaining to volcanic explosions^{24,44,48}. In this case, the crater volume is given by:

$$V \propto Y^{-1} E \quad (3)$$

and the excavation depth is given by:

$$d \propto Y^{-1/3} E^{1/3} \quad (4)$$

For terrestrial conditions, the maximum excavation depth as a function of the total energy is reached when⁴⁴:

$$d_{\max} = (0.004 \text{ m J}^{-1/3}) E^{1/3} \quad (5)$$

For larger and smaller excavation depths, the resulting explosion crater has smaller dimensions. The contained depth for which, for deeper depth, the explosion typically does not present ejecta is given by⁴⁴:

$$d_{\text{cont}} = (0.008 \text{ m J}^{-1/3}) E^{1/3} \quad (6)$$

The experimental results that allowed the derivation of maximum excavation depth as a function of the total energy (equation (5)) were developed for physical conditions simulating basaltic rocks of terrestrial volcanoes. Even if the maximum excavation depth and the contained depth depend on the tensile strength of the medium⁴⁴, a general formulation of the model that depends on mediums' characteristics was not derived. Using equations (4)–(6), we provide a first-order estimation of the maximum excavation depth that depends on the tensile strength of the medium. Considering $(0.004 \text{ m J}^{-1/3}) E^{1/3} = K_1 Y^{-1/3} E^{1/3}$, where K_1 is a constant, and assuming the basaltic rock tensile strength (15 MPa) for which physical condition was derived from equation (5), we found that $K_1 \approx 1$. For the physical conditions of Titan's crust, we do not have available experimental data similar to that for terrestrial volcanoes to estimate the maximum excavation depth as a function of the explosion energy. Assuming a similar behaviour as for the terrestrial volcanoes, we assume for Titan's crust the dependence of the maximum excavation depth as $d_{\max} \sim Y^{-1/3} E^{1/3}$ that gives $d_{\max} \sim (0.022 \text{ m J}^{-1/3}) E^{1/3}$ for $Y = 0.1 \text{ MPa}$ and $d_{\max} \sim (0.007 \text{ m J}^{-1/3}) E^{1/3}$ for $Y = 2.2 \text{ MPa}$.

For terrestrial volcano conditions, the physical containment depth is twice the maximum excavation depth. Therefore, for Titan's crust conditions, we assume that the physical containment depth $d_{\text{cont}} \sim 2 \times Y^{-1/3} E^{1/3}$. We model the contained depth for Titan's crust as $d_{\text{cont}} \sim (0.043 \text{ m J}^{-1/3}) E^{1/3}$ for $Y = 0.1 \text{ MPa}$ and $d_{\text{cont}} \sim (0.015 \text{ m J}^{-1/3}) E^{1/3}$ for $Y = 2.2 \text{ MPa}$.

On Earth, the behaviour of the subsurface explosions is described introducing the scaled depth $d_{\text{sc}} = d \times E^{-1/3}$ (refs. ^{24,44}). The scaled crater diameter reaches a maximum (0.014 m J^{-1/3}) when the scaled depth is 0.004 m J^{-1/3} (ref. ⁴⁴). Therefore, the maximum crater diameter for a given explosion energy and for a point source explosion is then ~3.5 times the maximum excavation depth.

Data availability

The authors declare that the data supporting the findings of this study are available within the article and its supplementary information.

Code availability

The mathematical algorithms that support findings of this study are available from the corresponding author upon request.

References

48. Graettinger, A. H. et al. Maar-diatreme geometry and deposits: subsurface blast experiments with variable explosion depth. *Geochem. Geophys. Geosyst.* **15**, 740–764 (2014).