TITAN'S CRATER LAKES: CALDERA VS. KARST? K. L. Mitchell[1], J. S. Kargel[2], C. A. Wood[3], J. Radebaugh[4], R. M. C. Lopes[1], J. I. Lunine[4], E. R. Stofan[5], R. L. Kirk[6] and the Cassini RADAR Team, [1]Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 183-601, 4800 Oak Grove Dr., Pasadena 91109-8099, CA, USA, *Karl.L.Mitchell@jpl.nasa.gov*, [2]Dept. of Hydrology & Water Resources, Univ. Arizona, Tucson, AZ, [3]Wheeling Jesuit Univ., Wheeling, WV, and Planetary Science Institute, Tucson, AZ, [4]Lunar and Planetary Lab, Univ. Arizona, Tucson, AZ, [5]Proxemy Research Inc., Laytonsville, MD, [6]USGS Flagstaff, Flagstaff, AZ.

Introduction: Cassini SAR imagery obtained during the T16 Titan fly-by reveals the presence of radar-dark lakes at >70° N [1]. Several are in relatively steep-sided depressions, usually sub-circular (e.g. Fig. 1a), sometimes in an offset, nested configuration (e.g. Fig 1c), contrasting with irregular lakes that have shallow or no rims (e.g. Figs. 1b&d). Finally, several radar-bright but otherwise morphologically-similar structures occur mostly (e.g. Fig. 1b, denoted by arrows), but not exclusively, at lower lake district latitudes, and have been interpreted as dried-up lakes [1].

The case for cryovolcanism: One hypothesis for the steep-sided depressions is that they are calderas [2], similar to those on Venus, Earth, Mars and Io, in which case the liquids filling the depressions may be unrelated to the cryovolcanic processes. There are many examples of calderas elsewhere in the solar system, and many terrestrial ones contain lakes (e.g. Fig. 2a). Interpreting the nested structures as composite calderas seems particularly compelling.

An alternative origin may be as maars, much like the Espenberg Maars on Seward Peninsula, Alaska [3] (Fig. 2c – indicated by arrows), but formed by the explosive interaction of rising cryomagmas and methane clathrates or hydrocarbons (solid or liquid). The clathrate interaction is ruled out on the basis of the low explosive potential of methane clathrates heated by cryomagmas under Titan's 1.5-bar atmosphere, relative to terrestrial maar-forming interactions; we would expect Titan's maars to be smaller than terrestrial ones, but this is not the case, as many of the Titan features are larger than the largest terrestrial maars [3]. We cannot completely rule out interactions with hydrocarbons, which may provide for a highly explosive interaction, depending on composition and temperatures.

The case for karst: A karstic (dissolution) origin is also compelling, but is problematic, as it has never been proven in an extra-terrestrial setting and, in the case of Titan, exotic solvents and solutes are needed. Terrestrial karst most commonly forms in regions of soluble carbonate rock (e.g. Fig. 2d), but Titan's dominant surface material is thought to be water-ice, which is poorly soluble in liquid methane and ethane, and the presence of a lake on a water-ice bedrock seems unlikely to result in karstic dissolution even over long timescales. However, we do not know the timescales involved in limnological processes on Titan; it is not inconceivable that Titan's lakes have been active for orders of magnitude longer that terrestrial karstic systems. Furthermore, Titan karst might form due to dissolution of soluble solid hydrocarbons [4]. Solubilities in the range of 10^{-6} to 10^{-4} are sufficient. Candidate hydrocarbon systems include methane-ethylene, ethane-ethylene and ethane-acetylene.

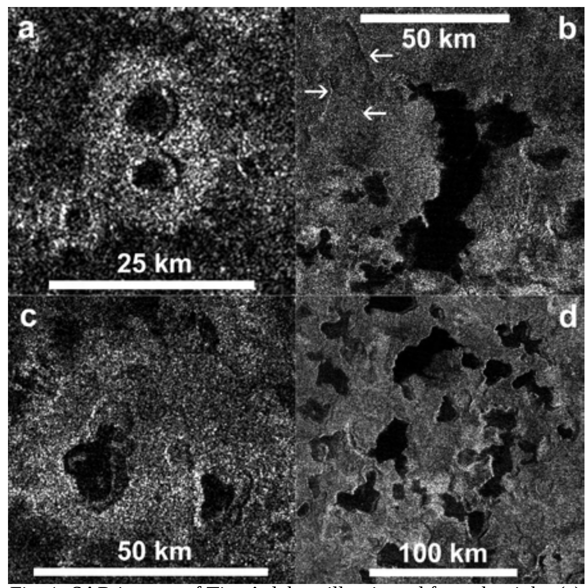

Fig. 1: SAR images of Titan's lakes, illuminated from the right. (a) Sub-circular in steep-sided rimmed depression; (b) Irregular with little topography – radar bright feature (arrows) interpreted as drained lake; (c) Sub-circular, nested, steep-rimmed depressions; (d) Complex region with irregular lakes and variable rim heights.

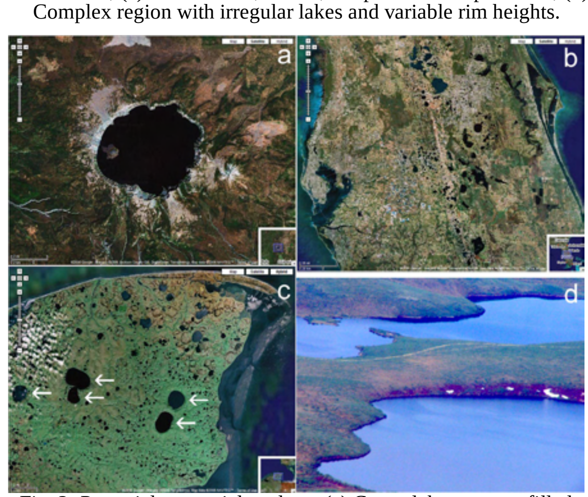

Fig. 2: Potential terrestrial analogs. (a) Crater lake, a water-filled caldera; (b) Karst lakes in central Florida; (c) Thermokarst lakes and volcanic maars (indicated with arrows) on Seward Peninsula, Alaska; (d) Photo of steep-sided thermokarst lakes on the Yuktoyaktuk Peninsula, Canada. Satellite images ©Google/NAVTEC.

A further alternative, explored by [4], is thermokarst, which is known to form in permafrost regions and on glaciers (e.g. much of Alaska, USA, and the Canadian Northwest Territories) (Fig. 2e). Thermokarst is the result of melting of ground-ice due to insolation heating of the lake. Insolation is expected to be very weak at Titan's north pole but hypothetically some sort of hybrid process, involving chemical dissolution of a permafrost analogue, could occur on Titan. Titan's atmospheric and crustal volatile chemistry produce a complex assemblage of materials, generally carbonaceous, deposited on or near the surface [4], many that could result in karst/thermokarst scenarios.

Tests: We present several observations, and consider whether they are consistent with karst (including thermokarst) or caldera models (Table 1).

Observation	**Caldera**	**Karst**
Morphology – large depressions, often overlapping or nested, and sub-circular	Maybe[a]	Maybe[a]
Scale – up to many km in diameter	Yes	Maybe[b]
Topography – up to hundreds of m deep rims, often on locally raised topography	Yes	No[c]
Distribution – clustered, most commonly at lower Lakeland latitudes	Maybe	Maybe
Location – near the north pole	Maybe[d]	Yes
Radar backscatter – the surrounds are radar bright	Yes[e]	No
Associated landforms – a dome-like structure within a lake depression	Yes	Yes
Context – near-polar, containing lakes	Maybe[f]	Yes

Table 1: Observations, and consistency with caldera and karst hypotheses. (a) At higher latitudes, most rimmed lakes are irregular in morphology (most calderas are sub-circular). Nested, offset karst lakes are difficult to account for; (b) Terrestrial karst lakes are generally smaller, but there is no known theoretical limit; (c) Terrestrial karst lakes are shallower than some observed on Titan, and rarely present within topographic rises [5]; (d) This would be an unusual abundance without explanation and little to no secondary volcanic evidence; (e) Consistent with flows or explosive ejecta. No known karst-related explanation; (f) Calderas seem rare on Titan, and the morphologies observed here are unique to the lake district. A coincidence is possible, but requires explanation.

The caldera interpretation is consistent with observations. However, the distribution and context within the polar lake region is a serious constraint; latitudinal dependency of volcanic landforms is observed on other bodies (e.g. south polar Enceladus), but no interior model to-date has predicted this for Titan.

The irregular morphology of rimmed lakes at higher latitudes (e.g. Fig. 1d) is difficult to explain, as calderas tend towards (not exclusively) more circular structures, and taken without context of the more-circular and particularly the nested structures elsewhere, a karst interpretation may be preferred. There are also many features that are more consistent with evaporated or drained lakes than with calderas, despite a clear topographic rim (Fig. 1b).

A karst origin also has its issues. Terrestrial analogues are much smaller, (thermo-)karst lakes being generally sub-km in scale, although they can be much larger, and they are usually relatively shallow. However, the theoretical limit for any karst lake is the depth of the susceptible layer, the configuration of which for Titan is unknown, and even on the Earth some steep-sided examples exist (e.g. Fig. 2d).

Many have radar bright halos (Fig. 1a&c), with no known karstic explanation, although perhaps some sort of alteration could be envisaged. The main problem is that of the topography. We infer from preliminary stereo measurements [5] that the topography around some of these haloed lake depressions is locally positive, suggesting constructional processes more consistent with cryovolcanism, although thermokarst lakes in Berind Land Bridge National Preserve, Alaska, can occur amidst or on top of ice-rich domes.

In summary, the cases for karst/thermokarst and caldera origins for the nested structures each exhibit a range of consistencies and neither is ideal in explaining all observed lake depressions. An alternative interpretation might be that both processes operate in the same region. A form of polar "goo-cryovolcanism" [4] might operate exclusively on polar deposits, which could also be prone to dissolution or melting and, hence, karst-thermokarst formation.

Implications: The presence of putative calderas here lends credence to the use of terrestrial analogs for volcanic processes on Titan. The implication is that magma stalls at buoyancy/density traps in the upper crust to form magma chambers. The apparent focusing at this pole may suggest a latitudinally-dependent mantle supply, or a fortuitous hot spot [2].

A karst origin requires the presence of an abundant surface material susceptible to dissolution in liquid hydrocarbons. Given the estimated rim heights of some of the lake depressions (~600 m [5]), we would require a present-day inventory equivalent to several m globally, all confined locally to the lake district. Theoretically, acetylene seems to be the best fit, as it should be highly soluble in liquid methane ($4x10^{-4}$) and abundant (predicted 86 m global inventory), but the presence of acetylene has not been confirmed by VIMS despite seemingly showing an abundance of the less soluble ($2x10^{-5}$) benzene (predicted 14 cm global inventory) [6]. Furthermore, acetylene should be radar-dark, and so is unlikely to form the bulk of the surface materials, although it could be plentiful in the near-subsurface. Alternatives might be clathrate (methane or CO2) or propyne.

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