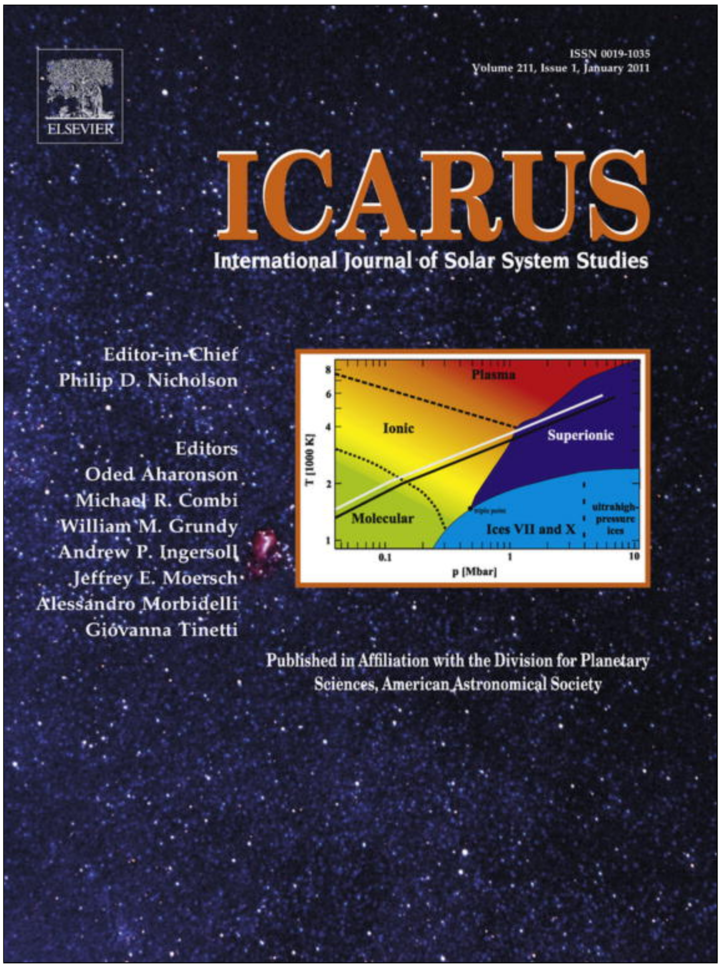
ISSN 0019-1035
Volume 211, Issue 1, January 2011
ELSEVIER
ICARUS
International Journal of Solar System Studies
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Icarus 216 (2011) 136–140

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Note

Organic sedimentary deposits in Titan's dry lakebeds: Probable evaporite

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ARTICLE INFO

Article history:
Received 22 February 2011
Revised 1 July 2011
Accepted 19 August 2011
Available online 1 September 2011

Keyword:
Titan

ABSTRACT

We report the discovery of organic sedimentary deposits at the bottom of dry lakebeds near Titan's north pole in observations from the *Cassini* Visual and Infrared Mapping Spectrometer (VIMS). We show evidence that the deposits are evaporitic, making Titan just the third known planetary body with evaporitic processes after Earth and Mars, and is the first that uses a solvent other than water.

1. Introduction

Evaporites, formed on planetary surfaces when dissolved chemical solids precipitate out of saturated solution as their liquid solvent evaporates, are only known to exist in two astronomical locations: Earth and Mars. On Earth there are a variety of evaporite constituents including carbonates ($CaCO_3$), sulfates ($CaSO_4$), and halides (NaCl), progressing in order of increasing solubility. The relative abundance of these materials depends on surrounding bedrock source materials and fluid compositions. NASA's rover Opportunity discovered evaporitic deposits on Mars (Squyres et al., 2004) that are instead primarily composed of sulfates – different from Earth's due to a highly acidic formation environment (Bibring et al., 2006; Bullock and Moore, 2007). The discovery of standing bodies of liquid hydrocarbon on Saturn's moon Titan (Stofan et al., 2007; Brown et al., 2008) allows for the possibility of a physically similar evaporite formation mechanism there, albeit with exotic chemistry relative to that on the terrestrial planets.

Because Titan's hydrocarbon lakes and seas represent the only known extant extraterrestrial hydrological[1] cycle, their state and dynamics are of considerable interest to place Earth's hydrology into context. Turtle et al. (2011) saw surface darkening in the wake of a large equatorial storm, empirically demonstrating that rain reaches the surface of Titan. Recent evidence for surface changes shows that some lakes can appear and disappear with time (Hayes et al., 2011; Turtle et al., 2009), indicating a dynamic hydrological system. *Cassini* RADAR shows steep-walled depressions that are not presently filled with liquid, but that may have been filled in the past (Stofan et al., 2007; Hayes et al., 2008). Near-infrared imaging revealed concentric deposits around the south-polar lake Ontario Lacus that evidence previously higher lake levels (Barnes et al., 2009a), and using multiple images acquired years apart showed that south-polar lake Ontario Lacus may be drying up right now (Turtle et al., 2011). In this note, we show that the lake dessication process drives the formation of evaporite deposits in the floors of dry lakebeds.

2. Observations

Previous Visual and Infrared Mapping Spectrometer (VIMS) north polar lake observations were inhibited by winter night-time darkness (Barnes et al., 2009b). In designing *Cassini*'s T69 flyby of Titan (2010 June 5) our goal was to improve understanding of Titan's lakes, in particular their composition from spectral analyses and their shorelines from imaging the lake margins. To do so, we specifically targeted areas around the margins of Ligeia Mare that had been observed by the *Cassini* RADAR instrument on the T25 (2007 February 22), T28 (2008 April 10) and T29 (2008 April 27) flybys. Previous experiences have shown that combined VIMS and RADAR coverage of the same area at high spatial resolution yields more science than separate high-resolution coverage of different areas (Soderblom et al., 2007; Barnes et al., 2007b; Le Mouélic et al., 2008; Soderblom et al., 2009; Barnes et al., 2011; Tosi et al., 2010).

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[1] Here we use the word 'hydrological' to refer generally to 'volatilological', *i.e.* any substance on a planetary surface that undergoes processes physically similar to those of water in Earth's hydrological cycle. This avoids uncomfortable, confusing, and unnecessary reference to a 'methanological' cycle on Titan in the same way that the word 'magnetohydrodynamics', for instance, is used to refer to the motion of plasmas in space due to the similarity to hydrodynamics, despite there being no water present.

0019-1035/$ - see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2011.08.022

This work focuses on a set of lakes and lakebeds located in the region south of Ligeia Mare (75°N 135°E). VIMS obtained four separate spectral mapping cubes of this area on 2010 June 5 during the T69 flyby egress after closest approach. The first of these, `CM_1654399736_1`, has spatial sampling of ∼2.5 km/pixel, an exposure time of 60 ms, and was acquired with a sub-spacecraft point of 39.36°N 153.14°E. The second cube, `CM_1654400219_1`, has a best spatial sampling of 3.6 km/pixel, an exposure time of 160 ms, and was acquired with a sub-spacecraft point of 29.06°N 153.28°E. The third relevant VIMS cube was `CM_1654401134_1`, which has a best spatial sampling of 6.0 km/pixel, an exposure time of 160 ms, and was acquired with a sub-spacecraft point of 18.98°N 153.26°E. The final and least reliable VIMS cube that we use is `CM_1654404762_1`, which has a best spatial sampling of 15.8 km/pixel, an exposure time of 120 ms, and was acquired with a sub-spacecraft point of 7.57°N 152.53°E. Because the spacecraft trajectory led away from Titan, each progressive cube has coarser spatial sampling than the previous cube. When mosaiced, as shown in Fig. 1A, the changing observing geometry (incidence, emission, and phase angles) between the four cubes leads to significant seams.

We use a rudimentary bootstrap technique to compensate for differing influence from atmospheric haze so that the four cubes can be intercompared. We started with the cube with finest spatial sampling, `CM_1654399736_1`, in the northeast corner, assigning a color image based on the scheme described in Barnes et al. (2007a), with red from the atmospheric window at 5 μm, green from 2 μm, and blue from 1.3 μm. Haze scattering in the 1.3 μm is severe at these emission angles; while this renders the blue channel less useful, we keep this scheme for intercomparability with VIMS images published in previous papers. For subsequent cubes we then independently varied the contrast and brightness in each color channel separately such that it matched that from the best cube. The resulting VIMS color map is shown in Fig. 1A.

We obtained the *Cassini* RADAR data from the Planetary Data System (PDS) imaging node in a pre-reduced and calibrated format as applied by the *Cassini* RADAR team. We show in Fig. 1C a mosaiced version of the normalized RADAR cross-section σ_0 from these two flybys.

3. Analysis

The isolated patches that appear bright orange in Fig. 1A (mapped as yellow in Fig. 1B) represent instances of Titan's 5-μm-bright spectral unit (Barnes et al., 2005). The areas' high reflectivity in the 2.8-μm window relative to the 2.7-μm window, the overall high reflectivity at 5 μm, and broad trends at shorter wavelengths identify it as 5-μm-bright terrain. This spectrum is thought to represent water–ice–poor material (Barnes et al., 2009a).

A few other instances of this unit have been mapped on Titan. A thin annulus of similar 5-μm-bright material was seen by VIMS surrounding south-polar lake Ontario Lacus on the T38 (2007 December 5) Titan flyby. This may represent a 'bathtub ring' indicative of deposition and prior lake-level change (Barnes et al., 2009a). Some 5-μm-bright material exists in the interdunes between sand dunes in northern Fensal (Barnes et al., 2008). Much larger in extent are the 5-μm-bright areas Tui (Barnes et al., 2006) and Hotei (Barnes et al., 2005; Soderblom et al., 2009) Regios, both located near 25°S latitude (Fig. 3, bottom). Despite these other instances, a definitive physical origin for this spectral unit has not yet been determined (though cryovolcanism has been proposed as a possibility (Barnes et al., 2006).

In addition to the new VIMS data, the study area also has RADAR coverage from T28 (2008 April 10), and T29 (2008 April 27). To interpret our compositional results in conjunction with the local surface geology, we compare our view with that of the *Cassini* RADAR instrument for geologic context. The result is striking.

Many of the areas identified in RADAR as empty lakes (Hayes et al., 2008) (Fig. 1D) spatially correlate with the 5-μm-bright spectral unit in the VIMS data (Fig. 1E and F). Uyuni Lacuna (Fig. 2A), Atacama Lacuna (Fig. 2C), Ngami Lacuna, Jerid Lacuna, Racetrack Lacuna, Melrhir Lacuna, and many other unnamed areas all show RADAR-empty-lake morphologies and 5-μm-bright floors. The fidelity with which the extent of the 5-μm-bright unit matches the shape of the RADAR-empty lakes leaves no doubt that the two are related.

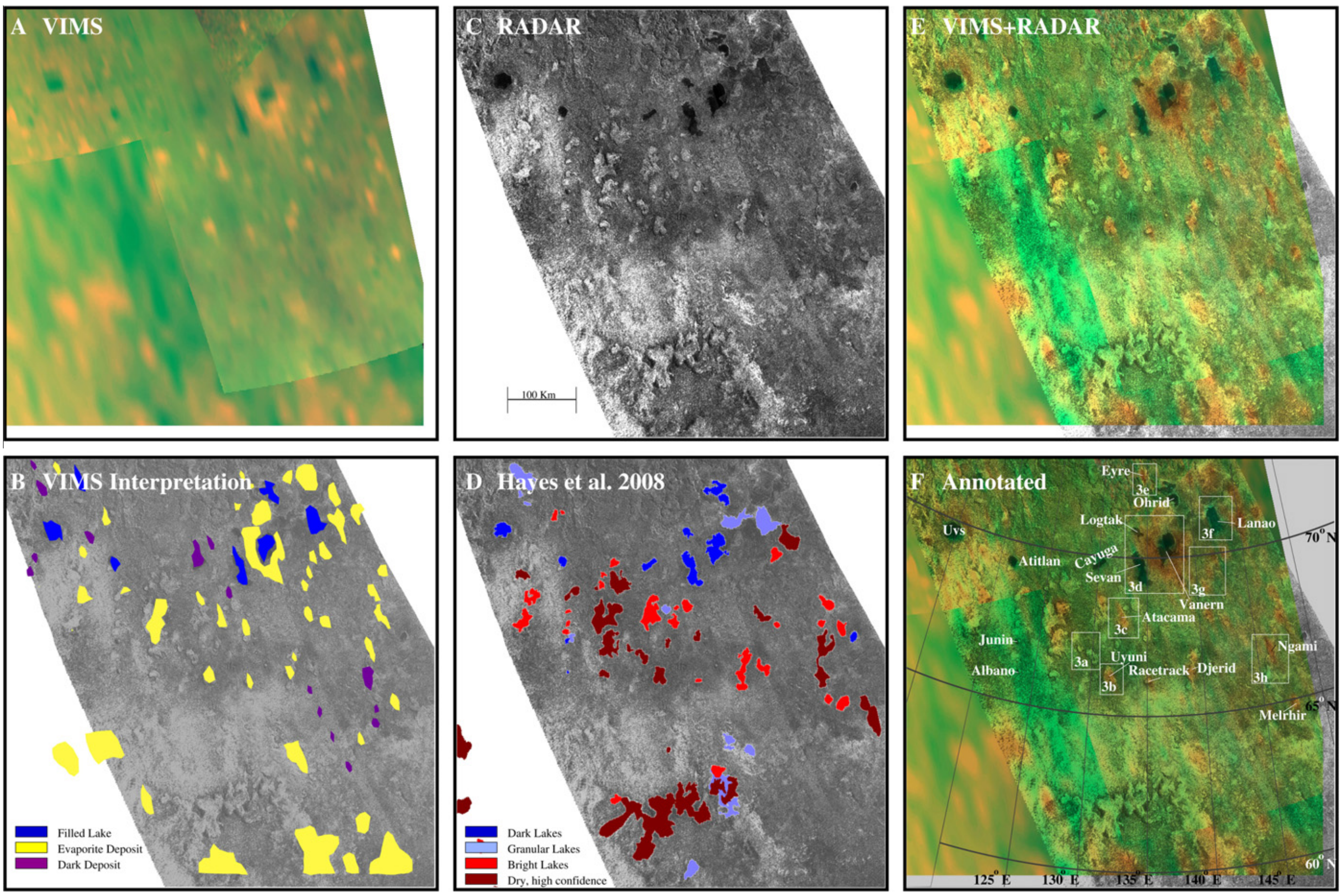

Fig. 1. This figure shows the area south of the north-polar sea Ligeia Mare on Titan in orthographic projection using data from both the VIMS and RADAR instruments onboard *Cassini*. (A) The VIMS view, color-mapped with $R = 5$ μm, $G = 2$ μm, $B = 1.3$ μm. We show an interpreted map of the VIMS data in (B); here dark blue corresponds to areas where VIMS sees open liquids, yellow to those 5-μm-bright areas that we interpret to be evaporite deposits, and purple to dark areas that may be either wetted sediments or open lakes smaller than a single VIMS pixel in size. Part (C) shows the Synthetic Aperture Radar (SAR) view from *Cassini*'s RADAR instrument, with brightness signifying the radar scattering cross-section parameter σ_0. A map from the RADAR data in (D) shows the what Hayes et al. (2008) interpret to be filled lakes (dark blue), "partially-filled" lakes (light blue), dry lakebeds (light red), and dry lakebeds with a high level of confidence (dark red). In (E) we show a combined VIMS-RADAR view that allows direct intercomparison between the two datasets. In HSV (hue-saturation-value) colorspace, the VIMS data are used for hue and saturation, and the RADAR data are assigned to value (brightness). (F) An annotated version of the VIMS-RADAR combined view from part (C), with the location of the zoomed-in views from Fig. 2 indicated by the white boxes.

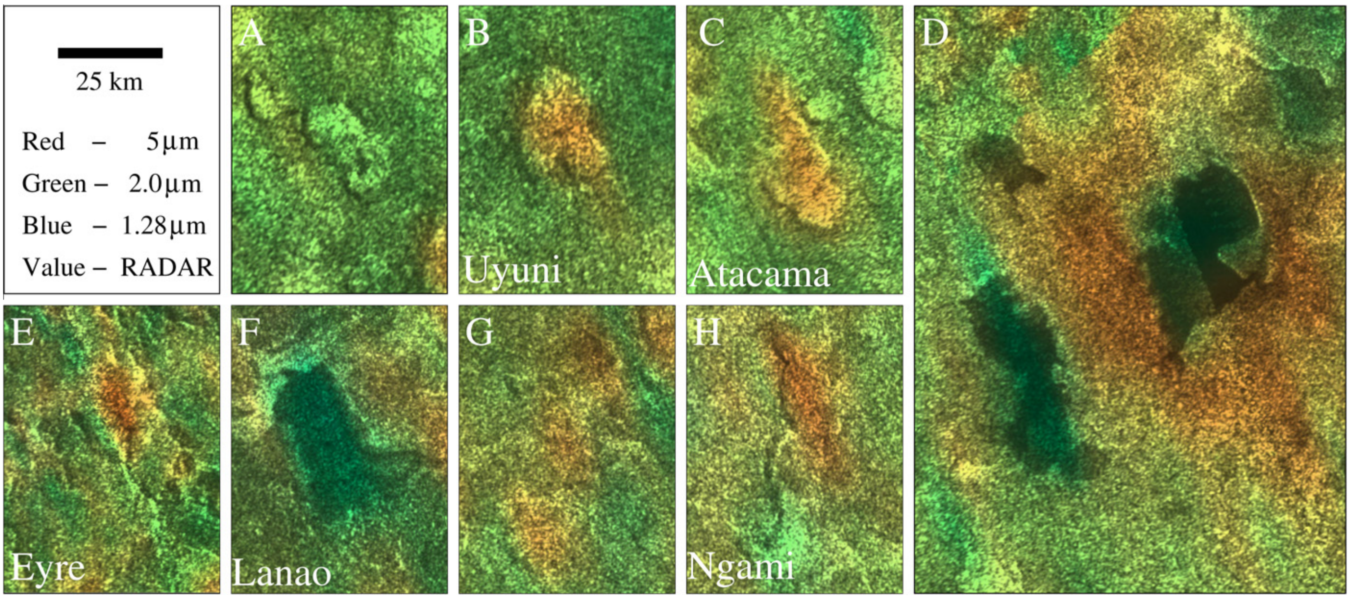

Fig. 2. This figure shows zoomed-in versions of features of interest described in the text. Part (A) shows unnamed RADAR-empty lakes northwest of Uyuni Lacus that do not have evaporite deposits on their floors. Part (B) shows Uyuni Lacus, which does have evaporite, as does Atacama Lacus in part (C) and Ngami Lacus in part (H). Part (D) shows the complex around Logtak Lacus (in the northwest), Sevan Lacus (in the southwest), and Vänern Lacus (in the east). Vänern Lacus in particular is surrounded by an evaporite deposit 20 km wide. Eyre Lacus in part (E) shows as a dry lakebed in VIMS observations, but was not initially identified as a dry lakebed in the RADAR data (Hayes et al., 2008). It was, however, later shown to be a deep basin by the SARtopo technique (Stiles et al., 2009). Part (F) shows Lanao Lacus, determined to be a shallow filled lake. The 5-µm-bright spectral units in part (G) are evaporites that do not occur in steep-walled depressions identified by RADAR as empty lakes. The southern part of part (H) shows what may be an area presently filled with liquid that was not filled during the T28/T29 RADAR passes 3 years earlier.

Not all of the RADAR-empty lakes have 5-µm-bright spectral units at their bottoms, however. The RADAR-empty lakes shown in Fig. 2A show no significant spectral differences at all when compared to the VIMS background unit. Similar areas can be found east of the area shown in Fig. 2A, between Atitlán Lacus and Cayuga Lacus, east of Atacama Lacuna, and the areas at the southern end of our study area.

From the correlation with RADAR-empty lakes we infer that the 5-µm-bright units south of Ligeia Mare must be either sedimentary or evaporitic deposits left behind in dry lakebeds. A purely sedimentary scenario might result from the settling of fine-grained erosion products in placid lakes. The small particle size that would be expected from this scenario could reproduce a 5-µm-bright spectrum. Such a purely sedimentary origin does not, however, explain why neighboring empty lakes show different floor deposits. The sediment hypothesis would also require channelbeds to be composed of the same type of sediment – the channels that we see in our study area do not have 5-µm-bright floors. Thus a sedimentary-only origin for the 5-µm-bright material is not consistent with all the observations.

RADAR-empty lakes are identified because they are depressions hundreds of meters deep with steep cliffs marking their margins as inferred from RADAR altimetry (Hayes et al., 2008). Hence rainfall runoff (and potentially groundwater methane as well) must flow into them. A potential explanation for the difference between the 5-µm-bright empty lakes and the background-spectrum empty lakes may rest in the mechanism by which liquids are removed from the lakes.

If a RADAR-empty lake lies in a closed depression with no outlets, then chemicals dissolved in raindrops, either during their passage through the hazy atmosphere or during their runoff on the surface, must build up in the resulting lake. On Earth this leads to saltwater seas– a mixture of solvent (water) and solute (salt). As inflow continues to bring solutes in, evaporation of the lake liquid systematically removes the solvents. Over time the solutes would then reach saturation and begin to precipitate out of solution. The deposits that result might then be analogs for salty evaporites that form on Earth.

Other RADAR-empty lakes whose walls are not continuous or that fill sufficiently for liquid to overflow them will behave differently. These lakes will never saturate with solute, as outlet streams will prevent solute build-up. Alternatively, closed depressions whose floors remain above the level of the local alkanofer table may empty via percolation into porous regolith (Hayes et al., 2008), and not via evaporation, thus preventing evaporite formation. Deposits on the floors of empty lakes in either of these scenarios would be sediments eroded from the surrounding surface by fluvial processes (Jaumann et al., 2008). This scenario is consistent with these empty lakes sharing a spectral signature with the background unit in VIMS.

The resulting landscape may resemble that west of the Wasach Front in the US state of Utah. There Utah lake, which has a river and many streams leading into it, has an outlet (the Jordan River) and is thus freshwater. Its sediments are not evaporitic. Downstream the Jordan flows into the Great Salt Lake. As its name implies, the Great Salt Lake is saturated in solute (salt). It has no outlets. And its periphery is dominated by a huge evaporite deposit, the Bonneville Salt Flats (Fig. 3 top), which resulted from evaporation in the large, Pleistocene-aged Lake Bonneville.

The cause of the relatively high RADAR reflectivity observed in dry lakebeds remains uncertain. Several scenarios are consistent with both RADAR-bright lakebeds and the evaporitic interpretation. VIMS sees compositional variations that might contribute to variable RADAR reflectivity. Volume scattering could also explain the brightness if the evaporite layer is at least a meter deep and contains subsurface horizons resulting from episodic drying and reflooding. While many lakebeds on Earth are smooth at *Cassini* RADAR wavelengths, some, like the Devil's Golf Course in Death Valley, California, USA, exhibit high surface roughness resulting from complex deposition and dissolution patterns.

4. Discussion

The VIMS dark patches correlate very well with those areas identified by Hayes et al. (2008) as lakes in RADAR. In particular, Uvs Lacus, Atitlán Lacus, Logtak Lacus, Sevan Lacus, Vänern Lacus (see Fig. 2D), and Ohrid Lacus (Fig. 1F) all appear as filled lakes to both RADAR and VIMS. Cayuga Lacus appears dark in VIMS, but does not fill any single pixels and thus was identified as only a possible lake in the VIMS data.

The set of features identified by Hayes et al. (2008) as "granular lakes" are transitional between filled and empty lakes. Some of the granular lakes are thought to be partially filled with liquid, with their increased RADAR backscatter deriving from the 2.2-cm RADAR beam penetrating through a shallow liquid layer and reflecting off of the lake bottom. Others may be liquid-saturated mudflats. VIMS can test for the presence of standing liquids more easily than *Cassini* RADAR because the shorter VIMS wavelength can only penetrate a few millimeters into liquid (Clark et al., 2010). VIMS can, therefore, investigate whether granular lakes are truly shallow lakes, or whether a different explanation is needed.

RADAR-granular Lanao Lacus is confirmed as a filled, shallow lake. VIMS sees Lanao to be as dark as the other set of filled lakes (Fig. 1A). *Cassini* RADAR shows a lake-like shape, but unlike filled lakes with no returned RADAR signal because of liquid absorptions, Lanao returns a uniform signal above the background across its area (Fig. 2F). This is consistent with liquids distributed evenly across a shallow basin, typical of ephemeral lakes in Earth's deserts (Lorenz et al., 2010). With this predicted shallow depth, however, we cannot rule out the possibility that this lake has filled in the time interval between the *Cassini* RADAR and VIMS observations.

Two other RADAR-granular lakes were not filled with liquid as seen by VIMS on the T69 Titan flyby. The area west of Lanao Lacus (Fig. 2F) and northeast of Vänern Lacus was identified as granular in RADAR (Hayes et al., 2008), but does not show the dark-lake spectral signature in VIMS. Its spectrum resembles that of the background surface material. A small RADAR-granular lake west of Atacama Lacuna shows the same disconnect. We see two possibilities for the status of these

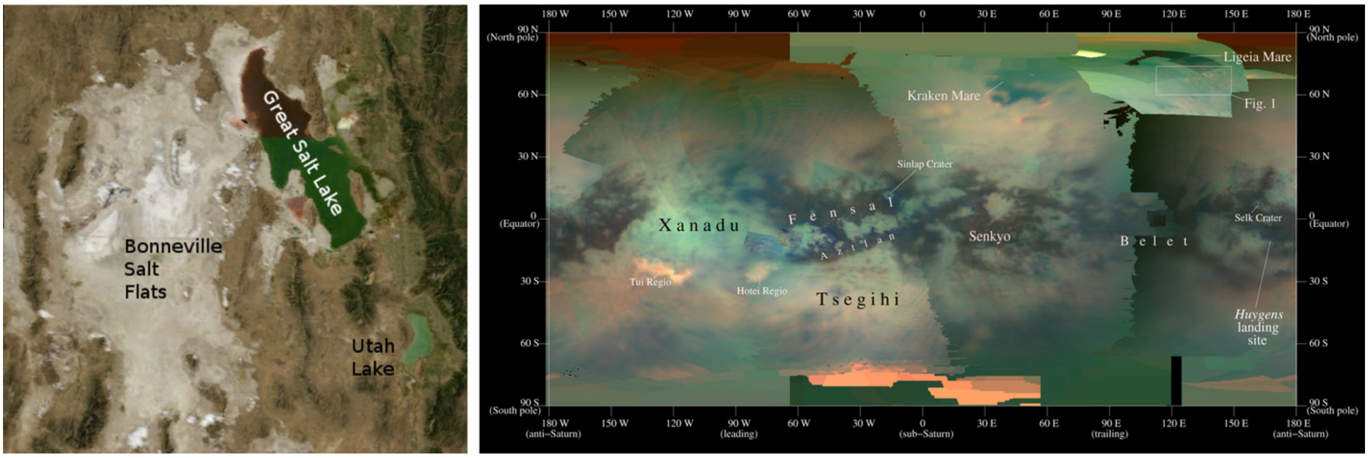

Fig. 3. (left) This satellite image (from NASA Blue Marble) shows the environs of the Great Salt Lake in Utah, USA, as discussed in the text. Despite being in close proximity to the Great Salt Lake, Utah Lake is freshwater, has an outlet that is invisible at this resolution, and has no evaporite sediments. The Great Salt Lake, on the other hand, which has no outlets, is surrounded by evaporite deposits in the form of the Bonneville Salt Flats. (right) Global cylindrical map of Titan, using the color scheme $R = 5$ μm, $G = 2$ μm, and $B = 1.3$ μm (following Barnes et al., 2007a).

apparently empty RADAR-granular lakes. They could have emptied in the 3 Earth-years between the RADAR image and the VIMS observations. Or they may represent areas that were not filled during the *Cassini* RADAR passes and are instead flat wetted plains that may or may not have previously been filled with liquid.

In one spot, south of Ngami Lacuna shown in Fig. 2H, an area identified by *Cassini* RADAR as an empty lake may be presently filled with liquid according to VIMS data. The spectrum is dark, but not as dark as the unambiguous lakes farther north. Hence, this area may either be a dark, wet mudflat or just a dry lake filled with sediments that brighten its spectrum.

By exploiting the correlation between the 5-μm-bright unit and RADAR-empty lakes, we can then use VIMS to identify dry lakebed deposits more sensitively and more robustly than using RADAR alone. Vänern Lacus (Fig. 2D) is surrounded by evaporite. Several VIMS 5-μm-bright spectral units do not have associated RADAR-empty lakes using the data from Hayes et al. (2008). Specifically, VIMS sees Eyre Lacus and the VIMS 5-μm-bright spectral units east of Lanao Lacus and southeast of Vänern Lacuna as possibly evaporitic. These areas do have margins that correlate with brights returns in the SAR data. They were not identified as RADAR-empty lakes because their margins are not (except for Eyre Lacuna) tall cliffs.

That the evaporitic lakebeds are able to maintain their spectral character in the face of the relentless settling of atmospheric haze implies that they must have been filled in the geologically recent past. Given that a coating tens of μm in depth of haze fallout would be sufficient to overprint the evaporites' spectral signature, and using the estimated rate of haze fallout of 0.1 μm per Titan year from Rannou et al. (2002), the lakes must have been filled in the last few tens of thousands of Earth years.

5. Implications

On Titan, the composition of such evaporites would necessarily be very different from that of Earth's salt flats. Methane and ethane are nonpolar molecules, hence we expect that their solutes would be quite different from those of liquid water. Several studies (Cordier et al., 2009; Barnes et al., 2009a) have suggested possibilities for species that might dissolve in such a solvent mixture as Titan's lake liquids. Most of these candidates are organics. On Titan, such species exist in atmospheric haze particles that derive from the complex chemistry ongoing in Titan's upper atmosphere (Vinatier et al., 2010). While we do not know the specific composition of the putative evaporites, they will necessarily not be water ice, consistent with the spectral character of the 5-μm-bright unit as described above. McKay (1996) shows a solubility upper limit of tholin in liquid methane of 0.03% by mass. Even this low level of solubility should produce detectable evaporitic deposits at least 10 m depth of methane solute were evaporated. Alternatively, a more volatile species like CO_2 (McCord et al., 2008) or benzene (Clark et al., 2010), which would not appear in room-temperature tholins, remain a possibility.

The similarity in spectral character between the evaporitic dry lakebeds at Titan's poles and the 5-μm-bright tropical Tui and Hotei Regios, while in no way definitive, allows for the possibility of a common origin. *Cassini* RADAR topography indicates that both Tui and Hotei are regional basins (Soderblom et al., 2009), their morphology resembles north polar dry lakes (Moore and Howard, 2010), and rivers flow toward them (Wall et al., 2009). Within Hotei Regio, *i.e.* to the north of Hotei Arcus, the 5-μm-bright area is low-lying according to RADAR stereo and exits between lobate flows seen in RADAR (Soderblom et al., 2009). If the Tui/Hotei 5-μm-bright material is evaporite, then that would imply that these areas are dry lakebeds that have been filled with liquid in geologically recent times (less than ~3000 years ago), and may again fill up on either seasonal or Milankovic (Aharonson et al., 2009) timescales. Such a scenario is not incompatible with the hypothesis of cryovolcanism at Hotei (Soderblom et al., 2009), as the bright Hotei Arcus and the RADAR flows both stand above the 5-μm-bright material and do not show the spectral signature of evaporite.

A common evaporitic origin for 5-μm-bright material would help to clarify the composition of that material. Tui Regio displays one of the few true absorption lines thus far observed on Titan (McCord et al., 2008; Clark et al., 2010). Its existence in the deposits south of Ligeia cannot be confirmed due to low signal-to-noise in our data there, but it may still be present. Many organic species have absorptions in this range. Laboratory measurements suggest that the compound HC_3N or other nitriles could be reasonable candidates for this 4.92 μm absorption feature (Clark et al., 2010). While the specific identity of the organic evaporite has not yet been determined, part of it must be a compound with both high solubility in methane in Titan conditions and a 4.92 μm absorption feature.

Any identification presents a problem, however: with mixed organic material falling uniformly across Titan, why are strong absorptions from solids seen only at Tui and Hotei Regios, and what would concentrate HC_3N there but not elsewhere? Evaporitic processes can answer both questions. The process of precipitating solids from evaporating saturated liquids can create crystals, allowing for long optical path lengths and deep absorption features. And dissolution followed by recrystallization provides a mechanism by which to selectively transport and purify compounds like HC_3N in lake bottoms. In doing so, the bottom of these lakes may, therefore, represent a potentially vast organic sink not accounted for in present calculations (Lorenz et al., 2008).

Acknowledgments

The authors acknowledge support from the *Cassini* Project and helpful discussions with Ralph D. Lorenz and Christopher P. McKay.

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