Active shoreline of Ontario Lacus, Titan: A morphological study of the lake and its surroundings

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[1]   Of more than 400 filled lakes now identified on Titan, the first and largest reported in the southern latitudes is Ontario Lacus, which is dark in both infrared and microwave. Here we describe recent observations including synthetic aperture radar (SAR) images by Cassini's radar instrument ($\lambda = 2$ cm) and show morphological evidence for active material transport and erosion. Ontario Lacus lies in a shallow depression, with greater relief on the southwestern shore and a gently sloping, possibly wave-generated beach to the northeast. The lake has a closed internal drainage system fed by Earth-like rivers, deltas and alluvial fans. Evidence for active shoreline processes, including the wave-modified lakefront and deltaic deposition, indicates that Ontario is a dynamic feature undergoing typical terrestrial forms of littoral modification. **Citation:** Wall, S., et al. (2010), Active shoreline of Ontario Lacus, Titan: A morphological study of the lake and its surroundings, *Geophys. Res. Lett.*, *37*, L05202, doi:10.1029/2009GL041821.

1. Introduction

[2]   Circumstantial evidence that Titan's dark lakes are liquid-filled comes from a variety of properties measured by the Cassini RADAR [*Elachi et al.*, 2004; *Stofan et al.*, 2007]. Methane precipitation has not been directly observed but is widely predicted [*Lorenz*, 1993], and the nature of storms has been described [*Tokano et al.*, 2006; *Hueso and Sánchez-Lavega*, 2006]. Large-scale oceans do not exist [e.g., *West et al.*, 2005; *Elachi et al.*, 2005, 2006], but what appear to be liquid-filled basins have been imaged, ranging in size from <10 to more than 10^5 km^2 [*Stofan et al.*, 2007; *Hayes et al.*, 2008]. Ontario Lacus, a 200 km × 70 km lake at 74S, 180W, was first observed in near-infrared [*Turtle et al.*, 2009]. *Barnes et al.* [2009] provided the first geomorphic analysis of Ontario's shore and suggested lake level changes, best understood as due to the presence in the lake of liquid methane [*Lunine et al.*, 2009]. Therefore, Ontario Lacus' spectroscopic and time-dependent properties imply it is a mixed ethane-methane lake.

[3]   Two SAR swaths with resolution cell sizes [*Weik*, 1989] between 350 and 500 m, radiometry and an altimetry track over Ontario Lacus were obtained 22 June 2009, 8 July 2009 and 21 December 2008. The SAR swaths are mosaicked in Figure 1 (see auxiliary material for full image).[14] Along the shoreline of Ontario, deeply incised bays (at 'A') resemble drowned river valleys flooded by a rise in lake level. At the NW corner, the shore intersects a large radar-bright region 'B', located 300–500 m above the lake surface that we interpret as a mountainous region similar to other mountainous terrain seen on Titan [*Radebaugh et al.*, 2007]. Here the liquid embays the brighter unit, revealing topographic lows that may be further flooded. Farther east begins a long smooth section of the lakeshore that we interpret as a beach ('C'). A river valley ('D') appears to connect to the apex of a fan-shape body ('E') interpreted as an alluvial fan. Smooth lines, parallel to the current shoreline, are consistent with raised beaches from earlier lake highstands. Lines parallel to the shore are visible within the lake from 'C' to 'E', likely representing shorelines submerged at shallow depth (meters or less) under the lake surface. The overall morphology of this shore of the lake, with long smooth beaches, is consistent with wave modification [e.g., *Woodroffe*, 2003]. Similar features are seen at Lake Michigan, USA, which has a wave-dominated shoreline (Figure 2a).

[4]   About 100 km farther to the south lies a curious feature ('F') composed of both a round-headed bay intruding into the shore and two intrusions of the brighter shore material into the lake. On close inspection, this feature can be identified in previous infrared images [*Turtle et al.*, 2009; *Barnes et al.*, 2009]. We interpret the dark oval areas as liquid-filled depressions, possibly formed by melting or

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[14]Auxiliary materials are available in the HTML. doi:10:1029/2009GL041821.
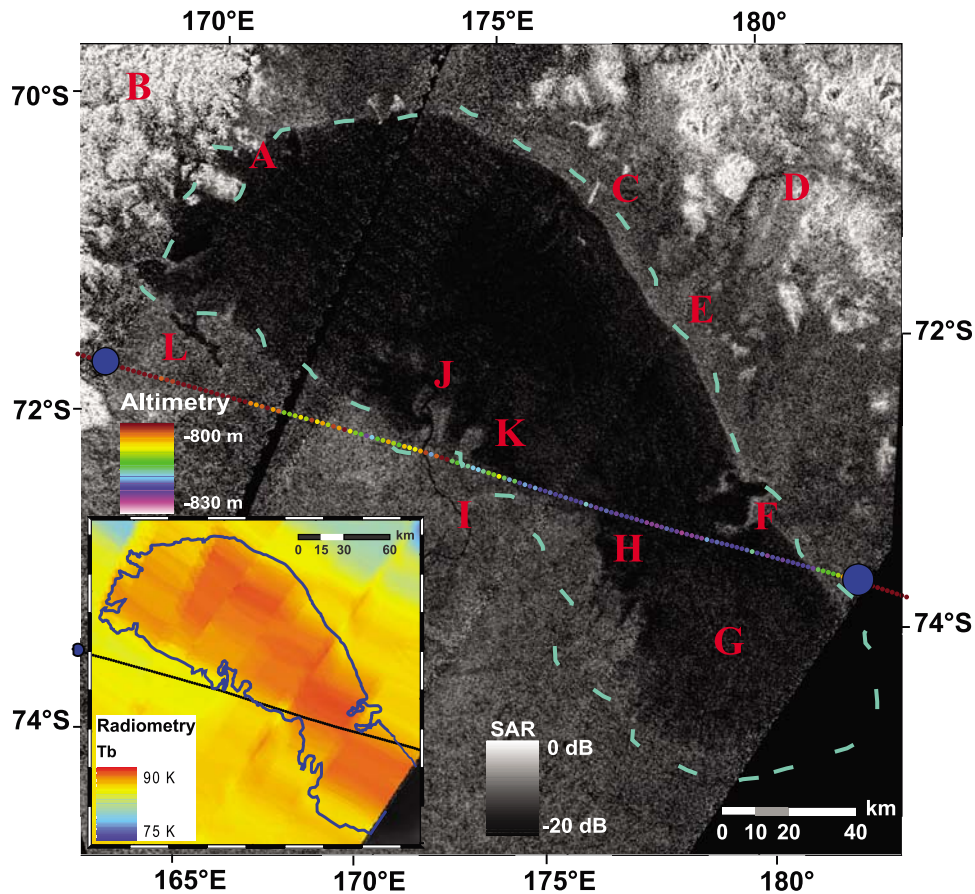
Figure 1. Polar stereographic mosaic of Ontario Lacus from SAR passes T57 and T58, with altimetry overlain. North is up, SAR image has illumination from left and incidence angle varying from 24 to 44 degrees. The corrugated linear patterns in the lake are processing artifacts. The inset shows passive radiometry, acquired coincident with SAR. Radar altimetry is shown as a color-coded stripe across both images (blue circles indicate footprint sizes), and an outline of an earlier IR image is shown as a dashed line with collocation error <3 km (see text). Letter callouts are referenced in the text.

dissolution over the crest of a diapiric structure that formed the raised rims around the depressions. The dark embayment appears to cut across the shore-parallel raised beach, suggesting that it is relatively recent.

[5] The central lake interior is generally very dark (at or below the radar noise floor) with brighter patches towards the southern end ('G') that may be variations in texture on the liquid's surface, shallow areas where solid or semisolid
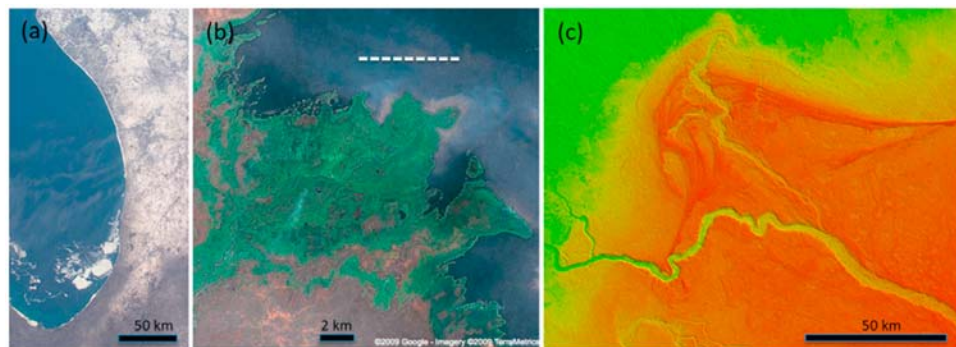

Figure 2. (a) The smooth shoreline of Lake Michigan is shaped by wave action, as seen in this International Space Station image of the lake. Image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center, ISS006-E-29393 (http://eol.jsc.nasa.gov). (b) Image of the Semliki River delta of Lake Albert, on the Uganda-Democratic Republic of the Congo border. The Semliki River originally fed a delta lobe to the south; the abandoned river channel is indicated by the dashed white line. Google Earth imagery © Google Inc. Used with permission. (c) Shaded relief view of Shuttle Radar Topography Mission DEM showing a wave modified delta from palaeolake Megachad where wave-formed bars and beach ridges modify the delta front.
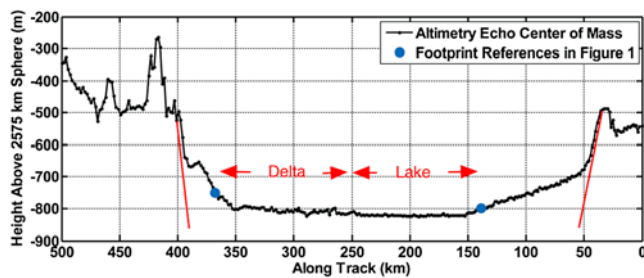
Figure 3. Radar altimetry taken 21 December 2008 (track is shown in Figure 1). Reported heights represent the altimetry echo center of mass. Positions of the lake and deltas are indicated. Red lines illustrate the possible bounding faults of a graben in which the lake is located. The flooded valley lake morphology is located at the lower end of the graben (to the left). Blue dots refer to locations on the Figure 1 track.

structures reach the surface, or, in shallower places, micro-wave penetration to the bottom revealing lake bathymetry [*Paillou et al.*, 2008; A. Hayes et al., Bathymetry and absorptivity of Titan's Ontario Lacus, submitted to *Journal of Geophysical Research*, 2010].

[6] Continuing along the shoreline, the indented coastline at 'H' may represent flooded river valleys, with a mor-phology reminiscent of estuaries, but given the limited resolution we are unable to identify any channels inland from the shore. In contrast, at 'I' a ~1 km wide channel similar to others elsewhere on Titan [*Elachi et al.*, 2005, 2006; *Barnes et al.*, 2007; *Lorenz et al.*, 2008] appears to discharge into the lake forming a fluvially dominated delta. From the morphology of the delta, we conclude that switching of the distributary channels has occurred, pro-ducing two delta lobes ('J', 'K'). 'K' may be an abandoned delta lobe or may be fed by a sub-resolution river channel. Analogous delta switching can be seen in the delta of the Semliki River at the southern end of Lake Albert (Figure 2b), which is fluvially dominated. Although the SAR image of Ontario Lacus is lower resolution, the delta morphology appears to be more complex, possibly indicating wave reworking of the delta front. Figure 2c depicts a digital ele-vation map (DEM) of a wave modified delta from palaeo-lake Megachad where wave formed bars and beach ridges modify the delta front [*Schuster et al.*, 2005]. Continuing along the shoreline, the diagonal line cutting the image is a gap in the radar data. Further west, where SAR image quality is lower, a complex embayment with a wider (~3 km) channel ends in a near-perpendicular "T" intersection (at 'L') that we interpret as a flooded valley system.

[7] The overall appearance of Ontario Lacus in the SAR swaths is quite different than in the near-infrared image acquired 6 June 2005 [*Turtle et al.*, 2009]. The lakeshore in that image is shown by a dashed line in Figure 1 with a co-location error of <3 km, which can be interpreted to indicate that the shoreline has receded inward by ~10 km [*Lunine et al.*, 2009; A. Hayes et al., Observations and modeling of transient surface liquid in Titan's south polar region from Cassini, submitted to *Icarus*, 2009].

[8] Altimetry data offer strong evidence that Ontario Lacus is a basin filled with liquid. Detected heights (Figure 3) reveal a flat lake surface with shorelines elevated perhaps a few tens of meters to the east and much less so at the

southern shore. Individual echoes show very strong specular reflection, thus an extremely flat lake surface, with <3 mm rms height variation over 100-meter lengths [*Wye et al.*, 2009]. If wind-wave generation theories [e.g., *Ghafoor et al.*, 2000; *Notarnicola et al.*, 2009; *Lorenz et al.*, 2005] apply under Titan conditions, then either the winds were very weak (<0.3 m/sec [*Notarnicola et al.*, 2009] during the altimetry observation, or the liquid material is much more resistant to wave generation than previously thought [*Wye et al.*, 2009]. Thus the lake may have been calm when the altimetry data were collected, but at other times waves must have been present to form the beach on the northeastern side of the lake. With no similar beach on the southwestern shore, and no evidence of structural or other causes for the asymmetry, some period of prevailing wind from the W or SW is implied – generally consistent with a circulation model developed by *Tokano* [2008]. The altimetry data indicate a break in topography at around 50 km and 380 km along track, which could represent fault scarps indicating that Ontario Lacus lies within a rift valley or graben (see Figure 3). Altimetry data also cross the boundary between units suggested by *Barnes et al.* [2009], but the footprint size does not allow discrimination of Unit 2 slope as sug-gested in that work.

[9] Radiometry data (Figure 1, inset) show that the lake area has high emissivity. We measure a normal incidence maximum brightness temperature of 88.5 K (with absolute calibration of ~1–1.5 K [*Janssen et al.*, 2009]) in the darkest (thus assumed deepest) part of the lake. For methane-ethane mixtures of dielectric constant of 1.7–1.9 [*Paillou et al.*, 2008] would correspond to a physical temperature of 90.0–90.8 K. The large-scale average temperature recorded by CIRS from 2004 to 2008 at these latitudes is ~92 K [*Jennings et al.*, 2009], only marginally higher than our result. If the difference is physically significant and not due to statistical uncertainties in the radiometric calibration, it may imply an effective dielectric constant slightly higher due to suspended or dissolved solid organics, or an effect of sensing the bottom through shallow liquid. Evaporative cooling [*Mitri et al.*, 2007] by summer winds could also explain the observation, but would require this cooling effect to exceed the warming by summer sunshine. Cyclic evaporation and refilling would strengthen the interpretation of multiple shorelines and flooded valleys.

2. Discussion

[10] Cassini microwave data illustrate that Ontario is an active liquid-filled lake, with evidence for wave modifica-tion, deltaic deposition of material, and changes in lake level. Shoreline morphology differs on either side of the lake. The northeastern side (Figure 1, C, E, F) has a con-structional wave-dominated shoreline with a raised beach. The southwestern shore (Figure 1, J, K, H, G) is an indented coastline with ria-like flooded valleys and local delta development at the river mouth. Beach development along the northeast shore suggests onshore winds (from S–SW) and wave activity, consistent with global prediction [*Tokano*, 2008]. The raised beach indicates former lake shorelines when the lake level was higher. The southwestern shore lacks wave-formed sedimentary structures, possibly due to offshore winds. Furthermore, the morphology sug-gests a drowned coast indicating a relative rise in lake level.

The different shoreline morphologies suggest a tilting of the basin floor towards the west, which may possibly be due to tectonic tilting within a graben (Figure 3b). All of these morphologies, the altimetry data indicating that at times the lake is extremely smooth [*Wye et al.*, 2009], the marginally lower temperature inferred from radiometry data, and evidence for lake level change (Hayes et al., submitted manuscript, 2009) all characterize a dynamic lacustrine environment on Titan, with the level of activity likely related to seasonal cycling [*Lunine et al.*, 2009] or longer term oscillations in the insolation associated with variations in the orbit of Saturn [*Aharonson et al.*, 2009]. This dynamic environment reinforces our interpretation of multiple shorelines, and flooded valleys.

[11] We have identified a depositional delta at Ontario, the first example of one on Titan, indicating persistent flow in the feeding channel that delivers sediment to the lake. Quiescent conditions would be expected to allow material to fall out of suspension and accumulate locally. The area of the main lobe of the deposit (Figure 1, J) is approximately 97 km^2; that of the second lobe just to the southeast is 50 km^2 (these areas vary by of order a few km^2 depending on the choice of boundary). Doubling this area to give an estimate of the overall delta size, we obtain an area nearly two orders of magnitude smaller than terrestrial river deltas fed by comparable width rivers. For comparison, rivers on Earth with a width of 1 km immediately upstream from their deltas include the Indus, Mississippi, Irrawady, and Song Hong (Red) Rivers, which have delta areas of 29500, 28500, 20500, and 11900 km^2, respectively [*Coleman and Wright*, 1975]. The size of a delta is a function of the sediment discharge and accommodation space [*Goodbred and Kuehl*, 2000]. The depth profile of Ontario Lacus is poorly constrained, but if we extrapolate from the shore topography the lake is likely to be relatively shallow, which could accommodate a large delta. The lobate morphology of the delta is also consistent with a shallow-water delta, suggesting low sediment discharge and thus probably low sediment supply, slow flow velocity and a low sediment transport capacity.

[12] As Titan is passing through northern spring equinox in its nearly 30-Earth year annual cycle, future Cassini observations at Ontario will of necessity be by RADAR, since it will be in darkness for the next decade and a half. The snapshot of Ontario reported here provides a firm foundation for the detection of changes on seasonal timescales and reveals a lake with morphologic and seasonal variations typical of terrestrial lakes.

References

Aharonson, O., et al. (2009), An asymmetric distribution of lakes on Titan as a possible consequence of orbital forcing, *Nat. Geosci.*, *2*, 851–854, doi:10.1038/ngeo698.

Barnes, J., et al. (2007), Near-infrared spectral mapping of Titan's mountains and channels, *J. Geophys. Res.*, *112*, E11006, doi:10.1029/2007JE002932.

Barnes, J., et al. (2009), Shoreline features of Titan's Ontario Lacus from *Cassini*/VIMS observations, *Icarus*, *201*, 217–225, doi:10.1016/j.icarus.2008.12.028.

Coleman, J., and L. Wright (1975), Modern river deltas: Variability of processes and sand bodies, in *Deltas Models for Exploration*, edited by M. L. Broussard, pp. 99–149, Houston Geol. Soc., Houston, Tex.

Elachi, C., et al. (2004), RADAR: The Cassini Titan Radar Mapper, *Space Sci. Rev.*, *115*, 71–110, doi:10.1007/s11214-004-1438-9.

Elachi, C., et al. (2005), Cassini radar views the surface of Titan, *Science*, *308*, 970–974, doi:10.1126/science.1109919.

Elachi, C., et al. (2006), Titan Radar Mapper observations from Cassini's T3 flyby, *Nature*, *441*, 709–713, doi:10.1038/nature04786.

Ghafoor, N. A.-L., J. C. Zarnecki, P. Challenor, and M. A. Srokosz (2000), Wind-driven surface waves on Titan, *J. Geophys. Res.*, *105*, 12,077–12,091, doi:10.1029/1999JE001066.

Goodbred, S., and S. A. Kuehl (2000), The significance of large sediment supply, active tectonism, and eustacy on margin sequence development: Late Quaternary stratigraphy and evolution of the Ganges-Brahmaputra delta, *Sediment. Geol.*, *133*, 227–248, doi:10.1016/S0037-0738(00)00041-5.

Hayes, A., et al. (2008), Hydrocarbon lakes on Titan: Distribution and interaction with a porous regolith, *Geophys. Res. Lett.*, *35*, L09204, doi:10.1029/2008GL033409.

Hueso, R., and A. Sánchez-Lavega (2006), Methane storms on Saturn's moon Titan, *Nature*, *442*, 428–431, doi:10.1038/nature04933.

Janssen, M., et al. (2009), Titan's surface at 2.2-cm wavelength imaged by the Cassini RADAR radiometer: Calibration and first results, *Icarus*, *200*, 222–239, doi:10.1016/j.icarus.2008.10.017.

Jennings, D., et al. (2009), Titan's surface brightness temperatures, *Astrophys. J.*, *691*, L103–L105, doi:10.1088/0004-637X/691/2/L103.

Lorenz, R. (1993), The life, death and afterlife of a raindrop on Titan, *Planet. Space Sci.*, *41*(9), 647–655, doi:10.1016/0032-0633(93)90048-7.

Lorenz, R., et al. (2005), Sea-surface wave growth under extraterrestrial atmospheres—Preliminary wind tunnel experiments with application to Mars and Titan, *Icarus*, *175*, 556–560, doi:10.1016/j.icarus.2004.11.019.

Lorenz, R., et al. (2008), Fluvial channels on Titan: Initial Cassini RADAR observations, *Planet. Space Sci.*, *56*(8), 1132–1144, doi:10.1016/j.pss.2008.02.009.

Lunine, J., et al. (2009), Evidence for liquid in Ontario Lacus (Titan) from Cassini-observed changes, *Bull. Am. Astron. Soc.*, *41*, 164.

Mitri, G., A. Showman, J. Lunine, and R. Lorenz (2007), Hydrocarbon lakes on Titan, *Icarus*, *186*(2), 385–394, doi:10.1016/j.icarus.2006.09.004.

Notarnicola, C., B. Ventura, D. Casarano, and F. Posa (2009), Cassini radar data: Estimation of Titan's lake features by means of a Bayesian inversion algorithm, *IEEE Trans. Geosci. Remote Sens.*, *47*, 1503–1511, doi:10.1109/TGRS.2008.2005906.

Paillou, P., K. Mitchell, S. Wall, G. Ruffié, C. Wood, R. Lorenz, E. Stofan, J. Lunine, R. Lopes, and P. Encrenaz (2008), Microwave dielectric constant of liquid hydrocarbons: Application to the depth estimation of Titan's lakes, *Geophys. Res. Lett.*, *35*, L05202, doi:10.1029/2007GL032515.

Radebaugh, J., et al. (2007), Mountains on Titan observed by Cassini Radar, *Icarus*, *192*(1), 77–91, doi:10.1016/j.icarus.2007.06.020.

Schuster, M., et al. (2005), Holocene Lake Mega-Chad paleoshorelines from space, *Quat. Sci. Rev.*, *24*, 1821–1827, doi:10.1016/j.quascirev.2005.02.001.

Stofan, E., et al. (2007), The lakes of Titan, *Nature*, *445*, 61–64, doi:10.1038/nature05438.

Tokano, T. (2008), Dune-forming winds on Titan and the influence of topography, *Icarus*, *194*(1), 243–262, doi:10.1016/j.icarus.2007.10.007.

Tokano, T., et al. (2006), Methane drizzle on Titan, *Nature*, *442*, 432–435, doi:10.1038/nature04948.

Turtle, E. P., J. E. Perry, A. S. McEwen, A. D. DelGenio, J. Barbara, R. A. West, D. D. Dawson, and C. C. Porco (2009), Cassini imaging of Titan's high-latitude lakes, clouds, and south-polar surface changes, *Geophys. Res. Lett.*, *36*, L02204, doi:10.1029/2008GL036186.

Weik, M. (1989), *Communications Standard Dictionary*, 2nd ed., Van Nostrand Reinhold, New York.

West, R., et al. (2005), No oceans on Titan from the absence of a near-infrared specular reflection, *Nature*, *436*, 670–672, doi:10.1038/nature03824.

Woodroffe, C. (2003), *Coasts, Form, Process and Evolution*, Cambridge University Press, Cambridge, U. K.

Wye, L., H. Zebker, and R. Lorenz (2009), Smoothness of Titan's Ontario Lacus: Constraints from Cassini RADAR specular reflection data, *Geophys. Res. Lett.*, *36*, L16201, doi:10.1029/2009GL039588.

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