Titan's inventory of organic surface materials

Ralph D. Lorenz, Karl L. Mitchell, Randolph L. Kirk, Alexander G. Hayes, Oded Aharonson, Howard A. Zebker, Philippe Paillou, Jani Radebaugh, Jonathan I. Lunine, Michael A. Janssen, et al.

Titan's Inventory of Organic Surface Materials

Ralph D. Lorenz[1,*], Karl L. Mitchell[2], Randolph L. Kirk[3], Alexander G. Hayes[4], Oded Aharonson[4], Howard A. Zebker[5], Phillipe Paillou[6], Jani Radebaugh[7], Jonathan I. Lunine[8], Michael A. Janssen[2], Stephen D. Wall[2], Rosaly M. Lopes[2], Bryan Stiles[2], Steve Ostro[2], Giuseppe Mitri[2], Ellen R. Stofan[9] and the Cassini RADAR Team

[1] Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723,

[2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109.

[3] U. S. Geological Survey, Flagstaff, AZ 86001.

[4] Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA

[5] Stanford University , Stanford CA 94305

[6] OASU-L3AB UMR 5804, BP 89, 33270 Floirac, France

[7] Department of Geological Sciences, Brigham Young University, Provo, UT.

[8] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721

[9] Proxemy Research, Rectortown, VA 20140

Submitted 21 September 2007 to Geophysical Research Letters

Revised version 2007GL032118R Accepted 20th November 2007

Abstract

Cassini RADAR observations now permit an initial assessment of the inventory of two classes, presumed to be organic, of Titan surface materials: polar lake liquids and equatorial dune sands. Several hundred lakes or seas have been observed, of which dozens are each estimated to contain more hydrocarbon liquid than the entire known oil and gas reserves on Earth. Dark dunes cover some 20% of Titan's surface, and comprise a volume of material several hundred times larger than Earth's coal reserves. Overall, however, the identified surface inventories (>$3x10^4$ km^3 of liquid, and >$2x10^5$ km^3 of dune sands) are small compared with estimated photochemical production on Titan over the age of the solar system. The sand volume is too large to be accounted for simply by erosion in observed river channels or ejecta from observed impact craters. The lakes are adequate in extent to buffer atmospheric methane against photolysis in the short term, but do not contain enough methane to sustain the atmosphere over geologic time. Unless frequent resupply from the interior buffers this greenhouse gas at exactly the right rate, dramatic climate change on Titan is likely in its past, present and future.

1. Introduction

It has been long realized (e.g. Hunten, 1973) that thick deposits of photochemical materials may have accumulated on Titan's surface. Prior to the arrival of Cassini-Huygens, some 20 different organic molecules had been identified in Titan's atmosphere (e.g. Lorenz and Mitton, 2002), but the composition and extent of surface deposits was unknown. In this paper we report an assessment of the volume of liquid and solid organic materials from radar imaging data over ~20% of Titan's surface.

Two principal surface carbon reservoirs are considered: lakes and dunes. There may be considerable deposits of other organic materials, for example in Titan's midlatitudes where neither of these feature types are seen, and indeed global measurements of Titan's dielectric constant (Elachi et al., 2005) suggest that porous and/or organic materials make up much of the surface. This interpretation is not unique, nor can we assess any potential subsurface reservoirs such as an aquifer system that may hydraulically connect the lakes. We restrict the present analysis to areas where we can make morphological identification of aeolian sediment and liquids in lakes. Compositions have not been measured directly, but can be inferred to be predominantly carbon-bearing as follows.

Only methane, ethane and propane are liquids at Titan's surface conditions, but propane is produced in photochemical models only 1/40th as abundantly as ethane (e.g. Yung and DeMore, 1999). Some organic solids may be dissolved as traces (Raulin, 1987) up to a few per cent and in equilibrium with the atmosphere about 5% dissolved nitrogen is present, but for brevity we consider the lakes as an ethane/methane mix.

The dune sand is known to be radar-dark, as well as dark at near-infrared window wavelengths between 0.94 and 5 microns since the radar-determined sand seas correspond (Lorenz et al., 2006a) to regions seen to be dark in near-infrared groundbased observations and dunes were seen in Huygens images (Soderblom et al., 2007).. These factors suggest, but do not prove, an organic component, such as the photochemical 'tholin' material produced in laboratory simulations, rather than pure water ice.

2. Lakes

Although a surface reservoir of hydrocarbon liquids was long expected on Titan, convincing evidence for such liquids was not found until radar imaging covered high latitude areas (Stofan et al., 2007.) Above 55^{o}N, radar observations have now (through T30 – May 2007) covered 55.4% of the terrain : of this, some 10% (~400,000km^2, or 0.5% of Titan's surface) is identified as covered by lakes or seas – see figure 1. A variety of lake morphologies imply diverse formation mechanisms that may include terrain flooding and karst dissolution (Mitchell et al., in preparation). Features range in size from a few kilometers (the smallest recognizable in our best data of ~300m/pixel) to several hundred km. The combination of low radar reflectivity and high microwave emissivity plus the feature morphology and association with channels together point to present-day liquid.

To determine the lake depth we use terrestrial analogs as a guide. A brief survey of terrestrial lakes (see figure 2) indicates that a convenient and reasonably effective estimate is that a lake has an aspect ratio of 1/1000 (i.e. the average depth d=0.0010 X, where the lake area is X^2, or equivalently its depth in meters equals the size in kilometers.) A least-squares linear fit to the world's 20 largest lakes yields d=0.0015 X + 66. In practice, the diverse lake formation settings – from deep rift, fault or glacial lakes to shallow playas - lead to variations of an order of magnitude about these values. A survey (Hayes et al., in preparation – see also figure 1) of the Titan lakes indicates a median area of 100km^2, and thus a depth of ~10m and a volume of 1km^3. However, a 'similar-shape' model like this will find the liquid volume dominated by the largest lake – so far the largest lake or sea imaged is a 400x200km (80,000km^2) section of what is presumably a rather larger (as yet unnamed) feature at 70^{o}N, 315^{o}W, which would correspondingly be ~300m deep, or have a total volume of some ~25,000km^3, even without allowing for unobserved areas of this feature (which near-infrared imaging shows to be part of a large, irregular optically-dark feature with an area of some 340,000km^2 (Turtle et al., 2007)).

Another metric is the height of nearby topography. Terrestrial examples suggest that average lake depth is often a factor of 10 less than the height of the highest nearby terrain, although again there are extremes (e.g. Lake Baikal, Earth's deepest lake at 1600m, has mountains of ~3400m nearby, whereas the Great Salt Lake has a depth of only a few m but has nearby km-high mountains – i.e. the depth/terrain ratio can vary from about 2 to several hundred.) Altimetry and other data show that there is relief of ~700m or more in Titan's North polar lakeland terrain, as in a few other areas on Titan. Thus a characteristic depth of 70m would be implied, in good agreement with the 10-300m range suggested by area scaling above.

A final, and completely independent, measure is radiometric. The darkest parts of some lakes, generally the largest ones, are 'black holes', offering no measureable radar return down to the instrument noise floor of ~ -26 dB (Stofan et al., 2007). This requires not only that the surface reflection be very small (consistent with a smooth surface of a low dielectric constant material, such as a liquid hydrocarbon surface unroughened by waves) but also requires that the liquid be deep and/or lossy enough to suppress a bottom reflection. Lake bottoms with sediment density increasing smoothly with depth could also suppress bottom reflections via gradient-index impedance matching : however, there are morphological indications such as dark channels incised in almost-as-dark lakes that suggest that at least in some places bottom reflections are seen. Assuming then that such lakebed features are being hidden in 'black' areas by column absorption, a minimum depth can be inferred : the lower the assumed loss tangent δ, the deeper the lake must be. Clean liquid hydrocarbons have $\delta \sim 10^{-4}$ to 10^{-3} (Sen et al., 1992; Rodriguez et al., 2003) although suspended or dissolved polar molecules such as nitriles and small tholin particles could increase these values. A penetration depth (1/e one-way absorption – see e.g. similar calculations elsewhere in the Saturnian system, Ostro et al., 2006) of $\lambda/2\pi\delta\sqrt{\varepsilon}$, with λ the radar wavelength of 2.2cm and ε the real part of the dielectric constant (~2), would therefore be 2-20m – lakes with nonzero reflectivity or visible lakebed features are therefore likely shallower than this range.

In summary, several lines of evidence point towards smaller lakes on Titan (~100km^2) having a depth of the order of 10m, and the handful of large 'seas' having depths ten or more times greater. It is noteworthy, that dozens of Titan's lakes individually contain ~200km^3 of liquid methane/ethane, an amount equal to the ~130 billion tonnes of proven natural gas reserves on Earth. Indeed, Titan's total inventory of liquids exceeds terrestrial oil and gas reserves by a factor of several hundred (~400-500 GT or ~800-1000 km^3, Falkowski et al., 2000; BP 2007).

Taking a conservative average depth of 20m, and a total lake area of ~400,000km^2 gives an observed inventory of some 8000 km^3, although if the larger lakes or seas have larger depths, an inventory of the order of 5-10 times this is likely. This is the inventory that has been directly observed by radar to date. If we make the assumption that the unobserved 45% of terrain north of 55^{o}N has a similar coverage, we double the inventory. A further doubling arises if we assume that southern polar areas have a similar inventory to the North, leading to a likely inventory of $3x10^4 – 3x10^5$ km^3 of liquid. Radar imaging of the southern polar region is planned for Cassini's extended mission, but a lake-shaped, optically-dark region (Turtle et al., 2007) is already known ('Lacus Ontario', area ~40,000km^2).

3. Dunes

Some 40% of Titan's equatorial areas (up to 30^o latitude) are covered in 1-2km wide longitudinal sand dunes (Lorenz et al, 2006a; Radebaugh et al., 2007), correlating with areas seen to have a distinct dark near-infrared spectral type (e.g. Soderblom et al., 2007), although very few are found poleward of 30^o . As on Earth, a range of dune size and interdune sand depth is observed. First, when the radar illumination is broadside-on to large dunes and interdune sand is thick enough that the intrinsic radar albedo of the surface is uniform, topographic shading is the major contributor to brightness variation in the scene. This permits a radarclinometric estimate of dune height of the largest dunes of ~150m (Lorenz et al., 2006a). The typical dune width to interdune distance ratio is 1-4, so we can assign an area-average sand dune thickness (assuming a triangular cross-section with height) of 15-50m. To this must be added the thickness of sand in the interdune areas, estimated below as ~5m, and thus we adopt a typical area-averaged sand thickness for thick-sand areas of 30m.

More typically, with off-broadside observations, smaller dune height and especially with thinner interdune sand, the duneform is seen only as a dark streak, against a brighter exposed or thinly-covered interdune background (as for many radar observations of dunes on Earth). In these cases, radarclinometric measurement of height is impossible. However, field data of Earth dunes show (Lancaster, 1995) that longitudinal dunes have height:width of 0.01-0.2, implying Titan dune heights of 10-400m (similar heights result from considering the height:spacing ratios).

We can also apply a radiometric constraint, namely that the dunes appear dark against the bright interdune material by obscuring it. Rodriguez et al. (2003) determine loss tangent δ of tholin of between 0.001 and .05. The corresponding penetration depths as above ($\sim\lambda/10\delta$) are 2m and 0.04m. Thus a minimum thickness of dark streaks (and dark interdune areas where topographic shading is seen) of a meter or so seems likely, although is in this case less constraining than the morphological similarity range of >10m above. Again adopting a local dune coverage fraction of 20-50%, we therefore find an area-average sand thickness of 2-200m and adopt 10m as a working value.

Assuming roughly equal areas of thick and thin sand (noting that particular resolution and viewing azimuth is needed to identify the former – although dark streaks are more commonly seen in data so far, better imagery of the same areas might show topographic shading), the sand seas (i.e. 40% of the half of Titan:s surface that lies between $\pm 30^{\circ}$ latitude) have an average sand depth of 20m, which corresponds to a to a total inventory of some 3.2×10^{5} km^{3} of material. This corresponds to about 400 times the ~900 billion tonnes of proven coal reserves on Earth (BP, 2007), a material which has some superficial similarities with the likely dune sand on Titan. The figure above is perhaps more likely to underestimate the inventory than to overestimate it : a reasonable range is therefore $2\text{-}8\times10^{5}$ km^{3}.

4. Discussion and Conclusions

The results reported here must be considered preliminary, not least since they are based on only 20% coverage of Titan's surface, of which most is in the northern hemisphere and the equatorial regions. However, the hemispheres would have to be very different to give results that diverge widely from the estimates presented here. The inventory is substantial, exceeding in absolute terms the biospheric, oceanic and fossil fuel reservoirs on Earth – see table 1. In terms of column abundance (mass/area) Titan's carbon inventory may approach Earth's non-carbonate reservoirs.

The total inventory we measure is substantially smaller than the reservoir estimated to be produced throughout the age of the solar system if methane photoloysis were to have occurred continuously at its present rate. The apparent dearth of material (compared to these model predictions – a summary is given in Lorenz and Lunine (1995), of several hundred meters thickness, or ~10^7-10^8 km^3) may indicate one or more of four things. First, other undetected organic materials are present, but not morphologically distinct. It is commonly assumed on the basis of bulk cosmological abundance that Titan's bedrock is dominated by water ice, but the near-surface may in fact be dominated by organic material.. Furthermore, even at the low latitudes dominated by arid landforms like dunes, the Huygens probe indicated that at least some surface materials are moistened by liquid methane (Lorenz et al., 2006b; Niemann et al., 2005) so some amount of liquid is present (perhaps in very large amounts) beyond the obvious lakeforms. Second, the photochemical models may not correctly predict the ultimate yields of surface deposits (c.f. the relative yields of solids and liquids – see next paragraph). Thirdly, photochemical production may have been interrupted for long periods in Titan's past if the delivery of methane to the surface was episodic and led to occasional methane depletion. The identification of cryovolcanic features on the surface (Sotin et al., 2005, Lopes et al., 2007) supports such a picture. A final more speculative possibility is that some process has destroyed or subducted the deposits, such that they no longer exist at the surface.

Note that the volume of sand considerably exceeds the amount of sand-sized material produced in impact ejecta for the known craters. Applying the sediment productions in Lorenz et al. (1995) for the known Titan craters yields only ~500km^3 of mm-sized material. It is possible that the larger volumes of bigger ejecta particles could have been broken down into sand by other processes. The observed river channels, covering perhaps 0.1% of the surface and having incision depths of 100m or less, are only able to account for ~$10^4 km^3$ of material. In sum, geological processes cannot account simply for the large volume of sand-sized material on Titan, supporting a photochemical origin for much of it (Lorenz et al., 2006a).

The uncertainty in lake volume compared to dune volume spans a liquid:solid ratio of 0.03-1. Allowing for half of the liquid to be methane (e.g. see the ocean:atmosphere equilibrium discussion in Lunine et al., 1983; Lorenz et al., 1999), solid materials must dominate over liquid ethane. This contrasts with the predictions of photochemical models which indicated a converse relationship, that acetylene and other solids would amount to less than a third of the amount of liquid ethane (e.g. the acetylene:ethane production in three models reviewed in Lorenz and

Lunine 1995 ranged from 0.2 to 0.8). Unless strong assumptions are made about the relative amounts of unobserved material such as subsurface ethane aquifers, models of photochemical production (and perhaps subsequent chemical processing in lakes) need to explain the predominance of solid materials. We note in this context that a major surprise from Cassini has been the complexity of the organic species formed, even in the ionosphere. Benzene has been detected in some abundance even at 1000km altitude and some polycyclic aromatic hydrocarbons (PAHs) like anthracene and its derivatives have been inferred (Waite et al., 2007). This unexpectedly rapid synthesis of heavy (solid) organics may be the reason there is more sand than liquid.

Finally, the liquid inventory, while extending over a large enough area to permit evaporative fluxes to match photochemical depletion on short timescales (Mitri et al., 2007), is not enough in volume terms to sustain the concentration of this greenhouse gas in the atmosphere on geological timescales. Put another way, there is an order of magnitude less liquid in the lakes than there is methane in the atmosphere, and photochemical models predict that inventory to be depleted in ~10 Myr. This makes the present climatic situation somewhat precarious – the observed surface reservoir, even if mostly methane, is unable to buffer the atmospheric methane for long, and unless volcanic resupply matches methane loss at just the right rate, significant climate change is likely in the future and by implication in the past (Lorenz et al., 1997; 1999). Stronger volcanic fluxes of methane might lead to wetter conditions, perhaps producing flood features that cannot be readily explained in the present climate. Periods without resupply might lead initially to conditions dryer than present, but then (as the greenhouse warming of methane is lost) cooling and condensation of some of the nitrogen atmosphere onto the surface – a partial collapse (Lorenz et al., 1997).

The apparent ocean-atmosphere equilibrium is very different on Earth, where the condensable greenhouse gas (water) in the air has a global equivalent depth of only ~2 cm, tiny compared to the ~2.4km global average depth of its surface reservoir. The situation on Mars may be intermediate (table 1) – if the permanent polar caps and regolith contain tens of times the atmospheric inventory of CO_2 (Read and Lewis, 2004), but recent work (e..g Byrne and Ingersoll, 2003) suggests the caps have only a veneer of a few m of CO_2 ice, making Mars rather like Titan from a volatile inventory perspective. On Titan, if the liquid in the lakes participates in a seasonal cycle (e.g. Stevenson and Potter, 1986; Mitri et al., 2007), it has only a small influence on the overall meteorology and climate, since the liquid inventory (~200 kgm^{-2}, or 3 mbar or perhaps a few times higher than this) is small compared with the ~60mbar of methane in the atmosphere, in contrast to the ~30% Mars seasonal pressure cycle. Further study would be needed to consider how the methane reservoir could influence seasonal changes in cloud patterns (e.g. Mitchell et al., 2006; Rannou et al., 2006).

Future Cassini observations will help make a more complete inventory, notably in the Southern hemisphere, and indications of surface composition from near-infrared spectroscopy will be useful to understand the chemical species involved in the global carbon cycles. Indirectly, the changing patterns of methane clouds on Titan, especially in the equinox period 2009-2011 during Cassini's proposed extended mission may show the participation of surface methane moisture in the climate system. Beyond this, important goals for a possible future mission might be to assess sediment and liquid depths directly with ground-penetrating radar, and to search in-situ for isotopic and other indications of chemical processing and volatile release from the interior.

Acknowledgement

This work was supported by the Cassini Project, managed by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

BP, Statistical Review of World Energy, June 2007. BP PLC, London, UK, 2007.

Byrne, S. and A. P. Ingersoll, A Sublimation Model for Martian South Polar Ice Features, Science, 299, 1051-1053, 2003

Elachi, C. and 34 co-authors, Cassini Radar Views the Surface of Titan Science, 308, 970-974, 2005.

Falkowski, P. and 16 co-authors, The Global Carbon Cycle: A Test of Our Knowledge of Earth as a System, Science, 290, 291-296, 2007.

Lancaster, N. Geomorphology of Desert Dunes, Routledge, London, 1995.

Lopes, R. M. and 43 co-authors. Cryovolcanic features on Titan's surface as revealed by the Cassini Titan Radar Mapper. Icarus, 186, 395-412, 2007.

Lorenz, R. D. and J.I.Lunine, Erosion on Titan : Past and Present, *Icarus*, 122, 79-91, 1996

Lorenz, R. D. and J. Mitton, Lifting Titan's Veil, Cambridge University Press, 2002

Lorenz, R. D., C. P. McKay and J. I. Lunine, Photochemically-Driven Collapse of Titan's Atmosphere, *Science*, 275, 642-644, 1997

Lorenz, R. D. , C. P. McKay, and J. I. Lunine, Analytic Stability of Titan's Climate : Sensitivity to Volatile Inventory, Planetary and Space Science, 47, 1503-1515, 1999

Lorenz, R. D. and 39 co-authors, The Sand Seas of Titan : Cassini RADAR observations of Longitudinal Dunes, Science, 312, 724-727, 2006a

Lorenz, R. D., H. Niemann, D. Harpold, J. Zarnecki, Titan's Damp Surface : Constraints on Titan Surface Thermal Properties from the Temperature Evolution of the Huygens GCMS inlet, Meteoritics and Planetary Science. *41,* 1405-1414, 2006b

Lunine, J.I., Stevenson, D.J. and Yung, Y.L. Ethane ocean on Titan. *Science* **222**, 1229-1230, 1983.

Mitchell, J. L., R. T. Pierrehumbert, D. M. W. Frierson and R. Caballero, The Dynamics behind Titan's methane clouds, Proceedings of the National Academy of Sciences, 103, 18421-18426, 2006

Mitri, G. , A. P. Showman, J. I. Lunine, and R. D. Lorenz, Hydrocarbon lakes on Titan, Icarus, 186, 385-394, 2007

Niemann, H. and 17 co-authors. 2005. Huygens Probe Gas Chromatograph Mass Spectrometer: The Atmosphere and Surface of Titan, Nature, 438, 779-784, 2005

Ostro, S. J.and 18 co-authors, Cassini RADAR Observations of Enceladus, Tethys, Dione, Rhea, Iapetus, Hyperion, and Phoebe, *Icarus*, 183, 479-490, 2006

Radebaugh, J., R. Lorenz, J. Lunine, S. Wall, G. Boubin, E. Reffet, R. Kirk, R. Lopes, E. Stofan, L. Soderblom, M. Allison, M. Janssen, P. Paillou, P. Callahan and the Cassini Radar Team, Dunes on Titan observed by Cassini Radar, Icarus, in revision, 2007.

Rannou, P., Montmessin, F., Hourdin, F. and S. Lebonnois, The Latitudinal Distribution of Clouds on Titan, Science, 311, 201-205, 2006.

Raulin, F. Organic Chemistry in the Oceans of Titan, Advances in Space Research, 7, 71-81, 1987

Read, P. L. and S. R. Lewis, The Martian Climate Revisited : Atmosphere and Environment of a Desert Planet, Praxis-Springer, Chichester, UK 2004

Rodriguez, S., P. Paillou, M. Dobrijevic,G. Ruffié, P. Coll, J.M. Bernard, and P. Encrenaz. Impact of aerosols present in Titan's atmosphere on the CASSINI radar experiment, Icarus, 164, 213-227, 2003.

Sen, A. D., V. G. Anicich and T. Arakelian, Dielectric constant of liquid alkanes and hydrocarbon mixtures, Journal of Physics D: Applied Physics 25, 516-521, 1992.

Soderblom, L. and 26 co-authors. Correlations between Cassini VIMS spectra and RADAR SAR images: Implications for Titan's surface composition and the character of the Huygens Probe landing site. Planetary and Space Science, in press.

Stevenson, D.J. and Potter, B. E. Titan's latitudinal temperature distribution and seasonal cycle. *Geophys. Res. Letters* **13**, 93-96, 1986.

Stofan, E.R and 37 co-authors, The Lakes of Titan, Nature, 441, 61-64, 2007.

Turtle, E. P., J. E. Perry, A. S. McEwen, R. A. West, D. D. Dawson, C. C. Porco and S. Fussner, Cassini Imaging Science Subsystem Observations of Titan's High-Latitude Lakes, Abstract

#6063 in Ices, Oceans and Fire: satellites of the Outer Solar System Workshop, Boulder, CO, August 11-13, 2007.

Waite, J. H., D. T. Young, T. E. Cravens, A. J. Coates, F. J. Crary, B. Magee, and J. Westlake, The Process of tholin formation in Titan's upper atmosphere, *Science, 316,* 870–876, 2007.

Yung, Y. L. and W. D. DeMore, Photochemistry of Planetary Atmospheres, Oxford University Press, 1999

Figures

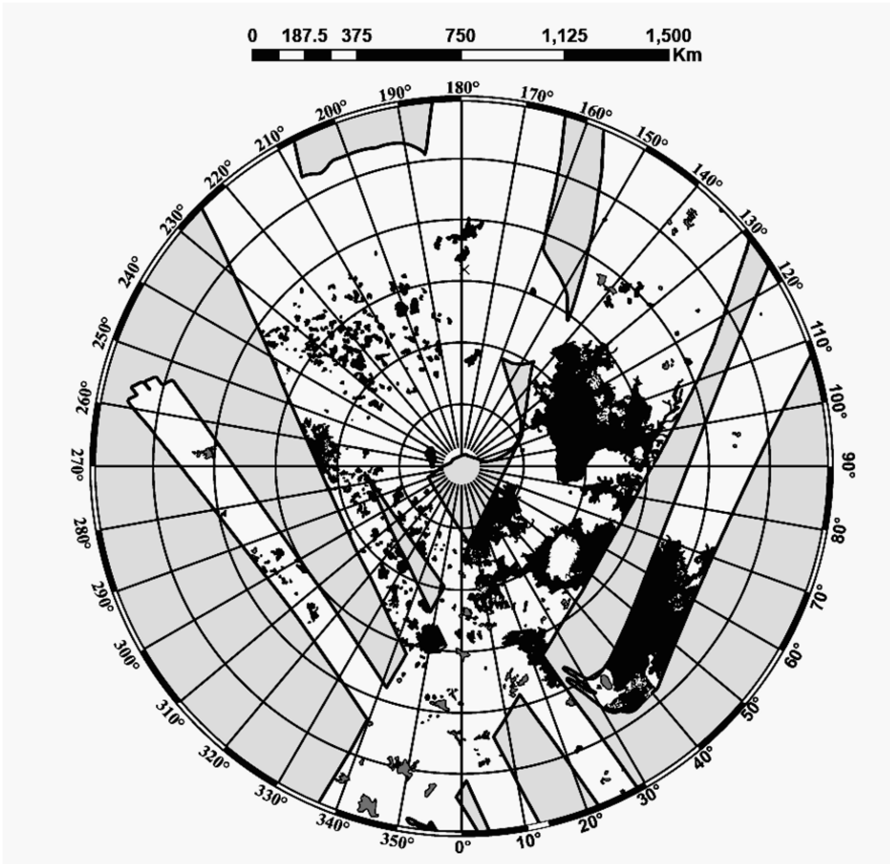

Figure 1. A map of Titan's north polar region (5 degree latitude circles) with areas identified as lakes shown as dark grey against the radar swaths in white. Light grey areas have not been imaged by radar as yet.

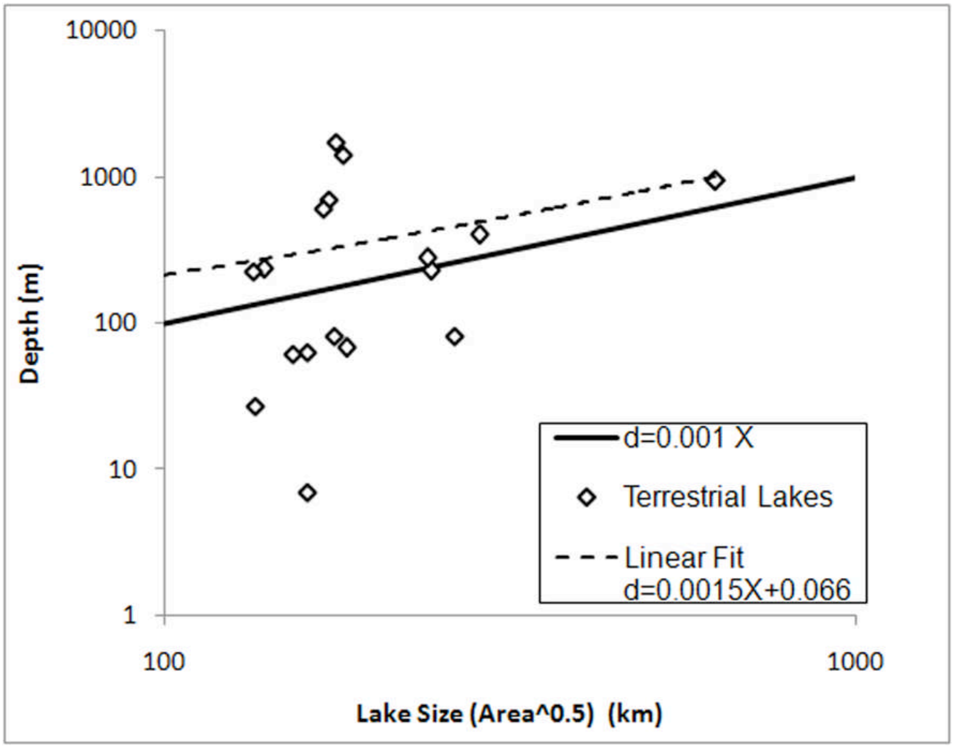

Figure 2. Lake size/depth correlation for the Earth's 20 largest lakes.

Table 1. Titan Carbon inventory compared with other planetary reservoirs.

	Reservoir	Inventory (a) km^3	Inventory GT Carbon	Column Mass kg/m^2	Pressure mbar
Titan					
	Methane in Atmosphere	800,000	360,000	4000	60
	Ethane/Methane Lakes	30,000-300,000	16,000-160,000	*200-2000*	*3-30*
	Sand Dunes	200,000-800,000	160,000-640,000	2000-6400	40
	Fine Impact Ejecta	400			
	Erosion from River channels	8000			
Earth Carbon					
	Gas		140[(1)],132[(2)]		
	Oil		230[(1)],356[(2)]		
	Coal		3500[(1)],900[(2)]		
	Atmosphere		720		0.3
	Biosphere		2000		
	Ocean		38,000		
	Lithosphere (Kerogens)		$1.5x10^7$		
	Lithosphere (Carbonates)		$6x10^7$		
Earth Water					
	Atmosphere			20	*~2*
	Oceans	$1.3x10^9$		$2.4x10^6$	240,000
	Lakes	125,000			
	Icecaps	$>3x10^7$			
Mars					
	Atmosphere	*27,000*	*5900*	150[(3)]	*6*
	Seasonal Frost Caps	*7000*	*1600*	40[(3)]	*1.5*
	Polar Layered Deposits	*4000*	*900*	23[(3)]	*1*
	Permanent Polar Caps	*900,000*	*200,000*	5000[(3,4)]	*185*
	Regolith	*180,000*	*40,000*	1000[(3)]	*37*
Venus					
	Atmosphere	*$5.8x10^8$*	*$1.25x10^8$*	*10^6*	90,000

References and Notes

Indirectly-determined quantities shown in italics
Expressed as volume of condensed species
1) Falkowski et al., 2000
2) BP, 2007
3) Read and Lewis, 2004
4) may be much less – see Byrne and Ingersoll, 2003