Comparison of Titan's north polar lakes with terrestrial analogs

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[1] The discovery of hydrocarbon lakes in the polar regions of Titan offers a unique opportunity to compare terrestrial lakes with those in an extraterrestrial setting. We selected 114 terrestrial lakes formed by different processes as analogs for comparison with the 190 Titanian lakes that we had mapped in our previous study. Using the Shuttle Radar Topography Mission (SRTM) C-band backscatter data and the SRTM Water Body Data (SWBD), we carried out an assessment of manual mapping versus existing automated mapping techniques, and found the automated techniques to produce as good representations of the lake shorelines as the manual mapping in the terrestrial dataset. We then calculated and compared terrestrial and Titanian shoreline statistical parameters including fractal dimension, shoreline development index and an elongation index. We found different lake generation mechanisms on Earth produce "statistically different" shorelines. However, we cannot identify any one mechanism or set of mechanisms to be responsible for forming the depressions enclosing the lakes on Titan, on the basis of our statistical analyses.

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1. Introduction

[2] Lacustrine features have been observed in both the north and south polar regions of Saturn's largest moon, Titan, by multiple instruments onboard the NASA Cassini orbiter, including the RADAR instrument [*Elachi et al.*, 2004], the Visual and Infrared Mapping Spectrometer (VIMS) [*Brown et al.*, 2004] and the Imaging Science Subsystem (ISS) [*Porco et al.*, 2005; *Turtle et al.*, 2009]. Although RADAR data collected in the early phase of the Cassini mission provided a number of lines of evidence for these features being potential lakes (Figure 1a) [*Stofan et al.*, 2007], conclusive evidence for the presence of liquid in these features was provided in the form of ethane detection in the south polar Ontario Lacus by the VIMS instrument [*Brown et al.*, 2008] and the specular reflection observed in the VIMS dataset corresponding to the north polar Kraken Mare [*Stephan et al.*, 2010]. Thus, for the first time, we have the opportunity to compare lakes on Earth with extraterrestrial examples.

[3] A few processes (mainly karst and volcanic), based on morphology, have been proposed to be involved in the formation of the liquid-filled depressions at the poles of Titan [e.g., *Mitchell et al.*, 2007; *Wood et al.*, 2007; *Kargel et al.*, 2007]. The purpose of this study is to quantitatively compare the shorelines of Titan's polar lakes to terrestrial analogs formed by different processes, and investigate whether the principal processes responsible for the origin of the lake basins on Titan can be deduced.

[4] Our previous study of Titan's north polar shorelines revealed them to be closely approximated by fractal shapes [*Sharma and Byrne*, 2010], a property also demonstrated by terrestrial shorelines [*Mandelbrot*, 1967; *Richardson*, 1961; *Sapoval et al.*, 2004], i.e., measured lengths of these shorelines increases, as the measuring scale decreases, because smaller measuring scales are sensitive to smaller features of the shoreline. We performed a similar fractal analysis on terrestrial lake shorelines and created additional statistical descriptors of shoreline morphology in order to compare them to Titan's lakes. This comparative analysis was prompted by the idea that different surface processes may yield shorelines with different roughnesses. We investigate the validity of this idea and whether we can interpret the fractal dimensions of Titan's shorelines in terms of the surficial processes at work.

2. Instruments and Datasets

[5] Titanian lake shorelines were characterized with data from the RADAR instrument onboard the Cassini spacecraft, which is a Ku-band (13.7 GHz, 2.17 cm wavelength), linearly polarized device [*Elachi et al.*, 2004]. We utilized Synthetic Aperture Radar (SAR) data in the form of Basic Image Data Record (BIDR) files as the base mapping dataset for this analysis. Cassini SAR covered 27% of the surface of Titan during the "prime" (nominal) mission period until June 2008 [*Lorenz and Radebaugh*, 2009]. The resolution of the SAR swaths ranges from ~300m at best to up to 1500m. Using GIS software, ArcMAP from ESRI, we mapped the shorelines of 190 radar-dark features, which have perimeters longer than 70km.

[6] To study the terrestrial lakes, we used data from the Shuttle Radar Topography Mission (SRTM), which flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000 [*Farr et al.*, 2007]. This mission mapped ~80% of the Earth's landmass (60°N-56°S) at wavelengths of 5.66 cm (C-band) and 3.1 cm (X-band). For this study, we have used only the C-band backscatter data (resolution of 1 arc second, ~30m at the equator). We also used shorelines from the SRTM Water Body Data (SWBD) that were derived from the backscatter data through automated algorithms [*Slater et al.*, 2006]. The SRTM is an appropriate choice to characterize the terrestrial lakes for comparison with those on Titan, due to its almost global coverage and similar wavelength to the Cassini RADAR. In spite of the different resolutions, comparison of data from the SRTM and Cassini RADAR is justified since the statistical parameters calculated in this study are either invariant

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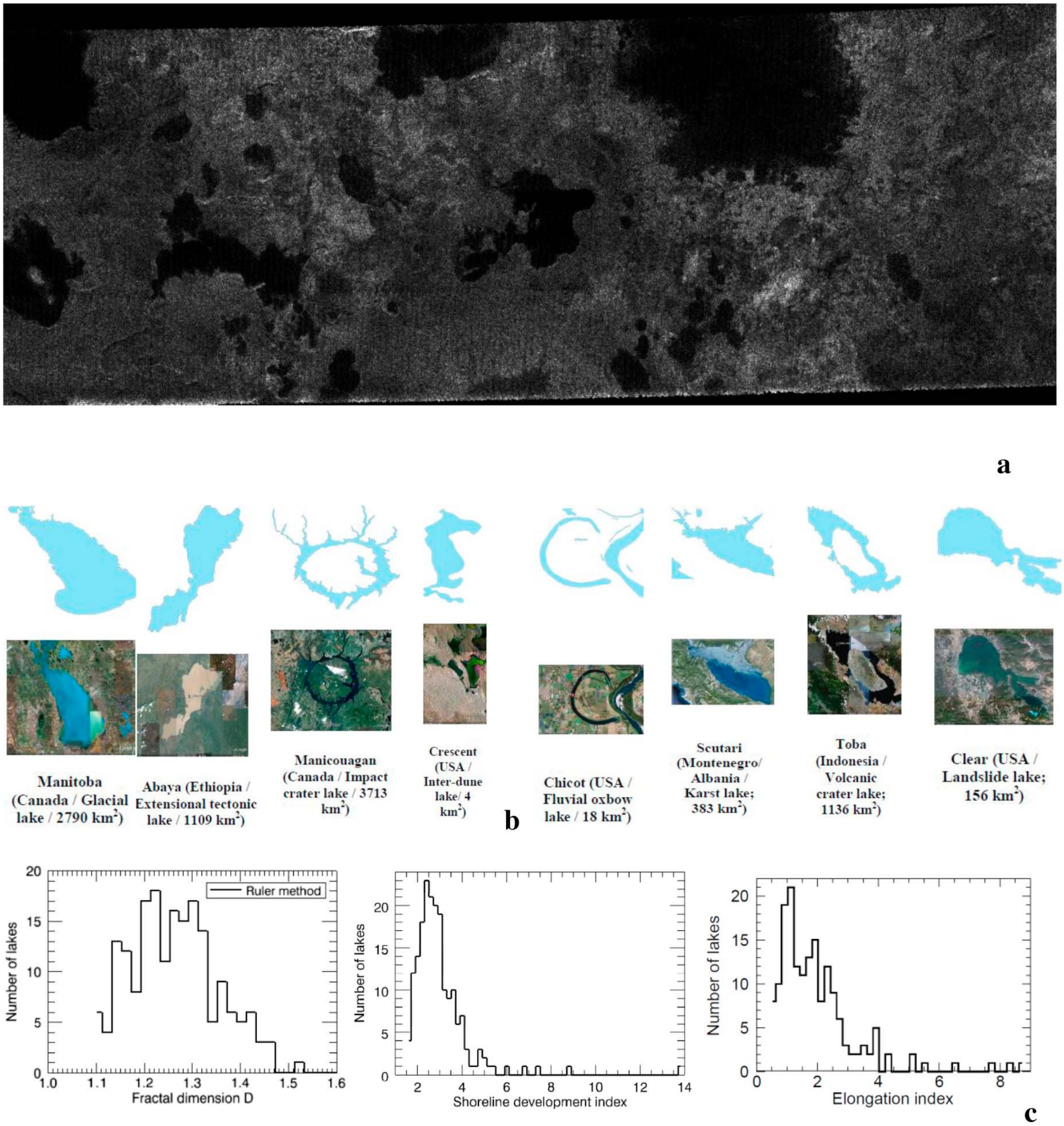

Figure 1. (a) Radar-dark hydrocarbon lakes in Cassini SAR swath (T16 flyby, 80°N, 92°W, 420 km × 150 km; Planetary photojournal, product ID PIA08630). (b) Terrestrial lakes formed by different processes (SRTM Water Body Data (SWBD) and Google Earth imagery). (c) Histograms of statistical parameters for Titan's lake shorelines, including fractal dimension with mean of 1.27, shoreline development index with mean of 2.995 and elongation index with mean of 2.27.

or weakly variant with scale (these parameters include a fractal and two other measures of the shape of lake shorelines discussed in detail in section 4).

3. Classification and Selection of Terrestrial Analogs

[7] Terrestrial lakes can broadly be classified into nine different types on the basis of their formation mechanisms [*Hutchinson*, 1957; *Cole*, 1975]. The basins enclosing lakes on Earth can form as a result of glacial erosion/deposition, impacts, volcanism (caldera lakes), tectonic uplift/subsidence, fluvial processes (oxbow lakes), aeolian processes (interdune lakes), dissolution of limestone (karst), landslide and periglacial/thermokarst processes. Figure 1b shows SWBD shorelines and corresponding Google Earth satellite images of example terrestrial lakes corresponding to each process type excluding thermokarst lakes since the SRTM data do not cover the high latitudes where these lakes are located.

[8] Since it is not yet understood which surface processes create the lakes on Titan, we chose to use surface area as the

criterion for selecting terrestrial analogs for comparison with Titan's lakes. We calculated the surface area for the 190 Titanian lake shorelines (classified as "dark lakes" by *Hayes et al.* [2008]) mapped for our previous study [*Sharma and Byrne*, 2010] and found the lakes to range in size from thousands of square kilometers to as small as 50 km^2, with a mean area of $\sim$1400 km^2. The large lakes on Titan are a distinct unit from the small lakes. Larger lakes on Titan differ both in terms of surface area and shoreline morphology from the smaller Titanian lakes, with the larger ones having more complex and intricate shorelines with dendritic features and the smaller ones with simpler and smoother shorelines [*Stofan et al.*, 2007; *Hayes et al.*, 2008]. Choosing 5000 km^2 to be an approximate demarcation between the small and large lakes on Titan, we find that a majority of the lakes (184) are smaller than 5000 km^2, while the remaining six are larger. On Earth, although smaller lakes can form by many processes; the largest lakes, like the Great Lakes in North America and the Rift Valley lakes in Africa, are formed mainly by two predominant processes: glaciation and tectonism. It is possible that on Titan also, different processes are forming the smaller and bigger lakes and we will therefore analyze the larger lakes separately. We chose 114 terrestrial lakes, which include lakes of each process type (excluding thermokarst lakes), as possible analogs to the Titanian lakes for our study. Amongst these, 94 lakes have surface areas smaller than 5000 km^2, while the remaining 20 are amongst the largest lakes on Earth. The 114 terrestrial lakes in our database include 20 glacial lakes, 20 volcanic caldera lakes, 6 impact crater lakes (rare on Earth, with even fewer having SRTM coverage), 20 tectonically formed lakes, 20 karst lakes, 10 fluvial oxbow lakes, 10 aeolian interdune lakes and 8 lakes formed by landslides (like the impact crater lakes, very few of these landslide lakes are found on the Earth). These terrestrial analogs were chosen based on the classification of *Hutchinson* [1957] and *Cole* [1975]. Although we have classified the terrestrial lakes in our database into different process types, it is important to note that this is not a rigorous classification, since after its initial formation, each lake may be subsequently modified by many processes.

4. Statistical Parameters

4.1. Fractal Dimension

[9] The fractal dimension can be estimated by the ruler/divider technique where the perimeter of the shoreline is measured at many different length scales. A power-law fit to perimeter (P) vs. length scale (R) has an exponent of $1-D_R$, where D_R is the ruler fractal dimension (for details of the calculation, please refer to *Sharma and Byrne* [2010]). For the 190 Titanian lake shorelines mapped for our previous study, the mean ruler dimension was found to be 1.27 at length scales between 1 and 10 km (Figure 1c). Fractal dimension is independent of the dataset resolution since a fractal shape by definition is scale-invariant (as long as we do not attempt to map features smaller than the resolution). As the results of our previous study [*Sharma and Byrne*, 2010] indicated, both the terrestrial and Titanian lake shorelines are well described as fractal shapes.

[10] An alternative method of estimating fractal dimension by counting the boxes of different sizes required to cover a shoreline was considered less accurate (see *Sharma and Byrne* [2010] for rationale). Estimates of the fractal dimension of terrestrial lakes from this box-counting method are relegated to the auxiliary material (Text S1).[1]

4.2. Shoreline Development Index

[11] The shoreline development index (D_L) is the ratio of the shoreline length or perimeter (P) of the lake to the circumference of a circle that has the same area (A) as the lake [*Hutchinson*, 1957; *Cole*, 1975] expressed as $P/\sqrt{4\pi A}$. The closer the shape of a lake is to a circle, the smaller will be its D_L value (a completely circular lake has the smallest possible value of 1.0). Karst basin lakes, volcanic caldera lakes and impact crater lakes are usually quasi-circular in shape and thus are expected to have D_L values approaching unity. In contrast, lakes formed through tectonic activity usually have more elongated, narrow shapes and are thus expected to have higher values of D_L. For the 190 Titanian shorelines mapped for our previous study, the mean shoreline development index was calculated to be 2.995 (Figure 1c). The shoreline development index depends on the relationship between perimeter and surface area, which together vary weakly with resolution and can be related to the fractal dimension through power-law relations, as shown in previous studies [e.g., *Cheng*, 1995]. The calculation of the shoreline development index is thus at most weakly affected by dataset resolution.

[12] Apart from the shape of the lake, the value of this index is also affected by the irregularity of the shoreline. A lake shoreline that is very rough and intricate will have a higher overall perimeter and thus have a higher D_L value, but so will a shoreline that is highly elongated. For example, the linear Rift Valley lake Abaya (shown in Figure 1b), formed by tectonic processes, has a high D_L value of 2.9, but so does the more circular lake Manicouagan (also shown in Figure 1b) formed by an impact, due to its very intricate shoreline (D_L = 4.1). Thus, we introduce another parameter that can be used as an independent proxy for the elongation of the lake.

4.3. Elongation Index/Aspect Ratio Index

[13] We define the elongation index as the maximum ratio of two perpendicular dimensions of a shape. For lakes that are almost circular in shape, the value of this index will be close to 1.0, while lakes that are elongated in shape will have larger elongation indices associated with them. We calculated the mean elongation index for Titan's 190 lake shorelines to be 2.27 (Figure 1c). The calculation of the elongation index only depends on the overall shape of the lake, which varies very weakly with resolution and thus this parameter is also very weakly affected by dataset resolution.

5. Analysis of Terrestrial Analogs

5.1. Analysis of Backscatter Data

[14] The SWBD lake outlines were produced from the SRTM backscatter data by National Geospatial Agency contractors through automated techniques [*Slater et al.*, 2006]. However, the 190 Titanian lake shorelines from our previous study [*Sharma and Byrne*, 2010] were manually mapped from Cassini RADAR backscatter data. Before

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL049577.

using the same statistical techniques to analyze and compare the manually mapped shorelines on Titan and the automatically mapped shorelines on Earth, we tested to determine if it would be a valid comparison. We selected 16 example terrestrial lake outlines (2 corresponding to each process type) from the SWBD (generated through automated routines) and also obtained the corresponding SRTM C-band RADAR backscatter data (T. Farr, personal communication, 2010–2011). We performed some initial processing on the backscatter data, including contrast stretching and mosaicking. Next, we manually outlined the shorelines of these example terrestrial lakes using the same methods and criteria employed to map Titan's shorelines [*Sharma and Byrne*, 2010]. Before carrying out the fractal analysis, we converted these shorelines from latitude and longitude to stereographic coordinates centered on each of the lakes. Figure 2a compares the manual and automated mapping techniques for an example terrestrial lake. As seen in this figure, we find both the mapping techniques to produce lake representations that look similar. To quantify this comparison, we compared the ruler fractal dimensions, shoreline development indices and elongation indices of the manually mapped shorelines and the shorelines produced through automated routines (Table S1 in the auxiliary material). We find good correlation (see Figure 2b) between the parameters calculated from the manually and automatically mapped shoreline data, as indicated by the calculated correlation coefficients ($r = 0.73$ for ruler dimensions, 0.89 for shoreline development indices and 0.97 for elongation indices). We thus find that the automated mapping of *Slater et al.* [2006] works as well as manual mapping for producing accurate representations of the lake shorelines from the SRTM dataset.

5.2. Analysis of SWBD

[15] We processed the SWBD outlines corresponding to our chosen 114 lake shorelines, including converting multipart polygons to single polygons and combining data for lakes spanning more than a single $1° \times 1°$ SWBD tile. We transformed the SWBD from their initial geographic projection to a stereographic projection centered on the lake and then evaluated the statistical quantities described in section 4 (Tables S2 and S3 in the auxiliary material).

[16] To assess the significance of the differences in the means of statistical parameters corresponding to different processes, we performed an analysis of variance (ANOVA) statistical test, which is a way of splitting the variance of the entire population into variance within sub-groups versus variance between groups. Results of this test are reported as an F-ratio, which can be converted into the probability that variability between groups occurs only by chance. A high value of the F-ratio indicates the differences between the sub-groups are statistically significant. A probability of occurrence by chance of 5% is considered the usual cutoff for statistical significance. Using the ruler fractal dimensions of the 114 terrestrial lakes, we derive an F-ratio of 5.52, which would occur by chance only 0.002% of the time, indicating that the differences between the lakes formed by various processes are statistically significant. Using the shoreline development indices and the elongation indices, we derive values of F-ratio of 8.59 (which could occur by chance 2.57e-06% of the time) and 6.47 (which could occur by chance 2.3e-04% of the time), respectively. All of these results indicate that the terrestrial lakes formed by different processes do indeed belong to different populations with different means. Such a statistical analysis can therefore be used to distinguish between groups of terrestrial lakes formed by different processes.

5.3. Comparison With Titan's North Polar Lake Shorelines

[17] In Figure 2c, we compare the fractal dimensions, shoreline development indices and elongation indices for the 94 terrestrial lakes and the 184 Titanian lakes, with surface areas smaller than 5000 km^2. We observe overlap between statistical parameters for Titan's lake shorelines and all the terrestrial processes considered here.

[18] Out of the 190 Titanian lakes that we had mapped for our previous study, six have areas larger than 5000 km^2. We selected 20 of the largest lakes on the Earth (larger than 5000 km^2), 10 each formed by glacial and tectonic processes (Table S3 in the auxiliary material), for comparison with Titan's large lakes. We calculated their ruler fractal dimensions and shoreline development indices and compared them with Titan's large lakes, as shown in Figure 2d. We again observe overlap of the large Titanian lakes with both tectonic and glacial terrestrial lakes.

[19] To quantitatively examine our observation of overlapping parameters, we performed the Kolmogorov-Smirnov (K-S) test for comparing the distribution of parameters for Titan's lake shorelines against each of the terrestrial process datasets and against all the terrestrial lakes as one group. This is a non-parametric test, i.e., it does not make any assumptions about the population distribution of the datasets [*Press et al.*, 2007]. This test can thus be used to examine to a certain required level of significance, the null hypothesis that two data sets are drawn from the same population distribution function. Disproving the null hypothesis in effect proves that the data sets are from different distributions. Results of this test are reported in the form of two parameters: the K-S statistic D, which can be converted into the probability (p-value) indicating the significance of the observed D value. An estimate of the D statistic higher than the critical value, combined with a small p-value, indicates that the two datasets are derived from different distributions. Table S4 in the auxiliary material shows the results of the K-S test performed using the shoreline statistical parameters corresponding to all the lakes in our database for Titan (190) and Earth (114).

[20] The results indicate that the distribution of Titanian shoreline parameters is not statistically similar to the distribution of terrestrial lakes formed by any one particular process. One must interpret these results with caution, since they are limited by the small number of data points per subgroup, as compared to the Titanian lakes. There could be a number of possible explanations for this difference in distribution of parameters between Earth and Titan, a few of which we have listed here:

[21] 1. Lakes on Titan may also be divisible into many subpopulations like terrestrial lakes. However, using the currently available data, there is no independent way to classify each Titanian lake according to process type. Therefore, when we combine all the Titanian lakes into one group for comparing with individual terrestrial process types, we do not observe a distribution of parameters for Titan that matches any of the individual processes. Even on comparing all the terrestrial lakes as one group with all the Titanian lakes,

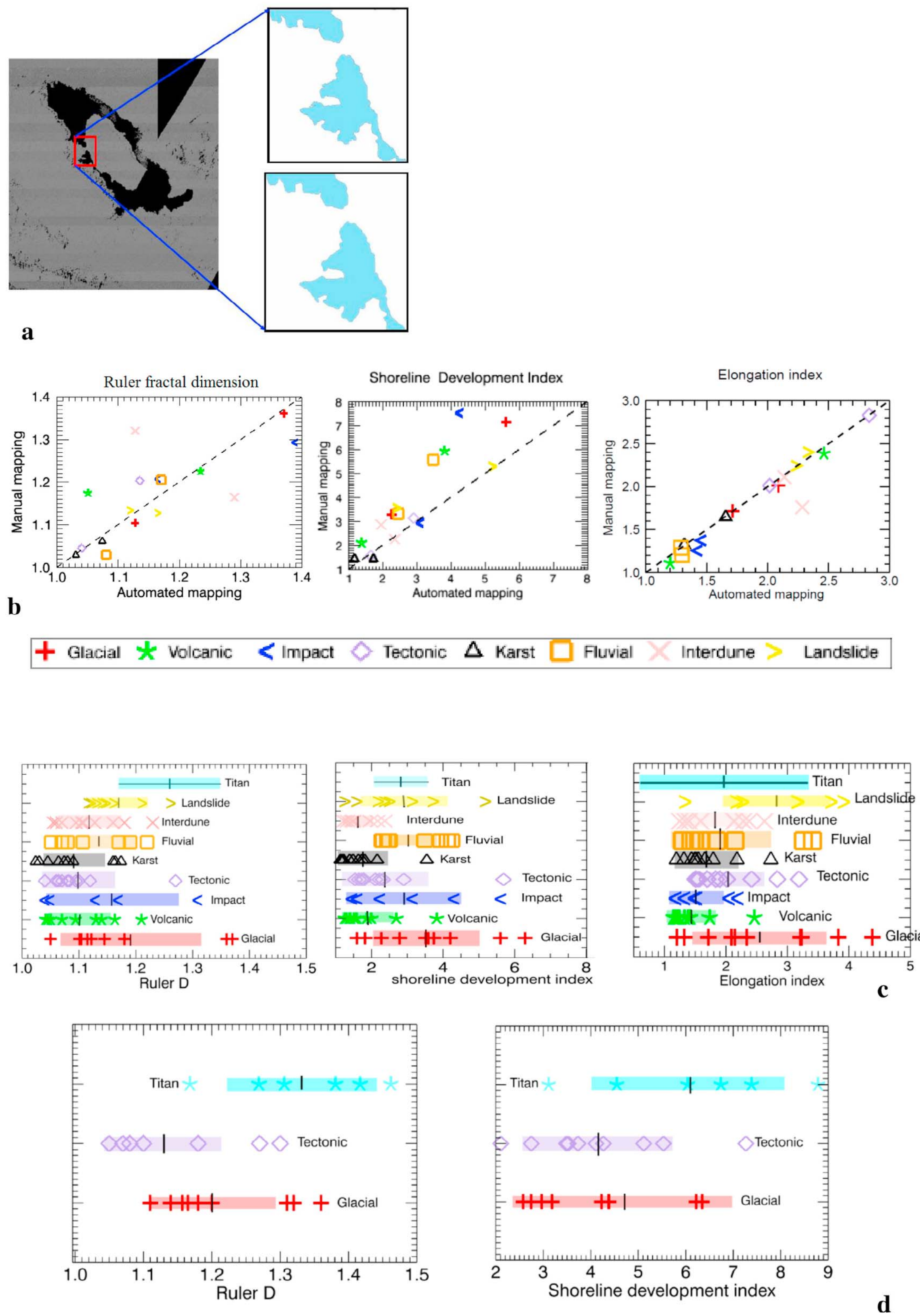

Figure 2. (a) SRTM C-band backscatter data of volcanic lake Toba with comparison of manual (upper) v/s automated (SWBD lower) mapping techniques. (b) Comparison of shoreline characterization parameters of terrestrial lakes generated from manual v/s automated mapping for various formation mechanisms. (c) Comparison of shoreline parameters for 94 terrestrial and 184 Titanian lakes smaller than 5000 km^2. Vertical lines denote mean values and shaded boxes indicate 1σ ranges. (d) As above for 20 terrestrial and 6 Titanian lakes larger than 5000 km^2.

we find the same result which could imply that the mix of processes responsible for lake formation differs between Earth and Titan.

[22] 2. Our statistical analysis is limited by the small number of data points for terrestrial analogs in some of the sub-groups, and thus this analysis may not be sufficient to differentiate between terrestrial and Titanian lake shorelines. It is possible that a very rare form of terrestrial lake (e.g., impact) could be the most dominant lake type on Titan.

[23] 3. Lake shorelines on Earth may be smoother/less complex compared to the Titanian shorelines, because the terrestrial shorelines are influenced by multiple surface processes (often in response to long-term climate change) that could smooth them over time (although short-term seasonal changes have been observed on Titan in the form of retreat of lake shorelines [*Turtle et al.*, 2011a] and varying cloud activity [*Turtle et al.*, 2011b], Titan has not been observed on a long enough timescale to detect climate change similar to what has been observed in the Earth's case).

[24] 4. Erosive processes on terrestrial lake shorelines might be subdued due to the presence of vegetation (plant roots would hold on to the soil and thus minimize erosion).

[25] In conclusion, the difference in the distribution of shoreline parameters for Titanian and terrestrial lakes implies that although this statistical analysis can be used to distinguish between groups of lakes formed by different surface process on Earth, it cannot be used to deduce the process(es) responsible for forming the lake basins on Titan.

6. Summary

[26] We have carried out a statistical analysis of the lake shorelines (formed by different processes) on Earth and Titan to address the question of whether there is a connection between the surface processes and the roughness parameters of the lake shorelines formed by them.

[27] 1. We carried out an assessment of manual mapping versus automated mapping techniques by manually outlining the shorelines of terrestrial lakes using the SRTM C-band backscatter data, and comparing them with data generated through automated routines (SWBD). We found good correlation between the statistical parameters calculated for both the manual and automated data, indicating that the automated routines of *Slater et al.* [2006] produce as good representations of the lake shorelines as the manual mapping in the SRTM dataset.

[28] 2. Shorelines on both Earth and Titan can be described as self-similar fractals. Using data from the SRTM for the terrestrial lakes and the Cassini RADAR for the Titanian lakes, we calculated ruler/divider fractal dimension, shoreline development index and elongation index for 114 terrestrial lakes formed by different processes and for the 190 Titanian shorelines that we had mapped as part of our previous study. For Titan's north polar lakes, the mean shoreline development index was calculated to be 2.995 and the mean elongation index was calculated to be 2.27. The mean ruler fractal dimension for Titan's lakes had been calculated in our previous study to be 1.27.

[29] 3. We found statistically significant differences in the shoreline parameters of terrestrial lakes formed by different surface processes, which suggests that these parameters can be related to the surface processes forming the lake shorelines.

[30] 4. However, on comparing the range of values of statistical parameters for Earth's and Titan's lakes, we found overlap between Titan's lakes and terrestrial lakes formed by multiple processes. Moreover, we determined that the distribution of Titan's shoreline parameters does not match the distribution of any of the terrestrial process datasets. We thus conclude that there is no one process or set of processes that we can propose, on the basis of shoreline morphology alone, to be responsible for forming the depressions containing the lakes on Titan. We separately compared the six largest lakes on Titan (with areas larger than 5000 km^2) with 20 of the largest lakes on Earth, formed through either glacial or tectonic processes. Again, we did not find any one process to be more probable than the other in forming the large lakes on Titan.

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