Comparison of Geomorphological Characteristics of Titan Lakes with Potential Earth Analogues

Final Report

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Geol 394

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Abstract:

The recent discovery of the lakes on Titan has been met with interest from the scientific community. Lakes have been discovered on the surface of Titan that cover extensive areas of the moon, but the process of formation of the lakes is still unknown. This report examined evidence for two processes by which these lakes could have formed, and attempts to conclude the most appropriate and likely method of formation. To do this, I compared probability distributions of lake properties on Titan to distributions of the same properties of lakes formed by two different mechanisms on Earth, thermokarst lakes and cindercones. The objectives were to first determine whether lakes formed by different processes on Earth are statistically different from one another, and second to examine whether lake dimension distributions from either of these Earth analogue processes have similar characteristics to those on Titan. The initial conclusion is that while the Titan lakes cannot have formed the same way as the aforementioned processes, it is possible that the lakes have been elongated via a similar process to the thermokarst lakes, and thus have statistically similar property distributions.

Introduction:

Ever since the CASSINI mission arrived at Titan and began collecting data, there has been an interest in the unique features of this moon of Saturn. The lakes on Titan have particularly become a feature of interest because they identify Titan as the only terrestrial body in the solar system to have a liquid on its surface (other than Earth, of course). The surface temperature of Titan is very low (95K); therefore, the liquid cannot be water. Using CASSINI radar mapping, the liquid has been identified as being composed primarily of methane (West et al. 2007). The radar data from the CASSINI mission has shown evidence that these methane lakes exist, the question of how these lakes formed is still subject to debate.

The surface temperature on Titan ranges between the boiling and freezing point of methane and ethane (which has also been identified as a constituent of the lakes; Lunine and Lorenz, 2009). The combination of the temperature range and other atmospheric properties (pressure, wind patterns, etc.) allows for a methane-hydrological cycle (or "methanological cycle") (ibid). According to West et al. (2007), the relative methane humidity on Titan is less than 100% everywhere except at the poles, this means that methane in areas outside the poles can evaporate and contribute to the hydrological cycle. Titan's lakes are clustered around the poles, this lends credence to the methanological cycle hypothesis, where precipitation would occur at the poles, but evaporation rates would be lower than precipitation rates, thus allowing lakes to form from this accumulation of methane liquid. The "methanological cycle" cannot be compared directly to Earth's hydrological cycle as there are stark differences. Titan's methanological cycle actually incorporates both methane and ethane, and the lack of a global methane ocean presents problems in identification of a continued source of methane to drive the cycles (Lunine and Lorenz, 2009). There are a variety of other differences in how the Titan and Earth climates behave. While the presence of a methanological cycle might help explain how the liquid methane fills the depressions, there is still a mystery as to how the depressions form.

Titan does not have plate tectonics and radar mapping has shown few impact craters, which suggests that tectonics and impact mechanisms are not likely the primary method of forming these depressions (Stofan, 2010). Two major mechanisms for lake formation have been proposed: a) cryomagmatic expulsion from sub-surface water-ammonia reservoirs as cryovolcanism (Zebker et al., 2007); and b) formation of lakes by processes similar to thermokarst formation on Earth (West et al., 2007). Both of these processes would incorporate precipitated methane to fill the depressions left behind. These processes would be significantly different in that cryovolcanism on Titan would result from short-term episodic processes, while thermokarst lake formation would occur more slowly. These differences in mechanisms might lead to significant differences in the sizes, shapes, and size distribution of these lakes.

In a recent paper, Sharma and Byrne (2011) studied the morphology of lakes formed by various processes on Earth and compared them to lakes on Titan. They compared Titan lakes to almost all of the lake types on Earth that are formed via typical processes (excluding thermokarst lakes). Unfortunately, the Titan lakes did not match the characteristics of any of the Earth lakes.

Statement of the Problem:

The purpose of this study is to examine the morphology of Titan lakes and to compare selected morphological characteristics to those of potential Earth analogues lakes. The process of formation of the lakes on Titan is currently unknown, and there appears to be no process of formation of Earth lakes that can be replicated identically on Titan due to significantly different temperatures, solid phases, and liquid phases (Lorenz 2002). While the development of thermokarst lakes or a similar process on Titan is possible, the evolution of thermokarst lakes is poorly understood even on Earth. This study delves into these problems, and will hopefully help to shed some light on them.

Background and Previous Research:

An underlying assumption in evaluating surface processes on Earth and extraterrestrial surfaces is that form follows process. This means that similar forms on extraterrestrial planets or moons may have formed by similar processes to Earth. An initial understanding of the processes on Earth (which is at times lacking) is required in order to understand the forms and processes on other extraterrestrial bodies. Apart from this, a comparison between the major properties (e.g. temperature, gravitational constants, etc.) of Earth and other bodies must be made in order to understand whether certain processes on Earth are applicable elsewhere. Therefore, Table I summarizes the basic properties that have been determined for Earth and Titan (Lorenz 2002). Note the significantly larger size, gravitational constant, and density of Earth relative to Titan. Titan appears to have a surface fluid and a cycling of this fluid between the atmosphere and the lakes, but this fluid is not water because the temperature is much colder than required to freeze water. The surface solid on Titan; however, is likely composed mostly of water ice, and the fluid is likely a less dense mixture of methane, ethane and other hydrocarbons. This material may freeze near the poles of Titan.

Table I: Comparison of Major properties of Earth and Titan:

Parameter	**Earth**	**Titan**
Gravitational constant	9.814 m/s^2	1.3 m/s^2
Average density	5,515 kg/m^3	1,879 kg/m^3
"crust" density	~ 2,900 kg/m3	917 kg/m^3 (water ice)
Surface fluid : density Viscosity	Water; 1,000 kg/m^3 0.01 poise	Methane, ethane, other hydrocarbons ~600 kg/m^3 Unknown (greater than water)
"magma" composition Density viscosity	Basalt ~ 2,600-2,800 kg/m3 ~ 3 x 10^3 poise	Ammonia-water-methanol Unknown (lower than Earth) Unknown
Atmosphere composition	N_2 78% O_2 21%	N_2 95% CH_4 4.5%
Surface Temp (avg)	287 K	93.7 K
Atmospheric pressure	101.3 kPa	146.7 kPa
Freezing pt. of fluid	273.15 K	90.7 K
Ave Heat Flux	5mW/m^2	65mW/m^2 (continental)
Geothermal gradient	.022 K/m	.003 K/m

Surficial expressions of volcanism on Earth and Titan:

Volcanic landforms result from eruption of a fluid, gas, or mixture under pressure, and usually have well-defined eruptive centers. The shape of the volcano depends upon the characteristics of the erupted material (phase, density, viscosity, temperature) and whether the magma undergoes phase transition (e.g. liquid to gas) upon eruption and whether the material freezes (liquid to solid) after eruption. On Earth, the erupting magma usually is of a lower density and viscosity than the surrounding solid material through which it has ascended. Magmas cool at the Earth surface and freeze to form solid materials. Therefore, eruptions can form various landforms: craters, low gradient lava flows, or steep landforms built of extruded solids.

On Earth, Volcanoes range in size from massive volcanic centers to small cindercones that are often found in cinder cone fields. These small volcanoes form from extrusive lava flows and pyroclastic material that erupt over a short period of time to form volcanoes in the shape of cones (Porter 1972). Porter (1972) examined the morphology of a few hundred cinder cones near Mauna Kea on Hawaii, measured some of the same characteristics of theses cinder cones, and created probability distributions with his results, a process that is replicated in this paper.

Recent research suggests evidence for volcanism on Titan, with identified volcanic centers ranging in size from small eruptive centers to large volcanoes. Magma on Titan is not hot silicate liquids, but it is likely a fluid composed of methane, ammonia, and water-ice slurry

(Zebker et al. 2007). The source of this “magma” may be a shallow underground “sea” of cryomagma (ibid). Similar to small volcanoes on Earth, it is possible that cryomagma can form extrusive flows and form cones that are similar to the cinder cones found on Earth. The main components of the crust of Titan are water-ice and silicate rocks, which will allow for similar extrusive flows onto Titan’s surface (ibid). According to Zebker et al. (2007), there is even evidence for cryovolcanism that can be seen in features such as domes and calderas, which have been reported on the surface of Titan. Regardless of the materials, it seems as though both volcanic and cryovolcanic methods yield domes and cones that appear circular from the surface (Fagents et al. 2003). So while volcanism on Earth and cryovolcanism on Titan are inherently different, the two processes can result in similar features (ibid).

Surficial Expressions of a Thermokarst Landscape on Earth:

Thermokarst lakes form by the thawing of ice-rich permafrost (Yoshikawa et al. 2003). Near-surface soils in permafrost areas can have ice-filled pore spaces that represent up to 90% of the volume of the soil. Pingoes and other landforms in permafrost areas have even higher concentrations of ice by volume. Upon thawing, the ice is transformed to water which accumulates in topographic lows (which were original concentrations of ice). The result is a landscape of lakes that are extensive features on the Coastal Plain of Alaska and Siberia, permafrost regions that were largely unglaciated during the last glacial maximum (K. Yoshikawa et al. 2009).

Lake elongation

A distinctive feature of thermokarst lakes in Siberia and Alaska (and paleo-features on the Coastal Plains of N. Carolina, Virginia and Maryland) is the elongation of the lakes in the direction of prevailing Coastal Plain topographic gradients. Because these regions of Siberia and Alaska were permafrost regions during both glacial and interglacial periods it is difficult to directly connect morphology to process and the mechanisms of lake elongation are poorly understood. Thermokarst lakes in a given population (i.e. in a given region of Siberia or Alaska) may be of similar ages and experienced a similar history. Study of thaw lakes that are forming in permafrost formed in post-glacial sediments, however, might provide insight into the original shapes of thaw lakes prior to elongation. These “young” thaw lakes are circular or square in outline (Riordan et al. 2006). Lake elongation mechanisms are poorly understood, but two main hypotheses have been proposed: shoreline erosion due to waves and thaw slumping due to groundwater flow in the direction of the prevailing topographic gradient

While there is the potential of a freeze-thaw cycle on Titan (McEwen et al. 2011), it is unlikely that the process of thermokarst formation on Earth could be replicated on Titan due to less frequent methane phase changes (ibid). Even though the formation process may not be identical, it is possible that depressions could be formed via an upwelling of cryomagma. Seasonal precipitation could fill in these depressions and form lakes (Lunine and Lorenz, 2009).

The more interesting prospect is the process of lake elongation happening on Titan, a method that could be similar to thermokarst lakes elongation on Earth. According to Pelletier et al. (2005), thermokarst lakes on Earth are gradually elongating due to a process called “thaw slumping”. Thaw slumping is the thawing of permafrost ice due to the movement of groundwater beneath and down the gradient of the land. It is reasonable to see how a similar process can work on Titan, only with a liquid other water.

If this is the case, probability distributions of lake characteristics on Titan should be similar to those of elongated thermokarst lakes on Earth. Therefore in this study has examined whether there may be two separate processes that shape the Titan Lakes: one process responsible for the formation of a topographic depression and another process responsible for lake elongation.

Hypotheses:

The Hypotheses of this paper are:

H1: On Earth, the shapes and size distributions of thermokarst lakes are distinct from cindercones (proxy for small eruptive centers envisioned for cryovolcanoes).

H2: The shapes and size distributions of Titan lakes are statistically similar to thermokarst lakes but are not statistically similar to cindercones (proxy for small eruptive centers envisioned for cryovolcanoes).

H3: Lakes on Titan have shapes (as measured by elongation ratios) and size distributions that are similar to those created by thermokarst processes on Earth.

Experiment Design:

Identification of Earth Analogue Populations:

To perform this experiment, I needed to identify regions of Earth with measureable populations of thermokarst and volcanogenic features that occur in "fields", similar to the features on Titan. Thermokarst lakes form in permafrost areas of Siberia and Alaska, and are most evident in regions that were not affected by Pleistocene Glaciation. Earth analogue thermokarst lakes were chosen from Coastal Plain regions of Alaska and Siberia. Two different regions were chosen because it is likely that surface ages of these regions might be significantly different, which may be reflected in the size, and particularly the elongation ratio of their lakes.

For the Earth analogue volcanic process, I also chose features that occurred in fields and previous studies of cinder cone fields suggested that the cinder cone volcanoes along the Mexican Volcanic Belt and near Mauna Kea in Hawaii are the most extensive fields of young volcanic centers that could be measured for this study

Measurement of lake dimensions and calculation of the elongation index:

Characteristics of Earth analogue lakes were evaluated from high resolution air photographs that were acquired through Google Earth. Major and minor axis lengths were measured for each of the lakes. Lake and cinder cone size was expressed using the major axis. To determine shape, I simply used the elongation index (major axis divided by minor axis), which is a dimensionless number that can be used to compare the elipticity of the Earth thermokarst lakes, cindercones, and Titan lakes.

Probability distributions of lake data:

After taking the measurements, I compiled the data and created probability distributions of the data. Lake dimension data was analyzed by plotting histograms and calculating median, mode, kurtosis, and skew for the probability distribution of each measured dimension. The following statistical measurements were also determined for each population. The standard deviation of a data set measures how dispersed the values are from the mean value. The equation for standard deviation is:

$s = \sqrt{\frac{\Sigma(x-\bar{x})}{n-1}}$ Where $\bar{x}$ is the mean and n is the number of points in the sample

The skewness of a probability distribution measures the asymmetry of a distribution from its mean. Skewness can be either positive (asymmetrically tails towards more positive values) or negative (asymmetrically tails towards more negative values). The equation for the skewness of a data set is:

$$\frac{n}{(n-1)(n-2)} * \Sigma(\frac{x-\bar{x}}{s})^3$$

The kurtosis determines the relative "peakedness" of a probability distribution. A positive kurtosis indicates a fairly peaked distribution, while a negative kurtosis indicates a fairly flat distribution. The equation for the kurtosis of a data set is:

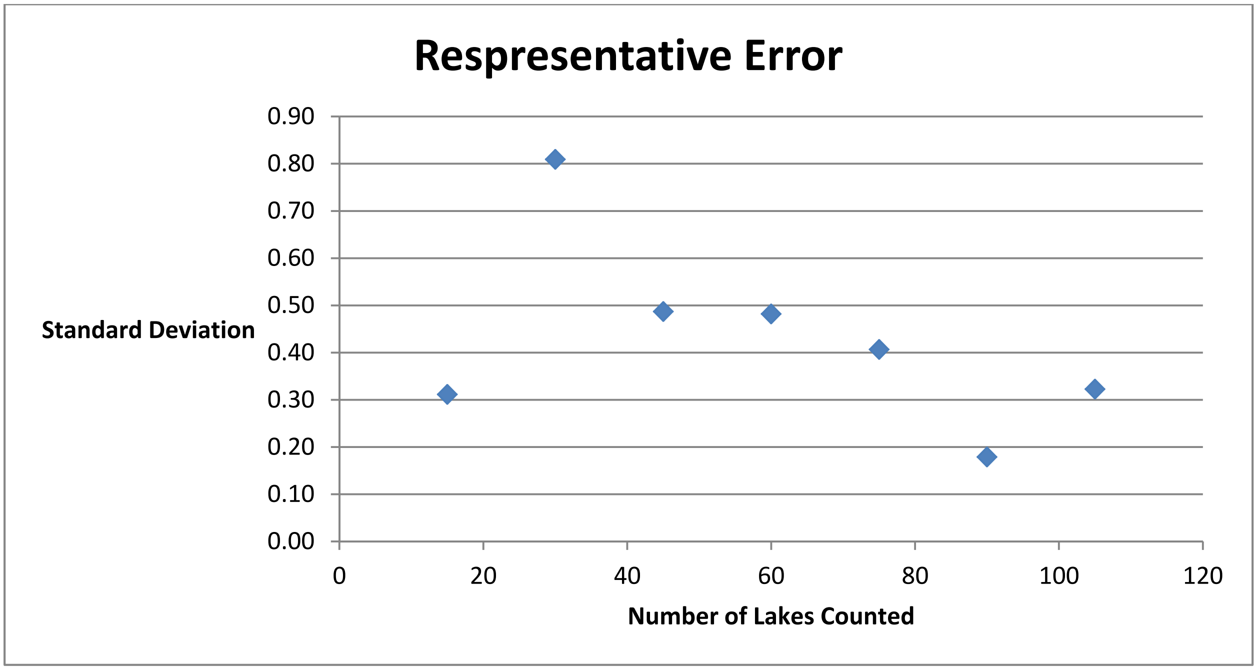
$$\left\{\frac{n(n+1)}{(n-1)(n-2)(n-3)} * \Sigma\left(\frac{x-\bar{x}}{s}\right)^4\right\} - \frac{3(n-1)^2}{(n-2)(n-3)}$$

Data bases for Titan Lakes:

The recent paper by Sharma and Byrne (2011) measured the lake dimensions of the smaller lakes on Titan that I used for my Earth analogue lakes. I therefore gathered the results from their paper involving the Titan lakes dimensions, and compared them to my Earth analogue data.

Error Analysis:

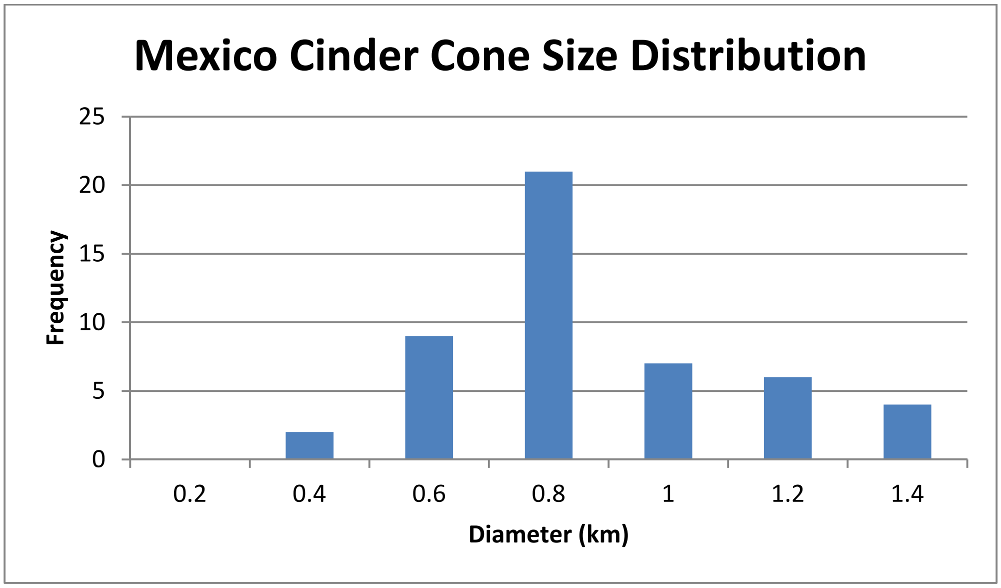
For this project, I measured the dimensions of individual lakes and examined the population of lakes within a region. Therefore, there are two potential sources of error: a) error in the measurement sizes of individual lakes, and b) error in the distribution of lake dimensions that develop from working with non-representative samples (too small of a sample size). For the error in the measurement of individual lakes, I used two techniques which each supplied a unique error. The first technique was the operator error, and this is was found by measuring a known length (e.g. a runway at BWI airport of 9,501 ft) several times and determining the max difference of measured length to actual length. The other technique was in testing the resolution of the aerial photos. For this technique I measured the same runway as before, but from different altitudes. The two techniques produced rather small errors; small enough that the uncertainties for each datum point will actually be contained within size of the points. For the error in distribution sizes, I calculated the median for a different number of thermokarst lakes (integrals of 15), when there are an appropriate number of samples, the median should be contained within a small range of values. The figure below shows how the spread seems too narrow to a particular median, showing that a large enough population was used. While this method proved feasible for the thermokarst lakes, the number of small volcanoes is limited, so the measured population of those was the entire population.

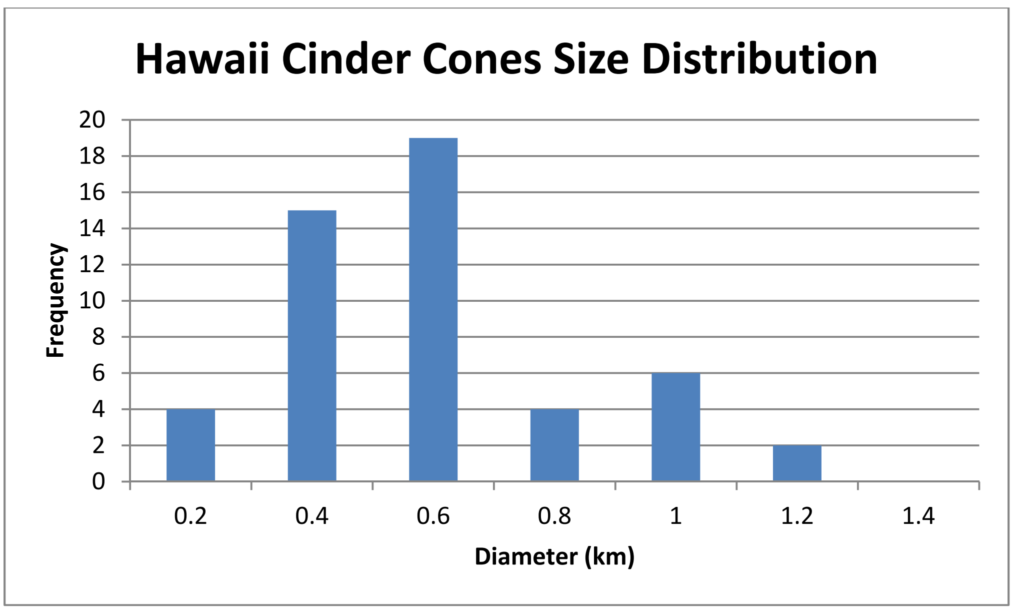


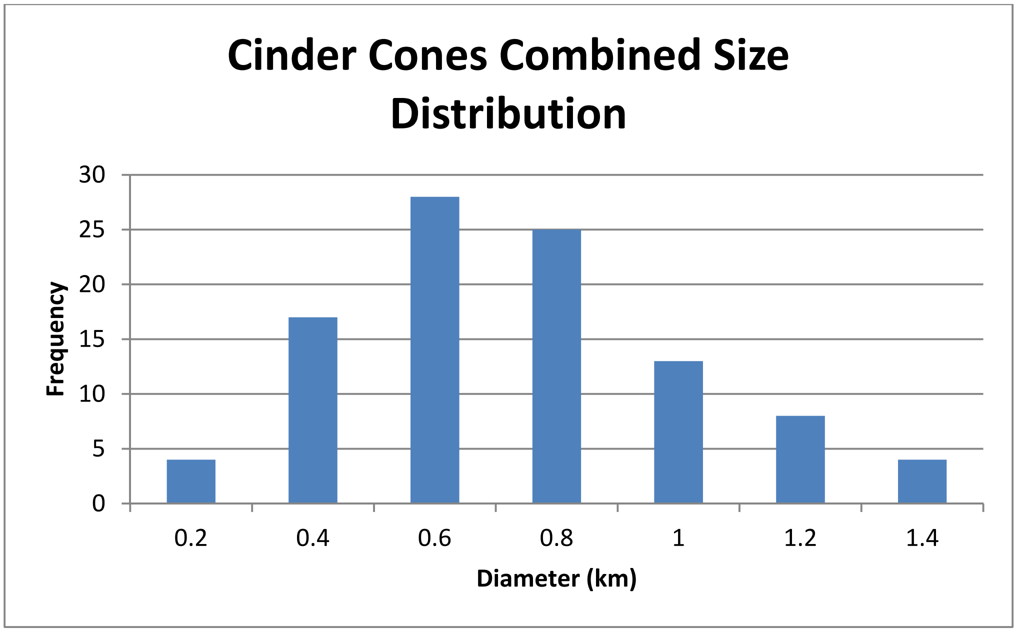
RESULTS

Presentation of cinder cone data:

Size distribution of cindercones:

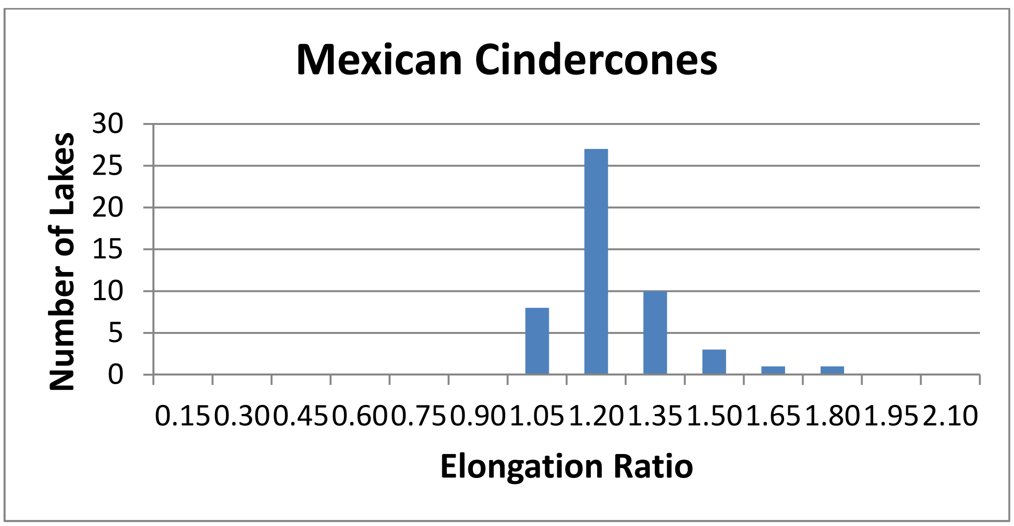


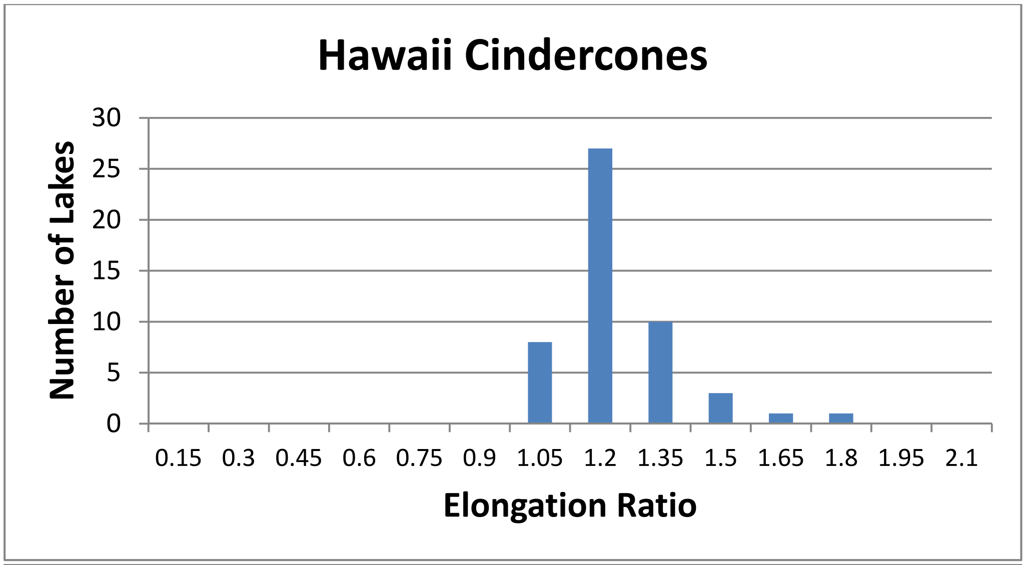


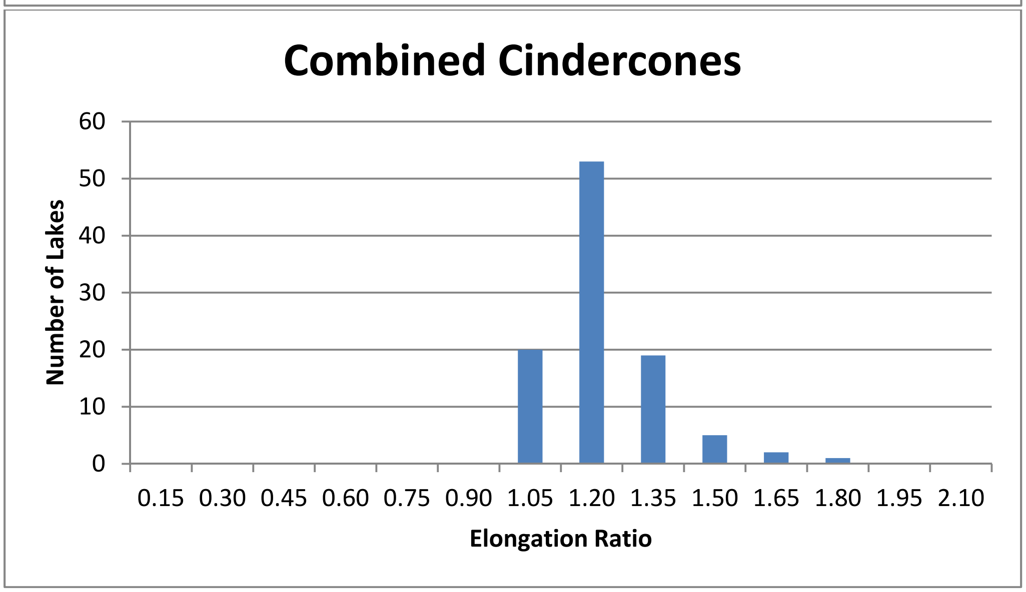


As you can see from the above plots, the size distribution does not seem to change radically between the two populations. The Hawaii cinder cones appear slightly smaller, but both have similar distributions. The mean, standard deviation, and median can be seen in the "Comparison of Size Distribution Table" below.

Elongation ratio:





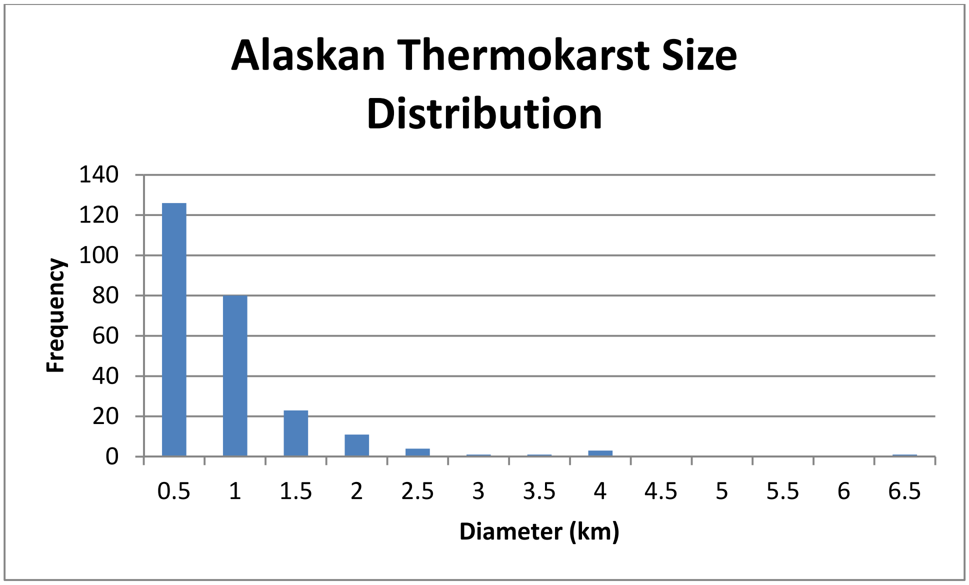


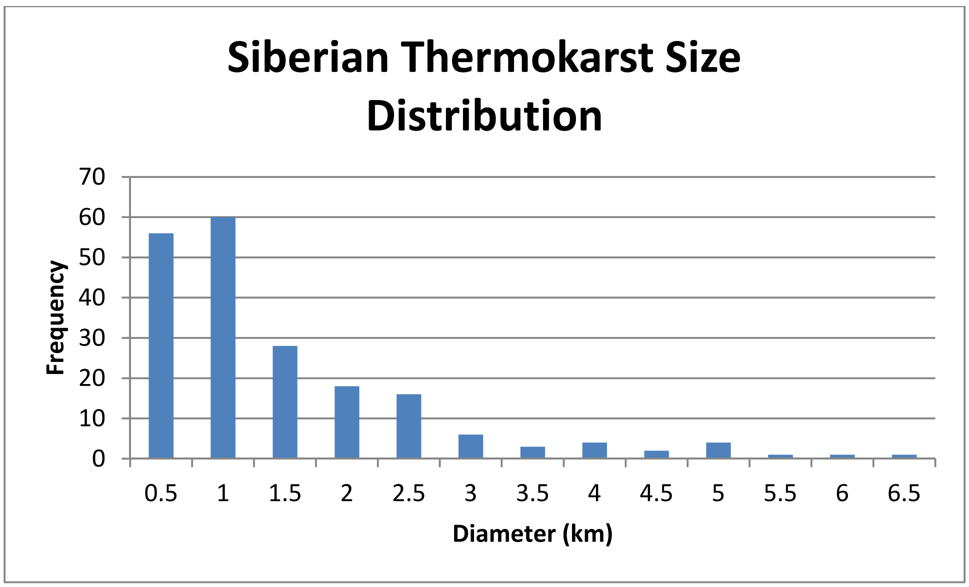
It is easy to see in the above plots how the distributions of the different populations are nearly identical. They also are strongly peaked at just over 1, which implies that they are all very round. The mean, standard deviation, skew, and kurtosis can all be found in the "Comparison of Elongation Ratio Table" below.

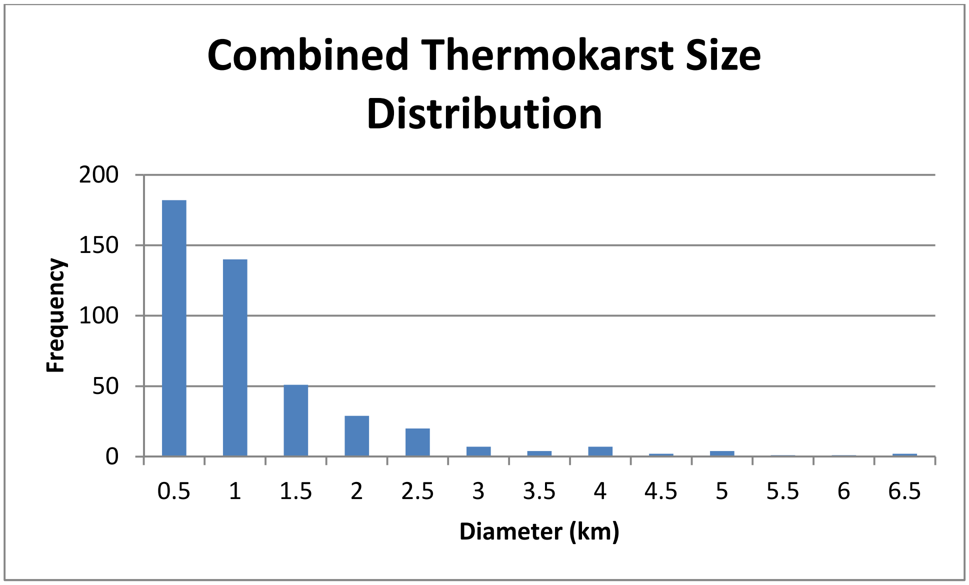
Presentation of Thermokarst Lake Data:

Note: Many more thermokarst lake fields are available to study than cinder cone fields. Therefore, Siberian data were examined as a separate population from the Alaskan thermokarst lake data.

Size Distribution:

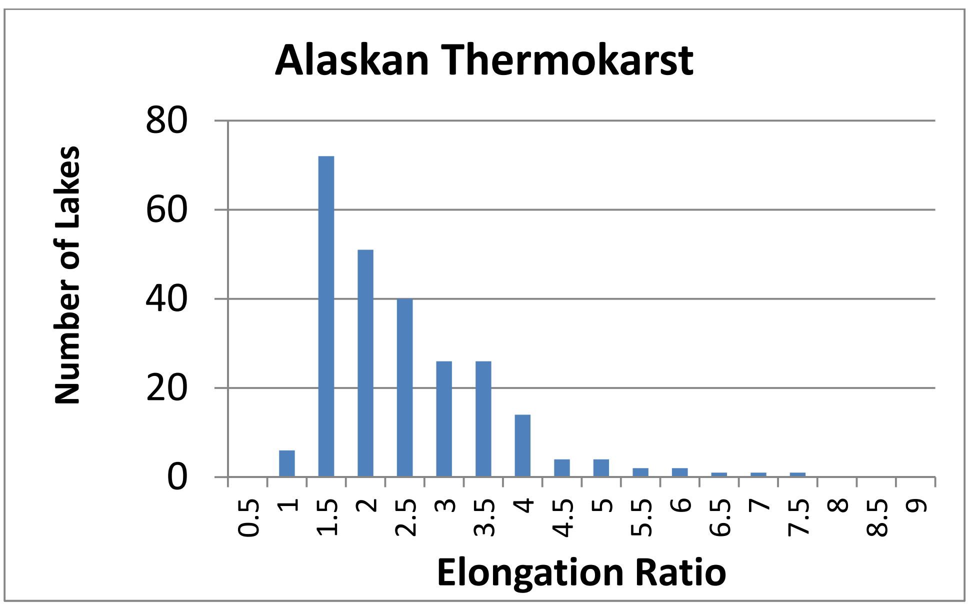


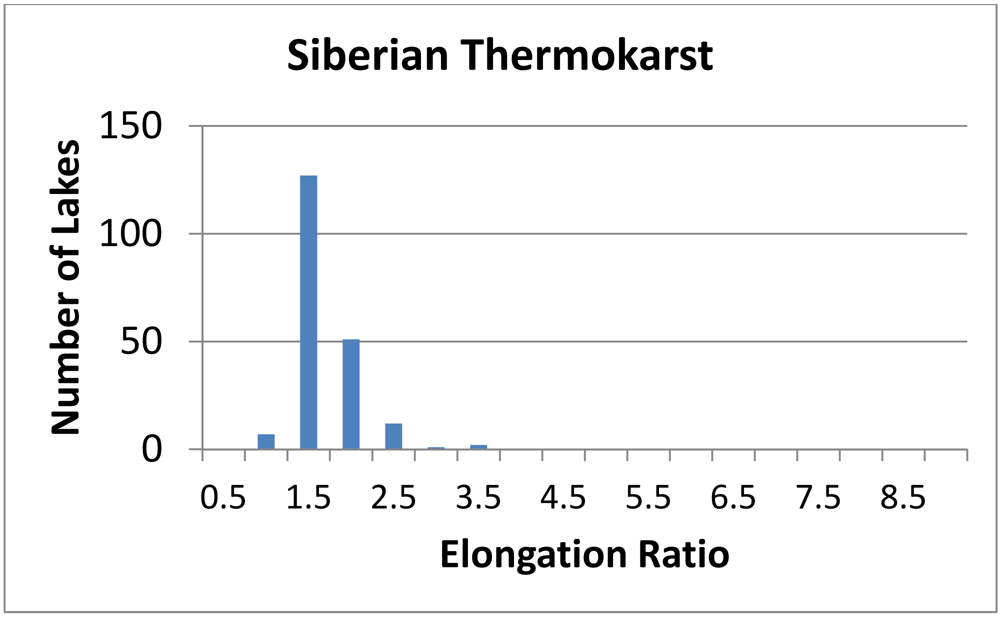


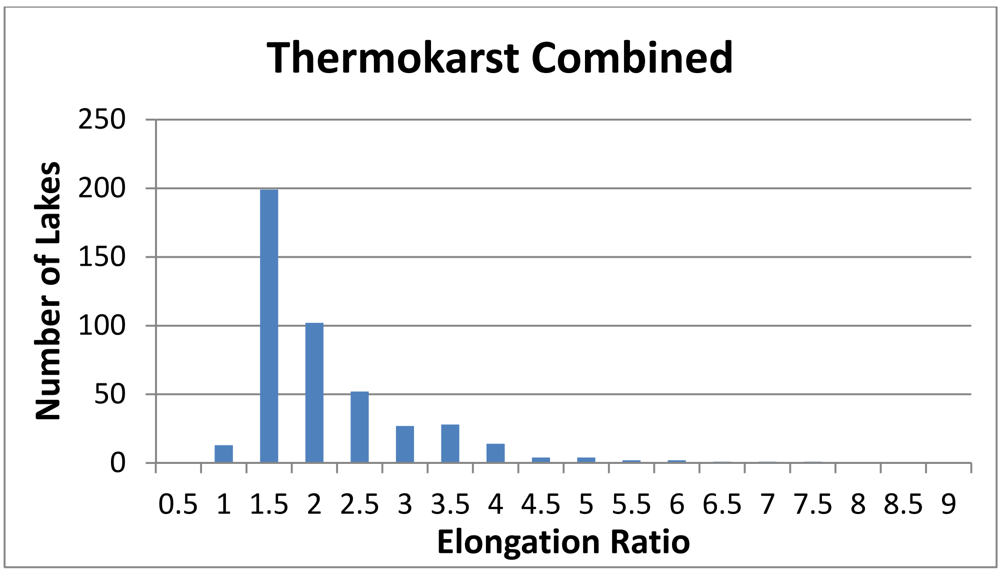


The plots above indicate that while the size distributions for the lake populations are similar, they are not identical. The Siberian lakes appear to be have more large lakes than the Alaskan lakes. This is further indicated in the “Comparison of Size Distribution Table”, where the mean and median are significantly higher in the Siberian population. This is an indication that there is an age difference between the populations.

Elongation Ratio:

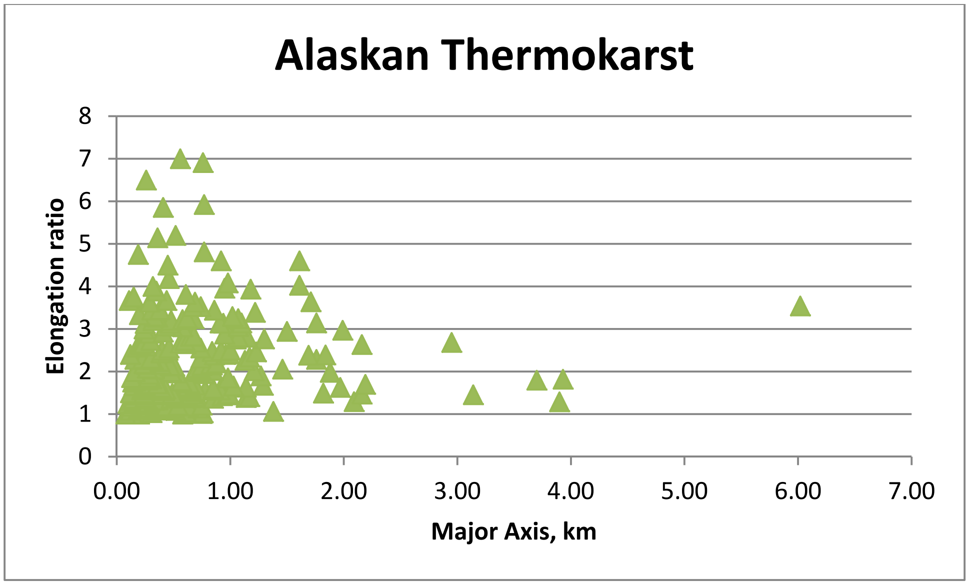


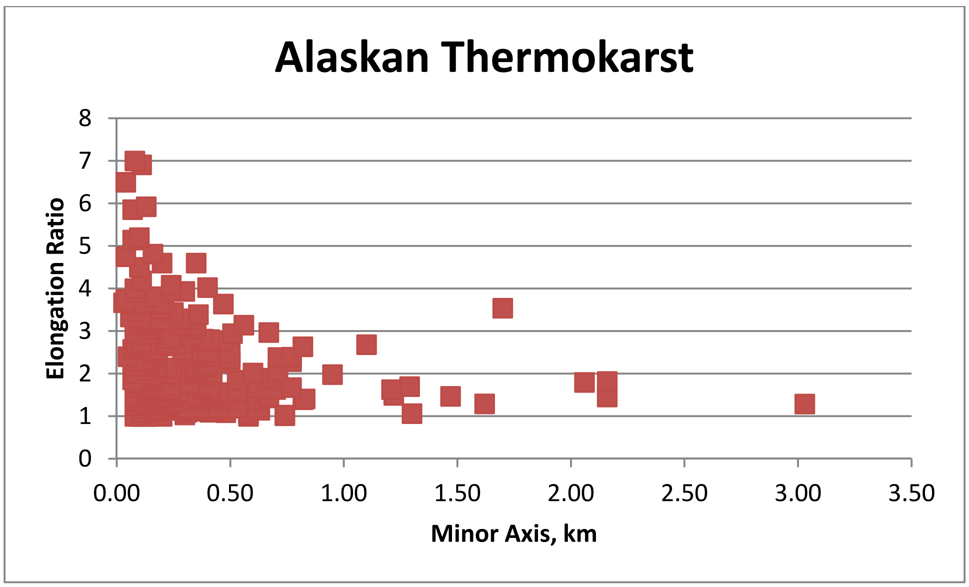


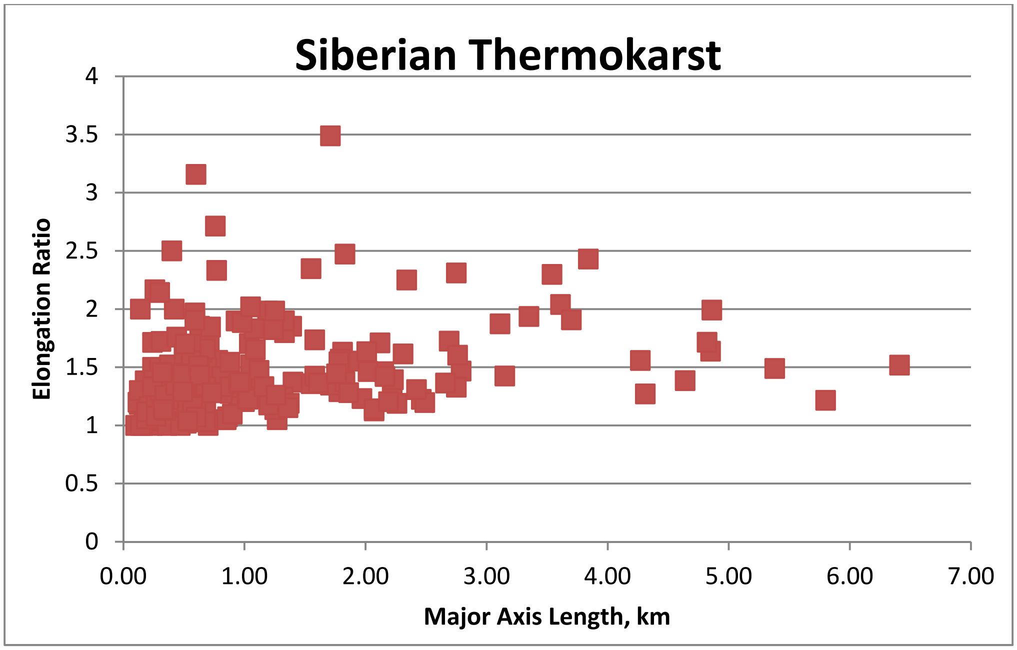


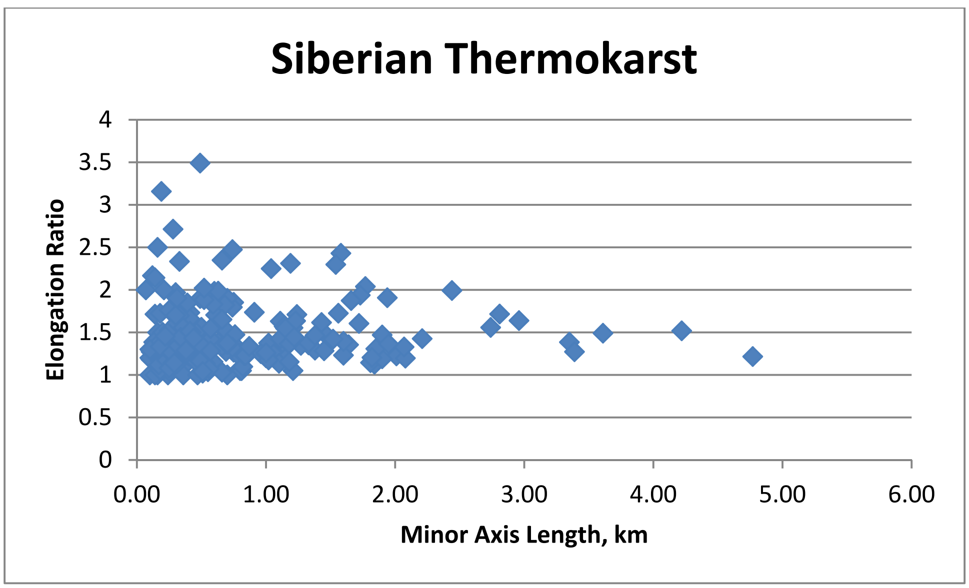
These plots once again indicate that the two thermokarst populations are different. The Alaskan thermokarst lakes appear much more elongated than the Siberian lakes. The values for the mean, standard deviation, skew, and kurtosis for the two populations can be seen in the "Comparison of Elongation Ratio Table" below. The difference in size and elongation between the two populations may indicate that as the lakes evolve, their elongation ratio may change with age.

Which are the most elongated in a population, the small or the large ones?









Above are plots of the major or minor axis plotted against the elongation ratio. While it seems more noticeable with the minor than major axis, there seems to be an indication that as the lakes get bigger, they also get more elongated. Again, it is possible that this could indicate that lakes' elongation ratios change as they get bigger (or smaller).

Comparison of Size Distribution Table:

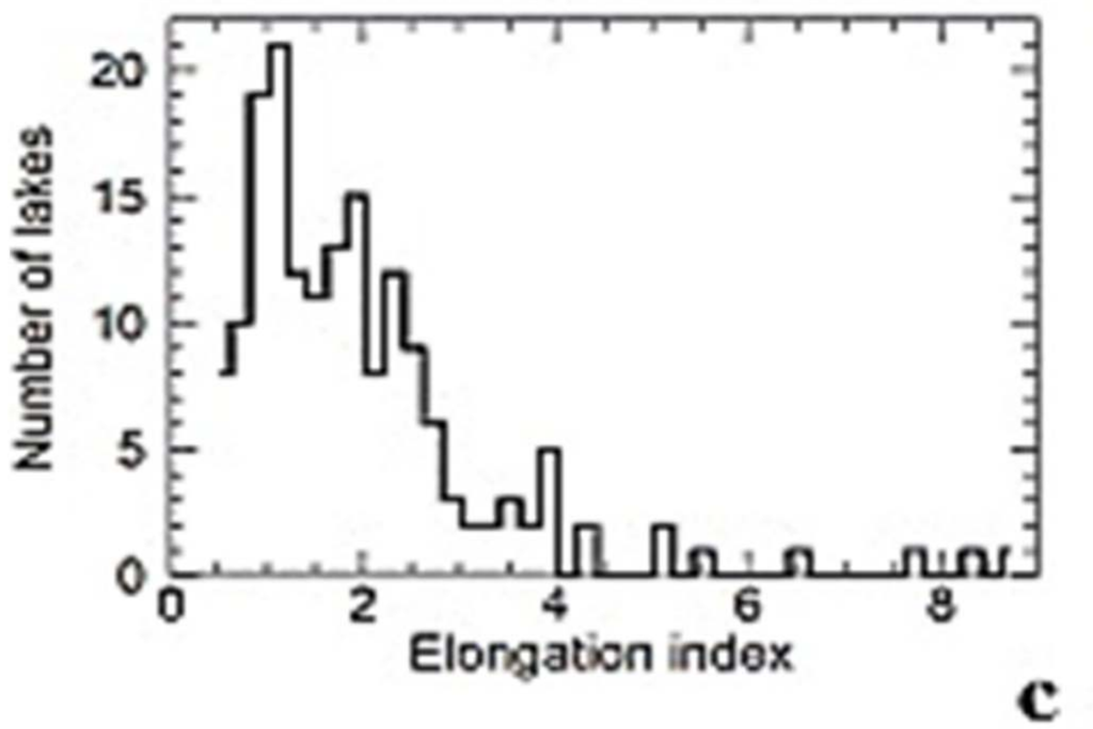
Lake Type	Median (km)	Std. Dev. (km)	Mean (km)
Earth Small Volcanoes (n=100)	.62	.45	.68
Alaska Thermokarst (n=250)	.49	.70	.70
Siberian Thermokarst (n=200)	.87	1.17	1.24
Earth Thermokarst (Combined) (n=450)	.63	.97	.94
Titan Lakes (n=27)	47	62.23	63.67

Comparison of Elongation Ratio Table:

Lake Type	Elongation Ratio: Mean	Elongation Ratio: St. Dev.	Skew	Kurtosis
Alaskan Thermokarst	2.25	1.10	1.74	2.40
Siberian Thermokarst	1.46	0.39	3.44	12.28
Cindercones (n=100)	1.15	0.13	4.23	17.92
Titan Lakes	2.27 (bimodal)	1.60	1.46	1.31

Comparison of Populations:

The two tables above compare some of the statistical properties of all of the different lake populations. It is easy to see how the population for the cinder cones is significantly different from the populations of the other lake types, while remaining similar to each other. The thermokarst lake types on the other hand appear different from each other as well as to the cinder cones and Titan lakes. The Titan lakes (elongation plot seen below) also appear to have a different elongation ratio from the other lake types. There does however appear to be some similarities between the distributions of the elongation ratios of the Titan lakes and the Alaskan lakes.



Conclusions:

There seems to be an indication that none of the lake types are similar to each other. There seems to be an indication that the Titan lakes have formed via a different process than Earth analogue cinder cone or thermokarst lakes. However, there does appear to be an indication that as the thermokarst lakes age or change in size, their elongation ratio might change as well. It is not entirely known what causes this, or if the processes could be replicated on Titan.

Summary:

While the formation of the lakes on Titan remains unknown, it is not necessarily impossible that there is a process of lake formation on Earth that could work on Titan as well. The indications that thermokarst lakes may change in size and/or elongation ratio over time seem to be significant. It even seems possible that the lakes on Titan could have formed via a certain process similar to Earth, and then elongated by some other process. Future research should focus on the evolution of thermokarst lakes, and determine if it is possible that Titan lakes could have evolved via a similar method, this would help to shed some light on how the lakes on Titan may have formed.

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