QUANTITIVE ANALYSIS OF CALDERA SHAPES ON EARTH, MARS, AND IO. Rowan Huang[1], Jani Radebaugh[1], Eric H. Christiansen[1], [1]Department of Geological Sciences, Brigham Young University, Provo, UT, 84602 (huang.rowan@gmail.com).

Introduction: Calderas are volcanic craters that typically form when overlying rock collapses into a magma chamber voided by eruption [1,2]. Wood [3] defines three classes based on magma composition, eruption style, and tectonic setting: basaltic shield, ash flow, and stratocone. On Earth, Wood's classifications are straightforward, and it is relatively easy to classify a volcano as such. However, on extraterrestrial bodies, in-situ data is not available, so it is more difficult to classify these volcanic features based on composition and eruption style. This is especially true of paterae on Jupiter's moon Io, as they exhibit ambiguous magmatic associations, large sizes, and irregular shapes [4].

Given that the three terrestrial caldera groups can be classified based on morphological characteristics, shape could be used to inform the origins of other planetary volcanic craters. These classifications could then predict composition and eruption style for these craters, augmenting our understanding of the geologic history of planets.

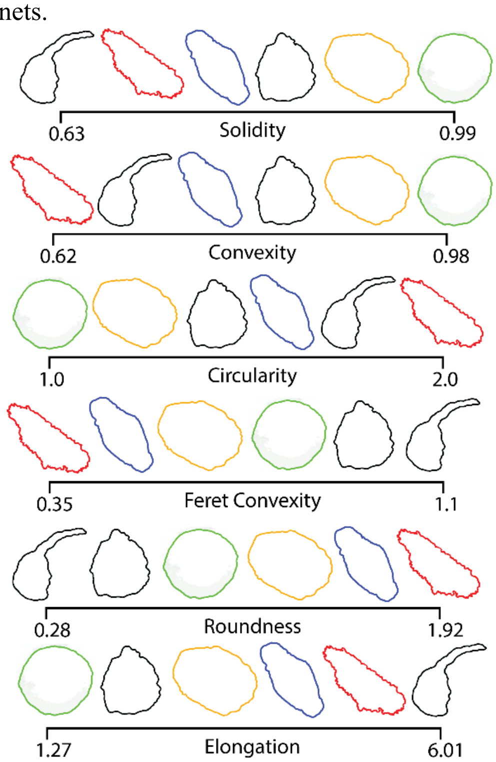

Figure 1. *Six variables used to classify caldera shapes.*

Method: Building on previous studies of geometric morphometrics (a technique that quantifies shape using landmark points) [5], we have expanded our analysis to include more traditional measures of shape [6,7] (Fig. 1). Previous studies using this methodology included 10 of each type of terrestrial caldera, 16 martian calderas, and 10 ionian paterae [7]. This study expands these selections and reveals the effect of increasing the sample size on classification, including 56 terrestrial calderas (18 ash flow, 19 basaltic shield, 19 stratocones), 16 martian basaltic shields, and 51 ionian paterae. ArcGIS Pro was used to map individual volcanic craters by tracing their topographic rims. Convex hulls and bounding rectangles were generated for each crater along with area, perimeter, and maximum feret diameter.

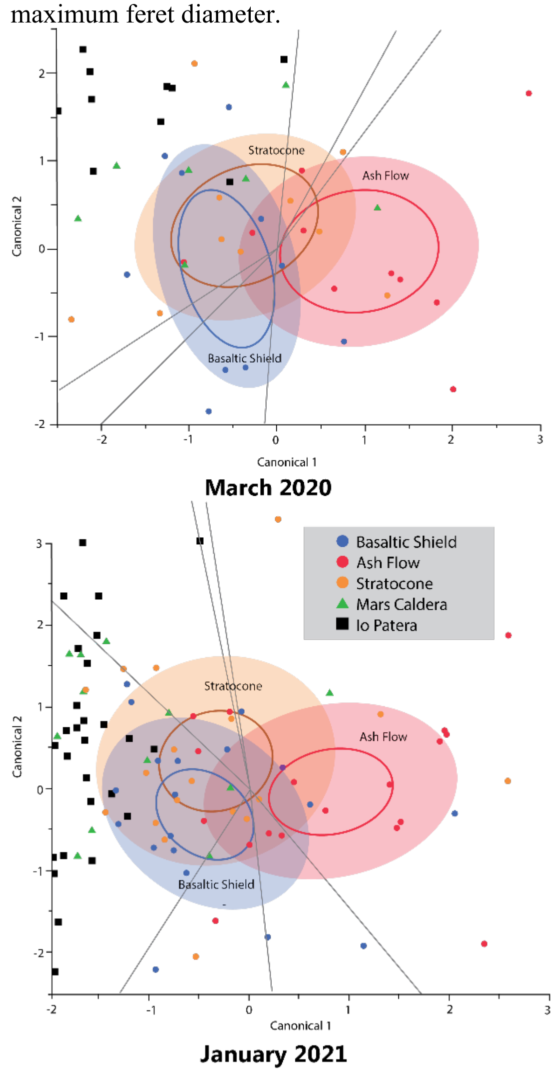

Figure 2. *Change in discriminant analyses with different sample sizes. Shaded ellipses represent 95% confidence limits for the mean. Top is derived from 30 calderas and bottom from 56 calderas.*

Two-dimensional morphometric parameters were calculated and examined using the statistical analysis software JMP. These parameters describe shape factors such as roughness, form, and aspect ratio. Parameters that were highly correlated with one another and that were size related were eliminated from analysis.

Results and Discussion: We used six calculated parameters: Solidity, Convexity, Feret Convexity, Circularity, Roundness, and Elongation (Fig. 1). These variables were chosen because they are relatively independent and poorly correlated with one another as well as independent of size.

Discriminant analysis is the best technique for classifying craters morphometrically as it minimizes class overlap based on variable combinations [7]. Classifications and group overlaps change somewhat based on the sample size (Fig. 2). With the larger dataset, the percent of terrestrial calderas correctly classified in the training set improved from 46.7% to 60.7%. Nonetheless, discriminant analysis still shows relatively high degrees of overlap between terrestrial crater shapes, especially basaltic shield and stratocone (Fig. 2). Ionian paterae and martian calderas generally lie to the left of the terrestrial calderas in Fig. 2.

The overlap between basaltic shield and stratocone ellipses occurs in previous, smaller data sets, where we suggested that crater morphology may reflect eruption style and volcano morphology [7]. However, this may not be the case, as implied by the high degree of overlap with ash flow calderas in this instance. Instead, the similarity between basaltic shield and stratocone calderas may be a reflection of their size (irregularities affect the shape more than in large ash flow craters).

Discriminant analysis also shows the effect of terrestrial surface processes on crater shape: ash flow calderas, which are on average the oldest and largest of our terrestrial craters, plot farthest to the right on the discriminant analysis because of their low convexity—which may be the result of erosion (Fig. 2). Ash flow caldera topographic rims are more ragged than other calderas. Ionian paterae and martian calderas plot farthest to the left because their rims are smooth and relatively uneroded. These craters overlap only sparingly with terrestrial calderas, suggesting that terrestrial calderas are not comparable to those on other bodies because of the modification of their rims.

We also performed cluster analysis, which groups craters with those of similar shapes. Hierarchal clustering of terrestrial calderas shows poor relations between classes and shape—craters of various types are clustered together, and no cluster consists of a single crater type. This supports our discriminant analysis that suggests that the shapes of terrestrial calderas are not overtly distinct from one another. When martian calderas are included, they also show poor clustering, so their shapes are like those of terrestrial calderas. However, ionian paterae reside on a separate branch and from there form three distinct clusters even though size is not included (Fig. 3). They have unique shapes compared to the other volcanic craters. Many of the measured ionian paterae have distinct "avocado" shapes, oblong with bulges on one end. The shapes are unlike the measured terrestrial and martian calderas, which are generally circular or elliptical. Because of this unique shape, these ionian paterae are distinctly elongated with large concavities.

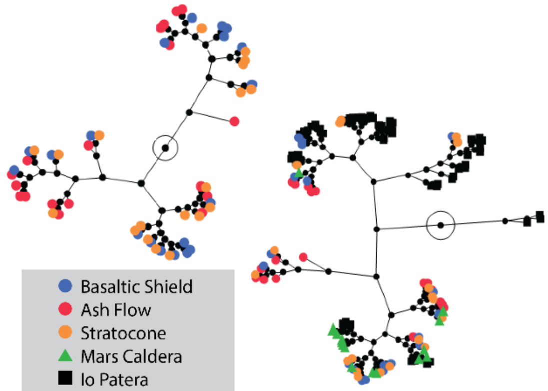

Figure 3. *Constellation plots of hierarchal clusters of morphometric data. Top left terrestrial calderas only, bottom right all measured calderas (Io paterae in black).*

The clustering of paterae may additionally be due to the smoothness of their inferred outlines, a result of relatively low-resolution images of Io. For this reason, most clusters on the constellation plot that include martian calderas also contain ionian paterae. This is may be another reason for the discriminant analysis grouping of these classes, which were distinct because of their smoothness as measured by convexity (perimeter of the convex hull divided by the true perimeter).

Future Work: To reduce sampling bias and improve classifications, we will continue to add more terrestrial and martian calderas and the uniquely shaped ionian paterae to our analysis. To examine the impact of image resolution, we plan to examine if features in low- and high-resolution images of Io group differently in our analyses. For eroded terrestrial calderas, we will investigate techniques for estimating original terrestrial collapse crater shape for more equitable comparisons with those on other planets where erosion is not as important.

References: [1] Lipman (1997) *Bull. Volcanology* 59, 198-218. [2] Francis et al. (1993) Volcanoes 521. [3] Wood (1984) *JGR Solid Earth* 89, 8391-8406. [4] Radebaugh et al. (2001) *JGR Planets* 106, 33105-33020. [5] Slezak (2017) M.S. Thesis, Brigham Young University. [6] Huang R. I. (2020) *LPSC L,* Abstract #2783. [7] Huang R. I. (2019) *LPSC LI,* Abstract #2825 [8] Liu et al. (2015) *GeoResJ*, 8, 14-30.