Quanitative Analysis of Caldera Shape: Earth, Mars, and Io. R. Huang, J. Radebaugh, E. H. Christiansen, Department of Geological Sciences, Brigham Young University, Provo, UT, 84602 (huang.rowan@gmail.com).

Introduction: Calderas are a type of volcanic crater common on Earth and other planetary bodies that typically form by collapse of rock into underlying magma reservoirs emptied by eruption [1, 2]. Wood [3] has defined three terrestrial caldera types: ash-flow, basaltic shield, and stratocone (more commonly known as stratovolcano). These classifications are defined by factors such as composition, eruption style, and tectonic setting. These are straightforward and informative groups on Earth, but because in-situ data are lacking, features on extraterrestrial bodies are harder to classify. For example, paterae on Jupiter’s moon Io are unique in their shapes and sizes and possess an unclear magmatic style that has not yet been fully discerned [4].

While eruption style, geologic history, and composition are difficult to study remotely, satellites provide excellent images of volcanic crater shapes. If these three terrestrial caldera groups can be classified distinctly by morphological characteristics, these classifications can be used to predict aspects of planetary craters with unclear origins. This has implications for predicting planetary geologic histories as well as exploring the relationship between caldera types and their morphologies.

Method: We have previously used geometric morphometrics, or the use of quantitative characteristics of shape, to study craters [5]. We have subsequently built on this analysis by using more traditional measures of shape [6]. Formerly, only terrestrial calderas and a selection of martian calderas were examined, but our study has been expanded to include an updated assortment of terrestrial craters (10 calderas of each type), as well as a more representative range of martian calderas (16 total). We have also included a small sample of ionian paterae (10 paterae) as a proof of concept into which we plan to extend the work.

In order to calculate morphometric values, the outline of the topographic rim of each crater was traced in ArcGIS Pro (Fig. 1). We define topographic rim as “The escarpment that bounds the subsided caldera” [7]. The geoprocessing tool “Minimum Bounding Geometry” was used to generate a convex hull and bounding rectangles for each crater. The convex hull is the shape that encompasses all points of the true shape but minimizes perimeter; it is a shape with no concavities. The convex hull is a useful geometry to study when compared with an object’s real shape because it can represent the object’s irregularity. When a collapse crater has concavities, it is very distinctive, which can aid in delineating the differences between crater classifications. Shapes like the convex hull and rectangles are used to calculate centroid latitude and longitude, area, perimeter, bounding rectangle dimensions, and the maximum feret diameter (maximum distance between two parallel lines tangential to the topographic outline). From these, two-dimensional morphometric parameters were outlined (defined in [6]).

Next, the statistical analysis program JMP was used to refine the aforementioned two-dimensional variables. Many of these parameters are strongly correlated to each other, rendering them redundant. The unnecessary variables were discarded. We also did not use extensive variables, such as crater area and perimeter.

Figure 1: Image of the Io patera Yaw with its topographic outline in red (left). On the right is the same patera with its convex hull (blue) and minimum bounding rectangle (black).

Figure 2: Relative order of six selected crater outlines for each of the optimized variables.
Results: We found 5 variables to be relatively independent and poorly correlated to one another – circularity, solidity, convexity, feret convexity, and roundness (Fig. 2). Circularity is a measure of the shape’s irregularity by comparing the perimeter of the shape to the perimeter of a perfect circle with the same area. Solidity measures the area-based roughness of the shape. Low solidity has many concavities, and if the solidity approaches 1, the crater has few concavities and the area of its convex hull is similar to the real shape. Likewise, convexity is a measure of perimeter roughness. A shape with low convexity will have a very ragged outline, and as convexity approaches 1, the convex hull’s perimeter is like the actual perimeter. Feret convexity compares the perimeter of a circle with a diameter equal to the shape’s longest axis to the shape’s perimeter, making it a measure of textural roughness. Conversely, roundness compares the shape’s area to the area of a circle with a diameter from the long axis of the shape.

Previously, we found discriminant analysis to be the best technique for classifying craters morphometrically. Because of the complex nature of the craters, univariate and bivariate comparisons of the data points resulted in high degrees of overlap, and clustering was a poor option for defining groups. Discriminant analysis therefore remains the best for this morphometry.

Discriminant analysis is a multivariate technique that classifies the data by combining given variables in such a way that overlap between classes is minimized. We found the lowest error in a discriminant analysis of solidity, convexity, and roundness (Fig. 3). We used a quadratic fitting method, but similar results were produced with a linear model. Overlain, but not included in classification groups, are data points representing ionian paterae and martian calderas.

This analysis discerned little difference between the terrestrial craters. There is a high degree of overlap and groups are indistinct. Ten out of 30 craters were misclassified. There may be several reasons for the overlap; one may be the low numbers of shapes. In addition, crater tracing and measurement is limited by the image resolution and environmental factors such as snow and vegetation cover. Other aspects of crater shape may also influence the discriminant analysis.

Despite these shortcomings, initial conclusions can still be drawn. We see a more distinct class of ash-flow calderas because they have generally lower convexities—the shape of their outline is rougher than basaltic shield and stratocone calderas. This may result from many ash-flow calderas being much older and therefore more eroded than their counterparts. We also see close clustering of martian calderas along the basaltic shield classification. This may be unsurprising; most of Mars’ volcanoes are known to be basaltic, and their shield shapes are well aligned with those of Earth’s basalt shield volcanoes. This is promising because it shows that, despite currently unexplained deviations, this type of classification can sort volcanoes with similar origins together.

There is also a similarity between basaltic shield and stratocone crater groups that can be telling of origin. While not to this degree, we have seen overlap of these two classes in previous comparisons of other calderas. This may be due to eruption style through central or flank vent, while ash-flow calderas more commonly collapse into a larger void and involve ring vents. Both basaltic shields and stratovolcanoes develop edifices, while ash-flow calderas rarely do [1]. Perhaps the overlap suggests that crater shape is more a reflection of eruption style than composition. To solidify this result, analysis of a larger sample set should be undertaken.

Most of the Io patera data thus far analyzed lie in the midst of the estimated class contours, so it is hard to draw any conclusions at this time. We also acknowledge that the patera data is a currently small sample of ten among >400 volcanic craters on the surface of Io.

Future Work: Future work should involve the addition of many more terrestrial calderas as well as more ionian paterae to reduce bias in sampling, outlining, and analysis. We also believe erosion and mass wasting has a role in altering caldera shape and biasing terrestrial data, so we plan to explore options for estimating original collapse shape for calderas on Earth.