QUANTITIVE ANALYSIS OF CALDERA SHAPE. 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 a type of volcanic crater that typically form by collapse of overlying rock into underlying magma reservoirs following eruptive emptying. Calderas are the most common type of volcanic crater on Earth and other planets. The three terrestrial caldera types defined by Wood [1] are ash flow, basaltic shield, and stratocone. While the classification of terrestrial calderas into one of these groups is informative and relatively straightforward, volcanic craters on other planetary bodies, such as ionian paterae [2], are harder to classify. They have eruption styles, eruptive product compositions, and geologic histories that cannot be easily studied. Thus, understanding their origins is more complex. However, the shapes of volcanic collapse features can be studied on other planetary bodies and on Earth. If the three types of terrestrial calderas can be shown to have distinct morphological differences, one may be able to use these differences to classify an otherwise undefined planetary caldera and gain insight into its origin, which in turn would have important implications for planetary histories. The goal of this project is to quantify terrestrial caldera shapes and see if crater shape can be used to successfully classify them into one of the three groups. Ultimately, we seek to use the distinctions revealed to understand the types and origins of calderas on volcanoes on other worlds.

Method: We have previously used geometric morphometrics to study crater shapes [3]. Here, we extend the analysis to more traditional measures of shape using a small subset of calderas from our earlier work.

For this proof of concept study, ten terrestrial calderas of each type, as well as six martian shield calderas, were selected for shape analysis. To quantify morphological characteristics of the calderas, the rim of each was outlined in ArcGIS Pro. The topographic rim was defined as the "escarpment that bounds the subsided caldera" [4]. Minimum Bounding Geometry tools were used to create a convex hull (minimum bounding shape with no concavities) and bounding rectangles for each outline. These were used to calculate centroid latitude and longitude, area, perimeter, dimensions of bounding rectangle, and feret diameters (maximum and minimum distance between two parallel lines tangential to the particle outline). From these we calculated a variety of two dimensional shape parameters as outlined in [5].

Using the statistical analysis program JMP, we refined the number of variables used to classify shape. Many shape parameters have been defined [5], but a number of them are strongly correlated with one another, making them redundant; such parameters were not used in our analysis. For example, since convexity correlates strongly with defect area, concavity index, and Paris factor, we retained only convexity. Size parameters such as absolute area and perimeter were ignored. The preserved variables were examined using univariate, bivariate, and multivariate analysis, including scatter plots, hierarchal clustering, and discriminant analysis.

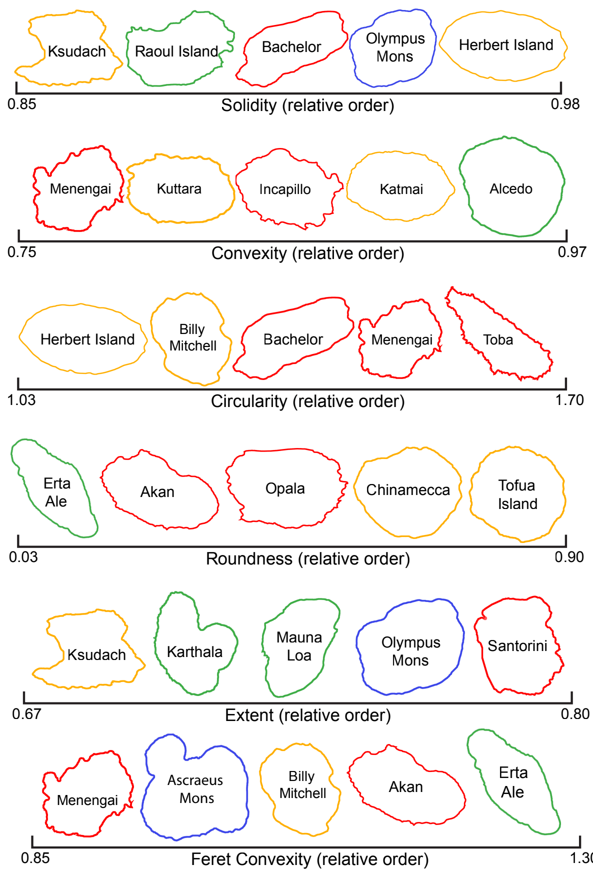

Fig. 1. Visualization of caldera shape and the way it changes with each of the six variables used in discriminant analysis. Calderas are not to scale. BS outlined in green, SC in orange-yellow, AF in red, and MC in blue.

Results: Six variables were found to be relatively independent of one another and useful for describing caldera shape (Fig. 1): solidity, convexity, circularity, roundness, extent, and feret convexity. Solidity is area-based roughness as the ratios of the shape area to the area of the convex hull; a low solidity has many and large concavities like "bites" taken out of a shape. Convexity is the ratio of perimeter of the convex hull to the actual perimeter of the caldera. A shape with a low convexity has a more sinuous outline than that of a high-convexity shape. Circulairty is a measure of compactness. Shapes with low circularity have small perimeters and large areas like circles, while high circularity denotes a large perimeter relative to its area, so it has a ragged shape. Roundness represents how close the shape is to a true circle with a roundness of 1. A shape with high roundness is more circular than one with low roundness. Extent compares the shape's area to the area of a rectangle with the shape's longest and shortest axis lengths. Shapes with larger extents are more like rectangles than shapes with low extents. Lastly, feret convexity measures how close a shape is in perimeter to a perfect circle with a diameter the length of the shape's longest axis. Shapes with high feret convexity are elongate and elliptical. Obviously, even some of these shape parameters are correlated, but they still describe significant differences as seen in Fig. 1.

When examined with univariate statistics, many of the examined parameters have overlapping values and terrestrial caldera types are not clearly different from one another. Bivariate analysis using scatterplots proved to be a poor classifier of crater shapes. There is a high degree of overlap and scatter among the caldera types. This makes groups ill-defined and the relationships between them unclear.

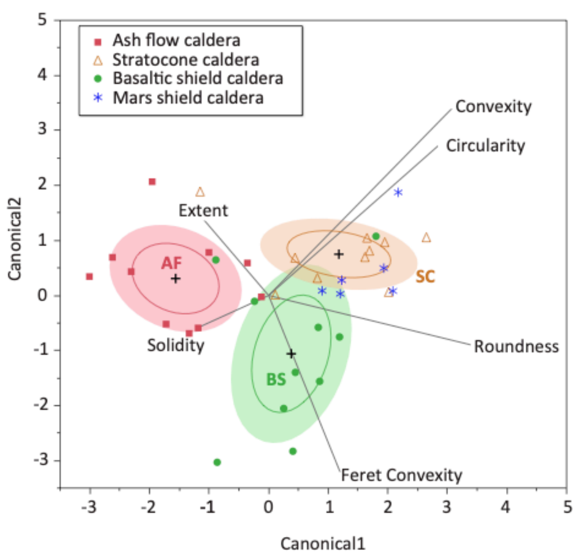

Fig. 2. Discriminant analysis of caldera types using the variables solidity, convexity, feret convexity, roundness, circularity, and extent. The caldera classes are abbreviated as follows: AF for ash flow, BS for basaltic shield, SC for stratocone, and MC for martian shield. The shaded areas correspond to the 95% confidence limits for the mean, the colored contours include ~50% of the observed values, and the labeled lines (biplot rays) represent the degree of association of each measure with the canonical variable.

On the other hand, discriminant analysis of several shape parameters proved to be reliable method for grouping the terrestrial data. As shown in Fig. 2, the three types of terrestrial calderas are clearly distinct with little overlap. We used a quadratic fitting method on the assumption that the within-group covariance matrices differ, but a linear model produced essentially the same results. Five of the thirty calderas are misclassified. Because of the small sample size these results are tentative, but they show promise of being able to distinguish different types of terrestrial calderas. For example, ash-flow calderas have generally low circularity. Their outlines tend to be more ragged and sinuous. While this may be a testament to the complex nature of ash-flow caldera collapse, the difference may also be due to erosion and deterioration of the crater rim, as the studied ash-flow calderas are older than basaltic shield and stratocone calderas on average. The association with feret convexity suggests that terrestrial basaltic shield calderas are more elongate and oval compared to more circular stratocone calderas. This could be the result of the association with tectonic rifting, movement of the volcano relative to a "fixed" mantle plume source, or flank failure and associated rifting on terrestrial basaltic shields.

We also used the discriminant model to analyze the shapes of martian calderas from the Tharsis region (Fig. 2). Although three of the martian calderas plot within the 95% confidence ellipse for terrestrial basaltic shields, the others plot with calderas on stratocones. Moreover, all of the martian calderas are classified as stratocone calderas using the discriminant model constructed from the terrestrial volcanoes. Perhaps an association with rifting or with the motion of plume-related volcanoes over "fixed" thermal anomalies (and the lack of these processes on Mars) creates differences in caldera shapes. On the large martian shields examined here, the magma reservoirs may be so large that many fractures in multiple directions are involved in the collapse, preventing a single oblong shape from forming. On the other hand, the unexpected correlation of martian calderas with terrestrial stratocone calderas may be caused by our small and perhaps biased sample of both terrestrial and martian calderas.

Future Work: We intend to extend this approach to include many more calderas, both on Earth and other bodies, to obtain a more statistically sound description and classification of terrestrial calderas. We will compare them with volcanic collapse features on other planets and moons. We will also explore outlining calderas with smoother lines to estimate the original collapse shape, rather than precisely tracing erosionally modified topographic rims.

References: [1] Wood (1984) *JGR Solid Earth, 89,* 8391-8406. [2] Radebaugh et al. (2001) *JGR Planets, 106,* 33105-33020. [3] Slezak (2017) M.S. Thesis, Brigham Young University. [4] Lipman (1997) *BV, 59*, 198-218. [5] Liu et al. (2015) *GeoResJ, 8,* 14-30. [6] Francis et al. (1993) *Volcanoes* 521.