Quantitative Planetary Landform Analysis Using Geometric Morphometrics. T. J. Slezak[1], J. Radebaugh[1], and E.H. Christiansen[1], [1]School of Physical and Mathematical Sciences, Department of Geological Sciences, Brigham Young University, Provo, UT 84602, (tjs@byu.edu).

Introduction: Complex forms may originate from simple processes. A fundamental task of planetary geology is to identify the mechanisms of formation for similarly shaped, circular to sub-circular crater structures differing in geologic settings and planetary context [1,2,3]. Craterforms, or depressions of any origin, are the most common geologic feature on most planetary bodies and can result from several very different geologic processes. The primary hypothesis of this work is that landforms differing in mechanism of formation (e.g., volcanic vs impact-induced) will display subtle, yet analytically determinable differences in form across respective populations.

This study is intended provide new information that can be used understand to understand the formation mechanisms for paterae on Io (see Fig 1) and other crater-forms in the solar system without a comprehensive dataset. Methods able to extract the information preserved in landform shape in a way that is both quantitative and analytically tractable provide advantages to modern inferences of morphometric studies. We introduce geometric morphometrics and investigate the hypothesis that natural craterform morphologies can be quantitatively distinguished. We then apply the technique to characterize and contrast impact craters and paterae on Io.

Background: Prior morphometric studies of craterforms utilize form (shape) factors as the primary means for quantitative analysis (e.g., [4], [5]). Shape factors such as circularity and elliticity describe shape with dimensionless quantities derived from measurable perimeter, area, major and minor axis length, volume, orientation, and depth. Shape factors are not sufficient quantities to describe geologic landforms due to their lack of respect for topological homology and inability to preserve information of the specific geometries they quantify. Current crater identification criteria is non-diagnostic and contextual in nature, agreements among interpretations can differ by up to ±45% per instance [6]. Landform morphology holds information about the geologic processes of its formation. This study examines the geometry present in landform morphology and provides a quantitative comparison of shape for differing landform populations.

Geometric Morphometrics: Methods of quantitative analysis that are able to preserve complete shape information and spatial orientations throughout data analysis comprise the discipline of geometric morphometrics. These methods are particularly well-suited to the evaluation of landform morphology by the ability to descriptively compare landforms in spaces where patterns in form can be readily visually established. This is achieved through Procrustes superimposition to remove translation, rotation, and scaling from shape, with shape

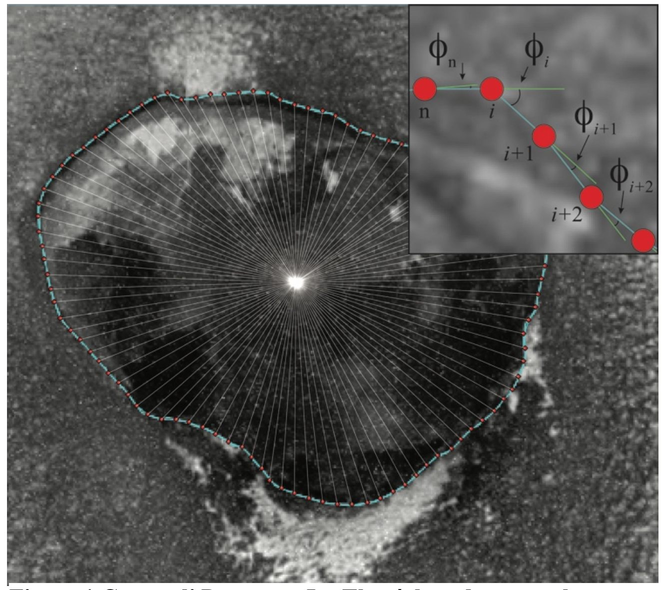

Figure 1 Camaxtli Patera on Io: The ϕ-based approach to outline analysis. Coordinates from raw outlines are interpolated to n=100 with equidistant spacing. The patera is ~56 km wide.

defined as “the geometric properties of a configuration of points invariant to translation, rotation, and scaling changes” [7]. Crater-forms inherently display a tendency in shape towards an ideal circle, this provides a useful analytical basis of evaluation. Differences in shape from homologous craters can be established *a priori* from observations of identified end-member morphologies. While scale is an important consideration of geomorphology it is most effectively considered following analysis if further interpretations are necessary.
Primary methods of outline (boundary) analysis are Fourier-based (Fig. 2) and ϕ-based (Fig. 1 and 3). Outline-based (boundary) methods approach shape analysis using Fourier and ϕ-based methods. **A**pplying these methods to geologic studies allows features to be quantified for detailed, natural, and analytically tractable comparisons [8].

Method: Data is collected from *Galileo* SSI and *Voyager* NAC imagery of paterae on Io constrained to mean resolutions of ≤1 km/px and emission angles ≤30°. These parameters provide the most conformal setting for the raw outline data of paterae on Io to be collected. We use polar stereographic projections aligned to the central coordinates of each image. We collect a similar sample size of lunar simple craters (<5 km diameter) from *LROC* NAC imagery.

A raw outline for each landform is then collected using the tpsDig software [9] (Fig. 1). The outlines of each landform are interpolated individually to a set of n=100 points equally spaced in distance on the perimeter of the outline. Outline datasets from each population are combined and imported into a statistical analysis package where Procrustes superimposition is performed. The modified dataset is then analyzed using Elliptic Fourier Analysis (*EFA*) [10] and transposed using Principal Component Analysis [11]. Figure 3 presents a case-study of comparative outline analysis applied to Linné crater and Camaxtli Patera (Fig 1) using Z-R Fourier Analysis [12-13] and a calculated shape function.

Results: We demonstrate the application of shape analysis to quantitatively differentiate populations of lunar simple craters and paterae on Io using Elliptic Fourier Analysis (*EFA*) (Fig. 2) [10-11]. Results provided

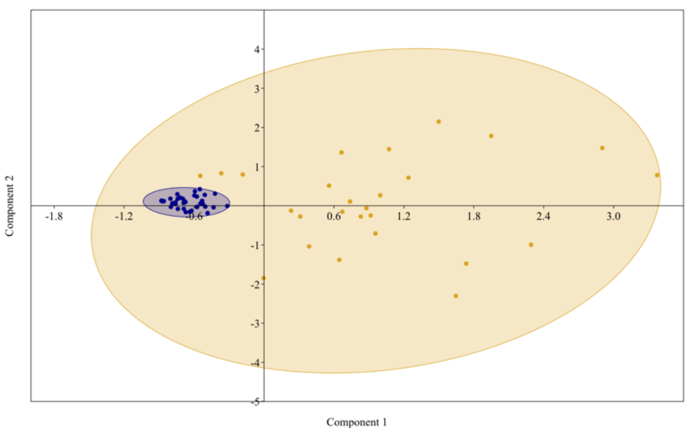

Figure 3 Elliptic Fourier Analysis (EFA-PCA) results from outline data showing the morphometric distribution between of Paterae on Io (gold) and Lunar Simple Craters (blue).

from Eigenshape analysis by the ϕ-based approach allow increased resolution to inspect individual irregularities in form. Eigenshape analysis is similarly capable of differentiating non-homologous crater-form populations (i.e. impact craters from paterae). It is particularly well-suited to detect linear edges, sharp angles, and general aspects of morphologic asymmetry. We demonstrate the application of Z-R Fourier Analysis (Fig. 3) and a calculated shape function to evaluate the shape morphologies of Linné crater and Camaxtli patera over the interval (2π). The analyzed lunar craters are differentiated from paterae on Io using quantified outlines and shape analysis. The 95% confidence ellipses show that paterae on Io are not well classified in context to simple lunar craters alone.

Conclusion: Methods of geometric morphometrics in outline (boundary) analysis allow adaptations for natural geologic form to be quantified and compared in studies of geomorphology. The rich information provided by landform shape lacks natural units from which it can be readily observationally quantified. A conformal mapping setting for data collection is critical to the valid evaluation and uniform interpretation of shape

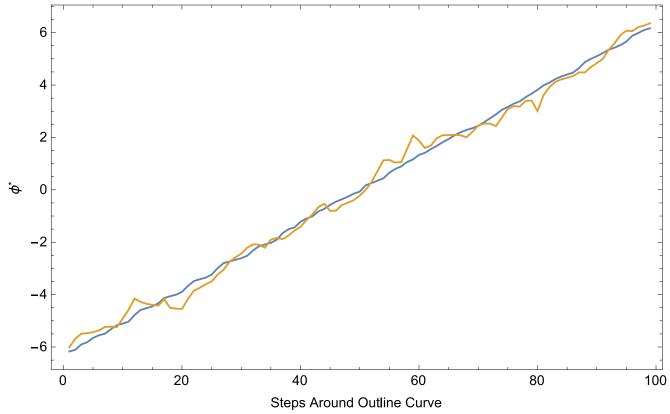

Figure 3 Comparison of Linné crater (blue) and Camaxtli patera (gold) in the ϕ^* form of the Zahn and Roskies (Z-R) shape function [13-14].

analysis in planetary landforms. This study introduces new analytical methods to morphometric crater studies and diversity in landform morphologies. Future work will publish these methods and others not detailed here with applications to enhanced analysis of global landform populations using GIS and PDS compatible data.

Acknowledgments: The authors thank Norm Macleod for his insight, guidance, support, and use of his *Mathematica*® code in adapting geometric morphometrics to planetary studies. The authors thank Trent Hare for his assistance to maintain conformal image projections.

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