Piecing Together the Bombardment Record: An examination of elliptical craters on Saturn's Moons Tethys & Dione and implications for satellite evolution. Sierra N. Ferguson[1], Alyssa R. Rhoden[2], Steven J. Desch[1], [1]School of Earth and Space Exploration, Arizona State University, Tempe Arizona, sierra.ferguson@asu.edu, [2]Southwest Research Institute, Division of Space Sciences, Boulder Colorado.

Introduction: How old are the inner moons of Saturn? This question is actively debated [1-3], spurred by recent measurements by the *Cassini-Huygens* mission, and dynamical modeling. Modeling of resonances between the inner moons (Mimas, Enceladus, Tethys, Dione, & Rhea) results in a maximum age of 100 Myr, although this scenario is based on the Q of Saturn and how it has changed with time [3]. A combined dynamics-thermal evolution analysis by [4] found ages between 4 Gyr and 1 Gyr. Older moons are more likely to have had subsurface oceans within the last Gyr, but neither old nor young moons can easily explain present-day oceans in these moons. Several studies have suggested oceans within Dione [4-6] and Tethys [4], and there is ample evidence of a present-day ocean within Enceladus [7-10].

The main method we use to date planetary bodies is through analyzing their craters. Previous studies of cratering within the Saturnian system [11-13] have found surface ages of these satellites to be around ~4 Gyr. However, the cratering records of moons in the Saturnian system do not match those of Jupiter, Uranus' moons, Pluto, and Charon [14,15], which suggests an additional, planetocentric population of impactors affected the Saturnian system. Characterizing this additional source is of key importance to understanding the complete size frequency distribution (SFD) of the system. Determining the Saturnian system impactor SFD, and constraining the source and longevity of planetocentric material, would provide critical clues as to the formation and evolution of Saturn's satellite system.

Elliptical craters, in particular, are useful for characterizing the impactor population that affected Saturn's moons. These craters are inferred to have formed by objects with impact angles less than about 15°. The elongated nature of these craters records the azimuthal direction of the impactor that created it, providing information about its dynamical origin. Elliptical craters have been of use within the inner solar system to explore the range of impact angles as well as crater orientation to look for changes in planetary obliquity [16,17].

Our previous work [18] examined the regional elliptical crater populations across Tethys and Dione and found a strong preferred orientation of craters on Dione, but a wider distribution of orientations on Tethys. We interpreted this distinction to be caused by the different impactor sources at play in the Saturn system. In this study, we utilize the basemaps of Tethys and Dione to examine the global distributions of elliptical craters across the satellites to evaluate if there is a global trend in elliptical crater orientations and what that means for the source population of these craters. We find significant differences in the elliptical crater populations of these two moons, at both regional and global scales, with implications for the impactor population within the Saturnian system.

Methods: We utilized ArcGIS and the basemaps created by [19,20] in an equi-rectangular projection spanning -180° to +180° in longitude and 60° N to 60° S in latitude. Polar imagery is sparse for these moons, so latitude was restricted. Within ArcGIS, we used the Crater Helper tool [21], which accounts for distortion in shape when mapping in an equal-area projection. We mapped a crater as elliptical if it displayed an elongated major axis (**Figure 1a**). To limit our visual bias, we mapped craters that appeared even minimally elongated and then removed craters below a certain ellipticity threshold. To distinguish between craters, we calculated the ellipticity, defined as the ratio between the major axis and the minor axis. If the ellipticity was ≥ 1.2, the crater was classified as elliptical [17]. We also measured the orientation (i.e., azimuth) of the elliptical crater. This measurement shows the direction of the major axis of the crater measured from 0° N and increasing clockwise to +180° which we have plotted on a rose diagram **(Figure 1B).**

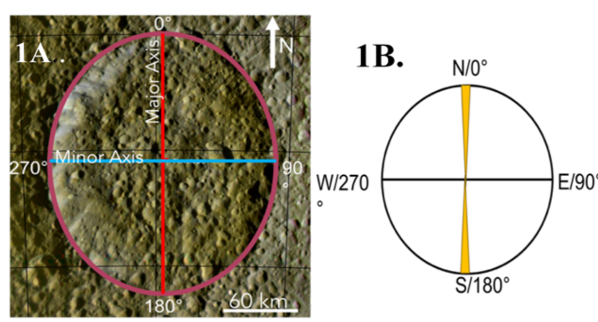

Figure 1a. A schematic showing the crater Penelope on Tethys (from the mosaic produced by Paul Schenk, viewed in JMars). Here we highlight how the major and minor axis are measured. **1b**. A schematic showing an example rose diagram for Penelope's orientation. We would measure the orientation as 0°/180° and it's represented as such on a rose diagram.

Results: Across the surface of Tethys, we counted 1591 craters that appeared to be elliptical, and 1059 craters with ellipticity ≥ 1.2. On Dione, we counted 1250 apparently elliptical craters, and 625 craters with ellipticity ≥ 1.2. **Figure 2** shows histograms for the orientations of the craters in the mid latitudes 50° N to 50° S and higher latitudes of 50° S to 60° S and 50° N to 60° N.

Across Tethys we observe a wider spread in orientations regardless of latitude and no clear preference for cratering occurring on one hemisphere over the other. On Dione, we observe more clustering along an East/West orientation that is concentrated more between 40°N and 40°S. On both moons, the elliptical craters at high latitudes (~60°) are predominantly oriented north-south.

Discussion/Preliminary Conclusions: We mapped roughly twice as many elliptical craters on Tethys as Dione, and the elliptical craters on Dione are more strongly peaked in orientation. Dione's surface exhibits considerably more geologic activity, so we may be seeing overprinting of the elliptical crater population. We are currently investigating stratigraphic relationships to test this hypothesis. If confirmed, it would suggest that the impacting material that created these craters (i.e. planetocentric material) has become more concentrated in terms of impact angle over time. Otherwise, the disparity could suggest that Tethys experienced a different bombardment history than Dione, which suggests a population of impactors that decreased with distance from Saturn. Similar mapping of Mimas and Rhea will help further constrain the characteristics of the impactors than made elliptical craters.

The difference in orientation between mid/low latitudes (more east-west) and higher latitudes (strongly north-south) also offers clues as to the dynamics of the impactor population. Further dynamical modeling using N-body simulations are needed to determine whether a heliocentric population alone can explain all of these characteristics. If a planetocentric population is also involved, as expected from other crater mapping studies, such simulations would allow us to determine the fraction of each population that has impacted the surface. We are also examining the elliptical crater distributions for signs of an apex/anti-apex asymmetry, which may provide more clues to the planetocentric vs heliocentric sources [22].

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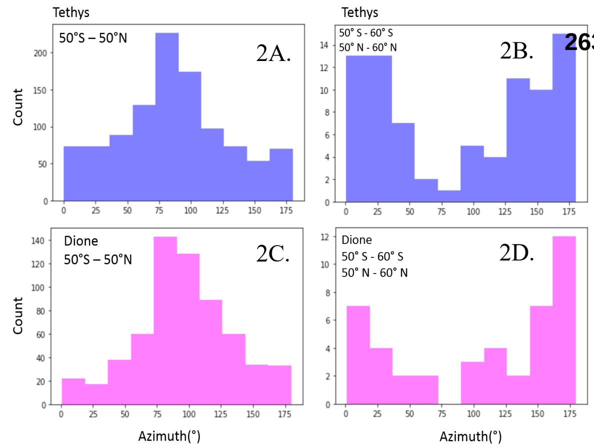

Figure 2A. Histogram depicting orientation values for elliptical craters in the mid-latitude ranges on Tethys. Orientation data on Tethys shows more of a spread in the mid-latitudes than Dione. 2B. High-latitude orientations for Tethys. 2C. Mid-latitude orientations for Dione. 2D. High-latitude orientations for Dione. On both satellites, the higher latitude regions display more of a pronounced trend to being primarily orientated north-south versus east-west. Dione's mid-latitude areas trend to concentrate more around being

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