IMPLICATIONS OF EUROPA'S GLOBAL CYCLOID POPULATION. K. J. Mohr[1], A. R. Rhoden[1], T. A. Hurford[2], and D. Dubois[3,4], [1]School of Earth & Space Exploration, Arizona State University, Tempe, AZ 85282, kyle.mohr@asu.edu, [2]NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD 20771, [3]LATMOS, University of Versailles St. Quentin, Paris-Saclay University, Guyancourt, France, [4]NASA Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91011.

Introduction: Cycloids are arcuate features observed on the surface of Europa proposed to record the stress changes that occurred during their formation [1,2]. These features are interpreted to be tensile cracks that form due to diurnal stresses from Europa's orbital eccentricity [1,2,3]. The shapes of cycloids can, thus, be used to constrain parameters that contribute to tidal stress, such as the interior structure and rotation history of Europa. Cycloids have been mapped regionally from Voyager and Galileo images [4,5], but the only published global map of cycloids [3] did not include a database or digital map, limiting its usefulness. For this study, we completed a global map of cycloids and generated a database of cusp angle measurements to obtain new constraints on the thickness and rheology of Europa's icy shell and on the formation of different fracture types observed on Europa

Background: Physical models have been developed to successfully explain the orientations and locations of many fractures observed on Europa's surface, including the arcuate paths of cycloids [6]. Early models were heavily based on an eccentricity-driven stress field; other parameters have also been considered, including stress from non-synchronous rotation (NSR) of Europa's ice shell and the possibility of Europa having a forced obliquity due to interactions with Jupiter's other large moons [1,7].

A stress field that includes obliquity and spin pole precession provides the best matches to individual cycloids [1], the orientations of lineaments [7], and the global distribution of strike-slip faults [10]. However, cycloids and lineaments have different implications for NSR; cycloids record substantial longitudinal reorientation while lineaments do not. Both cycloids and lineaments are thought to form through tensile failure, at orientations perpendicular to the maximum tensile stress direction [2]. Hence, the reason for this discrepancy is not obvious. It could indicate a change in tidal stress conditions with time, perhaps due to a change in ice shell thickness or rheology. Unfortunately, the challenging nature of cycloid modeling has limited its application to only six features whereas more than 100 lineaments have been mapped and analyzed.

To further investigate the formation conditions of cycloids, and their relationship to lineaments, we measure the orientations of all observed cycloids at their cusps, when the physical model of their formation would be most similar to that of a lineament. We then compare the results to the orientations predicted by the tidal stress model most compatible with observed lineaments [7]. Our preliminary results indicate a lack

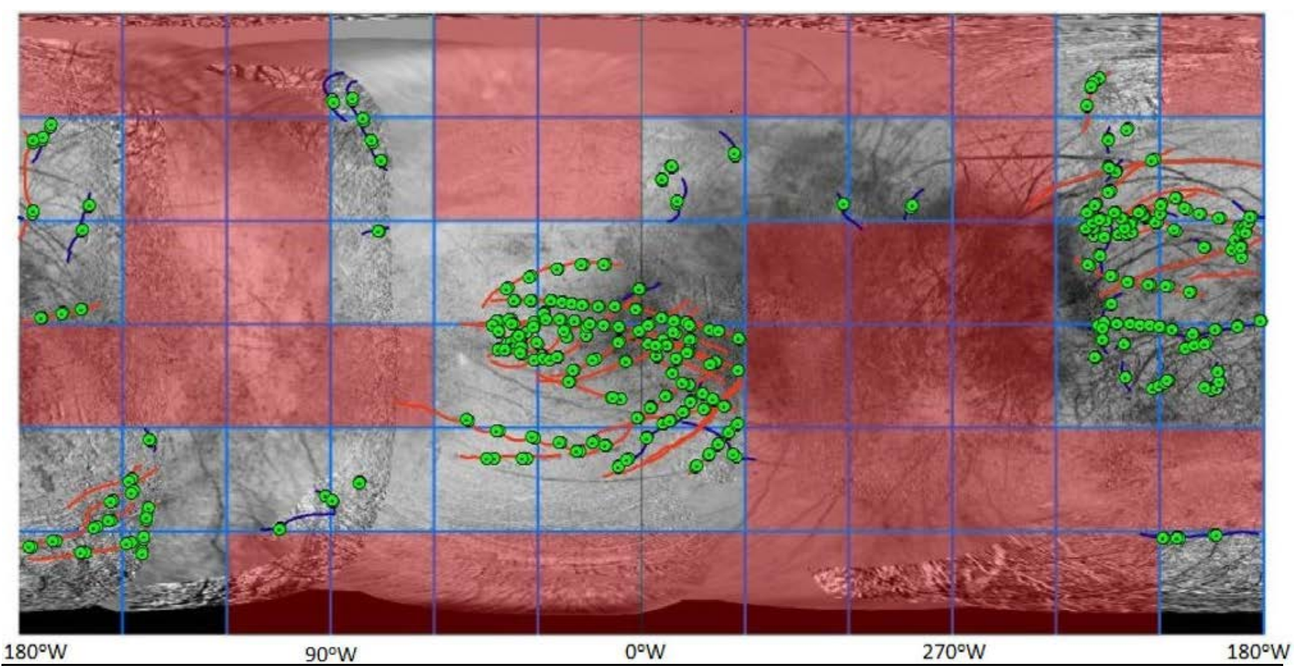

Figure 1. The global distribution of cycloids on Europa, which combines features from a global mapping study (red) and features identified during the measurement phase of this study (blue), reveals two main clusters of cycloids that are offset from the equator. Green circles represent cusps whose orientations we measured; no cusps were found in areas shaded in red.

of agreement between the cycloids and lineaments, even with these additional cycloid data, which supports either a change in tidal stress conditions, and the resulting fracture type, with time. Alternatively, cycloid cusps may form by a different mechanism than tensile failure, such as through the initiation of tailcracks [e.g. 3].

Data and Methods: Using ArcMAP 10.3, we mapped 88 cycloids in the USGS Europa Global Mosaic (Figure 1), which is comprised of Voyager and Galileo images. The initial cycloid mapping was conducted by David Dubois (red features); additional cycloids were added during the measurement phase of this study (blue features).

Each cycloid was numbered, along with every cusp that occurred along a single cycloid. The orientation of each cusp was measured by first mapping a line segment beginning at the center of the cusp and extending outward along the adjoining ridge in what would presumably be the "takeoff angle" of the fracture from the cusp. Due to the uncertainty as to the direction a cycloid propagated, line segment measurements were taken from both sides of each cusp. All cusps were noted with a degree of confidence, 1-3, with 1 being most certain and 3 being least certain.

Takeoff angles were measured from each cusp using a Linear Directional Mean tool in ArcMAP 10.3, converting the line segments into azimuthal directions in degrees from North, increasing in degrees clockwise beginning with 0^{o}N. All cusp measurements were plotted on the new global map as represented by the green circles shown in Figure 1.

Discussion: The global map suggests that cycloids are concentrated in two clusters approximately on the opposite sides of Europa at 0^{o}W and 180^{o}W (Figure 1). This could be the effect of observational bias due to the lack of high-resolution images in most regions, lighting angles, foreshortening at the poles, and/or the presences of chaos features. However, it is worth noting that these clusters are found in lower-resolution images and may, therefore, be robust in regards to resolution.

The fact that these two clusters are offset at the equator is significant and consistent with the hypothesis that cycloids are tidally-driven fractures that are sensitive to both eccentricity and obliquity [1,8]. The exact locations of the clusters can be used to further constrain the spin pole direction and the failure strength of the ice shell.

The azimuth distributions of the ~250 cycloid cusps were found to be predominantly E-W. Models of observed lineaments would lead to a prediction of N-S azimuths at the locations of the cycloids clusters [7]. Notably, predicted E-W orientations [7], are $30\text{-}90^{o}$ east of the observed clusters.

There are several possibilities for the discrepancy: 1) the best fit tidal stress model used to make the predictions of lineament azimuths [7] differed from the stress field that formed cycloids, perhaps due to a change in ice shell properties, 2) the ice shell may have slowly rotated, due to non-synchronous rotation, which is somehow better preserved by cycloids than lineaments, or 3) the cusp formation model of [2] is oversimplified, as suggested by [3]. The measurements presented here will enable us to better differentiate between these possibilities.

Conclusion: The global cycloid map indicates two dense clusters that are not centered at the equator and are offset in opposite directions, which is consistent with the hypothesis of cycloids being tidally-driven fractures caused by eccentricity and obliquity. The lack of cycloids outside of the clusters should be investigated more to determine the role of observational bias. If future mission data confirms that cycloids are only concentrated in these areas, it would provide important constraints on the magnitude of stress required to form a cycloid and the timescale over which cycloids are over-printed by newer geologic features.

The cusp angles found in this study do not match predictions using the tidal stress model that best matches observed lineaments, providing a new set of constraints on the tidal stress field, Europa's ice shell structure and rheology, and the failure processes of cycloids vs. lineaments. We will next focus on creating predictions of cusp angles using different interior models for Europa's ice shell and applying statistical tests to determine which model best matches the observations. In addition, we will compare the observed cusp angles with expectations from the tailcrack formation model [3].

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