DISTRIBUTION OF THE YOUNGEST TECTONIC FEATURES ON EUROPA.

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Introduction: Introduction: Tectonic lineaments are ubiquitous on the surface of Europa, and are hypothesized to have formed as the result of tides generated from Europa's eccentric orbit [1 and references therein]. Estimates of the age of the surface suggest that it is relatively young, 40-90 million years on average, based on the paucity of impact craters [2]. All of the surface features (ridges, cycloids, troughs, chaos, etc.) must have formed within that time frame, with chaos being the most recent widespread surface feature [3]. The lack of impact craters and of contiguous and high- resolution image data make it a significant challenge to identify the youngest Europan surfaces. Such locations are of high scientific interest for understanding Europa's surface history and feature-formation models, but also for identifying where to place future landed spacecraft to maximize the chance of sampling fresh material that is less processed by the Jovian radiation environment.

We search for evidence of recent tectonic activity by identifying the stratigraphically youngest features, defined as geologically young, ridgeless surface fractures [4]. Thus far, at least six separate types of fractures have been identified that are proposed to have distinct formation mechanisms [1, 5]: (1) linear fractures; (2) cycloidal fractures; (3) tailcracks; (4) endogenic process fractures; (5) flexure fractures; and (6) fold hinge fractures. Of these, three through six are small in length and are not currently believed to form in response to the global stress field. In total 16 high-resolution regions of Europa have been mapped and 2000 surface fractures have been identified. Here, we present the results from one region E15reg01 (Figure 1), as a proof of concept.

Methods: Surface fractures on Europa were mapped using Galileo images processed and projected using the software package ISIS (Integrated Systems for Imagers and Spectrometers, Version 2) for use in an ArcGIS environment. For consistency, all mosaics or images were projected using an orthographic projection (to preserve lengths).

In the analysis of the fracture maps, determining whether the tectonic fractures crosscut or are superposed by chaos or lenticulae is key to estimating the minimum age of the surface. The fractures described above are each hypothesized to have formed as a result of different loading conditions. Each feature type and their crosscutting relationships within the region suggest a different combination of the global/local stress field. All identifiable troughs were mapped in each region and were classified according to fracture type. The linear fractures are also separated by relative age based on their crosscutting relationships (Figure 1).

Unlike ridges, where the superposition of younger ridges over older ridges is easy to discern, the crosscutting relationships among fractures are typically subtle and somewhat ambiguous, since they are generally narrower and commonly at or close to the limits of image resolution. When two troughs intersect, one trough is bisected and is thus the older of the two troughs. Therefore, the trough that is continuous when comparing two troughs is the younger one. Two criteria were considered when mapping either linear fractures or cycloidal troughs. (1) If a linear fracture does not crosscut a well-developed ridge (double ridge), then the trough is likely old and is therefore not mapped. (2) We assume that the linear fractures are a precursor to ridges and if the linear fractures have well developed edifices (i.e., already starting to resemble ridges), they are not mapped.

Once the youngest linear fracture set has been identified in each region we calculate the average trend of each set of tectonic troughs. We define a linear fracture set as containing at least two fractures that share a common trend and appear to have the same morphological characteristics. Then we use the program SatStressGUI V5 [6, 7] to compare the theoretical stress field to the stress orientation needed to form the observed feature. This program is designed to calculate the theoretical stress fields due to any of the proposed stress regimes (diurnal, nonsynchronous rotation (NSR), true polar wander, obliquity, etc.). Here, we only use the diurnal and NSR stresses. This is because the fractures tend to be long (100s of km) and linear (as compared to cycloids), which implies that they did not form in response to a short period stress (e.g. cycloids). The young age of Europa and the complexity of the surface necessitate a short period of NSR, so for this work we tested NSR periods of 12,000 years and 100,000 years [1]. We also alter the viscosity of the upper brittle crust between $1*10^{21}$ and $1*10^{22}$ Pa S. There is uncertainity in the bulk viscosity of the upper crust and is not assumed to be constant through the whole layer, this works as an boundary range for acceptable values [see 8-10]. This creates four scenarios in which it is possible to compare how recently the stress orientation was perpendicular to the strike of the feature.

Results: For this work we present one region, the E15 regmap (220 m/pixel and centered at 220° W 40° N) (Figure 1). We see three of our six classified trough morphologies: tectonic, cycloidal, and endogenic process, grouped into five distinct systematic trough sets (Fig. 1b). Set 1 tectonic troughs, which are the oldest, have an average trend of 358°, set 2 troughs have an average trend of 100°, set 3 troughs have an average trend of 90°, set 4 troughs have an average trend of 345°, and set 5 troughs, the most recent, have an average trend of 330°. Hence, the difference in orientation between successive sets is 102°, 170°, 75°, and 165°, respectively, with a cumulative orientation change of 512° during tectonic trough development, in a clockwise sense.

In all four of our model runs there is a tensile stress perpendicular to the orientation of the observed fracture; here we show how long it has been since the orientation was in the optimal direction for set 5 (Table 1).

Table 1: Time since present (yrs) when maximum tension was perpendicular to the observed feature for set 5.

Period (yrs)	1*10^{21} Pa S	1*10^{22} Pa S
12,000	2,450 yrs	2,550 yrs
100,000	15,500 yrs	20,400 yrs

Discussion: We define the moment of tensile failure as being perpendicular to the strike of the feature. This is when the stress is greater than the tensile failure of the material. Previous work has defined the tensile failure of ice as ~60 kPa [11,12] and we use that as a baseline for our models as well . Once the time to initial failure has been established, it becomes possible to identify how long time since the first set in the region formed (Table 2). This is based on the 512° of cumulative orientation change observed from set 1 to set 5.

Table 2: Total time since NSR failure initiated from oldest set (set 1) within region

Period (yrs)	1*10^{21} Pa S	1*10^{22} Pa S
12,000	19,516 yrs	19,616 yrs
100,000	157,722 yrs	162,622 yrs

Conclusions: The model assumptions that we have made today suggest that the total time since formation of the linear troughs within this region could have happened within the last 160,000 years. For this to be true the NSR period must be less than 100,000 years. These models also suggest that the youngest fractures could have formed within the last 2,500 years if the period was 12,000 year. The primary limiting factor in further constraining the age is the image resolution. This region presents an excellent test case for Clipper to look for even younger linear fractures.

References: [1] Kattenhorn S. A. & Hurford T. A. (2009) In: Europa, 199-236. [2] Bierhaus, B. et al. (2009) In: Europa, 161–180 [3] Greeley R. et al., (2000) JGRP 105 22559-22578. [4] Head et al., (1999) JGR 104 24,223-24,236. [5] Kay, J.P. and Kattenhorn, S.T. (2009) LPSC XL Abstract # 2454. [6] Wahr J. et al. (2009) Icarus, 200 188- 206. [7] Patthoff et al., (2016) AGU, abstract # 2147. [8] Dombard A.J. and McKinnon W.B. (2006) J. Struct. Geol., 28, 2259-2269. [9] Dombard A.J. and Cheng A.F. (2008) LPSC XXXVIII, Abs.#2221. [10] Goguen J.D. et al. (2013) Icarus,226, 1128-1137. [11] Hoppa et al., (1999) Science 285:1899–1902. [12] Hurford T.A. and Sarid A.R. (2007) Icarus 186:218–233.

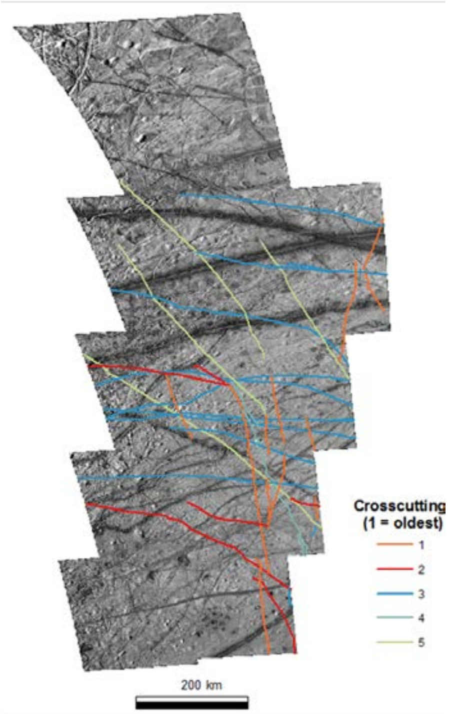

Figure 1: E15Reg Map. Linear fractures of in color with five sets in total