PUSH, PULL, SHEAR, OR OVERPRINTING? QUANTITATIVE STRAIN ANALYSIS OF LINEAE ON EUROPA.
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Introduction: Jupiter's moon Europa is thought to have a global saltwater ocean beneath an icy shell, as revealed by the detection of an induced magnetic field [1]. The presence of a liquid ocean implies the possibility of habitable environments and the emergence of life. Europa has experienced recent geologic resurfacing, in part through globally distributed linear surface features, called linea, that include bands and ridges. We study here the kinematics of these lineae to better understand their origin and relation with the underlying ocean.

The first type of lineae, also called bands, feature different morphologies that have been qualitatively classified as "ridged", "lineated", or "smooth" [2]. Most band formation hypotheses involve extension. Prockter et al. [3] proposed that band formation is analogous to seafloor spreading, and associated differences in morphologies due to spreading rates. Howell and Pappalardo [4] linked band morphologies to the strength and thickness of the ice shell's brittle lithosphere, where ridged bands form when the brittle layer is thicker, smooth bands when the layer is thinner, and lineated bands form at intermediate thicknesses. Their models also showed that a higher magnitude of strain is required to form smooth bands than ridged bands.

Ridges, including double ridges and ridge complexes, are another type of lineae. Melosh and Turtle [5] proposed that double ridges form due to incremental ice wedging and Johnston and Montési [6], furthered this idea by studying the surface expression of crystallizing water intrusion. Nimmo and Gaidos [7] proposed that double ridges are the result of heating caused by repeated strike-slip motion on a vertical fault. Culha et al. [8] showed that double ridges may accommodate contraction, which may relate to the drainage of melt from shear heating [7]. Ridges were also proposed to accommodate contraction in a reconstruction by Patterson et al. [9]. None of these models involve ice shell extension. Head et al. [10] proposed that double ridges and ridge complexes evolved from a simple crack or trough into progressively more complex structures. This evolution is consistent with ridges starting as a crack, with non-synchronous rotation explaining the variety of orientations observed [11]. Locations on the surface of Europa where double ridges transition into ridge complexes, as well as places where ridge complexes transition into ridged bands, argue for a common origin for all lineae. It could be deduced that progressively more complex ridges and bands develop with increasing strain.

Here, we explore whether the morphologies of bands and ridges may be the result of the magnitude of strain and the strain regime in order to understand the relationship between these varied landforms.

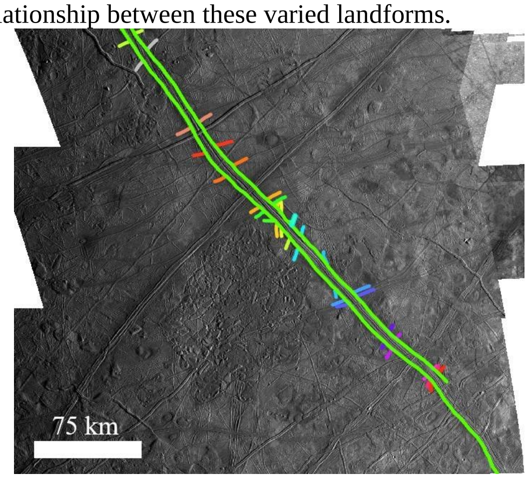

Figure 1: Map of Agave Linea (green outline) near Conamara Chaos. The colored lines mark background features that intersect Agave Linea at various angles.

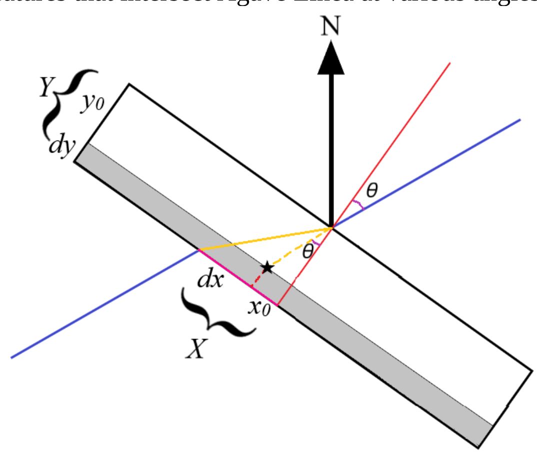

Figure 2: Schematic diagram of a linea (black rectangle) intersecting a background feature or marker (blue line). The linea has an original width (white rectangle) that increases if it is stretched (grey rectangle). The red line represents the direction normal to the linea, and θ is the angle between this and the marker orientation. The black star represents the location the marker would have appeared before any strain, with an initial offset x_0 from the angle θ. The yellow line is a tie line connecting the two points where the background feature is crossed by the feature of interest. X, dx, x_0, Y, dy, and y_0 are defined in the text.

Methods: To determine the magnitudes of normal and shear strain associated with the different morphologies of bands and ridges, we analyze the apparent offset of preexisting features (markers) that intersect a linea at various angles. We map these on USGS Galileo SSI images using ArcGIS Pro. The example of Agave Linea is shown in Figure 1.

Measurements. From the mapping, we report the width Y and orientation β of the linea studied. Assuming an initial width of y_0, and extensional opening dy, the observed with is

$$Y = y_0 + dy \quad (1)$$

y_0 also corresponds to the width of the terrain that is resurfaced during ridge formation, for example by plastic deformation, cryovolcanic flows, and uplift [8]. We measure the angle θ between the normal to the linea and the orientation of the preexisting marker. Since the marker is at an angle to the linea, it would be offset across the linea by

$$x_0 = y_0 \tan(\theta) \quad (2)$$

even without any strain. The actual offset, X, is equal to this distance plus any shear offset, dx.

$$X = dx + y_0 \tan\theta \quad (3)$$

Correlation Plot. Equation 3 implies that X and $\tan\theta$ should be linearly related. We report these measurements on a correlation plot (Figure 3) and extract the original width y_0 of the linea, the shear offset dx, and the uncertainty of these quantities using a least-square fit.

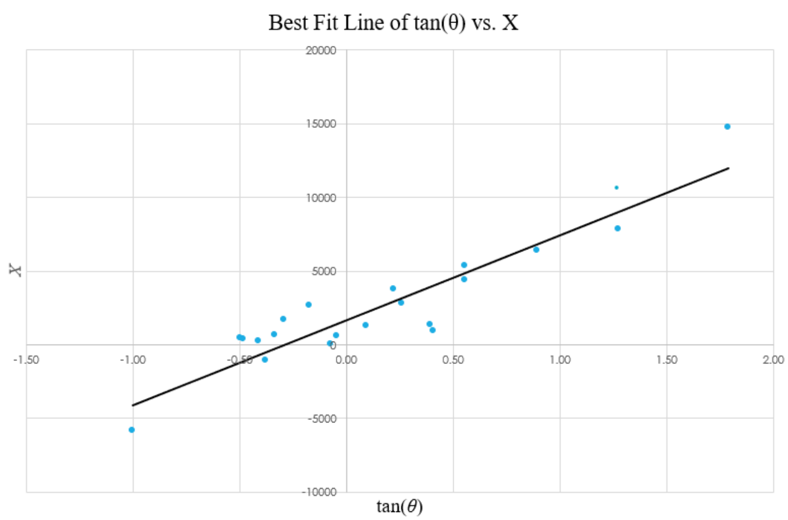

Figure 3: Correlation between X and $\tan\theta$ for mapping done on the ridge complex Agave Linea.

Strain. The offsets and initial width are used to express the shear strain γ and the normal strain ε across the linea according to:

$$\gamma = \frac{dx}{y_0} = \frac{X}{y_0} - \tan(\theta) \quad (4)$$

$$\varepsilon = \frac{dy}{y_0} = \frac{Y}{y_0} - 1 \quad (5)$$

Results: Agave Linea is a prominent ridge complex in the Conamara Chaos region (Figure 1). The current width of Agave Linea is Y ~ 7100 m. The correlation plot of Figure 3 implies that its initial width y_0 = 5800 m ± 1200 m. Thus, extension across Agave Linea is between 0 and 2400 m corresponding to a normal strain of ε = 0.2 ± 0.2. Comparing this value to the total width, we interpret the majority of the surface morphology of Agave Linea as not due to extension.

The shear offset dx is 1700 m ± 800 m, which corresponds to a shear strain γ = 0.3 ± 0.15. Thus, it appears that Agave Linea experiences more shear strain than normal strain

Importantly, no extension is required. Instead, the preexisting terrain was uplifted and resurfaced with minimal tectonic extension.

Conclusions and Future Work: The initial analysis on Agave Linea shows that some process besides extension is likely responsible for the surface morphology This may be an indication of cryovolcanism or uplift [8]. The preexisting terrain sometimes appears faintly on the ridge flanks but the surface generally has been smoothed over by a process still to be determined [8] We plan to map other lineae to verify that conclusions apply to multiple locations and to investigate if double ridges and smooth, lineated, and ridged bands present systematic variations of strain.

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