GLOBAL-SCALE TIDAL FORCING AND PLATE TECTONICS HAVE BOTH SHAPED THE TECTONIC EVOLUTION OF EUROPA.

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Introduction: Europa, Jupiter's fourth largest moon, has an anomalously young surface age (~40-90 million years old), and has an extensively fractured surface [1-3]. Conventional models for tectonic features on Europa have invoked global-scale tidal forcings (e.g., diurnal forcing, obliquity, nonsynchronous rotation (NSR), and true polar wander (TPW)) as the mechanisms responsible for fracturing the icy shell [4-7]. In an attempt to examine the complex history of deformation on Europa in the context of global tidal stress models, we examined a multitude of tectonic feature types, orientations, and ages across a broad region of Europa's anti-Jovian hemisphere. This study focuses on Argadnel Regio, a complex region of deformation consisting of an intertwining network of low albedo bands and ridges [8], and Agenor Linea, a ~1,500 km long band-like strike-slip fault [9-10]. We rigorously mapped ridges, cycloids, bands, chaos, and troughs over 697,000 km^2 of Europa's terrain and statistically compared the mapped fractures with predicted fractures resulting from NSR and TPW using the numerical global tidal stress model, SatStressGUI.

Methods: To test whether or not fracture on Europa were reconcilable with global scale stresses, we first mapped all tectonic features within and surrounding Argadnel Regio and Agenor Linea located on Europa's anti-Jovian hemisphere (Figure 1). We then compared the orientations and spatial distributions of these observed fractures with predicted fracture orientations and spatial distributions global scale stress models, specifically those for nonsynchronous rotation (NSR) and true polar wander (TPW).

Mapping. We mapped a variety of tectonic features using the highest resolution imagery available taken during Galileo's 15th and 17th orbits of Jupiter. This image mosaic contains images with resolutions ranging from 200 - 400 m/pix with illumination from the northeast. We used this mosaic to map chaos, troughs, cycloids, ridges, and bands. We then analyzed the dominant orientations of linear tectonic features and the relative age relationships across the range of mapped tectonic features to characterize the geologic history of the region.

Modeling. We used an open source viscoelastic global stress modeling software, SatStressGUI, (github.com/SatStressGUI) [11] to calculate the predicted orientations of the fractures given a set of material properties for Europa's upper ice layer, lower ice layer, liquid ocean layer, and core. For NSR, we tested a range of eight NSR periods for which stresses were sufficient to break the ice shell (>1 MPa [12]). For TPW, we created a grid of locations for potential paleopoles and modeled the predicted stress orientations for 133 possible TPW scenarios.

Results: After mapping geologic feature types, orientations, and ages and comparing our observations with global tidal stress models, we found that Europa's oldest fractures (two sets of intersecting ridges oriented NE-SW and NW-SE) most closely align with the predicted stresses from two separate episodes of TPW. In the first episode, the paleo-pole travels ~45° north eastward onto the other side of the globe (from 60°N, 140°E to 075°N, 340°E), but without passing through the present day pole at 90°N. This generates fractures oriented NW-SE. During the second episode of TPW, the paleopole travels 15° north eastward (from 075°N, 340°E to 090°N, 180°E) towards the present day pole location. This generates a second set of fractures oriented NE-SW.

Dilational bands located to the north of Argadnel Regio that dilated pre-existing cycloids in a north-south extensional direction align more closely with a global stress field that would have been produced by a more recent stage of NSR with a period of 100,000 years.

While these models accounted for fracture sets in Europa's oldest terrain (TPW) and younger dilated cycloids (NSR), many young tectonic features are not consistent with the predictions of TPW nor NSR stress fields, such as: 1) ~700-km-long, right-stepping én echelon bands with sigmoidal geometries within Argadnel Regio that are consistent with broadly-distributed, left-lateral shearing, 2) left-stepping én echelon bands younger than the ~700 km long sigmoidal bands that are consistent with right-lateral shearing, 3) clockwise rotations of circular rafts of material within Argadnel Regio also consistent with right-lateral shearing, and 4) bands (~5 km wide, ~10 km long) oriented ~045° and located ~100 km south of Agenor Linea that are consistent with an early phase of left-lateral shearing along Agenor Linea that pre-dates more recent right-lateral shearing [10].

Discussion: While mapped fractures within and surrounding Argadnel Regio and Agenor Linea do not align with stresses from NSR and TPW, previous studies based on numerical and physical models have proposed plate tectonics as a potential mechanism responsible from fracturing and resurfacing Europa's icy crust [16-25]. However, observational evidence (e.g., geologic evidence of translation or rotation across plate boundaries or broadly distributed lateral shearing within plates) is necessary to confirm the existence of plate tectonics on Europa. After extensively mapping bands, ridges, and other tectonic features across Argadnel Regio and Agenor Linea, we find that young tectonic features, such as sigmoidal dilational bands, align better with broadly distributed lateral shearing, a necessary component of plate tectonics, than with global tidal stress models. The misalignment of tectonic features with conventional global-tidal stress models, in addition to the presence of tectonic features resembling artifacts of broad-scale lateral shearing, suggests that deformation on Europa may need to be re-evaluated under a plate-tectonic paradigm in combination with global tidal stress models, occurring as contemporaneous processes. Plate tectonics would not only help explain complex deformation on Europa, but would also provide a mechanism for recycling Europa's icy crust and maintaining the moon's young surface age.

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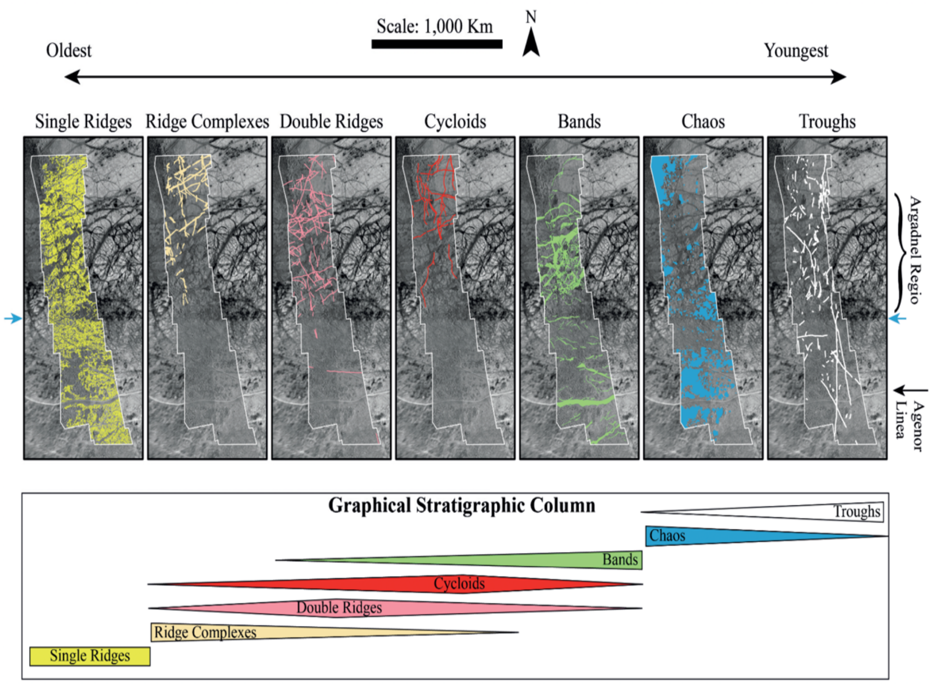

Figure 1: Detailed mapping of sites (white polygon) incorporating Argadnel Regio and Agenor Linea reveal how the distribution of feature types change latitudinally on Europa. While the maps of geologic features are organized such that the oldest features are on the left and the youngest features are on the right, there are inconsistencies within these general age relationships, shown in the "graphical stratigraphic column". Blue arrows annotate an ~E-W linear boundary across which the deformation style abruptly changes from the complex band networks of Argadnel Regio to intersecting sets of single ridges. Basemap is from the Europa global mosaic in Europa_2000 Mercator projection centered at 20°S, 139. 573°E.