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Analysis of very-high-resolution Galileo images and implications for resurfacing mechanisms on Europa

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ABSTRACT

The young (<100 Ma) surface of Jupiter's icy satellite Europa raises the key questions: (1) what are the resurfacing mechanisms for creating Europa's young surface, and (2) how have these processes evolved through time? To address these questions we analyze the nine high-resolution frames obtained by the Galileo Solid State Imager (SSI)—eight at 16 m/pixel and one at 8 m/pixel (commonly quoted at the planned 6–12 m/pixel as in Greeley et al., 2000)—during the E12 flyby of Europa in Dec. 1997. This dataset is now two decades old, but it has not been analyzed in detail until this work. Despite the largely different viewing and lighting conditions, we mosaic these high-resolution frames into the 220 m/pixel regional context frame. We then perform geomorphologic mapping of the high-resolution image mosaic and the regional image frame, for comparison, and we also create a structural map of the high-resolution image mosaic. The units in the geomorphologic map are defined by surface texture, landform shape (morphology), dimension, and relative albedo. The structural map units include interpretations from the geomorphologic map units and their interpretation implies potential kinematic processes for the formation of particular structures. Our primary mapping observations include the regular spacing and gentle slopes of the ridge-and-trough terrain, the sharp boundaries and preserved structures of the chaos terrain, and the symmetry but irregular size of double ridges. We then evaluate proposed formation mechanisms for these and other mapped features. The high-resolution images also reveal an abundance of small (<100 m) pits, the presence of a newly identified high-albedo smooth material, and potential tectonic fabric, all of which have possible implications for the surface history. The mapping and structural analyses lead to the key finding that local-scale resurfacing mechanisms have transitioned from distributed deformation expressed by the formation of the ridged plains to discrete deformation characterized by the formation of chaos and isolated fractures. This finding is consistent with simultaneous ice-shell thickening and cooling occurring as the ice-shell deformed.

1. Introduction

Voyager and Galileo Solid State Imager (SSI) images of Europa reveal complex surface features exemplified by a wide variety of crosscutting surface structures with diverse morphologic expressions (e.g., Pappalardo et al., 1999). Additionally, the paucity of recognizable craters with diameters > 10 km requires that Europa's surface is young, on the order of 60 Ma (Zahnle et al., 1998). Unraveling the cause of this young surface age combined with the complexity of Europa's surface features has led to competing hypotheses for the formation of key landforms—chaos structures, double ridges, and ridge-and-trough terrain. For chaos terrain these hypotheses include melt-through (Greenberg et al., 1999; O'Brien, 2002), diapirism (Pappalardo et al., 1998a; 1998b; Schenk and Pappalardo, 2004), and the collapse of a melt-lens within the ice shell (Schmidt et al., 2011; Soderlund et al., 2013); for double ridges, cryovolcanism (Fagents and Greeley, 1997; Kadel et al., 1998), tidal squeezing (Greenberg et al., 1998), linear diapirism (Head et al., 1999), shear heating (Nimmo and Gaidos, 2002), compression (Sullivan et al., 1998), wedging (Melosh and Turtle, 2004; Han and Melosh, 2010; Johnston and Montesi, 2014), and compaction (Aydin, 2006); and for ridge-and-trough terrain, extensional tilt-blocks (Kattenhorn, 2002), and folding (Leonard et al., 2015).

Although these competing hypotheses make specific predictions, their validation has been hampered by the lack of definitive observations due to the generally low-resolution images

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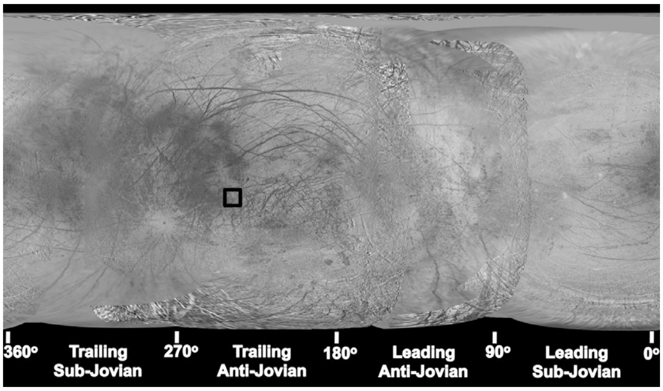

Fig. 1. The USGS Global mosaic of Europa in West positive coordinate system. The black box indicates the approximate location of the regional resolution image in Fig. 2(A). This area occurs between a chaos region (to the west) and a region characterized by bands and ridged plains (to the east, also known as the wedges region).

at >220 m/pixel. In order to address this issue, we use the previously unanalyzed 12ESMOTTLE01 and 02 high-resolution (8–16 m/pixel, see Section 3.1) image strip to evaluate these hypotheses by refining the morphologic requirements or contstraints on the surface feature formation mechanisms and thus narrow down the potential hypotheses. This work allows us to construct a geomorphologic map with the map units defined by surface texture, landform shape, dimension, and albedo. The geomorphologic map forms the basis for constructing a structural map, which correlates the mapped landforms to interpreted structures. This correlation in turn allows us to infer plausible kinematic processes for the observed morphologic features, leading to a better understanding of the resurfacing processes that have kept Europa's surface young.

The key findings of this work include: (1) Europa's surface deformation has transitioned from a distributed to a discrete mode over the discernable surface history, possibly resulting from the progressive cooling and thickening of the ice shell; (2) ridge-and-trough terrain exhibit gentle, quasi-symmetric slopes and regular spacing indicating folding as a likely formation process; (3) the consistent size and shape of double ridges along their length, but variation in size as a unit suggest compaction or linear diapirism formation mechanism, though neither appear to fit perfectly; (4) chaos terrain exhibits abrupt and heavily deformed boundaries with preserved pre-existing structures on the interior, favoring a water lens collapse formation mechanism; (5) secondary cratering processes may also contribute to resurfacing (~0.5% of the surface); (6) fine lineations are prevalent in the high-resolution images and are interpreted as a tectonic fabric; and (7) the presence of a newly identified *high albedo smooth* material may be indicative of a surface process operating at even a finer scale than is resolvable by the high-resolution images.

2. Regional geology

During its extended mission, the Galileo spacecraft imaged less than 0.03% of Europa's surface at 8–16 m/pixel, the highest resolution obtained of Europa's surface to date (Doggett et al., 2009; Greeley et al., 2000). One of the highest resolution imaged areas of Europa was obtained during Galileo's E12 flyby of the Trailing Anti-Jovian hemisphere (Fig. 1) and overlaps with an area imaged at regional resolution (~230 m/pixel during the E11 flyby (Fig. 2(A)). Previous work in the anti-Jovian hemisphere has been focused on the "wedges" region, Argadnel Regio (Schenk and McKinnon, 1989; Prockter et al., 1999, 2002), an area interpreted to have resulted from extensional tectonics (Helfenstein and Parmentier, 1983; Greenberg et al., 1998).

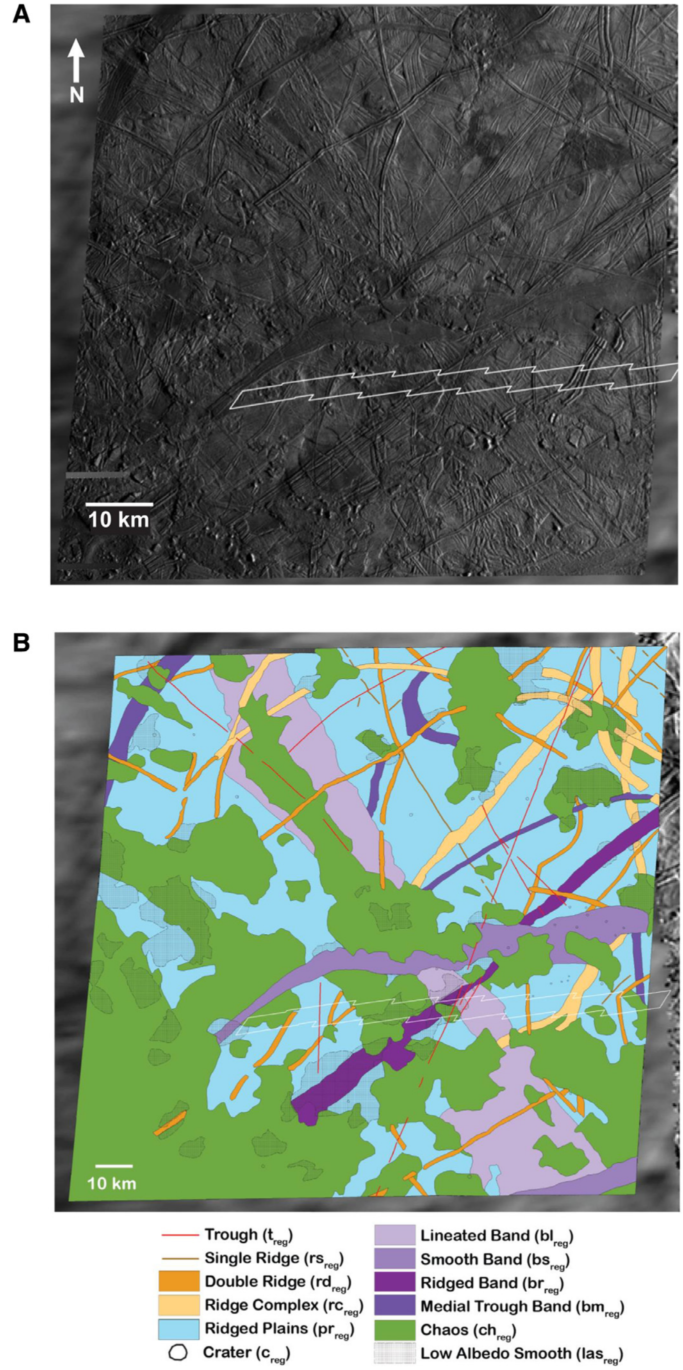

Fig. 2. (A) Regional resolution image (220 m/pixel) taken by Galileo SSI (11ES-REGMAP01 or 11E0017) with white outline indicating location of the high-resolution image mosaic (Fig. 3(A)). The image was taken at an incidence angle of 74° and an emission angle of 23°. Simple cylindrical projection, north is up. (B) Geomorphologic map of the regional resolution image (Fig. (A)) and coresponding key. The unit descriptions are in Section 4 and pictured in Fig. 4. The white outline indicates the location of the high-resolution image mosaic (Fig. 3(A)). Note the *lineated band* identified in the regional image that crosses through the high-resolution image mosaic (Section 7.2.6).

There are five primary terrain types identified on Europa (Figueredo and Greeley, 2000, 2004; Greeley et al., 2000): ridges, plains, chaos, bands, and crater terrain. This study region borders an area of chaos terrain to the west and an area of ridged plains terrain to the east, and therefore it is interesting to investigate as an area of terrain transition (Figs. 1, 2(A) and (B); e.g., Figueredo and Greeley, 2004). Also, this transition in terrain type