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Geometry and spatial distribution of lenticulae on Europa

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ABSTRACT

The surface of Europa contains several types of roughly elliptical features, collectively called lenticulae. Lenticulae may have positive relief (domes) or negative relief (pits), may disrupt the crust (chaos), or discolor the surface (spots); some lenticulae have attributes of both domes and chaos (dome/chaos). We map the location, dimensions and shapes of all lenticulae and their interactions with other lenticulae and lineaments. We find that (1) pits and domes have similar sizes; (2) chaos are larger than the other lenticulae; (3) pits are clustered within the trailing antijovian quadrant and the leading subjovian quadrant whereas domes, dome/chaos, and chaos terrains are more uniformly distributed; (4) the areal density for all lenticulae is not uniform; (5) lenticulae do not divert the path of younger lineaments such as ridges. Taken together, these observations are consistent with conceptual models in which lenticulae are created by intrusion of liquid water bodies, or convection within, the ice shell. Additionally, the observations are consistent with the notion that each type of lenticula is a surface expression of dynamics within the ice shell at a different stage of lenticulae evolution. The similar size and shape of pits and domes suggests that one may evolve into the other. Because domes are more numerous and more uniformly distributed than pits, they are more likely to represent the end stage of this evolution, assuming the end-stage leaves a longer-lasting surface expression. Models also predict that larger features are more likely to disrupt the crust, which is consistent with dome/chaos and chaos being larger than pits and domes. We find no examples of lineaments offsetting pits but lineaments do cross some chaos. Pits also have a preferred northwest-southeast elongation, whereas domes, dome/chaos, and chaos do not have a preferred orientation. If lenticulae orientation is influenced by crustal stress, then pits may have formed during a shorter time interval than the other features. As a result, pits may sample a shorter, more recent time period than domes, dome/chaos, and chaos, consistent with pits being the earliest stage in the evolution of lenticulae. We find no strong evidence that lineaments are deflected by lenticulae, implying either that the stresses created by lenticulae are too small to influence lineaments, or that the complete evolution of lenticulae occurs on a time scale that is short compared to the time between the formation of lineaments at a given location.

1. Introduction

The surface of Europa contains many quasi-elliptical features with lateral dimensions of a few kilometers to tens of kilometers. The International Astronomical Union (IAU) defines morphologies that have low albedo and circular shapes as lenticulae. In our study, we will call all quasi-elliptical features (except craters) lenticulae.

Outside of lenticulae, Europa's crust contains many other morphologic features. The most abundant features are lineaments, long linear tectonic features (Pappalardo and Sullivan, 1996; Schenk and McKinnon, 1989; Sullivan et al., 1998; Tufts et al., 2000). There are multiple types of lineaments including ridges (e.g., Fig. 1f) and bands (e.g., lineament under lenticula in Fig. 1e) (e.g., Kattenhorn and Hurford, 2009).

Lenticulae have been grouped into 5 categories based on a) their topography, b) interaction with crust that predates the lenticulae, mainly lineaments, and c) albedo.

1. Pits are concave features (topographic depressions) whose floors and walls have been crossed by lineaments, although the age of the lineaments relative to the pit cannot be determined (Fig. 1a). Both Greenberg et al. (2003) and Schenk and McKinnon (2001) report that pit bottoms are up to 200–300 m deep.
2. Domes are convex features and, similar to pits, contain lineaments within their top surface and walls (Fig. 1b). In

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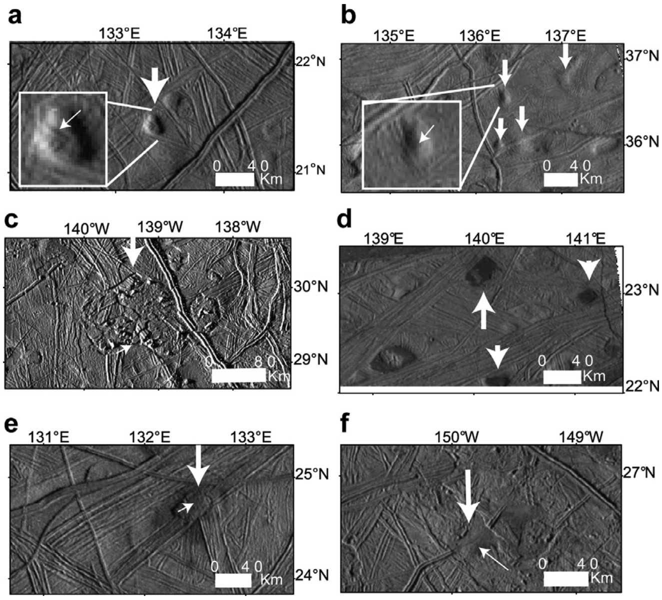

Fig. 1. Examples of lenticulae on Europa's surface. Panels a, b, c, and d show pits, domes, chaos, and spots, respectively. Panels e and f show dome/chaos features. The small white arrows in a, b, c, e and f point to the morphologies that help identify the features. The magnified images show lineaments on the walls and floors of a pit (a) and dome (b). The small white arrow in panel c points to the block of disrupted crust that predates the formation of the chaos. The white arrow in panel e points to the small circular formations within the dome/chaos. These variations in dome/chaos give the feature a coarse texture. In panel f, the white arrow points to the lineament that can be traced through the dome/chaos.

Greenberg et al. (2003), domes are identified as "uplifts". The heights of domes typically vary between 40 and 100 m (Fagents, 2003).

3. Originally, chaotic terrain was defined as uplifted areas where the preexisting crust was fractured into multiple "blocks" (Carr et al., 1998). Some previous literature identifies chaos as "dome-like" features (e.g., Miyamoto et al., 2005). Here chaos features are convex features in which the surface is broken into distinct blocks and pre-existing crossing features are disrupted (Fig. 1c). There are large chaos regions, which are identified as chaotic terrain (e.g., Greenberg et al., 1998; Schmidt et al., 2011). We also call chaotic terrain chaos because, similarly, they have disrupted the crust. We include some features identified as small chaos (Fagents, 2003; Spaun et al., 2004) in the chaos category.
4. Spots are low albedo concave features that do not have lineaments preserved within the feature (Fig. 1d). Spots are mostly 10–20 km across (Carr et al., 1998; Pappalardo et al., 1998; Spaun et al., 1999).
5. Finally, we introduce an intermediate category called "dome/chaos". In other literature, these features have been identified as domes ("Type 1 dome" Doggett et al., 2009; Miyamoto et al., 2005), chaos, or small chaos regions (Fagents, 2003; Spaun et al., 2004). The surface appears as either rough (Fig. 1e) or smooth (Fig. 1f). The roughness is visually similar to the patches of material between the individual blocks preserved in chaos.

Lenticulae are the surface expression of processes that occur within the ice shell or underlying ocean. Proposed processes include plumes and convection in the ocean (Barr and Showman, 2009; Sotin et al., 1999; Spaun and Head, 2001; Thomson and Delaney, 2001); plumes and convection in the ice shell (McKinnon, 1999; Pappalardo and Head, 2001; Rathbun et al., 1998); melt-through (Greenberg et al., 1998; 1999; 2001; 2003); cryovolcanism (Fagents et al., 1998); sills (Collins et al., 2000; Craft, 2013; Dombard et al., 2013; Manga and Wang, 2007; Michaut and Manga, 2014); and impact (Collins and Nimmo, 2009). Greenberg et al. (1999) suggest that all types of lenticulae have a common origin, and document different stages in the evolution of dynamics within the ice shell.

Here we map and measure geometric properties of lenticulae. We identify patterns in spatial location, mean radius, aspect ratio and orientation of each type of lenticula. We further characterized the interactions between lenticulae and lineaments. Based on these measurements, we can then evaluate the proposed models for the formation of lenticulae.

2. Methods

We map lenticulae on Galileo's Solid State Images (SSI) that are projected on to a nonplanar map with a planetographic coordinate system. We determine the area, density, and global location based on the mapped points with ArcGIS software. Examples of our mapping are illustrated in Supplementary Fig. 1. In order to determine aspect ratio and orientation, we use the least-squares method to fit ellipses to the lenticulae. We measure the orientation, major and minor axis lengths, and area of each fitted ellipse. We compare the fitted ellipse area to the actual mapped area.

We report the confidence in outlining each feature through a Bayesian approach and Monte Carlo simulations. In the simulation, the mapped points are displaced in a random direction within 2 pixels and reanalyzed over 100 times. The standard deviation of this randomization defines the 68% confidence interval (1 standard deviation). By applying a Monte Carlo method to mapped features, we can confirm that there is sufficient image resolution to determine geometric properties of mapped features. Scarcity of pixels will result in inconsistent mapping.

Once the lenticulae are mapped, we identify them as domes, pits, spots, chaos, or dome/chaos based on topography, interaction with previous crust, and albedo. The lineament-lenticula interactions and shadows help determine the lenticula type. The shadows cast by lineaments allows us to determine if lenticulae are concave or convex. Last, some of the methods used to define lenticulae are based on the properties of the crust within the lenticulae (is the crust replaced? preserved? or broken up, yet preserved?). Since identifying lenticulae depends on elevation and the surrounding features, high-resolution images are required. If the attributes (e.g., shadows, lineaments) that aid in identifying the type of feature are less than 10 pixels in width (Dickey, 2014), then we map them but give them a low confidence score (described next). In order to avoid features less than 10 pixels in width, most of the mapped images have a resolution better than 200 m/pixel. We did not map all of the features. Our total mapped area is 3.29% of the surface.

The map is divided into quadrants as presented in Fig. 2. We map lenticulae that appear in images better than 250 m/pixel (Fig. 2). However, not all mapped features are included in the final results. Observations are assigned a score of 1–3 according to the certainty in the observation. The certainty test distinguishes between the features we are confident in categorizing as a type of lenticula from features that might fall under multiple types of lenticulae. The global mapping analysis (such as density of features in an area) uses all of the mapped features, but the analyses that show feature attributes (including lenticula-lineament interactions) are based on the most confident features (features numbered 1). An example of a feature with each type of confidence score is provided in the supplementary material (Supplementary Figs. 9–11).