

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 antiojovian 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.

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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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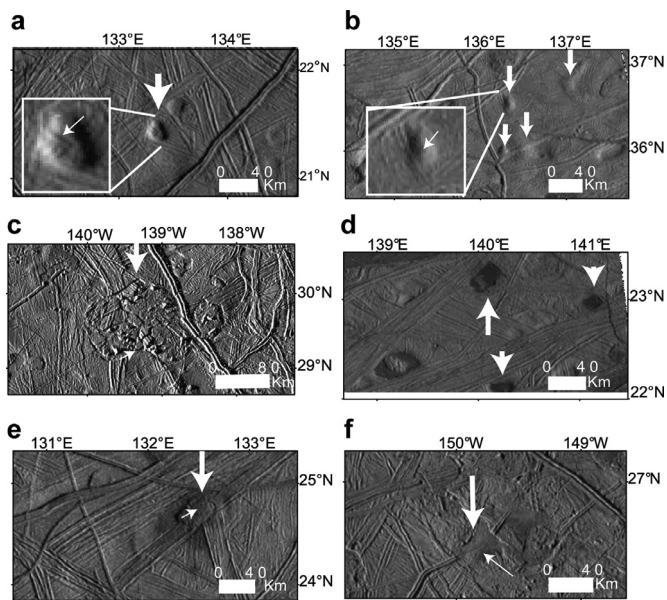


Fig. 1. Examples of lenticulae on Europa's surface. Panels a, b, c, and d show pits, domes, chaos, and spots, respectively. Panels e and f show dome/chaos features. The small white arrows in a, b, c, e and f point to the morphologies that help identify the features. The magnified images show lineaments 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; Dombar 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).

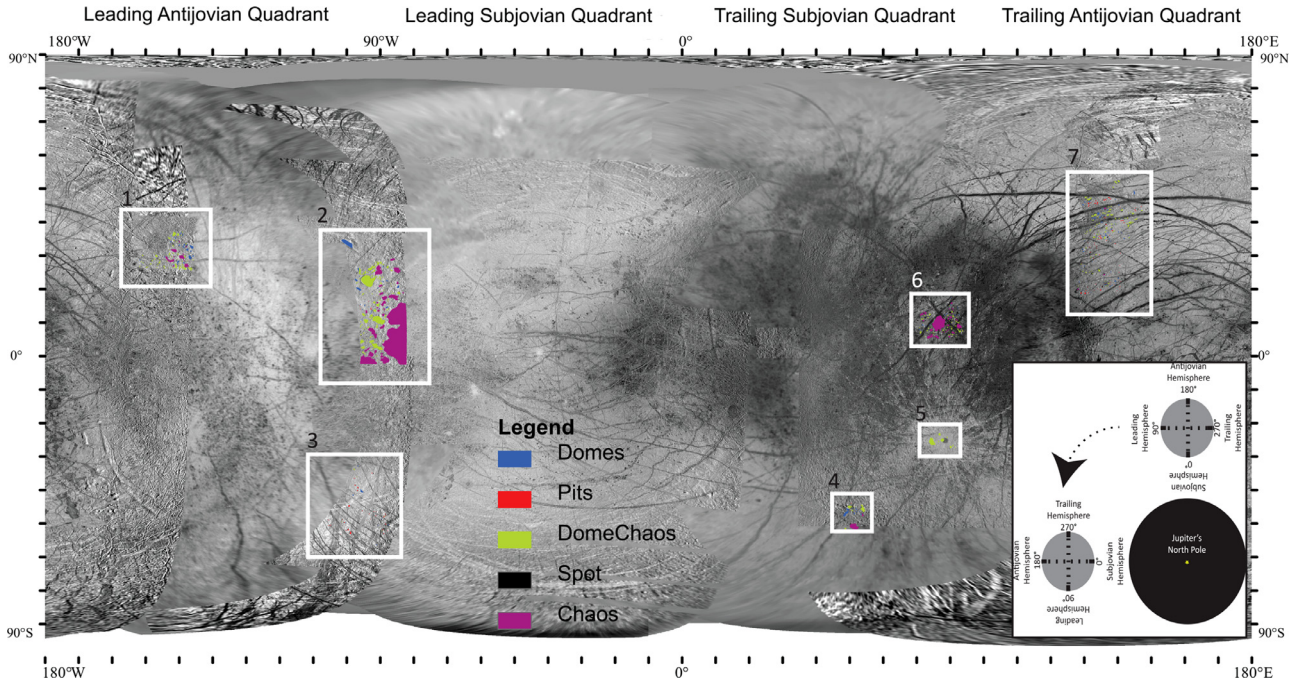


Fig. 2. Global map of Europa with all of the mapped features. The numbered boxes correspond to Supplementary Figs. 2–8. In the lower right corner we illustrate the definition of Europa's hemispheres (Doggett et al., 2009).

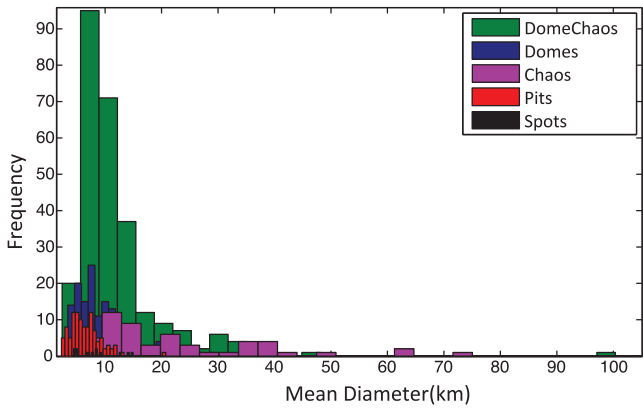


Fig. 3. Histogram of average diameter for all types of lenticulae. In increasing order of mean radius: pits, domes, dome/chaos, and chaos. Bin width is determined by requiring 15 bins to span the range of smallest to largest mean radius.

3. Results

3.1. Geometry of lenticulae

Table 1 summarizes the dimensions (major and minor axes, area), orientations, and aspect ratios of each type of lenticula. In increasing order of mean radius are pits, domes, dome/chaos, and chaos (Fig. 3). There are not enough spots to obtain a statistically significant mean size. However, according to the averages of 13 spots, they have similar sizes to pits. Our results for sizes are consistent with Singer et al. (2010).

Most of the lenticulae have a similar relationship between aspect ratio and mean radius: larger features have greater ellipticity (Fig. 4) except for large chaos features, which have smaller ellipticity. Unlike other types of lenticulae, pits are preferentially elongated in the northwest-southeast direction (Fig. 5). A one-sample *t*-test with a 95% confidence interval reveals a *p*-Value of 0.003,

indicating that the preferred orientation is statistically significant. Domes, dome/chaos, and chaos do not have a preferred orientation.

3.2. Spatial distribution of lenticulae

We mapped a total of 9.8×10^5 km², 3.29% of Europa's surface. We identified 109 pits, 135 domes, 269 dome/chaos, 13 spots, and 54 chaos with confidence (score 1, Supplementary Fig. 9). Of all the mapped features, 20% of lenticulae fall in the uncertain category (scores 2 or 3, Supplementary Figs. 10–11). There are not enough spots mapped to reach significant numbers for interpreting spatial and geometric patterns. The uncertainty in our mapping affects the mean geometric properties (diameters, areas, and orientations) less than 1%, thus, the variation we report for geometric properties is 1 standard deviation from a Gaussian distribution average. Last, we compare the difference between the area of each feature and the area of the ellipse fit to the feature. On average, each feature's area is within 12–15% of the area of the best-fit ellipse, confirming that it is not unreasonable to approximate lenticulae as ellipses to characterize dimensions and orientations.

In order to confirm that lenticulae spacing and spatial density are not biased by small sample sizes, we regenerate the entire mapping exercise based on the measured lenticulae sizes (Table 1) and area covered by high-resolution images. To create synthetic maps, in each mapped region we randomly position the features we mapped (pit, dome, chaos, dome/chaos) but assign the radius from the averages and standard deviations of the ensemble of mapped features. We generate 1000 random maps to see if there is a bias due to small areas of the maps or large lenticulae that fill a substantial fraction of the region. We can then compare the simulations to the original mapping.

On Europa, pits mainly appear in the trailing antijovian and leading subjovian quadrants. According to the iterative mapping exercise, the results are not a consequence of small number statistics. If the results were biased by the ratio between total mapped area and total area covered by lenticulae, we would expect more than 10% of the synthetic maps to show fewer pits in the leading antijovian quadrant and trailing subjovian quadrants. Instead,

Table 1

Lenticulae attributes. The reported uncertainty is one standard deviation from the Gaussian mean. Feature attributes are based only on the most confident features (confidence score 1). The total mapped area is based on all features.

Feature	Minor diameter (km)	Major diameter (km)	Mean diameter (km)	Average area (km ²)	Mean Azimuth of major axis (from north)	Total mapped area (km ²)	Count
Pit	4.8 ± 2.1	8.3 ± 4.0	6.6 ± 2.8	30.0 ± 25.7	−6.9 ± 26.0	3.27 × 10 ³	109
Dome	6.8 ± 3.6	12.1 ± 7.9	9.5 ± 5.5	72.4 ± 107.6	−1.4 ± 27.5	9.79 × 10 ³	135
Dome/chaos	8.6 ± 6.7	14.9 ± 10.9	11.7 ± 8.5	125.3 ± 450.7	0.2 ± 25.9	3.37 × 10 ⁴	269
Spot	5.8 ± 2.5	10.7 ± 5.0	8.3 ± 3.6	45.4 ± 41.1	−16.3 ± 17.7	5.9 × 10 ²	13
Chaos	17.6 ± 14.9	30.9 ± 24.9	24.2 ± 19.1	587.4 ± 1289.9	−2.0 ± 26.7	1.1 × 10 ⁵	54

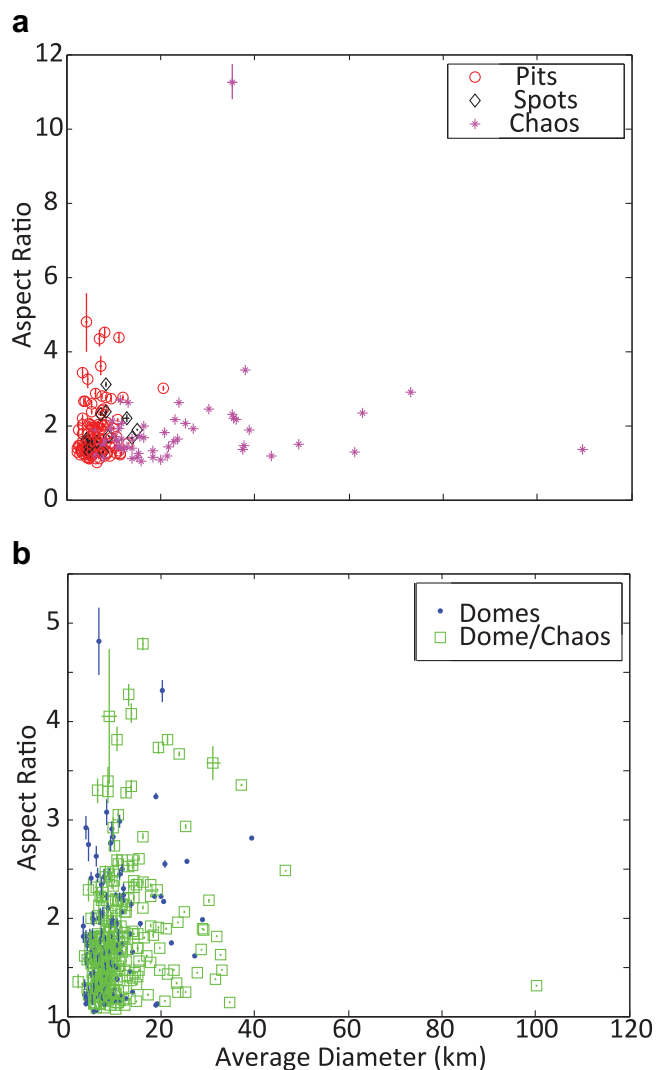


Fig. 4. Average diameter as a function of aspect ratio for a) pits, spots and chaos, and b) domes and dome/chaos. All features have similar aspect ratios but large chaos features are more circular.

we observe only 0.4% of cases had fewer than 9 pits in the leading antijovian quadrant. In the trailing subjovian quadrant, 51 of 1000 cases had less than 3 pits, confirming that pits are not randomly distributed over the mapped surface. Although a very small area is mapped, the other features are randomly distributed so, by comparison, the distribution of pits is distinct. Also, features are larger in the trailing subjovian quadrant and leading antijovian quadrant, although lenticulae in those two quadrants are not as numerous as in the trailing antijovian quadrant and leading subjovian quadrant.

Figs. 2 and 6, and Table 2 summarize the lenticulae mapping in each quadrant. These figures and table incorporate all of the

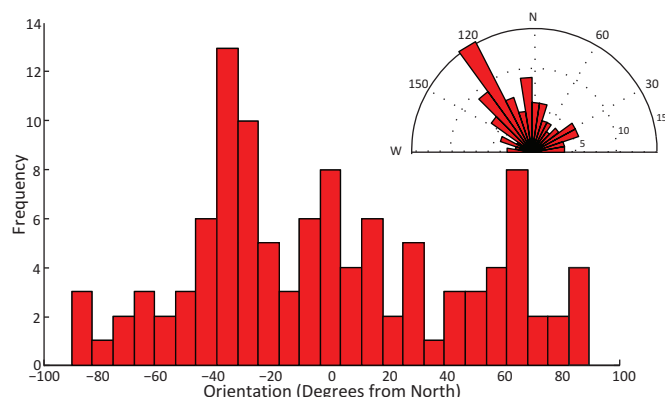


Fig. 5. Orientation distribution of pits. The rose diagram in the top right corner is divided into 20 bins and the histogram is divided into 25 bins. Pits preferentially strike northwest-southeast.

mapped features, including the features that we did not map with confidence.

There is a wide range of estimates of the area covered by lenticulae. For example, chaotic terrain may cover 20% (Figueredo and Greeley, 2003) to 40% (Riley et al., 2000) of Europa's surface and may be spatially highly variable (Neish et al., 2012). Spaun et al. (2004) found that the number of small chaotic terrains per unit area (spatial density) is greater in the leading and trailing quadrants and at 330°W. According to our taxonomy, small chaotic terrain includes some dome/chaos and chaos. The discrepancy may arise, in part, because of regional variations in lenticulae areal density, though identifying regional variations is limited by having only two swaths of high-resolution images. Noting the limited coverage, we did find that the leading quadrant has a higher percentage of the surface covered by lenticulae. Also, variations in definition of chaos terrain make a significant difference. As described by Greenberg et al. (2003), each literature adopts the words "pits", "domes", "spots", and "chaos" differently with individual features placed in different categories. Additionally, identifying all of the lenticulae is difficult. We recognize that our area density values are lower bounds to the actual density, where the largest errors are in chaos and dome/chaos. In our study, the finite size of features in the Monte Carlo statistical mapping simulations, in particular large chaos features, leads to large uncertainties of up to 50% in the area covered by chaos. The mapped areas are not large enough to obtain statistically significant chaos density values.

3.3. Interactions between features

Some lineaments that cross lenticulae offset lenticulae (Supplementary Fig. 12). Although we define chaos and dome/chaos as lenticulae that disrupt or erase pre-existing features, 21% of chaos and dome/chaos features have at least one lineament that crosses the feature (Supplementary Fig. 13). The lineaments that cross cut lenticulae are younger features. A similar analysis is difficult to do

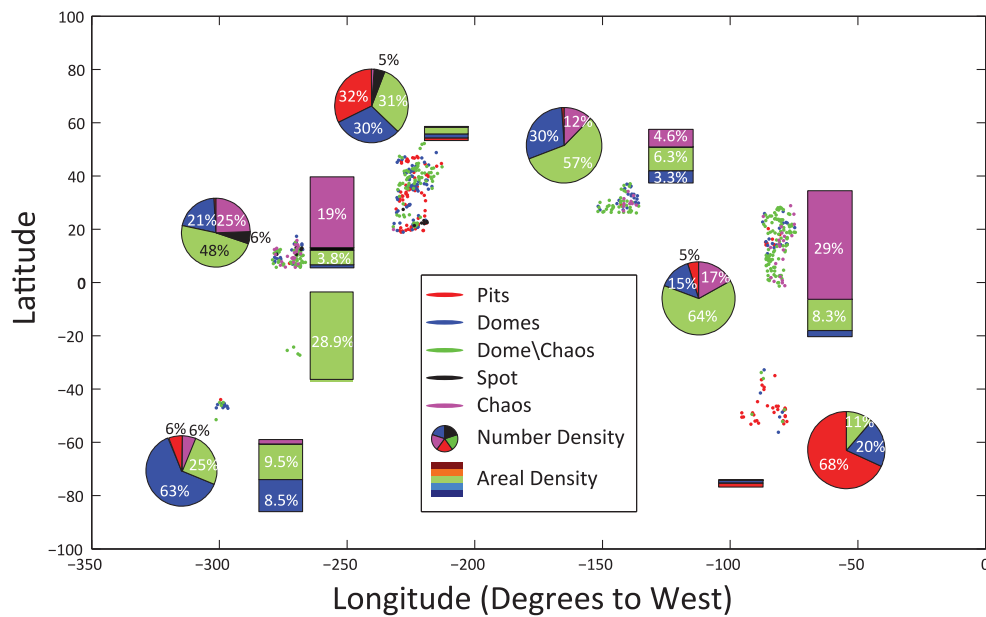


Fig. 6. The location of each mapped feature is shown with a circle. There are pie and bar diagrams on either side of the mapped areas. The pie diagrams present the number of each type of feature found in the mapped area. The bar diagrams indicate the percent of area each of the lenticula types cover the mapped area. The total size of the bar diagram corresponds to the percent of total area covered by lenticulae. The values used in this plot are based on features with all confidence levels. Only percentages greater than 3% are shown.

Table 2

Summary of regional mapping. The top 5 rows list the number of mapped features. The bottom 6 rows list the percent of Europa's surface covered by each type of feature.

	Trailing subjovian quadrant	Trailing antijovian quadrant	Leading Antijovian quadrant	Leading subjovian quadrant	Total number/mean percent cover
Pit #	2	82	4	35	123
Dome #	25	84	30	33	172
Dome/chaos #	37	106	55	110	308
Spot #	2	16	0	0	18
Chaos #	19	11	12	28	70
Pit area	0.03%	0.6%	0.1%	0.3%	0.4%
Dome area	2.4%	1.0%	5.3%	1.4%	1.5%
Dome/chaos area	7.4%	2.2%	5.3%	6.4%	4.8%
Spot area	0.2%	0.2%	0%	0%	0.1%
Chaos area	14.0%	0.7%	3.9%	22.0%	11.7%
Total lent. coverage	24.03%	4.7%	14.5%	30.1%	18.5%

with pits and domes, because pits and domes do not erase pre-existing features. Therefore the only way we can confirm relative age is if we can observe lateral displacement across lineaments. There are multiple studied examples of lineaments that have significant lateral offset (Culha et al., 2014; Pappalardo and Sullivan, 1996; Schenk and McKinnon, 1989; Sullivan et al., 1998; Tufts et al., 2000). Thus we expect that lenticulae may also be broken and offset by lineaments. Greenberg et al. (2003) provides an example of a pit that shows lateral displacement across a lineament. Further examination, however, shows that older cross cut lineaments are offset in the opposite direction. Therefore, this is not an example of offset but, more likely, two pits along a lineament. We found no examples of pits and domes with offsets across lineament. Additionally, the suggestion of Greenberg et al. (2003) that pits generally avoid structural and tectonic features is not consistent with our data. The abundance of lineaments on pits suggests that pits formed after the lineaments that are found on their walls and floors, and that pits do not avoid structural or tectonic features (e.g., pit on the right of white arrow in Supplementary Fig. 15). Of the studied pits, only 5% are not in the vicinity of lineaments.

We did not find any obvious cases where lineaments altered their paths around lenticulae. A total of 14 regions were noted to have a lenticula with nonlinear lineaments in their vicinity (e.g., Supplementary Figs. 13–15). We are not able to confidently determine the sequence of formation for any of the 14 cases, and thus it is not possible to identify the origin of lineament curvature. Regardless, of these 14 lenticulae, 9 regions have lenticulae tangent to curving lineaments; however, distinguishing between deflected lineaments and uplifted lineaments is not always possible (Supplementary Fig. 13). Of the studied regions, there are 2 regions where the lineament within the lenticula and outside the lenticula curves in the same direction (Supplementary Fig. 14). There is a single example of a lineament curving towards a lenticula. Last, there are 5 regions where there is a curving lineament in the vicinity of a lenticula (Supplementary Figs. 13 and 15). None of the 14 lenticulae is a pit or spot.

There are multiple examples of dark, spot-like, convex features under dome/chaos features (Fig. 1e). It is not clear if the darker region is related to spots.

4. Discussion

4.1. Inferences

We draw 5 conclusions from the mapping: (1) pits and domes have similar sizes; (2) pits are clustered in certain regions of the surface whereas domes, dome/chaos, and chaos are more uniformly distributed; (3) chaos are larger than the other lenticulae; (4) area density for all lenticulae is not uniform; and (5) since most lineaments appear linear near and on lenticulae, lenticulae probably do not divert the path of lineaments. We now use these observations to draw inferences about the processes that form lenticulae and then compare formation models to our measurements.

As suggested by [Greenberg et al. \(1999\)](#), the similar sizes of lenticulae suggest that they have a common origin and each type represents a different stage in the evolution of a single process. However, their spatial distributions are not similar: pits are clustered, and domes and chaos are more uniformly distributed. [Greenberg et al. \(2003\)](#) observes an antipodal spatial distribution of pits, which is in agreement with our cluster observation. Unlike pits, we cannot determine whether dome/chaos and chaos form in clusters because they are randomly distributed over the surface and we cannot establish ages.

The portion of lenticulae adjacent to lineaments does not appear sheared, implying that the surface behaves nearly rigidly on either side of the lineament, consistent with rigid offsets inferred from lineament cross-cutting relationships ([Culha et al., 2014](#); [Pappalardo and Sullivan, 1996](#); [Schenk and McKinnon, 1989](#); [Sullivan et al., 1998](#); [Tufts et al., 2000](#)). Also, the various lenticulae and lineament interactions show that lenticulae can record offset across lineaments (Supplementary Fig. 12). Although lenticulae may be deformed by lineaments, lenticulae do not obviously alter the path of lineaments. The absence of changes in lineament orientation may result from the size of lenticulae; however, we do not observe orientation changes along lineaments near large lenticulae. Only 14 lenticulae out of 692 lenticulae may have diverted lineaments, suggesting that lenticulae either have a small effect on stresses in the ice shell or that these effects have a short duration. Since lenticulae do not significantly alter the properties of, or dynamics within, the ice shell and there are very small amounts of surface strain outside of lineaments ([Culha et al., 2014](#)), lenticulae presumably obtain their shape and orientation during their formation.

The scarcity of pits relative to domes, dome/chaos, and chaos suggests that pits are relatively short lived and therefore are younger features. Additional evidence for the short lifetime of pits is their preferred orientation. As noted in [Section 3.3](#), the absence of surface strain after pits formed implies that pit orientation is generated during their initial formation and pit shape is influenced by properties of the ice shell such as stress. Since stress within the ice shell may change over time, for example by polar wander (e.g., [Ojakangas and Stevenson, 1989](#); [Leith and McKinnon, 1996](#); [Rhoden et al., 2011](#)) and orbital evolution (e.g., [Hoppa et al., 1999](#); [Husmann and Spohn, 2004](#)), lenticulae with similar orientations must have formed at similar times. Preferred orientation is not observed for domes, chaos, and dome/chaos. If orientation of lenticulae is influenced by stress in the ice shell, then pits sample a shorter, more recent time period. Domes, dome/chaos, and chaos sample a longer history of conditions in the ice shell and thus have no preferred orientation.

4.2. Models for the formation of lenticulae

A variety of models have been proposed to form the different types of lenticulae. Here we summarize models and assess whether they are consistent with our observations.

4.2.1. Plumes and convection in the ocean

Heat from the rocky interior of Europa, salinity variations in the ocean, and tidally induced frictional heating may generate thermal plumes in the ocean ([Thomson and Delaney, 2001](#)), which would influence the ice shell and ultimately create pits, domes, dome/chaos, and chaos on Europa's surface. If the convection is vigorous enough, and the ice shell is thin enough, the ice shell may melt to create chaos. Whether these criteria can be met, however, is not clear ([Barr and Showman, 2009](#); [Sotin et al., 1999](#); [Spaun and Head, 2001](#)). Plumes and convection in the ocean could explain the disruption of the crust and the formation of pits as incipient disruption, where the negative relief arises from the contraction of water as ice melts. But plumes and convection in the ocean model cannot explain why dome/chaos and chaos features have positive relief. Refreezing of the melted ice would return the ice to its original topography.

4.2.2. Plumes and convection in the ice shell

Europa's ice shell may be thick enough and hot enough to undergo solid-state convection (e.g., [McKinnon, 1999](#)). Upwellings and downwellings may produce positive (domes, chaos, and dome/chaos) and negative (pits) relief lenticulae (e.g., [Rathbun et al., 1998](#); [Pappalardo and Head, 2001](#)). Normal stagnant lid convection, however, cannot explain the relief, size and spacing of lenticulae because density variations in the convecting ice are small (e.g., [Nimmo and Manga, 2002](#); [Freeman et al., 2004](#); [Showman and Han, 2004](#); [2005](#)). Anisotropic rheology does not enhance relief ([Rudolph and Manga, 2012](#)). Thermochemical convection ([Han and Showman, 2005](#)) or melting from tidal heating ([Sotin et al., 2002](#)) or some combination (e.g., [Tobie et al., 2003](#); [Mitri and Showman, 2008](#); [Schmidt et al., 2011](#)) may give rise to larger density variations within the ice and hence larger relief.

The vigor of convection can vary throughout the ice shell or ocean, which could explain the nonuniform areal density of lenticulae. Because we observe pits to be clustered, if all lenticulae are produced by convection, downwelling and upwelling regions must not be uniformly distributed. Plumes can form clusters if the ascent distance is much greater than plume size ([Kelly and Bercovici, 1997](#); [Manga, 1997](#)), however, the dimensions of lenticulae are comparable to estimates of the thickness of the ice shell ([Showman and Han, 2004](#); [Williams and Greeley, 1998](#)). Although rare, the presence of large chaos terrains such as Mitten (Murias Chaos) is consistent with thick shell models ([Figueredo et al., 2002](#)), but also could be explained using thin shell models ([Williams and Greeley, 1998](#)).

4.2.3. Melt-through

Convection within the ice shell and/or the underlying ocean might partially or completely melt the crust and form pits, domes, chaos and dome/chaos. [Greenberg et al. \(1998; 1999; 2001; 2003\)](#) and [Carr et al. \(1998\)](#) suggest that tidal heating can melt ice and form pits. The thinning of the solid ice layer allows ice above the melt to be disrupted and form chaos features, with larger pockets of melt more likely to disrupt the overlying ice ([Walker and Schmidt, 2015](#)). A key challenge with the melt-through model is creating melt close enough to the surface if the only source of heat is tidal heating ([Nimmo and Giese, 2005](#); [O'Brien et al., 2002](#)). It is not clear why domes and chaos should have positive relief: refreezing of liquid water in the ice shell should return the surface elevation to the pre-melting topography because there is no net addition of mass into the ice shell.

The melt-through model implies that there should be a greater density of features where tidal heating is the largest, at the poles ([Sotin et al., 2009](#)). Tidal dissipation should be symmetric about the equator, but we observe an asymmetry in the density of pits about the equator in the leading subjovian quadrant. [Schenk et al.](#)

(2008) proposed that true polar wander has occurred, with paleopoles in the present day leading antijovian and trailing subjovian quadrants. However, our observations are the opposite of those expected for the inferred paleopoles (Schenk et al., 2008).

Thus melt-through or near-surface melting might explain the formation of pits and why chaos are larger than pits, but it does not obviously explain the magnitude of lenticulae topography (Singer et al., 2010) and the asymmetry of feature density about the equator.

4.2.4. Cryovolcanism

The extrusion or explosive eruption of water onto Europa's surface could create features analogous to lava flows or pyroclastic deposits, respectively (Fagents, 2003). Deposition on the surface would cover pre-existing features, as do some of the lenticulae categorized as spots and dome/chaos. Chaos, in contrast, appears to preserve pre-existing terrain. Cryovolcanism does not explain how pits and domes form. However, similar to the melt-through model, pits and domes could document early stages in the cryovolcanic process and reflect the cryomagmatic processes that occur within the ice shell.

4.2.5. Sills

The intrusion of liquid water (or warm ice) as sills can deform the ice shell leaving lenticulae as the surface expression of their location and size (Collins et al., 2000; Craft, 2013; Dombard et al., 2013; Michaut and Manga, 2014). While the sill is liquid, the surface appears as a pit owing to the higher density of liquid water compared to ice. Following solidification, the expansion of water can raise the surface to form a dome; large enough intrusions may disrupt the overlying ice to form chaos or deliver liquid to the surface to form dome/chaos (Schmidt et al., 2011). Quantitative predictions of the sill model (e.g., Michaut and Manga, 2014) do not disagree with any of geometric attributes of lenticulae, but this model does not provide any explanation for the spatial distribution of features. Further, the origin of the intruded water is unknown, but may be a pressurized underlying ocean (Manga and Wang, 2007). Kattenhorn and Prockter (2014) propose that a process analogous to subduction occurs in the ice shell. The region between Minos Linea and Udaeus Linea, a hypothesized subsumption zone, has series of pits (Supplementary Fig. 8). The pits are not aligned parallel to the proposed subsumption zone; rather, they form a line parallel to Minos Linea. Regardless of their alignment, there are 12 pits along the putative subsumption zone and these may have their origin in the upwelling and/or cryovolcanism that Kattenhorn and Prockter (2014) suggest might accompany subduction.

Our mapping suggests that pits are shorter lived than domes and form in clusters. If lenticulae are the surface expression of sills, then our observations would confirm that pits evolve into domes. Liquid sills cool and solidify over time scales that are shorter than the topographic relaxation timescale for domes, which would explain why pits are shorter lived than domes. Since pits are clustered the implication is then that the other lenticulae also formed in clusters but they are now too numerous to preserve information about the initial distribution.

4.2.6. Impact

Collins and Nimmo (2009) entertain the idea that chaos and dome/chaos might be a result of impacts. An impact would thin the crust and cause a larger area to partially melt. The model is not consistent with larger densities of chaos terrain in the subjovian hemisphere. If dome/chaos and chaos were impact craters then objects would impact Europa on the antijovian hemisphere as well. Moreover the morphology of lenticulae does not resemble other features identified as impact craters (e.g., Moore et al., 1998; Greeley et al., 2000).

5. Summary

In this study, we map and measure geometric properties of domes, pits, chaos, and spots on Europa's surface. We introduce a new categorization called dome/chaos. Dome/chaos are rough or smooth elliptical features. Unlike chaos, dome/chaos features do not preserve distinct blocks of the previous crust within the feature. Pits and domes have similar sizes, though domes are slightly larger. Pits and spots are not uniformly distributed over the surface unlike domes, dome/chaos and chaos. Also, unlike the other features, pits have a preferred elongation in the northwest-southeast direction. Spots are the least abundant feature. Similar to spots, some dome/chaos are surrounded by dark regions. Chaos are the largest features on average.

As summarized by Collins and Nimmo (2009) the most parsimonious explanation is that each class of lenticula represents a different stage in an evolutionary sequence of a common process. This is the case for the convection-based models and models that attribute lenticulae to sills within the ice shell. Our observations and results are consistent with pits evolving into domes, dome/chaos, and chaos depending on the volume of the liquid body or diapir and crustal properties. If sills or other liquid bodies in the ice shell create lenticulae, then our results suggest pits evolve into domes. From the scarcity and preferred orientation of pits, we infer that pits are short lived compared to domes, dome/chaos, and chaos. Large sills or plumes may thin the ice shell promoting disruption of the ice or deposition on the surface, consistent with chaos and dome/chaos being larger than pits and domes. If diapirs in the ice shell create lenticulae, then pits and domes may evolve into dome/chaos and chaos. None of our observations allow us to favor either an origin by convective phenomena, provided lenticulae are all associated with upwellings, or origin by sills.

Our ability to test models for the formation of pits, spots, domes and chaos is limited by both the area imaged at high resolution (only a few percent of the surface) and having only a two-dimensional view of the surface expression of the lenticula-forming processes. The Clipper Mission will further our understanding by addressing both shortcomings in current data. First, the Europa Imaging System (EIS) will provide high resolution coverage of more of Europa's surface. Spectroscopic measurements from a Mapping Imaging Spectrometer for Europa (MISE) and thermal emission (E-THEMIS) will identify possible compositional or textural variations that can be used to infer the source of materials that comprise lenticulae. Second, additional dimensions, both time or space, will be revealed, first through images acquired 40 years after the Galileo Mission, which may reveal temporal changes. Additional spatial dimensions of lenticulae can be assessed by ice-penetrating radar that might be able to identify the subsurface structures that are associated with lenticulae, including sills or other bodies of liquid. Several of the questions that motivated the mapping presented in this paper remain unanswered in the absence of data from these various instruments: how do lenticulae form? how do heterogeneities in the crust influence the structures preserved on Europa's surface? can liquid water from the subsurface ocean reach the surface? do lenticulae record processes such as polar wander or changes in orbital evolution? The premise remains that lenticulae preserved on Europa's surface record the evolution of Europa's interior and near-surface environments.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at [10.1016/j.icarus.2015.12.052](https://doi.org/10.1016/j.icarus.2015.12.052)

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