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Conamara Chaos Region, Europa: Reconstruction of mobile polygonal ice blocks

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Abstract. New Galileo images of Europa reveal regions of chaotic terrain in otherwise highly-lineated background plains. Examination of Conamara Chaos shows that 59% of the region is composed of fine-textured matrix material lying at low elevations and formed by destruction of lineated plains, while the remainder consists of 139 fragmented polygons of linear-textured background plains. Using through-trending linear features, we reconstruct the original positions of chaos polygons and find that significant lateral translation and rotation have occurred: 78% of the polygons have undergone horizontal translations with most moving between 1 and 5 km, and 81% have rotated (average rotation of ~11°). Movement of polygons appears to be inward from the chaos margins and clockwise in the center, while polygon rotation is evenly clockwise and counterclockwise. Chaos formation in this region thus involves destruction of over half of the pre-existing terrain, and mobilization, translation, and rotation of the remaining polygons, implying elevated near-surface temperatures and a highly mobile substrate over lateral scales of ~100 km.

Introduction

Europa, the Galilean satellite between Io and Ganymede, has few craters, implying a young surface, and an abundance of surface features thought to be linked to tidal deformation [e.g., *Malin and Pieri*, 1986]. On the basis of relatively low-resolution Voyager images (>1.9 km), the icy surface was divided into two terrain types: lineated bright plains and mottled terrain [*Lucchitta and Soderblom*, 1982]. Recent high-resolution Galileo imaging showed that many areas of mottled terrain are characterized by an abundance of pits, spots and domes (lenticulae) and larger regions characterized by disorganized polygonal blocks similar in structure to surrounding lineated bright terrain and intervening matrix-like material (together known as chaos) [*Carr et al.*, 1998; *Pappalardo et al*, 1998; *Greeley et al.*, 1998]. During the sixth orbit of the Galileo mission (E6), images were obtained of a region named Conamara Chaos (8°N, 274°W) at a resolution of up to 54 m/pixel. These images (Fig. 1) revealed details of an irregularly shaped region (125 km x 75 km) with a discrete inward-facing, cliff-like boundary (Fig. 2) and containing two terrain types [*Carr et al.*, 1998]: 1) fragmented and dislocated polygons of background plains up to 20 km in diameter with 100-200 m high margins, and 2) a matrix of finer textured material lying at lower elevations.

Both lenticulae and linea are observed in the terrain surrounding the chaos region. Linea are ridges, troughs, and lineated bands that crosscut each other at different angles and form patterns characteristic of background plains. Lenticulae can be classified as domes, spots, and pits and are typically 7-15 km in diameter with positive and negative topography of tens to hundreds of meters (Fig. 3). Domes upwarp but do not usually disrupt the background terrain. Pits are low albedo areas containing rough-textured matrix and small disrupted blocks of background terrain similar to chaos. Spots are ovoidal smooth areas of low albedo that resemble frozen ponds of melt. A diapiric origin has been suggested for lenticulae in which upwelling causes surface flexure, often accompanied by localized heating, collapse, and possibly extrusion [*Head et al.*, 1997; *Pappalardo et al*, 1998]. Cross-cutting relationships show that lenticulae and chaos regions postdate the majority of linea.

In this analysis, we address the questions: What is the nature and structure of Conamara Chaos? How much of the pre-existing surface has been modified or destroyed? How much movement of the remaining polygons has taken place? What are the implications for the formation of chaos terrain? To address these questions, we carry out a detailed analysis of the characteristics of Conamara Chaos, mapping geologic units, assessing stratigraphic relationships, and studying the properties of polygons and matrix in detail. As part of this analysis we use structural patterns within the unfragmented background plains to reconstruct the chaos polygons into their original positions in order to assess the movements of the polygons and the formation of the matrix. These observations will help to constrain hypotheses for the origin of chaos.

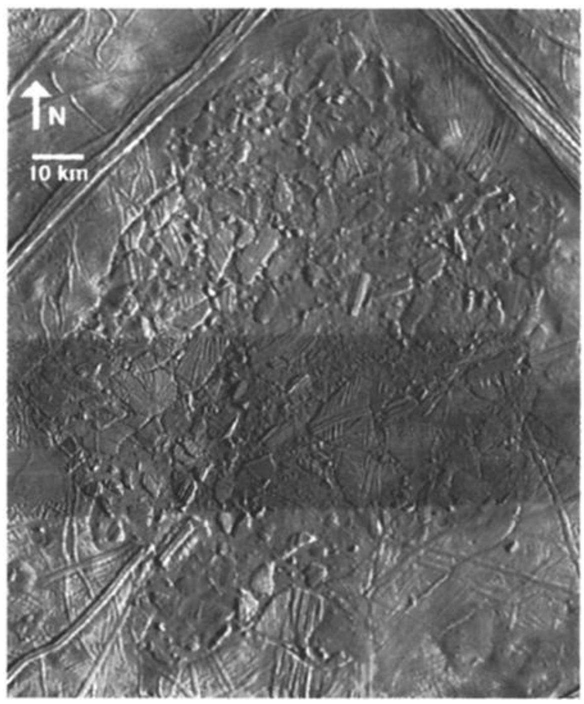

Figure 1. Galileo image mosaic of Conamara Chaos obtained during the E6 encounter (background is 180 m/pixel resolution; central swath is 54 m/pixel resolution). Illumination is from the east. Projection is orthographic, centered at 8°N, 274°W.

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Image Analysis

On the basis of cross-cutting relationships, Conamara Chaos (Fig. 1) is a relatively young surface feature, with a distinct boundary generally composed of an inward-facing escarpment that cuts the surrounding plains. It occurs just below the apex of two major linea (NE-trending: Asterius Linea; NW-trending: Agava Linea). The eastern chaos boundary shows evidence of minor strike-slip movement, and the eastern and southern boundaries are partially surrounded by lenticulae. Conamara Chaos postdates the vast majority of linear features in the background plains and predates rays from the young crater Pwyll [*Carr et al.*, 1998].

The interior of the chaos region contains two major units: linear-textured polygons and matrix. Linear-textured polygons are angular fragments exhibiting recognizable linear textures (e.g., ridges, grooves, bands) typical of background plains [*Greeley et al.*, 1998]. Where visible, these textures are usually sharp and crisp.

The matrix, lying at lower elevations between polygons, can be divided into four subunits: 1) micro-polygons (smaller plate-like structures that show very faint evidence of linear texture, appear very highly degraded, and are at a lower topographic level than the polygons), 2) angular blocks (steep-sided angular fragments of linear-textured polygons that show a steep tilt towards one side and a high cliff on the opposite side; these appear as if they may have been tilted relative to the plane of the Europan surface), 3) peaks (individual relatively equidimensional features usually less than 2 km across; these show little or no linear texture and tend to be isolated peaks standing above the topographic level of the matrix, sometimes appearing higher than plate margins on the basis of shadow measurements), and 4) hummocky material (a rough textured surface that is distributed between other matrix subunits and includes jumbled surface blocks from ~1 km in diameter down to the limit of the image resolution). Measurements made in the E6 high-resolution coverage (Fig. 1) indicate that greater than three-fourths of the matrix consists of the hummocky subunit. We mapped the position and areal abundance of all polygons and found that the chaos contains 59% matrix and 41% linear-textured polygons (Fig. 2). Thus, chaos formation apparently involves the loss, conversion, or replacement of over half of the background terrain into matrix. We next investigate whether this process occurred in situ, or whether it was accompanied by movement of polygons of background terrain.

Figure 2. Galileo image of Conamara Chaos with the matrix removed. The remaining 139 linear textured polygons were used in the reconstruction. White X's indicate observed lenticulae in nearby background lineated plains. Black X's indicate the centers of candidate lenticulae within the chaos.

Figure 3. Reconstruction of polygons to their estimated original positions in the Conamara Chaos region. The lines are traces of major linea that cross both the background plains and chaos blocks. These and many other linea were used as guides for the polygon reconstruction.

Reconstruction of Conamara Chaos

In order to analyze possible movement of polygons, we created a reconstruction of Conamara Chaos using a mosaic of image data of 180 m/pixel and 54 m/pixel resolution (Fig. 1). Using computer image processing techniques, we removed the matrix units and created an image showing only the linear-textured polygons within the chaos region (Fig. 2). On the basis of our regional geologic mapping, we identified numerous long, linear, ridges and troughs that appear to have extended across the region prior to chaos formation (Fig. 3). The number of these throughgoing linea, as well as the similarity of textures on both sides of the chaos boundary, gave us confidence that the terrain predating chaos formation was unfragmented background plains. Using the projected position of the throughgoing linea and the background texture of the polygons, we refitted polygons within the chaos area by moving them until their major structures best fit the marginal, throughgoing, and neighboring trends.

We started at the edges of the chaos and began refitting polygons to the outside boundaries by translation and rotation. If a good fit was not found, polygons were moved farther from the boundaries until a majority of the linea on the polygons

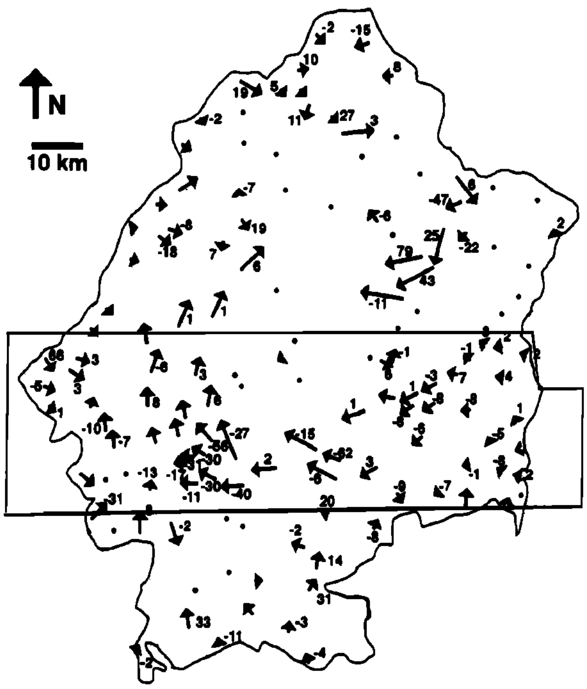

Figure 4. Polygon movement interpreted to have occurred during chaos formation. Direction and amount of movement are indicated by vectors (arrows); arrowhead is present position, tail is reconstructed (interpreted original) position, and length of vector is distance of translation. Numbers are amounts of rotation in degrees (positive numbers are clockwise, negative are counterclockwise). Dots indicate position of polygons that were not refitted due to uncertainty or lack of data indicating translation. 54 m/pixel images are located within the gray box.

matched other linea on other polygons and/or linea outside the chaos region. If a polygon had a good fit (e.g., on the basis of a major throughgoing linea or a fit at the margins) we moved neighboring polygons to it in a similar manner (Fig. 3). We marked the centers of the polygons at their current position and again after reconstruction; vectors connect these two points (Fig. 4), with an arrowhead pointing in the direction from the proposed original location of the polygons to their observed current positions in the E6 images. Thus the arrows show the translation of polygons that we interpret to have accompanied chaos formation. We are confident of our translation measurements in the high resolution area within ~500 m and in the lower resolution area to within ~ 1 km.

Rotations were also measured. Background linea tend to be relatively straight on a regional scale but some show slight curvature that might influence the accuracy of rotation reconstruction. For reference, we analyzed 25 linea in the area of the Conamara mosaic outside the chaos region that were in excess of 50 km in length. For each of these linea, we measured the angle between a straight line connecting their end points and a line drawn from one end to a point representing the maximum distance of the linea from this straight line. For 25 linea the range of these angles was from 0° to 19°, with an average of 8°. These variations are smaller than those we observed in the polygons (average rotation of ~11°). We thus consider that the latter may be considered good estimates of the sign and relative magnitudes of polygon rotation Numbers shown adjacent to the arrows (Fig. 4) mark the clockwise rotation in degrees that the polygons are interpreted to have undergone during chaos formation; negative numbers denote a counterclockwise rotation. Polygons for which there was no unambiguous evidence of rotation or translation (e.g., they contained no prominent linear features that could be fit to regional throughgoing trends, contained linear features that could match to more than one local linea, or had few surrounding similar polygons) remain in their presently observed positions and are marked with a dot. Among the factors that influence the accuracy of the reconstruction are the resolution of the images, the number of linea on each plate and their orientations, the distance from the edge of a plate that distinctive patterns occur, the uniqueness of textural morphology, and the sizes of polygons.

Results of polygon reconstruction

Of the 139 linear-textured polygons mapped in the chaos, all but 22% have been determined to have undergone some movement; there was insufficient evidence to determine whether any of the remaining 22% underwent movement. Linear textured polygons within the chaos (Figs. 1, 2, 3) generally have prominent ridges typical of the type of terrain seen outside the chaos. Some polygons have apparently separated at the centers of prominent double ridges, thus indicating possible structural weakness along the centers of such ridges; others appear to have broken along the edges of prominent ridges.

The reconstruction provides information about the movement of polygons during chaos formation (Fig. 4). The largest translation measured is about 8 km, 22% translated ≥ 5 km, and the average is ≈ 2 km. Of the 108 linear textured polygons that we determined to have translated, 81% of these also rotated during chaos formation; 19% of the translated polygons have undergone little or no rotation. We assumed that the shortest rotational direction was the most likely one. Of the 81% that rotated, 54% rotated counterclockwise and 46% rotated clockwise (Fig 4). Clockwise rotation is relatively evenly distributed throughout the chaos, while there is a tendency for counterclockwise rotation to be concentrated in the southwestern part of the chaos. The maximum polygon rotation that we measured is 79° degrees, while the average rotation is about 11°; 75% of the rotated polygons have rotated 15° or less.

We also observed trends in the movement of polygons within Conamara Chaos (Fig. 4). The vast majority (80%) of polygons within 10 km of the chaos boundary have moved away from the edges. Most of the polygons within the western half of Conamara have moved northward. Polygons in the northeastern half of Conamara have moved mostly southward, while those in the eastern and southeastern part have moved westward and southwestward. At the southeastern margin of the chaos minor strike-slip displacement (both left- and right-lateral) may have influenced the direction of polygon movement. As one moves radially inward from the chaos margin, the amount of polygon displacement typically increases by factors of 2-4. Within the chaos, there is a general sense of collective clockwise movement of the polygons.

Examination of the reconstructed polygons and the displacement vectors (Figs. 3, 4) shows no strong evidence for preferential areas of polygon destruction within the chaos, such as a large area devoid of polygons, or a number of large distinct centers of destruction. Rather, matrix material has been produced relatively evenly throughout the area within the boundaries of the chaos. Similarly, although there is abundant evidence for some translation and rotation of the polygons, trends do not suggest that polygons have moved long distances into broad areas that had undergone complete polygon destruction. There are areas ~5-10 km across that are currently devoid of polygons (Figs. 1, 2) that are the same scale as lenticulae.

On the basis of cross-cutting relationships, the formation of both chaos and lenticulae occurred relatively late in the history of the region, postdating the vast majority of the linear features of the background plains (lenticulae along the southern margin of the chaos are marked by white X's in Fig. 2). Some areas within the chaos have similar textures, shapes and sizes to lenticulae located outside the chaos (candidates within the chaos are marked as black X's in Fig. 2). Could lenticulae and chaos formation have occurred simultaneously and could their mechanisms of formation be related? For example, could Conamara Chaos have formed by the coalescence of a locally high areal density of lenticulae? The upwelling associated with domes might be expected to cause outward translation of polygons, while the formation of negative topography associated with pits and spots might be expected to cause inward movement of polygons. However, we observe no consistent migration of polygons either toward or away from candidate lenticulae or the broader regions of chaos matrix (compare Figs. 2 and 3). Thus, although lenticulae formation may have accompanied chaos formation, the direction of polygon translation and rotation seems to be characterized by broader patterns, such as a general clockwise translation (Fig. 4).

Discussion and conclusions

On the basis of our analyses, we are able to address several questions about the nature and evolution of Conamara Chaos.

1. How much of the background surface has been modified beyond recognition? We find that 41% of the area within Conamara Chaos is composed of linear textured polygons similar to the surrounding background terrain; the remaining 59% of the region is matrix, made up of surface material that has been heavily modified, destroyed or replaced. For the matrix units, high resolution images show a range of highly modified and degraded terrain that lies at lower topographic levels than the polygons. Polygons are generally randomly distributed throughout the chaos.

2. How much movement of polygons has there been? We found that 78% of all the linear textured polygons have undergone detectable minimum translations of 1-2 km; most have moved more than 1 km but less than 5 km. We find evidence that 81% of the translated polygons have rotated, 46% clockwise and 54% in a counterclockwise direction. Average rotation is ~11° and 75% of the polygons have rotated 15° or less.

3. Has there been preferential movement of polygons within the chaos? About 80% of the polygons within 10 km of the edges have moved away from the edges, toward the interior of the chaos region, and the amount of movement has been minor compared to that in the interior. Polygons near the center have been translated greater distances and in a general clockwise direction. Most polygons on the east side of the chaos region have moved toward the west. The polygons on the western side of the chaos have generally moved north.

4. What is the scale and nature of the loss of lineated terrain in the chaos? Many irregular matrix areas with diameters between 5 and 15 km occur within the reconstructed chaos. Matrix formation appears to have been widespread and relatively evenly distributed; the morphology of the matrix suggests that lineated terrain was destroyed in situ, by fragmentation, degradation, partial melting, tilting, and foundering of background lineated terrain [e.g., *Carr et al.*, 1998]. The scale of areas of lineated terrain destruction (5-15 km) is similar to the dimensions of lenticulae in the area surrounding the chaos region.

On the basis of these conclusions, we hypothesize the following sequence of events and processes:

1) Matrix formation: A broadly distributed temperature increase in the shallow subsurface caused destruction of over half of the overlying surface material, and the formation of widely distributed polygonal blocks of pre-existing lineated plains material. Thermal causes for matrix formation are favored over large-scale tectonic translation mechanisms because no evidence is seen for significant horizontal shear movement or biaxial extension in the surroundings. No evidence is seen for impact disruption or fragmentation (e.g., secondary craters, ejecta, concentric rings). The scale of the upwelling is more difficult to assess. The presence of abundant lenticulae in the surrounding area suggests that the chaos might have formed from a concentration of these features and their coalescence. The areal density of lenticulae in the surrounding region suggests that Conamara Chaos could have had as many as 12-15 lenticulae within it, although we find positive evidence for only a few at the present (Fig. 3). Reconstruction of polygons (Figs. 3, 4) shows several matrix regions of a scale comparable to that of lenticulae; there is little evidence, however, that adjacent polygons have moved away from, or into these areas.

2) Polygon migration: Disruption of the structural integrity of the chaos region by matrix formation was accompanied by migration and rotation of remaining polygons. Increased levels of translation and rotation in the interior of the chaos indicates that mobility was greatest there. The pattern of migration and rotation of the polygons remains unexplained; the slight majority of counterclockwise rotation of polygons is consistent with Coriolis forces expected for the present northern hemisphere position of Conamara Chaos, but the general clockwise translation of the polygons is not. Coriolis forces on Europa are expected to be extremely weak, and the overall pattern is in the wrong direction.

The patterns of formation of matrix and scale of migration of polygons described in this study support models which suggest a very thin brittle ice layer overlying a much more mobile shallow subsurface layer of water, partial melt or extremely ductile ice [*Carr et al.*, 1998; *Pappalardo et al.*, 1998; *Williams and Greeley, submitted GRL*, 1998] during chaos formation.

3) Solidification: Following matrix formation and polygon migration, the near-surface region cooled and thickened sufficiently to behave structurally coherently, as evidenced by the several linea that crosscut matrix, polygons and surrounding background plains.

On the basis of these observations and interpretations, we conclude that chaos formation took place by areally significant and widespread matrix formation, and migration and rotation of the remaining polygons. We favor a thermal anomaly as the mechanism of chaos formation but we cannot yet confidently distinguish between coalescence of lenticulae (favored by the apparent simultaneity, morphology and scale) and larger-scale (~100 km) thermal upwelling (favored by the broad patterns of translation of polygons), or a combination of both. Comparison of the Conamara Chaos area with other regions of chaos revealed by Galileo will provide additional perspectives on the history, scales, and styles of thermal upwelling and heat loss on Europa, and the relationship between chaos and lenticulae.

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