Chaos Formation on Europa:

Models and Assumptions

Joseph Shoer

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I. Introduction

Of all the planetary bodies in the solar system, Europa is among the most likely to ignite the imagination. Images of a landscape resembling the terrestrial arctic or Antarctic drove scientists to compare Europa's surface with ice features on Earth. These comparisons led investigators to theorize that the moon's surface overlies a liquid ocean. A significant unknown in studies of Europa is the thickness of the surface ice layer. The internal structure of the ice shell will have substantial effects on both the surface and subsurface environments. If the crust is thin, the possibility exists that Europa may have a biosphere including photosynthetic organisms. This exciting idea remains untestable, but analysis of surface features can illuminate constraints on the subsurface environment. In particular, proposed formation mechanisms of Europan chaos are predicated on differing assumptions about the crust thickness and composition. Analysis of these models may help establish restrictions on properties of the ice crust and underlying ocean.

II. The ice shell and chaos

The scientific fascination with Europa arises from the strong possibility that a global water ocean exists under the ice crust. Evidence for a subsurface liquid ocean comes from tectonic features (Greenberg and Geissler 2002). Fractures, ridges, and displaced plates in the ice crust seem similar to sea ice features on Earth (Greeley *et al*. 1998). Strike-slip faults correlate with the expected behavior of an ice layer subject to diurnal tides (Greenberg and Geissler 2002). Dilational bands exposing new ice surface (Greenberg and Geissler 2002) might be analogous to refreezing Arctic leads (Greeley *et al*. 1998). In addition, some uniquely

Europan features seem easily accounted for as variations on the theme of terrestrial sea ice features, such as cycloidal cracks and double ridges (Greenberg and Geissler 2002). The liquid ocean interpretation of Europa’s internal structure is generally accepted (Greenberg and Geissler 2002; Collins *et al*. 2002; Greeley *et al*. 1998; Schenk and Pappalardo 2004; Nimmo and Giese 2005) so for the purposes of this paper, it will be assumed that Europa has a global subsurface ocean. However, the thickness of the ice crust over the ocean remains a topic of debate (Greenberg and Geissler 2002; Collins *et al*. 2002; Schenk and Pappalardo 2004; Nimmo and Giese 2005; Cox *et al*. 2005; Billings and Kattenhorn 2003).

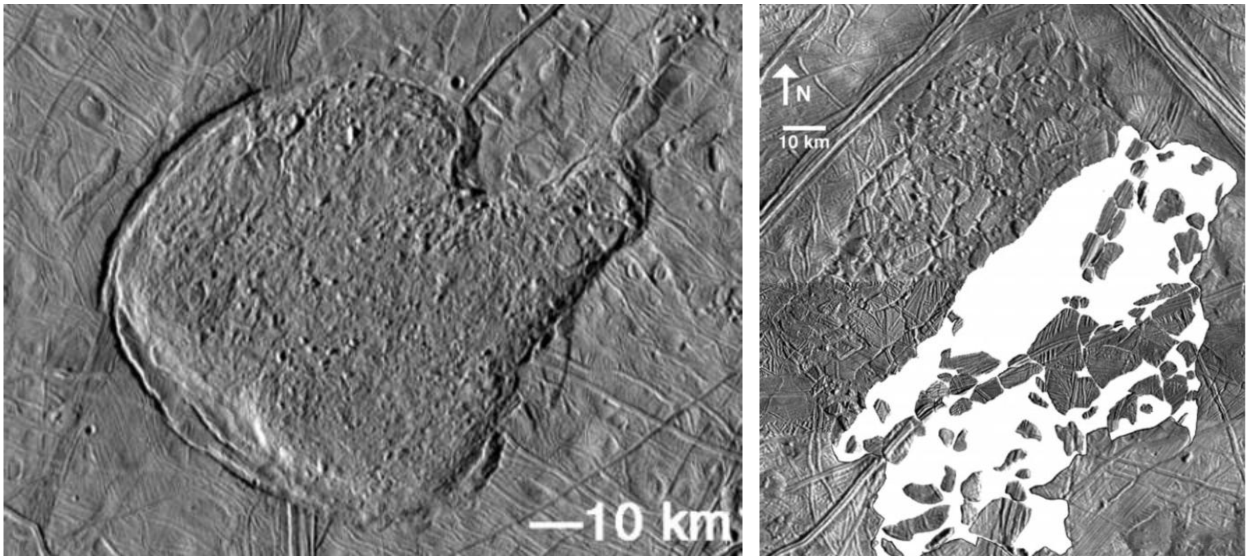

Figure 1. Examples of chaos. *Left*: The “Mitten,” chaos composed almost entirely of matrix material. The surrounding crust exhibits an obvious downward slope towards the chaos, and has broken into a series of concentric fractures on the southwest border. *Right:* Conamara Chaos, with readily apparent rafts jumbled among the matrix. The lower portion of the chaos has been reconstructed to illustrate preservation of preexisting ridge systems on the raft surfaces. Note how the chaos is bounded by ridge systems to the north. (Greenberg *et al*. 1999)

In addition to tectonic features, Europa’s icy surface contains regions of chaotic terrain (Greenberg and Geissler 2002, Collins *et al*. 2002; Nimmo and Giese 2005). Europan chaoses consist of a hummocky matrix of rough material that usually domes upward. Observed chaoses have diameters ranging from over a thousand kilometers down to the limits of resolution, less than 1 km (Greenberg *et al*. 1999). Tilted ice rafts may be embedded in the matrix (Greenberg and Geissler 2002; Nimmo and Giese 2005; Collins *et al*. 2002). The rafts often preserve the original pre-chaos terrain on their surfaces (Greenberg *et al*. 1999). The original positions and orientations of the rafts can be reconstructed by matching preserved features, showing that the rafts have translated and rotated from their original locations (see Figure 1).

Chaoses are bound by either a steep escarpment looming above the matrix or a “beach” sloping down from surrounding terrain to underlie the matrix material. Sloping boundaries can be accompanied by cracks running parallel to the chaos edge, suggesting that the surrounding ice crust broke and sagged to form the inward-facing slope (for example, the “Mitten” chaos; Figure 1). Chaoses are often bounded by ridge systems, though some ridges form peninsulas and bridges across chaotic terrain, probably because ridge formation involves substantial thickening and strengthening of the ice crust (Greenberg *et al*. 1999). After emplacement, chaoses are modified or obliterated by continual tectonic processes such as cracking and ridge formation (Greenberg *et al*. 1999; Greenberg and Geissler 2002).

III. Models of chaos formation: melt-through, diapir heating, or impact?

Several formation mechanisms have been proposed based on different structures of the ice crust, with assumed crust thickness ranging from several kilometers to tens of kilometers. Thus, determining how chaoses are formed is important for constraining the thickness of Europa’s ice crust. Two major hypotheses rely on endogenic thermal processes such as rising diapirs of warm material (ice or water) and tidal heating. Another theory postulates that crust-penetrating impact events produce chaos. A fourth model, in which warm ice is extruded cryovolcanically onto the surface (Nimmo and Giese 2005), has fallen out of favor because cryovolcanic ice should be less buoyant than the cold ice it must rise through (Greenberg *et al*. 1999).

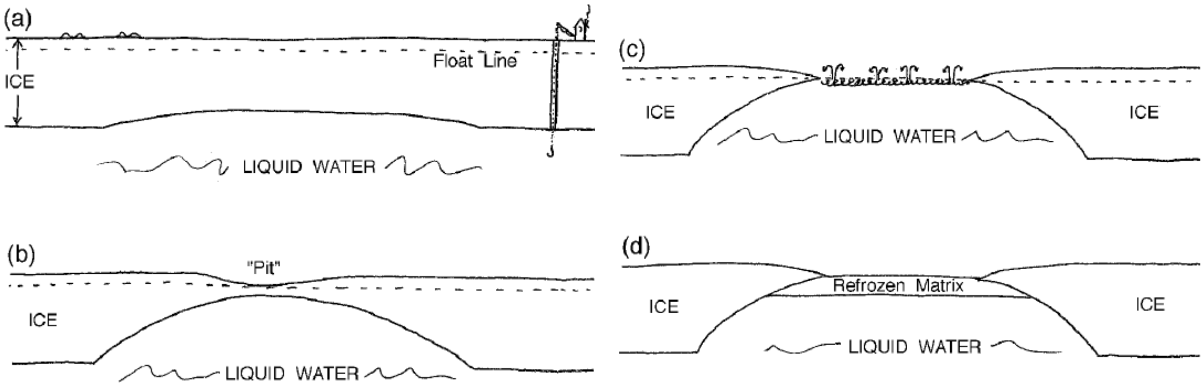

Figure 2. The process of the melt-through model. (a) Local heating begins to melt the crust. Note signs of Europan life evident in this diagram. (b) Thinned crust sags. (c) A hole forms and exposed water boils. (d) The hole begins to refreeze, forming chaos matrix. (Greenberg *et al*. 1999)

The appearance that rafts have *floated* from their original locations led to a model involving exposure of the subsurface ocean. In this “melt-through” hypothesis, the crust must be globally thin, possibly as low as 2 km (Nimmo and Giese 2005). Greenberg *et al*. (1999) propose that local heat sources could melt the crust from below, thinning the ice until it sags in the middle and forming a “pit” that may be the precursor to a littoral chaos boundary. Eventually the ice will melt through and expose the liquid water underneath to space. The water will immediately boil, roiling the hole in the crust. Any portions of the crust left intact will float in the liquid, forming the observed rafts. Pieces of the littoral boundary may also break off as rafts, leaving a cliff-like boundary. Finally, as the heat diminishes, the water will re-freeze into a lumpy matrix, trapping any rafts in place and completing the process of chaos formation.

This model is supported by a qualitative rather than quantitative argument. Greenberg *et al.* (1999) describe in detail a plausible physical process for chaos formation but do not include physical computations. Like many hypotheses in planetary geology, the melt-through model relies on interpretations of observed morphology for support. Greenberg *et al*. (1999) argue that their model “fits the geological evidence well,” producing features consistent with chaos, but they acknowledge that “the process of melting must be quantified” through geophysical modeling for stronger support. The weaknesses of this model lie in the need for a thin (of order 1 km) shell and persistent local heating: it is unclear whether tidal heating is sufficient to maintain a thin crust on Europa, and the amount of sustained local heating necessary to melt through the crust in a typical chaos region is comparable to Europa’s total tidal heating budget (Greenberg *et al*. 1999).

Another model which relies on endogenic thermal processes explains chaos as the result of surface ice blocks sliding on a partial melt substrate. In this case, a layer of partial melt forms just under the cold outer surface ice. This melt could be delivered in the form of a rising liquid dike which spreads out near the surface into a sill, or could form within the ice shell if a rising diapir of warm ice impinges on a layer of salt-contaminated ice with a low melting temperature. A layer of partial melt would decouple fractured surface ice from the underlying crust, allowing it to break into chunks, slide on the partial melt substrate, and assume the jumbled configurations of chaos rafts. Collins *et al.* (2000) proposed this model, with salt contaminants, as a refinement of the hypothesis that chaos forms over a clean, warm ice substrate resulting from rising diapirs: a substrate of clean ice would not produce the observed tilted rafts. This hypothesis does not require the crust to be as thin as the melt-through model.

Evidence for the partial melt hypothesis comes from simple physical models. Collins *et al.* (2000) performed an extensive set of calculations to support the partial melt theory. Comparisons to thermal anomalies at terrestrial mid-ocean ridges were used to constrain the amount of energy available for local heating of the crust. The partial-melt model was evaluated against the earlier warm ice substrate model by comparing the two hypotheses' predictions of the foundering and tilting behavior of rafts. It was found that a partial-melt model reproduced the observed relative distribution of rafts embedded within the matrix and floating atop it, as well as tilted rafts. These calculations encompassed the viscosity of warm ice, relative densities of the partial melt substrate and surface ice blocks, as well as torque exerted on ice chunks of various shapes.

A third intriguing theory is that chaoses could be impact-generated features. Europa's rapidly changing surface has few craters; but chaos and crater formation may be related. The large craters Tyre, Callanish, and Mananàn were formed by bolides of order 1-2 km in diameter and contain chaos in their centers, which could be the result of crustal penetration (Greenberg *et al*. 1999; Cox *et al*. 2005). The impactors responsible for these "leaky craters" were smaller than the median size of bolides in the Jovian system, suggesting that crust-penetrating impact events should be common (Cox *et al*. 2005). This model is consistent with a crust up to 4-7 km thick (Cox *et al*. 2005).

Experiments to characterize the morphology of impact or explosion craters on floating ice produce results consistent with chaos on Europa, indicating that chaoses might be produced by impacts with sufficient kinetic energy to break the ice crust (Billings and Kattenhorn 2003; Cox *et al*. 2005). Billings and Kattenhorn (2003) compared experimental explosion craters in terrestrial sea ice with chaos on Europa. They find morphological similarities between the two, and back up their comparisons by pointing out that chaos size distribution matches Europan cratering populations, preexisting fractures in the ice surface will bound impact-generated chaos in the observed manner, and wave flexing from an impact can account for observed chaos morphology (Billings and Kattenhorn 2003). In another experiment (Cox *et al*. 2005), ice projectiles fired into laboratory-made ice sheets with fluid substrates generated several types of chaos-like morphologies, from "leaky craters" similar to Tyre to areas of widespread ice fragmentation.

IV. Discussion

All the models discussed above are capable of producing chaos, depending on certain assumptions. However, the assumptions may not necessarily be warranted; scientists must avoid oversimplifying a situation or formulating a general rule from a specific case. More data is necessary to constrain the hypotheses: the thickness and composition (specifically, the concentration of impurities) of the ice shell, as well as the state of Europa's mantle, are unknown parameters that can have profound effects on the behavior of these models (Schenk and Pappalardo 2004; Nimmo and Giese 2005).

Topographic profiles of Conamara Chaos led Schenk and Pappalardo (2004) to conclude that the data are most consistent with diapir upwelling in a thick shell. This analysis is predicated on the observation that some rafts are at lower elevations than domes in the nearby matrix. Elevation contrasts across the chaos imply density contrasts: less dense ice will be more buoyant than relatively more dense ice. In a melt-through event, if the original ice crust (and, therefore, rafts) contained a substantial fraction of impurities, then refrozen ice (i.e., matrix) would likely be clean and thus less dense, causing matrix uplift. Though Schenk and Pappalardo (2004) cannot rule out the melt-through hypothesis, they find that the necessary density contrasts are implausibly high compared to contrasts a diapir model requires to produce the observed topography. However, contrasts in relief are also difficult to produce through diapirism, and Schenk and Pappalardo (2004) base their support for the diapir model on an assumption about the composition of the diapir.[1] Data on the composition (and, therefore, density) of the Europan ocean and crust are necessary to support these arguments.

Detailed computational simulations have been carried out to quantitatively assess the feasibility of the melt-through and diapir models. Using numerical models based on thermal conductivity and matrix buoyancy, Nimmo and Gliese (2005) determined that neither melt-through nor diapirism can account for chaos formation. The diapir simulation developed is based on an explicit set of reasonable assumptions, such as taking the diapir to be a geometrically simple shape and assuming the crust surface temperature to be constant since insolation will dominate subsurface heating at that layer. The simulations did not produce enough partial melt to cause chaos formation for any reasonable parameter values (Figure 3). The melt-through hypothesis was addressed by modeling the forces exerted on refrozen matrix in a hole in the crust. Nimmo and Gliese (2005) assume that the matrix is welded to the original shell wall and, implicitly, that it refreezes at lower elevation than the surrounding crust. As in Schenk and Pappalardo's (2004) analysis, implausible density contrasts were required to produce

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[1] The exact statement is, "compositional buoyancy induced by thermal segregation of non-ice phases during plume ascent could produce uplifts of several hundred meters." I took that to mean that liquid water in a water/ice diapir separates out and leaves ice, causing some difference in composition that makes the diapir more buoyant than the surrounding crust.

chaos morphology. However, Nimmo and Gliese (2005) dismiss possible matrix extrusions onto the surface crust from a chaos near Tyre as an observational artifact. This is generalized to an assertion that all chaoses have sheer boundaries. Conversely, some chaoses are observed to have littoral boundaries (see Figure 1), and therefore this simulation of the melt-through hypothesis may not be valid in all cases.

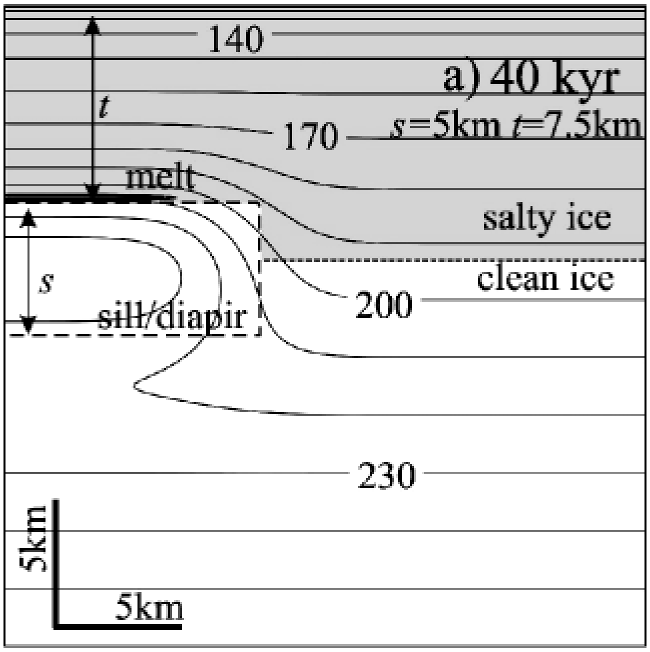

Figure 3. Results of a numerical simulation of temperature as a function of position in the ice crust. The diapir starts at T=250 K. Resulting thermal contours are shown after 40 kyr. Melting is induced in the salty ice just above the diapir, though it is only 30 m thick and >7 km from the surface. (Nimmo and Giese, 2005)

Detailed quantitative analyses are needed to further support or constrain the melt-through and impact hypotheses. The melt-through hypothesis is conceptually appealing, but has some severe shortcomings imposed by the requisite density contrasts and local heating. It is theoretically possible for Europa's mantle to provide the needed heat flux, but the condition of the mantle cannot be easily determined from observations of the moon's surface (Nimmo and Gliese 2005). Perhaps experimentation can determine whether a melt-through event would generate chaos morphology, as impact experiments have done. Laboratory data could be collected on the maximum crust thickness allowing melt-through chaos formation, and these results could be scaled up to a Europan value. The impact hypothesis will also benefit from further analysis. It has been demonstrated that impact cratering may play a significant role in forming chaoses, and analysis of stress induced by waves emanating from an impact site supports this model, but with narrow crust thickness constraints (Cox *et al.* 2005; Billings and Kattenhorn 2004). Additional modeling and experimentation would refine the constraints on these hypotheses.

V. Conclusions

A wide range of models can account for chaos formation on Europa: melt-through, diapirism, and penetrating impacts could each generate the appropriate morphologies under proper conditions, and all are driven by plausible physical mechanisms. However, they are based on substantially different assumptions about the thickness and subsurface structure of Europa's ice crust. As is often the case in planetary geology, more evidence is required before this debate can be resolved; studies of Europa are particularly limited by available data. Only about 10% of Europa's surface has been imaged at high enough resolution to definitively identify chaos terrain (Greenberg *et al*. 1999), let alone study it in detail. Mapping more chaoses will build a better data set of chaos morphologies, and possibly place additional constraints on the models.

Crust thickness may, in fact, be highly variable on Europa. As estimated by Greenberg *et al.* (1999), a melt-through hypothesis could be viable on a surface where ice crust thickness is near zero. Diapir-induced melting could occur in crust thicknesses ranging over tens of kilometers (Collins *et al*. 2002; Schenk and Pappalardo 2004). Chaos-generating impacts appear to occur on Europa regardless, since craters are observed with chaos on their floors (Greenberg *et al*. 1999; Cox *et al*. 2005). Without a global crust thickness constraint, the possibility remains that more than one chaos formation mechanism is at work. Once again, further study of hitherto unobserved chaoses could favor one formation model or identify different chaoses that have obviously been formed by different processes.

Compelling evidence for a liquid water ocean underlying Europa's outer ice crust has driven studies of the moon. In particular, the prospect of life has caused some scientists to develop imaginative ideas for a biosphere near Europa's surface (i.e., Greenberg and Geissler 2002). The thickness of the crust and the frequency of liquid exposure at the surface could play an important role in both geological and biological processes, making the study of chaoses and their formation vital to understanding the subsurface environment. The limited data currently available do not allow stringent constraints to be placed on chaos formation models. This is one of many reasons why exploration of Europa must be made a priority in future missions to the outer planets.

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