

Chaotic Terrain on Europa

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Chaotic terrain covers approximately one-quarter of Europa's surface, and is formed by disruption of the preexisting surface into isolated plates, and formation of lumpy matrix material between the plates. Key observations include the motion of plates of preexisting terrain within chaos areas, the matrix material commonly elevated above the background terrain, associated dark hydrated materials exposed at the surface, concentration into two antipodal areas around the equator, and a large and continuous range of different sizes and morphologies. Of the models that have been proposed to explain chaotic terrain formation, a melt-through model and a brine-mobilization model best fit the observations. The melt-through model faces serious energy problems, while some details of the brine-mobilization model lack sufficient quantification. None of the existing models offer a completely satisfactory explanation for chaos formation yet, but future data from an orbiting spacecraft could decisively test the hypotheses.

1. INTRODUCTION

It was recognized from Voyager images that isolated patches of Europa's surface have been disrupted, exhibiting a hummocky surface, breakup of prominent ridges, and emplacement of dark reddish-brown material (*Lucchitta and Soderblom*, 1982). These collections of uneven splotches on Europa's smooth face were dubbed "mottled terrain" in Voyager-based analyses; later small, isolated spots were dubbed "lenticulae" after the Latin word for freckles. Early ideas for the formation of mottled terrain involved some kind of tectonic disruption of preexisting terrain, accompanied by emplacement of dark material from below (*Lucchitta and Soderblom*, 1982). An alternative idea was that mottled terrain is older and has been subjected to more exogenic (impact and charged particle) modification (*Malin and Pieri*, 1986). High-resolution Galileo images of Europa have revealed mottled terrain to be a collection of highly disrupted areas on Europa's surface, now dubbed "chaotic terrain." With more detailed data, models for chaotic terrain formation can be more tightly constrained, but none of them yet provide an entirely satisfactory explanation. Our intent is that the synthesis of observations and models outlined in this chapter will inspire further efforts to understand this widespread and enigmatic type of terrain, which appears to be unique to Europa.

Conamara Chaos (Fig. 1) has become one of the iconic images of Europa. Because it is the most well-defined and well-imaged chaos area on Europa, it has also become the most well-studied (e.g., *Carr et al.*, 1998; *Spaun et al.*, 1998;

Greenberg et al., 1999; *Head and Pappalardo*, 1999; *Schenk and Pappalardo*, 2004). Figure 2 is a higher-resolution closeup of the center of Conamara, and Fig. 3 is from an even higher-resolution image sequence near the center of Fig. 2. Figures 1 and 2 show many of the typical characteristics of chaotic terrain: an area where the preexisting surface has been disrupted, commonly broken into separate plates, with a lumpy matrix filling in between the plates (*Carr et al.*, 1998). Shadows in these low-Sun images give the impression that the matrix is lower than the plates and the surrounding terrain, because a scarp commonly separates the original surface from the matrix below. Some of the plates appear to have moved from their original positions, and some of them are tilted. Are these observations truly typical of chaotic terrain? In this chapter we will show morphological, topographic, and size characteristics of a variety of chaotic terrain areas to gain a wider perspective.

One point of contention has been the definition of chaotic terrain, and which features should be lumped together, and which ones should be split apart. There is agreement that all features showing the type of lumpy, disrupted matrix such as that seen between the plates in Conamara should be considered chaotic terrain. However, there is disagreement (e.g., *Pappalardo et al.*, 1999; *Greenberg et al.*, 1999) about whether other features, termed "pits, spots, and domes" should be considered in the same class as chaotic terrain. Figure 4 shows a provocative example of such features mixed with chaotic terrain. In this image, there are several small features that appear to have disrupted chaotic terrain in their centers, usually with associated dark mate-

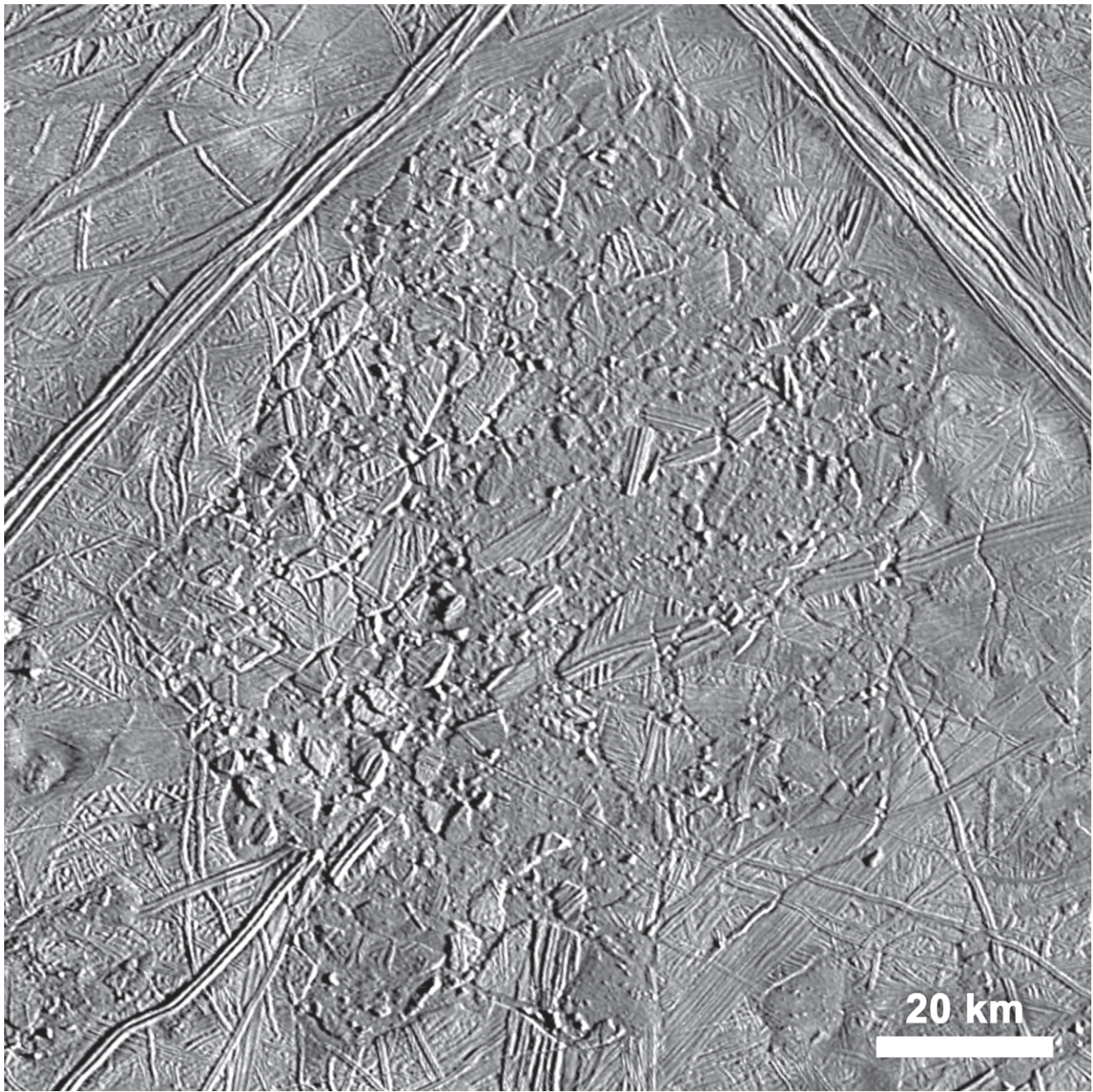


Fig. 1. As one of the most well-studied regions on Europa, Conamara Chaos is the archetype for chaotic terrain. Broken plates of pre-existing terrain are surrounded by a disorganized lumpy matrix. Galileo E6ESDRKLIN01 observation, with illumination from the right. North is to the top.

rial around the edge. Intermixed with these chaotic terrain features are both negative-relief pits and positive-relief domes where the original surface has not been disrupted. There are also patches covered in dark material (spots). There is even one clear example (Fig. 4, arrow) of a pit, filled with dark material, with a dome of disrupted material rising from the center. Similar relationships can be observed in the area surrounding Conamara Chaos (*Pappalardo et al.*, 1998a). The principle of parsimony would guide us to seek a simple explanation for all of these features together, rather than separate explanations for each type of feature.

In this chapter we use “chaotic terrain” as an umbrella term to include features referred to in other works as chaos, lenticulae, micro-chaos, or “pits, spots, and domes.” There are combined and transitional examples among all of these features, and we seek a common explanation for all of them, so we do not wish to give them separate names and draw what may be arbitrary boundaries within this class of features. We begin by considering the morphology, topography, spectral properties, size distribution, and geographic distribution of chaotic terrain, and then we compare all the observational constraints to various theoretical models that

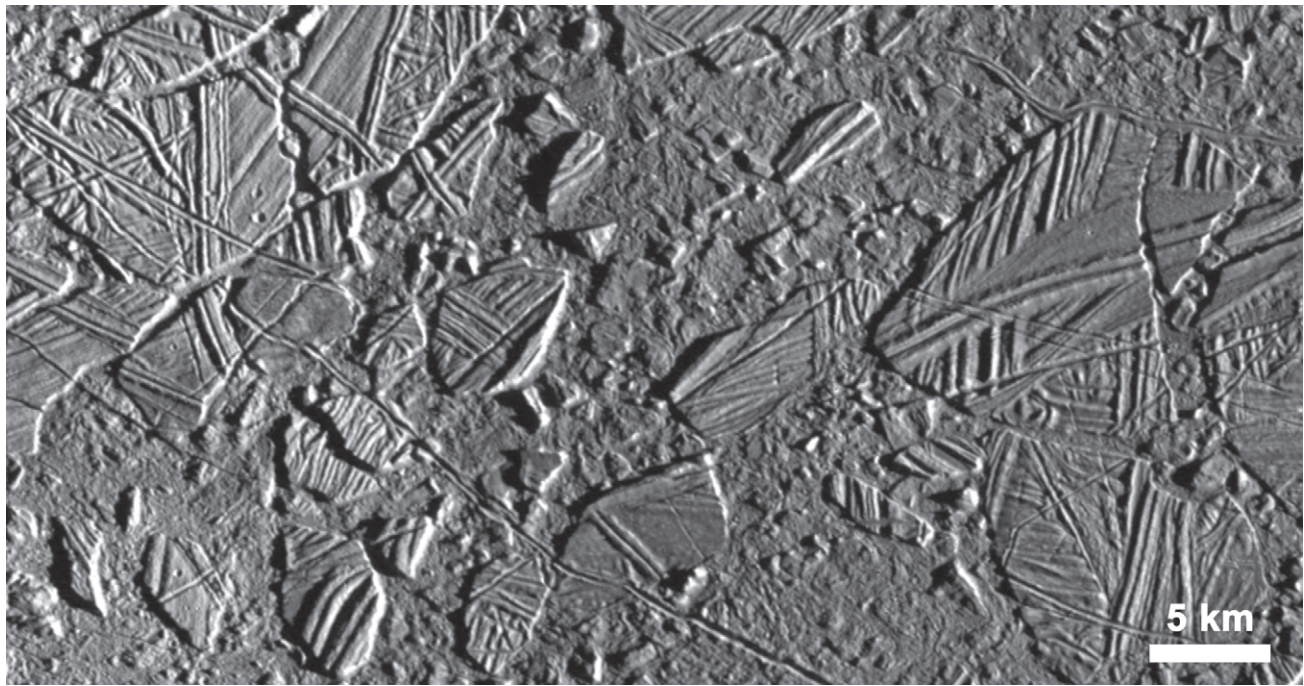


Fig. 2. Closeup of the center of Conamara Chaos, showing tilted plates and jumbled blocks within the matrix. Galileo E6ESBRTPLN01 observation, with illumination from the right.

have been proposed to explain their formation. Because chaotic terrain formation is a widespread process on Europa, finding an appropriate geophysical mechanism is important for understanding the implications of chaos for icy shell thickness, sources of heat in Europa, and material exchange between the icy shell and the underlying ocean.

2. MORPHOLOGY

Several studies have taken the approach of mapping chaotic terrain on a feature-by-feature classification basis (see chapter by Doggett et al.). *Greeley et al.* (2000) described a set of basic mapping conventions for Europa, and subdivided chaotic terrain into “platy chaos material” that has preserved plates of preexisting terrain within a hummocky matrix and “knobby chaos material” that appears to be entirely composed of rugged matrix material. *Figueredo and Greeley* (2004) added “elevated chaos” that appears to be elevated above the surrounding plains, and “subdued chaos” where the plates are present but less distinct from the matrix. *Prockter et al.* (1999) produced a geological map of an area imaged only at high-Sun angles, and derived a different classification scheme more heavily based on albedo patterns than the near-terminator mapping by *Figueredo and Greeley* (2004).

While the classification approach is expedient for geological mapping, it can sometimes draw arbitrary distinctions between types of chaotic terrain when there is a continuum of morphology observed. Here we take an approach of describing each type of morphological element com-

monly observed in chaotic terrain, and then discuss how these elements occur together to form different overall morphologies of chaotic terrain. Because the goal of this chapter is to discuss the different geophysical models for forming chaotic terrain, concentrating on the morphological elements that such models must produce is the most illuminating path.

2.1. Matrix

The irregular lumpy material that comprises the matrix between plates is part of what gives chaotic terrain its name. Figure 3 is a high-resolution image from the center of Conamara Chaos, showing a small plate surrounded by matrix material. There is no apparent pattern in this area; subkilometer-sized ice blocks poke up in a jumble. Yet the pattern in the background between the larger blocks is not entirely random, as many areas show similarly sized small lumps, spaced out across the surface, giving a sponge-like texture. *Head et al.* (1999) also pointed out examples in this area of groups of discontinuous ridges, and “subdued lineated polygons” that appear to be transitional between the plates of preexisting terrain and the lumpy matrix. An example is marked with an arrow in Fig. 3, where a small square of slightly elevated matrix is crossed by several parallel lineaments.

A more dramatic and unusual example of the preservation of order within chaotic matrix is in Thrace Macula (Fig. 5), where many of the ridges in the exterior terrain can be traced through the otherwise irregular, lumpy chaotic

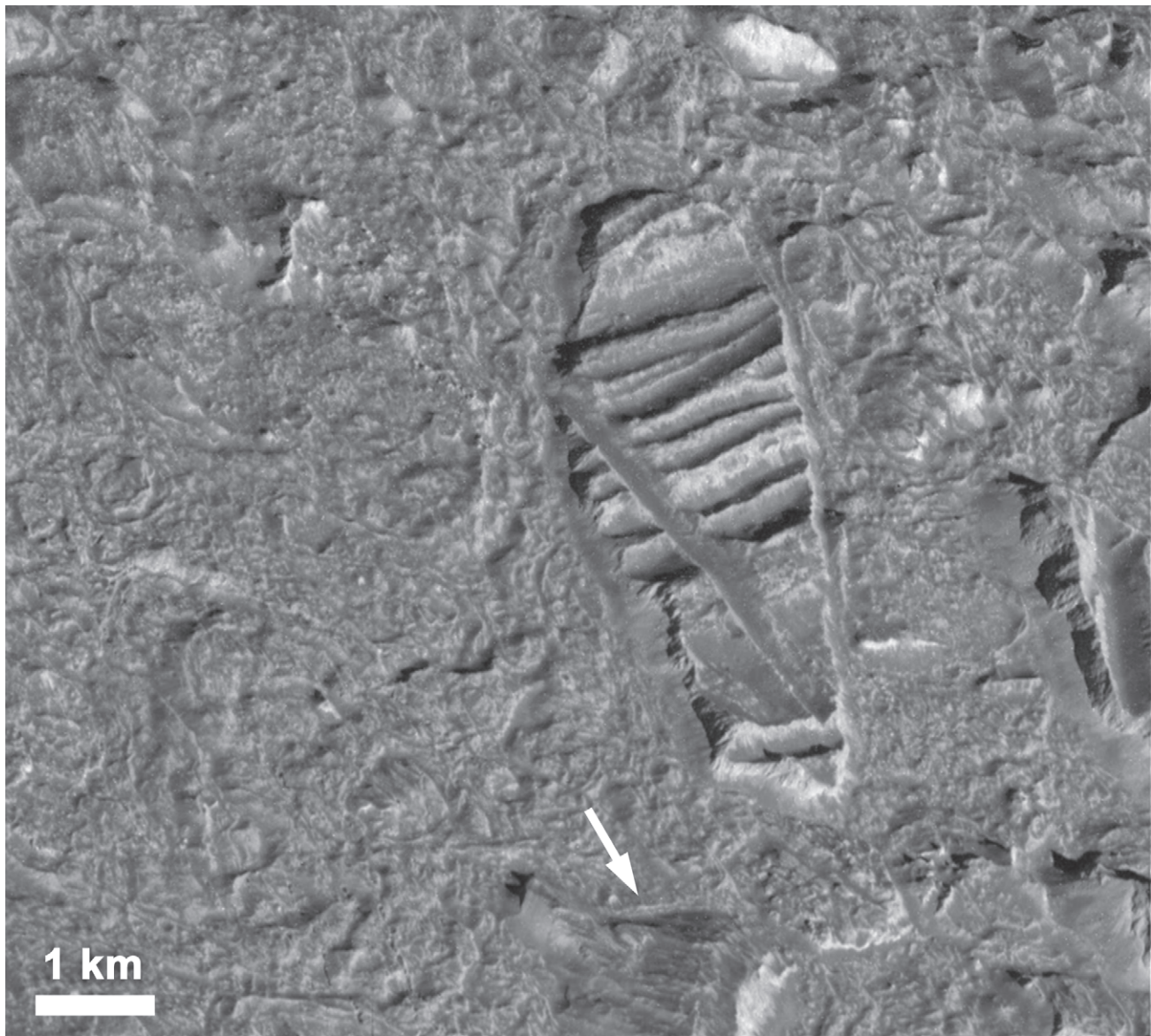


Fig. 3. A single plate of preexisting terrain surrounded by matrix material in the center of Conamara Chaos. Note the cliffs and talus slopes along the bottom and left edges of the plate, and the distributed low hills and discontinuous ridges in the matrix. Arrow points out a subdued lineated polygon (see text). Galileo 12ESCHAOS_01 observation, with illumination from the lower right. North is to the top right.

matrix. It appears that the material that makes up the chaotic terrain matrix in Thrace has been disrupted or degraded *in situ* rather than being entirely new material emplaced cryovolcanically (cf. *Fagents*, 2003). *Head et al.* (1999) came to a similar conclusion based on the high-resolution images of Conamara, arguing that the matrix is largely preexisting terrain that has been disrupted in place. More high-resolution images of chaotic terrain are necessary to resolve if this phenomenon is widespread.

2.2. Plates

Plates of preexisting terrain within chaos areas span about an order of magnitude in size. The largest plates in Fig. 1 are about 20 km across, while the smallest recogniz-

able plates in Fig. 2 are approximately 1 km across. Below this size, only locally high-standing peaks are seen within the matrix, which may be remnants of smaller plates that have either tilted or undergone mass wasting to obscure their original surface texture (*Collins et al.*, 2000).

The shadows in Figs. 1 and 2 show that the plates in Conamara Chaos are locally higher than the matrix material. *Williams and Greeley* (1998) used these shadows to estimate that the blocks lie 40–150 m above the matrix. Figure 3 shows a typical margin of one of these high-standing blocks. Along the bottom and left sides of the block, it is apparent that the block terminates in a steep cliff, and that a talus slope of darker loose material has accumulated at the base of the slope (see chapter by *Moore et al.*), possibly aided by sublimation degradation (*Moore et al.*, 1999).

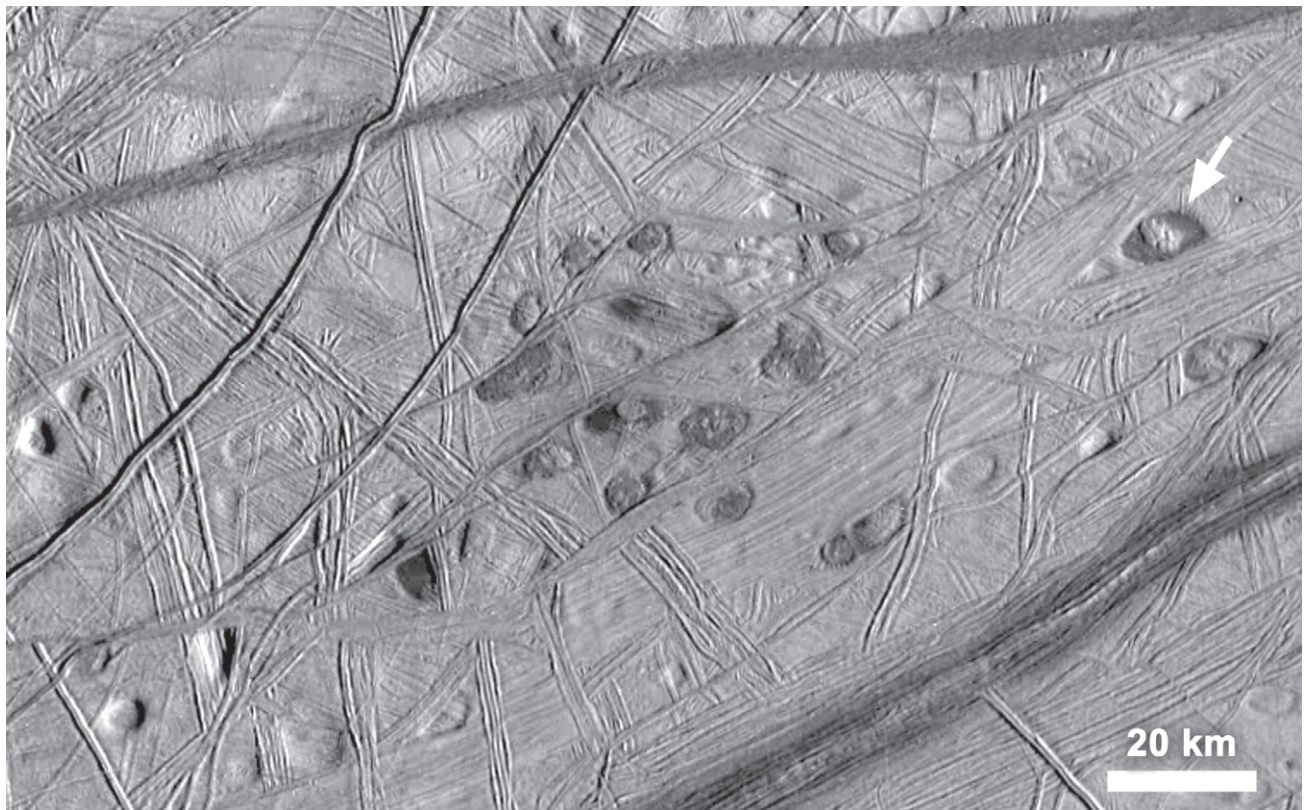


Fig. 4. A collection of small chaotic terrain features intermixed with undisrupted pits and domes, many with associated dark material. At least one feature (top right, arrow) prominently displays pit, dark spot, dome, and chaotic terrain characteristics, supporting the consideration of all such features as a group. Galileo 15ESREGMAP01 observation, with illumination from the right.

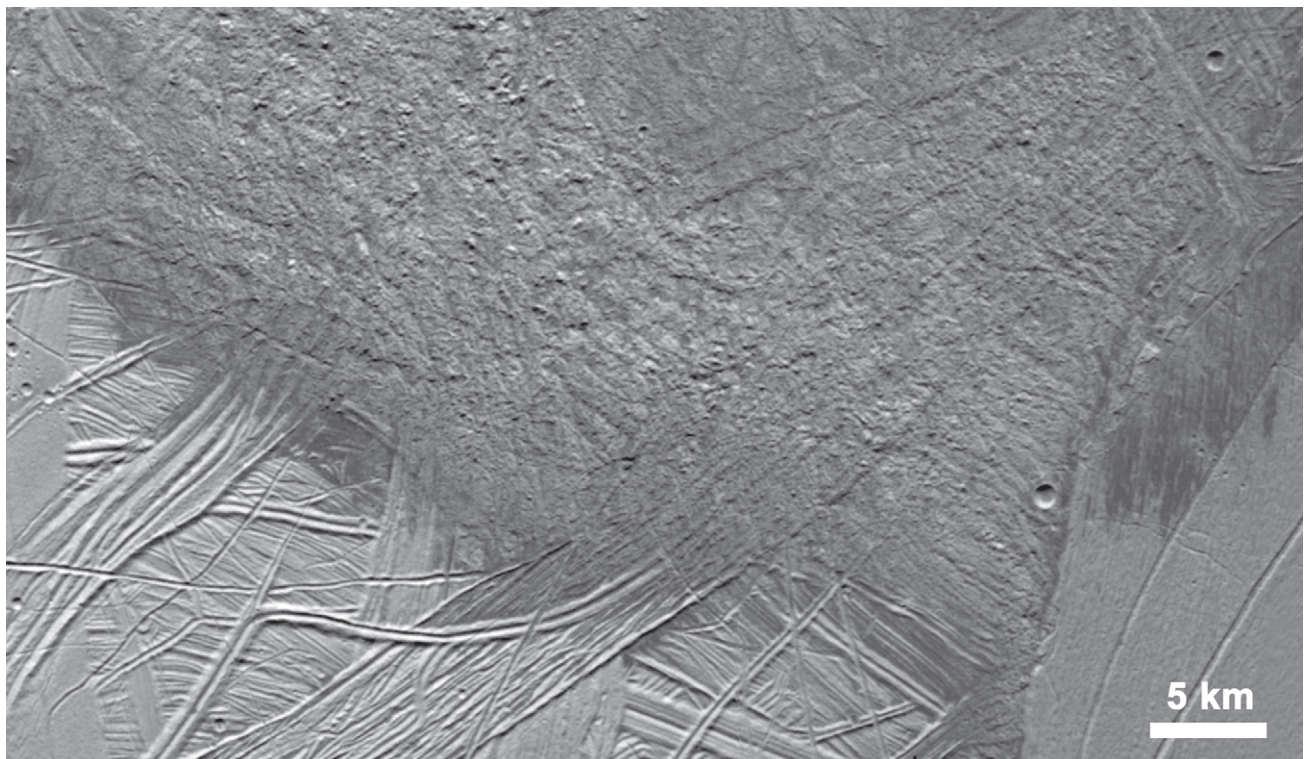


Fig. 5. The matrix material in Thrace Macula shows clear remnants of the preexisting ridged terrain, implying that some process has degraded the surface material *in situ*. Galileo 17ESTHRACE01 observation, with illumination from the top.

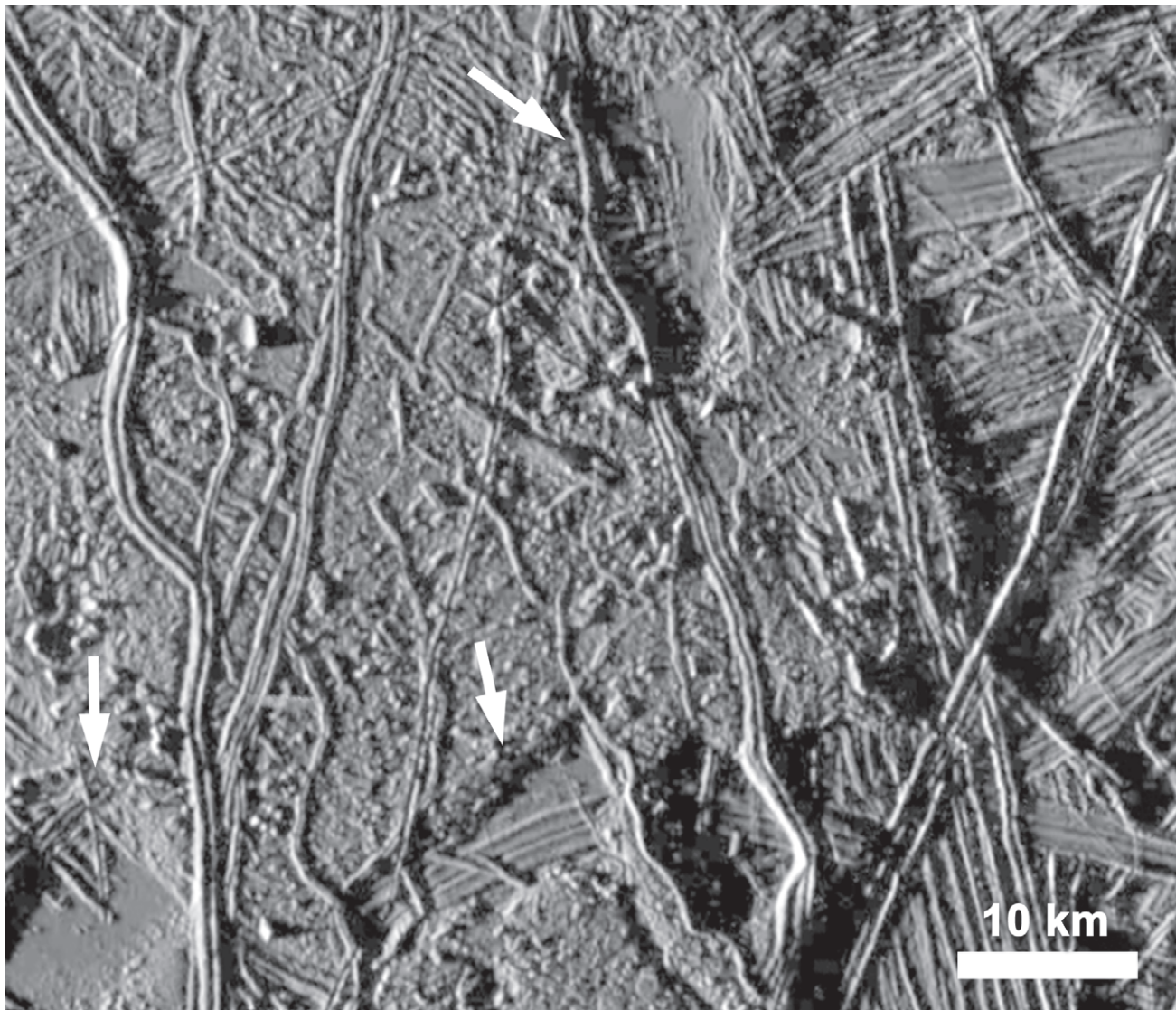


Fig. 6. An area of chaotic terrain in which the isolated “plates” or preexisting material are lower than the matrix (arrows). Many of them appear to be embayed by smooth material. Several younger ridges cut across this area of chaotic terrain. Galileo 25ESNPOLE01 observation, with illumination from the left; the north pole of Europa is just outside the scene to the lower left.

There are also several examples within Conamara of tilted plates that have a cliff on one edge, and slope gently into the matrix along another edge (Fig. 2).

Figure 6 shows a possible counterexample to the locally high-standing plates common to many areas. In this area of chaotic terrain near the north pole of Europa, the matrix material is locally higher standing than the isolated patches of preexisting material within it. In this case, it appears that the matrix has a rounded edge that slopes down onto the surface of the plates. The plates in this chaos area are unusual in that the preexisting ridges appear to be embayed by smooth material (possibly similar to embayed ridges at some chaos margins; see next section). Whether these isolated patches of preexisting terrain within the matrix of this chaos area meet the normal definition of “plates” is debatable, but it serves as an interesting example to contrast with Conamara.

One of the most intriguing observations about plates is that many of them have moved from their original positions.

In numerous areas of chaotic terrain, one can observe pieces of preexisting ridges on plates that have moved from their original locations, which are interpolated from ridges in the surrounding undisrupted terrain. In most areas, only a handful of plates can be reconstructed in such a fashion because of resolution or area limitations, but in Conamara Chaos, *Spaun et al.* (1998) used several throughgoing ridges to reconstruct the inferred original positions of dozens of plates (cf. Fig. 10 of *Greenberg et al.*, 1999). The reconstruction showed that at least 78% of the blocks shifted from their initial position, by an average of 2 km of lateral translation. The largest translation was 8 km, and 22% of the plates moved over 5 km. Plates appeared to move inward from the boundaries, and there was no apparent pattern of movement toward or away from matrix-rich areas. There appeared to be an overall clockwise movement of plates around the chaos, but we should point out that the study lacked a formal error analysis in the reconstructions, instead giving an estimate of 0.5–1 km confidence in the initial positions. The

method of reconstruction by throughgoing ridges is more accurate perpendicular to the ridge than parallel to the ridge, so the exact pattern of movement may not be entirely reliable.

In addition to lateral translation, *Spaun et al.* (1998) measured rotation of the plates around their vertical axes. The inferred rotation was evenly distributed between clockwise and counterclockwise. The magnitude of rotation was generally small, with 75% of the plates having rotated less than 15° relative to their initial orientations.

2.3. Margins

Like many areas of chaotic terrain, most of the boundary of Conamara is defined by an inward-facing scarp (Fig. 1). Closer inspection of this image shows that part of the boundary (especially in the southeastern portion) is formed by areas where the chaotic matrix is level with, or even appears to dome up above, the surrounding terrain. Such a relationship is shown more clearly in an area of chaotic terrain near Agenor Linea (Fig. 7). Near the top of the image, there is a clear scarp leading down into the chaotic matrix, while near the bottom, the matrix appears to grade directly into the surrounding terrain. It is interesting to note on this image that right next to the inward-facing scarp, some of the plates are clearly higher than the undisrupted terrain nearby, as they cast shadows all the way across the matrix and scarp and onto the surrounding terrain.

In contrast to the inward-facing scarps, there are also many chaotic terrain boundaries formed by matrix domed up over the surrounding terrain. In some cases it appears as if the matrix material has viscously flowed onto its surroundings. For example, the boundaries of Murias Chaos (Fig. 8a) are formed of matrix doming above the surroundings, and circumferential fractures just outside the matrix edge may be due to flexure as a load is emplaced on the

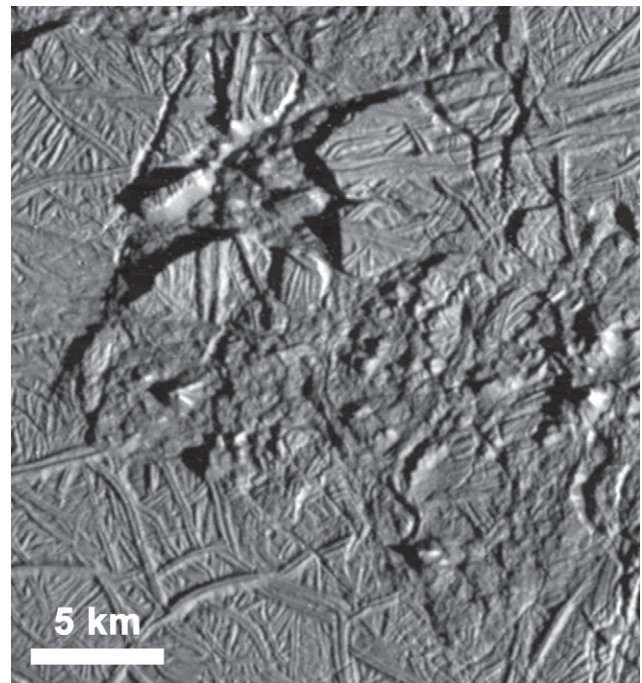


Fig. 7. Chaos region north of Agenor Linea shows both an inward-facing scarp boundary (top) and a level boundary (bottom) between matrix and surrounding terrain. Note that some plates within the chaos cast shadows beyond the edge of the chaos region, showing that the plates have been uplifted relative to the surrounding terrain. Galileo 17ESAGENOR03 observation, with illumination from the right.

crust (*Figueredo et al.*, 2002). Troughs around smaller areas of chaotic terrain with such margins (sometimes referred to as disrupted domes) have been estimated to be hundreds of meters deep, and may also be due to flexure (*Williams and Greeley*, 1998). In another example, a domed region of chaotic matrix near Europa's south pole appears to have

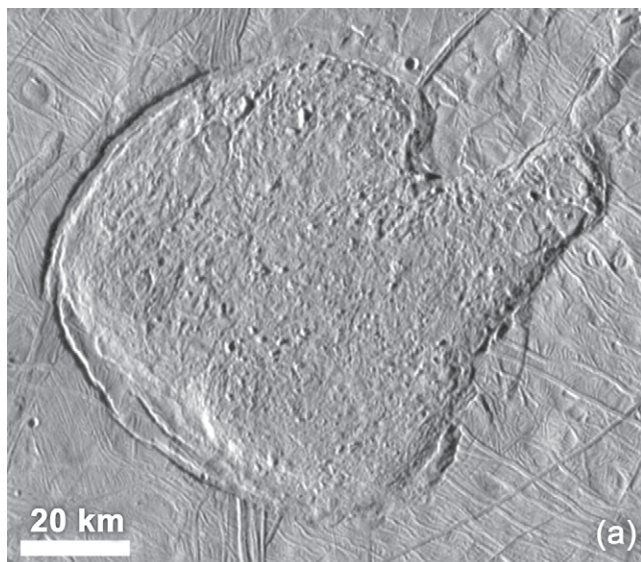


Fig. 8. Chaotic terrain on Europa in which the matrix material slopes upward from the surrounding terrain. (a) Murias Chaos stands 400–600 m above its base, and the fractured trough along the west side may be due to flexure from loading (*Figueredo et al.*, 2002). Galileo 15ESREGMAP02 observation, with illumination from the left. (b) Chaotic matrix appears to flow into the ridge running left-to-right across the image. Galileo 17ESSOUTH01 observation, with illumination from the top left.

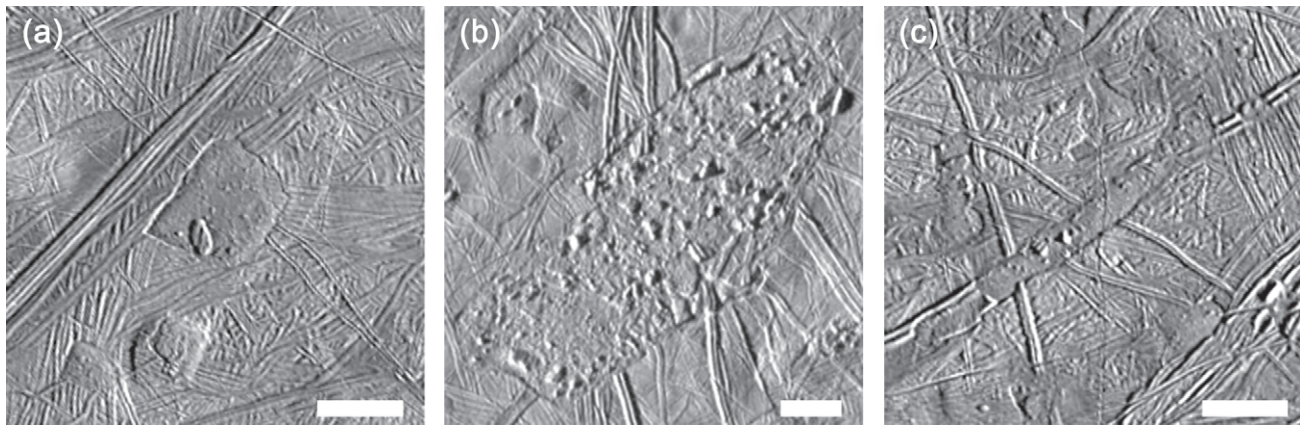


Fig. 9. There is no single mode of interaction between chaotic terrain and prominent preexisting ridges. (a) Chaos appearing to avoid a ridge. Galileo E6ESDRKLIN01 observation, with illumination from the right. (b) Chaos ignoring the presence of ridges. Galileo 15ESREGMAP02 observation, with illumination from the left. (c) Chaos forming largely within the confines of a ridge. Galileo E6ESDRKLIN01 observation, with illumination from the right. All scale bars are 10 km.

pushed up against the side of a preexisting ridge, suggesting horizontal flow (Fig. 8b).

Greenberg *et al.* (1999) observed that the margins of some chaotic terrain areas tend to avoid large preexisting ridges. The margins on Conamara avoid the two large crossing ridges to the north (Fig. 1), and smaller chaos areas (Fig. 9a) sometimes behave similarly. However, there are also many counterexamples in which chaos margins ignore ridges (Fig. 9b), or even seem to be confined within ridges (Fig. 9c). A more rigorous analysis of the interaction between chaotic terrain and large ridges is needed to see whether ridges affect chaos terrain margins.

Boundaries of chaotic terrain areas are commonly accompanied by deposits of smooth dark material. Figure 5 shows an excellent example of this at Thrace Macula, with smooth dark material diffusing out from the morphological chaos boundary into topographic lows. Whether this is due to liquid coming from the subsurface (Fagents, 2003) or from sublimation of bright surface frosts (Fagents *et al.*, 2000) is unclear. Similar dark deposits infilling between ridges are seen around Castalia Macula, a large dark area next to chaotic terrain. Stereo data of that area shows that while the dark material is confined to topographic lows, it is far from being flat (Prockter and Schenk, 2005), so a simple explanation of pooling liquids does not fit the observations, unless substantial surface motion has taken place afterward.

2.4. Combinations of Morphological Elements

Areas of chaotic terrain can range from being comprised mostly of plates with small intervening lanes of matrix, to being mostly matrix with few or no plates. Conamara Chaos lies in the middle, with 59% matrix and 41% plates by area (Spaun *et al.*, 1998). Spaun (2002) mapped the interiors of chaotic terrain in eight additional regions and found that a roughly half-and-half mix of plates and matrix was typical for the majority of chaos areas.

One correlation that is observed with chaos margins is that areas with a prominent inward-facing scarp tend to have

abundant plates (e.g., Figs. 1 and 7), while areas with matrix doming above the surrounding terrain tend to be mostly plate-free (e.g., Fig. 8) (Figueredo and Greeley, 2004). As stated at the beginning of this section, most mapping to date has been on a chaos-by-chaos basis instead of mapping the morphological features inside areas of chaotic terrain. Spaun (2002) mapped the interior morphology within several regions of chaotic terrain but there was little quantification of the proportions of plates and matrix for areas other than Conamara. More work needs to be done to quantify the relationships between matrix types, abundance and motion of blocks, and the nature of chaos margins.

3. TOPOGRAPHY

In some areas of chaotic terrain, the matrix appears to be domed above the adjacent terrain. However, there is usually a trough surrounding this type of chaos, so it is not immediately apparent how high the chaos matrix stands with respect to distant background terrain. Photoclinometry measurements of Murias Chaos (Fig. 8a) show that even though the surrounding trough is depressed by 300–400 m from the background terrain, the chaos matrix itself rises 400–600 m above its base, placing it about 100 m above the background terrain (Figueredo *et al.*, 2002). Stereo topography of a large dome-shaped feature next to Castalia Macula, with chaotic terrain exposed on its crest, shows that the top of the feature rises more than 1 km from its base (Prockter and Schenk, 2005). An unusual chaos area (Fig. 10) is cut by a block of crust that seems to have been “punched up,” raising part of the chaos onto a flat mesa 900 m high (Figueredo and Greeley, 2000).

If chaos areas that appear to have domical topography are in fact high standing, what about the topography of chaos areas with inward-facing scarps, where the matrix appears to be low? Stereo topography of two small (~10 km diameter) chaos areas near Tyre show that even though they have an inward-facing scarp, the matrix in the center of the chaos areas stands 100–200 m above the background terrain (Nimmo and Giese, 2005). Stereo coverage of Cona-

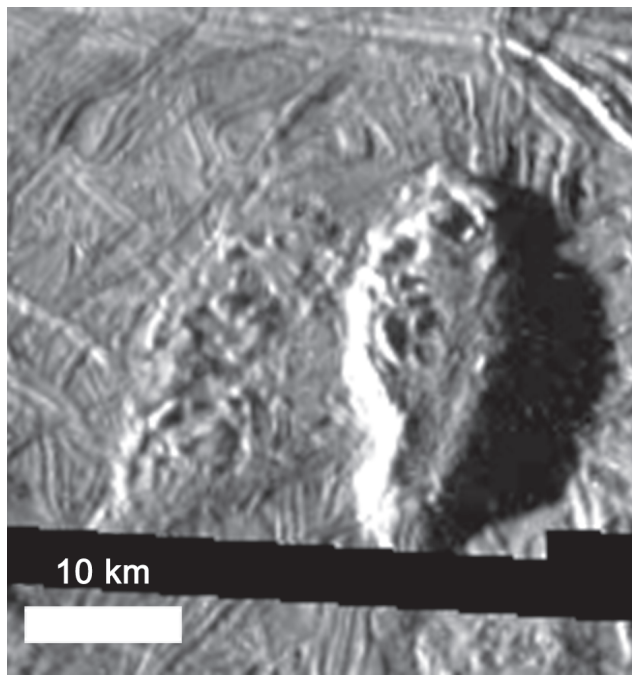


Fig. 10. A plateau nearly 1 km high cuts across this chaotic terrain area. Galileo 15ESREGMAP02 observation, with illumination from the left.

mara Chaos shows that the matrix in the interior is also uplifted in several dome-shaped regions, standing up to 250 m above the surrounding terrain (*Schenk and Pappalardo, 2004*). The uplifts in Conamara appear to be associated with the terrain that is composed of matrix without plates. In fact, even though most plates are clearly locally higher than the matrix, many of the surfaces of the plates are actually topographically lower than the more distant matrix-rich areas (see Fig. 15 for an illustration).

Even with the limited reliable topographic coverage from the Galileo mission, the message seems clear that the formation of chaotic terrain involves doming of the surface at some stage in the process. It is interesting to note that Murias Chaos, an almost plate-free chaos, appears to be one large dome, while Conamara Chaos appears to be composed of multiple domes, with the abundant plates existing in the interstices between the domes.

4. SPECTRAL PROPERTIES

Areas of chaotic terrain are almost always associated with dark reddish-brown material on the surface. The exact composition of this material is unknown (see chapter by Carlson et al.), but the color is probably due to radiolysis of surface materials producing reddish sulfur compounds (*Carlson et al., 2002*). Infrared spectra of this material shows distorted water absorption bands, interpreted to be a hydrated material such as heavily hydrated sulfate salts (*McCord et al., 2002; Dalton et al., 2005*), or sulfuric acid hydrate (*Carlson et al., 2005*). Knowledge of the composition of the contaminant material mixed into the water ice in chaotic terrain is important, because hydrated salts or sulfuric acid hydrate will melt at lower temperatures than

pure water ice, and could possibly play an important role in the formation of chaotic terrain (see section 8.3).

As noted in section 2 above, some areas of chaotic terrain are surrounded by a deposit of dark material that seems to fill topographic lows. On orbit E12, Galileo collected a moderately high-resolution color observation of Conamara Chaos. *Head and Pappalardo (1999)* showed from this observation that both the matrix and most of the smaller blocks are covered in the reddish-brown material, while some large blocks with prominent ridge segments tend to be closer to the color of the undisrupted background terrain. Some of the chaos boundaries are also sharp color transitions, while others show small amounts of the dark material fingering in between ridges (like the boundary of Thrace Macula; see Fig. 5). The large blocks within the chaos also show an enhanced amount of dark material lying in between the ridges, as compared to the background terrain outside the chaos.

5. SIZE DISTRIBUTION

Features that match the description of chaotic terrain range over at least a 3-order-of-magnitude size range, from kilometer-scale features all the way up to regions more than 1300 km across. For some regions of chaotic terrain, it is relatively simple to define the boundary and map the surface area. However, there are many cases where fractures extend out from large patches of chaotic terrain to link up with nearby smaller patches. Figure 11 shows one such example, where larger chaos areas at the top and right edges of the frame are connected via narrow fractures to a small chaos area near the center. Should all this be counted as one chaos area? Are the regions between the fractures counted as undisrupted preexisting terrain or as chaos plates? Even Conamara Chaos exhibits similar boundary definition problems on the eastern side, with fractures leading to small neighboring chaos areas. Faced with a similar situation with fractures connecting two neighboring domes, *Riley et al. (2000)* decided to count them as separate chaos areas. In contrast, *Spaun et al. (1999)* and *Figueredo and Greeley (2004)* argued that these observations show the process of chaotic terrain growing by merging smaller chaos areas together (see chapter by Doggett et al.). Seen in this light, the topographic observations within Conamara where the matrix forms several domes with lower broken plates in between (*Schenk and Pappalardo, 2004*) appears to be a more advanced stage of the merging process that may be observed in Fig. 11.

Much ink has been expended discussing the exact nature of the size distribution of chaotic terrain, an issue of contention because the apparent existence of a preferred size and spacing for chaotic terrain features was used to advocate a diapiric model of formation (e.g., *Pappalardo et al., 1998a, 1999; Spaun, 2002*). Advocates for the alternative melt-through model (e.g., *Greenberg et al., 1999; Riley et al., 2000*) instead argued that there is no preferred size for chaotic terrain, and that the number of features rises continuously with decreasing size. At the worst, the reader was confronted with data from two research groups plot-

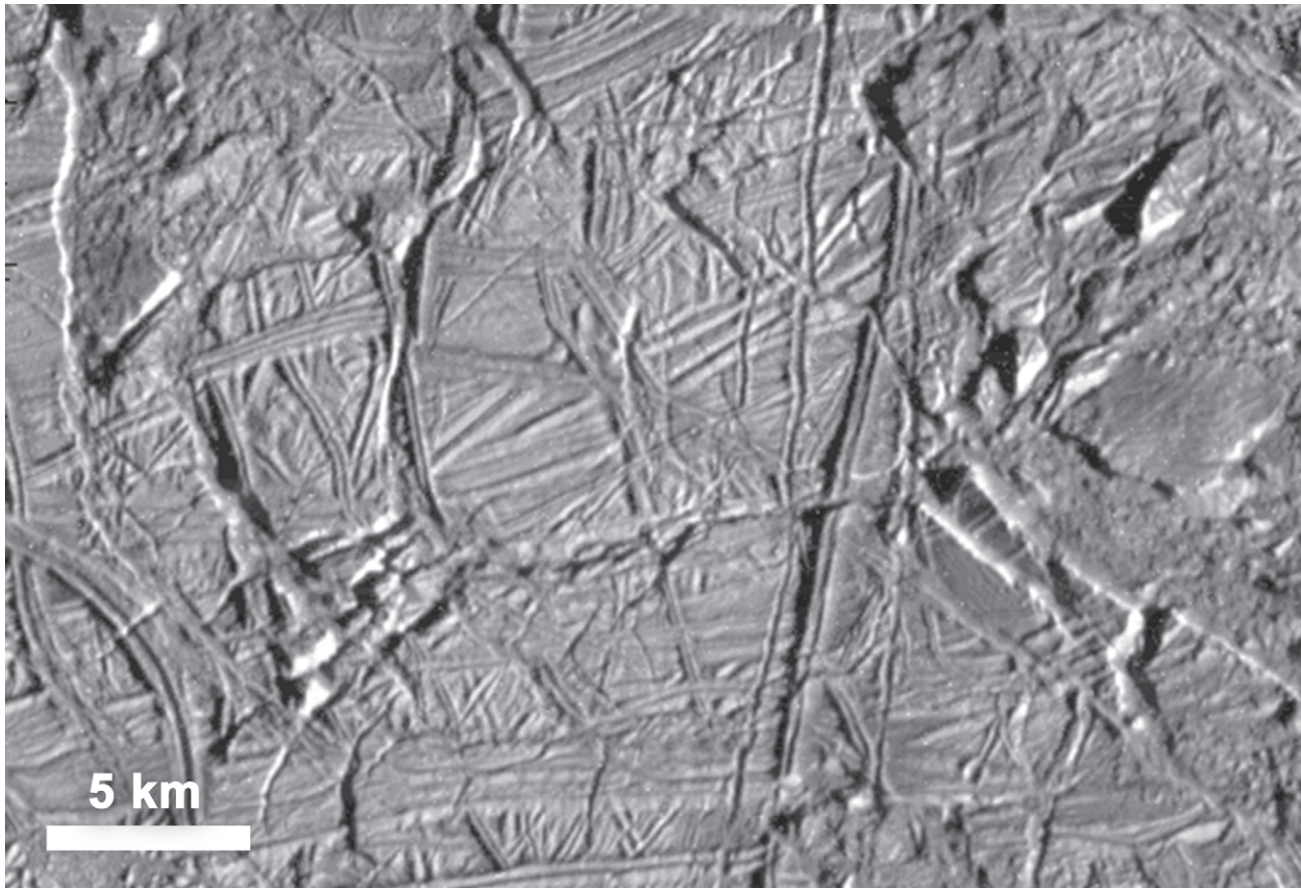


Fig. 11. Two large chaos regions at the top and right are connected to a smaller chaos region in the lower left by narrow troughs or fractures. Should this be considered as one chaos area? In the view of *Spaun et al.* (1999) and *Figueredo and Greeley* (2004), this may be an example of chaotic terrain growth through absorbing neighboring chaos regions. Galileo 17ESDISSTR01 observation, with illumination from the right.

ted in such a way as to make it impossible to visually compare them, e.g., a histogram of feature diameters on a linear scale (*Spaun*, 2002) vs. a cumulative plot of feature areas on a logarithmic scale (*Greenberg et al.*, 1999). In an attempt to settle this confusion, we have rebinned all the chaotic terrain size data published in the literature and plotted it on one graph (Fig. 12). The two main opposing studies on the subject, *Riley et al.* (2000) and *Spaun* (2002), both mapped large regions of Europa at regional resolution (~200 m/pixel). Replotting their data in a common format on Fig. 12a shows that their regional results are almost identical. It is ironic that the artifacts of data display led *Riley et al.* to argue for the existence of more small chaos areas than *Spaun*, as the most significant divergence between the two data sets is the larger number of small chaos areas measured by *Spaun*.

Hoppa et al. (2001) used a region of Europa imaged at two different resolutions to show that more small chaos areas will be recognized at higher resolution, the implication being that some, if not all, of the downturn in chaos abundance at small sizes in the regional data is a resolution effect. Both *Riley et al.* (2000) and *Spaun* (2002) mapped a few small areas imaged at higher resolution, and these data

are also plotted on Fig. 12a. The flattening of the distribution at small sizes in the high-resolution data for both mapping groups demonstrates that *Hoppa et al.*'s basic point is correct. However, this high-resolution mapping took place in areas of mottled terrain, so the absolute abundance of small chaos areas (the vertical position on the graph) at small sizes may not be applicable globally. *Riley et al.* claim that the chaos abundance from the high-resolution data can be used on the rest of the global database to "correct for recognizability" and that doing so erases any peak in the size-frequency distribution of chaotic terrain. However, the distribution must roll over somewhere; chaotic terrain cannot become infinitesimally small. Indeed, the highest-resolution images of Europa at 6 m/pixel within mottled terrain did not reveal a new class of even smaller chaotic terrain areas. It appears that at the tens-of-meters scale, the primary processes modifying Europa's surface are surface regolith processes, and not endogenic processes like chaos formation. Perhaps the noted dropoff in chaos abundance below an area of 3 km² (~2 km diameter) is real, and not a resolution artifact. Only the collection of a large sample of high-resolution imaging data of Europa's surface can confidently resolve this issue.

Two groups have also reported the size distribution of pits and domes separately from chaotic terrain in general. Figure 12b shows the size distribution of pits and domes from Greenberg *et al.* (2003) compared to domes measured by Rathbun *et al.* (1998). The Greenberg *et al.* measurements are from several observations, while the Rathbun *et al.* measurements are only from the regional resolution Galileo E6ESDRKLN01 mosaic, in the area of Conamara Chaos. The dropoff at small sizes in the Rathbun data therefore may be a resolution effect, much like the resolution effect for chaos. In fact, the Rathbun *et al.* line lies almost directly on top of the peak of the Riley *et al.* (2000) and Spaun (2002) regional size distribution lines for chaotic terrain shown in Fig. 12a. Compared to the size distribution of small chaos regions mapped at high resolution by Riley *et al.* and Spaun, the Greenberg *et al.* data for pits and domes appears to be more strongly peaked near an area of 10 km² (3–4 km diameter), but this may be a resolution effect, because Greenberg *et al.* did not include the same high-resolution images included by Riley *et al.* It is interesting to note that the size distribution of pits and domes is very similar, further reinforcing the impression from Fig. 4 that they are somehow related.

6. GEOGRAPHIC AND TEMPORAL DISTRIBUTION

After mapping the 10% of the surface seen in regional-scale (~ 200 m pixel⁻¹) Galileo imaging of Europa, Riley *et al.* (2000) concluded that 28% of the surface is covered by

chaotic terrain. Sampling from high-resolution data covering 7400 km² revealed a larger population of small chaos areas that were not observed in regional imaging (Riley *et al.*, 2000; Hoppa *et al.*, 2001) (see previous section). Extrapolating from high-resolution sampling to the rest of the globe, Riley *et al.* added another 12% to the chaos surface coverage estimate for a total of $\sim 40\%$. In separate geological mapping work by Figueredo and Greeley (2003), they reported that approximately 20% of the surface is covered by chaotic terrain. This leaves a significant discrepancy in the reported surface coverage of chaotic terrain.

There is a direct correlation between areas of chaotic terrain seen at moderate and high resolution, and the “mottled terrain” seen in lower-resolution global-scale images. Pappalardo *et al.* (1998b) mapped mottled terrain distribution across Europa from global-scale images. They showed that the mottled terrain is concentrated in two roughly oval-shaped and antipodal areas filling areas within 40° of the equator, centered at approximately 120° and 300°W (west longitude). This pattern may also be seen in the global geological map of Europa presented in the chapter by Doggett *et al.* Geological mapping of regional-scale images by Figueredo and Greeley (2004) shows a similar concentration of chaotic terrain near the equator. Pappalardo *et al.* (1998b) argued that the observed mottled terrain distribution is best fit by the compressional zones predicted from the nonsynchronous rotation stress model, swept out through the last few tens of degrees of rotation. Figueredo and Greeley (2000), with a more spatially limited but more highly detailed dataset, argued instead that the pattern of chaos dis-

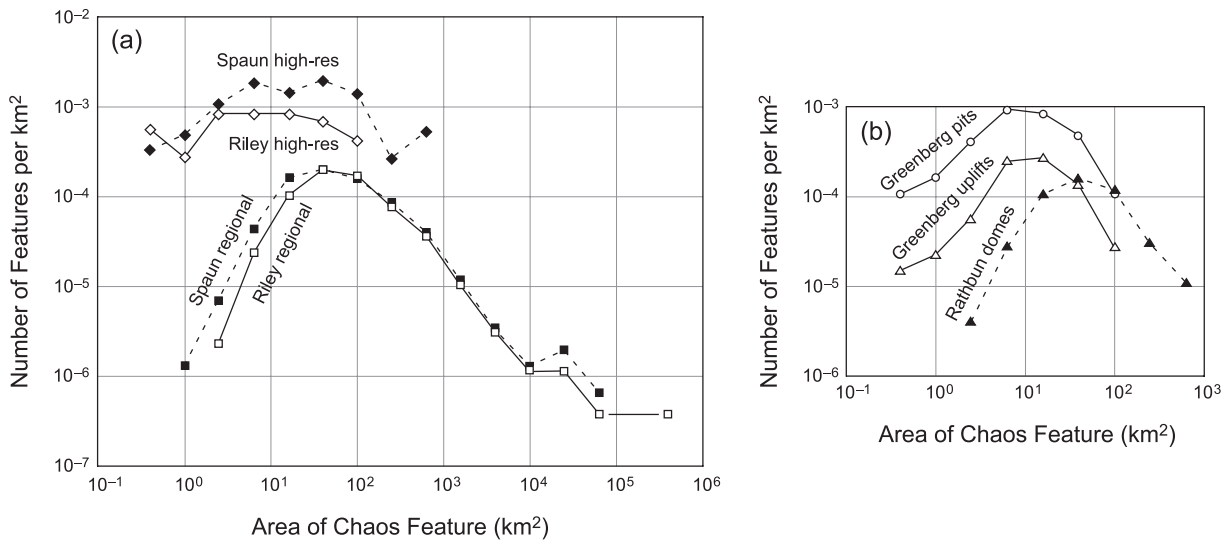


Fig. 12. (a) Size distributions of chaotic terrain measured by Riley *et al.* (2000) and Spaun (2002), rebinned and plotted on the same axes. The two studies, which came to different conclusions about the size distribution, show remarkably good agreement. The “regional” lines come from a large amount of Galileo regional image data obtained at approximately 200 m pixel⁻¹, while the “high-res” lines are from Galileo observations at a few tens of meters per pixel. More chaotic terrain is recognized at higher resolution, in agreement with Hoppa *et al.* (2001), although it is unclear whether the dropoff in chaos abundance at ~ 3 km² (~ 1 km diameter) is real. (b) Size distribution of pits and domes from Greenberg *et al.* (2003) compared to domes measured by Rathbun *et al.* (1998). For comparison to (a), the Rathbun *et al.* line lies almost directly on top of the peak of the Riley *et al.* (2000) and Spaun (2002) regional size distribution lines for chaotic terrain.

tribution is a good fit to local icy shell thickness minima predicted by tidal heating models near the leading and trailing points (Ojakangas and Stevenson, 1989). Based on mapping of high-resolution areas, Spaul et al. (2004) reported that chaotic terrain occurs in smaller, more abundant and closely spaced patches near the leading and trailing points and at 330°W, rather than near the antijovian point, but they concluded that the interpretation of geographic patterns at high resolution is hampered by the limited imaging data coverage. It is also interesting to note that the concentrations of chaos regions near 120°W and 300°W closely correspond to the positions of the paleopoles proposed by Schenk et al. (2008) in their polar wander scenario. Because tidal heating is most strongly concentrated near the poles, this possible correlation hints at tidal heating being a strongly controlling factor in chaotic terrain formation. In this hypothesis, it also implies that chaos formation would have predated the reorientation event, although the timing of that event is currently unknown.

Geological mapping of Europa has generally found that chaotic terrain crosscuts almost all other features (e.g., Prockter et al., 1999; Figueredo and Greeley, 2000; see chapter by Doggett et al.) and thus puts it at or near the top of the time sequence of feature formation. This suggests that the formation of chaotic terrain may be a relatively recent phenomenon. There are also interesting examples of chaotic terrain cut by younger features. Prockter and Schenk (2005) showed older chaotic terrain cut by the formation of a nearly 1-km-tall dome at Castalia Macula (Fig. 13), while Riley et al. (2006) pointed out an area of chaotic terrain near the south pole crosscut by ridges and younger chaos (Fig. 14). Greenberg et al. (1999) mapped chaotic

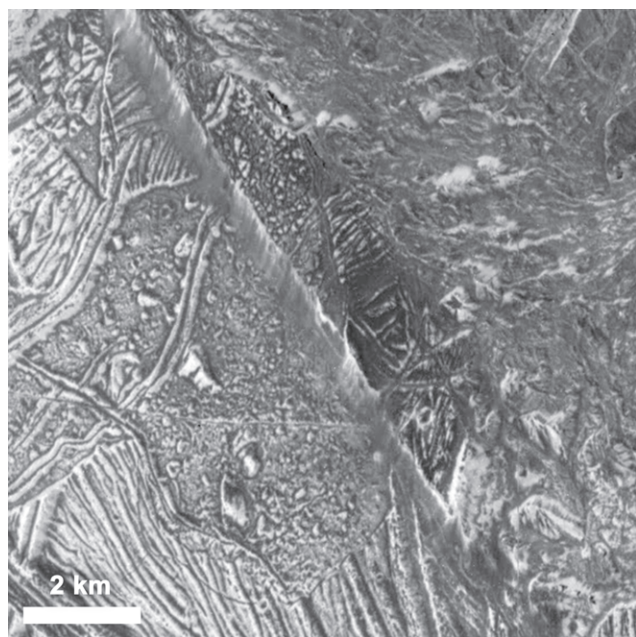


Fig. 13. An older patch of chaotic terrain is cut by a large cliff resulting from surface uplift north of Castalia Macula. Galileo 14ESDRKSPT01 observation, with illumination from overhead.

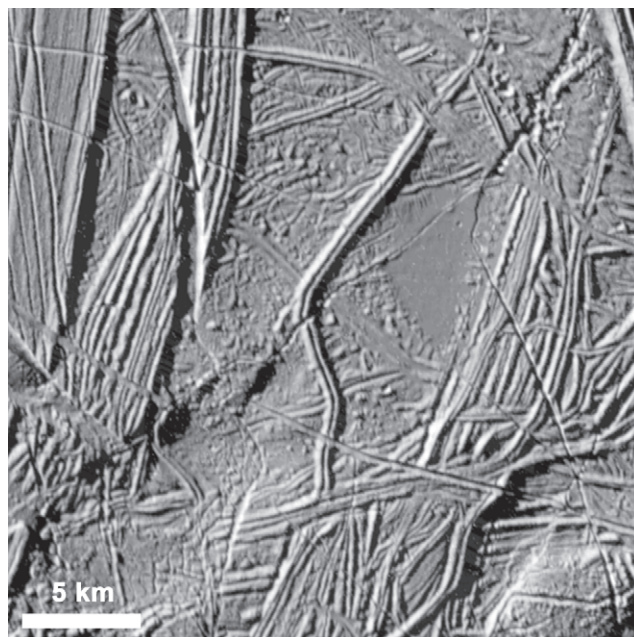


Fig. 14. Possible example of old chaotic terrain near the south pole of Europa, mapped by Riley et al. (2006). Lumpy matrix-like material is exposed between several generations of ridges. Galileo 17ESSOUTH01 observation, with illumination from the left.

terrain on Europa, splitting it into two categories: “fresh” chaos, which is largely unmodified by any other features; and “modified” chaos, which is distinguished by a smoother matrix and more subdued edges. They reported that modified chaos appears to be more commonly crosscut by younger tectonic features, although the extent to which this occurs has not been quantified. Figueredo and Greeley (2004) also included a “subdued” chaos unit in their geological mapping, with similar characteristics to the “modified” chaos of Greenberg et al., and found that it was slightly older than other chaotic terrain units in the time sequence.

Greenberg et al. (1999) also identified features such as isolated polygonal blocks and “fins” inferred to be tilted crustal blocks, unassociated with any surrounding chaotic terrain. They interpreted these features as evidence of older chaotic terrain that has been mostly destroyed by later resurfacing, and Hoppa et al. (2001) used this to argue that chaos formation and ridge formation are both continuous and ongoing processes throughout European history. A thorough statistical analysis of the frequency of crosscutting relationships would more thoroughly address whether ridges and chaos could be forming at a constant rate through time, or whether chaos formation is more common in recent times.

A possible constraint on the duration of the chaos formation process comes from studying the relationship between chaotic terrain and secondary craters. Bierhaus et al. (2001) studied the distribution of small craters in high-resolution images of Conamara Chaos, and found that the vast majority of the craters were related to a ray from the impact crater Pwyll to the south. These secondaries all formed in a

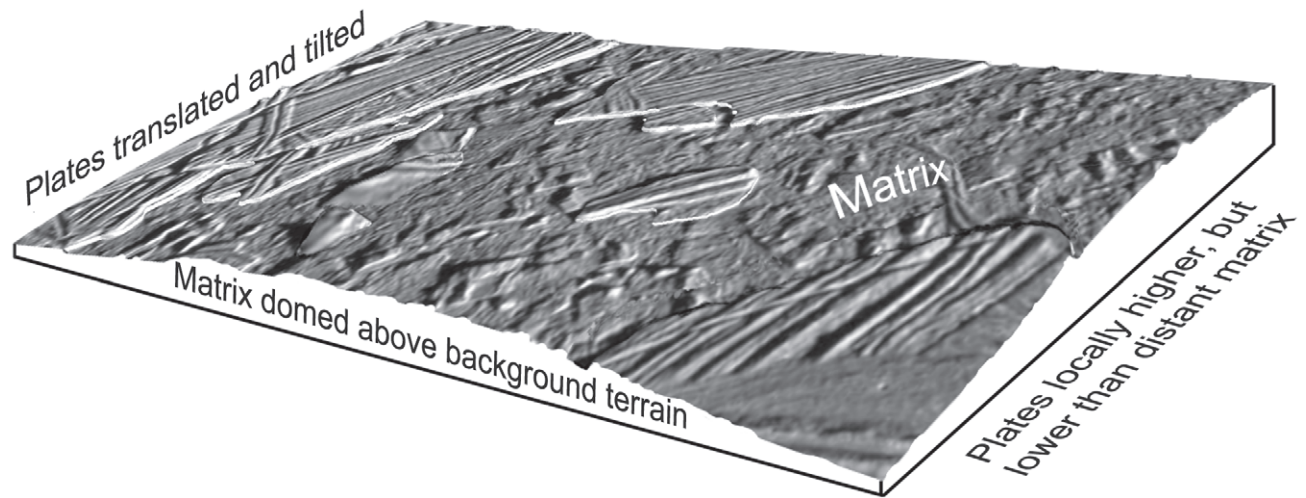


Fig. 15. Illustration of four of the eight “hard” observational constraints on chaotic terrain formation.

geological instant, and yet there are more Pwyll secondary craters preserved on the blocks of preexisting terrain in the chaos than there are in the matrix. Bierhaus et al. argued that this is not an effect of lack of recognition in the matrix, but rather there has been post-Pwyll activity in Conamara that has modified the matrix and not the blocks. An alternative explanation would be that the matrix material is less cohesive and may not preserve impact craters as well (similar to the loss of small craters in the lunar highlands), but such an effect would have to not be size selective in order to explain the crater distribution data. Even more perplexingly, the density of craters in all chaotic terrain is higher than in the ridged terrain (with overlapping error bars; see chapter by Bierhaus et al.). If this crater density difference is borne out by future observations, this would contradict the cross-cutting relationships.

7. SUMMARY OF OBSERVATIONAL CONSTRAINTS FOR CHAOS FORMATION MODELS

Before we consider theoretical models for chaotic terrain formation, let us first summarize the observational constraints from the previous five sections. A few of these constraints are illustrated in Fig. 15. Any viable model for chaotic terrain formation must be able to explain the following “hard” observational constraints:

H1: Formation of irregular, lumpy matrix material

H2: Plates of preexisting terrain usually higher than adjacent matrix (~100 m)

H3: Plates tilted, rotated, and translated horizontally (a few kilometers distance)

H4: Chaos with abundant plates are usually bounded by inward-facing scarps; chaos with few plates are usually bounded by matrix doming above the surroundings

H5: Matrix material is usually topographically higher than background terrain by 100–250 m, and can stand higher than the plates in the same chaos region

H6: Exposure of dark hydrated sulfurous salt/acid material in matrix, on small plates, and in surrounding topographic lows

H7: Areas of chaotic terrain range from approximately 1 km to over 1000 km in diameter

H8: Chaotic terrain is more concentrated in antipodal regions near the equator

In addition, there are some “soft” observational constraints that may be real, or they may be observational biases, misinterpretations, or misclassifications of feature types presently assumed to be part of chaotic terrain. Models that can also explain these observations will be considered more successful than those models that cannot explain the following:

S1: Undisrupted pits and domes exist in association with chaotic terrain

S2: Preservation of preexisting structure in degraded form within the chaos matrix

S3: Plates of preexisting terrain have a minimum size of approximately 1 km

S4: Ridges are preferentially preserved during chaos formation

S5: Dark matrix material can flow out onto preexisting surface

S6: Domes cutting across chaotic terrain can stand up to 1 km high

S7: Large chaotic terrain regions grow by a process of merging smaller regions together

S8: Matrix formation may be long-lived, wiping out small craters

8. MODELS FOR CHAOTIC TERRAIN FORMATION

In this section, we discuss five models for the formation of chaotic terrain that have been proposed in the literature and compare each model to the observational constraints above. The results of this section are summarized in Table 1,

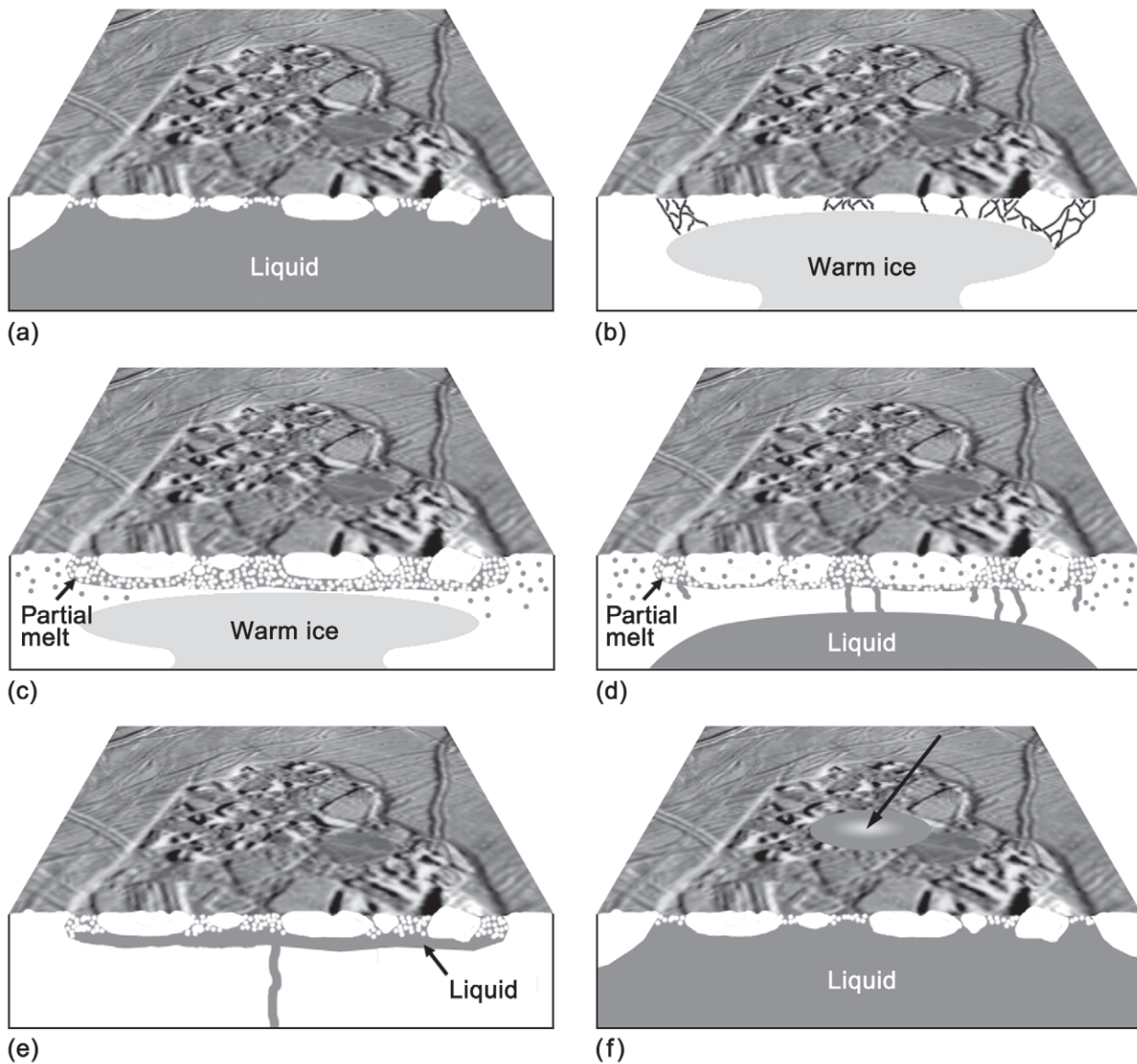


Fig. 16. Illustration of candidate chaotic terrain formation models: (a) melt-through; (b) diapirism; (c) brine mobilization driven by diapirism; (d) brine mobilization driven by partial melt-through; (e) sill formation; (f) impact. See text for explanation of the models.

which shows for each combination of model and observation whether there is a natural explanation, whether special circumstances are required, or whether the model does not plausibly explain that observation.

8.1. Melting Through the Icy Shell

The visual similarity between chaotic terrain and terrestrial pack ice inspired some to consider models in which the plates are the equivalent of tabular icebergs floating in an underlying ocean, and the matrix is composed of lower-lying sea ice formed as the top of that ocean froze (Fig. 16a) (Carr *et al.*, 1998; Greeley *et al.*, 1998). This is envisioned to happen as a result of a heat source at the base of the icy shell melting the overlying ice, creating a hole melted through the ice and exposing the ocean below (Greenberg

et al., 1999; Thomson and Delaney, 2001). If the plates observed in Conamara Chaos were free-floating icebergs, their heights would indicate that the ice in those blocks was 0.5–2 km thick at the time they froze into the surrounding matrix (Williams and Greeley, 1998).

The model of Greenberg *et al.* (1999) begins with the first stage of melting, thinning the ice crust and producing a pit. If melting progresses at a constant rate as the melting front reaches the surface, then topographic highs such as ridges, which may be isostatically supported regions of thicker ice, would be the last areas to melt and may be preserved as the floating plates within the chaotic terrain. However, as the melting front nears the surface, its propagation speed will be inversely proportional to its proximity to the surface, due to thermal conduction through the ice and radiation of the energy into space, so in actuality the

bases of ridges will melt faster and the topography should flatten out instead of producing ridged plates (Goodman *et al.*, 2004).

Initial objections to the melt-through model were raised because of the tremendous amount of energy required to produce and maintain melt at Europa's surface (Pappalardo *et al.*, 1999; Collins *et al.*, 2000), and the tendency for the warm ice at the base of the shell to flow in from the sides to fill the hole (Stevenson, 2000). Of the two objections, the energy argument is more difficult to surmount. Maintaining a surface temperature at 270 K would require a heat flux of roughly 300 W m^{-2} (Goodman *et al.*, 2004), about 25 times the current solar insolation, and more than 10^3 times the likely globally averaged tidal heat production, even assuming that Europa's silicate interior is as dissipative as Io's (e.g., Nimmo and Giese, 2005). Complete melt-through of the icy shell may not actually be necessary to form chaotic terrain, and thinning the icy shell may have interesting effects, but this remains to be quantified (see the end of section 8.3). Regarding the ice flow objection, more careful consideration of ice rheology shows that the ice infill process is somewhat slower than envisioned by Stevenson (Nimmo, 2004), but the main unknown is the thickness of the icy shell. If Europa's silicate mantle is Io-like in its tidal dissipation, the equilibrium icy shell thickness is about 2 km, while in the absence of silicate dissipation the equilibrium thickness is tens of kilometers (e.g., Ojakangas and Stevenson, 1989). Thicker icy shells not only have more total ice to melt through, but they also have a deeper channel of warm ice at the bottom to promote inflow. There will be a critical icy shell thickness (probably on the order of 10 km) above which inflow will be faster than melting, preventing melt-through, so an independent constraint on the thickness of the icy shell is crucial to the validity of this model.

O'Brien *et al.* (2002) modeled the melting process and found that complete melt-through of an icy shell 6 km thick could be achieved in $\sim 10^4$ yr by concentrating a few percent of Europa's total tidal heat output (roughly 7 TW, assuming tidal dissipation in an Io-like mantle) within a region 200 km across. They also demonstrated that the melting process was orders of magnitude faster than ice inflow for the shell thicknesses they assumed, limiting the thickness of the warm ice channel that could flow at the base of the shell. The complete melt-through found in this model is at odds with a simple energy-balance model, because the heat supplied in the model to melt the ice is insufficient to maintain open water at the surface (Goodman *et al.*, 2004). It turns out that the numerical scheme of O'Brien *et al.* lacked the resolution to accurately treat near-surface effects; the constant grid spacing of 100 m lost resolution of the heat conduction problem and became numerically unstable as the melt approached the surface. An improved model with adaptive grid spacing (Goodman *et al.*, 2004) showed that the ice will asymptotically approach an equilibrium thickness, on the order of 100 m for the energy and shell thickness values assumed by O'Brien *et al.* It is thus unclear

whether melt-through of the kind originally envisaged (Carr *et al.*, 1998; Greenberg *et al.*, 1999; Thomson and Delaney, 2001), with open water at Europa's surface, is physically possible.

What is a plausible source of heat supplied to the base of the icy shell? As discussed above, it is possible that Europa's silicate mantle is highly dissipative and generates ~ 7 TW of heat. A direct path from seafloor heat sources to the base of the icy shell is hydrothermal plumes rising through the ocean (see chapter by Vance and Goodman). The hot water will rise until it reaches neutral buoyancy, so the density stratification of the ocean is critically important for determining if a plume will reach the base of the icy shell. Thomson and Delaney (2001) investigated hydrothermal plumes that would rise and then stall at the base of the icy shell, delivering enough heat for melt-through events. They envisioned an ocean that undergoes stratification and destratification events, with chaos formation coinciding with oceanic conditions that allow hydrothermal plumes to deliver heat to the icy shell. Goodman *et al.* (2004) argued for an essentially unstratified ocean and conducted scaled physical experiments to determine the dynamics of hydrothermal plumes in an unstratified, rotating environment. The plumes start as narrow, rotationally confined cylinders, but when they run up against a solid boundary such as the base of the icy shell, they spread laterally into inverted cones with a width of 25–50 km. This will spread the heat from a point source on the ocean floor over a large area of the icy shell. The resulting heat flux ($0.1\text{--}10 \text{ W m}^{-2}$) is insufficient by more than an order of magnitude to cause complete melt-through events. Melt-through requires a near-surface heat flux of $\sim 300 \text{ W m}^{-2}$, or 3% of the total heat flow of Europa assumed by O'Brien *et al.* (2002), concentrated into a region 25 km wide. Putting more heat into the bottom of the plume at the seafloor heat source serves to spread the heat over a larger area of the icy shell as the plume grows wider. Lowell and DuBose (2005) investigated the nature of possible hydrothermal source areas, and found that the reduced gravity on Europa leads to weaker hydrothermal plume sources as compared to sources on the Earth's seafloor. The heating patch size found by Goodman *et al.* (2004) is smaller than chaos areas such as Conamara, but much larger than the more numerous small chaos areas.

Given the constraints on hydrothermal plume size, Goodman *et al.* (2004, appendix A) used the O'Brien *et al.* (2002) melting model to investigate the expected size distribution of chaotic terrain formed from these plumes. A power-law distribution of plume lifetimes could explain the observed distribution of chaos areas much larger than 10 km diameter. However, a power-law distribution of plume lifetimes cannot explain the observed size distribution of chaos areas smaller than 10 km. In order to produce the observed numerous small chaos areas, one would need to posit an infinite spike in the plume distribution at a total power equal to the amount needed to melt through only at the center of the plume. This is equivalent to turning off the plume at its

base as soon as the first melt reaches the surface, but there is no readily apparent feedback mechanism between melt at the surface and a seafloor heat source supplying it.

The question of stratification in Europa's ocean brings up another interesting idea for melting through the icy shell of Europa. *Melosh et al.* (2004) pointed out that if the ocean is composed of relatively fresh water, a "stratosphere" of near-freezing water can stably stratify on top of water a few degrees warmer. As the warmer bottom water heats up from the rocky core below, the stratification can overturn, bringing warm water in contact with the icy shell and leading to episodic, widespread melt through events. Salt dissolved in the water eliminates the dip in the temperature-density relationship, and induced magnetic field evidence from Europa indicates that the ocean must be somewhat salty (*Zimmer et al.*, 2000; *Hand and Chyba*, 2007). However, there are also pressure effects on the solution of salt that can operate deep in Europa's ocean and lead to stratification and inhibition of hydrothermal plume rise (*Vance and Brown*, 2005; see chapter by Vance and Goodman).

The melt-through model explains the motion of the chaos plates by currents in the water pushing the floating plates through the liquid. *Thomson and Delaney* (2001) noted that the motion of the plates in Conamara Chaos measured by *Spaun et al.* (1998) is consistent with Coriolis-driven motion in the top of an ascending hydrothermal plume. However, *Goodman et al.* (2004) calculated the forces on the plates due to such fluid motion, and found that the stresses exerted by currents on the plates (~1 Pa) were too small to move the plates even through a thin layer of weak slush.

Once the heat source is turned off, the hole in the icy shell will begin to refreeze back to its equilibrium thickness, staying relatively thin for ~1 m.y. (*Buck et al.*, 2002). As the ice thickens, the surface will return to its premelting elevation and the original pit will disappear. If the matrix ice is welded to the margins, it will appear to dome up in the center as refreezing progresses, but it will not rise above the elevation of the background terrain unless there are compositional contrasts between the refreezing ice and the original unmelted ice (*Nimmo and Giese*, 2005). If there is a mechanism other than refreezing that can trap salts within the icy shell, it may be possible to produce such compositional contrasts, but this issue has not been well explored.

Melt-Through Model:

Comparison to Observational Constraints

The melt-through model can be compared to the hard and soft observational constraints on chaos formation as follows.

H1: Matrix material is formed by melting and disruption of parts of the surface ice.

H2: The plates are floating in the ocean below and stand high because they are thicker remnants of the icy shell than the material in the matrix.

H3: Plates can easily translate, rotate, and tilt if the icy shell is melted through, but the driving force for plate motion is unclear.

H4: Inward-facing scarps form by calving icebergs from the margin of the melted area; matrix could slope onto pieces of surrounding terrain that originally tilted into the molten matrix.

H5: The surface will not rise above the background terrain unless there is a mechanism to produce significant density variations between the refrozen ice and the original icy shell.

H6: Exposure of the ocean at the surface provides the hydrated sulfurous contaminants.

H7: The range of possible sizes of melt-through areas depends on the mechanism invoked to heat the base of the icy shell. Some mechanisms, such as hydrothermal plumes in an unstratified ocean, would predict a paucity of small (<~5 km diameter) chaos areas (see appendix A of *Goodman et al.*, 2004).

H8: The geographic distribution of chaotic terrain may be due to enhanced tidal heating, because melt-through events may be more common where tidal heating is more intense. If this was the controlling factor, chaos should be more common at the poles, but perhaps the cold surface temperature at the poles inhibits surface melting, or polar wander has subsequently occurred.

The melt-through model can also easily explain two of the soft constraints. Pits (but not domes) are a natural consequence of melting. The minimum size of plates may be a consequence of tilting when the plate width is smaller than the plate thickness.

8.2. Diapirism

It was recognized early in the Galileo tour that pits, spots, and domes on Europa (Fig. 4), including some with chaos characteristics, might be the surface expression of rising diapirs (Fig. 16b) (*Pappalardo et al.*, 1998a), analogous to salt diapirs on Earth. Diapirs have been used to explain collections of similar-sized small domes (*Rathbun et al.*, 1998) as well as large dome features such as Murias Chaos (*Figueredo et al.*, 2002) and Thera Macula (*Mével and Mercier*, 2007). As discussed below, such diapirs typically arise due to either thermal or compositional buoyancy. On Europa, there is also the potential complication of locally enhanced tidal heating and generation of melt (discussed below). Theoretical aspects of diapirism are discussed in more detail in the chapter by Barr and Showman.

One significant problem for the diapirism hypothesis is that in conventional thermal convection, the size of individual diapirs is rather uniform, because it is set by the thickness of the thermal boundary layer. This behavior is clearly different from the observed wide size-spectrum of chaos regions. While it is possible that some large chaos regions are generated by merging diapirs (*Spaun et al.*, 1999; *Figueredo and Greeley*, 2004; *Schenk and Pappa-*

lardo, 2004; Mével and Mercier, 2007), the wide size range of individual, roughly axisymmetric features is difficult to explain by such merging.

The behavior of thermal convection in strongly temperature-dependent materials, such as ice, is fairly well understood (e.g., Solomatin, 1995; chapter by Barr and Showman). The temperature contrasts are set by the rheological properties of the ice, and are typically small (a few tens of Kelvin) (Nimmo and Manga, 2002). As a result of the low-temperature contrast and the presence of a thick stagnant lid, the topography generated by simple thermal diapirs is also small (typically a few tens of meters) (Showman and Han, 2004). Because the lid is cold, the convective strains are small and incompatible with the high strains associated with chaos block rotation or lateral matrix flow. Thus, simple thermal convection is not a satisfactory mechanism for generating chaos, and as a result several additional physical processes have been proposed.

One potentially important process is the yielding of the near-surface material. If stresses are large enough to cause yielding (plastic or brittle failure) of the near-surface ice then both surface velocity and surface topography can increase significantly. For instance, Showman and Han (2005) demonstrated that if the plastic yield stresses are sufficiently small (a few tens of kilopascals), significant surface strains and topographic amplitudes of ~ 100 m can result. For reference, a plastic yield stress on the order of 10^4 Pa is similar to the yield stress required to move giant icebergs through polar pack ice on Earth (Lichey and Hellmer, 2001). It should be noted that the elegant model of Hoppa *et al.* (1999) for the formation of cycloidal fractures on Europa requires a similarly low fracture propagation stress. The Showman and Han (2005) model demonstrated complete surface recycling, which is bad for preserving plates, but could plausibly provide a source for matrix-rich features that appear to flow over the background terrain, such as Murias Chaos (Figueredo *et al.*, 2002). Miyamoto *et al.* (2005) showed that such surface flows of warm ice are possible if the effusion rate is on the order of $0.01\text{--}0.1\text{ km}^3\text{ yr}^{-1}$, which would require a wide supply conduit. One problem with the Showman and Han (2005) model is that it is unable to produce features smaller than 30–100 km diameter (a few times the shell thickness), which is much larger than many of the observed domes (e.g., Rathbun *et al.*, 1998; Greenberg *et al.*, 2003) that have been proposed as diapiric features.

Another way of increasing surface topography is to appeal to compositional buoyancy. Han and Showman (2005) demonstrated that, as expected, larger surface topography can be generated if compositional density contrasts are present in addition to thermal contrasts. However, as with pure thermal convection, the generation of surface topography comparable to that observed in some chaos regions requires a weak near-surface ice layer, again suggesting that some kind of yielding process might be important, while the length-scale of features generated is again significantly

larger than many chaos regions. Pappalardo and Barr (2004) specifically appealed to compositional density contrasts arising from the preferential removal of a low-melting-temperature, dense component (brine) from the icy shell in warm upwellings. This idea of the linkage between convection and brine production will be discussed in more detail in the next section.

Another important way in which Europa's icy shell differs from that of standard convective settings is that the heat production is expected to vary with the local viscosity (e.g., Ojakangas and Stevenson, 1989). This effect is potentially extremely important, because it can lead to a thermal runaway and the production of local melt even in pure ice (McKinnon, 1999; Wang and Stevenson, 2000; Sotin *et al.*, 2002; Tobie *et al.*, 2003; Mitri and Showman, 2008; chapter by Barr and Showman). In the absence of other effects, however, this melting is still relatively deep because of the presence of a stagnant lid at the top of the icy shell (e.g., Sotin *et al.*, 2002; Nimmo and Giese, 2005). Because tidal strain rates are higher toward the poles, a prediction of any model in which tidal heating is important would be that chaotic terrain is formed more frequently nearer the poles.

Diapirism Model:

Comparison to Observational Constraints

The diapirism model can be compared to the hard and soft observational constraints on chaos formation as follows.

H1: Matrix material could be formed by pervasive fracturing and plastic yielding of surface ice, although the details of this process have not been investigated.

H2: It is difficult to explain why the matrix material would subside relative to the plates without calling for material removal through tidally induced melting right near the surface.

H3: Unless yielding occurs, the diapirism model generates surface strains close to zero. Topographic gradients and a sufficiently weak lid might explain the formation and mobility of the plates (Showman and Han, 2005).

H4: Inward-facing scarps are difficult to explain for the same reason as H2. Doming of material above surroundings in plate-free chaos may be similar to the ice extrusion mechanism outlined by Figueredo *et al.* (2002).

H5: Matrix material will stand significantly higher than the background and plates if yielding and/or compositional convection are important.

H6: Exposure of dark material may be due to sublimation of warm surface ice.

H7: The diapirism model has a strong preferential size distribution, which is not simple to reconcile with the large range of sizes observed. The creation of larger features through merging diapirs or thermal runaways may partially alleviate this problem.

H8: The geographic distribution of chaotic terrain may be a result of enhanced tidal heating, which would drive more intense convection and possibly more melting within

the diapirs. If this was the controlling factor, chaos should be more common at the poles, but perhaps the cold surface temperature thickens the stagnant lid or the pole has shifted.

The diapirism model also offers easy explanations for the soft constraints regarding the formation of undisrupted pits and domes, preservation of preexisting structure in the matrix, and growing chaotic terrain through mergers. This relatively slow process may be the best one to explain the apparently long formation time for matrix material.

8.3. Brine Mobilization

While there is certainly compositional heterogeneity on the surface of Europa, compositional variations within the icy shell are relatively unconstrained. Interesting behaviors can arise from consideration of non-water-ice materials within the shell, some of which may be relevant to the formation of chaotic terrain. *Head and Pappalardo* (1999) and *Collins et al.* (2000) considered the effect of low-melting-point materials mixed within the ice as the ice was being heated. Heating induces partial melting within the icy shell, dramatically lowering the ice viscosity and allowing percolation of liquids through the shell.

Head and Pappalardo (1999) specifically examined salts trapped within the ice, comparing potential processes on Europa to processes observed to happen within salty terrestrial sea ice. If sea ice freezes rapidly, it can trap significant amounts of salt within its structure, while slower-freezing ice rejects brines from its growing crystal structure. A similar process may occur on Europa whenever ocean water is in the upper part of the icy shell, trapping brines near the surface and freezing cleaner ice beneath. Such excursions of the ocean to the near-surface may occur due to overall variations in icy shell thickness, complete or partial melt-through events, or intrusion of ocean water into the icy shell as dikes or sills.

In terrestrial sea ice, frozen brines tend to form interconnected networks, allowing them to mobilize when a critical temperature (and thus a critical partial melt fraction) is reached. This brine mobilization could lead to disintegration of surface features in the matrix, effusion of salty fluids into low areas within and surrounding the chaos, and a detachment layer allowing for plate motion (*Head and Pappalardo*, 1999). Drainage of brine from the icy shell could also compositionally enhance the buoyancy of the remaining ice (e.g., *Pappalardo and Barr*, 2004). For example, a density contrast between briny ice and clean ice of 100 kg m^{-3} could produce the observed 100–200-m elevations if a 1-km thickness of ice was “cleaned out.” Basal flow of ice would be required to balance volume loss from brine drainage.

Another effect of impurities in the icy shell is that they will change the thermal conductivity. For example, the hydrated salts that could form the frozen brine channels near Europa’s surface have a low thermal conductivity and thus could enhance the trapping of subsurface heat (*Prieto-Ballesteros and Kargel*, 2005), if they are present in suffi-

cient quantities. *Kargel et al.* (2007) used a similar argument of heat trapping by hydrated salts and clathrates to explain chaotic terrain on Mars (which is only superficially similar to European chaos).

Both *Head and Pappalardo* (1999) and *Collins et al.* (2000) envisioned a diapiric heat source where clean ice in its solid state could mobilize lower-melting-temperature brines in the upper icy shell (Fig. 16c). A problematic aspect of conventional thermal convection is the presence of a thick stagnant lid, as outlined in the previous section. This lid, combined with the low surface temperatures, ensures that it is very difficult to generate melting within a few kilometers of the surface of the satellite (e.g., *Tobie et al.*, 2003), which makes it hard to cause plate motion or matrix degradation. *Nimmo and Giese* (2005) examined the thermal equilibration of a warm ice diapir with cold briny near-surface ice and could not generate significant melt within 7 km of the surface. It is possible that some combination of brine production plus surface yielding (e.g., *Han and Showman*, 2005) could allow near-surface melting and generate the observed features. Feedbacks between convection and melt production are likely to be complex. *Showman and Han* (2005) proposed that plastic yielding near the surface may occur preferentially where partial melt is formed, providing a way to produce a combination of plates and matrix.

Although the brine-mobilization model has previously been tied to the diapirism model in the literature, the essential aspect of the model is that subsurface heating mobilizes brines within the icy shell. Ice shell thinning from a heat source applied to the base of the shell could also cause brine mobilization within the shell as the partial-melting isotherms intersect the near-surface ice (Fig. 16d). Such a hybrid model would allow near-surface melting (a problem with most diapirism models), while not requiring the enormous magnitude of energy demanded by the melt-through model. Localization of brine mobilization and drainage beneath areas of enhanced matrix formation could also leave them topographically elevated via Pratt isostasy once the icy shell returned to its equilibrium thickness, addressing another difficulty of the melt-through model. A basal heat source could be locally enhanced by tidal heating arising from the reduced ice viscosity related to warming and melt production. Although we propose such a hybrid model as a promising avenue for further investigation, this model has not been fully developed, so our evaluation of the brine-mobilization model below is based on the diapir-driven version previously proposed in the literature.

Brine-Mobilization Model: Comparison to Observational Constraints

The brine-mobilization model can be compared to the hard and soft observational constraints on chaos formation as follows.

H1: Matrix material is formed by disaggregation of near-surface ice as the brine within it mobilizes.

H2: If the brine drains from the matrix material to other

locations, it will lose volume compared to the nearby plates, leaving it locally lower standing.

H3: The significant drop in viscosity from partial melting may enable motion of plates, although the volume and depth requirements on this melt have not been quantified. Thermal equilibration of diapirs with near-surface ice may not produce enough melt to significantly mobilize the surface (Nimmo and Giese, 2005), although it could enhance the yielding process (see the diapir model).

H4: Inward-facing scarps are related to loss of volume in the matrix. Doming of material above surroundings could be related to ice upwelling.

H5: Drainage of brine from the area of chaotic terrain leaves the ice compositionally buoyant. Reasonable density differences will produce the required topography (Pappalardo and Barr, 2004), but the detailed mechanisms of initial brine emplacement and brine drainage could be better quantified.

H6: Brines may effuse onto low areas of the surface on and around the chaos.

H7: The size distribution of diapirs is a critical challenge to compare to the size distribution of chaotic terrain. However, the possibility of isolated brine “pockets” and the lateral mobility of brine give additional free parameters to help explain the full range of chaotic terrain sizes.

H8: Enhanced tidal heating could help to explain the geographic distribution of chaotic terrain. If this was the controlling factor, chaos should be more common at the poles, but perhaps the cold surface temperature at the poles inhibits chaos formation or polar wander has occurred.

The brine-mobilization model inherits many of the soft constraint compatibilities from the diapirism model, but pockets of mobilized brine may do a better job of explaining the sizes of plates.

8.4. Injection of Sills

Another way to deliver liquid into the icy shell of Europa is to inject it directly from the ocean. Crawford and Stevenson (1988) investigated the propagation of fluid-filled cracks from the base of the icy shell, and found that the process is difficult unless exsolved gases help to open the crack. Collins *et al.* (2000) suggested that sills of melt could form within Europa’s icy shell from pressurized water injected from the ocean (Fig. 16e). Manga and Wang (2007) investigated the pressure that would build up in the ocean as Europa’s icy shell thickens. They found that, although it is difficult to get water all the way to erupting at the surface of Europa, it is possible to form sills within the icy shell from pressure buildup in the ocean. The maximum sill thickness they could generate through this mechanism was about 10 m, meaning that about 10 m of surface topography would be generated. Compared to the above mechanisms for chaotic terrain formation, sill injection has not been extensively studied. Hybrid sill/brine-mobilization models are not as promising as other hybrid models, because the injection of ocean water into the sill does not pro-

duce topographic uplift from decreasing the column density of the icy shell.

Sill-Injection Model:

Comparison to Observational Constraints

The sill-injection model can be compared to the hard and soft observational constraints on chaos formation as follows.

H1 Matrix material may be formed by fracturing and yielding of the near-surface ice, although the exact mechanism is unclear.

H2: If the plates are floating in the liquid of the sill, the topographic difference between plates and matrix could be explained, but the expected thinness of the sill precludes free-floating plates.

H3: Plates will be decoupled by the sill and could easily translate horizontally, but tilting may be more difficult to explain in a thin liquid layer.

H4: Sills do not offer a natural explanation for chaos margins.

H5: Freezing of the sill can cause updoming above surrounding terrain, but not enough to explain the observations unless material is continually pumped into the same sill to freeze a thicker layer.

H6: Pressurization of injected ocean water as the sill freezes may drive small effusions of cryovolcanic materials.

H7: The horizontal extent of likely sills on Europa has not been modeled.

H8: Sills may form where it is easiest to propagate dikes into the icy shell from a pressurized ocean, but this does not bear any obvious relationship to the observed distribution of chaotic terrain.

Sills do not offer any particularly easy explanations for any of the soft observational constraints.

8.5. Impact

Because chaotic terrain formation involves disruption of surface materials, an exogenic impact mechanism has been posited for their formation, in contrast to endogenic heating mechanisms (Fig. 16f). Billings and Kattenhorn (2003) noted similar morphologies between chaotic terrain on Europa and terrestrial explosion craters on floating ice. In the explosion craters, floating plates of the original ice surface are preserved in a slushy matrix, filling an irregular hole in the ice. Cox *et al.* (2005) compared chaotic terrain to impact experiments into ice targets floating on a liquid substrate. Their impact experiments show catastrophic disruption of the floating ice over some threshold energy value, and Cox *et al.* argued that this could explain some large areas of chaotic terrain.

A difficulty for the impact hypothesis is that there are already two good examples on Europa of impacts that seem to have penetrated the icy shell to some extent, the features Tyre and Callanish (see chapter by Schenk and Turtle). Both of them are surrounded by secondary craters and by multiple rings of concentric fractures, much like large impact

TABLE 1. Comparison of models for chaotic terrain formation to the observational constraints enumerated in section 7.

Observational Constraint (H = hard constraint; S = soft constraint)	Melt Through	Diapirism	Brine Mobilization	Sill Injection	Impact
H1: Formation of matrix material	✓	★	✓	✗	✓
H2: Plates locally higher than matrix	✓	✗	✓	✗	✓
H3: Plates tilt, rotate, and translate	✓	★	★	★	✓
H4: Nature of chaotic terrain margins	★	★	★	✗	★
H5: Matrix topographically high	★	★	✓	★	★
H6: Dark hydrated salts/acid	✓	★	✓	✓	✓
H7: Diameter range ~1–1000 km	★	✗	★	✓	✗
H8: Concentrated near the equator	★	★	★	✗	✗
S1: Associated pits and domes	✗	✓	✓	✗	✗
S2: Preexisting structures preserved	✗	✓	✓	✓	✗
S3: Plate size >1 km	✓	✗	★	★	✓
S4: Ridges preferentially preserved	✓	★	★	★	✗
S5: Matrix material forms viscous flows	✗	✓	✓	★	★
S6: Associated domes ~1 km high	✗	★	★	★	✗
S7: Chaos regions grow by merging	★	✓	✓	✓	✗
S8: Matrix formation long-lived?	✗	★	★	★	✗

Symbols: ✓ = This model naturally explains this observation. ★ = Special, but plausible, circumstances may be required to produce this observation from this model. ✗ = This model does not plausibly explain this observation.

basins on other bodies in the solar system. The impact hypothesis can only explain large areas of chaotic terrain and not small ones (which would not penetrate the ice), leading to two problems with the basic argument. First, there is a case of multiple explanations for the same thing: If impacts explain large chaos areas, then another explanation is needed for small ones. Second, there is a case of one explanation for multiple unrelated features: Tyre and Callanish being formed through the same mechanism as Conamara Chaos and Murias Chaos. Therefore, the principle of parsimony does not favor the impact hypothesis for chaotic terrain formation.

Impact Model:

Comparison to Observational Constraints

The impact model can be compared to the hard and soft observational constraints on chaos formation as follows.

H1: Matrix material is formed by catastrophic disruption of the surface ice during the impact event.

H2: The plates are floating in the ocean below and are remnants of the original icy shell.

H3: Plates can easily translate, rotate, and tilt, and there are likely to be dynamic waves and currents in the water that would push the plates.

H4: Inward-facing scarps show the boundary of the disrupted area, but it is difficult to explain other chaos areas where matrix slopes down onto the adjacent terrain.

H5: There is no mechanism to dome the surface above the background terrain unless the refrozen ice has a different density than the original icy shell (see point H5 for the melt-through model).

H6: Exposure of the ocean provides the hydrated sulfurous contaminants.

H7: This model can only explain the largest end of the observed size range for chaotic terrain, unless radical variations in icy shell thickness are called upon.

H8: Impacts should be evenly distributed, so geographic preference would have to be explained through large differences in the target material from region to region.

Impacts can naturally explain the soft constraint of the minimum size of plates, because plates that are taller than they are wide will tip over in the ocean. Most of the other soft constraints are extremely difficult or impossible to explain in the impact scenario.

9. SUMMARY AND CONCLUSIONS

Table 1 summarizes how well the various models outlined in section 8 fit the observations. This table is not meant to be the end of the story, but rather is meant as a guide to where future work could be done to build a better model of chaotic terrain formation. While the simple diapir, sill-injection, and impact models fail to explain several key observations, the melt-through and brine-mobilization models can explain the key observations and many of the secondary observations.

As discussed above, a major issue with the melt-through model is the large energy fluxes required to completely melt the icy shell. A further problem is that, at least for the hydrothermal plume model, it appears to be difficult to generate a significant number of the most abundant features, which are smaller than 10 km across. On the other hand, because it is likely that the shell thickness exerts a strong

control on the minimum lengthscale of surface features, the melt-through model is more capable of explaining small chaos features than models requiring shells tens of kilometers thick, if the melting patch can be of arbitrary size. One further aspect of the melt-through model that requires further quantification is the possible formation of lateral density contrasts after refreezing, leading to uplifted matrix material. The process that initially charges the upper icy shell with salts would have to be significantly different than the refreezing process to explain such variations, and the injection of ocean water into dikes and sills is a promising possibility in this respect.

Some aspects of the brine-mobilization model, especially the ability to generate surface motion and the details of draining brines out of the icy shell, require more quantitative verification. The generation of brine-rich melts at shallow depths is difficult, but possible if diapirism resulting in localized tidal heating and/or surface yielding is invoked. Diapirism of pure ice alone is unable to explain the wide size spectrum of chaos regions, but the presence of local pockets of brine could plausibly produce smaller features that would explain the observations. Similar to the melt-through model, the process by which the icy shell accumulates impurities needs further investigation.

We conclude that a hybrid model invoking some degree of shell thinning or surface yielding (thus generating near-surface melting and smaller-scale features) coupled with brine production (probably as a result of tidal dissipation and diapirism) is perhaps the most plausible mechanism to explain all the observations. As yet, no quantitative model incorporating all the relevant processes has been developed.

A particular issue for all the existing models is that it seems hard to generate both very large (~1000 km) and very small (~1 km) features with the same process. Current models of both hydrothermal plumes and diapirs produce sharply peaked size distributions; invoking variably sized brine pockets is currently *ad hoc* and shifts the question to what originally caused those pockets. One possibility is that feedbacks between convective stresses and yielding, or between temperature and tidal heating, yield a broader spectrum of convective length scales.

Despite the decade of study since Galileo returned stunning images of chaotic terrain, it is clear that its origin is still not fully understood. Further modeling efforts still may not resolve the issue without new observations. Fortunately, plans are currently under development to launch a Europa orbiter. Uniform high-resolution image coverage would provide a much more stable platform of observations on which to base chaos formation models. Moreover, the spacecraft would be equipped with instruments such as laser ranging and ice-penetrating radar, which will be able to definitively test the different model predictions for chaos formation. This current review will undoubtedly appear naïve to the authors of a post-Europa-orbiter review of chaos formation. Nonetheless, we hope to be alive to read it, and that the enigma of chaotic terrain will finally be resolved.

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