Brine mobilization during lithospheric heating on Europa: Implications for formation of chaos terrain, lenticula texture, and color variations

James W. Head III and Robert T. Pappalardo

Department of Geological Sciences, Brown University, Providence, Rhode Island

Abstract. The background lineated plains on Europa are locally highly modified and destroyed in regions known as chaos and lenticulae. Produced there are (1) isolated fragments and polygons of background material which rotate and translate, (2) matrix, which fills in the areas between the fragments and polygons, and (3) surface discolorations. Using observations and constraints from high-resolution Galileo images, we find that a model for the formation of these terrains which involves mobilization and migration of brines, and a possible percolation phase transition as the Euroman lithosphere is warmed, can readily explain the vast majority of their characteristics. In addition, the presence of melt fractions of a few percent in the adjacent ice framework may enhance the creep rate and the accompanying deformation rates. The characteristics and distribution of lenticulae suggest that among the strong candidates for heat sources for brine migration and ice mobilization processes is diapirism linked to solid-state convection in a layer underlying a brittle lid and possibly overlying a liquid water layer.

1. Introduction and Background

On the basis of Voyager data, Luccitba and Soderblom [1982] subdivided the surface of Europa into lineated plains and mottled terrain. Galileo imaging showed that areas of lineated plains consist of abundant crisscrossing sets of ridges, bands, and wedges [Greeley et al., 1998a]; mottled terrain is characterized by regions of disrupted lineated plains. Within mottled terrain occur scattered individual features 7-15 km in diameter (pits, spots, and domes) called lenticulae [Pappalardo et al., 1998], and larger regions of disrupted terrain known as chaos [Carr et al., 1998]. High-resolution images of lenticulae [Greeley et al., 1998a; Head et al., 1997, also manuscript in preparation, 1999] and chaos [Greeley et al., 1998a; Carr et al., 1998; Head et al., 1997, 1999a, 1999b, and manuscript in preparation, 1999; Collins et al., 1999; Spaun et al., 1998, 1999] have provided a set of characteristics and constraints that must be addressed when considering hypotheses for the origin of these terrains.

2. Key Observations and Constraints from Descriptions of Lenticulae and Chaos

Lenticulae (Figure 1) are circular to somewhat elliptical pits, domes, and dark spots which average 7-15 km in diameter and are separated by distances of about 50 km. Domes warp background plains but do not disrupt them, except for some marginal faults, but within and associated with pits and spots the background terrain is highly modified and destroyed, apparently broken down into small fragments ("micro-chaos") which can migrate laterally. Darkening, which corresponds to surface color variations, accompanies many of the pits and spots, and they are sometimes surrounded by a topographic annulus which can be filled with smooth dark plains [Greeley et al., 1998a; Head et al., 1997, and manuscript in preparation, 1999]. Chaos terrain has been most well studied in the Conamara Chaos region [Spaun et al., 1998; Head et al., 1999a,b] where disrupted polygons of preexisting background plains are situated in a fine-grained matrix which makes up over half of the chaos region (Figure 2a). Matrix has formed by destruction of polygons within a region defined by a generally continuous bounding inward facing scarp. Polygons have predominantly angular outlines and sharp boundaries and dimensions of up to 20 km in diameter, but more commonly in the 5-10 km range. Polygons blocks have undergone horizontal translations of typically 1.5 km, and the vast majority have also undergone some rotation in the plane of the surface. The color of the polygons and matrix within the chaos differs from the typical background plains outside the chaos and is often similar to that observed in lenticulae.

Chaos regions contain many of the same features and characteristics as lenticulae, but the scale of the deposits and structures is different [Spaun et al., 1998, 1999]. Conamara Chaos, for example [Carr et al., 1998, Spaun et al., 1998], is 125 x 75 km in diameter, occurs in an area characterized by abundant surrounding lenticulae, and consists of ~40% polygons of background lineated plains that have been broken, rotated, and translated, and ~60% matrix. Matrix consists of several subunits (Figure 2b) [Spaun et al., 1999]. Angular polygons are steep-sided angular fragments of linear texture that show a steep tilt toward one side and a high cliff on the opposite side. Micro-polygonal blocks are smaller plate-like structures that show very faint evidence of linear texture; they appear highly degraded and are sometimes at a lower topographic elevation than the linear textured polygons. Peak material consists of individual, often elongated features usually less than 2 km across; they show very little to no linear texture and tend to be isolated peaks or groups of peaks rising above the topographic level of the matrix. Hummocky matrix consists of a rough-

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Figure 1. Examples of lenticulae (pits, spots, and domes) on Europa [after Pappalardo et al., 1998]: (a) dome, where background plains have been walled upward but not modified; (b) dome with median fracture; (c) dome like plateau apparently modified by uplift and disruption; (d) depression containing modified background plains and "micro-chaos" texture; (e) depressed annulus surrounding disrupted plateau, and (f) annulus of dark smooth material surrounding disrupted area. North is at top.

3. The Nature and Mobility of Brines

Models for the formation of the European ice shell involve solidification of a global water ocean containing salts and other related minor species [Kargel, 1991]. Solidification involves entrapment of species that have a lower melting temperature than water (e.g., brines) in the water ice crystal interstices. Although details of the formation of the European ice shell are unknown, the physical principles and related processes can be studied theoretically [e.g., Hobbs, 1974], in the laboratory [e.g., Kargel, 1998], and using analogs [e.g., Greeley et al., 1998b]. The formation, evolution, and destruction of sea ice on Earth provides a useful analog to understand the behavior of briney ice on Europa. Here we summarize key aspects of these processes [Weeks and Ackley, 1986] and highlight those that might be relevant to chaos and lenticulae on Europa.

Sea ice, or marine ice, forms when open ocean temperatures decrease below the freezing point of seawater (about -1.8°C) [Weeks, 1958; Weeks and Lee, 1962; Weeks and Ackley, 1982]. A variety of processes are involved depending on water and atmospheric temperature duration and variation patterns, atmospheric precipitation, and winds. The resulting sea ice consists of pure water ice with brine and air inclusions, the size and geometry of inclusions depend on ice crystal structure, temperature, and bulk salinity. Ice commonly forms predictable patterns of crystal orientation, and changes in texture, grain size, and composition with depth are observed, related to pressure and temperature gradients. Initially, an annual ice layer is produced, in many places this undergoes complete annual formation and destruction, but in some, cases multiple annual layers accumulate. Lower melting temperature species (e.g., brines) are contained between crystals in the ice and form brine networks.

Brines tend to migrate within solid sea ice due to temperature and concentration variations, density/ buoyancy characteristics, and the resulting gravity gradients. Examination of sea ice in the field shows that brines can migrate along pathways that range in scale from microns to meters. Brine drainage channels up to 10 cm in diameter and 6 m in length have been observed [Edie and Martin, 1975; Niedrauer and Martin, 1979]. Also observed are major brine flux events that show that brines can be mobilized, migrate, and be redeposited elsewhere, causing loss of up to tens of percent of the volume of the sea ice. This causes changes in the physical state of sea ice from rigid ice to slush over very short time periods (hours to days).

For example, loading on a sea-ice layer in the Arctic by snowstorm deposits has been observed to produce a complete upward flushing of the brine network [Hudier and Ingram, 1985]. Freezing of an Antarctic surface slush layer has been observed to result in downward brine network drainage, which induces convection within the ice; the rejected dense brine is
replaced by upper ocean seawater, increasing the overall heat flux into the overlying sea ice [Lytle and Ackley, 1996]. In the Eastern Weddell Sea [McPhee et al., 1996], basal melting of pack ice by vertical oceanic heat fluxes resulted in the flooding of the surface by upward brine percolation, accompanied by large “boils” of upward percolating brine; this slushy snow/brine mixture subsequently refroze, replacing the ice melting on the bottom. Similar types of brine migration and flooding events have been seen elsewhere. For example, in pack ice in the Eastern Weddell Sea [Ackley et al., 1995], increased air temperatures caused top heating and mobilization of sea-ice brines, resulting in surface flooding of snow-covered sea ice; as air temperatures dropped, the brine-saturated snow froze. In summary, observational evidence in a variety of sea-ice environments shows that a wide range of conditions (e.g., top-heating, bottom heating, loading) can lead to brine mobilization, vertical and lateral brine migration over short periods of time, and concurrent changes in the physical properties of the substrate (e.g., ice to slush, brine extraction, and flooding).

What are the physical processes involved in these events, and how might they be applicable to Europa? Observations in the laboratory and in the field show that brines can be distributed throughout sea ice, making up volume percentages typically 5-40%, but sometimes up to 80% [Richardson and Keller, 1966]. The range of observed scales of brine pockets and networks [Edie and Martin, 1975; Niedrauer and Martin, 1979] shows the transport pathways along which percolation and migration occur; however, until recently the details of the transition from inclusions to brine transport have not been well studied or understood.

Recent work has shown that a marked transition in the fluid transport properties of terrestrial sea ice occurs at a critical brine volume fraction ($V_c$) of $>5\%$, or critical temperature ($T_c$)
of about −5°C for a salinity of 5 ppt. For colder temperatures, the ice is impermeable to fluid transport, but for temperatures warmer than the ice, brine can migrate and transport heat through the ice ([Golden et al., 1998]. The bulk material properties of sea ice (e.g., salinity and permeability) vary dramatically over a small temperature range, and percolation theory ([Stauffer and Aharony, 1992] has been used to understand further the critical behavior of resultant brine transport. Open bonds (brine) and closed bonds (ice) can exhibit connectedness; open clusters are produced when open bonds become interconnected, and there is a percolation threshold at which average cluster size changes to an infinite cluster, and percolation occurs in the open bonds. Following this, fluid transport may occur largely through brine channels considerably greater than the size of the open bonds ([Weeks and Ackley, 1982; Fransen et al., 1994; Lytle and Ackley, 1996]. Percolation theory and models of percolation from materials analogous to sea ice ([Golden et al., 1998] yield critical brine volume values consistent with observations in sea ice; in other environments the critical volume fraction values may vary with ice crystal structure, perhaps up to a value of 40%. The critical volume fraction of brine needed for free percolation will also depend on ice fabric, geometry and nature of connectivity of pore spaces (likely depending on their mode of origin and evolution), and the mineralogy and composition of the solid phase (not necessarily solid water ice [Kargel, 1991]).

In summary, frozen water containing brines exhibits a marked transition in its fluid transport properties at critical brine volume fraction and temperature values. Such ice is impermeable to brine transport at coldest temperatures, and at warmer temperatures, brine can migrate and transport heat rapidly through brine channels to cause net volume decreases, flooding, and changes in the physical properties of materials.

Accompanying processes might include density changes and heat generation associated with ice I crystal structure changes ([Hobbs, 1974], and density variations related to hydration reactions in brine components ([Hogenboom et al., 1995]). Furthermore, evolving brine compositions and concentrations might have an effect and be even more important on Europa than in sea ice. For example, if European brines are hypersaline ([Kargel, 1991], a small change in salinity can force a much larger change in brine density than in less saline seawater. Finally, recent experiments have shown that in ice, the presence of a melt fraction of a few percent has a very large effect on the fluidity of the ice ([De La Chapelle et al., 1999]. The presence of small amounts of melt can remove sliding dislocations and decrease the internal stress field which develops during primary creep. Thus the contribution of basal glide to deformation increases with melt content, while the contribution of the stronger slip systems is correspondingly reduced. The resulting stress is thus more uniform in ice containing a liquid phase than within melt-free ice, and the creep rate is considerably enhanced. We now examine the possible implications of these physical processes for terrain on Europa.

4. Interpretation of European Lenticulae and Chaos by Heating and Brine Mobilization

Can the features observed in chaos and lenticulae on Europa be explained by heating, the percolation phase transition, brine mobilization and migration? In order to consider this model we first begin with lenticulae and then address the larger chaos terrains.

4.1. Lenticulae

Some lenticulae show dome-like structure, with background ridged plains upbowed and perhaps faulted on the margins (Figure 1); this, together with other lenticulae characteristics suggested to Pappalardo et al. [1998] and Head et al. [1997], and
manuscript in preparation, 1999] that these features represented positive diapirs rising from a layer below (Figure 2). Heat rising advectively in the diapir is thought to be related to a host of other features associated with lenticulae, including (1) destruction of domed background plains and their conversion into fragments and platelets, (2) production of a fine-grained matrix material, (3) production of smooth, volcanic-like plains in adjacent moats and surroundings, (4) surface discoloration of the central and marginal parts of the lenticulae. Previously, these phenomena have been attributed primarily to near-surface heating, melting, and associated volcanism, and/or sublimation [Pappalardo et al., 1998; Wilson and Head, 1998, 1999; Fagents et al., 1998, 1999]. Modeling suggests that these diapiric features could be characterized by near-surface temperatures in the range 250-270 K [Rathbun et al., 1998] and, most likely, ~260 K [McKinnon, 1999].

Another plausible explanation is one in which the elevated near-surface temperatures caused by advective heat transfer bring the shallow parts of the lithosphere (above and adjacent to the diapir) to the critical brine volume fraction/temperature value for brine mobilization and/or the percolation phase transition to occur. Upon reaching this critical point (Figures 3 and 4), brine mobilization and migration should take place, changing the physical properties of the substrate from a brittle lid to more incoherent, perhaps mushy-like material, and causing lateral and vertical migration of brines, depending on density contrasts, concentration gradients, and pressure gradients. The ~100 K Europa surface temperatures probably mean that there is a thin brittle surface caprace where temperatures are sufficiently low that the caprace is relatively impermeable to fluid transport. Below this thin layer, brine migration could proceed predominantly downward and out into adjacent areas,

**Figure 3.** Block diagram illustrating the interpretation of pits, spots and domes as the surface manifestation of positive diapirs. On left, the diapiric rise of warm ice causes mechanical modification of surface to form domes. On right, thermal alteration from the warm ice causes surface alteration and possible melting [after Pappalardo et al., 1998].

**Figure 4.** Block diagram illustrating the possible role of brine mobilization and migration in the formation of many of the features associated with lenticulae. Elevated near-surface temperatures caused by advective heat transfer bring the shallow parts of the lithosphere above and adjacent to the diapir to the critical brine volume fraction/temperature value for brine mobilization and migration to occur. Brine mobilization (hauchured area) changes the physical properties of the subsurface (area represented by X) and is accompanied by density changes, and lateral and vertical migration of brines. Mobilization could cause breakup of the background ridged plains above the diapir, and associated foundering, plate formation, tilting, rotation, and translation of the micro-chaos textural elements, leaving fragments of former high-topography ridges. Matrix could form by near-complete disaggregation. Brine migration could proceed downward and out into adjacent low areas formed by the rim syncline to produce the low albedo plains seen in some lenticulae. Color differences are interpreted to be caused by thermally induced brine migration processes.
emplacement. The subhed to smooth adjacent areas have puzzled observers in that they appear to be partially mantled and partially embayed, suggesting a combination of cryovolcanic flooding and pyroclastic mantling [Head et al., 1998; Fagents et al., 1999]. This brine migration explanation seems more plausible; heating would cause subhed of topography and movement of brines into adjacent low lows (Figure 4).

These interpretations appear to be supported by the color data in that the major discolorations in the solid-state imaging (SSI) multispectral data [Denk et al., 1998, 1999] occur in and adjacent to the lenticulae and chaos regions (Plate 1 and Figure 6). We interpret these discolorations to be the surface manifestations of solubilized brine-containing material [Head et al., 1999c]. Near-Infrared Mapping Spectrometer (NIMS) data have been interpreted in terms of the presence of surface salts (such as MgSO₄·XH₂O), and correlations with areas characterized by discolorations detected in SSI data have been made [McCord et al., 1998, 1999], the source of the coloration itself is unknown, and the species are thought to represent as yet undetermined impurities. Although simple grain size effects cannot be ruled out as an important contributor to the spectral and color anomalies [Dalton and Clark, 1998], the high level of correlation of the color anomalies with candidate processes that produce migration and surface emplacement of brines [Head et al., 1999c] strengthens the case for a compositional origin (Figure 4).

4.2. Chaos

Very high resolution images (E1/2, 9 m/pixel) reveal the detailed texture of the polygons and matrix [Head et al., 1999a, b] in chaos terrain. Mechanisms for the formation of the chaos terrain include complete melt through of a thin ice layer from an ocean just below the surface [Carr et al., 1998; Greenberg et al., 1998; 1999] and a variety of other hypotheses including sill-like intrusions and broad convective thermal anomalies (summarized by Collins et al. [1999]). In contrast, in the interpretation outlined here, the vast majority of the characteris
Plate 1. Portion of a color composite of the Conamara Chaos region obtained during Galileo orbit El2. Violet, green, and 756 nm filters, displayed in orthographic projection, centered at 0.2°S, 50.9°W.
Figure 7. Conamara Chaos very high resolution images. At top, the background is data from encounter E6 at 54 m/pixel, and the higher resolution inset (outlined by white lines representing image frames) is the very high resolution data (9 m/pixel) obtained on E12. Formation of chaos involves the destruction of the coherence of significant regions previously comprising background ridged plains, and the formation of matrix and enclosed polygons. Detailed mapping of this region performed by Head et al. [1999a, b] suggests that the matrix is composed of a variety of subunits that may be related in terms of their morphologic features and may represent a sequence of progressive degradation from pristine background plains, to polygons, and then through a series of progressively more morphologically degraded units to produce matrix. Here, subunits have been placed into a candidate sequence representing the interpretation of a progressive level of degradation beginning with (a) polygons of background plains, (b) subdued lineated polygon facies, (c) discontinuous ridge and scarp facies, (d) hummocky and pitted matrix facies, which comprises the majority of the matrix area, and
tics observed at moderate [Greeley et al., 1998a; Carr et al., 1998, Spaun et al., 1998] and high resolution [Head et al., 1999a, b] can be explained by heating, brine mobilization and migration, in response to diapirc rise of warm convecting subsurface ice.

4.2.1. Modification of chaos polygons. One of the key observations about chaos polygons [Head et al., 1999a] is that they appear to display a degradational sequence from unmodified polygons, through a gradual softening and degradation of surface features and block formation, to low-standing highly degraded polygons with abundant surface blocks in the tens of meters scale (Figure 7). Accompanying the change in degradation state is a decrease in polygon size and a decrease in apparent elevation of the polygon. These trends could result from the modified polygons having undergone brine mobilization (perhaps reaching the percolation phase transition) with subsequent brine migration. Minimal amounts of brine migration would result largely in near-surface readjustments and settling, causing relative smoothing of the rough lineated background texture, degradation, and block formation by disaggregation [Head et al., 1999a, b]. Larger amounts of brine migration would cause breakup of subdued polygons, more pervasive disaggregation, abundant block formation and settling, and polygon subsidence to a level depending on brine content and level of migration. Such types of vertical movement could mimic different levels of topography produced by isostatic adjustments of blocks in a fluid layer [e.g., Williams and Greeley, 1998].

Another characteristic of polygons and blocks within the matrix is that some smaller members of the block population appear to be tilted and rotated in the plane of the surface, and several others appear as peaks several hundred meters high, with little to no surface texture like that of background plains (Figures 2b and 7). These angular fragments are similar to the appearance of drifting icebergs in terrestrial high-latitude oceans (calved, rotated, large fragments of ice floating in a liquid substrate, whose surfaces have undergone alteration by melting and deposition). This similarity has led some workers to consider the possibility that these features represent analogous Europa “icebergs” or blocks floating in a region melted through from a very near-surface ocean [Carr et al., 1998, Greenberg et al., 1998, 1999; Williams and Greeley, 1998].

Alternatively, these features may be explained by brine migration. Near-surface heating should cause large-scale brine mobilization. If this process is completely homogeneous, then brines will migrate vertically (up or down) depending on their density relative to their surroundings. Five factors suggest that the process is not likely to be homogeneous, resulting in lateral variations in terrain breakup: (1) there are lateral variations in surface topography in the background ridged plains ranging from a few tens of meters to over 200 meters [Greeley et al., 1998a], (2) there are likely to be lateral variations in thermal structure, (3) there are likely to be lateral and vertical variations in the brine content, (4) there are likely to be lateral variations in thermally or dynamically produced topography (as seen in the lenticulae, J. Head et al., manuscript in preparation, 1999)) (Figures 3 and 4), and (5) subsurface structure (fractures, lithologic boundaries, and discontinuities) that might tend to channel or hinder brine migration. Any or all of these could contribute to polygon fragment listing, rotation, and peak formation (Figure 8).
Figure 8. Block diagram illustrating some of the main characteristics of chaos terrain and how they might be explained by brine mobilization and migration. In this model, brine mobilization (hatchured area) utilizes the physical properties of much of the substrate (area represented by Xs), which dominates much of the chaos matrix, particularly in the area above the maximum heat input (center front of diagram). Along the margins of the chaos, blocks are undercut and translate inward, and sometimes rotate into the chaos (label A). Further away from the margin, the lateral gradient results in fracturing and faulting and slight inward displacement (B). Within the chaos, areas immediately above the major heat input undergo the most pervasive destruction of background plains. Polygons are formed and progressively disaggregated and degraded to create matrix facies (C and D) (see Figure 7). Some larger polygons rotate and translate up to a few kilometers (E), moving generally away from the most highly modified regions. These are interpreted to have moved along a shallow decollement surface in response to mobilization of the underlying layer, perhaps aided by minor slopes associated with topographic changes related to heating and mobilization (see Figure 4). Lateral heterogeneities in brine concentrations and heat input may produce observed variations within the chaos terrain, such as percentage of matrix, character and extent of matrix subunits, and coherence and migration of polygons.

Consider, for example, the fate of a segment at the margins of a larger polygon undergoing brine migration (Figure 8). Lateral migration of brine from below the brittle surface will cause a decrease in the volume of material below that surface, producing a lateral gradient in the degree of volume decrease (i.e., most brine will migrate from the margins, least from the interior). This gradient will cause subsidence preferentially toward the margins of the polygon and will produce an accompanying stress gradient that will favor fracturing, tilting, separation, and lateral movement of the region in the direction of the brine migration (Figure 8). This process can readily cause the variations in the topography of polygons that appear to be tilted in the plain of the surface.

4.2.2. Isolated peaks. Isolated peaks and groups of peaks can be explained by the same processes operating on a smaller scale (on smaller fragments), and any local topographic variations may be enhanced by the local topography and structure of the preexisting substrate (Figure 8). For example, in several cases, peaks in the matrix occur preferentially near prominent ridges in adjacent polygons (Head et al., 1999a, b) and this initial high topography may account for the locally high topography of the peaks (Figure 8). In addition, any of the several factors listed above as possibly causing lateral variations could produce locally high regions (e.g., a block of pure ice that did not undergo significant brine migration).

4.2.3. Polygon formation and migration. Another characteristic of chaos regions is the formation of polygons of background ridged plains and their migration for distances measured in kilometers (Greeley et al., 1998a; Carr et al., 1998; Head et al., 1999a, b; Collins et al., 1999; Spaul et al., 1998, 1999; Greenberg et al., 1998, 1999; Williams and Greeley, 1998). Detailed analysis of high resolution images of regions within Conamara Chaos shows various examples of this breakup and polygon migration (Head et al., 1999a, b). In all cases, breakup and polygon migration appear to be accompanied by surface degradation, broad block tilting, rotation of smaller blocks at larger polygon margins, and formation of peaks at polygon margins adjacent to areas of high topography. All of these phenomena could be explained by brine mobilization and migration, perhaps aided by the presence of melt fractions of a few percent in the adjacent ice framework (De La Chapelle et al., 1999).

In addition, regional gradients in brine mobilization and migration can create stresses that can account for polygon breakup. Consider, for example, a large region of background ridged plains surrounded by newly formed localized heat sources (lenticulae). As these cause localized brine mobilization in the area immediately above the heat source, they also set up more regional thermal gradients that can produce brine mobilization gradients, which in turn, will produce variations in surface stresses in the outer brittle layer that might result in fracturing of this brittle layer. Thus variations in such gradients have the potential to cause stresses that could result in fracturing and breakup of background ridged plains terrain into polygons.

But what factors might cause migration of these polygonal blocks? Some of the most significant environments for large-scale lateral migration of rock masses on Earth are gravitational gradients aided by heterogeneities in the physical properties of the substrate, specifically, shallow brittle-ductile transitions in the case of detachment faults (Davis and Lister, 1998; Huddleston, 1992), and pore-water pressure lubrication in the case of some large-scale thrust sheets (Hubbert and Rubey, 1959). In these situations, formation of a mobile near-surface layer or discontinuity (decollement) permits gravitational forces to move rock masses hundreds to thousands of square kilometers in area over lateral distances of many tens to hundreds of kilometers, often leaving the deeper substrate exposed (Davis and Lister, 1998; Huddleston, 1992). In some cases the mobile surface layer is deformed at the margins, and sometimes is deformed internally, but commonly the rock masses are translated great distances without significant large-scale internal deformation (Davis and Lister, 1998; Huddleston, 1992). Similar processes may have operated on Europa with percolation phase transitions, partial brine mobilization and migration, and/or the presence of melt fractions of a few percent in the adjacent ice framework enhancing deformation rates (e.g., De La Chapelle et al., 1999). These situations would result in a distinctive change in the physical properties of a zone or layer at depth to produce decollements, as brines that were once a coherent part of the frozen ice substrate became partially molten and mobile (Figure 8).

In the case of a homogeneous layer of mobilized brine at depth, blocks would tend to migrate in the direction dictated by gravity gradients and local topographic variations. Large blocks might tend to migrate along topographic gradients (off of lenticulae, or toward regions of recently formed chaos matrix, for example). Analysis of this type of behavior in a number of terrestrial environments (Davis and Lister, 1988; Huddleston, 1992; Hubbert and Rubey, 1959) shows that extremely low topographic gradients are sufficient to cause large-scale movement. Assessment of areas observed at high-
resolution on Europa [Head et al., 1998a, b] shows that migration occurs primarily toward regions of maximum development of matrix material. Thus brine mobilization on Europa appears to be a plausible process for detachment-style motion of surface polygons and their lateral migration for distances measured in kilometers (Figure 8). Production of a detachment layer might be aided if initial surface freezing of the European ice shell produced a layer dominated by water ice and the abundance of enclosed brines increased with depth. In addition, the lateral migration of detached brille plates will expose deeper subsurface layers, those representing the brine-rich mobile layers. As we discuss in more detail below, such areas in Conamara Chaos are characterized by discolorations which can be plausibly associated with the presence of brines [McCord et al., 1998, 1999; Denk et al., 1998; 1999; Head et al., 1999c].

4.2.4. Hummocky matrix. Another texture that is characteristic of the Conamara Chaos matrix is hummocky material [Head et al., 1999b; Spahn et al., 1998, 1999], a rough textured surface that is distributed between other submatrix units and includes jumbled surface blocks from ~1 km in diameter down to the image resolution (Figure 2b). At moderate resolution (~180 pix/pixel) this terrain bears a striking similarity to that seen in the central parts of lenticulae described above. Brine mobilization and migration provide a mechanism for production of such terrain. First, in areas of the most significant thermal flux (for example, above lenticulae) the substrate is most likely to undergo the percolation phase transition, and accompanying brine migration will cause extensive disaggregation and destruction of the background ridged plains texture, and production of a hummocky surface (Figures 1, 4). This may be analogous to a process operating at a different scale on Earth, the formation of hydrothermal breccias, which involve selective dissolution and precipitation of different phases, the physical translation and mixing of material, and the formation of angular rock fragments in a chaotic matrix (a breccia) (J. Kargel, personal communication, 1999). Second, the progressive destruction of polygons described above can also produce this hummocky texture, as polygons become completely disaggregated and fragmented in situ (Figure 7). Third, lateral migration of polygons can expose subsurface layers which, in contrast to the tectonically lineated surface texture, could be characterized by finer-scale textures associated with brine migration and resolidification. Indeed, the hummocky and somewhat pitted texture of a significant part of the matrix substrate [Head et al., 1999a] may well be related to the processes of brine migration and resolidification (Figures 7, 8).

5. Surface Color Variations

Multispectral images obtained by the Galileo SSI system for regions characterized by lenticulae and chaos show that surface discolorations are preferentially correlated with these features [Denk et al., 1998, 1999; Clark et al., 1998; Head et al., 1999c], as described above. Lenticulae show surface discolorations which are most prominent in the central micro-chaos regions and adjacent lows and nearby areas (Plate 1 and Figure 6). Chaos shows prominent color variations and discolorations within and along the margins of the chaos, compared to the generally homogeneous background plains (Plate 1 and Figure 6). Analysis of Conamara Chaos provides important information including the following: (1) most polygons within Conamara are discolored, in contrast to the background ridged plains exterior to Conamara; (2) the vast majority of the matrix material is discolored; (3) lenticulae marginal to the chaos are discolored; (4) some of the most prominent ridges and ridge segments within the chaos appear least discolored. Widespread brine mobilization, migration, and percolation caused by subsurface heating can account for all of these characteristics. Exposure of briny oceans in the intervening areas caused by melt-through from an ocean just below the surface [Carr et al., 1998; Greenberg et al., 1998, 1999] might account for the observed color characteristics of the matrix, but less readily explains the color variations in the polygons. Brine mobilization also offers a viable alternative to explosive cryovolcanism as a mechanism for producing dark deposits with feather edges that appear to subdue and possibly mantle terrain adjacent to chaos, lenticulae, and ridges [Head et al., 1998; Pagenst et al., 1999].

6. Summary and Conclusions

Can the features observed in chaos and lenticulae on Europa be explained by the percolation phase transition, brine mobilization and migration, and related processes? We find that the range of morphologies and color attributes of lenticulae, and chaos polygons and matrix can be reasonably accounted for by such processes. This, combined with the very high likelihood that brines are admixed in the crust of Europa [Kargel, 1991], leads us to the conclusion that this model deserves serious consideration in terms of further analysis of the evolution of the surface of Europa and the origin and evolution of mottled terrain. Some models for the surface features on Europa call on complete melt-through from an ocean at very shallow depths below the surface [Carr et al., 1998; Greenberg et al., 1998, 1999], but such a process is not concordant with the current understanding of Europa's thermal balance [Ojakangas and Stevenson, 1989]. Although the percolation phase transition, brine mobilization and migration, and related processes would also occur if the thermal gradient were sufficiently steep that liquid water existed very close to the surface, these processes provide a mechanism that does not require the heat input necessary for melt through [e.g., Pappalardo et al., 1999a]. Solid state convection and warm ice diapirism [Pappalardo et al., 1998], perhaps augmented by local tidal heating [McKinnon, 1999] could initiate these processes and plausibly produce the range of observed features.

Not addressed by this treatment are several important questions that require additional detailed examination. What range of brine percentages and temperatures might lead to mobilization and migration and to the percolation phase transition under Euopan conditions? How will the presence of melt or salt fractions of a few percent in the ice framework influence the creep rate and the accompanying deformation rates there? How does the distribution of brines change with geological time and crustal evolution? Can a combination of morphological and remote sensing analyses be used to estimate the presence and abundance of brines in the European ice? What are the sources of heat for formation of lenticulae and chaos? In the case of the lenticulae, heat sources are interpreted to be related to diapirism linked to solid state convection in a layer underlying a brittle thin lid and possibly overlying a liquid water layer [Pappalardo et al., 1998]; do the larger chaos areas require areally extensive heating sources, or can they be accounted for thermal coalescence of multiple lenticulae? How old are these regions and do
they represent a special time in the geological history of Europa? What are the implications of the brine migration mechanism for the presence of an ocean on Europa at the present time [Carr et al., 1998; Pappalardo et al., 1999b]? These related questions can be addressed with data collected on the Galileo Europa Mission and upcoming remote sensing and landing missions to Europa.

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J. W. Head and R. T. Pappalardo, Department of Geological Sciences, Brown University, Box 1846, Providence, RI 02912 (James_IHead_III@brown.edu)

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