JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. E4, PAGES 7567-7576, APRIL 25, 2001

A model of Europa's crustal structure: Recent Galileo results and implications for an ocean

Nicole A. Spaun and James W. Head III

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

Abstract. Recent results from the Galileo Near-Infrared Mapping Spectrometer (NIMS) experiment suggest that hydrated magnesium sulfate salts may be present on the surface of Europa. We use this interpretation and a model for the chemical budget of Europa's outer water-rich layer to determine (1) how Europa's profile atop the mantle may have evolved by cooling and fractional crystallization from an initial liquid state and (2) the potential effects of this evolution on the surface geology. This model leads to predictions that the lower part is composed of layers of heavily hydrated magnesium sulfates, which effectively isolate any ocean from direct physical contact with the silicate mantle. These lower layers are overlain by an ocean which has an icy solid upper layer present at the surface; this ocean may have persisted through time. Eutectic conditions are predicted to lead to thickening of the overlying ice shell and freezing out of the ocean, although tidal heating may maintain the liquid layer. Mechanisms such as solid-state convection can further serve to thicken, thin, and/or mix the ice shell. Thermal diapirism could be induced by convection, and compositional diapirism could be driven by density instabilities within the layers. In this model, early global compression would have given way to later global expansion.

1. Introduction

Jupiter's moon Europa has a relatively young icy surface [*Lucchitta and Soderblom*, 1982; *Pappalardo et al.*, 1999]. It has been suggested that Europa may maintain a liquid water ocean beneath its icy surface, and thus a key question is, What is Europa's crustal structure? One interpretation of the recent results from the Galileo Near-Infrared Mapping Spectrometer (NIMS) suggests the presence of magnesium sulfate hydrate and perhaps other salts on the surface of Europa [*McCord et al.*, 1998, 1999]. These salts are generally concentrated in the reddish areas of mottled terrain and some linear endogenic features; however, the salts are not responsible for the coloration. The reddish color may come from other materials associated and/or entrained with the colorless salts, or the color may be from the exposure of brines to radiation. Mottled terrain is composed of endogenic features such as ridges, long linear features of positive topography, and chaos and lenticulae, which are disrupted features that have been inferred to exhibit thermal alteration or exposure/extrusion of a subsurface material [*Greeley et al.*, 1998; *Spaun et al.*, 1998; *Pappalardo et al.*, 1999; *Greenberg et al.*, 1999; *Fagents et al.*, 2000]. Therefore models for the formation of these geological features rely heavily upon predictions of the nature of the crust. Another interpretation of the NIMS data has recently been proposed by *Carlson et al.* [1999], citing sulfuric acid and colored radiolytic products as the best match to the Europan spectra and thus mottled terrain material. While this interpretation may also have implications for the crustal profile of Europa, we address the magnesium sulfate interpretation within this work. This model is the next step beyond considering first-order models, where water is the primary component in the Europan crust [*Pappalardo et al.*, 1998; *Greenberg et al.*, 1999], and the prelude to future detailed modeling of more complex possible Europan crustal compositions.

We address the plausibility of a Europan ocean by considering the evolution of the Europan crust with water and magnesium sulfate as the critical components [*Spaun et al.*, 1999, 2000]. We present a simple model for the differentiation of the crust, determine the thickness of the proposed crustal layers, and consider the geological implications of the crustal profiles. We can thus assess the depth to and size of a potential ocean in this model.

2. Model

2.1. Initial Conditions

Recent results from Galileo gravity data agree with previous suggestions that Europa is differentiated, with a dominantly metallic core underlying a rock mantle and a water ice-liquid outer crust [*Cassen et al.*, 1982; *Schubert et al.*, 1986; *Anderson et al.*, 1997, 1998]. Geologically, crust is a compositional term denoting a body's outermost layer that has undergone chemical differentiation, and thus Europa's crust is the entire water-rich outer layer overlying the siliceous mantle [*Pappalardo and Head*, 1999]. The mechanical terms for Europa's crust, as we use them, are defined following *Pappalardo and Head* [1999]: ice shell or lid is the solid upper crust, ocean is the liquid part of the crust, lithosphere is the brittle part of the ice shell, and asthenosphere is the ductile part of the ice shell.

Our model assumes that Europa's evolution follows the aqueous differentiation of chondrites; thus, after core and

Paper number 2000JE001270.
0148-0227/01/2000JE001270$09 00

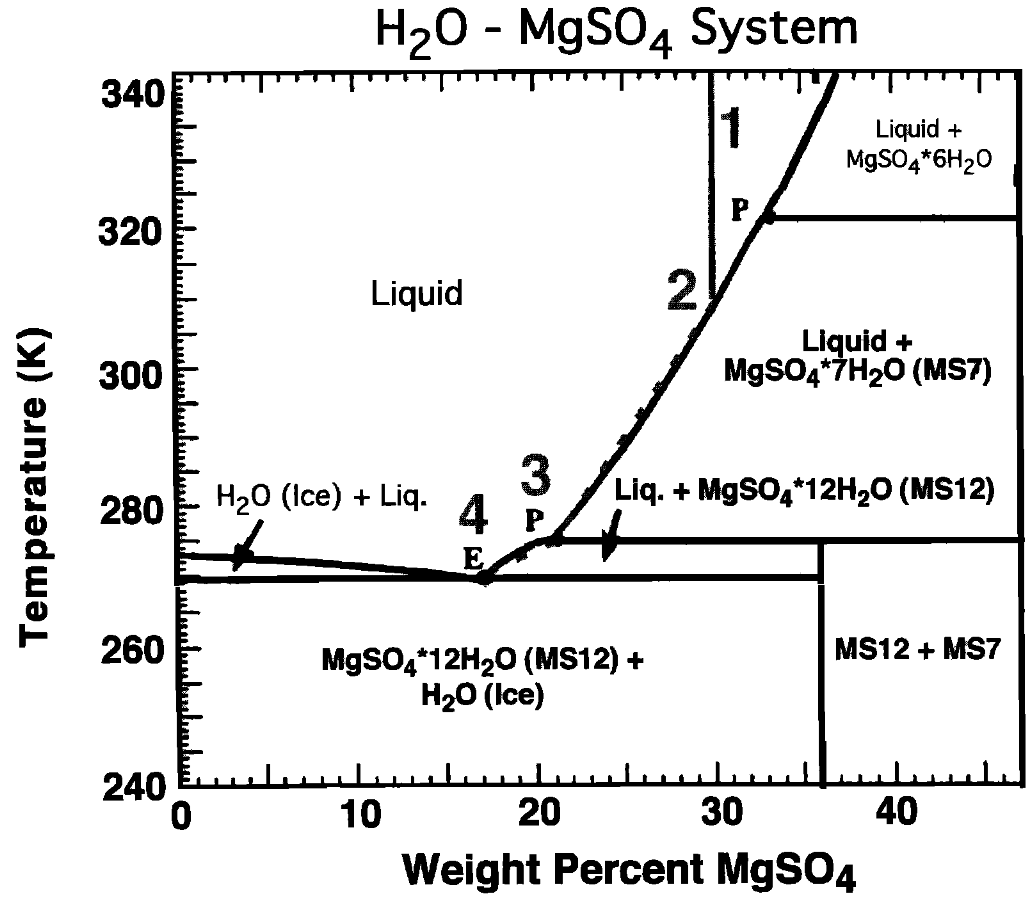


Figure 1. The phase diagram for the binary magnesium sulfate-water system at 0.1 MPa (after *Hogenboom et al.*, [1995]). The solid shaded line indicates the initial conditions and the shaded numbers correlate to the onset of the corresponding stage of crystallization in the model. The shaded dashed line indicates the path of the liquid brine in the system. P, Peritectic points; E, Eutectic point.

mantle formation, the initially liquid crust of Europa contains 70% H_2O and 30% $MgSO_4$ [after *Kargel*, 1991]. In the *Kargel* [1991] and *Kargel et al.* [2000] models, Na_2SO_4 was also a minor product (a few percent) of the differentiation. We consider only the binary system between water and magnesium sulfates (Figure 1); readers are referred to *Kargel et al.* [2000] for treatment of the ternary system. Their results indicate that small amounts of sodium sulfate hydrates should form together with magnesium sulfates, thus suggesting that both brines behave similarly under Europan conditions. Figure 2 depicts the crystallization sequence for our binary model. Neither this work nor *Kargel et al.* [2000] consider variations in the phase diagram due to pressure changes. The pressure at the bottom of the Europan ocean is estimated to be 200 MPa. *Hogenboom et al.* [1995] have shown that the eutectic point shifts slightly with increasing pressure to 200 MPa; however, the shift does not alter the sequence of crystallization, and thus we do not further consider it in this first-order model.

We assume fractional crystallization occurs, where heavier solids sink out and lighter ones float and are thus removed from the system. This is a reasonable assumption owing to the great differences in density and viscosity of the materials [*Kargel*, 1991; *Hogenboom et al.*, 1995]. Therefore our model assumes an idealized initial condition that the crust is totally liquid which then undergoes perfect fractional crystallization. This is opposite to the idealized model of *Kargel* [1991] and *Kargel et al.* [2000], who assumed that the crust developed incrementally by perfect fractional partial melting of the interior. Comparison of the models indicates that these two very different approaches yield notably similar results, although some details differ.

The initially liquid state is an interesting case which might approximate conditions following a catastrophic global crustal melting event, where the model describes the path of resurfacing. The model could also approximate conditions following a regional crustal melt-through event [e.g., *Greenberg et al.*, 1999]. Solidification of brine flows or plutons could follow a similar crystallization sequence, although obviously, the thicknesses of the layers produced would differ from those calculated in this work.

2.2. Stage 1

The exposure of liquid to space will foster rapid cooling to form a thin (few Kilometers) heterogeneous layer of 70% H_2O and 30% $MgSO_4$, thus insulating the ocean from space (Figure 2). Conduction across this lid and convection within the ocean will serve to cool the liquid crust. Heat conduction will also thicken the initial lid. Because our model is not time constrained, it is difficult to address issues concerning the thickening of this lid, such as how thick will it be by the time the rest of the ocean reaches the eutectic, what is the

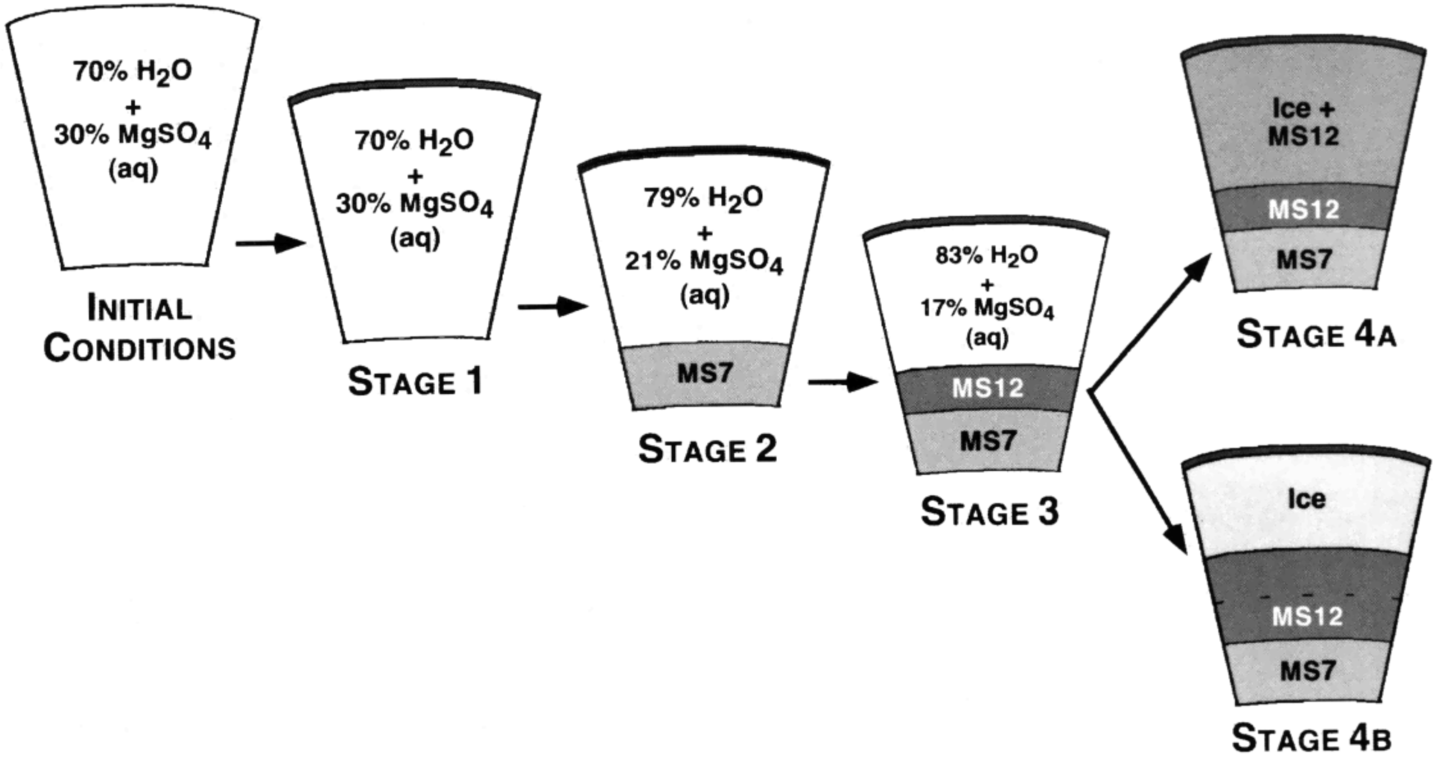


Figure 2. The crystallization sequence derived in our model. The diagrams are not to scale but illustrate qualitatively the possible profiles of Europa's crust through time. The initial conditions are a wholly liquid crust composed of 70% H_2O and 30% $MgSO_4$. Stage 1 is the formation of a thin, heterogeneous surface layer/lid containing 70% H_2O and 30% $MgSO_4$. Stage 2 is the formation of a layer of MS7 which physically isolates the ocean from the mantle. Stage 3 occurs when an MS12 layer forms atop the MS7 layer. There are two options for Stage 4 eutectic freezing: stage 4a and 4b. Stage 4a is when a heterogeneous layer of ice plus MS12 forms and floats over the freezing eutectic ocean. Continued crystallization of ice plus MS12 adds to the thickening lid and may eventually solidify the ocean. Stage 4b occurs when ice and MS12 form and separate according to density. The MS12 layer sinks and adds to the previous MS12 layer formed in stage 3. The ice will float out above the eutectic ocean and serve to thicken the overlying lid. Continued crystallization of ice and MS12 will increase the sizes of those layers while squeezing the ocean until it freezes into ice and MS12.

composition of this thickening lid, and how will that affect the ocean. We thus neglect the conductive freezing of this lid and assume it is initially thin. We can also assume that liquid convection keeps the temperature at the top of the ocean approximately equal to that at the base. If the liquid convection were very vigorous, crystals would not be able to settle, and thus a thick solid-solution ocean would be maintained; this ocean would consequently be the end of the model as long as vigorous convection continued. Because such a case is not as interesting to model, we therefore assume less vigorous convection, allowing crystal settling and thus perfect fractional crystallization to occur. According to the H_2O-$MgSO_4$ phase diagram (Figure 1), solids will not begin to crystallize until a temperature of $T = 308$ K is achieved.

2.3. Stage 2: Reaching the Liquidus

When the temperature drops to 308 K, the path reaches the liquidus on the phase diagram. $MgSO_4{\cdot}7H_2O$ (MS7) will begin to precipitate. The density of MS7 is 1680 kg/m^3 [*Hogenboom et al.*, 1995], and it will thus sink out of the residual liquid, which is now 79% H_2O and 21% $MgSO_4$. This will form a layer of MS7 between the ocean and the mantle, effectively physically isolating the ocean from the silicate mantle (Figure 2). The separation of the mantle from the ocean implies that chemical interactions between the two cannot occur. Heat from the interior of Europa, which is small compared to the heat supplied to the ocean from tidal heating, can conduct across the isolating salt layers and contribute to the thermal profile of the ocean, but significant internal heating events will have to melt the overlying salt layers before the silicate mantle and ocean reservoir are in direct contact again.

2.4. Stage 3: The Peritectic Point

At $T = 275$ K the peritectic point is reached, and $MgSO_4{\cdot}12H_2O$ (MS12) will begin to crystallize. With a density of 1500 kg/m^3, the MS12 will sink out of the residual liquid, which is now 83% H_2O and 17% $MgSO_4$. The MS12 will form a layer, stable to density driven overturns, atop the MS7 and beneath the briny ocean (Figure 2).

2.5. Stage 4: The Eutectic Point

With MS12 crystallization, the liquid is driven along the liquidus on the phase diagram to $T = 269$ K, the eutectic point. At the eutectic point, ice and MS12 begin to form. There are two possible paths that the differentiation may take: (1) heterogeneous or (2) homogenous formation of layers.

2.6. Stage 4A

Fast cooling and/or turbulence will lead to a heterogeneous layer of ice plus MS12. The mixed layer has a density of ≈ 1130 kg/m^3, lighter than the eutectic liquid ($\rho \approx 1190$ kg/m^3), and will thus float over the ocean and under the surface layer (Figure 2). This is the first time since the formation of the surface layer that significant thickening of the lid occurs within our model, and this has several implications for the thermal profile and geological predications (see sections 4.1 and 4.2). At this point, the underlying ocean may continue to freeze solid if eutectic conditions persist. Thus a completely solid Europan crust will be, from the top down, a thin heterogeneous initial layer of 70% H_2O and 30% $MgSO_4$, a mixed layer of ice plus MS12, the eutectic ocean, a layer of MS12, and a layer of MS7.

2.7. Stage 4B

Slow cooling and/or little turbulence allows the ice and MS12 to stratify by density and thus separate during crystallization. The ice ($\rho = 917$ kg/m^3) floats above the eutectic liquid, and the MS12 sinks below (Figure 2). The ocean may continue to freeze solid at this point. Therefore the final, solid crustal profile, from the top down, is a thin heterogeneous initial layer of 70% H_2O and 30% $MgSO_4$, a layer of pure ice, the eutectic ocean, a layer of MS12, and a layer of MS7.

3. Thickness of Crustal Layers

Galileo gravity data were used to obtain the moment of inertia for Europa [*Anderson et al.*, 1997, 1998], and this was used to model the moon's internal profile, considering likely core compositions (Fe or Fe-FeS); in all cases, a crustal mixture of water-ice was assumed with a density of 1050 kg/m^3, though other densities were considered in their plots. The crust of Europa was determined to be 80-170 km thick [*Anderson et al.*, 1998].

In our model, we consider a saline Europan crust, which has a greater bulk density ($\rho = 1360$ kg/m^3). To balance the contrast in density between interior and exterior of Europa and thus match the moment of inertia, a thicker crust is required [see *Anderson et al.*, 1998]. Using the plots from *Anderson et al.* [1997, 1998] and the above bulk density, we find that for a mostly solid crust of 70% H_2O and 30% $MgSO_4$ the whole crust will be 130-210 km thick. We can calculate the volume of the crust for the extremes of crustal thickness and thus arrive at a value for the initial mass of both water and magnesium sulfate in each case (130 and 210 km). Calculating crustal layer thicknesses involves a complex balancing of factors. For example, a liquid containing 70% water and 30% magnesium sulfate will produce MS7 crystals composed of 51% H_2O and 49% $MgSO_4$, while leaving a residual liquid of 79% water and 21% magnesium sulfate. Thus we find that 23% of the initial allotted mass of H_2O and 53% of the original mass of $MgSO_4$ go into MS7 crystallization and are thus removed from the system. We use the mass and the density of the materials to determine the volume of each layer. Because we know the radial location

Table 1. The Crustal Layer Thicknesses in the Model

Crustal Thickness	130 km	210 km
Stage 1. Initial lid	~ 1 km	~ 1 km
Stage 2: MS7 layer	35 km	60 km
Stage 3: MS12 layer	17 km	28 km
Stage 4a: Ice + MS12	80 km	127 km
Stage 4b: MS12 layer	30 km	48 km
Stage 4b: Ice layer	47 km	74 km

We have determined the thickness values for both the 130 and 210 km thick crustal cases to show the range of possible layer thicknesses. Note that these values are for a completely solid Europan crust, and therefore the stage 4 eutectic values listed are the maximum layer thickness for that crustal profile. In stage 4, incomplete solidification will yield a residual ocean reducing the thickness of the solid crustal layers. Thus we can also view the stage 4 layer values as the maximum thickness of a potential ocean at the eutectic point of $T = 269$ K.

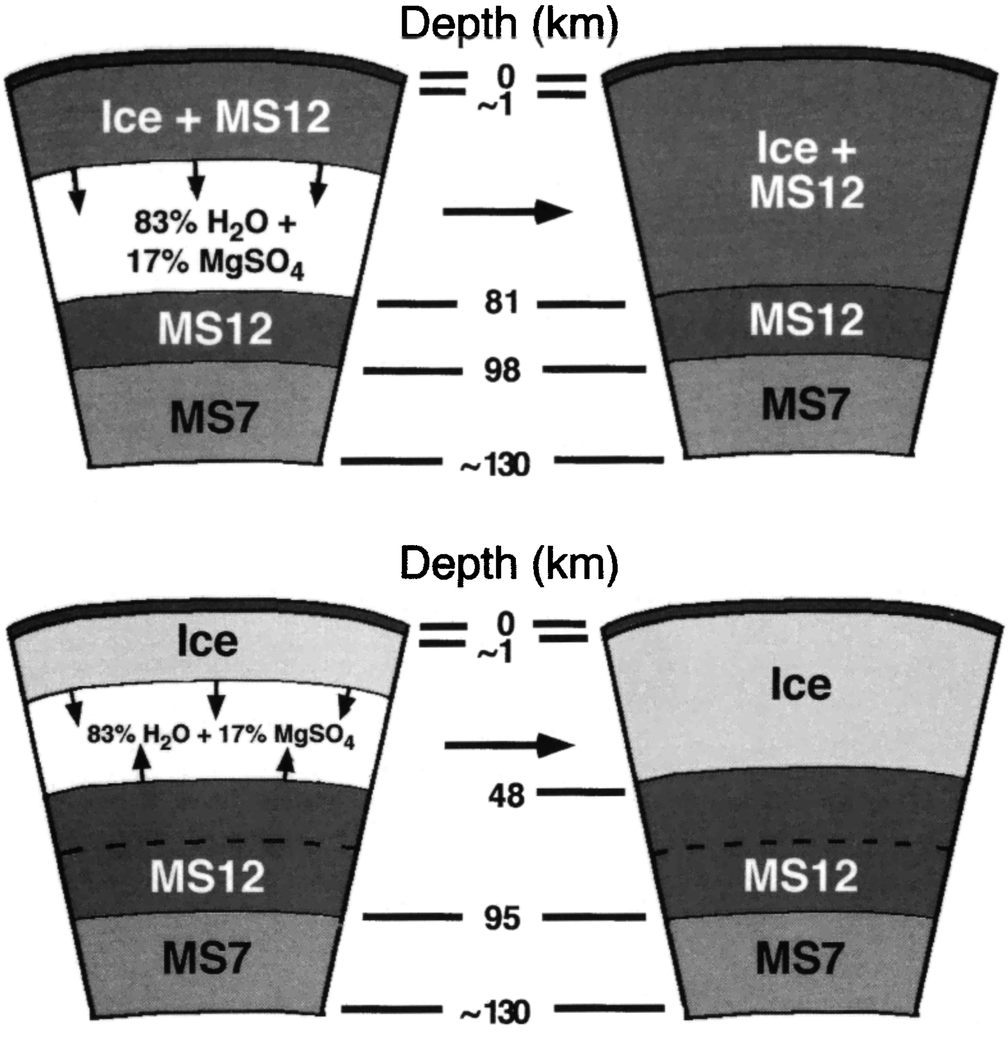


Figure 3. The crustal layer thicknesses illustrated for the minimum case of a 130 km thick Europan crust. The depth from surface is shown in kilometers. (top) Stages 4a and (bottom) 4b are shown both as solidifying and solid. The illustrations are not to scale.

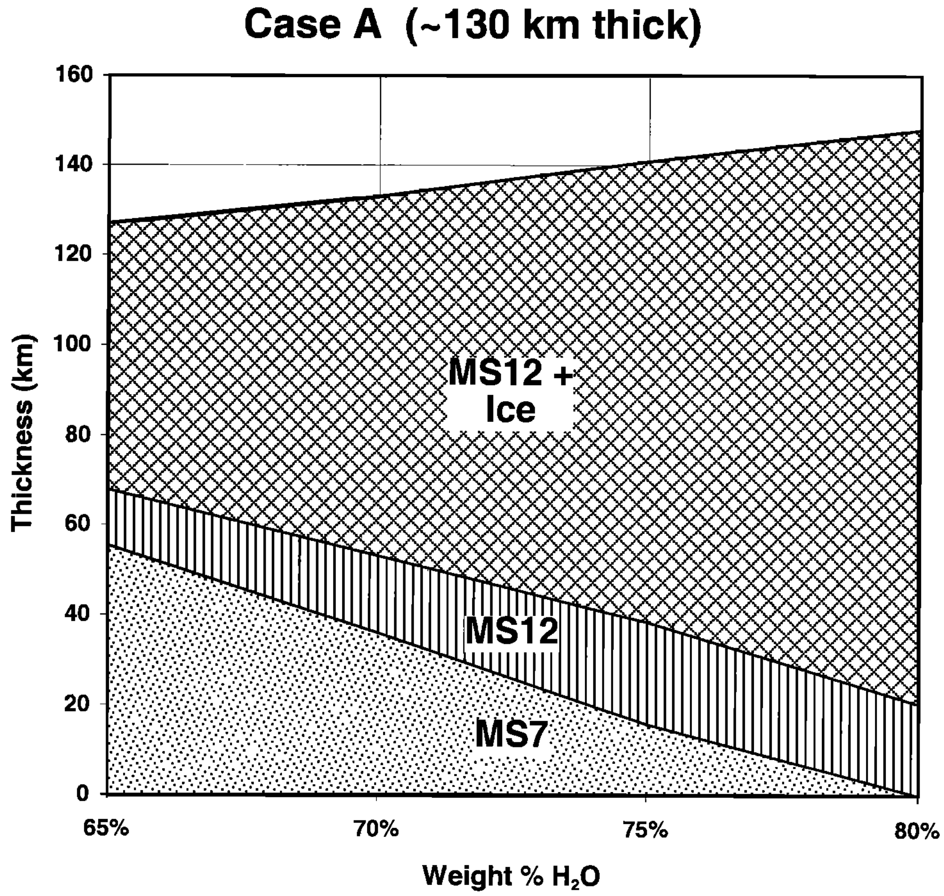
of the layer, we then calculate the thickness of the layer. Table 1 summarizes the results for both the extrema, 130 and 210 km crustal thickness, and Figure 3 depicts the depth from surface results for the 130 km case.

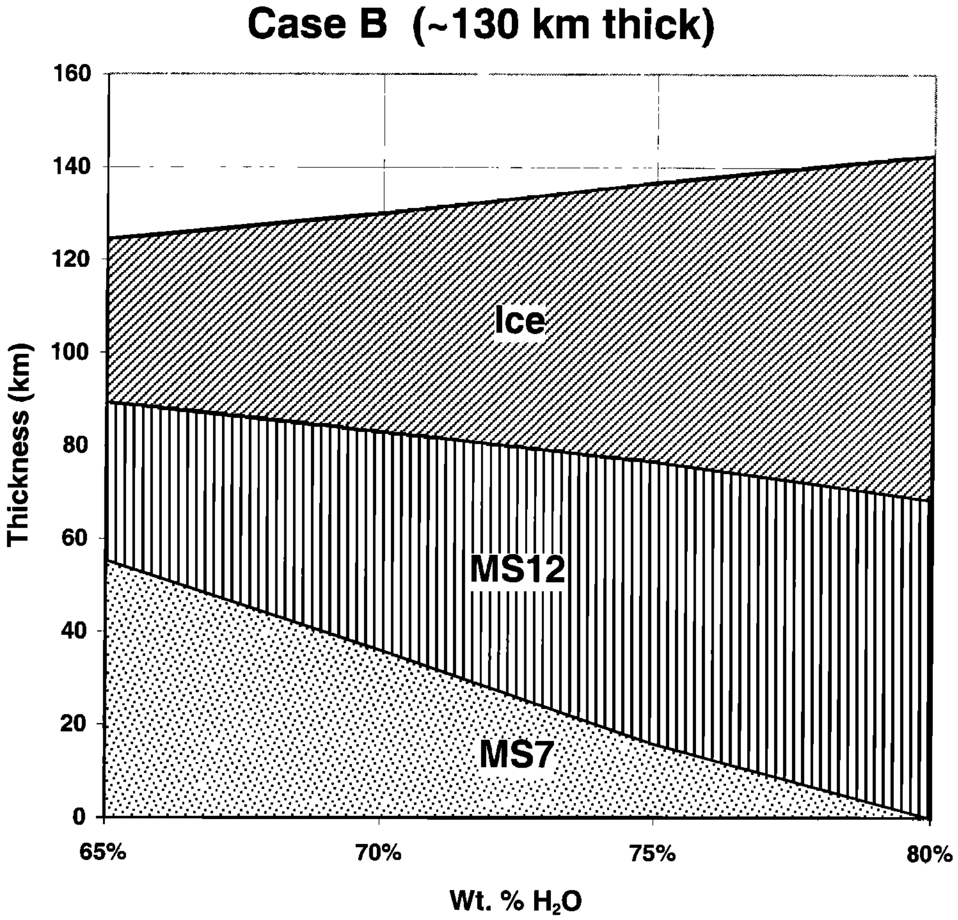
As a test of the sensitivity of our model to initial composition, we recalculated the values of layer thickness for initial compositions from 65 to 80% H_2O. Figure 4 illustrates the 130 km thick crustal profile under the varying initial compositions. Because the bulk density of Europa was not proportionately varied during this test, the overall crustal thickness of Europa increases with increasing water content. The disappearance of the MS7 layer at 79% H_2O occurs because a peritectic is reached on the phase diagram (Figure 1) and, at this point, MS12 forms instead of MS7. The sensitivity test illustrates that varying the composition in this range will only change the thicknesses of the layers proportionately and not the crystallization sequence. Note that in the ternary system considering sodium sulfate the thickness of these layers would also be different, although the sequence would be similar with sodium sulfate hydrates forming with the magnesium sulfate hydrates.

4. Discussion

4.1 Crustal Stress Profile

During the early stages, Europa will undergo global compression as dense phases crystallize. The crystallization of ice in stage 4, as either pure ice or ice plus MS12, involves a 3% volumetric expansion. Thus, in the later stages, Europa will undergo global expansion. Observations have shown that dominantly extensional features are found on Europa [*Greeley et al.*, 1998; *Pappalardo et al.*, 1999]. It is possible that this is evidence of a late global expansion. Early estimates of expansion on Europa from Voyager 2 data suggest 5–15% expansion is necessary to accommodate observed features [*Smith et al.*, 1979]. To date, the amount of expansion on Europa from Galileo images has not been geologically constrained. Of course, the Europan surface is very young [*Lucchitta and Soderblom,* 1982; *Zahnle et al.*, 1998], and thus significant resurfacing has occurred over the course of Europan history. Therefore evidence of global compression and/or expansion is probably no longer observable, unless it was delayed or extended into very recently in Europa's history.


Case A (~130 km thick)
Thickness (km)
0
20
40
60
80
100
120
140
160
MS12 + Ice
MS12
MS7
65%
70%
75%
80%
Weight % H_2O


Case B (~130 km thick)
Thickness (km)
0
20
40
60
80
100
120
140
160
Ice
MS12
MS7
65%
70%
75%
80%
Wt. % H_2O

4.2. Thermal and Density Profiles

In Europa's early history it is likely that the crust, as we know it, did not exist until after the core and mantle formed. After this, heat input to the overlying water-rich layer from the mantle and core would be great enough to be off the phase diagram in Figure 1. Therefore our initial condition for Europa is a water-rich liquid solution layer overlying the mantle. The liquid convection occurring in this solution and later residual ocean maintains a constant temperature across the liquid body. This temperature is determined by Europa's initial heat allotment (e.g., accretional heating), the gain of heat from Europa's interior, and the loss of heat to space by conduction. Soon after the formation of this water-rich layer and with exposure of the solution to the cold vacuum of space, a thin heterogeneous lid of ~70% H_2O and 30% $MgSO_4$ will be formed in stage 1. This lid will remain very thin owing to high internal heat sources. The thermal balance between internal heating and heat conduction across the lid, from the interior out to space, will maintain a liquid solution ocean beneath this lid and atop the mantle until the temperature drops to T = 308 K and the liquidus is reached, thus allowing fractional crystallization of solids to occur. Significant thickening of the upper lid will not occur until the eutectic point is reached in stage 4. Stages 2 and 3 form bottom layers of MS7 and MS12, respectively. These layers physically and chemically isolate the silicate mantle from the overlying ocean. Conduction of heat from the interior across these salt layers will add to the crustal heat budget. Significant internal heating events may later affect the phase of the layers overlying the mantle, but this work is only concerned with the original compositional profile and not the possible remelting of layers once they are formed.

There are many observed geological features (see *Pappalardo et al.* [1999] for a review) which show surface disruption, such as in chaos and lenticulae, or exposure of newer material, such as ridges and bands (Plate 1). During stages 1, 2, and 3 these features may be explained by the thinning of the surface layer and the extrusion/exposure of the subsurface ocean, as suggested in the melt-through model (see *Greenberg et al.* [1999] for details). These features would obtain their reddish coloration from material entrained with the brines in the ocean or from surface weathering of the brines. This mechanism of feature formation is restricted to early stages in the history of Europa, as thickening of the lid in stage 4 should prevent such melt-through. It is also possible that heavy bombardment by projectiles early in Europa's history could break and/or break through this surface layer, leading to large-scale resurfacing by the freezing of a new thin layer from the residual ocean. As the Europan surface is very young [*Lucchitta and Soderblom*, 1982; *Zahnle et al.*, 1998] and significant resurfacing has occurred over the course of Europan history, evidence of an early heavy bombardment is likely to have been erased by now.

Another major heat source on Europa is tidal heating. Heat input to the crust must keep the ocean temperature over 269 K to prevent eutectic freezing and thus thickening of the lid. With a surface temperature of 100 K, a thermal gradient of 169 K/km is thus required for the 1 km thick lid; therefore it is likely that evolution will proceed to stage 4, the eutectic point, because of the small temperature change required to go from stage 3 to stage 4.

At stage 4a a heterogeneous layer of ice plus MS12 will crystallize and float, forming beneath the thin brittle lid. As the ice shell thickens, the thermal gradient of this shell will decrease. The lower part of the ice shell may exhibit ductile behavior and act as an asthenosphere. At a critical value of shell thickness, the asthenosphere may undergo solid-state convection. It has been suggested that tidal heating may focus within a convecting layer [*Ojakangas and Stevenson*, 1989; *McKinnon*, 1999]. This basal heating of the ice shell may be able to reach a steady state where the current shell thickness and underlying ocean are maintained. Thermal diapirism may occur within this layer, possibly causing the segregation of salts from ice. The coloration of features would be created by the extrusion of this briny diapiric material which either entrains contaminants or becomes red after exposure to radiation. The salt-rich areas could also be formed by the mobilization of salts already present within the overlying thin heterogeneous layer [*Head and Pappalardo*, 1999].

In our stratified model we find that the layers are stable to overturn driven by compositional density gradients. However, it is possible that density instabilities will exist within the ice plus MS12 layer in stage 4a. The density contrast between MS12 and ice is ~ 580 kg/m^3. If this MS12 plus ice layer is poorly mixed such that pockets of ice exist, then compositional diapirism may occur [see also *Kargel et al.*, 2000], similar to upwelling of terrestrial salt domes. Again, salts and contaminants entrained within the diapirs may account for the saline spectral signature and the geological feature coloration, while diapirs are ultimately responsible for the formation of the features. Also, isolated pockets of salts may occur, and thus rising thermal diapirs encountering the pockets could create a partial melt because hydrated salts melt at lower temperatures than pure ice. This partial melt would be briny and thus create features containing salts.

If eutectic freezing occurs as stage 4b instead, a layer of pure ice will form and float out above the eutectic liquid, just under the thin lid, while denser MS12 will form and sink beneath the eutectic ocean. The ice shell may thicken to a critical value and possibly convect as explained above. In a convecting Europan ice shell, thermal diapirism can occur and create the observed surface features [*Rathbun et al.*, 1998; *Pappalardo et al.*, 1998]. The reddish coloration and saline spectral signature of features is hard to explain by the rise of icy diapiric material unless it has entrained some briny ocean material from the ocean-asthenosphere interface. It is more likely that a thermal diapir impinging on the thin heterogeneous layer causes brine mobilization within that layer [*Head and Pappalardo*, 1999]. The movement of salts to areas of higher heating and the driving off of ice should create salty surface features that appear reddish through space weathering or the presence of

Figure 4. The crustal layer thicknesses for the initial composition range 65-80% H_2O for both eutectic cases as a test of sensitivity of the model. The disappearance of the MS7 layer at 79% H_2O composition corresponds to a peritectic point on the phase diagram (Figure 1). While the thicknesses of the layers will shift proportionately, the overall sequence remains unchanged.

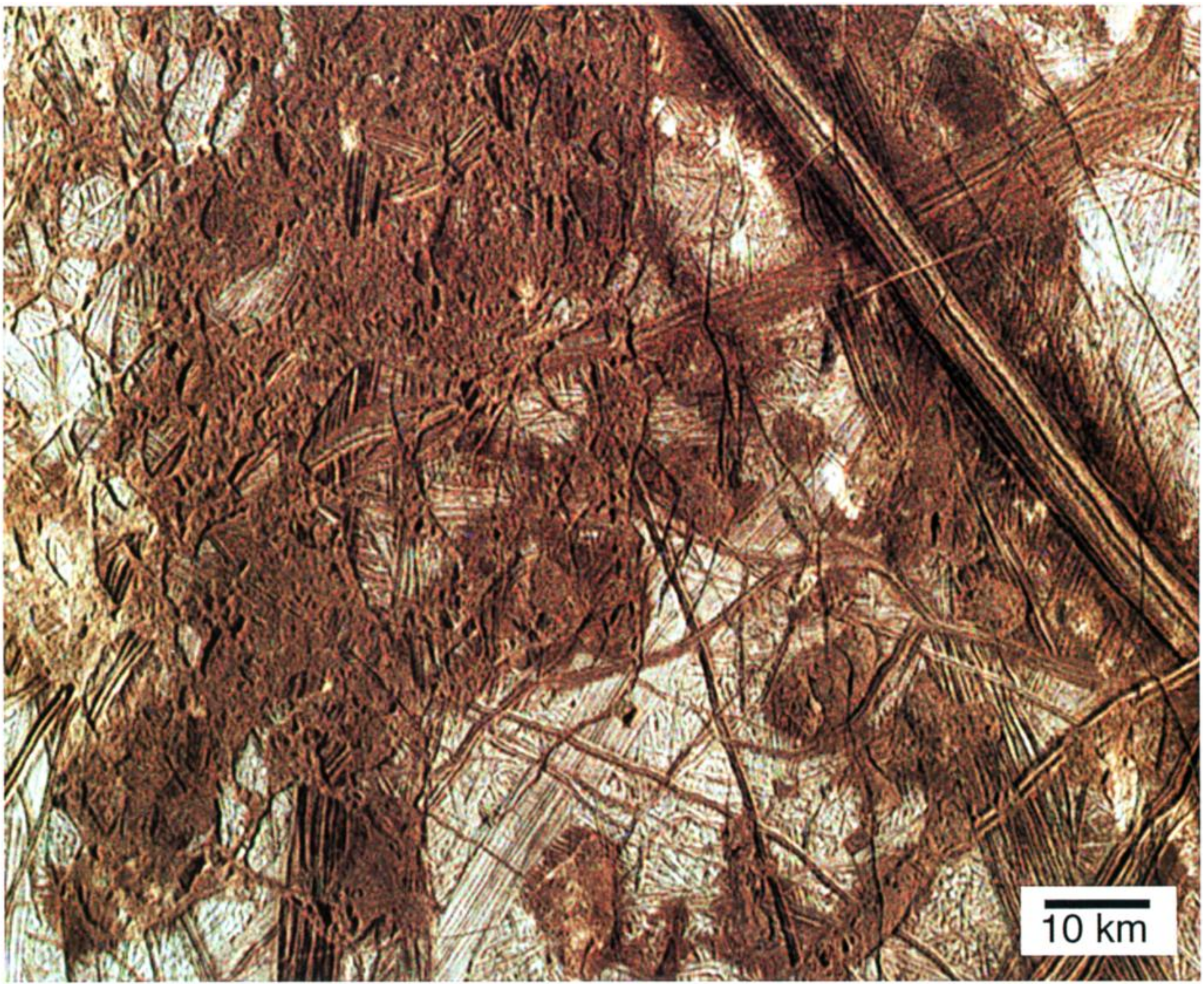


Plate 1. A color mosaic of the Conamara Chaos region on Europa (8°N, 271°W). The Galileo Near-Infrared Mapping Spectrometer has suggested the presence of magnesium sulfate hydrates within the reddish areas of mottled terrain. In images such as these we see that the reddish material, deemed salt-rich, is associated with disrupted features, such as chaos and lenticulae, and also linear features such as ridges. Mosaic created by the DLR, Berlin, Germany.

contaminant materials. A related model by *Collins et al.* [2000] favors a partial melt forming within the thin heterogeneous surface layer by impinging thermal diapirs from the asthenosphere. This partial melt will be saline and, through extrusion or brine mobilization, can account for the appearance of observed geological features.

5. Conclusions

We have outlined a simple model of the evolution of Europa's outer water-rich layer by cooling and fractional crystallization from an initially liquid state. (1) In this model, differentiation of Europa's crust will begin with a thin, brittle conductive lid overlying an ocean, then formation of basal hydrated salt layers isolating the ocean from the mantle, and last a thickening lid of ice, or ice plus hydrated salt, overlying a eutectic ocean, which is driven deeper with progressive freezing. (2) The isolation of the ocean from the mantle has implications for potential mantle hydrothermal heat sources. Current models for the possible hydrothermal evolution of life on Europa need to take into account the possible physical separation of the silicate mantle from the briny ocean. (3) Solid-state convection may occur in the thickening lid potentially driving thermal diapirism; dissipation of tidal heat in this layer may serve to maintain an ocean at depth. (4) Early global compression may have given way to global expansion by the crystallization of ice later in the history of Europa.

Acknowledgments. This work was conducted under the guidance of Marc Parmentier; we truly appreciate his help and support. We thank Jeff Kargel and Tom McCord for helpful reviews and many excellent discussions. We would also like to thank Geoff Collins for productive discussions. This work was supported by grant 958512 from NASA JPL to J.W.H.

References

Anderson, J. D., E. L. Lau, W. L. Sjogren, G. Schubert, and W. B Moore, Europa's differentiated internal structure: Inferences from two Galileo encounters, *Science, 276*, 1236-1239, 1997.

Anderson, J. D., G. Schubert, R. A. Jacobson, E. L. Lau, W B. Moore, and W. L. Sjogren, Europa's differentiated internal structure: Inferences from four Galileo encounters, *Science, 281*, 2019-2022, 1998.

Carlson, R., R. E. Johnson, and M. S. Anderson, Sulfuric acid on Europa and the radiolytic sulfur cycle, *Science, 286*, 97–99, 1999.

Cassen, P. M., S. J. Peale, and R. T. Reynolds, Structure and thermal evolution of the Galilean satellites, in *Satellites of Jupiter*, edited by D. Morrison, pp. 93-128, Univ. of Ariz. Press, Tucson, 1982.

Collins, G. C., J. W. Head, R. T. Pappalardo, and N. A. Spaun, Evaluation of models for the formation of chaotic terrain on Europa, *J. Geophys. Res., 105*(E1), 1709-1716, 2000.

Fagents, S. A., R. Greeley, R. J. Sullivan, R. T. Pappalardo, and L. M. Prockter, Cryomagmatic mechanisms for the formation of Rhadamnthys Linea, triple band margins, and other low albedo features on Europa, *Icarus, 144*, 54-88, 2000.

Greeley, R., R. Sullivan, M. D. Coon, P. E. Geissler, B. R. Tufts, J. W. Head, R. T. Pappalardo, and J M. Moore, Initial Galileo SSI observations, *Icarus, 135*, 25–40, 1998.

Greenberg, R., G. V. Hoppa, B. R. Tufts, P. Geissler, J. Riley, and the Galileo SSI Team, Chaos on Europa, *Icarus, 141*, 263-286, 1999.

Head, J. W., and R T. Pappalardo, Brine mobilization during lithospheric heating on Europa: Implications for formation of chaos terrain, lenticulae texture, and color variations, *J. Geophys Res*, *104*(E12), 143–155, 1999.

Hogenboom, D. L., J. S. Kargel, J. P. Ganasan, and L. Lee, Magnesium sulfate-water to 400 MPa using a novel piezometer: Densities, phase equilibria, and planetological implications, *Icarus, 115*, 258-277, 1995.

Kargel, J. S., Brine volcanism and the interior structures of asteroids and icy satellites, *Icarus, 94*, 368-390, 1991.

Kargel, J. S., J. Z. Kaye, J. W. Head III, G M. Marion, R. Sassen, J K. Crowley, O. P. Ballesteros, S. A. Grant, and D L. Hogenboom, Europa's crust and ocean: Origin, composition, and the prospects for life, *Icarus, 148*, 226-265, 2000.

Lucchitta, B K., and L. A. Soderblom, The geology of Europa, in *Satellites of Jupiter*, edited by D. Morrison, pp. 521-555, Univ of Ariz. Press, Tucson, 1982.

McCord, T. B., et al., Salts on Europa's surface detected by Galileo's near infrared mapping spectrometer, *Science, 280*, 1242–1245, 1998.

McCord, T. B., et al., Hydrated salt minerals on Europa's surface from the Galileo near-infrared mapping spectrometer (NIMS) investigation, *J. Geophys. Res., 104*(E5), 11,827–11,851, 1999.

McKinnon, W. B., Convective instability in Europa's floating ice shell, *Geophys. Res. Lett., 26*(7), 951-954, 1999.

Ojakangas, G. W., and D. J. Stevenson, Thermal state of an ice shell on Europa, *Icarus, 81*, 221-241, 1989.

Pappalardo, R. T., and J. W. Head, Europa: Role of the ductile layer [CD-ROM], *Lunar Planet Sci. Conf. XXX*, abstract 1967, 1999.

Pappalardo, R. T., et al., Geological evidence for solid-state convection in Europa's ice shell, *Nature, 391*, 365-368, 1998.

Pappalardo, R. T., et al., Does Europa have a subsurface ocean?, *J. Geophys Res., 104*(E10), 24,015-24,055, 1999.

Rathbun, J. A., G. S. Musser, and S. W. Squyres, Ice diapirs on Europa: Implications for liquid water, *Geophys Res. Lett., 25*(22), 4157–4160, 1998.

Schubert, G., T. Spohn, and R. T. Reynolds, in *Satellites*, edited by J. A Burns and M. S. Matthews, pp. 629-688, Univ. of Ariz. Press, Tucson, 1986.

Smith, B. A., et al., The Galilean satellites and Jupiter: Voyager 2 imaging science results, *Science, 206*, 927–950, 1979

Spaun, N. A., Modeling Europa's crustal evolution (abstract), *Eos Trans. AGU, 80*(46), Fall Meet. Suppl., F606, 1999

Spaun, N. A., J. W. Head, G. C. Collins, L. M. Prockter, and R. T. Pappalardo, Conamara Chaos region, Europa· Reconstruction of mobile polygonal ice blocks, *Geophys. Res. Lett., 25*(23), 4277-4280, 1998.

Spaun, N. A., E. M. Parmentier, and J. W. Head, Modeling Europa's crustal evolution: Implications for an ocean [CD-ROM], *Lunar Planet Sci. Conf. XXXI*, abstract 1039, 2000.

Zahnle, K., L. Dones, and H. F. Levison, Cratering rates on the Galilean satellites, *Icarus, 136*, 202–222, 1998.

J. W. Head III and N. A. Spaun, Department of Geological Sciences, Box 1846, Brown University, Providence, RI 02912. (Nicole_Spaun@brown.edu)

(Received April 10, 2000; revised October 2, 2000; accepted January 4, 2001.)