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Causes, characteristics and consequences of convective diapirism on Europa

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[1] We investigate the hypothesis that the ~10 km diameter dome-shaped features seen on Europa's surface are caused by strongly temperature-dependent convection, in which upwellings form isolated diapirs or thermals. We use the observed lower limit on dome diameter of 4 km to deduce that the conductive (stagnant) lid thickness must be $\leq$5 km. Such a lid thickness implies a minimum surface heat flux of 90 mWm^{-2}, compatible with recent estimates of tidal heating. We also use the mean observed dome diameter to infer a lower thermal boundary layer thickness of ~1 km. We find that the ice is probably deforming in the diffusion creep regime with a grain size in the range 0.02–0.06 mm. The fraction of internal heating is >0.5, the ice viscosity 10^{12}–10^{13} Pa s, and the crustal solidification rate <5km/Ma. *INDEX TERMS:* 6218 Planetology: Solar System Objects: Jovian satellites; 5430 Planetology: Solid Surface Planets: Interiors (8147); 5418 Planetology: Solid Surface Planets: Heat flow; 5455 Planetology: Solid Surface Planets: Origin and evolution. **Citation:** Nimmo, F., and M. Manga, Causes, characteristics and consequences of convective diapirism on Europa, *Geophys. Res. Lett.*, *29*(23), 2109, doi:10.1029/2002GL015754, 2002.

1. Introduction

[2] Some of the most visually distinctive features on Europa's surface are the ~10 km-diameter roughly circular lenticulae. Many are domes, showing positive elevations of up to ~100 m [*Fagents et al.*, 2000], and sometimes displaying surrounding moats [*Rathbun et al.*, 1998]. The domes appear to be some of the youngest features on the satellite, since they are only rarely disrupted by other tectonic features [*Pappalardo et al.*, 1998]. The surface age of Europa is of order 30 Ma, with an uncertainty of about a factor of 5 [*Zahnle et al.*, 1998]. The size-frequency distribution of the domes shows one peak, close to the minimum observed dome size [*Rathbun et al.*, 1998; *Spaun et al.*, 2001]. More than 90% of observed domes have diameters greater than 4 km, and the median dome diameter is in the range 7–11 km. *Spaun et al.* [2002] found an average dome spacing of 15–23 km.

[3] Most explanations for lenticulae formation have suggested some kind of diapiric or convective activity [*Pappalardo et al.*, 1998; *Rathbun et al.*, 1998; *Ruiz and Tejero*, submitted] though icy volcanism [*Fagents et al.*, 2000] and melt-through of the icy crust [*Greenberg et al.*, 1999] have also been considered. Numerical models of the surface deformation produced by rising and spreading diapirs [e.g., *Koch and Manga*, 1996; *Rathbun et al.*, 1998] are consistent with most lenticula morphologies.

[4] In this paper we investigate a specific model of diapirism. In strongly temperature-dependent convection, a stagnant lid forms at the surface with approximately iso-viscous convection occurring beneath this lid. The hot bottom boundary layer creates discrete buoyant regions or diapir plumes which will ascend and spread. These diapirs will spread laterally as the stagnant lid is approached. The density difference between the diapir and the surrounding ice gives rise to the surface deformation, which will also be affected by the stagnant lid thickness. Here, we use observations of dome diameter to constrain the thickness of the top (stagnant) and bottom thermal boundary layers, and hence infer the characteristics of the convecting system.

2. Effect of the Stagnant Lid

[5] Near the surface the ice is cold and will behave in a rigid fashion; at greater depths it will undergo ductile deformation. The near-surface, elastic portion of the stagnant lid may reduce the deformation caused by convection. Because both the stagnant lid thickness δ_0 and the effective elastic thickness t_e are controlled by temperature, they are likely to be related. Here we will simply assume that $t_e = \phi\,\delta_0$ where ϕ is a constant. On Earth, while the oceanic lithosphere thickness is ~100 km, t_e is usually in the range 20–50 km [e.g., *Watts*, 2001], so ϕ is in the approximate range 0.2–0.5. Here we will generally assume that ϕ = 0.4, and address uncertainties in section 6.

[6] An ascending spherical diapir of initial radius r will impose a stress on the surface elastic layer of maximum magnitude $2r\Delta\rho g$, where $\Delta\rho$ is the density difference and g is the acceleration due to gravity. The resulting surface topography h is given by [*Watts*, 2001]

$$h = \frac{2r\Delta\rho}{\rho}\,\frac{1}{1 + 16D\pi^4/\lambda^4\rho g},\ D = Et_e^3/12(1-\sigma^2). \quad (1)$$

[7] E is the Young's modulus, λ is the effective wavelength of the diapir, σ is the Poisson's ratio and ρ is the ice density. A numerical model for deformation due to axisymmetric loads [*Barnett et al.*, 2002] was used to confirm that $\lambda = 4r$ is the correct effective wavelength to use for a spherical diapir. Thus, given a diapir radius and stagnant lid thickness, the resulting surface deformation may be determined.

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3. Variable Viscosity Convection

[8] The deformation of ice may be described by [e.g., *Goldsby and Kohlstedt*, 2001]

$$\dot{\epsilon} = A g_s^{-p} \sigma^n \exp(-Q/RT) \tag{2}$$

where $\dot{\epsilon}$ is the strain rate, g_s the grain size, σ the differential stress, Q the activation energy, R the gas constant, T the absolute temperature and A, p and n are constants. For a specified stress, the effective viscosity $\eta = \sigma/\dot{\epsilon}$ may thus be written as [*Solomatov and Moresi*, 2000; hereafter *SM*]

$$\eta(T) = \frac{c}{\sigma^{n-1}} \exp(Q/RT) \approx \frac{b}{\sigma^{n-1}} \exp(-\gamma T) \tag{3}$$

where $\gamma = Q/RT_i^2$, $c = g_s^p/A$, b is a constant and T_i is the temperature of the convecting interior.

[9] The vigour of convection in a variable viscosity fluid is characterized by the Rayleigh number Ra_i [*SM*]

$$\mathrm{Ra}_i = \frac{\rho g \alpha_i \Delta T d^{\frac{n+2}{n}}}{\kappa_i^{\frac{1}{n}} c^{\frac{1}{n}} \exp(Q/nRT_i)} \tag{4}$$

where α is the thermal expansivity, $\Delta T = T_i - T_s$, T_s is the surface temperature, κ is the thermal diffusivity and the subscript $_i$ denotes quantities evaluated at the interior temperature. The effective temperature difference ΔT_e driving the convection beneath the stagnant lid is given by [*SM*] $\Delta T_e = 1.2(n+1)/\gamma$.

[10] In the case of internal heating, *SM* showed that the stagnant lid thickness δ_0 is given by

$$d/\delta_0 = (0.31 + 0.22n)\ (\gamma \Delta T)^{\frac{-2(n+1)}{n+2}}\ \mathrm{Ra}_i^{\frac{n}{n+2}}. \tag{5}$$

[11] If the hot bottom thermal boundary layer produces upwellings, the thickness of this layer δ_1 may be obtained by assuming that it is at the critical Rayleigh number $\mathrm{Ra}_{cr}(n)$ [e.g., *Solomatov*, 1995]:

$$\frac{\rho g \alpha_i (T_m - T_i) \delta_1^{\frac{n+2}{n}}}{\kappa_i^{1/n} c^{1/n} \exp(2Q/nR(T_i + T_m))} = Ra_{cr}(n) \tag{6}$$

where the relevant viscosity is that at the mean temperature in the layer [*Manga et al.*, 2001] and the base of the layer is assumed to be at T_m. We use $Ra_{cr}(n)$ as given by *Solomatov* [1995].

[12] Given T_i, δ_0 and δ_1 the fraction of internal heating (assumed uniform) μ may be obtained. Since the surface heat flux F equals that across the bottom boundary layer plus the internally-generated heat, we have for $\mu < 1$

$$(\delta_1(1-\mu) + \delta_0) \ln T_i = \delta_0 \ln T_m + (1-\mu)\delta_1 \ln T_s \tag{7}$$

where the logarithms arise from the thermal conductivity of ice, which equals $567/T$ [*Klinger*, 1980]. For a specifed value of μ, Equations (4–7) may be solved simultaneously to obtain T_i, δ_0 and δ_1.

Table 1. Values of Quantities Assumed for Europa

quantity	units	value
ρ	kg m^{-3}	917
g	m s^{-2}	1.3
α	K^{-1}	$6.24 \times 10^{-7} T$
κ	m^2 s^{-1}	$9.19 \times 10^{-2} T^{-2}$
d	km	30

Both α and κ are Dependent on Temperature (T).

[13] Experimental results [*Manga and Weeraratne*, 1999] show that the diapir radius is $r \approx 2.5\delta_1$. For non-Newtonian fluids, numerical simulations [*Houseman and Molnar*, 1997] show that the value of n has little effect on the typical diapir size. If the buoyancy is purely thermal, then it is given by $\rho\alpha\Delta T_e$; however, compositional buoyancy may also be important.

4. Parameters

[14] Table 1 summarizes the nominal parameters adopted for this study. The surface temperature of Europa is about 110 K [*Ojakangas and Stevenson*, 1989] and T_m is assumed to be 270 K. The thickness of the solid ice crust is a matter of some debate, although recent evidence from cratering studies [*Schenk*, 2002] suggest that it must be at least 20 km thick. Fortunately, most of the quantities of interest are independent of d.

[15] We use the same thermal properties of ice as *McKinnon* [1999], except for α and κ, which are assumed to be temperature-dependent [*Kirk and Stevenson*, 1987]. We use the rheological properties of *Goldsby and Kohlstedt* [2001] and focus on the diffusion creep (DC) regime, for reasons explained below. For the diffusion case, if the grain size g_s greatly exceeds the grain boundary width ($\sim 10^{-9}$ m) it can be shown that [*Goldsby and Kohlstedt*, 2001, Equation 4]

$$A = 42 V_m D_{0,V}/RT_i \tag{8}$$

where V_m is the molar volume (1.97×10^{-5} m^3) and $D_{0,V}$ is the volume diffusion pre-exponential (9.1×10^{-4} m^2 s^{-1}).

[16] The grain size on Europa is unknown. *McKinnon* [1999] argues that g_s at tidal strain rates is unlikely to exceed 1 mm, and may be less if grain growth is controlled by the presence of impurities.

5. Results

[17] Figure 1 shows the resulting maximum surface deformation as a function of initial diapir radius r for various values of δ_0. The diapir is assumed to be either spherical ($\lambda = 4r$) or elongated ($\lambda = 8r$); in the latter case the surface deformation is reduced by a factor of 4 to account for the spreading [*Koch and Manga*, 1996]. Assuming that the minimum detectable dome amplitude is about 10 m, Figure 1 shows that for spherical diapirs the minimum diapir radius to produce detectable surface features is about 1–2 times δ_0. Similar results are obtained for spreading diapirs. Since the minimum observed lenticula radius is 2 km, the value for δ_0 on Europa is unlikely to exceed 2–4 km. For the likely temperature of the convective interior

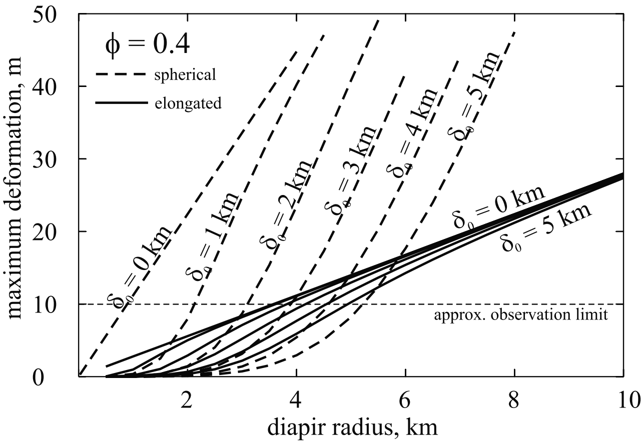

Figure 1. Surface deformation as a function of initial diapir radius and conductive lid thickness δ_0, calculated using equation (1) and $t_c = 0.4\ \delta_0$. Young's modulus 1 GPa, Poisson's ratio 0.25, thermal expansivity 1.4×10^{-4} K^{-1}, density contrast due to 40 K temperature contrast, other parameters given in Table 1. Dotted lines are for spherical diapir; solid lines are for diapir which is spreading laterally (see text).

($\sim$250 K; see below), the heat flux implied by this value of δ_0 is at least 100–200 mW m^{-2}.

[18] The median observed dome radius is $\approx$4 km. Taking into account lateral spreading, the initial diapir radius is therefore likely to be 2–4 km implying $\delta_1 = 0.8 - 1.6$ km. For a diapir radius of 3 km, the timescale for thermal decay is $\sim 10^5 a$. This result may explain why the domes are observed to be young [*Pappalardo et al.*, 1998]—diapirs have formed continuously through Europa's past, but only the youngest ones still retain enough heat to produce surface features.

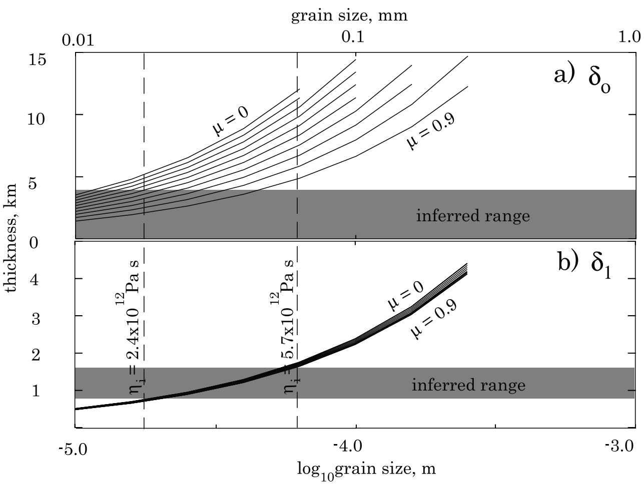

Figure 2. Theoretical boundary layer thicknesses as a function of grain size and fraction of internal heating μ. Shaded areas denote thickness ranges inferred from observations (see text). (a) Stagnant lid thickness (δ_0). (b) Bottom thermal boundary layer thickness (δ_1). Vertical dashed lines give upper and lower bounds on grain sizes; these end-members are tabulated in Table 2.

Table 2. Results for DC and GBS Rheologies [*Goldsby and Kohlstedt*, 2001] for Different Grain Sizes

quantity	unit	DC	DC	GBS
Q	kJ mol^{-1}	59	59	49
n	–	1	1	1.8
p	–	2	2	1.4
g_s	μm	20	60	1.6
μ	–	0.5	0.9	0.9
Ra_i	–	2.0×10^8	1.0×10^8	6.5×10^5
δ_0	km	3.9	4.7	3.3
δ_1	km	0.8	1.7	1.9
F	m W m^{-2}	119	104	146
η_i	Pa s	2.4×10^{12}	5.7×10^{12}	9×10^{12}
T_i	K	249	262	257

[19] Figure 2 plots both δ_0 and δ_1 as a function of grain size for different values of μ. Because δ_1 is assumed to be determined by local conditions (Equation 6), it is almost independent of μ. For the range of δ_1 inferred, the grain size must be in the range 0.02–0.06 mm. Figure 2a shows that for δ_0 there is a trade-off between grain size and μ. The lower limit on g_s and the upper limit on δ_0 of 4 km together imply $\mu \geq 0.5$, though this result is sensitive to small variations in the limiting values, and also assumes uniform internal heating, which may not be accurate [*Sotin et al.*, 2002]. Table 2 summarizes the results from the two end-member grain sizes. It also details the results of calculations using grain-boundary sliding (GBS) [*Goldsby and Kohlstedt*, 2001]. Because the effective viscosity is higher than in the (Newtonian) DC case, smaller grain sizes (<2 μm) are required.

6. Discussion

[20] We argue above that both δ_0 and δ_1 may be constrained by surface observations. The upper bound on δ_0 is especially significant because of the high heat fluxes it implies; it is therefore necessary to investigate the likely uncertainties.

[21] A larger value of δ_0 would be obtained if ϕ were overestimated or the stress due to the diapir were underestimated. *Nimmo et al.* [2002] use a viscoelastic approach which allows ϕ to be calculated as a function of rheology and strain rate. For DC rheology and strain rates in the range 10^{-10}–10^{-15} s^{-1} the value of ϕ is 0.21–0.55. Repeating the calculations in Figure 1 with $\phi = 0.2$ results in a minimum diapir radius of 0.8–2 δ_0. For a factor of two uncertainty, the observed 2 km minimum dome radius implies a mean stagnant lid thickness in the range 1–5 km. This range implies $t_e = 0.2$–3 km using $\phi = 0.2$–0.6, similar to previous t_e estimates [*Pappalardo et al.*, 1998; *Williams and Greeley*, 1998]. A lid thickness of $\leq$5 km implies the mean surface heat flux must be >90 mWm^{-2}, and is compatible with the estimates of thickness of the rigid part of the shell from *Carr et al.* [1998] and inferences of a ductile-brittle transition at 1–2 km depth [*Pappalardo et al.*, 1999; *Ruiz and Tejero*, 2000].

[22] *Ruiz and Tejero* [submitted] also find that convection is compatible with heat fluxes of 100–mWm^{-2}. These authors, however, concluded that GBS (superplastic flow) was a viable mechanism, while we think that DC is more likely. The most likely reason for the disagreement is that Ruiz and Tejero assume a constant (tidal) strain rate of 2 $\times$

$10^{-10}s^{-1}$, whereas ours is calculated from the convective timescale [*SM*]. The interactions between convective and tidal strains are currently poorly understood [*Sotin et al.*, 2002], so it is unclear which approach is correct.

[23] The most likely cause of the high heat flux is tidal dissipation within the crust [e.g., *Ojakangas and Stevenson*, 1989]. *Hussmann et al.*, [2002] concluded that tidally-generated heat fluxes of up to 300 mWm^{-2} can be produced for realistic viscosity structures. Although these authors concluded that such large heat fluxes could not be removed by convection, the results presented here suggest that removal of such heat is not in fact a problem.

[24] Pure internal heating only generates sinking plumes [*SM*], and for moderate fractions of internal heating the ascent velocity of diapirs is reduced [*Sotin and Labrosse*, 1999]. Thus, if domes are a manifestation of diapirism, a non-zero fraction of heating must occur within or below the bottom thermal boundary layer. Figure 2 provides a lower bound on μ of 0.5. *Weeraratne* [1999] found that rising diapirs were still generated when $\mu = 0.67$ in fluids with a temperature-dependent viscosity.

[25] The heat flux across the bottom thermal boundary layer may be due to viscous dissipation within the layer or heat added from the ocean below. The contributions of radiogenic and tidal heating to the ocean from the silicate interior probably total at least 10 mWm^{-2} [*Hussmann et al.*, 2002]. If the total heat flux through the base of the crust exceeds this value (see Table 2), a possible additional source of heat is latent heat of solidification. The required solidification rate is less than or 5 km over 1 Ma, consistent with the inferred surface age.

[26] The viscosities obtained ($\sim 10^{12}-10^{13}$ Pa s) are fixed by the constraints on δ_0 and δ_1, and require a small grain size (≤ 0.06 mm from Figure 2). While smaller than the estimated surface grain size of ~ 0.1 mm [*Geissler et al.*, 1998], it is easily achieved if grain growth is limited by impurities [*McKinnon*, 1999]. A process which has been neglected in this work is the grain size reduction caused by convective motion [*De Bresser et al.*, 1998]. This process results in an equilibrium grain size which is dependent on the vigour of convection.

[27] An advantage of the scaling expressions of section 3 is that they are almost all independent of d. Thus, our current uncertainty in the ice thickness has no effect on the value of F, δ_1 or δ_0. Conversely, the deduced value of δ_0 cannot be used to infer a layer thickness. Nonetheless, δ_0 does constrain the heat flux. Weak constraints may be imposed on d by the requirements that it must be large enough to allow convection to occur and that enough tidal heat is generated [*Hussmann et al.*, 2002].

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