Heat flow, lenticulae spacing, and possibility of convection in the ice shell of Europa

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Abstract

Two opposing models to explain the geological features observed on Europa's surface have been proposed. The thin-shell model states that the ice shell is only a few kilometers thick, transfers heat by conduction only, and can become locally thinner until it exposes an underlying ocean on the satellite's surface. According to the thick-shell model, the ice shell may be several tens of kilometers thick and have a lower convective layer, above which there is a cold stagnant lid that dissipates heat by conduction. Whichever the case, from magnetic data there is strong support for the presence of a layer of salty liquid water under the ice. The present study was performed to examine whether the possibility of convection is theoretically consistent with surface heat flows of $\sim$100–200 mW m^{-2}, deduced from a thin brittle lithosphere, and with the typical spacing of 15–23 km proposed for the features usually known as lenticulae. It was obtained that under Europa's ice shell conditions convection could occur and also account for high heat flows due to tidal heating of the convective (nearly isothermal) interior, but only if the dominant water ice rheology is superplastic flow (with activation energy of 49 kJ mol^{-1}; this is the rheology thought dominant in the warm interior of the ice shell). In this case the ice shell would be $\sim$15–50 km thick. Furthermore, in this scenario explaining the origin of the lenticulae related to convective processes requires ice grain size close to 1 mm and ice thickness around 15–20 km.

Keywords: Europa; Satellites of Jupiter; Thermal histories; Tides; Solid body

1. Introduction

Europa seems to be a geologically young world. Based on the density of impact craters observed on its surface, its age may be less than $\sim$50 Myr (Pappalardo et al., 1999b; Zahnle et al., 1998) and may therefore continue to be active today. Moreover, this jovian satellite shows a wide variety of terrains and geological structures (Greeley et al., 1998, 2000; Lucchita and Soderblom, 1982; Malin and Pieri, 1986). Two main models to explain the features observed have been proposed. According to the thin-shell model, there are features that indicate the existence of an ocean a few kilometers under the surface (e.g., Greenberg et al., 1999, 2000; Hoppa et al., 1999). In this scenario, the ocean would be exposed locally on the surface due to melt-through of a thermally conductive ice shell. In contrast, the thick-shell model proposes that under the brittle lithosphere, there is a thick layer of ductile ice, perhaps with a convective sublayer, irrespective of whether there is an internal ocean under this layer (e.g., Pappalardo and Head, 2001; Pappalardo et al., 1999a, 1999b). Regardless of which model is preferred, there are certain indications of an internal ocean in this satellite of Jupiter (Carr et al., 1998; Pappalardo et al., 1999b). The strongest support for this idea was provided by the magnetometer on board the *Galileo* spacecraft (Khurana et al., 1998; Kivelson et al., 1999, 2000; Zimmer et al., 2000). Thermal models also suggest that the case for an internal ocean on Europa is strong (Spohn and Schubert, 2002).

Evidence in favor of a thin brittle lithosphere, and the presence of features usually known as lenticulae in some regions of Europa offer some clues about the thermal structure of the ice shell, and therefore provide information on the water layer in general.

Analysis of the images of Europa taken from the Galileo spacecraft suggests that the depth of the brittle–ductile transition in the ice shell, which marks the base of the brittle lithosphere or rigid upper crust, would be 2 km at the most (e.g., Pappalardo et al., 1999b). Vertical heat flows of at least $\sim$100–200 mW m^{-2} are needed to put the brittle–ductile transition at a depth $\leq$2 km (McKinnon, 2000; Pappalardo et al., 1999b; Ruiz and Tejero, 1999, 2000). These heat flows are clearly higher than the theoretical values of $\leq$50 mW m^{-2} calculated by classical tidal heating models (Cassen et al., 1982; Ojakangas and Stevenson, 1989; Ross and Schubert, 1987; Squyres et al., 1983) . The explanation for these high heat flows could lie in the tidal heating either of a warm ice convective layer (McKinnon and Shock, 2001; Ruiz and Tejero, 2000) or of the rock/metal core (McKinnon and Shock, 2001).

The lenticulae are features of circular, elliptical, or even irregular shape, include domes, pits, dark spots, and areas of microchaos, and are considered by several authors as being among the youngest geological features of Europa (Figueredo and Greeley, 2000; Head et al., 1999; Pappalardo et al., 1998; Prockter et al., 1999). Their general size is in the range of a few kilometers to several tens of kilometers, and in some regions of Europa they are densely packed (Greeley et al., 1998; Pappalardo et al., 1998). Several explanations for their origin have been proposed, and these are related to interpretations made of the nature of the data itself. Some authors describe a mean diameter of $\sim$10 km for the lenticulae (Spaun et al., 1999, 2000, 2001), and a typical spacing for their distribution (Pappalardo et al., 1998) recently proposed to be 15–23 km (Spaun et al., 2002). These authors consider both results to indicate an origin related to diapirs ascending from a subsurface ice layer in solid-state convection. Their distribution in space would thus correspond to that of convective ascending plumes, and their spacing would consequently be related to the thickness of the convective layer (Pappalardo et al., 1998). A different opinion says that all these features need not be of the same origin (Greenberg et al., 1999; Leake et al., 2002), and rejects the use of the term lenticulae. According to this interpretation, typical lenticulae sizes and spacings are the consequence of observational bias, and the origin of microchaos features (and chaos regions) can be explained by melt-through of a thin (nonconvective) ice shell. This would have occurred throughout the geological history of Europa (Greenberg et al., 1999; Hoppa et al., 2001; Riley et al., 2000). Further possibilities include compositional diapirism (Kargel et al., 2000; Spaun and Head, 2001), or a magmatic origin (Fagents et al., 1998, 2000; Greeley et al., 1998).

Thus, the magnitude of surface heat flows and nature of lenticulae may have profound implications for the structure and dynamics of the ice shell and consequently may shed light on the presence or absence of a convective layer. In this paper, we first present an analysis of the possibility that convection starts in Europa's icy shell, based on limitations posed by general considerations of Europa's thermal state. We next explore whether high heat flows (suggested by a thin brittle lithosphere), and the proposed spacing between lenticulae, considered both independently and in combination, are consistent with a simple model that assumes the occurrence of convection in Europa's icy shell. Our calculations were based solely on the physical properties of water ice. The possibility of convection might be ruled out if substances such as ammonia (e.g., Deschamps and Sotin, 2001) or salts (e.g., Kargel et al., 2000) lowered the melting point of ice to a sufficient extent. However, it is not known whether these substances are present in sufficient amounts to significantly modify the rheological or thermal properties of water ice.

2. Shell thickness and heat flow in the onset of convection

In a classical work, Reynolds and Cassen (1979) proposed that the ice I shells of Ganymede and Callisto are unstable against solid-state convection, and indicated that their results could possibly be applied to Europa and other icy satellites. Later on, Squyres et al. (1983) calculated that an icy shell in Europa would be stable against convection if its thickness did not exceed $\sim$30 km. Based on this, it was proposed that tidal heating could perhaps allow the stable existence of a conductive shell floating over an internal liquid-water ocean (Ojakangas and Stevenson, 1989; Ross and Schubert, 1987; Squyres et al., 1983).

Subsequent works suggested that convection could have started in Europa in an ice shell thinner than $\sim$25 (or even 10) km (McKinnon, 1999; Pappalardo et al., 1998). In these studies, the viscosity of ice is calculated as a function of strain rates induced by tides in a floating shell. McKinnon (1999) also took into account varying viscosity across the layer due to temperature variations, using the scaling of Solomatov (1995) for Newtonian viscosities. The real behavior of water ice, as observed in laboratory experiments, is in fact non-Newtonian (e.g., Durham et al., 1997). However, considering that tidal stresses on Europa are much higher that those due to thermal buoyancy, McKinnon (1999) regards the application of a Newtonian viscosity methodology sufficient for this jovian satellite, as long as an average effective viscosity is appropriately defined in terms of tidal strain rates.

It has recently been proposed (Ruiz, 2001) that in the case of Callisto, the strict use of non-Newtonian viscosities would imply stability of the outer ice shell against convection, allowing the internal ocean to escape freezing, as suggested by magnetic evidence for this neighbor satellite spacecraft (Khurana et al., 1998; Kivelson et al., 1999; Zimmer et al., 2000). This would mean, that in the outer shell of large icy satellites, the onset of convection would be less likely than previously thought. Nevertheless, in absence of tidal stresses, deep within Callisto's outer shell, the dominant stresses are those arising from thermal buoyancy. This model cannot, therefore, be directly applied to the situation on Europa.

In the present section we analyze the stability against convection of a conductive ice shell on Europa. Although we follow partly the analysis of McKinnon (1999), some modifications were made with respect to several significant features. First, the melting point of ice was considered a function of the pressure (instead of using a constant temperature value). In the case of convection, this implies that both temperature in the well-mixed (nearly isothermal) interior and temperature-dependent parameters are not fixed. Also, this temperature is calculated independently for the different mechanisms and regimes of ductile deformation considered (see Section 2.3). It should be noted that a strict non-Newtonian modeling would be of interest.

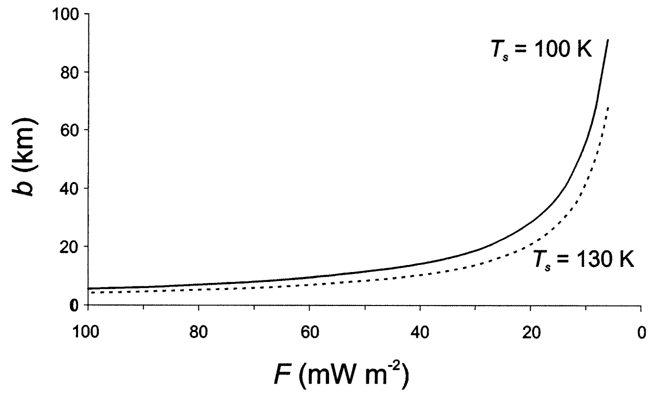

Fig. 1. Total thickness of a conductive ice shell of Europa, b, in terms of heat flow through the shell shown for $F \leq 100$ mW m^{-2} and two possible values of the surface temperature, T_s. Heat flow is represented in reverse order to show how b increases with satellite cooling.

2.1. Depth and temperature at the base of a conductive ice shell

Here we present a reasonable estimate of depth and temperature at the base of the outer ice layer of Europa, assuming that heat is transferred only by conduction. This estimate is required for the analysis of stability against convection of an ice shell that floats above an internal ocean.

Water ice I thermal conductivity is a function of the temperature, $k = k_0 T^{-1}$, where k_0 is a constant with a value of 567 W m^{-1} (Klinger 1980). As tidal heating in the ice shell is strongly temperature-dependent (Chyba et al., 1998; Ojakangas and Stevenson, 1989), the part of a conductive shell that contributes most to total heat flow is the deep and warm ice near its base. On these grounds, it may be considered that the shell is heated from below. Under these conditions (and assuming an energetic equilibrium situation), the temperature at the base of the shell is given by

$$T_\mathrm{b} = T_\mathrm{s} \exp\left(\frac{Fb}{k_0}\right), \quad (1)$$

where T_s is the surface temperature, F is the vertical heat flow through the shell, and b is the total ice shell thickness. In a spherical layer in energetic equilibrium heated from below, heat flow at a depth z increases with respect to the surface value in a proportion $r^2/(r - z)^2$, where r is the external radius of the sphere. Given that the mean radius of Europa is 1561 km (Davies et al., 1998), in a shell some tens of kilometers thick, Eq. (1) leads to the underestimation of bottom heat flow of only several percent, and so the real spherical geometry of the shell is not taken here into account.

T_b in Eq. (1) obviously corresponds to the melting point of ice, which is a function of pressure. The pressure at the ice shell base is given by $\rho g b$ (where $\rho = 930$ kg m^{-3} is the water ice I density, and $g = 1.31$ m s^{-2} is the acceleration due to gravity on Europa), so assuming the relation between temperature and pressure in the melting curve of ice I proposed by Chizhov (1993), T_b can also be written as

$$T_\mathrm{b} = 273.16\left(1 - \frac{\rho g b}{395.2\mathrm{MPa}}\right)^{1/9}. \quad (2)$$

If Eqs. (1) and (2) are solved simultaneously for a given value of F, we obtain T_b and b. In the present work, T_s is taken to be in the range 100–130 K. A value of 100 K is thought to be representive of the mean temperature at Europa's surface (Ojakangas and Stevenson, 1989). On the other hand, 130 K is close to the maximum value normally assigned to the base of a possible insulating regolith layer on the surface (Ross and Schubert, 1987; Shoemaker et al., 1982), or the maximum that could possibly be reached in the case of a solid-state greenhouse in the most superficial ice (Matson and Brown, 1989), although a reexamination of the solid-state greenhouse effect for Europa gave average surface temperatures of 93–104 K (Urquhart and Jakosky, 1996). In Fig. 1, b is represented in terms of F for temperatures of both 100 and 130 K. A lower limit for F can be taken from the current contribution due only to radioactive heat sources, ~6–8 mW m^{-2} (Cassen et al., 1982; Hussmann et al., 2002; Schubert et al., 1986; Spohn and Schubert, 2002; Squyres et al., 1983) , which corresponds to T_b ~ 263–268 K and b ~ 50–90 km.

2.2. The instability criterion

Stability against convection of a layer heated from below can be described by means of the Rayleigh number defined at the base layer viscosity,

$$\mathrm{Ra_b} = \frac{\alpha \rho g h^3 \Delta T}{\kappa \eta_\mathrm{b}}, \quad (3)$$

where α is the thermal expansion coefficient, h is the layer thickness, $\Delta T = T_b - T_s$ is the temperature difference between the base and the surface of the layer, κ is the thermal diffusion coefficient, and η_b is the effective viscosity at the layer base.

Several terms of Eq. (3) are functions of temperature. Thus, $\alpha = \alpha_0 T$, and $\kappa = \kappa_0 T^{-2}$, where the constants are $\alpha_0 = 6.24 \times 10^{-7}$ K^{-2}, and $\kappa_0 = 9.1875 \times 10^{-2}$ m^2 K^2 s^{-2} (Kirk and Stevenson, 1987); both functions are calculated in the analysis of convective state for $T = T_i$ (McKinnon, 1999), where T_i is the temperature of the well-mixed interior in the case of convection. In turn, ρ varies slightly with temperature and pressure (e.g., Lupo and Lewis, 1979), yet adopting a constant value does not alter the results significantly. Given that thermal conductivity varies with temperature, h does not represent the real thickness of the shell (symbolized by b); h is an effective thickness (McKinnon, 1999) that corresponds to a thermal equilibrium situation with a constant k calculated for $T = T_i$.

$$h = \frac{k_0 \Delta T}{F T_i} = \frac{b \Delta T}{T_i \ln(T_b/T_s)} \tag{4}$$

(as it is seen, h can be alternatively written in terms of the real thickness corresponding to F).

The viscosity of ice (considered a non-Newtonian material) can be calculated from the strain rate according to the equation

$$\eta = \frac{1}{3}\left(\frac{d^p}{A\dot{\varepsilon}^{n-1}}\right)^{1/n} \exp\left(\frac{Q}{nRT}\right), \tag{5}$$

where d is the grain size, p, A, and n are experimentally established constants depending on the creep mechanism, $\dot{\varepsilon}$ is the strain rate, Q is the activation energy for creep deformation, $R = 8.3145$ J mol^{-1} K^{-1} is the gas constant, and T is the temperature. Ojakangas and Stevenson (1989) calculated strain rates at present induced by tides in a floating shell on Europa. These authors obtained values ranging from 1.2 to 2.5×10^{-10} s^{-1}, depending on latitude and longitude. The use of a constant value of 2×10^{-10} s^{-1} does not affect the results significantly. If tidal strain rates are used in Eq. (5), η_{tidal} is obtained (McKinnon, 1999). According to McKinnon (1999), the average effective viscosity is

$$\eta_{\text{eff}} = \eta_{\text{tidal}}\, n^{-1/2}; \tag{6}$$

thus, if we take $T = T_b$ we get $\eta_{\text{eff}} = \eta_b$.

When the value Ra_b of a layer exceeds a certain critical value, Ra_b^*, this layer is unstable against convection. In the case of large viscosity variations across the layer, the critical value is given by (e.g., Solomatov, 1995)

$$\text{Ra}_b^* = 20.9\theta^4 = 20.9\left(\frac{Q\Delta T}{RT_i^2}\right)^4, \tag{7}$$

where θ is the Frank–Kamenetskii parameter. Under the conditions of icy satellites, convection involves the stagnant lid regime (McKinnon, 1998), in which there is an immobile lid over the convective sublayer. In this regime, the temperature contrast across the lower boundary layer can be approached according to (e.g., Moresi and Solomatov, 1995)

$$\Delta T_{\text{rh}} = T_b - T_i \sim \frac{RT_i^2}{Q}. \tag{8}$$

From this "second-degree approximation," an approximate estimate of T_i is obtained if we choose the solution

$$T_i \approx \left(\frac{Q^2}{4R^2} + \frac{QT_b}{R}\right)^{1/2} - \frac{Q}{2R}. \tag{9}$$

Although in this work Ra_b^* is nearly constant over the range of values analyzed, it is explicitly calculated in terms of F (and, consequently, of b).

Table 1
Flow laws parameters for ice in planetary conditions

	A (MPa^{-n} m^P s^{-1})	n	p	Q (kJ mol^{-1})
Superplastic flow ($T > 255$ K)[a]	3.0×10^{26}	1.8	1.4	192
Superplastic flow ($T < 255$ K)[a,b]	3.9×10^{-3}	1.8	1.4	49
Dislocation creep ($T > 258$ K)[a]	6.0×10^{28}	4	0	180
Dislocation creep A ($T = 240$–258 K)[c]	6.31×10^{11}	4	0	91
Dislocation creep B ($T < 240$ K)[c]	1.26×10^5	4	0	61

[a] Goldsby and Kohlstedt (2001).
[b] Goldsby and Kohlstedt (1997b).
[c] Durham et al. (1992, 1997).

2.3. Results: possibility of the onset of convection in the ice shell

Calculations were performed for two ductile deformation mechanisms (for reviews of water ice creep see Durham et al., 1997; Goldsby and Kohlstedt, 2001): superplastic flow (in which grain boundary sliding is the dominant process) and dislocation creep (which is controlled by motion of dislocations in the grain matrix). Experimentally obtained constant values for both mechanisms are provided in Table 1.

At low differential stress levels typical of icy satellite interiors, superplastic flow should dominate ductile deformation processes (Goldsby and Kohlstedt, 1997a, 2001). Although superplastic flow is also considered the prevailing ductile deformation mechanism on Europa (McKinnon, 1999; Pappalardo et al., 1998), warm temperatures and ice crystal growth (which is in turn temperature-enhanced) increase the role of dislocation creep. It has therefore been suggested that this mechanism should also be taken into account for Europa's ice shell modeling (Durham et al., 2001). Superplastic flow is grain-size-sensitive, whereas dislocation creep is grain-size-independent ($p = 0$). For superplastic flow, grain sizes of $d = 0.1$ mm and $d = 1$ mm

Table 2
Shell thickness and heat flow in the onset of convection

	b (km)	F (mW m^{-2})
Superplastic flow (Q = 192 kJ mol^{-1}, d = 0.1 mm)	33–51	11–12
Superplastic flow (Q = 192 kJ mol^{-1}, d = 1 mm)	No convection	
Superplastic flow (Q = 49 kJ mol^{-1}, d = 0.1 mm)	9–13	44–45
Superplastic flow (Q = 49 kJ mol^{-1}, d = 1 mm)	17–24	24
Dislocation creep (Q = 180 kJ mol^{-1})	No convection	
Dislocation creep A	39–53	10–11
Dislocation creep B	27–37	15

were used in the calculations. These end-member values were selected for several reasons. Spectral analysis of young fractures in the Tyre region suggests that the mean grain size of the shallow subsurface layer is 0.1 mm or greater (Geissler et al., 1998). A grain size lower than 0.1 mm would not be reasonable if there are no impurities, which limit the crystal growth (McKinnon, 1999). On the other hand, dislocation creep becomes an important flow mechanism when grain sizes are greater than ~1 mm (Durham et al., 2001; McKinnon, 1999).

Both superplastic flow and dislocation creep exhibit different regimes depending on temperature (Table 1). At high temperatures, enhanced creep rates and high apparent activation energies characterize these regimes and are probably related to premelting effects (Goldsby and Kohlstedt, 2001). The existence of these different regimes prompts the question of which is the most relevant for the analysis of stability of Europa's ice shell against convection. Obviously, the base of the icy shell would be involved in high-temperature regimes, but data for temperatures above 258 K are scarce (Durham et al. 2001; Goldsby and Kohlstedt, 2001). On the other hand, the potential convective layer could extend across a certain range of temperature including low-and high-temperatures regimes. According to Durham et al. (1992, 1997), two regimes characterize the flow law of dislocation creep for $T \leq 258$ K, regime A (Q = 91 kJ mol^{-1}) for $T > 240$ K, and regime B (Q = 61 kJ mol^{-1}) for $T < 240$ K. In contrast, Goldsby and Kohlstedt (2001) found only one regime for dislocation creep for $T < 258$ K, in which $Q \sim 60$ kJ mol^{-1}; this regime is similar to regime B mentioned above. As there is no conclusive evidence for the part played by the regimes described in Table 1, each possibility was considered in our calculations.

The results are summarized in Table 2. Ra_b^* and Ra_b are also shown in terms of thickness of the ice shell and conductive heat flow for T_s = 100 K in Figs. 2 and 3, respectively. Results show that for superplastic flow (Q = 49 kJ mol^{-1}) the onset of convection would occur in shells thicker than 9–24 km. This range of thicknesses is consistent with previous results (McKinnon, 1999; Pappalardo et al., 1998). The onset of convection requires a greater shell thickness if the deformation mechanism is dislocation creep. Finally, in the case of regimes characterized by enhanced creep rates,

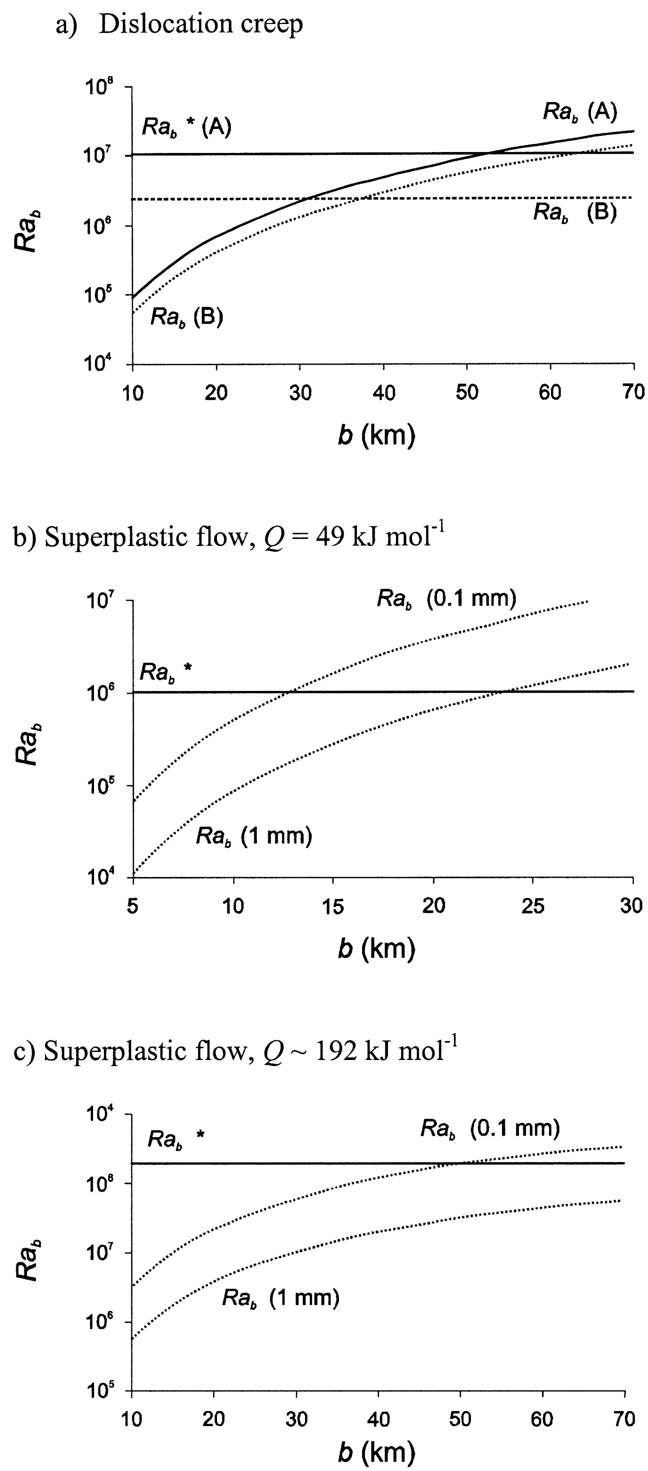

Fig. 2. Ra_b and Ra_2^* shown as a function of the thickness of a conductive Europa's ice shell for several flow mechanisms and T_s = 100 K. When Ra_b^* > Ra_b^*, the shell is unstable against solid-state convection. In (a), the results for the high-temperature regime of dislocation creep have not been represented, since $Ra_b < Ra_b$ over the entire range of b, and therefore the onset of convection could not take place for this creep mechanism.

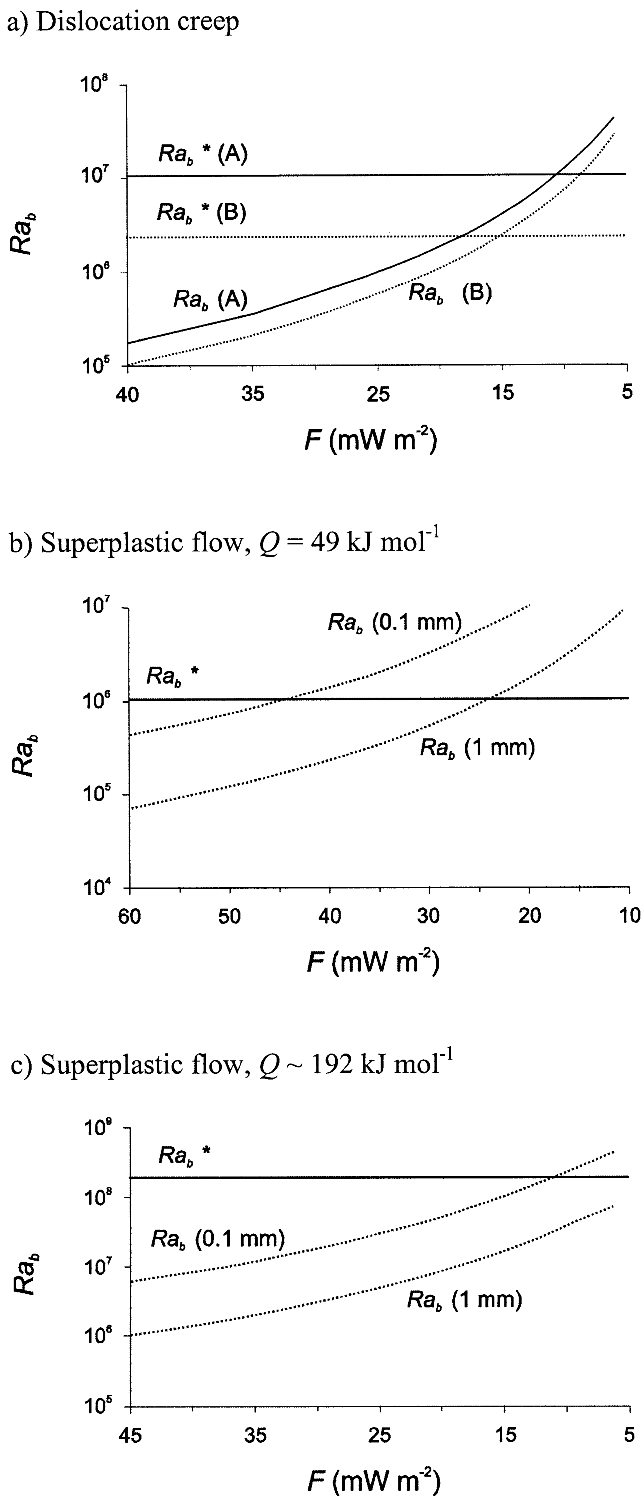

Fig. 3. Ra_b and Ra_2^* in terms of the heat flow through a conductive ice shell on Europa, F, for several flow mechanisms and $T_s = 100$ K. Heat flow is represented in reverse order to show how Ra_b increases with shell cooling. As in Fig. 2, in (a), the results for the high-temperature regime of dislocation creep have not been represented, because for this creep mechanism the onset of convection does not take place.

convection could begin only for superplastic flow, $Q \sim 192$ kJ mol^{-1}, in small grain sizes.

For the purpose of the present study, results are most significant when interpreted in terms of the heat flow required for the onset of convection (Table 2). Ra_b increases with cooling of the conductive shell (Fig. 3), and so the onset of convection requires that F is lower than a critical value, which depends on the flow mechanism and regime. Table 2 shows that for a particular flow mechanism and regime, heat flow at the onset of convection is almost independent of the surface temperature adopted for Europa. For a model of Europa that includes dynamic decoupling between the icy shell and rocky core by an ocean, the minimum contribution to F by tidal heating in the core would be ~12–16 mW m^{-2} (Ross and Schubert, 1987; Squyres et al., 1983). If to this we add the contribution of today's radiogenic sources, ~6–8 mW m^{-2}, heat flow through the ice shell would be at least ~20 mW m^{-2}. In Section 3.1 we will discuss recent suggestions of high heat flow from below the ice shell. Moreover, temperature-dependent tidal heating in the ice shell also contributes to total heat flow. In a conductive ice shell its contribution would be ~7 mW m^{-2} (Ojakangas and Stevenson, 1989). As described in Section 2.1, in this case the heat is mostly generated near the shell base, which can therefore be considered heated from below before the onset of convection (tidal heating in a convective ice shell would be greater, as shown in Section 3). Taking into account all heat flow sources, the minimum value of F would be about ~25–30 mW m^{-2}. Thus, it seems unlikely that the onset of convection could have taken place in the icy shell of Europa, unless the dominant mechanism of ductile deformation is superplastic flow with an activation energy of 49 kJ mol^{-1}.

3. Lithospheric heat flows and lenticulae spacing

A surface heat flow of ~100–200 mW m^{-2} implied by a brittle lithosphere 2 km thick has profound implications on the dynamics of Europa's outer shell. Indeed, it is clearly higher than the heat flow (≤45 mW m^{-2}), allowing the onset of convection in the ice shell. If convection starts, this implies that most heat dissipation takes place in the nearly isothermal interior of the convective layer. In contrast, if most heating takes place in the rock/metal core, then convection in the ice shell would not be able to start and the shell would only be a few kilometers thick.

Assuming a typical lenticulae spacing associated with the upwelling of a convective layer, then the spacing would be roughly twice the thickness of the convective layer (Pappalardo et al., 1998). This relation is based on the aspect ratio parameter, which is the quotient of convective perturbation wavelength and twice the thickness of the convective shell. An aspect ratio of 1 allows convective heat transfer through both layers heated from within and layers heated from below to be maximized (Turcotte and Schubert, 2002). Thus, a lenticulae spacing of 15–23 km would indicate a convective layer ~7–12 km thick.

If most heat flow is derived from tidal heating of a convective ice layer, a theoretical problem arises relative to a possible convective origin for lenticulae. There is no lower boundary layer in a convective layer heated from within and cooled from above, and there are no hot plumes rising between the cells (e.g., Turcotte and Schubert, 2002). Numerical experiments (Sotin and Labrosse, 1999) have shown that in convective layers heated from within and below (the most realistic option for the icy shell of Europa), hot plumes do not always develop in the lower boundary layer, and when they develop, they usually do not reach the upper boundary layer. On the other hand, tidal heating is temperature-dependent, so it would be intensified in rising plumes (McKinnon, 1999). In this way, its thermal buoyancy increases, possibly allowing the ascent of diapirs. It has also been pointed out that temperature-dependent tidal dissipation could produce melting within convective plumes (Sotin et al., 2002; Tobie et al., 2002; Wang and Stevenson, 2000), and this process perhaps plays some role in lenticulae formation.

Whichever the case, at least some lenticulae seem to have formed by intrusive processes (maybe diapirism), since certain domes have upwarped preexistent plains (e.g., Carr et al., 1998; Pappalardo et al., 1998; Pappalardo, 2000). These processes may have occurred independently of a convective layer. Thus, the modeling of thermally driven ice diapirs by Rathbun et al. (1998) does not require (though is compatible with) the occurrence of convection in the ice shell. It is proposed that the heating of shallow lithospheric portions could give rise to mobilization and migration of brines, and contribute to the alteration or even to the disruption of preexistent terrains and to the formation of lenticulae (Head and Pappalardo, 1999). In addition, although the latter authors suggest that heating might be due to diapirism linked to convection, this is not the only possibility.

In the following sections, we examine the viability of a convective model that takes into account high heat flows, lenticulae spacing, or both. Firstly, we will discuss the possible source of high heat flows.

3.1. Possible origins for the high heat flows

As mentioned in the introduction, a possible explanation for these high heat flows could be tidal heating in the warm ice of a convective layer. This heating could stabilize the ice shell and avoid total freezing of an internal ocean (McKinnon, 1999). Under tidal stresses, ice can behave like a viscoelastic (Maxwell) solid; thus, the tidal volumetric dissipation rate can be calculated according to (Ojakangas and Stevenson, 1989)

$$H = \frac{2\mu\dot{\varepsilon}^2}{\omega}\left[\frac{\omega\tau_M}{1+(\omega\tau_M)^2}\right], \tag{10}$$

where $\mu = 4 \times 10^9$ Pa is the ice rigidity, ω is the frequency of the forcing (for the case ω it can be equated with Europa's mean motion, 2.05×10^{-5} rad s^{-1}), and τ_M is the Maxwell time. As $\tau_M = \eta/\mu$ y $\eta = \eta_{tidal}$ Eq. (10) can be written as

$$H = \frac{2\eta_{tidal}\dot{\varepsilon}^2\mu^2}{\mu^2 + \omega^2\eta^2_{tidal}}. \tag{11}$$

This function presents a maximum for $\eta_{tidal} = \mu/\omega \sim 2 \times 10^{14}$ Pa s, $H_{max} \sim 8$ μW m^{-3}. On the other hand, the heat flow tidally dissipated in the nearly isothermal conditions of the well-mixed interior of a convective layer is

$$F_i = H_i b_i, \tag{12}$$

where H_i is the tidal volumetric dissipation rate for $T = T_i$ and b_i is the thickness of the convective layer under nearly isothermal conditions. This analysis does not take into account dissipation in the upper and lower boundary layers. Using H_{max} in (12), we obtain $F_{max} \sim 8$ mW m^{-2} km$_i^{-1}$. Taking heat flow at the shell base as ~10–40 mW m^{-2} (roughly corresponding to radioactive heating in the core and to the maximum F value permitting the onset of convection in the ice shell, according to the discussion of Section 2.3), a convective layer at least ~8–11 km thick is needed to justify $F \sim 100$ mW m^{-2}. These b_i values are similar to those expected if lenticulae spacing corresponds to that of upwelling from a convective layer, but represent a lower limit. If $F \sim 200$ mW m^{-2}, b_i should be at least ~20 km thick, thicker than that predicted from lenticulae spacing. Moreover, the viscosity of the convective interior need not correspond to the viscosity value for which $H = H_{max}$; if this were the case, according to Eq. (12), b_i would be higher.

Hussmann et al. (2002) calculated that surface heat flows up to 300 mW m^{-2} can be produced by tidal heating of a convective ice layer. These authors also stated that equilibrium between tidal heating and heat transfer is reached for $F \sim 20$ mW m^{-2} and ice shells ~30–40 km thick. These calculations take the ice viscosity as purely Newtonian (independent of tidal stresses or strain rates). On the other hand, Nimmo and Manga (2002) conclude that high heat flow could be removed by convection as for diffusion (Newtonian) creep as for superplastic flow.

Alternatively, high heat flows could also be originated by tidal heating in the rock and metal core. Some recent estimates of tidal heating in the rocky portion of Europa, based on several scalings of total dissipation in Io, have yielded heat flow values in the range ~190–290 mW m^{-2} (Geissler et al., 2001; O'Brien et al., 2002; Thomson and Delaney, 2001). These heat flows would stabilize an ice shell ~2–5 km thick, with a deep ocean below. Librational dissipation could also contribute to the total energy budget of Europa (Bills and Ray 2000, 2001), but its contribution is poorly constrained.

3.2. Thickness and heat flow of a convective layer tidally heated from within

In this section, we calculate thermal equilibrium states of the outer ice shell, assuming that convection does starts. These calculations take into account every possible rheology in Table 1 (and in the case of superplastic flow, for both assumed grain sizes) that would permit the onset of convection.

For a steady-state convective layer heated from within, Schubert et al. (2001) find the relation

$$\Theta = \frac{k(T_i - T_t)}{Hb_c^2} = 1.70 Ra_H^{-1/4}, \tag{13}$$

where Θ the dimensionless temperature ratio, T_t is the temperature of the top of the convective layer, b_c is the thickness of the convective layer, and Ra_H is the Rayleigh number defined for an internally heated layer,

$$Ra_H = \frac{\alpha\rho g H b_c^5}{k\kappa\eta_i}, \tag{14}$$

where, in turn, η_i is the effective viscosity calculated for $T = T_i$ according to Eq. (6); k can be considered constant, since most of the convective layer is a nearly isothermal. Thus, heat flow out of the convective layer can be obtained from

$$F_c = Hb_c = 0.49k\left[\frac{\alpha\rho g(T_i - T_t)^4}{\kappa\eta_i}\right]^{1/3}; \tag{15}$$

in turn, the thickness of the convective layer is

$$b_c = F_c H^{-1}. \tag{16}$$

On the other hand, through theoretical arguments and numerical experiments, Grasset and Parmentier (1998) obtained $T_i - T_t$ for a layer heated from within,

$$T_i - T_t = 2.23\Delta T_{rh} = 2.23\frac{RT_i^2}{Q}. \tag{17}$$

This equation is very similar to that derived from transient cooling experiments (Davaille and Jaupart, 1994).

Although this scenario does not account for the stagnant lid of the convective system, the procedure is appropriate because most of the convective layer is almost isoviscous. Nevertheless, a certain amount of heat enters the ice shell from below. This bottom heat flow was not taken into account since surface heat flow is mostly generated (in this setting; see Section 3.1) in the warm ice of the convective nearly isothermal interior. Thus, the method can be taken as a valid approximation.

In the stagnant lid above the actively convective layer, heat is transferred by conduction and thus its thickness is

$$b_{sl} = \frac{k_0}{F_c}\ln\left(\frac{T_t}{T_s}\right). \tag{18}$$

Tidal heating in the cold stagnant lid is not taken in account, since it must be negligible. We calculated T_t from T_i using Eq. (17), T_i from T_b using Eq. (9), and T_b by simultaneously solving Eq. (2), (15), (16), and (18) taking b as $b_{eff} = b_{sl} + b_c$ in Eq. (2).

In the formulation by Schubert et al. (2001), the convective layer is only heated from within, and so a lower boundary layer does not exist. However, Europa's ice shell is also heated from below by tidal and radioactive heating in the rocky core. In a layer heated both from within and below, the general pattern of heat transfer would not be very different to that occurring in a layer heated from below (Sotin and Labrosse, 1999), but there is a lower boundary layer. It is likely that heat transfer through the lower boundary layer is difficult to describe in a simple way (e.g., Nimmo and Stevenson, 2000; Sotin and Labrosse, 1999), although this transfers heat principally by conduction, and thus its thickness is dependent on heat flow at the base of the ice shell, F_b. According to the discussions of Sections 2.3 and 3.1, F_b is difficult to calculate, although it should be at least equivalent to the radioactive contribution. Thus, not taking into account tidal dissipation within the lower boundary layer, and taking $F_b = 6$ mW m^{-2}, it is possible to roughly estimate the maximum lower boundary layer thickness, b_{lw}, for every setting considered, from

$$b_{lw} \le \frac{k_0}{F_b}\ln\left(\frac{T_b}{T_i}\right). \tag{19}$$

The total ice shell thickness is $b = b_{eff} + b_{lw}$. In practice, our treatment equates to taking a lower boundary layer of negligible thickness; it is a useful procedure since the difference in calculating T_b from b_{eff} or b in Eq. (2) is no case greater than one degree, and therefore does not imply substantial variation in modeling F and b_c. Fig. 4 schematically presents the general structure of an ice shell in stagnant lid convection.

Finally, we took $H = H_i$ in Eq. (16). This assumption somewhat overestimates tidal dissipation within the upper boundary layer (where temperatures are lower than T_i. However, the contribution of the lower boundary layer (where temperatures are higher than T_i was not calculated. This, in turn, somewhat underestimates total tidal heating. We thus consider our tidal dissipation rate calculations to be representative of the convective layer.

3.3. Results: possible stable structures of a tidally heated convective ice shell

The results obtained are shown in Table 3 and provide the possible stable structures of a convective, tidally heated, ice shell. The value of b is given as a range between b_{eff} and $b_{eff} + b_{lw}$ (according to the discussion in the previous section). In every setting, b is less than the ∼80–170 thickness of the water layer (frozen, liquid, or both) consistent with the *Galileo* determination of the Europa's moment of

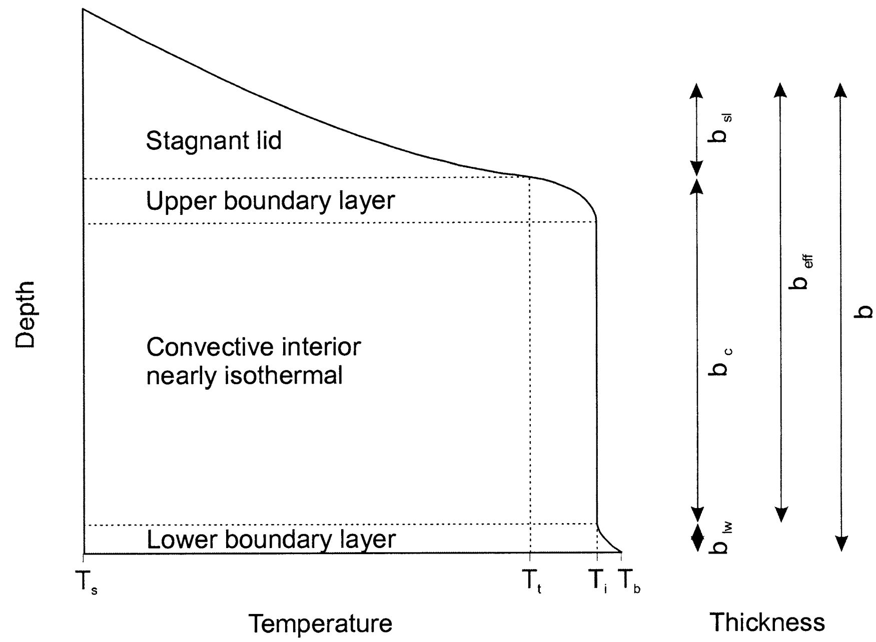

Fig. 4. Diagram showing the general structure of an ice shell in stagnant lid convection. The thickness of several layers involved in the modeling described in Section 3.2 are indicated on the right-hand side.

inertia (Anderson et al. 1998). This implies, in the case of stable convection, the existence of an internal ocean.

Table 3 shows that superplastic flow $Q = 49$ kJ mol^{-1} is the only creep mechanism that roughly satisfies the high surface heat flows of Europa: for this mechanism F_c = 80–130 mW m^{-2}. For other water ice rheologies, F_c is smaller and a thin brittle lithosphere on Europa cannot be supported.

With regard to the thickness of the convective layer, for dislocation creep regime *b* and superplastic flow $Q = 49$ kJ mol^{-1} and $d = 1$ mm, the b_c values obtained are consistent with the thickness suggested by *lenticulae* spacing. For superplastic flow $Q = 49$ and $\sim$192 kJ mol^{-1}, and $d = 0.1$ mm in both cases, convective layer thickness clearly exceeds that expected if *lenticulae* formation were related to convective upwellings. For dislocation creep regime A the b_c value obtained is thinner than that required for a convective origin of the *lenticulae*.

Thus, it is possible to reconcile the heat flow results with the *lenticulae* spacing predicted from a convective origin for these features, but only for superplastic flow $Q = 49$ kJ mol^{-1} and grain sizes near to 1 mm.

4. Summary and conclusions

Satisfying the instability criterion for the onset of convection in a Europa's floating ice shell imposes serious restrictions on both the thermal structure and rheology of the shell. Joint minimum estimates of tidal and radioactive heating in the rock and metal core are sufficiently high to almost preclude the onset of convection for the different

Table 3
Possible stable structues of an Europa's convective icy shell

	SF[a] $Q = 192$ kJ mol^{-1} $d = 0.1$ mm	SF[a] $Q = 49$ kJ mol^{-1} $d = 0.1$ mm	SF[a] $Q = 49$ kJ mol^{-1} $d = 1$ mm	Dislocation creep A	Dislocation creep B
T_b (K)	268	268	272	271–272	271–272
T_i (K)	265	257	260	265	262
T_t (K)	258	232	235	251	241
b_{lw} (km)	≤1	≤4	≤4	≤2	≤3
b_c (km)	38–40	44–45	10	5	9
b_{sl} (km)	11–15	2–4	4–6	9–13	6–9
b (km)	49–56	46–53	14–20	14–20	15–21
F (mW m^{-2})	35–36	133–134	80	41	57

[a] Superplastic flow.

rheologies considered for the ice shell, with the exception of superplastic flow $Q = 49$ kJ mol^{-1} (small grain sizes favor the possibility of convection). If nonradioactive contributions to the total heat budget are neglected, onset of convection would still be possible for dislocation creep regimes A and B, and superplastic flow $Q \sim 192$ kJ mol^{-1} in grain sizes close to 0.1 mm.

The results obtained with regard to the possibility of onset of convection are consistent with equilibrium heat flows that can be generated and transferred (toward the stagnant lid base) by a tidally heated convective ice layer. Indeed, heat flows of $\sim$100 mW m^{-2} are only obtained for superplastic flow $Q = 49$ kJ mol^{-1}.

From both arguments presented, it can be concluded that if the icy shell of Europa is convective, the dominant flow mechanism is superplastic flow $Q = 49$ kJ mol^{-1}, and the shell thickness is $\sim$15–50 km. This is precisely the flow mechanism thought dominant in the warm interior of Europa's ice shell (McKinnon, 1999; Pappalardo et al., 1998). The results suggest that if lenticulae spacing was related to convective processes, then grain size should be around 1 mm, and the shell thickness would not be much more than $\sim$15–20 km. These results are consistent with an ice shell at least $\sim$10–25 km thick inferred from the morphology and dimensions of impact craters (Moore et al., 1998, 2001; Schenk, 2002; Turtle and Ivanov, 2002) at the locations and times of impact. Our results are also consistent with a stagnant lid $\leq$5 km thick (and surface heat flow higher than 90 mW m^{-2}), deduced from surface deformation caused by domes if domes are related to convection (Nimmo and Manga, 2002).

In conclusion, convection may have started in the ice shell of Europa and it is also possible that outward transfer of heat tidally generated in the convective layer stabilizes a thin brittle lithosphere. Although these results are obtained only for a particular water ice rheology, this rheology is thought to be dominant in the warmest parts of Europa's ice shell. In this scenario, the ice shell is tens of kilometers thick, and to explain lenticulae as convective-related features, the ice grain size should approach 1 mm. A different ice rheology or considerable tidal heat generation in the rock/metal core would prevent the onset of convection; then the entire ice shell would transfer the heat by conduction and only be a few kilometers thick. The latter possibility is not favored by independent estimations of ice thickness from impact craters data. In any case, our results indicate that an ocean should exist below the icy shell.

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