

Heat Flow and Thermal State of the Crust of the Icy Galilean Satellites

Javier Ruiz

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Abstract The use of lithosphere strength indicators (as for example the effective elastic thickness of the lithosphere or the depth to the brittle-ductile transition) can give clues on the surface heat flow and the thermal state of the ice crust of icy satellites, which in turn has profound implications for the internal evolution, and the possible existence of internal oceans, in these planetary bodies. As shown in this review, this kind of approach has found very high (and possibly recent) surface heat flows for Europa and ancient high heat flows for Ganymede. On the other hand, the heavily cratered of Callisto suggests a cold and inactive outer ice shell throughout the entire history of that body. However, irrespective of the greatly different geology recorded on the surface of the icy Galilean satellites, there is evidence from orbital magnetic observations for internal oceans in all them. By considering heat flow estimates in the context existence of internal oceans, a more complete description of the thermal history of the icy Galilean satellites should emerge.

Keywords Galilean satellites · Heat flow · Ice crust thickness · Lithosphere strength · Internal oceans

1 Introduction

The three icy Galilean satellites (Europa, Ganymede and Callisto, after their distance from Jupiter; see Fig. 1) are a group of simultaneously heterogeneous and related bodies (for reviews of physical, geological and cratering characteristics of these bodies see, for example, Zimmer et al. 2000; Zahnle et al. 2003; Greeley et al. 2004; Moore et al. 2004; Pappalardo et al. 2004; Schubert et al. 2004): Europa has a geologically young surface, dating probably from $\sim 30\text{--}70$ Ma in average, is probably active today, and its interior is differentiated; otherwise, Callisto has a heavily cratered surface, which is one of the oldest surfaces in the Solar System, and an only partially differentiated interior; Ganymede is an

J. Ruiz (✉)
Departamento de Geodinámica, Facultad de Ciencias Geológicas, Universidad Complutense de Madrid, 28040 Madrid, Spain
e-mail: jaruiz@geo.ucm.es

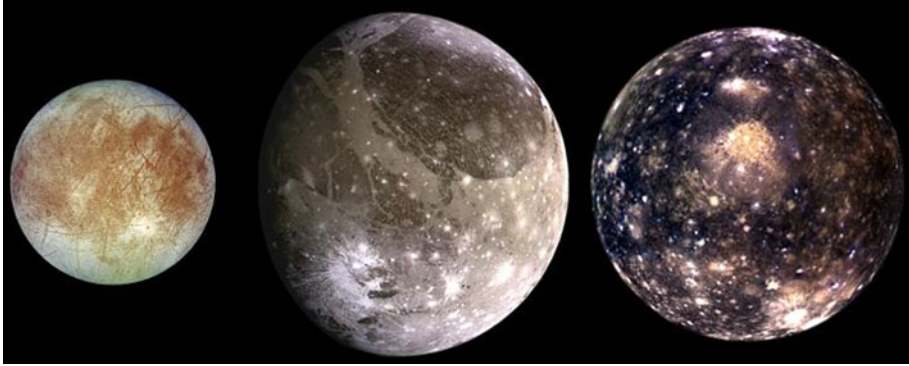


Fig. 1 The three icy Galilean satellites: Europa (*left*), Ganymede (*middle*) and Callisto (*right*), shown in the same scale. There are large geological differences between these bodies that cause very different surface appearances: the young surface of Europa has been extensively deformed and resurfaced, and includes numerous linear features and evidences of endogen activity; the surface of Ganymede includes both bright terrains that were anciently active and dark terrains very old and heavily cratered; the heavily cratered and very old surface of Callisto is somewhat similar to the dark terrains of Ganymede (Image source: JPL)

somewhat intermediate body, has regions showing an intense past geological activity and others retaining almost unmodified cratered terrains, a strongly differentiated interior, and even an active magnetic field internally generated. More surprising, independently of these differences, Europa and Callisto, and probably Ganymede, have retained extensive internal liquid oceans, as indicated by Galileo magnetometer measurements. Differences between icy Galilean satellites must have been greatly shaped by the availability (or absence) of tidal heating, which could be currently active in Europa.

The thermal state of the ice crusts of the icy Galilean satellites has been addressed by numerous theoretical works (e.g., Hussmann et al. 2002; Nimmo and Manga 2002; Tobie et al. 2003; Ruiz and Tejero 2003; López et al. 2003; Showman and Han 2004, 2005; Mitri and Showman 2005; Barr and Pappalardo 2005; Ruiz et al. 2007; Ruiz 2010; Travis et al. 2012), which mostly deal with the possible existence and nature of, and the influence of tidal heating on, solid-state convection in the crust. On the other hand, the use of indicators of the strength of the lithosphere of a planetary body can also potentially give information on its thermal state. Indeed, the depth to the brittle-ductile transition (BDT) and the effective elastic thickness of the lithosphere are related to the thermal structure of the outer layer of a planetary body (as is the thickness of the entire outer ice shell in the case of icy bodies), and for that reason can be used to deduce their surface heat flow (e.g., Ruiz and Tejero 2000; Ruiz 2005), which is an important parameter informing about the global thermal state. The advantage of this approach is its independence of any specific thermal model.

In this work, I review heat flow estimates based on lithosphere strength indicators available for icy Galilean satellites and compare them against theoretical constraints, and with constraints on the thickness of the ice crust for the case of Europa. These different lines of research, when simultaneously considered, provide a coherent, although still rough, vision of the thermal state of the icy crust of these remarkable planetary moons. Moreover, heat flows derived from lithospheric strength should serve as constraints for the construction and refinement of models of convection and thermal evolution of the ice crust of the icy Galilean satellites.

2 Lithospheric Strength and Heat flow

The BDT marks the depth under which temperatures are high enough to permit ductile (and temperature-dependent) creep to be dominant over brittle failure as deformation mechanism (e.g., Beeman et al. 1988). If the to the BDT depth is reasonably known for a given region and time, then it can be used to calculate the surface heat flow for that region and time (e.g., Ruiz and Tejero 2000; Ruiz 2005). The temperature T_{BDT} at the BDT is obtained by equating brittle (pressure-dependent) and ductile (temperature-dependent) strength at the BDT depth. The heat flow is then obtained by matching T_{BDT} to a temperature profile.

On the other hand, the effective elastic thickness of the lithosphere (T_e) is not the thickness of a real layer, but a measure of the total strength of the lithosphere (for reviews see Watts 2001; Watts and Burov 2003), integrating contributions from brittle and ductile layers and from the elastic core of the lithosphere (i.e., the central part of the lithosphere accommodating deformation elastically). Effective elastic thickness estimates can be converted to heat flow estimates following the equivalent strength envelope procedure described by McNutt (1984). This methodology is based on the condition that the bending moment of the mechanical lithosphere must be equal to the bending moment of the equivalent elastic layer of thickness T_e . The link between the strength envelope procedure and heat flow comes from the dependence of the ductile strength on temperature.

For a detailed description of this kind of methodologies applied to icy satellites see Ruiz (2005).

3 The Case of Europa

Estimates currently available for the BDT depth in Europa, were mainly derived following two different procedures: (1) the width of grabens around Callanish and Tyre, the two largest impact structures at Europa, can be used to obtain a lower limit for the BDT depth through simple geometrical considerations (e.g., Ruiz 2005; Lichtenberg et al. 2006); (2) the wavelength of folds observed in Astypalaea Linea can be related to the BDT depth through mechanical modeling of fold growth (Prockter and Pappalardo 2000; Dombard and McKinnon 2006). The corresponding BDT depth values are about 2–2.5 km or lower. The conversion of BDT depth to heat flow requires the use of the appropriate strain rate, which is not well known. However, a strain rate of 10^{-15} s^{-1} , typical of many terrestrial geological processes (e.g., Watts 2001), is in the lower end of the proposed values deduced for Europa (see Ruiz 2005), and provide therefore a reasonable lower limit for the surface heat flow, which is $\approx 65\text{--}110 \text{ mW m}^{-2}$ (see Ruiz 2005) for $BDT \approx 2\text{--}2.5 \text{ km}$.

Similarly, several estimates for the effective elastic thickness of the lithosphere of Europa have been proposed, that come from: (1) Distance of flexural bulges caused by dome (Williams and Greeley 1998) or ridge (Hurford et al. 2004) load; (2) Distance of tensile cracks due to ridge load (Billings and Kattenhorn 2002) (see Fig. 2); (3) Flexural modeling of topography profiles, deduced from photogrammetry or stereo images (Figueroa et al. 2002; Nimmo et al. 2003). The estimates based on flexural modeling are probably less reliable due to uncertainties in the used topography models. On the other hand, the referred calculations of effective elastic thicknesses of the lithosphere beneath domes or ridges, give a wide range of results due to different parameters used in the calculations; however, the obtained values, when re-calculated for the same laboratory parameters appropriate for water ice I, are all similar or lower than 0.4 km (Ruiz 2005).

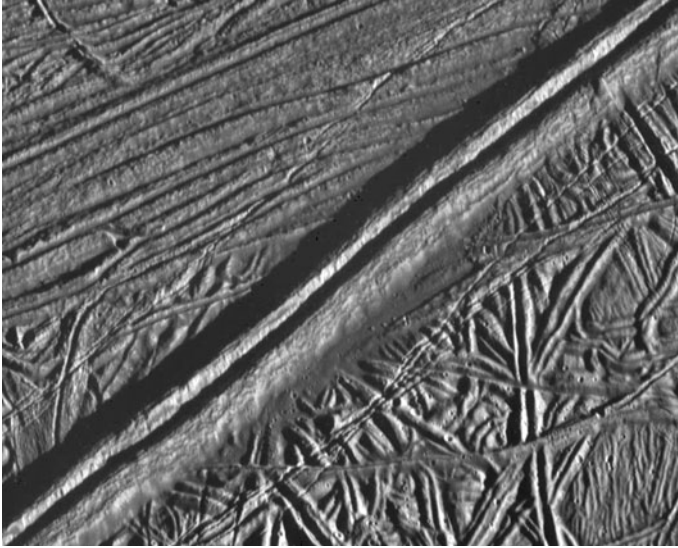


Fig. 2 A prominent double ridge on Europa (Androgeos Linea) is flanked by fractures, separated roughly 3 km from the axis of the ridge. Fractures were most probably caused by ridge load, and their distance to the axis of the ridge informs on the location of maximum tensile stresses related to bending of the lithosphere. Knowledge of this location, permits in turn to derive the effective elastic thickness of the lithosphere (see Hurford et al. 2004), and hence the local heat flow (Image source: JPL)

This implies a heat flow higher than $\sim 130 \text{ mW m}^{-2}$ for these features (for a strain rate of 10^{-15} s^{-1} ; Ruiz 2005).

Heat flows based on T_e deduced from loading by domes and ridges are higher than those calculated from the BDT depth, and might represent local (not average) conditions. Indeed, ridges and domes could be places of amplified heating, by shear heating at fractures (Nimmo and Gaidos 2002) or by tidal heating at raising warm diapirs (Sotin et al. 2002). Thus, there seems to be substantial variations in surface heat flow in Europa. Given the young surface of Europa the so-derived heat flows could be representative for the present-time. Moreover, heat flows based on BDT depth and T_e are much higher (Fig. 3) than the $\sim 6\text{--}8 \text{ mW m}^{-2}$ coming from present-day radiogenic heating (e.g., Cassen et al. 1982; Spohn and Schubert 2002), which implies an important role for tidal heating in the dynamics of this satellite, as previously proposed (e.g., Ojakangas and Stevenson 1989).

The size and characteristics of impact structures also informs on the thermal state of the crust. From the relation between crater size and topography, Schenk (2002) proposed that the ice shell of Europa was at least $\sim 19\text{--}25 \text{ km}$ thick when the impact structures were formed. If the whole ice crust is thermally conductive and has not internal heat sources (i.e., the crust is heated from below), an ice thickness higher than $\sim 19\text{--}25 \text{ km}$ implies a heat flow (the temperature at the base of the ice crust is given by the ice melting point, which is temperature- and pressure-dependent) of at most $\sim 20\text{--}30 \text{ mW m}^{-2}$ (Ruiz 2005). However, a certain contribution to the total heat flow of Europa could come from tidal heating within the ice crust (e.g., Ojakangas and Stevenson 1989). So, these heat flow values must be considered as upper limits to the heat flow reaching the crust base from below (Fig. 3). Moreover, the temperature at the crust base could be lowered by substances depressing the melting point of the ice (e.g., Kargel et al. 2000), in whose case the temperature contrast, and hence the heat flow, across an ice crust of given thickness would be lower.

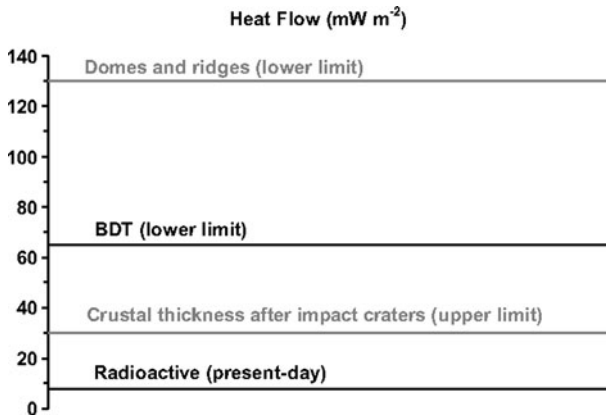


Fig. 3 Summary of the constraints for the heat flow of Europa obtained from indicators of lithospheric strength (the effective elastic thicknesses of the lithosphere loaded by domes and ridges, and the depth to the BDT), compared with estimates based on ice crust thickness and the equivalent radioactive (present-day) heat production in the rocky fraction of the satellite

But the actual situation is more complicated. The presence of numerous regions of features known as lenticulae, which are usually several km wide and spaced $\sim 15\text{--}30$ km apart, has been interpreted as the manifestation of diapirism related to a convective subsurface layer (Pappalardo et al. 1998). If the lower ice crust is effectively convective, the relation between heat flow and crust thickness is more complicated than in the purely conductive case, and the heat flow reaching the crust base (from the ocean below) cannot then be determined from lithospheric strength indicators, which only inform about the heat flow transferred through the lithosphere. However, the requirements for the initiation of convection in the ice crust give some information on the heat flow at the crust base, if convection really is operating: the analysis of stability against convection of a floating icy shell on Europa implies that the conductive heat flow must decrease under 45 mW m^{-2} (or lower depending on the exact parameters used) for the onset of convection (Ruiz and Tejero 2003).

Thus, surface heat flows calculated from the BDT depth or T_e are clearly higher than the heat flow reaching the base of the ice crust. The difference, which could be higher than a factor two, must be produced by tidal heating within the own ice crust (Ruiz 2005). This demonstrates that tidal heating of the ice crust is an important, and most probably dominant, contributor to the total heat budget of Europa. Importantly, this result is independent of whichever theoretical model of tidal heating in Europa.

A recent study of the topography (obtained from photogrammetry and photogrammetry) of two prominent chaos areas suggests that those terrains originated above shallow, a few kilometer deep at most, liquid briny bodies heated by thermal diapirs inside the ice crust that would persist to exist currently (Schmidt et al. 2011). Future analyses of brine stability and interaction with relatively clean ice diapirs could help to constraining the thermal state of the ice shell of Europa.

4 The Cases of Ganymede and Callisto

Ganymede and Callisto, although similar in size, have very different surfaces and geological histories. Ganymede experienced early phases of intense geological activity

(Pappalardo et al. 2004), whereas Callisto does not show definitive evidence of any kind of internal activity (Moore et al. 2004). It is clear that this difference must be related to the respective thermal histories of both bodies (e.g., Showman et al. 1997).

Some estimates of surface heat flow have been proposed for Ganymede (although they are less abundant than for Europa) based on BDT depth and T_e . The estimates of BDT depth are based on modeling of lithospheric extension in the grooved terrains (a terrain formed by swath of roughly parallel ridges and troughs with a striated appearance), which found a BDT ~ 5 km deep in the time when these terrains were formed, and hence heat flows around $50\text{--}100$ mW m^{-2} were derived (e.g., Dombard and McKinnon 2001; Bland et al. 2010). On the other hand, the estimates of effective elastic thickness of the lithosphere were performed by fitting the topography constructed from stereo images to flexural profiles for both ancient terrains (~ 4 Ga) and younger sulcus terrains, and obtained T_e values lower than $\sim 1\text{--}3$ km, from which heat flows in the range between 50 and 200 mW m^{-2} were derived (Nimmo et al. 2002; Nimmo and Pappalardo 2004; Barr 2012). These high heat flows support the possibility of episodes of substantial tidal heating in the early ($\sim 3\text{--}4$ Ga) history of Ganymede linked to the orbital evolution of the Galilean satellites (Showman et al. 1997; Bland et al. 2009), but they any constraints on the more recent thermal state of the moon.

Complementarily, recent analysis of the relaxation state of impact craters also suggests that Ganymede experienced periods of heat flow much higher than the supplied through radioactive heat production in the rocky fraction of the moon (Singer et al. 2012); moreover, these authors find regional variations in relaxation states of craters, suggesting different regional thermal histories for Ganymede, probably due to differences in tidal heating.

Appropriate estimates of heat flow in Callisto based on indicators of lithospheric strength are lacking, but the absence of definitive evidence for endogenic activity on the very old surface of this satellite indicates that this body has not experienced episodes of high heat flow. Moreover, the incomplete internal differentiation (Anderson et al. 2001) of Callisto implies that this body was not intensely heated throughout its geological history, which is consistent with their non inclusion in the Laplace resonance of the other Galilean satellites (e.g., Henrard 1983). As a consequence, Callisto has not experienced any relevant tidal heating. Alternatively (or complementarily), Barr and Canup (2010) have proposed that the difference in surface geology between Ganymede and Callisto could be related to the higher energy delivered by impacts to Ganymede (due to its closer proximity to Jupiter) during the late heavy bombardment, although it is not clear if the high values of heat flow calculated for this satellite from lithospheric strength indicators could be explained in this framework.

The present-day existence of an internal ocean in Callisto is therefore more intriguing than in the cases of Europa and (possibly) Ganymede, since these bodies have had, as above discussed, substantial supplies of tidal energy during, at least, a part of their history. Thus, the survival against freezing of the Callisto's ocean must be related to a limited cooling of the outer layers of this satellite, which suggests that if solid-state convection started in the outer ice shell of Callisto (see McKinnon 2006) this process was very inefficient in removing heat from the interior.

5 Conclusions: Implications for Internal Oceans

The dynamic of the ice crust of Europa is (or was, although it is difficult to think of this object as an inactive body in light of its very young surface) dominated by tidal heating in the own crust. Tidal heating in the ice crust would be concentrated in the warm interior of

a convective layer, and favors the maintenance of the internal heat and the existence of an internal ocean, which would be $\sim 20\text{--}30$ km beneath the surface (Schenk 2002; Schilling et al. 2004).

Tidal heating, although important, had a much limited duration in Ganymede, and it was non-existent in Callisto. Thus, the depth and state of internal oceans in Ganymede and Callisto are mostly related to the efficiency, or not, of solid-state convection in the ice crust in removing internal heat.

Thus, heat flow calculations based on indicators of lithospheric strength show that the intensity, duration and distribution (for example, in a regional or vertical sense) of tidal heating, and its influence on internal dynamics, is the key factor determining the existence, nature and evolution of internal oceans inside the icy Galilean satellites, and icy planetary bodies in general.

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