

HEAT FLOW AND BRITTLE-DUCTILE TRANSITION IN THE ICE SHELL OF EUROPA

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Observations of Conamara Chaos regio of Europa made by Galileo spacecraft suggests a rigid ice crust thickness of ~2 km at most, above a liquid water or ductile ice layer, during late stage of geological activity, that it could continue today [1, 2]. Moreover, the presence near Conamara Chaos of domes, pits and dark spots, is interpreted by Pappalardo et al. [2] as evidence of diapirism, which is probably induced from a ductile ice layer in convection below brittle ice.

A few kilometers (or only hundreds of meters) rigid crust, seems to involve the existence of high heat flows [3]. Still more, the thickness analysis of the potentially convective layer in the onset of convection, in relation to domes, pits and dark spots spaced, suggest heat flows of ~100-200 mW m⁻² at time of deformation [4], much higher than obtained by tidal heating models [5-7]. Here we analyze the brittle-ductile transition depth in the ice shell of Europa in terms of heat flow, using rheological profiles technique [8, 9], which is frequently used in comparison of frictional and ductile strength in terrestrial lithosphere. To determinate depth, "real" strength is the lower of both.

If we assume existence of cohesionless weakness planes in all orientations, frictional strength can be described by

$$(\sigma_1 - \sigma_3)_f = \mathbf{a} \mathbf{r} g h (1 - \mathbf{I}), \quad (1)$$

where \mathbf{r} is density above considered level (in Europa's shell, water ice density, 930 kg m⁻³), g is gravity acceleration, assumed here as surface value (1.31 m s⁻²), h is depth, and \mathbf{I} is the pore fluid factor (ratio between pore fluids pressure and lithostatic pressure). We can consider $\mathbf{I} = 0$ in an ice satellite, for that reason,

$$(\sigma_1 - \sigma_3)_f = \mathbf{a} \mathbf{r} g h. \quad (2)$$

\mathbf{a} is a coefficient that depends on tectonic regime. It maximum in compression and minimum in tension; respectively

$$\mathbf{a}_{comp} = B - 1, \quad (3)$$

$$\mathbf{a}_{ten} = 1 - 1/B, \quad (4)$$

where $B = \sigma_1 / \sigma_3$ is the stress ratio. It can be considered for cohesionless fracture surfaces as

$$B = 1 / [(1 + \mu^2)^{1/2} - \mu]^2, \quad (5)$$

where μ is the static coefficient of friction. For ice, $\mu = 0.55$

is the suitable value for stress in the normal to fracture plane lesser than 20 MPa [10]. Whereas different tectonic regimes we obtain $\mathbf{a}_{comp} = 1.86$ and $\mathbf{a}_{ten} = 0.65$.

Ductile strength can be calculated from general equation creep,

$$(\sigma_1 - \sigma_3)_d = (\cdot \varepsilon d^p / A)^{1/n} \exp(Q / nRT_h), \quad (6)$$

where ε is the strain rate, nominally $2 \times 10^{-10} \text{ s}^{-1}$ for Europa [2], d is grain size, Q is the activation for creep, $R = 8.3144 \text{ J mol}^{-1} \text{ K}^{-1}$ is the gas constant, T_h temperature in the considered depth, A , p and n are constants. The mechanism that dominate the deformation in the conditions of Europa's ice shell is grain boundary sliding, which depend on grain size [11]. From dates in [11] $Q = 49 \text{ kJ mol}^{-1}$, $A = 51.86 \text{ MPa}^{-n} \text{ mm}^p \text{ s}^{-1}$, $p = 1.4$ y $n = 1.8$ for grain boundary sliding. T_h is described by

$$T_h = T_s \exp(F h / k_0), \quad (7)$$

where T_s is the lithosphere's top temperature, F is the vertical heat flow through shell (assumed constant), y $k_0 = kT$ (where k is water ice's thermal conductivity) = 567 W m⁻¹ [12].

In this work we calculate the ductile strength in terms of heat flow. The calculations have been carried out starting from two different temperatures for the top of ice lithosphere: 100 K, considered representative of mean temperature on the Europa surface [13], and 130 K, which roughly corresponds to the one which is normally assigned to the base of a possible isolating regolith layer on the surface [7, 14]. We have made the calculations for grain size of 0.1 mm, corresponding to surface observations [2], y 1 mm. The results are shown in Figure 1.

It is observed that the involved heat flows for a thickness of brittle ice in Europa, in crust deformation time, of ~2 km at most, are strongly higher than obtained in tidal heating models [5-7]. If we take a thickness rigid crust of ~2 km, the heat flow must be ~100-200 mW m⁻². These values are equivalent to obtained from domes, pits and dark spots spaced for the onset of convection [4]. Elsewhere, for lower brittle ice thickness or larger grain heat flows should be higher. In any case, it seems difficult to have a heat flow lesser than ~100 mW m⁻² in the late stage geologically active, around two times the highest proposal theoretic estimations for Europa.

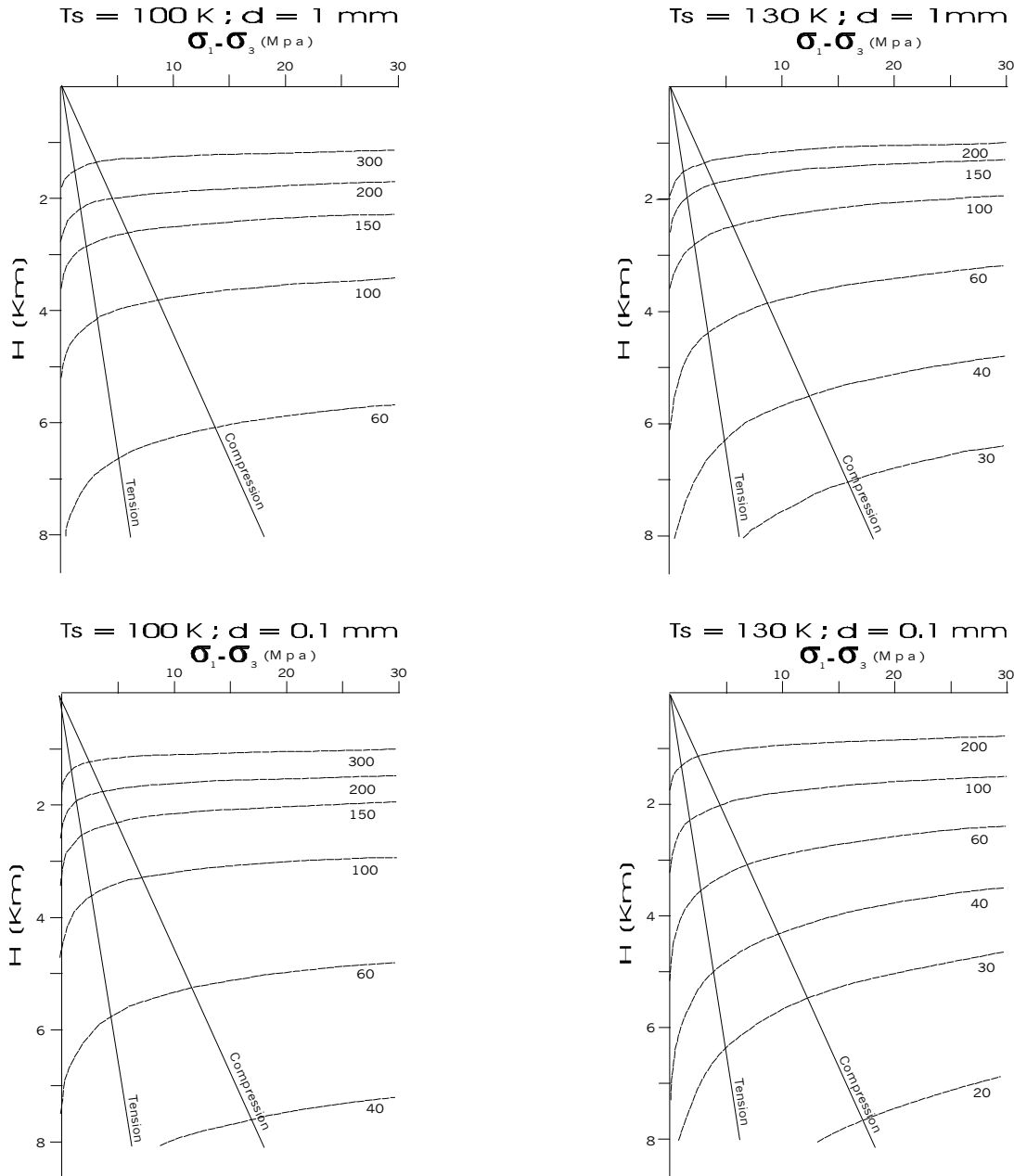


Figure 1. Ductile strength (dashed curves) compared with frictional strength (solid lines) for Europa's ice shell. Ductile strength is a function of heat flow, shown for every curve (mW m^{-2}).

References: [1] Carr, M.H. et al. (1998), *Nature* **391**, 363-365. [2] Pappalardo, R.T. et al. (1998), *Nature* **391**, 365-368. [3] Pappalardo, R.T. et al. (1997), *BAAS* **29**, No. 3. [4] Ruiz, J. (1998), submitted to *Earth Moon Planets*. [5] Cassen, P.M. et al. (1982), in *Satellites of Jupiter* (ed. Morrison, D.), 93-128. Univ. Arizona Press, Tucson. [6] Squy-

res, S.W. et al. (1983), *Nature* **301**, 225-226. [7] Ross, M.N. and Schubert, G. (1987), *Nature* **325**, 133-134. [8] Ranalli, G. and Murphy, D.C. (1987), *Tectonophysics* **132**, 281-295. [9] Ranalli, G. (1997), in *Orogeny Through Time* (eds. Burg, J.P. and Ford, M.), 19-37. Geological Society Special Publication No. 121. [10] Beeman, M. et al. (1988), *J. Geophys. Res.* **93**, 7625-7633. [11] Goldsby, D.L. and Kohlstedt, D.L. (1997), *Scripta Mat.* **37**, 1399-1406. [12] Klingner, J. (1980), *Science* **209**, 271-272. [13] Ojakangas, G.B. and Stevenson, D.J. (1989), *Icarus* **81**, 220-241. [14] Shoemaker, E.M. et al. (1982), in *Satellites of Jupiter* (ed. Morrison, D.), 435-520. Univ. Arizona Press, Tucson.