Evaluation of global expansion of Ganymede during the course of thermal evolution.

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Introduction:

Size of planetary and satellite's body should exhibit temporal variation reflecting the thermal and dynamical evolution of the interior so that if we can retrieve history of the size correctly we can trace the evolution of invisible interior. Up to now several origins resulting in the change of the size (volume) have been proposed and evaluated as follow;

1) change in internal temperature distribution (thermal evolution) via thermal expansion[1],
2) positional change of the phase boundary such as melting/solidification. In general phase change is associated with volume change.
3) differentiation and formation/destruction of layered structure,
4) chemical reaction between constituent materials such as hydration/dehydration,
and 5) compaction process of composite aggregates.

Particularly in the case of icy satellites all of these factors are expected to be plausible to make the volume to change largely. For example the thermal expansions of various ice phases are larger than those of silicate materials.(5×10^{-5} vs 2.4×10^{-5}). There exist several high pressure phases of H_2O ice in moderate pressure range where the interior of most icy satellite exist. These phase changes are associated with the volume change of over several percent. Furthermore melting/solidification of Ice-I are associated with large amount of the volume change. Because of these icy satellites are expected to exhibit fairly large amount of volume change during the course of the evolution.

Many researches have been conducted. [1,2]. Although change of the size(volume) is a simply- derived parameter its quantitative evaluation is not so simple. Many researches have focused instead resultant surface stress field, which is responsible for creating various recognizable surface features. Progress of solidification of the internal ocean such as in Europa by secular cooling is expected to increase volume/internal pressure, which form tensional crackings [3,4]

In this presentation we focus on the formation of surface stress field associated with volume changes in Ganymede. To evaluate this thermal evolution in the ice mantle is a key because of higher thermal expansion and existence of plural phase transitions of ice having large volume change. Here we utilized mixing length theory approach to evaluate detailed thermal model including thermal boundary layer.

Method

The thermal model: **Model:**

We consider thermal evolution of Ganymede to evaluate volume change. The basic structural model is a differentiated model given by Sohl *et al* (2002). [5] The heat source is decay of long-lived radiogenic elements in the core with chondritic abundance. The heat transport in the core is conduction and that in the icy mantle is evaluated by the mixing length theory following Kimura *et al* (2009). [6]

The heat transport equation is

$$\frac{\partial T}{\partial t}=\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2k_c\frac{\partial T}{\partial x}+r^2k_v\left[\frac{\partial T}{\partial r}-\left(\frac{\partial T}{\partial r}\right)_{ad}\right]\right)$$

,where kc is the thermal diffusion coefficient of ice, $(\partial T/\partial r)$s is the adiabatic temperature gradient, k_v is effective eddy diffusivity and the first and second terms on the right-hand side represent conductive and convective fluxes. The k_v is given as follows:

$$k_v=\begin{bmatrix} 0 & if\left(\frac{\partial T}{\partial r}-\left(\frac{\partial T}{\partial r}\right)_{ad}\right)>0 \\ \frac{\alpha g l^4}{18\nu}\left(\frac{\partial T}{\partial r}-\left(\frac{\partial T}{\partial r}\right)_{ad}\right) & if\left(\frac{\partial T}{\partial r}-\left(\frac{\partial T}{\partial r}\right)_{ad}\right)<0 \end{bmatrix}$$

where l is the mixing length, α is thermal expansivity, g is the gravitational acceleration, and ν is the local kinematic viscosity. Since ice has temperature-dependent viscosity we model ν as a function of fractional temperature to the local melting point of ice phase.

The heat transfer equation of core is

$$\frac{\partial T}{\partial t}=\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2k_{core}\frac{\partial T}{\partial r}\right)+\frac{Q}{C_p}$$

,where k_{core} is the thermal diffusion coefficient of core, Q is the heat production rate due to radioactive element, and C_p is the core specific heat.

Result:

Thermal evolution: Fig. 1 is the result of thermal evolution. Since we want to evaluate how successive phase transitions changes the volume in this model calculation the initial temperature was given as the adiabatic gradient passing the triple point of Ice I-liquid-Ice II. The representative phase-profile is Ice I – Ice II – Ice V – Ice VI from the surface.Since the phase boundary I to II is positive gradient with T while that II to V is negative gradient, the contribution of volume change associated with the temperature change is opposite between two cases.The rise and fall temperature distribution near the the phase boundary I to II after t = 1Gyr is expected to large amount of volume change (about 0.1~1% of the present Ganymede volume)

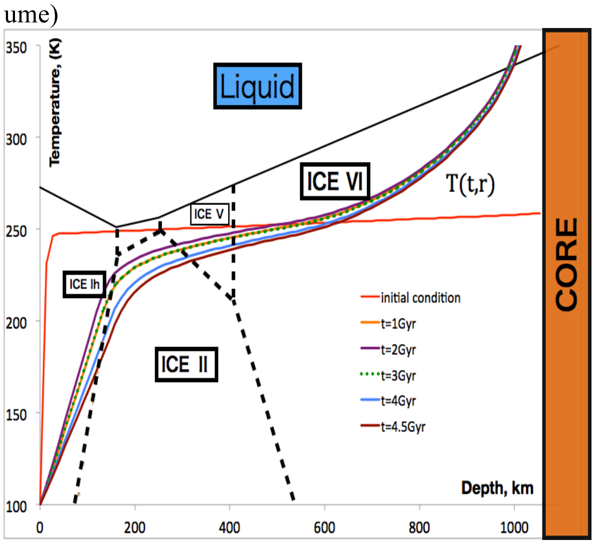

Figure 1: the thermal history of Ganymede

The Surface Stress:

D. L. Turcotte (1983) exmined about the tangential stress due to the interior volume expansion.[7]

The equation of the average tangential stress in the lithosphere is given follows:

$$\overline{\sigma}_{\theta}(t)=\frac{E\alpha_{v}\left[\frac{1}{6}(T_{e}(t)-T_{0})+\frac{1}{3}\delta\overline{T}_{c}(t)\right]}{(1-\nu)\left[1+\frac{2(1-2\nu)}{1-\nu}\frac{y_{e}(t)}{R}\right]}$$

,where $T_e(t)$, is the temperature of the lower thermal boundary, $\delta\overline{T}_c(t)$ is the mean temperature in the fuild core. The first term of umerator represents the effect of thermal expansion in the thermoelastic part. The second term represents the effect of excess pressure.

In case of Ganymede(Fig. 2), we mainly treat the the volume expansion ice mantle in order to simplify. (the volume of core is much smaller than core, furthermore the uncertainly of metal core is difficult to discuss about the effect of volume expansion.)

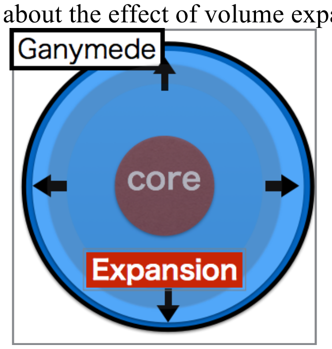

Figure 2 :Conceptual diagram of volume expansion

We estimate the tangential stress due to the thermal expansion of ice by using the equation.(Fig.3)

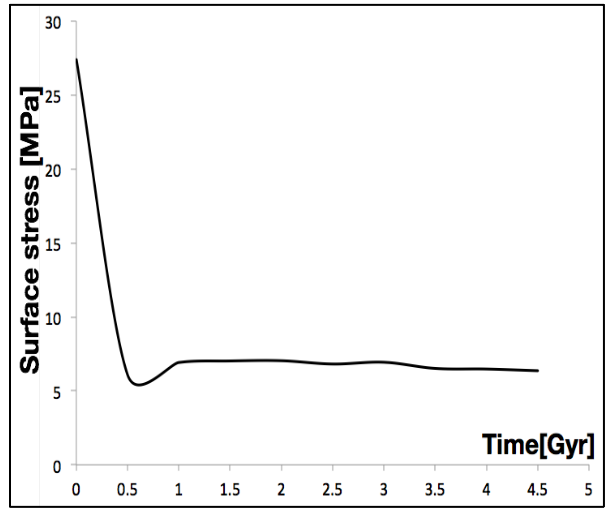

Figure 3: The tangential stress due to the thermal expansion.

Discussion:

We estimated the total volume change of ice mantle between initial temperature and present temperature distribution. (about -0.1% of the precent Ganymede volume)

Although total amount of volume changes due to Ice I-II phase change is contraction, we need to discuss about the volume change.(mentioned in the result section) According to the Figure 3, the large amount of thermal expansion had not been occurring after 0.5Gyr. The results indicates that the effect of phase changes may be larger than thermal expansion relatively after 0.5Gyr.

Because the phase change of I-II has been occurring in thermoelastic lithosphere, we may need to improve the present scheme and consider volume expansion of lithosphere in order to estimate the effect of phase change.

References: [1] Zuber, M. T., and E. M. Parmentier 1984. *Proc. Lunar Planet. Sci. Conf. 14th. JGR* **89,** B429–B437. [2] Bland, Michael T., Adam P. Showman, and Gabriel Tobie. *Icarus* 200.1 (2009): 207-221. [3] Kimura, Jun, Yasuko Yamagishi, and Kei Kurita, *Earth, planets and space* 59.2 (2007): 113-125. [4] Manga, M. and C.-Y. Wang (2007) ,GRL, 34, L07202. [5] Sohl, F., et al, *Icarus* 157.1 (2002): 104-119. [6] Kimura, Jun, Takashi Nakagawa, and Kei Kurita, *Icarus* 202.1 (2009): 216-224. [7] Turccote, D. L., *Proc. Lunar Planet. Sci. Conf. 13th,* Part 2*, J. Geophys. Res.* 88, suppl., A585–A587, 1983.