THERMAL CONVECTION IN EUROPA'S SILICATE MANTLE. L. Han[1], G. Tobie[2], and A.P. Showman[3], [1]Planetary Science Institute, 1700 E Fort Lowell, Suite 106, Tucson, AZ 85719. han@psi.edu, [2]UMR-CNRS 6112 Planetologie & Geodynamique, 2 rue de la Houssiniere, BP 92208, 44322 Nantes Cedex 3, France, [3] Department of Planetary Sciences, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721..

Summary: We perform numerical simulations in 3D spherical geometry to study the properties of convection in Europa's silicate mantle using the finite-element code CitcomS including temperature-dependent viscosity. Our simulations show that thermal convection occurs if the reference viscosity is 10^{18}–10^{19} PaS, rheological activation energy is $\sim$ 150-300 kJ/mol, and the viscosity contrast (due to temperature variation) is less than 10^6 in Europa's mantle. Convection cannot occur if the reference viscosity $\geq 10^{20}$ PaS or if the viscosity contrast $\geq 10^6$. These results imply that partial melting may be required for thermal convection to occur in Europa's silicate mantle.

Introduction: Galileo gravitational data demonstrate that Europa contains an ice/ocean layer and an underlying rock/metal layer, which is probably further differentiated into a silicate mantle and a metallic core [1-2]. Mantle dynamics determines (i) the global heat flux conducted from the mantle into the ocean (and its spatial and temporal variations), and (ii) the extent of intrusive or extrusive seafloor volcanism (if any).

The vast majority of thermal models for Europa's ice shell/ocean assume a homogeneous heat flux from the silicate and ignore the mantle dynamics completely [3-8]. Spatial temperature variation in Europa's silicate mantle can play a major role in partial melting or volcanism, and thereby influence the evolution of the ice shell [8-10]. A better understanding of the mantle thermal state and heat flux may allow more precise theoretical estimates of the ice-shell thickness (current ice-shell thermal models usually adopt arbitrary heat fluxes from the silicate equal to or greater than the radiogenic heat flux). Constraints on the likelihood of volcanism would also help determine whether hydrothermal plumes can cause local melt-throughs of the ice shell, as suggested to explain Europa's chaos features [10-12].

Here we present 3D spherical numerical simulations to study thermal convection in Europa's silicate mantle with temperature-dependent viscosity.

Model and Methods: By assuming an infinite Prandtl number and making the Boussinesq approximation for incompressible material, the non-dimensional equations governing thermal convection in Europa's silicate mantle are the continuity equation, momentum equations, and energy equation, respectively:

$$\nabla \cdot u = 0 \tag{1}$$

$$\nabla \sigma + Ra\theta \vec{r} = 0 \tag{2}$$

$$\frac{\partial \theta}{\partial t} + u \cdot \nabla \theta = \nabla^2 \theta + q \tag{3}$$

where u is the velocity, σ is the stress tensor, Ra is the Rayleigh number, θ is the temperature, $\vec{r}$ is the unit vector in the radial direction, t is time, and q is the internal heating. All the variables above are non-dimensional.

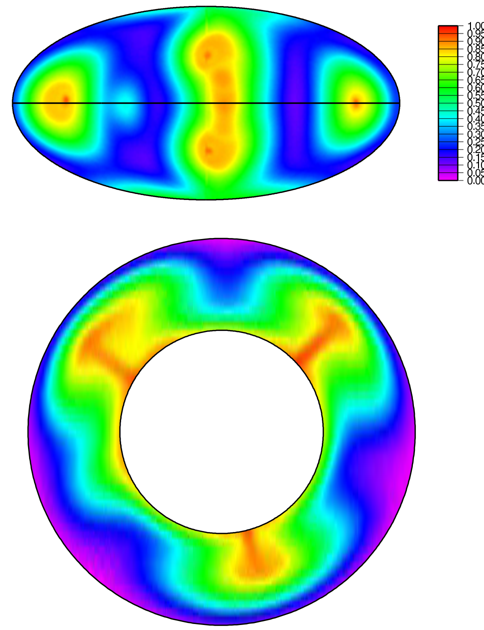

Figure 1: Preliminary results from a full 3D spherical model showing thermal convection in Europa's silicate mantle. Color gives temperature divided by 1500 K. The simulation implements temperature-dependent viscosity with an activation energy of 300 kJ/mol and viscosity contrast of 10^5. The top panel displays the temperature distribution on a constant radius spherical surface at depth of 500 km. The bottom panel displays the temperature distribution along the radial cross-section showed by the solid line in the top panel.

We solve the above equations in a three-dimensional spherical shell with the existing finite-element code CitcomS [13]. CitcomS is a powerful tool that has been well benchmarked and widely applied to numerical simulations of mantle convection on Earth and Mars [13-14].

In the simulations, temperature-depth-dependent viscosity is implemented as

$$\eta(T, z) = \eta_0(z) \exp\left(\frac{E^*}{R_u T}\right) \tag{4}$$

where $\eta_0(z)$ is the depth-dependent reference viscosity, T is temperature, z is the depth, and R_u is the universal gas constant. E^* is the activation energy, which has an expected value of ~ 150–300 kJ/mol for silicate rock. Our simulations use values spanning this range. In these preliminary simulations, we do not include internal heating.

Results and Discussions: Typical mantle viscosities on Mars and Earth are 10^{20}–10^{21} PaS. Our simulations show, however, that if the reference viscosity (the viscosity at the base of Europa's mantle) $\geq 10^{20}$ PaS and the activation energy is ~ 150–300 kJ/mol, no thermal convection occurs in Europa's silicate mantle. On the other hand, convection can occur if the reference viscosity is 10^{18}–10^{19} PaS, rheological activation energy is ~ 150-300 kJ/mol, and viscosity variation due to temperature variations is less than 10^6. Such low viscosities would require softening due to compositional effects or partial melting.

Figure 1 shows the results from a full 3D spherical-convection simulation of Europa's silicate mantle using CitcomS. The model has a Rayleigh number of $1.5\text{x}10^9$, reference viscosity (viscosity at the base of the mantle) of 10^{18} PaS, and rheological activation energy of 300 kJ/mol. The maximum viscosity contrast due to temperature change is 10^5. The temperature contrast between the top and bottom of silicate mantle is 1500K. From Figure 1, we can see that three robust upwelling (super) plumes develop in the spherical shell.

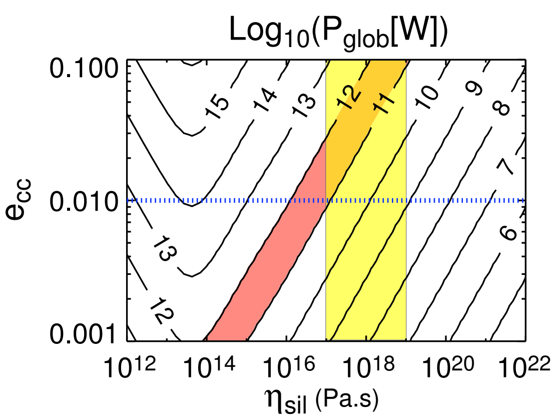

Figure 2: Global tidal dissipation rate in Europa's mantle as a function of silicate viscosity and orbital eccentricity. The pink-filled band indicates the range of radiogenic heating power over Europa's history, and the yellow-filled domain indicates an estimate of the minimum viscosity value in the mantle. The current eccentricity value is indicated with the blue-dotted line.

In our future simulations, we will include both homogeneous radiogenic heating and heterogeneous tidal heating in Europa's mantle. Fig. 2 show the expected global tidal dissipation rate (P_{glob}) in the silicate mantle as a function of orbital eccentricity and viscosity. For comparison, we indicate the total radiogenic heating rate ranging from 10^{11}–10^{12}W through Europa's history. This shows that for the current orbital eccentricity, tidal dissipation can be comparable to radiogenic heating for viscosities close to 10^{17}–10^{18} PaS, or even larger than radiogenic heating if the eccentricity exceeds its present value in the past.

Fig. 1 shows that lateral temperature variations of hundreds of K occur within Europa's mantle. Because the tidal heating rate varies spatially [15] and depends strongly on temperature [16-18], hot regions will experience greater heating rates than cool regions, which will enhance the temperature contrasts even more. The increase of dissipation with depth as well as with decreasing viscosity may help the generation of hot plumes, which are usually inhibited in homogeneously heated layers. The spatial patterns of the tidal-deformation field have been determined by [15] and will be used here to consistently compute the tidal-dissipation field from the 3D viscosity field.

The existence of hot plumes implies that partial melting (hence volcanism) can occur even when the spatially averaged temperature is less than the melting temperature [19]. A very strong coupling between plume dynamics, tidal heating and melt generation is thus expected. The only existing models of Europa's mantle [9] are spatially averaged parameterized convection models, which cannot take into account such a coupling. In these studies, the mantle heat flux can only be estimated as a global average value by assuming a homogeneous distribution of tidal heating. Only full numerical simulations of the mantle convection can properly quantify the spatial heterogeneity in temperature (and hence the true conditions under which volcanism will occur).

Acknowledgement: This work is supported by NASA OPR Program. We would like thank GeoFramework group at Caltech for maintaining the software used in the simulations.

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