RELAXATION OF LONG-WAVELENGTH TOPOGRAPHY AND THE THERMAL EVOLUTION OF RHEA. S. Kamata[1,2*] and F. Nimmo[1] [1]Dept. Earth and Planetary Sciences, University of California Santa Cruz, 1156 High St, Santa Cruz, CA 95064, USA, [2]Dept. Natural History Sciences, Hokkaido University, Kita-10 Nishi-8, Kita-ku, Sapporo, Hokkaido 060-0810, Japan (*skamata@ucsc.edu).

Summary: We investigated the viscoelastic relaxation of long-wavelength topography on Rhea using a thermally evolving interior model. Radiogenic heating results in the rapid development of a thick lithosphere that supports long-wavelength topography. Thus, the observed large relaxation fractions of impact basins and the degree-two shape require a sustained heat source in addition to long-lived radiogenic heating; tidal heating probably played an important role in the thermal evolution of Rhea.

Introduction: Long-wavelength topographies of solid planets and satellites can viscously relax over time. Since the viscosity of rocks and ice strongly depends on temperature, relaxation states of large-scale topographies provide a probe of the thermal history of a planetary body [1-4].

There are two observational constraints on the relaxation state of long-wavelength topography of Rhea. One is the shallow depth/diameter ratios of large impact basins [4]; relaxation fractions of Tirawa (397 km diameter) and Powehiwehi (268 km diameter) basins (corresponding harmonic degrees <~10) are estimated to be ~60-70%. Such high basin relaxation fractions imply a high heat flow and a thin lithosphere at the time of the impact [4]. Another observation is that the degree-2 gravity field departs slightly from hydrostatic equilibrium and thus is not fully relaxed. These two observations at different wavelengths place a constraint on the thermal evolution of Rhea; too low and too high heat fluxes cannot explain the former and latter observations, respectively. Below we carry out an analysis of relaxation of long-wavelength (degree 2-10) topography of Rhea using thermally evolving interior models and investigate plausible thermal evolution scenarios for Rhea.

Method and Model: In this study, we combine thermal evolution calculations and viscoelastic deformation calculations, taking the effect of freezing and melting of a H_2O layer into account. For the former calculation, we solve one-dimensional thermal conduction problem using a code described in [5]. For the latter calculation, we solve the spheroidal deformation of a Maxwell viscoelastic body using a code described in [1, 6]. We expand the load using spherical harmonics, and calculations are carried out for each harmonic degree; the effect of curvature is taken into account. The viscosity profile is updated using the thermal profile obtained by the thermal evolution calculation. Using this code, we calculate the time evolution of the gravitational secular and load Love numbers (denoted as k and k', respectively). The former and the latter are indices of relaxation fraction for degree-2 shape and for impact basins, respectively.

In this study, Rhea is assumed to be differentiated and to have a 356 km-thick H_2O layer overlying an elastic silicate core, whose radius is 408 km. For simplicity, we assume an isothermal initial state; an initial temperature T_0 of 150 or 270 K is adopted. For this initial study, long-lived radiogenic heat production in the silicate core is assumed to be the only heat source. Our nominal case assumes that the silicate composition corresponds to carbonaceous chondrites.

Preliminary Results: Figure 1 shows the time evolution of our nominal thermal evolution model (T_0 = 150 K, h = 1). Here, h is radiogenic heating rate normalized by the value for carbonaceous chondrites. A cold, highly viscous lithosphere develops rapidly because of a low surface temperature. After several 100 Myr, the silicate core heats up, and a subsurface ocean develops. Then, after ~1.5 Gyr, the interior cools again since the heat production rate decreases. If we reduce the amount of heat production rate by a factor of 0.3, a subsurface ocean does not develop. An extremely high initial temperature (270 K) leads to a much higher heat flux only for < 0.5 Gyr and has little effects on the later thermal state; the heat production rate in the core determines the long-term thermal state (note that radiogenic heating is the only heat source in our calculation).

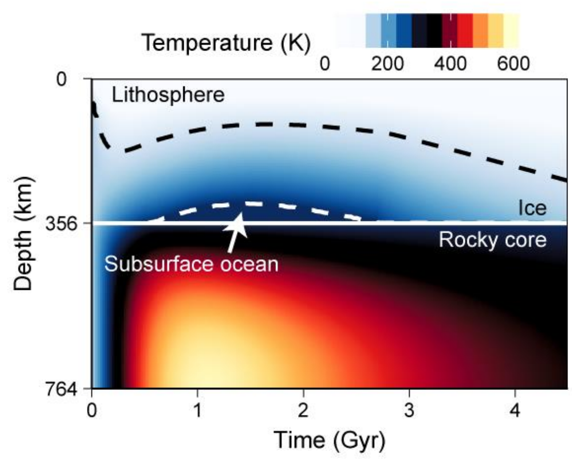

Figure 1: The time evolution of the temperature profile for our nominal case (T_0 = 150 K, h = 1). The melting temperature of ice is 273 K. The reference viscosity (at the melting temperature) is 10^{14} Pa s. The lithosphere is defined as a surface layer with a viscosity > 10^{27} Pa s. A rapid growth of the lithosphere occurs at <200 Myr.

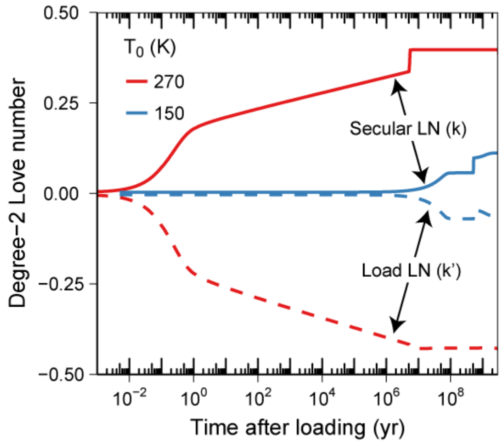

Figure 2: The time evolution of degree-2 secular and load Love numbers (not normalized by the fluid limit value). A loading age of 5 Myr, a reference viscosity of 10^{14} Pa s, and h = 1 are adopted, respectively. The initial lithospheric thickness is ~35 and ~10 km for T_0 = 150 and 270 K, respectively. Discontinuous changes occur at a time when subsurface ocean appears.

Figure 2 shows the time evolution of gravitational Love numbers (k and k') of degree 2. Results for a loading age of 5 Myr are shown. For our nominal case (T_0 = 150 K, blue lines), relaxation starts at ~10^7 yr and continues for billions of years, but the total amount of relaxation is small owing to the thick lithosphere. For a higher initial temperature case (T_0 = 270 K, red lines), on the other hand, relaxation starts very early (~10^{-1} yr) and reaches a steady state at ~10^7 yr. Such a large difference in the relaxation timescale arises only for very early loading; if we adopt a loading age of 1 Gyr, for example, the difference in relaxation fraction is very small because the near-surface viscosity structure (thus the lithospheric thickness) after loading is mainly determined by the radiogenic heating rate and not by the initial temperature [1].

Figure 3 summarizes the final relaxation fractions for a loading age of 5 Myr. To compute relaxation fraction, we also calculate the fluid Love number adopting a uniform low-viscosity structure. Even the hottest case does not lead to a relaxation fraction 60% for all harmonic degrees. We found that a reference viscosity of 10^{13} Pa s (i.e., a factor of 10 smaller than our nominal value) does not change this result significantly. We also found that if we adopt a later loading age, relaxation fraction decreases. Consequently, as long as long-lived radiogenic heating is the only heat source, high relaxation fractions as observed for large impact basins are unlikely to be achieved. Although relaxation is slightly more effective at degree-2, the relaxation fraction remains low; if the degree-2 shape of early Rhea was significantly out of hydrostatic equilibrium, that shape would have been retained for billions of years.

Discussion: Radiogenic heat production rate is important for development of a subsurface ocean. The development of a subsurface ocean, however, does not radically increase the relaxation of long-wavelength topography (Figure 3). This is because such a relaxation is primarily controlled by the near-surface viscosity structure [1].

Early, short-lived heat sources, such as accretional heat and the decay of short-lived radionuclides, may have contributed to maintain a hot interior for a short period. However, we found that sustaining the initial high temperature even for 10 Myr does not result in a significant increase in relaxation compared to our nominal case. A high relaxation fraction requires prolonged high temperatures. The most likely explanation is tidal heating via an ancient resonance, perhaps the 5:3 Dione:Rhea resonance in the past [8].

References: [1] Kamata and Nimmo (2014) *JGR, 119*, 2272–2289. [2] Kamata et al. (2013) *JGR, 118*, 398–415. [3] Robuchon et al. (2011) *Icarus, 214*, 82–90. [4] White et al. (2013), *Icarus*, *223*, 699–709. [5] Nimmo and Spencer (2014) *Icarus*, *246*, 2–10. [6] Kamata et al. (2012) *JGR*, *117*, doi:10.1029/2011JE003945. [7] Nimmo et al. (2010) *JGR*, *115*, doi:10.1029/2010JE003604. [8] Zhang and Nimmo (2009) *Icarus, 204,* 597–609.

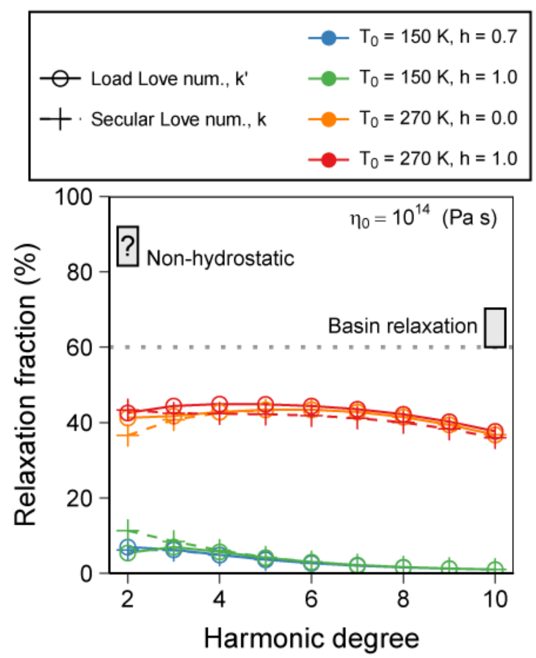

Figure 3: Final relaxation fraction as a function of harmonic degree. A loading age of 5 Myr and a reference viscosity of 10^{14} Pa s are adopted, respectively. A subsurface ocean develops for the cases for h = 1 and not for h < 1, respectively.