HIGHLY DEGRADED EARLY PRE-NECTARIAN IMPACT BASINS: IMPLICATIONS FOR THE TIMING OF THE MAGMA OCEAN SOLIDIFICATION

S. Kamata[1], S. Sugita[1,2], Y. Abe[1], Y. Ishihara[3], Y. Harada[4], N. Namiki[5], T. Iwata[6], H. Hanada[7], H. Araki[7], K. Matsumoto[7], and E. Tajika[1,2], [1]Dept. of Earth & Planet. Sci., Univ. of Tokyo (7-3-1 Bunkyo-ku, Tokyo, 113-0033, JAPAN; kamata@astrobio.k.u-tokyo.ac.jp), [2]Dept. of Comp. Sci. & Eng., Univ. of Tokyo (Chiba, JAPAN), [3]Natl. Inst. Adv. Indust. Sci. Tech. (Ibaraki, JAPAN), [4]Earthquake Res. Inst., Univ. of Tokyo (Tokyo, JAPAN), [5]Planet. Exploration Res. Cent., Chiba Inst. of Tech. (Chiba, JAPAN), [6]Japan Aerosp. Explorat. Agcy (Kanagawa, JAPAN), [7]Natl. Astron. Obs. Japan (Iwate, JAPAN).

Summary: We calculate the viscoelastic deformation of old lunar impact basins to find the paleo-thermal state that can reproduce the currently observed degraded surface and Moho topographies of early pre-Nectarian (PN) basins. Calculation results suggest that the lunar interior may be partially molten at the time of basin formation to account for observed basin structures, suggesting that early PN basins may have been formed before the complete solidification of the lunar global magma ocean.

Introduction: Impact basins, meteoritic craters with diameter >300 km, are prevailing large-scale topographies on the Moon, and the formation ages of the major lunar impact basins are estimated to be >3.7 Gy [e.g., 1]. Because the upper part of the Moon probably cooled rapidly during its early history, the viscoelastic relaxation of topography would have occurred more vigorously immediately after the basin formation than later [e.g., 2, 3]. Consequently, topographic undulations both at the surface and at the Moho (i.e., the boundary between the crust and mantle) around impact basins would reflect the thermal state of the lunar interior during the first billion years of its history [e.g., 2].

Estimations for the thermal state of the lunar interior during basin formation ages, however, have large uncertainties because of the low spatial resolution for the Moho topography. The Moho topography is estimated based on surface topography data and gravity field data. Based on recent high-spatial-resolution topography and gravity field measurements by Kaguya, LRO, and GRAIL, we can now conduct detailed analyses of crustal structure around impact basins [e.g., 4, 5].

Using the Kaguya gravity field data, we have obtained constraints on the thermal state around fresh impact basins, such as Orientale, during their formation ages [6]. However, information for the thermal state around highly degraded impact basins, such as Australe, is not obtained; the thermal state of the lunar interior before pre-Nectarian (PN) 5 is largely unconstrained.

In this study, we use recent Kaguya geodetic data and estimate crustal thicknesses around major impact basins. We then calculate viscoelastic deformation on a thermally evolving Moon and investigate the thermal state that can reproduce current crustal structures of highly degraded impact basins.

Geodetic Data Analysis: We obtain a global one-layer crustal thickness model using Kaguya lunar topography and gravity field models (STM359_grid-03 and SGM150j, respectively). In this study, we analyze crustal structure around impact basins with diameter ranging from 500 km to 1200 km. For each impact basin, we calculate azimuthally averaged surface and Moho topographies. We then measure the ratio R_H of the minimum crustal thickness $H_{\min}$ to the surrounding crustal thickness H_{sur}, where the latter is the crustal thickness at 1.5-2.5 times basin main rim radius away from the basin center. The crustal thickness ratio R_H is used as a measure for the degradation; viscoelastic deformation would increase the value of R_H. For example, a fresh impact basin, whose surface depression is deep and mantle uplift is large, exhibits $R_H \sim 0$ while a degraded impact basin, whose surface depression is shallow and mantle uplift is small, exhibits $R_H \sim 1$.

The crustal thickness ratio R_H for impact basins formed during and after PN 5 are smaller than 0.7 (Fig. 1). Furthermore, except for Imbrium, such impact basins exhibit $R_H < 0.5$, indicating that the crustal thickness near the basin center is significantly thinner than the surrounding thickness. In contrast, for most impact basins formed during PN 4 or earlier, R_H is larger than 0.7, indicating significantly flatter topographies. If the initial crustal structure of an impact basin formed during PN 4 or earlier was similar to the current crustal structure of an impact basin formed during PN 5 or later, a current large R_H for the former basin may result from substantial viscous or viscoelastic deformation, which requires a warm lunar interior. In the following, we refer to impact basins formed during PN 4 or earlier as "early pre-Nectarian basins."

Viscoelastic Deformation Calculation: We calculate thermal evolution and viscoelastic deformation independently. For the thermal evolution calculation, we solve the thermal conduction equation because thermal conduction is estimated to be the most important heat transportation mechanism for the lunar upper layer. We assume a wide variety of crustal conditions, such as its thickness (30-90 km), thermal conductivity (1.5-2.0 W/m/K), and radioactive element concentration (0.1-5.0 ppm of Th).

For each thermal evolution model, we calculate spheroidal deformations of a Maxwell viscoelastic sphere induced by loads at the surface and at the Moho, using a spectral scheme we developed [7]. This computationally efficient method enables us to conduct parametric studies using time-dependent, vertically realistically stratified viscosity profiles; thermal evolution during deformation can be incorporated directly into the calculation. We use dry anorthosite rheology for the crust and dry olivine rheology for the mantle. Using these time-dependent viscosity models, we calculate deformation of harmonic degrees from 2 to 70. Basin formation ages (i.e., loading ages) of 4.4-3.7 Gy are considered.

We assume the current surface and Moho topographies of fresh impact basins, such as Mendel-Rydberg (M-R), Orientale, and Humboldtianum, as the initial topographies. We expand topographies into spherical harmonics of degree up to 70. Using viscoelastic calculation results, we obtain relaxed surface and Moho topographies. We then measure the crustal thickness ratio R_H for relaxed crustal structure.

Early Lunar Thermal State Inferred from Basin Degradation: Fig. 2 shows the crustal thickness ratio R_H as a function of initial Moho temperature. Here, we assume the current surface and Moho topographies of M-R. Fig. 2 indicates that the initial Moho temperature higher than the solidus temperature of the peridotite (~1450 K) is necessary for achieving $R_H > 0.7$. We also found that $R_H > 0.7$ can be achieved with the initial Moho temperature lower than the solidus temperature if the surrounding crustal thickness $H_{sur} > 60$ km. Our estimate for the lunar thermal state required for substantial viscoelastic deformation is much hotter than previous estimates based on simple model calculations assuming time-independent, two-layer viscosity crust [3]; such simple model calculations may overestimate viscoelastic deformation largely [7].

Wilhelms [8] reported about 20 early pre-Nectarian, mid-sized (~500-1000 km) impact basins. Most of these basins have surrounding crustal thicknesses smaller than 60 km [e.g., 4], suggesting that the Moho underneath these basins may be partially melted around the time of their formation ages. The fact that degraded impact basins are globally identified suggests that the Moho may have been partially melted globally during early pre-Nectarian ages. This result further suggests that formations of early pre-Nectarian basins are prior to the complete solidification of the lunar global magma ocean. In other words, the timing of the lunar magma ocean solidification may correspond to the PN 4/PN 5 boundary.

Note that thermal states with subsolidus Moho may account for degraded crustal structure if the crustal structure for a currently degraded basin was initially much flatter than the current crustal structure of a fresh impact basin. Nevertheless, such initially shallower impact basin formation would require drastically different impact velocities or much lighter projectiles, and may not be very likely. Consequently, extremely flat crustal structures of early PN basins suggest that the lunar upper part was very hot and rheologically soft around formation ages of these impact basins.

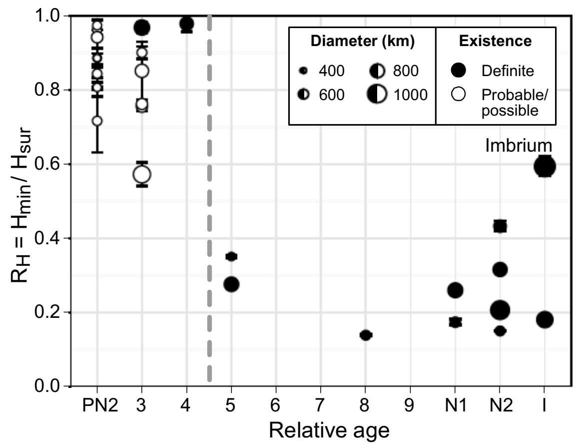

Fig. 1: The ratio of the minimum crustal thickness to the surrounding crustal thickness as a function of relative age. The properties of basins, such as age, are taken from a previous study [8]. PN, N, I indicate pre-Nectarian, Nectarian, and Imbrian, respectively.

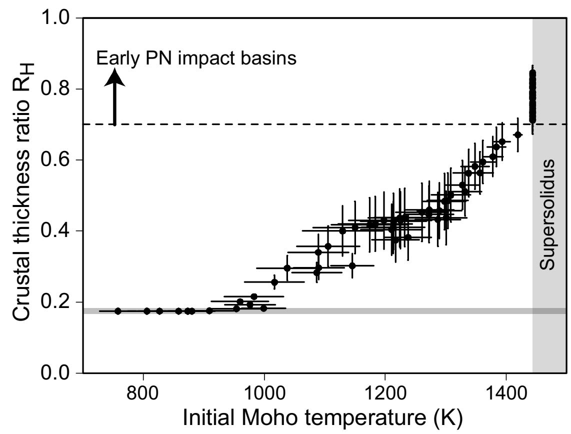

Fig. 2: The crustal thickness ratio R_H as a function of initial Moho temperature. The current crustal structure of Mendel-Rydberg (M-R) is assumed as the initial structure. The shaded region indicates supersolidus conditions. The gray horizontal line indicates R_H for the current crustal structure of M-R. The temperature is limited to the solidus, and excess heat is accumulated as latent heat in our calculations.

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