RADIOGENIC HEAT SOURCE CONCENTRATION IN THE LUNAR FARSIDE CRUST ESTIMATED FROM VISCOELASTIC DEFORMATION OF IMPACT BASINS.

S. Kamata[1], S. Sugita[1,2], Y. Abe[1], Y. Ishihara[3], Y. Harada[4], N. Namiki[5], T. Iwata[6], H. Hanada[3], and H. Araki[3], [1]Dept. of Earth & Planet. Sci., Univ. of Tokyo (7-3-1 Bunkyo, Tokyo, 113-0033, JAPAN; kamata@astrobio.k.u-tokyo.ac.jp), [2]Dept. of Comp. Sci. & Eng., Univ. of Tokyo (Kashiwa, Chiba, JAPAN), [3]National Astronomical Observatory of Japan (Oshu, Iwate, JAPAN), [4]Shanghai Astronomical Observatory (Shanghai, CHINA), [5]Planetary Exploration Research Center, Chiba Institute of Technology (Narashino, Chiba, JAPAN), [6]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (Sagamihara, Kanagawa, JAPAN).

Summary: Based on viscoelastic modeling of impact basins and KAGUYA-measured topography and gravity data, we derived an upper estimate for the mean concentration of radioactive elements in the lunar farside crust (<0.5 ppm), which is similar to the surface concentration on the FHT and much lower than SPA. This finding might suggest horizontal heterogeneity of lower crust on the farside of Moon.

Introduction: Decay of long-lived radioactive elements, such as Th, U, and K, in the crust is the most important heat source for long-term thermal evolution of a planet. Thus, their concentrations in the crust are keys to understand the thermal evolution of the upper layer of the Moon. In addition, since radioactive elements are incompatible elements and concentrate on melt than solid, their concentrations in the crust, which is considered to be formed by the global-scale crystallization of the lunar magma ocean (LMO), may reflect crystallization processes of the LMO.

The lunar global Gamma-ray measurements revealed that surface concentrations of radioactive elements on the Farside Highland Terrane (FHT) are much lower than those on the South Pole-Aitken Terrane (SPAT), where the crustal thickness is estimated to be about one fourth of the FHT [e.g., 1]. However, surface concentrations may strongly be altered by superposed ejecta from large basins [e.g., 2] and may not correspond to indigenous crustal concentration at the time of LMO solidification. Thus, the concentration of radioactive elements deep in the crust is very important for understanding the nature of LMO. In this study, we attempt to estimate the radioactive element concentration in FHT crust based of viscoelastic modeling and selenodetic measurements by KAGUYA spacecraft.

The lunar crust and mantle behave as viscoelastic bodies in geologically long timescales. The effective viscosity of silicates is mainly controlled by temperature. Thus, long-term deformation of the large-scale topographies on the Moon would give important constraints on the lunar thermal history. Impact basins are craters with diameter >300 km and are prevailing large-scale topographies on the Moon. The formation age of the major lunar basins is estimated to be older than 3.7 Gya [e.g., 3], and farside basins, unlike nearside basins, show little mare fill, which would obliterate gravity signature of post-impact deformation. Consequently, the long-term deformation of lunar farside basins would reflect the early, most likely the first billion years of pre-mare lunar thermal history.

The global lunar gravity field measured by KAGUYA clearly shows that major lunar farside basins have central positive free-air and Bouguer anomalies, indicating isostatically overcompensated mantle uplifts [e.g., 4, 5]. In this study, we estimate the initial surface and Moho topographies of farside basins and derive new constraints on the heat flux and on the amount of mean radiogenic heat source in farside crust. Because the ratios of the concentrations among the radioactive elements (i.e., K, Th, U) are almost constant on the Moon [e.g., 6], we use Th concentration as the measure for the total concentration of the radioactive elements.

Model calculation: We calculate thermal evolution and viscoelastic deformation independently. For the thermal evolution calculation, we solve the thermal conduction equation. This is because thermal conduction would be the most important heat transportation mechanism for the lunar upper layer because of its low temperature. We consider present-day (final state) mean Th concentrations of 0.1-1.5 ppm in the crust. The effects of impact heating and heat transportation from the deep hot layer through several mechanisms, such as thermal convection and magma ascent, are not considered. Since these mechanisms would increase the temperature of the crust, the crustal Th concentration obtained in this study would be an overestimate.

For each thermal evolution model, we calculate spheroidal deformations of a Maxwell viscoelastic sphere induced by loads at the surface and at the lunar Moho, using a spectral scheme we developed recently [7]. This method is a time-integration method and do not involve Laplace transformation. At each time step, the viscosity profile is updated using the temperature profile calculated in the thermal evolution calculation. We use dry anorthosite rheology for the crust and dry olivine rheology for the mantle. Using these time-evolving viscosity models, we calculate deformation of harmonic degrees of 2-70. Basin formation ages (i.e., loading ages) of 4.4-3.7 Gya are considered.

Estimating initial topography: Calculation results indicate that the initial heat flux and the degree of deformation depend on crustal thickness and mean Th concentration almost linearly. We thus use linear interpolation of nearest two calculation results in order to obtain the initial heat flux and the degree of deformation for a given crustal thickness and a given mean Th concentration.

Using these calculation results, we first estimate the initial surface and Moho topographies for different basin formation ages. The procedure to recover the initial surface and Moho topographies of a basin consists of the following six steps. First, the radially-averaged cross section for the basin is created, using KAGUYA topography data and a crustal thickness model [1]. Second, "a reference radius", which is 1.5-2.5 times the basin main rim radius, is determined. We use surface and Moho positions (distances from the lunar core) at the reference radius as "unperturbed" positions, and the difference between them is used as a reference crustal thickness. Also, the surface average Th concentration inside the reference radius is calculated using Lunar Prospector 0.5 degree data with the calibration equation given by *Gillis et al*. [8]. Third, we fit Legendre polynomials of degrees 2-70 within the reference radius and calculate their coefficients. Fourth, the effect of crustal thickness and mean Th concentration on the thermal evolution and on viscoelastic deformation are corrected by applying linear interpolation, assuming that the mean crustal Th concentration is the same as the surface concentration. Fifth, using these "interpolated" results, we determine the initial surface and Moho amplitudes, which are required for matching the final amplitudes with the fitting coefficients. Sixth, the initial surface and Moho topographies are obtained from the superposition of Legendre polynomials with initial amplitudes. We repeat these recovery steps from two to six for different reference radii, and mean and standard deviation of recovered initial topographies are calculated.

Constraints on initial heat fluxes: We chose Freundlich-Sharonov and Hertzsprung for our analysis. Both basins are located in the heart of FHT, where Th concentration is very low (<0.3 ppm) and the crust is thick (~70 km). These conditions are unique for the FHT. For Freundlich-Sharonov, the initial heat flux >30 mW/m^2 would require Moho topography too high; it would penetrate through the lunar surface (Fig. 1). Consequently, the initial heat flux <30 mW/m^2 is necessary for this basin. Similarly, the initial heat flux <35 mW/m^2 is necessary for Hertzsprung. These upper limits give ~1000 K at the Moho, which is several hundred K higher than a previous estimate based on non-elastic viscous model [3]. This difference comes from the difference in wavelength of deformation considered. We mainly consider deformation of mantle uplift, whose diameter is smaller than the basin.

Th concentration in the lunar farside crust: We calculated the upper limit of present-day mean Th concentration in the crust as a function of basin formation age based on the upper limit of the initial heat flux. A very low mean Th concentration <0.5 ppm is required for both basins (Fig. 2). This value is about one third of the Th concentration observed on the SPAT, which could represent a typical lower crust of the farside [9]. This result suggests that the enrichment of Th in the SPAT do not represent lower crustal material beneath the FHT and that Th concentration in the lower crust would vary from one region to another, similarly to observations on the surface. This may be a result of local variation in crystallization processes of the LMO.

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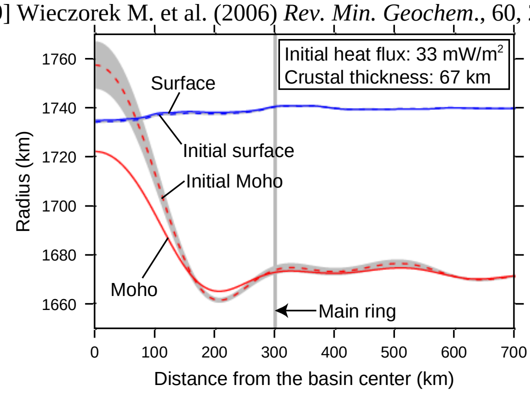

Fig. 1. Recovered initial surface and Moho topographies of Freundlich-Sharonov. Solid lines show observed surface and estimated Moho topographies. Dashed lines show recovered initial topographies. Gray regions indicate standard deviation of recovered topographies.

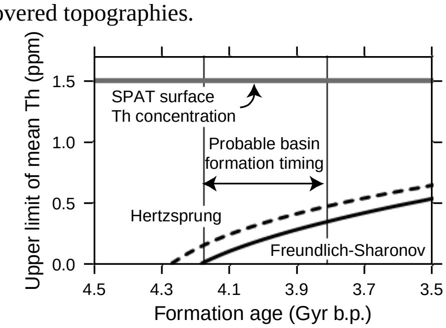

Fig. 2. Upper limit of present-day mean Th concentration in the crust versus formation age of a basin. The region above a curve gives higher heat flux than its upper limit constrained by viscoelastic calculations.