HIGH-CALCIUM PYROXENE EXPOSURES POSSIBLY FROM ANCIENT MAGMATIC INTRUSIONS OF LUNAR LINEAR GRAVITY ANOMALIES. G. Nishiyama[1], T. Morota[1], N. Namiki[2,3], K. Inoue[1], and S. Sugita[1], [1] Department of Earth and Planetary Science, The University of Tokyo (gaku.nishiyama@eps.s.u-tokyo.ac.jp), [2] National Astronomical Observatory of Japan, [3] The Graduate University for Advanced Studies, SOKENDAI.

Introduction: Multiple numerical simulations and gravity data have suggested that the Moon has experienced a volumetric expansion. In the initial stage of lunar thermal evolution, the lunar mantle overturn could have transported heat-producing elements and ilmenite-bearing cumulates (IBCs) to the lunar core-mantle boundary zone. Generated radiogenic heat would have gradually warmed the Moon, causing a km-scale expansion of its radius [1]. Evidence of such a volumetric change has been discovered in a high-resolution Bouguer gravity map of the Moon obtained by the NASA Gravity Recovery and Interior Laboratory (GRAIL) mission. Tens of linear gravity anomalies (LGAs) have been identified and interpreted as ancient intrusions or dikes formed under a globally-isotropic extension [2]. Valley-like topographies along LGAs also indicate horizontal tensile stress during its formation [3].

The composition of such subsurface intrusions may offer a hint for the lunar thermomechanical state in the expansion stage. As the titanium content suggests an ancient hot plume from the deep IBC zone [4], such compositional information is a good indicator of the property of ancient magmatic sources and, thus, a crucial constraint on the lunar thermal history.

The periphery of large craters on LGAs is a good site to investigate such old magmatic materials. In particular, LGA1 and 2 have 160-km-sized craters named Rowland and Roche, respectively, whose excavation depth could reach some portion of the intrusions [2]. These craters are located in highland regions; hence, basaltic material excavated from LGAs can be distinguished from the surrounding regolith.

In this study, we surveyed the spectral dataset around these two craters. Using both reflectance map and hyperspectral data, exposures revealing basaltic characteristics were identified. Whether these exposures could originate from LGA is then tested in comparison between GRAIL data and iSALE simulation. We finally discuss the implications of these magmatic intrusions.

Spectral Analysis Method: To identify possible basaltic exposures, we first used the Multiband Imager (MI) data from the Kaguya/SELENE mission. Spectral absorption depths at 950, 1050, and 1250 nm are composited as an RGB map after a continuum extraction. Then, spots that exhibit deep and fresh pyroxene-like absorption are selected manually as candidates for basaltic exposures. The TiO_2 and FeO contents are estimated from an empirical relationship between multi-band reflectance and abundance [5].

Next, hyperspectral data from the Moon Mineralogy Mapper (M^3) onboard the Chandrayaan-1 spacecraft is analyzed. While spectra of the lunar highland regolith are dominated by low-calcium pyroxene (LCP), basaltic magma, like present maria, contains high-calcium pyroxene (HCP) exhibiting absorptions at different wavelengths. Applying the modified Gaussian model to the continuum-removed M^3 spectra, we distinguish the type of pyroxene using the absorption centers of 1000- and 2000-nm bands.

Spectral Result: Rowland crater has no exposures with a clear indication of HCP in its periphery. The FeO content surrounding Rowland is as low as 4 wt. %, consistent with a typical highland regolith. While FeO higher than 8 wt. % is found at some locations, all their spectra show LCP-like features in M^3 data.

On the other hand, we found more than 30 exposures with basaltic spectra around Roche crater. Their FeO contents reach up to 14 wt. %. Most of their absorption wavelengths are distributed within the HCP range (Figure 1). These spectral features are similar to those of small maria, which also exist around Roche crater. However, the discovered HCP exposures are distinguished from the present maria because we exclude all the pond-like locations to avoid misdetection of mare basalts.

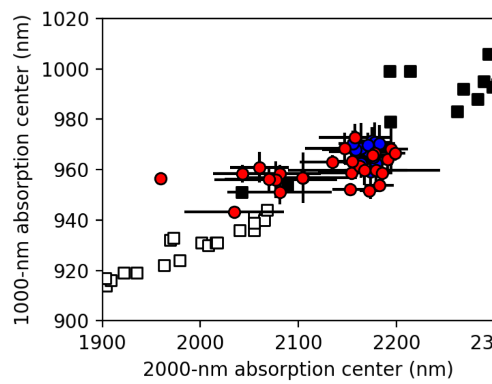

Figure 1. The absorption centers of fresh exposures around Roche crater. The x- and y- axes are absorption center wavelengths at 2000- and 1000-nm bands, respectively. The red and blue scatters correspond to values at non-mare basaltic exposures and nearby small maria, respectively. The black and white squares are data of synthetic HCP and LCP, respectively [6, 7, 8].

The source of HCP around Roche is neither ejecta from present surface maria, impact melt, nor mafic melt trapped within the crust during the magma ocean solidification. Based on an empirical ejecta thickness model, less than 20 % of the deposited material comes from craters on maria. The exposures do not exhibit cooling fractures like other impact melt. The analyzed exposures are not located at craters with a diameter of 8 km or larger, which cannot excavate trapped melt in depth [9].

Possibility of LGA Excavation: An alternative HCP source is an excavation of the LGA material. In the Bouguer gravity map, LGA inside both the craters is weak, indicating a certain influence by the impacts. However, the extents of the gravity drop differ between LGA 1 and 2. In order to quantify the LGA modification by impacts, we numerically examine under what condition the crater formation produces the observed LGA.

Our simulation consists of two parts; gravity fitting and subsurface modification simulation. We first made a variety of possible intrusion shapes that match the averaged Bouguer gravity of LGAs outside the craters. Assuming the top depth and density contrast from the crust, we fit the intrusion width. The deformation and excavation of subsurface material by the Rowland- and Roche-forming impacts are next simulated for each estimated structure. This work uses the iSALE shock physics code [10, 11, 12]. The LGA material was moved using the tracer positions in iSALE simulations, in which a 10-km projectile forms a crater with a radius of 75 km. The porosity change beneath the crater was also simulated with the dilatancy model for various initial porosities [13].

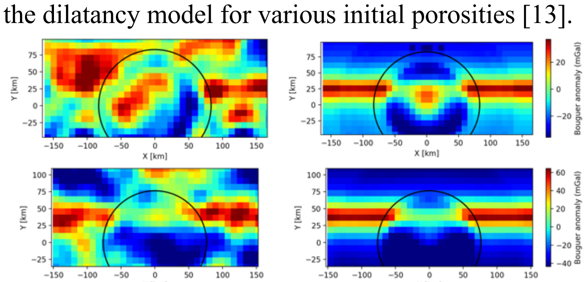

Figure 2. Comparison of Bouguer gravity maps. The upper and lower figures show results for Rowland and Roche, respectively. The left and right figures are data and simulation examples under assumptions of top depth and density contrast of 10 km and 400 kg/m^3.

Our result revealed that the gravity drops inside the craters are attributable to the impact only for Roche but not for Rowland. Figure 2 shows examples of Bouguer gravity comparison between data and simulation. Our simulation shows that the root of the LGA remains even after the impacts. As a result, the linear gravity signature of intrusion cannot be destroyed completely. Together with the gravity depression from the porosity change, a gravity drop similar to LGA2 inside Roche is reproduced in our modeling. However, the significant gravity drop of LGA1 adjacent to Rowland's rim does not agree with the impact simulation.

Discussion: The lack of HCP exposure and discrepancy between gravity simulation and data imply that LGA1 has not been excavated by Rowland. Because the coincidental formation of Rowland at the edge of LGA1 is unlikely, the most plausible reason is that LGA1 formation postdated the Rowland-forming impact and stopped at the rim. As the unloading of a crater bends the trajectories of magma ascent [14], a paleo-stress field might cause such a termination.

In contrast, the gravity consistency supports that HCP exposures around Roche crater can originate from the subsurface LGA2 material. Although the distribution of LGA ejecta estimated in our axisymmetric simulation does not cover all the HCP exposures, some detections are inside the ejecta blanket containing the LGA2 material when a shallow top depth is assumed in our simulation. After correcting contamination by highland regolith using the FeO contents, the LGA material has a TiO_2 content of 0.5–1.5 wt. %. Small young maria around LGA2 with ages of 2–3 Ga also possess TiO_2 content lower than 2 wt. %, almost the same level as the corrected value. This similarity implies that ancient LGA magmatism and young maria formation shared a common magma source or that the mantle composition was homogeneous in the early era of lunar history.

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