CONTROL PARAMETERS ON GRAVITATIONAL SIGNATURE OF LARGE IMPACT CRATERS ON THE MOON. M. Ding\textsuperscript{1}, J. M. Soderblom\textsuperscript{2}, F. Nimmo\textsuperscript{3}, C. J. Bierson\textsuperscript{4} and M. T. Zuber\textsuperscript{2}, \textsuperscript{1}State Key Laboratory of Lunar and Planetary Sci., Macau Univ. of Science and Technology, Macau, China (dingmin@alum.mit.edu), \textsuperscript{2}Dept. of Earth, Atmospheric and Planetary Sci., Massachusetts Institute of Technology, Cambridge, MA 02139, USA, \textsuperscript{3}Dept. of Earth and Planetary Sci., Univ. of California, Santa Cruz, CA 95064, USA.

Introduction: High resolution and precision gravity data from the Gravity Recovery and Interior Laboratory (GRAIL) mission provide an unprecedented opportunity to investigate the structure of impact craters and to infer formation and degradation processes. The Bouguer gravity of midsized craters (rim diameter $D_r$ of 20–100 km) is primarily controlled by crustal porosity among all the target properties \cite{1} whereas mantle uplift dominates for larger craters ($D_r > 200$ km) \cite{2–4}. Here, we compare the Bouguer gravity signatures of 150–650-km diameter impact craters in the Feldspathic Highlands Terrane (FHT) with those in the South Pole-Aitken Terrane (SPA) to identify the key target properties that control gravity anomalies of large impact craters. By combining existing hydrocode impact simulations \cite{5–7} with gravity modeling, we suggest that the lack of statistical distinction in the Bouguer gravity anomaly between the large FHT and SPA craters is due to competing effects of the thermal state and crustal thickness.

Comparison between Large FHT and SPA Craters: Large craters ($D_r$ of 150–650 km) identified in the Lunar Orbiter Laser Altimeter (LOLA) crater database \cite{8; 9} are shown in Fig. 1. Following Soderblom et al.\textsuperscript{3}, the central Bouguer anomaly (CBA) is defined as the difference between the area-weighted average Bouguer anomaly of the central region with a radial distance less than 0.2$R$ ($R$ is the crater radius) and that of the annular region from 0.5 to 1$R$. The non-negative CBA for the larger craters has captured their key gravity characteristic, which has been ascribed to impact-induced mantle uplift \cite{2; 3}. The effects of impact melts, post-impact (mare and breccia) infills, and crustal density and porosity have been found to be secondary effects.

**Figure 1.** Distribution of 150–650 km craters in the FHT and SPA, as well as in the nearside Procellarum KREEP Terrane (PKT).

In order to identify the target conditions relevant to mantle uplift (i.e., impact-induced uplift of the crust-mantle interface in the central region of an impact crater, hereafter denoted by $U_m$ in a unit of km), we focus on large craters in the FHT and SPA. Craters in the PKT are excluded due to the dominance of post-impact mare volcanism \cite{e.g., 10}. We find that the CBA-$D_r$ relationship for SPA and FHT craters are not statistically different (Fig. 2).

**Figure 2.** CBA-$D_r$ relationships for SPA (red) and FHT (blue) craters. Dots are observed crater CBAs. Solid lines are best-fit linear two-slope models with uncertainties in shaded regions, using the same method as \cite{3}. Dashed curves are gravity forward modeling results assuming $U_m$ depends on $T_c$ \cite{5} and $D_r$ \cite{11}. The larger scattering for the FHT craters is likely due to greater spatial extent with target property variations.

This observed statistical similarity is in contradiction with our expectation that, because of the thinner crust at SPA, those craters would show larger $U_m$ and more positive CBA. In order to quantify the expected influence of crustal thickness ($T_c$), we use $dU_m/dT_c = -0.1D_r^{0.23}$ \cite{5} based on iSALE hydrocode simulations of impact processes, and then combine with gravity forward modeling to estimate crater CBAs. To model the dashed curves in Fig. 2, we use the $U_m$-$D_r$ scaling relationship for the FHT craters from Milbury et al. \cite{11}: $U_m = 0.05(D_r - 130)$. Our gravity model assumes a density contrast of 670 kg/m\textsupersquare{} for the crust-mantle (Moho) interface, and that the Moho uplift of $U_m$ extends to 0.2$R$ and then linearly decreases to zero at 0.5$R$. Annular crustal thickening is included as a Moho depression from 0.5 to 1$R$ with a maximum depression of 0.25$U_m$ at 0.75$R$ \cite{2}. Gravity modeling results show that the expected CBAs for the SPA craters (red dashed curves
in Fig. 2) far exceeds the observations. Therefore, if the effect of \( T_i \) on \( U_m \) is as large as modeled by [5], other factors must be influencing either the basin diameter or CBA. The most likely is the thermal state.

**Thermal Evolution of the SPA:** With respect to the FHT, the thermal state of the SPA basin is influenced by two additional factors: impact heating of the SPA impact site; and lack of radiogenic heating due to impact excavation of crustal materials. SPA impact heating has been modeled to last \( \sim100 \) Ma after the impact event (at \( \sim4.25 \) Ga) [12]. The decrease in radiogenic heating can be estimated by calculating the time-dependent radiogenic heat production rate of uranium, thorium and potassium assuming a thorium concentration of 1 ppm and typical element concentration ratios [13]. Combining these two factors, we find that the surface heat flux in SPA is greater than that in the FHT for the first \( \sim90 \) Ma after the SPA formation, but less than FHT afterwards (Fig. 3).

Although this 90 Ma period is a relatively short geologically, the number of basin-sized impacts in this time was more than twice that in the following 260 Ma, assuming the lunar cratering chronology model of Le Feuvre & Wieczorek [14]. In addition, the pre-Nectarian craters are expected to be dominant in our analyzed craters due to the rapid decay of cratering rate with time. Thus, most of the craters we consider likely have formed when SPA was hotter than the FHT.

**Figure 3.** Modeled SPA thermal evolution path by adding the SPA impact heating and subtracting the radiogenic heating of a 10–35 km crust from the FHT thermal evolution path [13].

**Influence of Thermal State:** The influences of thermal state on \( U_m \) are multifold. Hotter target implies lower material strength and viscosity with enhanced impact melting, and thus is expected to increase \( U_m \) [5]. Simultaneously, more significant post-impact viscoelastic relaxation in a hotter target tends to reduce \( U_m \) [15]. The net outcome of the two mechanisms requires further quantification but likely will result in little to no appreciable change in \( U_m \).

A hotter thermal state is also expected to enlarge the crater size for a given impact energy [6; 7]. We can correct for the thermal effect on \( D_i \) by estimating the corresponding \( D_i^* \) for each SPA crater if it impacted the cooler FHT terrane. Impact hydrocode modeling [7] suggests that while \( D_i \) is influenced by the thermal state, the transient crater diameter \( D_i \) depends only on the impact energy. The scaling relationship \( D_i = aD_i^*b \) is thus useful for estimating \( D_i \) in varied target thermal state. Miljković et al. [7] find \( a_1 = 2.92 \) and \( b_1 = 0.77 \) for the nearside, and \( a_2 = 2.48 \) and \( b_2 = 0.84 \) for the FHT. The SPA thermal state in the pre-Nectarian period is expected to be hotter than FHT, but cooler than the nearside. Here we simply assume \( a_3 = 2.7 \) and \( b_3 = 0.81 \) for a preliminary test, and estimate \( D_i^* \) using \( a_3D_i^{*b_3} = a_3D_i^{*b_3} \). Fig. 4 shows that after correction, the SPA and FHT curves become clearly separated. In addition, the corrected observations (red shaded region) match our model predictions (dashed curve), which takes into account the effect of \( T_i \) [5]. Thus, we find that both the crustal thickness and temperature influence the observed CBA, and these two effects act to produce similar CBA-\( D_i \) relationships for the SPA and FHT craters (as shown in Fig. 2).

**Figure 4.** Same with Fig. 2, but the crater diameters of SPA craters are corrected to \( D_i^* \) to excluding the effect of thermal state on crater diameter.