Spatial Diffusion of Basin Melt by Impact Gardening: Implications for the Ejecta Source of Apollo Samples and Future Sampling. Tian Tian Liu1,2, Greg Michael1, Kai Wünnemann3,4 and Jürgen Oberst1,4, 1 Institute of Geodesy and Geoinformation Science, Technische Universität Berlin, 10623 Berlin, Germany (tiantian.liu@tu-berlin.de), 2 Freie Universität Berlin, Malteserstr., 74-100, Haus D, 12249 Berlin, Germany, 3 Museum für Naturkunde, Leibniz Institute for Evolution and Biodiversity Science, 10115 Berlin, Germany, 4 Institute of Planetary Research, German Aerospace Center (DLR), 12489 Berlin, Germany.

Introduction: The formation times of lunar impact basins is critical the calibration of the lunar chronology system and to understanding the late accretion history of the inner solar system. Ages of basins may be determined from radiometric dating of basin melt. However, the correct interpretation of the provenance and abundance of sampled basin melt are not fully understood. This melt has been gardened by a long sequence of subsequent impact events, diffusing its presence lateral distribution and abundance. We developed a numerical model to investigate this process by means of the Monte Carlo method in a spatially resolved model. The melt component was tracked globally, and compared at specific Apollo 14-17 (A14-17) and Luna 20 (L20) sampling sites with the results of radiometric dating of samples.

Model: This work refines the previous models, providing a more complete picture of the melt evolving distribution in three spatial dimensions [1,2].

We use the Monte Carlo method to simulate the impact gardening process. The size-frequency distribution of generated craters conforms to the production function (PF). The occurrence time of impacts is calculated combining the chronology function (CF) and PF [3]. The minimum crater diameter considered, Dmin, is chosen as 5 km.

An excavation depth, dexc, is approximated to one tenth of the transient crater diameter (Dt). Dt is related to the morphology of the final crater (Df): for simple craters, Df = 0.8D [4]; for complex craters, Df = (DD00.13/1.17)0.13 [5], where D0 is the simple-complex transition diameter, and taken as 21 km [6]. The volume of the excavated materials, Vexc, is estimated to be 1/3 of a disc with dexc in thickness and Dt in diameter. The total volume of the generated impact melt with a reset age as the current model time is: Vmelt = 1.4 × 106 D3.85 [7]. About 75% of Vmelt remains inside the crater, and about 25% of Vmelt is ejected.

About 85% of the ejected materials are deposited within five radii from the crater center [2,8]. We assume that ejecta material in patchy transition zones is also continually distributed as thin layers. Only the melt within five radii from the crater center is therefore traced. By assuming a continual distribution of melt in ejecta as a layer, the thickness of impact melt, δm, was obtained: δm(r) = Amr2 [2,8]. Am is recalculated for craters with different size. To conserve Vmelt, the integrated melt volume within five radii is taken to be exactly 25% of Vexc. The thickness of the ejecta layer decreases with distance from crater center, r: δ(r) = Ar−1 [4], where A is also varied for the craters with different D to conserve mass similar [9].

Materials ejected from craters have high kinetic energy and mix with local materials. Oberbeck et al. (1975) addressed such mixing process and proposed a mixing ratio of local material to ejecta, μ = 0.0183r0.87 [9]. Given the plausible overestimation, μ was thus modified by roughly half when μ is larger than 5.0: μ’ = μ/2+2.5 [10].

Thirty basin-forming events are included in our simulations. Their occurrence times were estimated based on superposed crater densities [11].

Global Melt Distribution of Basins: We present the global near-surface distribution of melt from the mid- to late-forming Serenitatis, Crisium and Imbrium basins (Figure 1), which presumably dominate melt contributions in collected samples. Without the disturbance of younger basin forming impacts, the melt from Imbrium is predominant near the surface, its fraction being 10 times larger than that from Serenitatis and double that of Crisium on average. Imbrium ejecta covered the northwest part of the pre-existing Crisium ejecta, decreasing its melt abundance near the surface. Serenitatis, which formed early, is located between the Imbrium and Crisium basins. The excavation zones of both Imbrium and Crisium basin contained the earlier Serenitatis ejecta. When forming, both impacts gardened Serenitatis melt, transporting it to farther locations. Therefore, the coverage of Serenitatis melt is almost equal to the total zone of both Crisium and Imbrium ejecta. In addition, local gardening by the subsequent smaller impacts caused regional anomalies of melt abundance. Here, the fraction of Imbrium and Crisium melt may be low. But it could help to generate melt enrich zones for the relatively old Serenitatis basin if the buried melt is re-excavated (e.g., two areas pointed out by the arrows in Figure 1c).

Melt Component at Apollo Landing Sites: The melt abundance in the top one meter over the A14-17 and L20 sampling sites over a 50-km radius region was estimated (Figure 2). The closer the sampling site to the late-forming basin, the higher the fraction of its melt. As seen from Figure 1, the A14-17 sampling sites were covered by Imbrium ejecta, and the L20 samples were extensively mixed with Crisium ejecta. Therefore, the Apollo 14-17 samples are expected to be dominated by Imbrium melt, and the fraction among ~3.88 Ga-melt was calculated to be ~1.0, which is also suggested by its high relative abundance at ~3.88 Ga in Figure 2a-d; and L20 samples would contain abundant Crisium melt.
with the fraction of 0.92 among ~4.08 Ga-melt, indicated by the high abundance of this particular age in the histogram (Figure 2e). All the A14-17 and L20 samples should be, at least, mixed with some Serenitas melt. Although the volume is small, its melt is still the major contribution in the melt of ~4.22 Ga with the fraction close to 1.0.

We determined the possible basin-source melt in the collected samples. Excluding the discussed Imbrium, Crisium, and Serenitas melt, it was found that all the sampling sites could be mixed with the old South Pole-Aitken (SPA) and/or Nubium melt. For the A14 samples, they could also contain Humorum melt; little other basin-sourced melt could be found in A15 samples; A16 samples could be mixed with Nectaris melt; A17 samples could have Smythii melt; L20 samples could contain Smythii and Nectaris melt. In addition, the results show that other than those basin-source melt, all the other peaks observed in radiometric datings are more likely caused by smaller-scale impact events.

**Conclusion and Applications:** We estimate the global abundance of melt from specific impact basin sources. The probable melt contribution is estimated for samples from specific Apollo and Lunar sites and compared with radiometric K-Ar ages of the samples. The model is also applied to predict the melt component at the potential landing site, such as China’s Chang’E-4 (CE-4, von Kármán crater) and Russian Luna-Glob (Boguslawsky crater) missions (Figure 1) [12,13]. It was found that surface regolith / rock at both sites is dominated by the ancient SPA melt, while the other basin events had no or only a small influence on the melt component. However, given the old age (i.e. implying that the surface has experienced extensive impact gardening), it may be better to aim at collecting re-excavated SPA melt from near the rim of larger impact craters located within the SPA basin. SPA melt abundance in CE-4 landing site is expected to be at least 20 times higher than at Luna-Glob landing site.


![Figure 1](image1.png)  
Figure 1 (Left) The global present-day distribution of melt from Imbrium (a), Crisium (b), and Serenitas (c) basin in the near-surface. The red stars indicate the sampling sites of A11-17 and L20. The blue stars are the potential landing site of CE-4 (von Kármán crater) Luna-Glob (Boguslawsky crater) missions. The same abbreviations used in Figure 2. The dashed curves outline the major melt distribution of Imbrium and Crisium basins. 

![Figure 2](image2.png)  
Figure 2 (Right) Relative melt abundances at the A14-17 and L20 sampling sites from samples (upper plots, K-Ar datings of highland rocks [1]) in comparison with simulation (lower histograms). Model histograms are shown in black (absolute scale, left) and in grey (logarithmic scale, right).