**FORMATION AND TRANSPORT OF CHANG'E-5 IMPACT GLASS BEADS.** Katarina Miljković[1], Alexander Nemchin[1], Marc Norman[2], Yuqi Qian[3, 4], James W. Head[4], [1]School of Earth and Planetary Science, Space Science and Technology Centre, Curtin University, Perth WA, Australia, [2]Australian National University, Australia, [3]China University of Geosciences, Wuhan, 430074, China, [4]Brown University, Providence, RI 02912 USA (katarina.miljkovic@curtin.edu.au).

**Introduction:** Particles of silicate glass formed either during volcanic eruptions or by impact melting are a ubiquitous component of all lunar soils. Impact glasses reflect the compositions of crustal target materials [e.g., 1] and collisional dynamics of the inner solar system [e.g., 2].

This study focuses on impact glasses returned from the Moon by the Chang'e-5 mission [3]. The Chang'e-5 landing site is located on a ~2 Ga basaltic unit [4], designated as Em4, at a distance of at least ~150 km from the nearest compositionally distinct highlands and mare basalt terranes [5]. These characteristics place testable limits on the transport distance of ejecta from impacts that occurred within the Em4 unit.

Here, we present the results of numerical impact simulations that produce melt in ejecta of small simple craters up to about 1 km in diameter. We focus on early ejecta jetting [6] as the likely formation mechanism for the investigated Chang'e-5 glass beads. This leads to a tentative identification of source impact craters represented by individual glass spherules in the Chang'e-5 regolith.

**Numerical impact modelling:** Numerical impact simulations were made using the iSALE-2D shock physics code (https://isale-code.github.io/) to investigate ejecta formation in small lunar craters within the Em4 unit. We simulated five impact crater diameters: 100, 210, 620, 830 and 1300 m. There are only a few craters exceeding 1 km in diameter within the Em4 unit. The assumed target consisted of a 7 m thick regolith layer over bedrock, which is appropriate for the area surrounding the landing site [7]. Typical material models were applied for lunar regolith and bedrock, using basalt equation of state for the lunar surface and dunite for the projectile material. The regolith layer over bedrock was assumed to have 44% porosity [8].

Two-layer models were adopted for smaller craters to account for the effect of different target cohesion and porosity between layers on the distribution of ejecta material (ejecta speed, ejecta angle, and deposition distance). Consequently, impact craters with diameters >100 m, larger than the top regolith thickness, experienced a reduced influence of regolith on the impact ejecta distribution.

Numerical impact simulations investigated spherule-forming conditions in high numerical resolution. The simulations were used to estimate shock pressures and temperatures in early ejecta as well as projected ballistic maximum transport and landing distance. High numerical resolution was required to resolve and track the early jets that are thought to form lunar regolith impact glasses.

To simulate a fine veneer of ejecta material satisfying spherule-forming conditions in such small craters on the Moon, we used two sets of simulations for the same impact crater. To simulate the ejecta formation, a high-resolution simulation was made (using 40 cells-per-projectile-radius, CPPR) and for simulating up to the transient crater stage, we used a more typical value of 12 CPPR. These runs were used to verify the impact condition and final crater size and morphology. CPPR is a measure of numerical accuracy and for specific simulations, such as early ejection, it is necessary to keep that number high.

To be considered as potential spherule-forming ejecta, physical constraints were placed on the ejected material. Temperatures of interest were taken to be between 1100 and 2000 K (827-1727°C) to ensure that melt is created. This range was chosen based on the estimated solidus and liquidus temperatures (~900-1150°C) for materials compositionally similar to Chang'e-5 regolith and basalts, and conditions at which volatile loss of Si from the melts becomes recognizable in the samples (~1500°C) [9].

Initial ejecta velocity vector was calculated from simulations, but then ejecta was assumed to travel ballistically across a flat surface (which is appropriate for the investigated source region of about 150-200 km radius surrounding the landing site). Furthermore, no friction was assumed for ejecta in flight. Altogether, such assumption represents the upper limit for the landing distance calculation. We focus on displaced material and ejecta that matches the temperature and motion/trajectory conditions. Only the fraction of ejecta that was moving slower than the escape velocity of the Moon (~2.4 km/s) was considered.

**Results**: The numerical impact simulations suggest that impacts forming craters between 100 and 1300 m in diameter all produce ejected material that meets the temperature criteria, with the volume of spherule-forming melt increasing with the crater volume, consistent with previous observations [6].

Ejected melt from the smallest crater modelled here (100 m) is produced almost entirely from the regolith layer. The effect of two layers is clearly visible in the

200 m model and to a lesser degree in the 600 m calculations. Consequently, the two largest craters were modelled with an assumption of a single bedrock layer.

Estimated ejecta temperatures can reach between 1100 and 1700 K (827-1427°C), suitable for producing the partially and fully molten beads based on calculated melting temperatures of the local regolith, with a fraction of the ejected material reaching temperatures exceeding 1900 K (1627°C), suitable for volatile loss of Si, in the larger craters. These temperature estimates were made using shock temperatures, tracked with high numerical confidence.

The mean velocity of ejected material meeting the spherule-forming conditions is, on average, 300 to 500 m/s in all craters, resulting in transportation distances up to several tens of km. Similar transportation distances estimated for craters of all sizes are the consequence of a consistent set of assumptions about impactor velocity, target conditions, and temperature limits where melting can occur.

Fig. 1 shows the data density of the maximum ballistic reach of the ejecta that satisfied the melt criteria. Impact simulation for a 200-m crater diameter produced more variability in ejecta temperature and speed compared to other crater sizes. The likely explanation is that the estimated excavation depth for a crater of this size is 15 m, which provides a subequal sampling of the two layers (regolith and bedrock) for the assumed regolith thickness of 7 m. This indicates that the regolith composition and local structure can have substantial influence on ejecta behavior, and the set of model parameters explored here may not capture the full range of conditions in lunar impacts.

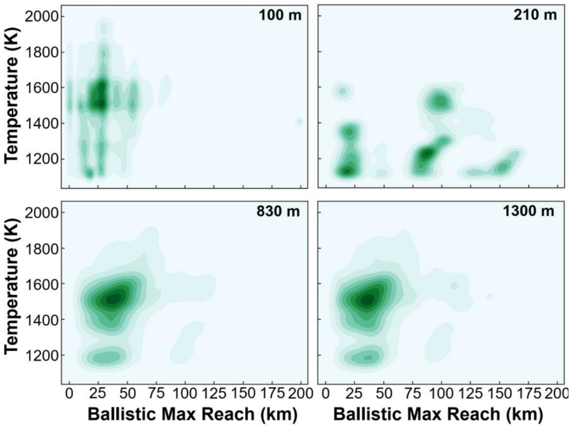

**Figure 1**. KDE (Kernel Density Estimate) data density diagram of the maximum ballistic reach of the ejecta that satisfied the melt criteria. The darker the shade, the more ejecta moved to such distance at such temperature estimates. Data density is translated from Lagrangian tracer particles from iSALE runs. From [10].

The temperature, speed and ballistic landing distance distributions of the ejecta satisfying the spherule-forming conditions in the study area (up to 200 km distance) can be roughly translated to ejecta mass from the 2D numerical simulation, by projecting into 3D space assuming axial symmetry. For simplicity, we only investigated the fraction of the ejecta that is ejected into the spherule-forming layer compared to the total excavated volume during cratering. For 200 m craters, 8 to 15% of the total transient crater volume satisfied the assumed constraints on spherule forming conditions, whereas for the modelled 500 m crater, this relative volume is only 0.5%. However, when the transient crater volume is considered, 500 m craters produce 100 times more volume/mass compared to 200 m craters, despite the difference in relative melt volumes. Furthermore, the excavation depth for 500 m craters is 5x that of 200 m craters, such that the spherule-forming ejecta from the larger craters comprise 6 times more volume/mass. Therefore, larger craters produce larger amounts of spherule-forming ejecta, and are, therefore, more likely sources.

**Conclusions:** Target and impact conditions (impact angle, size, and speed) would have a moderate effect on the ejection process [11]; Therefore, we limited the investigation to a combination of impact and target variations suitable for lunar regolith and small impacts on the Moon. Consequently, these models provide a baseline scenario in which the volume of melt produced in each crater and landing distance of ejecta would be the main factors that define the probability of sampling glass produced from individual impact craters [10].

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