# Using Impact Modeling to Determine the Redistribution of the Lunar Surface at the South Pole: Applications to Possible Landing Sites.

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**Introduction:** Here, we describe part of a comprehensive method utilizing impact modeling (iSALE-2D and iSALE-3D) to reconstruct the cratering and ejecta of a landing zone to supplement remote sensing data and possibly in-situ samples. In the case of the South Pole landing regions, we consider the formation of de Gerlache and Shackleton crater. We start by modeling Shackleton crater in 2D and 3D to determine the likely ejecta blanket layering and provenance of material around the crater rim, as well as the location of any impact melt.

The location of Shackleton and de Gerlache (Figure 1) relative to the Shoemaker crater and South Pole-Aitken basin suggests that excavated and ejected material underly the surface. Understanding how these craters blanket or transport impact melt to the underlying surfaces of the later formed craters will help elucidate the history and provenance of the regolith found at future landing sites. As such, the location of Shackleton and de Gerlach relative to the South Pole-Aitken basin implies the underlying bedrock and regolith sourced from possible South Pole-Aitken basin ejecta or impact melt. We utilize previous simulations of the South Pole-Aitken basin-forming impact to determine the layering and provenance of material underneath the South Pole region. From there, we use the SP-A output as the initial state of the surface upon which craters such as Shackleton and de Gerlach impact into and transport material.

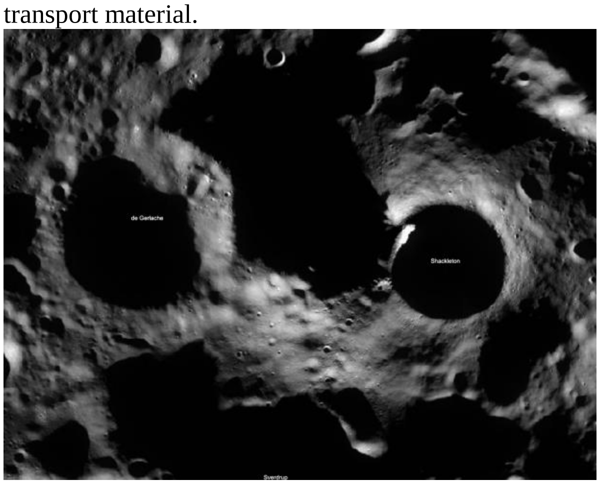


**Figure 1:** Lunar Reconnaissance Orbiter Camera's (LROC) Wide-angle Camera (WAC) image of the Shackleton, and de Gerlache craters at the South Pole of the Moon. Shackleton is a 21 km diameter crater, and de Gerlache is a little over 32 km across. Shoemaker crater is out of frame to the upper right of the image.

**Methods:** We used the iSALE-2D and 3D shock physics code [3,4,5,6], which is an extension of the SALE hydrocode [7,8], to simulate cratering near the South Pole. Previous studies validated the iSALE against comparable hydrocodes, cratering observations, and laboratory experiments [9]. We vary the impactor speed (12-17 km/s), diameter (1-5 km), and angle (in the 3D model; 30-90 degrees) to match the Shackleton and de Gerlache craters. The impact modeling employs the latest model parameters for lunar cratering [2,10,11]. First, we match the crater size using a simple vertical model. We then vary the impact angle and velocity to provide a thorough test of impact parameters and results.

We use a flat half-space dunite target surface with a surface gravity of 1.62 $m/s^2$ to approximate the Moon. Here, dunite is a proxy for the Moon's bulk mantle composition and the spherical impactor [12]. The iSALE ANEOS library accurately defines the dunite equation of state.

To determine the transportation history of material initially ejected by the South Pole-Aitken basin, we use the data from South Pole-Aitken basin-forming impacts [2], as shown in Figure 2, to determine the initial surface layers for the vertical impacts of Shackleton crater.

We place discrete Lagrangian tracers in each cell and track the motion of each volume of material through the simulation space. We follow the tracer trajectories and determine the locations where they emplace on the lunar surface relative to the current position of the crater. As an example of this technique, Figure 3 shows the final locations of ejected materials relative to the crater center for a 1 km diameter impactor striking the lunar surface at 45° and 15 km/s. We maintain accuracy while retaining reasonable computational speeds by using 20 cells per projectile radius resolutions [2,9,11]. The iSALE-3D simulations take between 2 and 21 days with parallel computing. Higher accuracy and detailed simulations require longer computation times and parallel computing nodes.

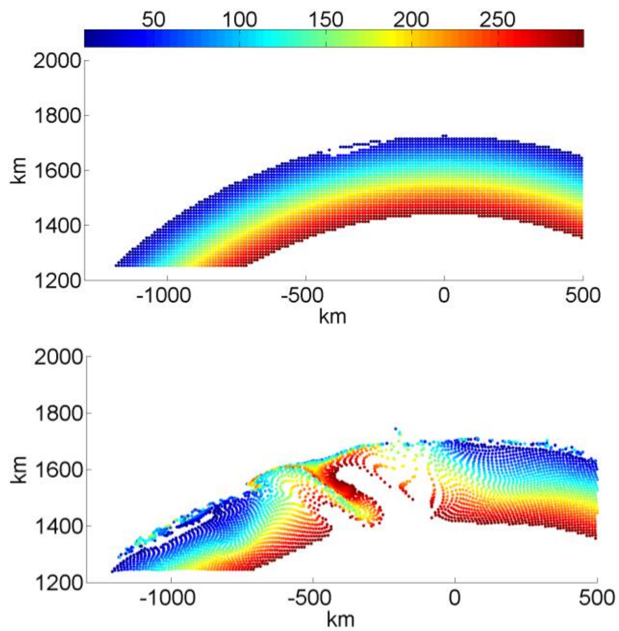


**Figure 2:** Cross-section along the direction of impact showing tracer provenance depth (in km) of the South Pole-Aitken basin forming impact in iSALE-3D. The South Pole is around 0 km on the x-axis. Here the nominal impact scenario of a 45° impact was used [2], and we show the before and after basin formation. The cross-section gives an estimation of how the region near the South Pole would form layers of crust and mantle material excavated by the impact process atop the initial crust. The color bar is provenance depth in km.

**Conclusions:** Here, we have outlined a method for combining a series of impact modeling efforts to better understand the cratering record of the South Pole region. We begin by using the output from 3D models of the South Pole-Aitken basin-forming impact and apply the results near the South Pole to follow-up simulations of Shackleton crater.

As this method is improved, we can then use the modeling to better explain the series of cratering events near the South Pole and at other sites on the Moon. For example, Apollo 17 collected core samples near a set of craters and avalanche deposits. Additionally, in the case of the Crisium basin, determination of the direction and volume of impact melt from the basin or a subsequent secondary crater may help explain the impact melt found via remote sensing [1] or possibly the Luna mission samples.

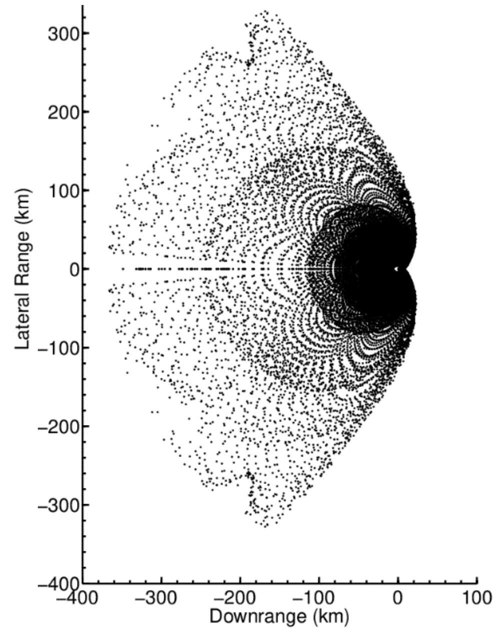


**Figure 3:** Example of a likely ejecta distribution for crater the size of Shackleton using a 1 km diameter impactor striking at 45° and 15 km/s. Each dot represents a tracer that follows the ejected path of parcels of lunar material. Both the initial (pre-impact) and final (post-ejection) locations of each parcel are known. From this data, we infer where the material underlying the regolith originates relatively to neighboring crater ejecta blankets [2].

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**References:** [1] Runyon, K. et al., JGR-Planets 2019. [2] Melosh, H. J. et al., Geology, 2017. [3] Wünnemann, K. et al., 2006. [4] Collins, G. et al., 2004. [5] Elbeshausen, D. et al. (2009) Icarus, 204, 716-731. [6] Elbeshausen D. and Wünnemann K. (2011) Proc. 11th Hyper. Imp. Symp. [7] Amsden et al., 1980. [8] Ivanov, B. et al., 1997 [9] Pierazzo, E. et al., 2008. [10] Ivanov, B. et al., 2010. [11] Collins, G., 2014. [12] Pierazzo, E. et al., 1997.