NUMERICAL MODELING OF THE FORMATION OF SHACKLETON CRATER AT THE LUNAR SOUTH POLE. S. H. Halim1, N. Barrett2, S. J. Boazman3,4, A. J. Gawronska5, C. M. Gilmour6, Harish7, K. McCanna8, A. V. Satyakumar9, J. Shah10 and D. A. Kringle11,12. 1Birkbeck, University of London, UK (email: shalim03@mail.bbk.ac.uk). 2University of Alberta, Canada. 3Natural History Museum, London, UK. 4University College London, UK. 5Miami University, Oxford, OH, USA. 6York University, Toronto, Canada. 7Physical Research Laboratory, India. 8University of Manchester, UK, 9CSIR – National Geophysical Research Institute (CSIR-NGRI), India. 10The University of Western Ontario, Canada. 11Lunar and Planetary Institute, Universities Space Research Association, Houston, TX, USA. 12NASA Solar System Exploration Research Virtual Institute.

Introduction: Shackleton crater is an area of interest for future lunar exploration due to its proximity to the South Pole-Aitken (SPA) basin and near coincidence with the south pole (Fig. 1). This bowl-shaped, near-axisymmetric simple crater (diameter, D = 21 km, depth, d = 4.2 km) has well-preserved walls and rim crest [1,2]. The crater floor is a permanently shadowed region (PSR) creating a potential cold-trap for volatiles to accumulate [3-5]. These volatiles may be an essential resource for developing a sustainable and long-term human presence on the lunar surface (e.g., [6]).

To determine the likely conditions that produced Shackleton crater we simulated impacts into the lunar surface. These simulations allowed us to investigate crater morphology, ejecta distribution, and impact melt generation. As volatiles may have been deposited in the polar regions prior to the Shackleton impact event, we also investigated the effect a volatile-bearing regolith layer in the target may have had on crater morphology.

Methods: We used the iSALE shock physics hydrocode [7-9] to simulate a projectile of chondritic composition (using a dunite equation of state [10,11]) vertically impacting a gabbroic anorthosite target [12]. The simulations explored impact velocities between 10 and 20 km/s to capture a reasonable range of those for the Moon [13]. Simple scaling approximations suggested an impactor diameter of ~1.5 km, so simulations explored diameters between 1 and 2 km. Computational cell size was fixed at 50 m with the cells per projectile radius being varied between 10 and 20 to model the desired radius. All simulations ran for 500 s post-impact with a constant gravitational acceleration field of 1.62 m/s². Lagrangian tracer particles were placed in each cell to track the pressure and temperature of material in that cell for the duration of each simulation. In the best-fit crater simulation, a simple impact melt volume was calculated by using tracer pressures and temperatures.

Once a crater with Shackleton’s morphology was produced in an anorthositic crust, a water-rich ice layer was added to the target to investigate the effect of volatile layers on crater morphology. Wet tuff, based on a Nevada tuff with a water content of 14.4 wt.% [14] at a temperature of 125 K, was used to simulate the volatile-bearing sediment layer (density = 1970 kg/m³), similar to that in terrestrial-based modelling [15].

Results: After considering a range of impactor diameter and velocity combinations, a best-fit scenario was produced.

Crater and ejecta geomorphology: An impactor with a diameter of 1.5 km and a velocity of 15 km/s resulting in an impact energy of $4.89 \times 10^{20}$ J, produced a crater similar in morphology to that of Shackleton (Fig. 2). The final crater depth, floor diameter, and rim to rim diameter were 4.1, 7.2, and 20.7 km, respectively, and a

---

**Fig. 1 Geographical context of Shackleton with mapped potential ejecta extent. White star indicates the south pole. A-A’ used for topographical profile compared to models.**

**Fig. 2 Result of best-fit simulation for Shackleton crater. Black line shows a topographical profile of Shackleton crater measured along the line A-A’ in Fig. 1 using LOLA DEM (5 m/px).**
d/D ratio of 0.20. These values agree well with observations of Shackleton [2]. Continuous ejecta was deposited ~20 km from the crater rim, agreeing well with scaling laws estimating continuous ejecta distribution to one crater diameter. Ejecta thicknesses at distances 5, 13, and 20 km from the rim were 150, 100, and 50 m thick, respectively. A computational cell size of 50 m prohibited more accurate quantification of ejecta thickness.

Impact melt generation: For the best-fit simulation crater, an impact melt volume of ~20 km$^3$ was calculated at 500 s (Fig. 3a). This is a minimum melt volume as it only considers material that recorded temperatures greater than the instantaneous melt temperature at the end of the simulation. The maximum melt volume calculated was ~62 km$^3$ based upon material that recorded a temperature >1513 K (target melt temperature) at any time during the simulation. Melt is concentrated in the crater floor, although small amounts of melt are deposited on the crater wall and rim (Fig. 3b).

Volatile-sediment layer: A mixed volatile-sediment layer with a thickness of 100 m (at a temperature of 125 K) was added into the target in the best-fit scenario. This layer was placed on the surface, 100 m below the surface, and 500 m below the surface, which led to final craters with d/D ratios of 0.20, 0.20, and 0.18, respectively. The 500 m burial scenario produces a morphology most similar to the rim and ejecta of Shackleton on the side opposite to the south pole (A′ along the profile, Fig. 4).

Discussion and conclusions: Our simulations show that Shackleton crater was likely produced by a 1.5 km diameter chondrite-like impactor at a velocity of 15 km/s. A minimum impact melt volume of ~20 km$^3$ is likely with a 90° impact angle (decreasing to ~13 km$^3$ at 45° using scaling laws [16]) and concentrated directly beneath the point of impact. A small volume of melt was possibly distributed on the crater walls and outside of the rim crest. Asymmetric rim crest heights and topography across the crater may have been influenced by the presence of subsurface volatile layers, pre-impact surface topography, or both. Specifically, a 100 m thick volatile-bearing layer buried 500 m in the pre-impact target where a layered terrain has been observed [17] is consistent with a relatively flat rim on the side of the crater opposite the south pole.

Acknowledgements: We thank USRA-LPI, CLSE, and NASA SSERVI for support. We also thank the developers of iSALE.


![Fig. 3](image1.png)  
**Fig. 3** The minimum (a) and maximum (b) extent of impact melt generated.

![Fig. 4](image2.png)  
**Fig. 4** Final crater morphology for a surface with a homogeneous target (left) and a target with a 100 m thick volatile layer buried at 500 m (right). Fig. 2 profile overlaid.