EARLY LUNAR CRUST HEALED ITSELF AFTER IMPACTS PUNCTURED HOLES.

V. Perera[1] and A. P. Jackson[2,3], [1]Applied Physics Laboratory, Johns Hopkins University, Laurel, MD, USA. (viranga.perera@jhuapl.edu), [2]Centre for Planetary Sciences, University of Toronto, Toronto, ON, Canada. and [3]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA.

Introduction: The early Moon likely had a unique rheological structure where an anorthositic crust floated atop a Lunar Magma Ocean (LMO) [e.g., 1]. The crust would have acted as a thermal blanket and slowed the cooling of the Moon, prolonging what would have taken $\sim 10^3$ yr to $\sim 10^7$ yr [2]. Recent work has shown that this tranquil cooling of the Moon would have been interrupted by a prolonged bombardment from debris released during the original Moon-forming giant impact [3]. Reimpacting debris may have either prolonged or expedited the cooling of the Moon depending on the degree to which the bombardment punctured holes into the lunar crust and delivered thermal energy [4]. While both the initial mass of the reimpacting debris population and the mass accretion rate as a function of time can be estimated based on Smoothed Particle Hydrodynamics (SPH) simulations [e.g., 5] and N-body simulations [3] respectively, the impact process itself is complex and requires hydrocode modeling to determine the consequence to the crust. In ongoing work using the iSALE hydrocode [6,7,8], we show the conditions under which impacts will puncture through the crust, expose hot magma, and increase the heat flux [9]. Yet, that increased heat flux is temporary since holes will be refilled by newly formed anorthosites. Notably, impact hydrocodes are generally not able to model the long term thermal evolution of a system after an impact. As such here we focus on the thermal evolution of holes generated in the early lunar crust to determine the implications for the overall cooling of the Moon.

Methods: We developed a two-dimensional thermal evolution code called iFill (*i*mpact *Fill*ing). iFill is similar to iMagma from [4]; however, while iMagma is a one-dimensional thermal evolution code that evolves the whole LMO, iFill is a two-dimensional thermal code that focuses on the local area of an impact site. iFill incrementally solidifies the local LMO and adds that material to both the solid mantle below and the floatation crust above. This models the fractional crystallization process after 80% of the initial LMO has crystallized, where denser material fall to the interior while less dense material float to the surface [e.g., 2]. Newly formed solids can either be placed at random horizontal locations or, more realistically, preferentially at horizontal locations with higher thermal flux.

iFill first reads in a two-dimensional iSALE material output that identifies the locations of the crust and magma material. We then start with a LMO depth that corresponds to the crustal thickness in the iSALE output. For instance, it is expected that when the lunar crust was $\sim$ 10 km thick, the LMO depth was $\sim$ 100 km. iFill then iteratively solidifies the LMO while calculating the time required to expel the heat of fusion and the energy released by secular cooling. At each step, the crustal thickness, conductive flux, and the surface temperature at each horizontal location is updated.

Similar to [4], we use the solidus temperature equation from [2] to estimate the temperature at the LMO-solid mantle boundary. Thus, we calculate the temperature within the LMO by following the adiabat from the LMO-solid mantle boundary with the assumption that the LMO is convecting through out the solidification process. The surface temperature is calculated self-consistently by equating the conductive flux through the crust to the radiative flux from the surface.

We set two stopping criteria for the iterations. First, similar to both [2] and [4], the iterations stop when only 1% of the original LMO remains. Second, the iterations stop if the LMO-solid mantle boundary and the crust-LMO boundary intersect each other. The second condition usually occurs when the remaining LMO is $\sim 1\%$.

Here we use the output of one of our iSALE simulations to demonstrate iFill. The iSALE simulation input parameters include an impactor diameter of 10 km, impacting speed of 4 km/s and a 10 km thick crust. In this simulation the impactor punctures through the crust, but crustal material resettles into the impact site leaving the crust thinned rather than directly exposing magma at the surface. Crustal thickness after the impact near the impact site is $\sim$ 3-5 km.

Results: The top left plot in Figure 1 shows that the portion of the crust that has been thinned by an impact produces 5 times the thermal flux as compared to the unperturbed crust far from the impact site ($\sim$ 2.0 vs. $\sim$ 0.4 W/m^2). Given the assumption that the rate of anorthosite formation under a given location is directly proportional to the thermal flux, we find that in $\sim$ 1 Myr crust near the impact site thickens sufficiently so that fluxes near and far from the impact site are roughly equalized. This hole thus has an effective lifetime of

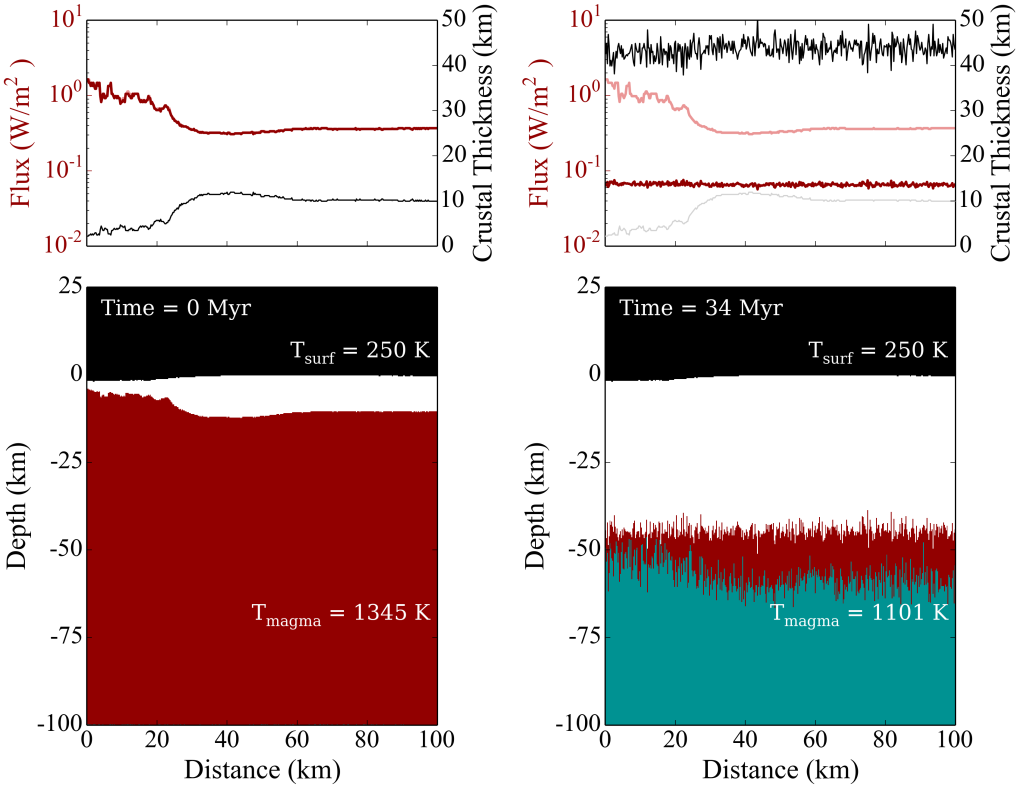

Figure 1: An example of a two-dimensional iFill thermal model. On the left is the half-space cross section of an iSALE output (bottom) and the corresponding flux and crustal thickness profiles (top). On the right is the thermally evolved iFill output showing the crust (in white) and the solid mantle (in dark cyan) have grown thicker while the quantity of magma (in red) has decreased. Lighter colors in the top panel shows the initial flux and crustal thickness profiles as references. Here solids are weighted towards horizontal positions with a higher thermal flux. The horizontally-averaged self-consistent surface temperature and the average temperature of the magma near the surface and the bottom are shown as T_{surf} and T_{magma} respectively.

around 1 Myr. Run to completion, solidification of the local LMO takes ∼ 30 Myr. This is similar to the solidification time of the global LMO with the effect of reimpacting debris removed [4] since this is equivalent to modelling the cooling of the global LMO with only a single hole.

Alongside the hole lifetime of around 1 Myr, it is notable that when run to completion (right hand panel of Figure 1) the increased cooling flux and magma crystallization rate beneath the hole location leads to a bulge in the solid mantle due to the correspondingly increased deposition rate. This would force the final LMO crystallization products, presumably including the ur-KREEP material, away from the hole site. While more work needs to be done examining whether this would be preserved through convection in the LMO and subsequently the solid mantle, it is possible that these deviations in the mantle might provide a way of identifying some of the final hole locations, despite the lack of surface topography.

References: [1] Wood, J. A., et al. (1970) Science, 167(3918), 602–604. [2] Elkins-Tanton, L. T., et al. (2011) Earth Planet. Sci. Lett., 304(3–4), 326–336. [3] Jackson, A. P. and Wyatt, M. C. (2012) MNRAS, 425(1), 657–679. [4] Perera, V., et al. (2018) JGR-Planets, 123, 1168–1191. [5] Marcus, R. A., et al. (2009) ApJL, 700(2), L118. [6] Amsden, A., et al. (1980) Los Alamos Scientific Lab Technical Report. [7] Collins, G. S., et al. (2004) Meteorit. Planet. Sci., 39, 217. [8] Wünnemann, K., et al. (2006) Icarus, 180, 514–527. [9] Jackson, A. P., et al. (in prep.).