CRATERING AND PENETRATION OF THE EARLY LUNAR CRUST.

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Introduction: Giant impacts are expected at the late stages of planet formation [e.g., 1]. There is substantial evidence for the occurrence of such impacts in our own solar system, in particular our Moon is believed to have originated in such an event [2,3]. Recent work has shown that typically at least a few percent of the impacting mass will have sufficient speed to escape the system [e.g., 4]. For the Moon-forming impact, at least 10^{23} kg ($\sim$ 1.3 lunar masses) of debris is estimated to have escaped onto heliocentric orbits, a substantial fraction of which subsequently reimpacted the Earth and the Moon over a period of $\sim$100 Myr [5]. At the same time the Moon would have been cooling from a mostly molten state, having formed from a high-energy impact event. Without impact bombardment, the Moon is thought to have solidified fairly slowly over around 10 Myr due to the early lunar crust functioning as a thermal blanket [e.g., 6]. Reimpacting debris however may have had a large influence on the cooling rate. They could have punctured the early crust, increased the thermal heat flux and thus expedited cooling. At the same time reimpacting debris would have carried substantial kinetic energy, which may have resulted in heating of the Moon. As such recent work found that reimpacting debris may have temporally altered the early lunar thermal evolution [7].

The initial mass of the reimpacting debris population and the mass accretion rate as a function of time are estimated based on Smoothed Particle Hydrodynamics (SPH) simulations [e.g., 4] and N-body simulations [5] respectively. Using those results recent work utilized a simple prescription to convert the mass accretion rate into an area of holes produced on the crust [7]. This simplification was used since the degree to which holes are produced depends on a number of parameters pertaining to both the impactor (e.g., size and velocity) and the crust (e.g., thickness and mechanical strength). Here we seek to improve the previous work by modeling the impact process using a hydrocode. This will help constrain the conditions under which holes are produced by reimpacting debris and in turn improve our understanding of the overall thermal evolution of the Moon. Our work can also provide insights for other bodies on which impacts strike a solid surface underlain by liquid, such as the icy moons of the giant planets [e.g., 8].

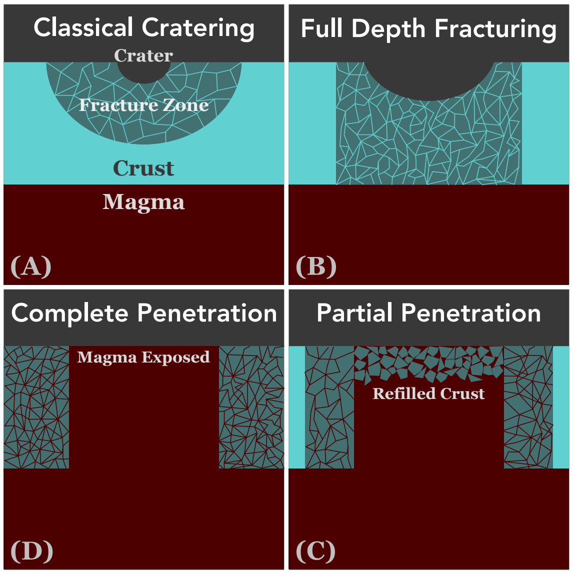

Figure 1: Illustration of the four types of craters created by impacts on the early lunar crust. Starting with the top left panel (classical cratering), the illustration progresses clockwise through more energetic impacts. With sufficient energy, impacts are able to completely remove crustal material locally and expose magma at the surface (complete penetration).

Methods: Here we use the iSALE hydrocode, which is tailored for impact simulations and has been tested against laboratory experiments [9,10,11]. We start each simulation with an impactor just above the surface of a crust, which itself is atop a liquid layer to represent molten magma. Since ANEOS equations of state for lunar crustal and mantle material are not available, we represent the lunar crust with ANEOS granite (e.g., [12]) and the lunar mantle (along with impactors) with ANEOS dunite (e.g., [13]). This choice of materials has been used in previous studies, and essentially here satisfies two important conditions: that the crust has a lower density than the magma to ensure stable buoyancy, and that the crustal material has a higher melting temperature than magma beneath.

We have run over 150 simulations varying the impactor diameter, impact velocity and crustal thickness.

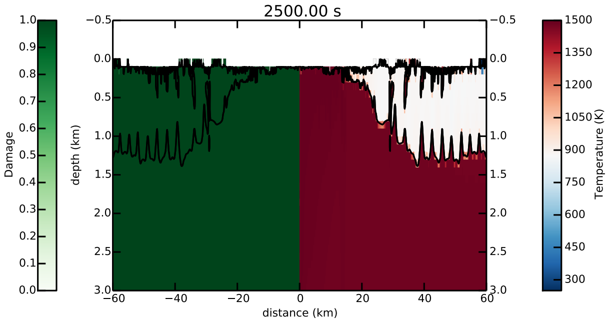

Figure 2: iSALE simulation showing complete penetration resulting from an impact of a 3-km body into 1-km thick crust at 5 km/s. The number above the panel indicates the simulation time (in seconds) at which the data is taken. The left side shows the damage factor, while the right side shows the temperature field. The LMO does not have mechanical strength and is always completely damaged.

We simulate impactors with diameters ranging from 100 m to 30 km and crustal thicknesses ranging from 1 to 40 km. Since the debris originates from near-Earth orbits impacts are concentrated at low velocities, and so we focus on impact velocities from 3 to 9 km/s with our highest impact velocities being 15 km/s. As we are primarily interested in the penetration of the crust and the boundary between cratering and penetration, we do not simulate the smallest impactors striking the thickest crust or the largest impactors striking the thinnest crust.

Results: In Figure 1 we illustrate the four types of cratering outcomes identified by our simulations: (1). 'Classical cratering' where fracturing is localized in a hemispherical volume, (2). 'Full depth fracturing' where the crust is fractured through to its base and as a result the fracture volume is approximately cylindrical, (3). 'Partial penetration' where the impactor penetrates through the crust but a significant amount of crustal material flows back to cover the hole and (4). 'Complete penetration' where magma remains directly exposed after the crust has relaxed (see Figure 2 for an example iSALE simulation). Figure 3 shows that impactors are able to penetrate the crust when their kinetic energy is sufficiently high to do the necessary mechanical work in removing crustal material. Since some of the kinetic energy goes into breaking and heating crustal material, more kinetic energy is required for penetration than merely work required to move crustal material.

Conclusions: We find that impact kinetic energy is a very good predictor of the size of hole produced by an impact, with the hole opening efficiency being around 5% by our measure of the work done in opening a hole. This contrasts with the case for craters where scaling relations are more complex. Hole production is much more closely tied to the transient cavity, whose size is also known to correlate well with impact energy. The onset of partial penetration occurs when the transient cavity breaches the base of the crust. This also leads to a minimum hole diameter that is approximately equal to the crust depth.

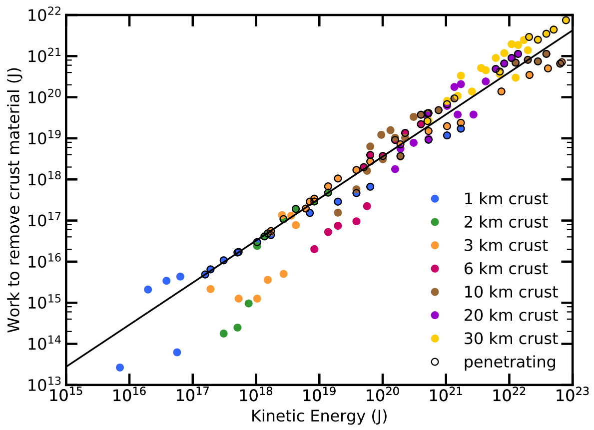

Figure 3: Impact kinetic energy versus a measure of the work done in opening a hole (weight of crust removed multiplied by depth of crust). Colors show impacts into crust of different thicknesses as shown in the legend. Black outlines indicate impacts resulting in partial and complete penetration, circles without black outlines indicate craters. The black line is a best-fit constrained to have a gradient of 1.

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