Crater Concentric Ridges: Remnants of Kelvin-Helmholtz Instabilities in Ejecta Flows? C. Atwood-Stone[1], J. N. McElwaine[2,3], J. E. Richardson[3], V. J. Bray[1] and A. S. McEwen[1], [1]Lunar & Planetary Laboratory, University of Arizona, 1629 E University Blvd. Tucson, AZ 85721, [2]Department of Earth Sciences, Durham University, UK. [3]Planetary Science Institute, Tucson.

Introduction & Background: We analyze the formation of a geologic facies that we call 'crater concentric ridges' (or CCRs) using Discrete Element Modeling (DEM). This facies is generally found around small (1-10 km), fresh craters in the lunar maria [see Fig. 1] [1], although they are also, less commonly, noted around highland craters. CCRs appear as short lengths of ridges concentric to the crater, which frequently curve their tips away from the crater [2], although specific morphologies can vary significantly [see Fig. 2]. In mare examples, where the surrounding topography is slight, the CCRs are distributed relatively evenly around the crater and tend to extend from roughly 1.2 crater radii to several crater radii [3].

In the 1970s, when these features were last studied [1,4], they were referred to as 'Lunar concentric dunes', however we find that name to be misleading as they do not form like dunes, do not have dune-like slopes, and are now found on Mercury as well as the Moon [5].

Methodology: We are numerically modeling ejecta flows to determine how the CCR facies is formed around impact craters. To do this we have been using an application of the Fortran Discrete Element Method (FDEM) code developed for analyzing granular flows [6]. This code models the individual interactions of large numbers of particles in order to accurately simulate how granular flows move and evolve over time.

In order to examine the formation mechanisms responsible for the creation of CCRs we are modeling various important parameters of the ejecta flow: ejecta velocities, total mass, and density of the ejecta particle stream calculated for different distances from specific lunar craters.

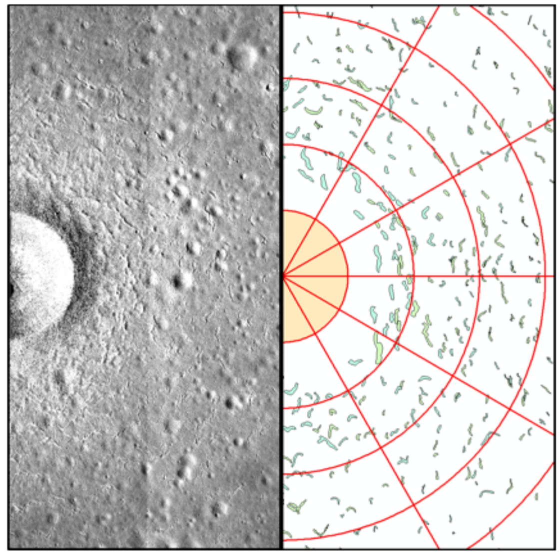

Fig. 1: Mosaic and Map of CCRs at Linné crater. Red lines delineate the separate areas used to calculate packing density.

Our current models look at a specific small region of the ejecta blanket and watch the flow evolve from the moment the first ejecta particles impact the ground until all motion ceases. Specifically our preliminary models are looking at the region of the ejecta blanket of Linné crater (~2km) between two and three crater radii from the crater center, which corresponds to initial ejecta flow velocities between 36 and 47 m/s and ejecta flow depths between 5.2 and 1.8 meters.

These simulations model ejecta flowing over an erodible granular substrate of particles identical to

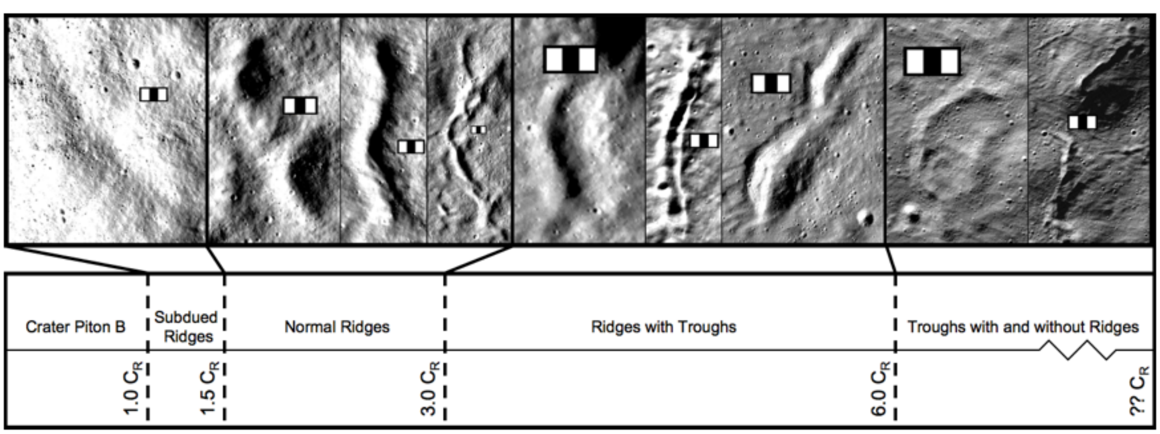

Fig. 2: CCR morphology progression. Close up images of CCRs from crater Piton B show how ridge morphology changes with distance from the crater. All images are rotated so that the crater is to the left. The scale bars are all 100 meters long.

those of the ejecta flow. This substrate represents the granular lunar regolith that real ejecta flows move over and erode. It is from the interactions between the ejecta and regolith layers that topographic features arise in our models.

Results: The simulations that we have run show Kelvin-Helmholtz instabilities forming in our modeled ejecta flows. Kelvin-Helmholtz instabilities are a type of shear instability that forms at the initially planar boundary between two fluids flowing with different speeds. This type of instability forms when small perturbations in the boundary are exaggerated by local pressure differentials to create a waveform boundary, after which the velocity differential between the two layers rolls the waves over [7]. This sort of instability is common between neighboring flows in the atmosphere and at the boundaries between the bands on giant planets. This sort of instability has also been observed for granular layers that are flowing next to each other down an inclined plane [8].

In our models we observe this type of instability forming prominently between the ejecta and regolith layers [see Fig. 3]. The creation of these instabilities depends on certain parameters of our models. Velocity of the ejecta needs to be sufficiently fast for the instabilities to start forming, and higher velocities will lead to larger amplitude instabilities. We also observe that the instabilities formed more easily with thicker flow layers. These factors suggest that the Kelvin-Helmholtz instabilities will not be able to form too close to the crater where the ejecta flow is slowest and also that they will not be able to form too far away where the ejecta layer is very thin. These restrictions on where the instabilities are able to form in the ejecta blanket could explain why CCRs form in an annulus around craters.

At the end of our simulations when all motion has ceased the waveforms of the Kelvin-Helmholtz instabilities are not prominent topographic features, and where they do remain they are too broad to be CCRs. However, as a result of the agitation the instabilities provide, narrow ridges are formed that sometimes remain after the flow has stopped. These ridges do not form in single layer flows or when the velocity of a two-layer flow is too slow for the instabilities to develop. It is these ridges, which appear to be a result of Kelvin-Helmholtz instabilities, that we propose are modeled versions of CCRs.

Future Work: Our current results come from preliminary models that we will be significantly improving. One of the most important issues that needs to be addressed is that our current models use only spherical particles to model the ejecta and regolith layers. This presents a problem because spheres are very good at

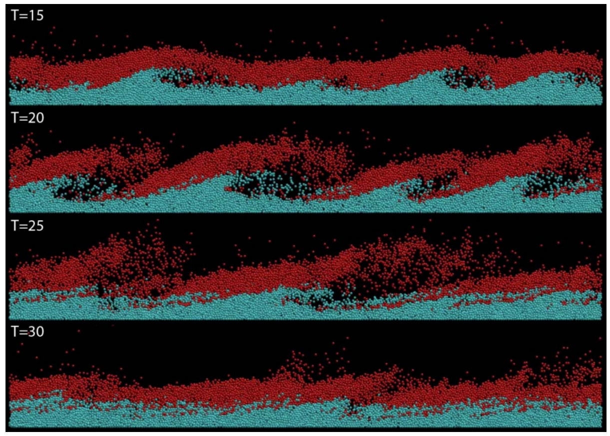

Fig. 3: Example timesteps from a simulation where Kelvin-Helmholtz instabilities clearly develop in the ejecta flow. The parameters for this simulation are a rough representation of two crater radii from Linné Crater.

settling down to flat surfaces once flows stop, as such it is difficult to form topographic features in our models. Since real ejecta particles are non-spherical we want to capture that behavior in our models. We expect that when we implement this change topographic features like ridges will become much more common and prominent.

Moving forward we also want to expand our models to cover a much wider parameter space. Our current models are all based on ejecta flows occurring at a few distances from the two-kilometer crater Linné. In the future we will be modeling flows occurring at an array of distances around several craters that host CCRs in their ejecta blankets, and a few that have no CCRs as a control group.

Once we have more realistic models to work with we will be comparing the ridge features produced in our simulations with observational data of CCRs, especially with topographic observations taken from NAC DTMs of the craters Linné and Piton B. These comparisons will allow us to truly evaluate Kelvin-Helmholtz instabilities as a formation mechanism for CCRs.

References: [1] Morrison & Oberbeck (1975), Proc. Lunar Sci. Conf., 6th:2503-2530. [2] Howard (1974), Proc. Of the 5th Lunar Conf. 1:61-69. [3] Melosh (1989), *Impact Cratering: A Geologic Process*. [4] Oberbeck et al. (1975), The Moon, 13:9-26. [5] Atwood-Stone et al. (2016), Icarus. [6] Borzsonyi, Ecke and McElwaine. (2009) Phys. Rev. Let. 103:178302. [7] Falkovich (2011), *Fluid Mechanics: A Short Course for Physicists*. [8] Goldfarb et al. (2002), 53rd Meeting of Division of Fluid Dynamics.