PLANETARY GRANULAR TOPOGRAPHY:
SLOPE ANGLES & CRATER CONCENTRIC RIDGES

by

Corwin Atwood-Stone

________________________________________
Copyright © Corwin Atwood-Stone 2018

A Dissertation Submitted to the Faculty of the
DEPARTMENT OF PLANETARY SCIENCES

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

2018
THE UNIVERSITY OF ARIZONA
GRADUATE COLLEGE

As members of the Dissertation Committee, we certify that we have read the dissertation prepared by Corwin Atwood-Stone, titled Planetary Granular Topography: Slope Angles & Crater Concentric Ridges and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

Alfred McEwen
Date: July 26, 2018

Veronica Bray
Date: July 26, 2018

Jon Pelletier
Date: July 26, 2018

Victor Baker
Date: July 26, 2018

Shane Byrne
Date: July 26, 2018

Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copies of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

Dissertation Director: Alfred McEwen
Date: July 26, 2018

Dissertation Director: Veronica Bray
Date: July 26, 2018
STATEMENT BY THE AUTHOR

This dissertation has been submitted in partial fulfillment of the requirements for an advanced degree at the University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this dissertation are allowable without special permission, provided that an accurate acknowledgement of the source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his or her judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: Corwin Atwood-Stone
Acknowledgements

As I near the end of this endeavor I find I owe thanks to many people for their help along the way.

To Veronica Bray: For shepherding me through so much of this process and for believing in my project enough to write an LDAP grant with me. And, consequently, to LDAP for funding that grant which has provided the support for so much of this work.

To my adviser, Alfred McEwen: For getting me pointed in the right direction and providing the suggestions that led to the various projects presented within.

To Jim McElwaine: For providing access to his FDEM code and for his help and expertise in running simulations. And further thanks for getting me set up in a castle while we worked together in England.

To the rest of my committee and coauthors: For providing helpful advice and suggestions on the course of the research presented here.

To Shane Byrne: For running the field trips that have been one of the true highlights of my graduate career. And to the rest of the field trip crew for making our adventures so much fun.

To Dr. Wilson: Whose suggestion that I look into the sand dunes of Titan for a class project in his sedimentology class helped lead me into planetary science. And whose passion for sedimentology helped lead me to the granular subject material studied in this dissertation.

To Brendan Miller: Who guided me along my first steps in independent research, even if I have left the stars for the planets.

To my family: Whose boundless support as I have pursued this path has been invaluable in keeping me on track.

And finally, to my amazing wife Michaela: Without whose endless help and support, both moral and actual, this dissertation never would have been finished. And who consequently knows more about Crater Concentric Ridges than any librarian should have to.
Dedication

For Grampa: I wish you could read this
# Table of Contents

LIST OF FIGURES .................................................................8
LIST OF TABLES ......................................................................9
ABSTRACT .............................................................................10
CHAPTER 1: INTRODUCTION ....................................................11
  1.1: Granular Topography ......................................................11
  1.2: Impact Crater Ejecta ......................................................12
  1.3: Overview of Dissertation ................................................13
CHAPTER 2: AVALANCHE SLOPE ANGLES IN LOW-GRAVITY ENVIRONMENTS FROM ACTIVE MARTIAN SAND DUNES ..................................................17
  2.1: Introduction ..................................................................17
  2.2: Methods ......................................................................21
  2.3: Results & Discussion ....................................................24
  2.4: Conclusions ..................................................................26
  2.5: Figures ........................................................................28
CHAPTER 3: A NEW STUDY OF CRATER CONCENTRIC RIDGES ON THE MOON .....32
  3.1: Background & Introduction ...........................................32
  3.2: Objectives & Methods ...................................................33
  3.3: Results & Interpretation ................................................35
    3.3.1: Ridge Morphology with Distance from Crater ...............36
    3.3.2: Areal Density of CCRs ..............................................37
    3.3.3: Ridge Topography ...................................................39
  3.4: Special Cases ..................................................................42
    3.4.1: Encke X: Examples of Suppression of CCR Formation by Melt-Rich Ejecta ....42
    3.4.2: Lassel D: Example of CCR Chains ................................42
    3.4.3: ‘Lick Rim’: Example of Topographical Influence on CCR Distribution ..........43
    3.4.4: Mösting C: Example of Degraded Ridges ......................44
    3.4.5: CCRs Around Highland Craters ...................................45
    3.4.6: Extra-Lunar CCRs ...................................................46
  3.5: Assessment of Formation Hypotheses ................................47
  3.6: Future Work ...................................................................49
  3.7: Figures & Tables ............................................................50
CHAPTER 4: A TOPOGRAPHIC EXAMINATION OF CRATER CONCENTRIC RIDGES . . .59
  4.1: Background & Introduction ...........................................59
  4.2: Objectives & Methods ...................................................61
    4.2.1: Two-Dimensional Data Collection ................................62
    4.2.2: Three-Dimensional Data Collection ............................63
  4.3: Results ..........................................................................66
    4.3.1: Two-Dimensional CCR Mapping Data ..........................66
    4.3.2: Topography of CCRs ................................................67
4.3.3: Interaction With Pre-Existing Topography ........................................... 70
4.3.4: Troughs .................................................................................. 72
4.4: Discussion .................................................................................. 73
4.4.1: Two-Dimensional CCR Mapping Data ........................................... 74
4.4.2: Topography of CCRs ................................................................ 76
4.4.3: Interaction With Pre-Existing Topography .................................... 77
4.4.4: Troughs ................................................................................. 79
4.5: Assessment of Formation Hypotheses ............................................ 81
4.6: Figures & Tables ........................................................................ 83

CHAPTER 5: CRATER CONCENTRIC RIDGES FORMED BY KELVIN-HELMHOLTZ
INSTABILITIES BETWEEN EJECTA AND REGOLITH: A SIMULATED EXPERIMENT .94
5.1: Background ................................................................................ 94
5.1.1: CCR Background ................................................................... 94
5.1.2: Kelvin-Helmholtz Instabilities .................................................. 96
5.2: Methods ..................................................................................... 97
5.2.1: Fortran Discrete Element Method .............................................. 97
5.2.2: Excavation Flow Properties Model .......................................... 98
5.2.3: Ejecta Simulation Set-Up ......................................................... 99
5.2.4: Measurement of Mixing ......................................................... 101
5.3: Results ....................................................................................... 102
5.3.1: Simulated Kelvin-Helmholtz Instabilities ................................. 102
5.3.2: Final Simulated Topography .................................................... 103
5.3.3: Ejecta Regolith Mixing Trends ................................................ 106
5.4: Discussion ................................................................................ 106
5.4.1: Kelvin-Helmholtz Instabilities .................................................. 106
5.4.2: Simulated Topography and CCRs ............................................. 108
5.4.3: Mixing Trends ....................................................................... 111
5.5: Conclusions ............................................................................... 112
5.6: Figures & Tables ........................................................................ 113

CHAPTER 6: CONCLUSIONS & FUTURE WORK ...................................... 125
6.1: Conclusions ............................................................................... 125
6.2: Future Work .............................................................................. 126
6.3: Future Application ..................................................................... 127
REFERENCES .................................................................................. 129
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>HiRISE Orthoimages of Dune Fields</td>
<td>28</td>
</tr>
<tr>
<td>2.2</td>
<td>Orthoimage &amp; DTM of Herschel Crater Dune</td>
<td>29</td>
</tr>
<tr>
<td>2.3</td>
<td>Topographic Profiles of Herschel Crater Dune</td>
<td>30</td>
</tr>
<tr>
<td>2.4</td>
<td>Histogram of Dune Slipface Slopes</td>
<td>31</td>
</tr>
<tr>
<td>3.1</td>
<td>CCR Morphology Progression</td>
<td>50</td>
</tr>
<tr>
<td>3.2</td>
<td>Locations of Craters with CCRs</td>
<td>50</td>
</tr>
<tr>
<td>3.3</td>
<td>Mosaic and Map of Linné Crater</td>
<td>51</td>
</tr>
<tr>
<td>3.4</td>
<td>Proposed CCR Interaction Morphologies</td>
<td>52</td>
</tr>
<tr>
<td>3.5</td>
<td>CCR Areal Density Graph</td>
<td>53</td>
</tr>
<tr>
<td>3.6</td>
<td>Topographic Data</td>
<td>54</td>
</tr>
<tr>
<td>3.7</td>
<td>Special Cases</td>
<td>55</td>
</tr>
<tr>
<td>3.8</td>
<td>CCRs around Highland Craters</td>
<td>56</td>
</tr>
<tr>
<td>3.9</td>
<td>Extra-Lunar CCR Possibilities</td>
<td>57</td>
</tr>
<tr>
<td>4.1</td>
<td>CCR Morphology Progression</td>
<td>83</td>
</tr>
<tr>
<td>4.2</td>
<td>Mosaic and Map of Linné Crater</td>
<td>83</td>
</tr>
<tr>
<td>4.3</td>
<td>Locations of Craters with CCRs</td>
<td>84</td>
</tr>
<tr>
<td>4.4</td>
<td>Areal Packing Density of CCRs</td>
<td>85</td>
</tr>
<tr>
<td>4.5</td>
<td>CCR Sinuosity Graph</td>
<td>86</td>
</tr>
<tr>
<td>4.6</td>
<td>CCR Height &amp; Slope Trends</td>
<td>87</td>
</tr>
<tr>
<td>4.7</td>
<td>CCR Slope &amp; Height Comparison</td>
<td>88</td>
</tr>
<tr>
<td>4.8</td>
<td>Three Dimensional CCR Morphology Insets</td>
<td>89</td>
</tr>
<tr>
<td>4.9</td>
<td>Three Dimensional Insets of CCRs Over Underlying Topography</td>
<td>90</td>
</tr>
<tr>
<td>4.10</td>
<td>Three Dimensional Insets of Crater Concentric Troughs</td>
<td>91</td>
</tr>
<tr>
<td>5.1</td>
<td>Crater Concentric Ridge Overview</td>
<td>113</td>
</tr>
<tr>
<td>5.2</td>
<td>Velocity &amp; Ejecta Depth Effects on K-H Instabilities</td>
<td>114</td>
</tr>
<tr>
<td>5.3</td>
<td>K-H Instabilities Between Ejecta and Regolith</td>
<td>115</td>
</tr>
<tr>
<td>5.4</td>
<td>Ridges in Final Topography</td>
<td>116</td>
</tr>
<tr>
<td>5.5</td>
<td>Troughs in Final Topography</td>
<td>117</td>
</tr>
<tr>
<td>5.6</td>
<td>Additional Simulated Topographic Features</td>
<td>118</td>
</tr>
<tr>
<td>5.7</td>
<td>Degree of Mixing Between Ejecta and Regolith</td>
<td>119</td>
</tr>
<tr>
<td>5.8</td>
<td>Ridge Morphology in Simulations &amp; Topography</td>
<td>120</td>
</tr>
<tr>
<td>5.9</td>
<td>Row of Ridges Morphology in Simulations &amp; Topography</td>
<td>121</td>
</tr>
<tr>
<td>5.10</td>
<td>Double Ridge Morphology in Simulations &amp; Topography</td>
<td>122</td>
</tr>
<tr>
<td>5.11</td>
<td>Ridge &amp; Trough Morphology in Simulations &amp; Topography</td>
<td>123</td>
</tr>
</tbody>
</table>
List of Tables

Table 3.1: Size and Location Data for CCRs .................................................................58
Table 4.1: List of Data Products ...................................................................................92
Table 4.2: Two-Dimensional CCR Measurements ..........................................................93
Table 4.3: Three-Dimensional CCR Measurements .......................................................93
Table 5.1: Values Used in Creating Simulations .............................................................124
Abstract

In the first portion of this dissertation I examine the effect of gravitational acceleration on the angle of repose of granular features. To do this I have used HiRISE DTMs to compare the slipface angles of Martian sand dunes with those measured on Earth. In doing this I have found that the slopes of active dunes on Mars do not differ from their terrestrial counterparts, and as such I have concluded that gravitational acceleration does not effect the angle of repose. In the second, larger portion of this dissertation I examine the morphology and formation of Crater Concentric Ridges (CCRs). These features, formerly known as 'Lunar Concentric Dunes', are ridges oriented concentrically to fresh craters a few kilometers in diameter. Using LROC NAC data I have created a catalog of 77 craters that have these features in their ejecta blankets. Further, I have used this data to map and measure the CCRs around eight craters of varying diameters in order to analyze their distributions. I have also been able to characterize the morphology of these ridges and how that morphology changes with distance from the host crater. Using DTMs made from NAC images I have studied the three-dimensional topography of CCRs in order to fully describe the morphology of these features. This morphological analysis has allowed me to refute several hypotheses for the formation of these features, including the previously accepted ballistic impact sedimentation and erosion hypothesis. In order to formulate a new theory for the formation of these features I have created simulations of crater ejecta flowing over regolith using discrete element modeling. In these simulations I found that Kelvin-Helmholtz instabilities form at the interface between the ejecta and regolith. I posit that these instabilities are responsible for the formation of Crater Concentric Ridges. This hypothesis is supported by the observation that the topography produced in my simulations strongly resembles that which I have measured and described around real lunar craters.
Chapter 1: Introduction

1.1: Granular Topography

Granular landforms are important, and very common, features on solid planetary bodies. On those bodies with significant atmospheres—such as Earth, Mars, or Titan—there are a plethora of different types of granular landforms that may be found, the detailed understanding of which are very important to understanding the geomorphology and surface history of these bodies. On airless bodies, which are more common than those with atmospheres, granular landforms are primarily the result of impact cratering. As such understanding the geomorphology of the features formed from crater ejecta can give deeper insight into the process of impact cratering, which dominates the surface geology of most planetary bodies.

A granular landform is one that is formed from vast numbers of individual particles of solid material. Since these features are not cemented together they are maintained by the competition between frictional forces between the particles, which act to preserve topography, and the downward force of gravity, which acts to dissipate topography. This can also be stated as the relation between the shear and normal stresses on the granular material known as the Mohr-Coulomb criterion for failure (Coulomb, 1776; Mohr, 1905). This competition of forces is responsible for controlling the maximum steepness at which any granular topographic feature can have a slope, which is called the angle of repose (Allen, 1969). The other aspects of their topography are controlled by how they were initially formed.

The most familiar granular landform is that of the sand dune, which is found in many deserts on Earth (Bagnold, 1941) and has more recently been observed and described on Mars and Titan (Masursky, 1973; Lorenz et al., 2006). These landforms, which come in many shapes, are formed as a result of wind blowing small, regularly shaped sand particles over a surface.
Over time these particles build up into topographic features called dunes where sand migrates up the shallow windward side and eventually avalanches down the steeper opposite face, which is at the angle of repose. (Bagnold, 1941; Allen, 1969) Earth is also home to many other granular features such as sand bars formed by ocean currents, alluvial fans created by sporadic river flows, and cinder cones formed during volcanic processes. However the most common source of granular features is one that is relatively uncommon on Earth: impact crater ejecta.

1.2: Impact Crater Ejecta

On most of the solid bodies in the solar system impact craters are very common surface features and as such it is important to understand their geologic characteristics. When an impactor hits the surface it creates high-energy pressure waves, which propagate through the surrounding area, opening up a crater (Melosh, 1989). The open space of this crater is formed through many processes including the vaporization and melting of target material and the injection of underlying rock into the surrounding subsurface, however of most interest to me is the ejection of granular material onto the surrounding terrain. During the impact process this granular ejecta is excavated from a large portion of the eventual crater, moving along curved subsurface paths before eventually being ejected (Melosh, 1989). This material is ejected from the crater at roughly 45° angles and the follows ballistic trajectories until it lands on the surrounding surface. The velocity of the ejecta depends on the size of the crater and from where in the crater it was ejected in a manner described by Maxwell’s Z Model for crater excavation (Maxwell, 1977). Material that is ejected from near the crater wall moves at relatively slow velocities and lands close to the crater, whereas ejecta material from near the center of the crater
moves at very high velocities and lands far away from the crater. These velocities are correspondingly higher in larger craters.

When the material impacts the surrounding area it excavates the surface to a degree and then forms an outward granular flow of mixed ejecta and surface material in a process known as ballistic impact sedimentation and erosion (Morrison & Oberbeck, 1975; Oberbeck et al. 1975). This region around the crater covered with ejecta material is known as the ejecta blanket and is broken up into two areas: the continuous and discontinuous ejecta (Melosh 1989). The continuous ejecta covers a roughly circular area around the crater out to about one crater radius from the wall of the crater. In this region the ejecta continuously covers the surface in a relatively thick layer, which results from the fact that most ejecta comes from the outer portions of the crater and is thus ejected slowly and lands over a relatively small area. Discontinuous ejecta is a patchy, thin cover outside this region because it has less ejecta landing on a larger total area. The ejecta blankets of craters can have a number of geomorphic features that are formed during the impact and outflow of ejecta material (Melosh, 1989). In this dissertation I will be closely considering one of those types of features: Crater Concentric Ridges.

1.3: Overview of Dissertation

In the second chapter of this dissertation I examine how the differing gravity of various planets will effect the formation of granular landforms. Specifically I study the effect of gravity on the dynamic angle of repose, a value that sets how steep granular landscapes can be. In order to do this I created a test study using active Martian sand dunes, which like all dunes should have slipfaces that form at the angle of repose. These slipfaces were measured using HiRISE (Hi-
Resolution Imaging Science Experiment) DTMs (Digital Terrain Models) and compared to terrestrial examples (McEwen et al. 2007).

In chapters three, four, and five I examine a specific type of granular ejecta morphology found on airless bodies using different data types and methods. I have dubbed this ejecta morphology ‘Crater Concentric Ridges’ or CCRs. These features, which were formerly known as ‘Lunar Concentric Dunes’, are ridges that form concentrically to craters between ~1-5 kilometers in diameter on the Moon. These ridges often have an arced shape and are commonly found in large numbers all around very fresh craters of the right size. These features were last studied in the late 1970s (Morrison and Oberbeck, 1978) with data and tools that are significantly inferior to those that are available now, as such much can be added to the current understanding of the landforms.

The third chapter focuses on understanding CCRs using high-resolution 2D images obtained from the LROC NAC (Lunar Reconnaissance Orbiter Camera – Narrow Angle Camera) to describe and understand these features (Robinson et al., 2010). After making a survey of the Moon to find as many craters with CCRs as possible I created mosaics of NAC images to show the full ejecta blanket of a selection of craters where both the available data, and the CCRs themselves, were numerous. From these mosaics I was able to create maps of CCRs to best understand how these features are distributed around craters and also gather statistical data on the sizes and shapes of the ridges themselves. Additionally high-resolution images allowed me to examine the varying morphologies of CCRs in significant detail. With these data I can begin considering different hypotheses for the formation of these ridges.

In the fourth chapter, I expand the understanding developed in chapter two by re-examining CCRs using 3D datasets. Specifically I used five DTMs created from LROC NAC
images, four of which were produced as part of this project by Sarah Sutton. These DTMs allow me to examine new features of the ridges in detail such as their heights and slopes. Furthermore, this 3D data facilitates examining how the formation of CCRs interacts with pre-existing topography. All of this information further informs our consideration of various hypotheses for the formation of CCRs and allows some of them to be discarded.

The fifth chapter of this dissertation moves from considering hypotheses using spacecraft data to testing hypotheses using numerical modeling. In order to do this I am using the FDEM (Fortran Discrete Element Method) code (Börzsönyi et al., 2009), which works by following large numbers of individual particles as they undergo granular motion. I have set up different simulations, corresponding to realistic ejecta launch parameters, to observe how CCRs might be formed. To do this I drop granular ‘ejecta’ particles moving with significant horizontal velocity onto a stationary bed of similar particles, which represent the regolith. In this fashion I can observe how topographic features might be formed as ejecta falls onto and runs over the terrain surrounding the crater. Then these results can be compared to the real world data that I have gathered and described in the previous two chapters.

In the sixth and final chapter I address the potential future of this work. More detailed simulations would allow me to gain an even better understanding of the mechanics of these ridges. High-resolution images from other airless bodies would allow me to consider how differences in circumstance in gravity and composition might affect CCR formation. Unfortunately these data do not exist as of yet, with the closest such data being from the MESSENGER mission to Mercury, which has allowed me to identify but not study CCRs on that planet. Additionally the methods described in the preceding chapters could be used to great effect to study other ejecta features on airless bodies as well as ejecta morphologies particular to
formation within an atmosphere. Some of these types of ejecta features have been examined in recent studies however reconsidering them via different techniques could prove fruitful.
Chapter 2: Avalanche Slope Angles in Low-Gravity Environments
from Active Martian Sand Dunes

This chapter was published as a paper in Geophysical Research Letters in 2013

Corwin Atwood-Stone and Alfred S. McEwen

The properties of granular material have an important effect on surface landforms and processes. Recently, it has been suggested that material properties called dynamic and static angle of repose vary with gravitational acceleration, which would have a significant effect on many planetary surface processes such as crater collapse and gully formation. In order to test that hypothesis, we measured lee slopes of active aeolian sand dunes on Mars using the High Resolution Imaging Experiment (HiRISE) DTMs (Digital Terrain Model). We examined dune fields in Nili Patera, Herschel Crater, and Gale Crater. Our measurements showed that the dynamic angles of repose for the sands in these areas are 33-34° in the first region and 30-31° in the other two. These results fall within the 30° to 35° window for the dynamic angles of repose for terrestrial dunes with similar flow depths and grain properties and thus show that this angle does not significantly vary with decreasing gravity.

2.1: Introduction

The angles of repose of dry, cohesionless granular materials have long been of interest to the planetary science community. These measures are useful in characterization and study of a wide array of planetary surface processes including formation of impact craters, sand dunes, subaqueous deposits, granular flows, pyroclastic cones, and scree slopes. They are also of
interest when planning in situ exploration that interacts with loose surface materials (Sullivan et al., 2011).

There are two different commonly described angles of repose: static and dynamic. The static angle is the slope above which a given granular material will become unstable and begin to avalanche. The dynamic angle is the slope at which a given avalanching granular material will stabilize and come to rest; this angle is always lower than the static angle of the same material. We use the terms static and dynamic angles of repose following Kleinhans et al. (2011); however, other sources use a wide variety of terms for these material properties.

Recent advances in the field of granular physics have shown that the ideas of static and dynamic angle of repose do not accurately represent the reality of granular avalanches. The newer, more physically accurate parameters are the angles $\theta_{\text{start}}$ and $\theta_{\text{stop}}$, which respectively describe the angles at which avalanches will initiate and come to rest (Forterre and Pouliquen, 2008). These quantities are both functions of the thickness of the flowing granular layer, which increase as the thickness of the flowing layer decreases (Forterre and Pouliquen, 2008). Although $\theta_{\text{start}}$ and $\theta_{\text{stop}}$ are a more technically accurate way to talk about grain avalanching, the papers whose results we are examining (and most work done on grain avalanches in low-gravity environments) use the “angles of repose,” and thus we frame most of our discussion in those terms.

On Earth, these angles are primarily a function of grain roughness, angularity, and sorting. Moisture content and interparticle forces such as electrostatics may also play a role (Allen, 1969, 1970; Carrigy, 1970; Cooke et al., 1993). It has long been assumed that the values of the angles of repose were independent of gravity. This is because when we examine the equations for the static angle of repose, the gravity term for both the shear and normal stresses is
identical and thus cancels out the equation entirely (Melosh, 2011, p. 328). A similar argument, which uses kinetic as opposed to static friction, applies to the dynamic angle of repose. This assumption has previously been tested using a few different methods.

One approach to studying the effects of gravity on the angle of repose is through computational numerical simulations. This has been done several times, including the recent studies of Ji and Shen (2006) and Nakashima et al. (2011), which used two-dimensional discrete element methods to study this effect. Both of these studies determined that the angle of repose is basically independent of gravity, at least within the studied range of 1/6 to 1 g.

A second way to look at this problem is with physical experimentation, although this presents some issues, as it requires simulation of different gravity environments. One way this has been done is by measuring the angles of repose in high-gravity environments created in a centrifuge (Brucks et al., 2007). This generally showed that the effect of gravity higher than the terrestrial value is negligible on the angles of repose. However, all of the solar system bodies with solid surfaces have lower gravity than Earth. One possible way to directly experiment with lower gravity is to use parabolic flights to produce brief periods of low gravity. This has been done several times, most recently by Kleinhans et al. (2011), using rotating drums of material to study these angles. In their study, they measured a number of different materials at gravities roughly approximating those of the Earth, Mars, and the Moon. Kleinhans et al. (2011) determined that for approximately lunar gravity (they used 0.1 g instead of 0.165 g), the static angle increased by roughly 5°, and the dynamic angle decreased by roughly 10° with respect to their values at Earth gravity. In contrast, a study by Nakashima et al. (2011), which measured the angle of repose using sand dropped from a hopper during parabolic flights, showed negligible variation due to gravity. A third study by Hofmeister et al. (2009) measured the dynamic angle of
repose using a combination of drop tower and centrifuge, which showed the dynamic angle of repose increasing with decreasing gravity.

If either the Kleinhans et al. (2011) or the Hofmeister et al. (2009) values do prove to be accurate, they would have a significant effect on our interpretation of planetary surfaces. For instance, the activity of high-latitude Martian gullies is observed to correspond to the presence of seasonal CO$_2$, so processes involving this volatile may drive the activity, thus allowing for their low observed slopes (Diniega et al., 2010; Hansen et al., 2011; Dundas et al., 2012). However, Horgan and Bell (2012) proposed that gully formation on the northern hemisphere dunes occurs in the summer when is CO$_2$ absent and speculate that the unusual morphology of dunes slip faces (i.e., gullies) is due to the higher static and lower dynamic angles of repose reported by Kleinhaus et al. (2011). The Kleinhaus et al. (2011) results would also have significant impact on the study of other planetary surface features whose geometries depend on the angles of repose, such as impact craters, aeolian dunes, pyroclastic cones, scree slopes, and subaqueous dunes and deltas. Another area of study that would be called into question by this result is the equilibrium shape of critically spinning rubble pile asteroids, which is controlled by the dynamic angle of repose (Harris et al., 2009).

Perhaps the best way to examine the effect of gravity on the angles of repose would be to measure these angles in situ on other planetary surfaces. This has been done on the Moon and Mars for the static angle of repose or friction angle (Mitchell et al., 1972; Moore et al., 1982; Sullivan et al., 2011). The data from these experiments appear typical for terrestrial soil simulants, which are thought to match the properties of the in situ regolith (Crosby et al., 2009). To our knowledge, the dynamic angle of repose has not been measured in situ anywhere but Earth. In this paper, we measure the dynamic angle of repose of sand on Mars using high-
It has been long established that the flat slip faces of active sand dunes are found at, or somewhat lower than, the dynamic angle of repose of their constituent sand (Carrigy, 1970; Allen, 1970; Cooke et al., 1993). By measuring the slopes of the slip faces of active Martian sand dunes, we should be able to determine the dynamic angle of repose of sand under a low-gravity environment. Active sand dunes are constantly reforming their slip faces, and thus we are confident that later processes did not significantly modify these slopes. Recent work using change detection between images of dune fields taken at different times has definitively shown that many Martian sand dunes are active (Chojnacki et al., 2011; Bridges et al., 2012a, 2012b; Silvestro et al., 2013). Also, by using HiRISE DTMs (digital terrain models) (Kirk et al., 2008), these slopes can be measured. Two DTMs of large active fields of barchan dunes are available, one of Nili Patera (Bridges et al., 2012b) and one in Herschel Crater (Bridges et al., 2012a) (see Figure 1). Additionally, we used a DTM of a small set of active dunes at Gale Crater (Silvestro et al., 2013), near the Curiosity landing site. These DTMs have 1 m postings and a vertical precision of ~20cm.

Using these data sets, we can measure the slopes of the slip faces, and thus the dynamic angle of repose of these conditions, to compare them to terrestrial dunes. On Earth, the dynamic angle of repose for sand, found from both dune slip faces and experimentation, ranges between approximately 30° and 35° (Carrigy, 1970; Cooke et al., 1993, and references therein) and the static angle is on average 2.5° higher (Cooke et al., 1993). The Martian and terrestrial dynamic
angle of repose measurements that we are comparing in this study are thus taken from measurements of real sand dunes; this is important as values determined from experimental setups can vary somewhat from those found in real landforms. Thus, if the dynamic angle is independent of gravity, we would expect to see that our measured Martian dynamic angles fall within this range. Alternately, Kleinhans et al.'s (2011) experiments for sand under roughly Martian gravity (0.38 g) suggest angles 5° to 7° lower than those found under terrestrial gravity.

In order to be certain that gravity is the only free parameter, we need to know whether other controls on the dynamic angle of repose differ between Earth and Mars. Significant controls on the dynamic angle of repose are the shapes of sand grains, grain sorting, moisture content, and flow thickness. Grain shape is broken into the categories of roundness and sphericity, and on Earth aeolian sand grains are often subrounded, although this and sphericity are somewhat variable (Livingstone and Warren, 1996). These variations are at least partially responsible for the 30-35° range of dynamic angle of repose in sand dunes. Measurements made of rippled aeolian sand in Gusev Crater by the Spirit rover indicate that these particular sands are largely subrounded and fairly spherical in character (McGlynn et al., 2011) also show that the inclusive graphic deviation of the grain sizes of these aeolian sediments ranges from 0.42 to 0.80, which according to the grain sorting schema described by Folk (1981) indicates that they are moderately well to well sorted, which is the same amount of grain sorting seen in terrestrial aeolian dunes (Cooke et al., 1993). The moisture content of equatorial Martian dunes should be minor, making them quite similar to desert dunes on Earth. Avalanche flows on subaerial terrestrial dunes are almost always less than 2 cm thick (Lowe, 1976; Cooke et al., 1993). Although we have no measurements of flow thickness on Mars, the total sand fluxes are
comparable (Bridges et al., 2012b). Thus, any major variations in dune slopes measured on Mars from those on Earth should be an effect of the lower gravitational acceleration.

To measure a dune field, we import the DTM into ArcMap 10, along with an orthoimage congruent to the DTM. A slope map was then created from the DTM to show the slopes of the slip faces. Noticeable artifacts affect the slope maps because the dark sand surfaces are relatively bland and featureless (Mattson et al., 2012), and as such the slope for each dune could not be simply read off the map. To accurately measure the slopes, we created topographic profiles through each slip face, which would read out elevation data with horizontal distance. We were then able to create a line of best fit down the slip face to estimate the slope. The dune crest and base of slip face are distinctive features and are well correlated in the stereo matching, so the extent of the slip face is well characterized in the DTM (when well illuminated).

We chose 30 dunes each from the Nili Patera and Herschel Crater dune fields (see Figure 1) and eight dunes from Gale Crater. Dunes were selected from all over the mapped region according to certain criteria, which allow for more confident measurement. First, we wanted slopes that were not in shadow in the orthoimages. Next we tried to avoid the most heavily artifacted slopes and those were the width of the slip face in the orthoimage did not match that in the DTM. We tried to select slip faces that were most planar, as opposed to significantly convex or concave; these correspond to the active dunes. Finally, we looked for slopes where the top and bottom of the slip face were roughly parallel (i.e., not curved portion of barchan dune), although this was not always possible. Five profiles were drawn through each chosen slope, as shown in Figure 2, thus assuring that we did not undervalue the slope of the slip face by taking a profile that did not follow exactly the downhill gradient. Each of the five profiles was cut down so that it only included data from the slip face, using specified elevation values to define the top and the
bottom of the slip face (see Figure 3). Each topographic profile was fit with a line, the steepest of which was taken to be the slope of the slip face. In cases where two adjacent profiles had roughly equal (and highest) slope, a sixth profile was taken between those two profiles and was used to calculate the slope of the dune slip face.

2.3: Results & Discussion

The slopes of the Herschel Crater dunes (barring a few outliers) range between 28° and 31°, weighted somewhat toward the top of that range (see Figure 4). Recalling that slip faces of sand dunes are found at or somewhat below the dynamic angle of repose (Carrigy, 1970; Cooke et al., 1993), we posit that the dynamic angle for the sand in the Herschel Crater dune field is ~30-31°. In Nili Patera, the slip face slopes (again barring a few outliers) range between 31° and 34°; thus, we posit that the dynamic angle of repose for this sand is ~33-34°. Finally, for the dunes near Gale Crater, the slopes range between 28° and 31°, strongly weighted toward the top of this range, suggesting a dynamic angle of repose of ~30-31°; however the data for the Gale Crater dunes are both sparser and of lower quality than the other two regions, and so this value is less certain. Our measurements in Gale Crater agree with those of Silvestro et al. (2013) based on the same HiRISE DTMs. Further, direct observational evidence from the Curiosity rover of the two sand dunes it has visited in Gale Crater shows that their lee slopes have angles between 29° 33° where evidence of granular flow is present (Ewing et al., 2017). Comparing these direct observations to our DTM measurements we find that our measurement methodology is fairly accurate, although it may suggest that we are under-measuring dune slip-faces by about a degree.

These measured values of dynamic angle of repose of ~30-31° and ~33-34° match the expected range of 30° to 35° found from both laboratory experiments and measurements of
terrestrial dunes (Cooke et al., 1993, and references therein) and are certainly not 5° to 7° lower than terrestrial values as predicted by Kleinhans et al. (2011). If our measurements of these dune slip faces are in fact a degree lower than reality, as may be suggested by observations from the Curiosity rover then the true slopes of these dunes would differ even more from the values predicted by Kleinhans et al. (2011). These results support the hypothesis that the dynamic angle of repose is due to low gravity. However, we believe this is improbable both because such a counteracting force would be unlikely to produce results this congruent with our expectations of the angle being independent of gravity and because the requisite interparticle forces would strongly inhibit the saltation required to produce the observed dune migration.

To be more technically accurate, this discussion should be framed in terms of $\theta_{stop}$ as was mentioned earlier. In this case, we still observe that Martian and terrestrial dunes exhibit the same range of angles on their lee slopes. Assuming similar thicknesses of granular flow in both cases, which seems reasonable given that the granular materials should be basically similar, that the overall landform morphology is the same, and that the sand fluxes are comparable (Bridges et al., 2012b), it would seem that the parameter $\theta_{stop}$ is mostly independent of gravity.

The results of Kleinhans et al. (2011) were used by Horgan and Bell (2012) to argue against the role of CO$_2$ frost in forming dune gullies in the north polar sand sea of Mars (Hansen et al. 2011). However, our results show that these slope angles should not be altered by the low-gravity environment, and we also note that Martian dune gullies have been directly observed to form only when there is CO$_2$ frost on the ground, at least in the southern hemisphere (Diniega et al., 2010; Dundas et al., 2012). Preliminary results of monitoring the northern dunes through the most recent summer also do not show gully formation (C. Hansen, personal communication, 2012).
Another interesting result comes from the observation that the dynamic angle appears to be ~3° lower in Herschel and Gale Craters than it is at Nili Patera. If this difference is due primarily to grain shape, it suggests that the sand grains at Herschel and Gale Craters are more rounded and smoother than those in Nili Patera. This difference could suggest that the sand was sourced further away and had to saltate farther to get to the dune field and thus become more rounded. The Nili Patera dunes appear to emanate from the well-exposed, high-albedo, actively eroding area of bedrock on the caldera floor where sand may have been scoured away by the wind (Michaels, 2011), whereas dunes at Herschel and Gale do not have an obvious local sand source. However, we do not know for certain the origin of the sands in any of these locations. Alternately, the higher degree of erosion on the Herschel and Gale sand grains could be a result of a longer weathering history in that area, perhaps due to sand being trapped. Nili Patera is a volcanic caldera at the summit of a broad shield volcano, so sand from distance sources might be less likely to be trapped here than Herschel or Gale craters. Thus, measuring dune slip faces in this manner may present an interesting method for estimating sand grain textures from orbital imagery. These measurements could also provide ideas about the distance between a dune and its source of sand.

2.4: Conclusions

By measuring the dynamic angle of repose of sand on Mars using the slip faces of active Martian sand dunes in Nili Patera, Herschel Crater, and Gale Crater, we are able to conclude that the dynamic angle of repose of dry granular material is, as was long suspected, independent of gravity. Since grain flows on dune slip faces are likely similar on the Earth and Mars, the more technically accurate parameter $\theta_{\text{stop}}$ is also shown to be independent of gravity. Our data do not
allow us to directly examine the relationship between the static angle of repose and decreasing gravity; however, previous results from landers and rovers have been interpreted as indicating that the static angle is also independent of gravity. Finally, our results showing that the slip faces in Nili Patera are on average $3^\circ$ steeper than those in Herschel and Gale craters indicate that the sand grains at Nili Patera are likely rougher than those at Herschel and Gale. This is interesting as we are thus able to learn about grain textures from orbital imagery.
2.5 Figures

**Figure 2.1:** HiRISE orthoimages of (a) the Herschel Crater dune field DTM [DTEEC_002860_1650_003572_1650_U01], (b) the Nili Patera dune field DTM [DTEEC_017762_1890_018039_1890_A01], and (c) the Gale Crater dune field DTM [DTEEC_012551_1750_012841_1750_U01]. The red alphanumeric codes on the orthoimages show the approximate locations of the different dunes measured for this project.
Figure 2.2: (a) Orthoimage and (b) DTM showing the 22nd dune slip face measured in Herschel Crater. The five lines drawn through the slip face of the dune show the positions of the five measured profiles of the slip face, where the center profile is usually the steepest profile. These figures show a good example in both image and DTM view of the kind of dune that was best for measuring.
Figure 2.3: This graph shows the five profiles from the 22nd dune slip face measured in Herschel Crater, each vertically offset from the others by 10 m for clarity (the bottom profile is at the correct elevation). The long profiles (with diamond markers) show the original profiles through the dune, the shorter overlaid profiles (with square markers) show the profiles cut down to just slip the face. The top and bottom elevations of the slip face in each profile are taken to be the same for consistency, in this case 1174 and 1167 m, respectively. Then the black lines of best fit are calculated from the shorter profiles and their equations displayed on the right-hand side of the graph. The slope angle for each profile is calculated from these equations and displayed below them. The center (green) profile is clearly the steepest here with slope 30.57°. A similar graph is used to calculate the slope of each of the measured dunes.
Figure 2.4: Histogram of measured slope angles from Herschel Crater, Nili Patera, and Gale Crater binned into 1° increments. The steepest bin filled by each dune field (excluding obvious outliers) is taken to be the angle of repose for the same of that region. Thus, Herschel Crater and Gale Crater have dynamic angles of repose of approximately 30-31° each, and Nili Patera has a dynamic angle of repose of approximately 33-34°.
Chapter 3: A New Study of Crater Concentric Ridges on the Moon

This chapter was published in Icarus in 2016

Corwin Atwood-Stone, Veronica J. Bray, and Alfred S. McEwen

Crater Concentric Ridges (CCRs) are topographic ridges found in the ejecta blankets of fresh few-kilometer-scale lunar craters. These ridges, which were last studied in detail in the late 1970s (referred to as ‘Lunar Concentric Dunes’), were hypothesized to form due to ballistic impact sedimentation and erosion. We have surveyed the Moon to find 59 craters with CCRs and have constructed mosaics of these craters where possible using high-resolution LROC NAC (Lunar Reconnaissance Orbiter Camera – Narrow Angle Camera) images. We then map from some of these mosaics in order to measure the CCRs and examine their morphologies. Ejecta scaling models and some of our observations of the CCRs contradict the current hypothesis for the formation of these features. We therefore propose new hypotheses to consider for the formation of CCRs, specifically interaction of ejecta with initial topography or formation via interactions of shocks in the ejecta. Additionally, for the first time we have found CCRs on Mercury, but they are rare or absent on Mars.

3.1: Background & Introduction

Crater Concentric Ridges (CCRs) are prominent morphologic features of ejecta blankets of some small (1-10 km) and well-preserved lunar craters (Fig. 1). CCRs have been previously described using the name ‘Lunar Concentric Dunes’, due to their dune-like appearance. These features are only found around relatively fresh craters indicating that they degrade rapidly [Morrison and Oberbeck, 1975; Howard, 1974]. They are seen most obviously around craters in
the mare, although when they are, less commonly, noted around highlands craters they tend to occur on pre-existing crater-facing slopes \cite{Morrison and Oberbeck, 1975}. The occurrence of CCRs around larger craters is less regular and located further from the crater rim \cite{Melosh, 1989; Morrison and Oberbeck, 1978}. CCRs appear as short lengths of ridges oriented concentrically to the crater, whose tips frequently curve outwards \cite{Howard, 1974}. They extend from about 1.2 to several crater radii, becoming less densely packed with increasing distance \cite{Morrison and Oberbeck, 1975}.

CCR morphology also changes with distance from the crater, ranging from classic CCRs to those accompanied by a down-range trough (Fig. 1). We will describe this accompanying morphology as Crater Concentric Troughs (CCTs). As distance from the crater increases CCTs become more prominent and ridges less so until CCRs are replaced by these troughs \cite{Morrison and Oberbeck, 1975}. Oberbeck et al. (1975) described these ridges as forming due to ballistic impact sedimentation and erosion. Specifically they were hypothesized to form when ejecta from a secondary crater interacts with the debris surge, formed by outflowing primary ejecta and entrained target material, thus stalling the debris surge and depositing a ridge \cite{Morrison and Oberbeck, 1975; Oberbeck et al., 1975}. They describe the CCTs as being concentric chains of secondary craters.

3.2: Objectives & Methods

CCR s have not been studied in detail since the late 1970s \cite{Morrison and Oberbeck, 1978}. We utilize new high-resolution data from the LROC NACs (Lunar Reconnaissance Orbiter Camera – Narrow Angle Camera) \cite{Robinson et al., 2010}, to examine these features. Previous studies have only identified a few craters (N \textless;10) with CCRs \cite[e.g., Morrison and
Oberbeck, 1975; Morrison and Oberbeck, 1978]. In our ongoing survey of the Moon we have identified 59 craters, ranging from 1 to 11 km in diameter, which have CCRs in their ejecta blankets (Fig. 2). In order to survey the Moon for these features we looked for fresh craters, which are easily identifiable in the lunar mare by the bright albedo of their ejecta. Fresh highlands craters are more challenging to find as they often lack this albedo difference. Our search for craters with CCRs is ongoing and not yet completed in any region.

For those craters with sufficient coverage by NAC images with appropriate (large) solar incidence angles to accentuate subtle topography, we produced mosaics using the Integrated Software for Imagers and Spectrometers (ISIS) (Fig. 3A; Keszthelyi et al. 2014) to view the entire ejecta blanket and study the morphologies of the CCRs in context. It is important to have NAC images with incidence angles between 60° to 80° (sun elevation 10° to 30°) so that there is significant topographic shading and enough shadows to see the CCRs well without having so much shadow that one side of the ridge would be completely obscured. Using these mosaics we mapped CCRs around the host craters using ArcMap by creating outlines of all the ridges in the ejecta blanket out to six crater radii from the center of each crater where possible (Fig. 3B). Thus far we have mapped CCRs around three mare craters: the 2 km crater Linné, the 5 km crater Piton B, and a 1 km crater found just south of Piton B which we will refer to as ’piton b2’ (see Table 1). Additionally we have made detailed measurements from these maps of the: area, length, width, and radial distance of each CCR. One important value we have calculated from these measurements is the areal packing density of the CCRs at different distances from the craters. This calculation was done by summing the areas of all the CCRs in a ring a certain distance from the crater (Fig. 3B) and dividing by the total area of the ring. In order to measure heights and slopes of selected CCRs we used NAC DTMs (Digital Terrain Model) where they
are available, and made shadow measurements in locations with appropriate images. CCRs were selected for topographic measurement based on the sun angle of the NAC image, sharpness of their visual features, physical separation from other ridges, and to give a range of distances from their host craters.

In addition to quantitative measurements we have also characterized the morphologies of the CCRs around our three study craters, classifying them according to whether they are sharply defined or subdued in character and if they are associated with CCTs (Fig. 1). We also note larger scale morphological characteristics such as how densely they are forming in a given area and if they are forming as part of an isolated chain of CCRs. One factor that may affect the formation of the CCRs is the presence of local large-scale topography. In order to investigate the effects of topography we have employed elevation data from the Global Lunar Digital Terrain Model 100 m [GLD100, Scholten et al., 2012] and the Lunar Orbiter Laser Altimeter (LOLA) datasets [Smith et al., 2010] to determine where CCRs form in relation to topography.

3.3: Results & Interpretation

Of our 59 craters with CCRs noted in the ejecta blankets, 38 are found in the mare, 19 are in the highlands and 2 are on the boundary (Fig. 2). Previous work [Morrison and Oberbeck, 1975] suggests that CCRs are less common around highlands craters, however after examining highlands craters with CCRs we posit that they may instead be more difficult to find. CCRs around highlands craters do not generally form as complete a pattern as they do around mare craters, and the pre-existing terrain around these craters is more complex, allowing CCRs to blend in. Thus, at some highlands craters CCRs may exist in the ejecta blanket without being
readily apparent. Additionally fresh highlands craters have a reduced albedo contrast with their surroundings, which facilitates searching for fresh craters in the lunar mare.

3.3.1: Ridge Morphology with Distance from Crater

Around mare craters in particular there is a fairly consistent pattern in the progression of general CCR morphologies that changes with increasing distance from the crater. Moving outwards from the host crater the CCRs take on different general morphologies (Fig. 1). Those ridges closest to the crater appear very subdued, meaning that they are smooth in appearance rather than sharp, perhaps as a result of being buried by the thick deposit of proximal ejecta. Moving outwards the ridges are often more sharply defined and can appear quite sinuous. Further out, CCTs are found immediately down range of the CCRs and past this region CCTs are sometimes found without an associated ridge. Many of the troughs downrange from these further ridges appear to be relatively well defined with a consistent arcuate shapes to the bottom of the troughs, and thus do not resemble chains of secondary craters as was originally hypothesized [Morrison and Oberbeck, 1975]. Additionally the CCRs get generally smaller in all dimensions (length, width, and height) the further away from the crater they are. However there are some definite outliers to the last trend of decreasing size, particularly occasional distant CCRs that are very long.

Additional morphological features of ridges that are sometimes observed in these ejecta blankets are: CCRs that intersect with each other, and ridges that have shallow depressions running along their crests (See Fig. 4). Both of these features could result from interference between CCRs. In the case of the intersecting ridges it is interesting to note that while sometimes one of the ridges truncates against the other, it is at least as common for neither to truncate and
for them to cross each other, forming an X morphology where they intersect. This is an especially important note as it rules out the possibility that these features are just the uprange rims of craters whose downrange rims have been erased. The ridges with depressions along their crests possibly formed as a result of two CCRs forming practically on top of one another with only a little offset. This appears to be one ridge with a shallow depression in its crest rather than two ridges whose crests are very close together. Another process that could produce morphologies like these double ridges is a cohesive slump off the crest of a single ridge. However since these features are likely composed of loose granular materials a slump seems unlikely to remain cohesive. Additionally, since CCRs appear to form well below the angle of repose (see section 3.3) it is unlikely that large slumps would occur. The ability to replicate both of these interference morphologies will be an important metric in judging the validity of any proposed formation hypothesis.

3.3.2: Areal Density of CCRs

In spatial extent the CCRs around these craters (Fig. 3) are found to quickly rise to their highest areal packing density around two crater radii from the center of the crater. They then decrease out to at least 7.5 crater radii in the case of Linné (Fig. 5), which is significantly further from the crater center than previous studies found CCRs [Morrison and Oberbeck, 1975]. The highest packing density, found at a distance of two crater radii from center of the host crater, varies in value with the size of the crater from ~35% at Piton B (D ~ 5 km) to ~16% at Linné to ~8% at ‘piton b2’ (D ~ 1 km). However with our limited dataset we cannot rule out the possibility that other factors, such as relative age, may be affecting these areal density values. Closer to the crater there are sparse CCRs that are generally quite large and very subdued, which
suggests that the continuous ejecta blanket is thick enough to mostly obscure the ridges that formed there, resulting in an observational bias against finding CCRs in this region. The continuous ejecta should be able to obscure the CCRs near the crater since these ridges are almost certainly ejecta features, and are therefore laid down simultaneously with the continuous ejecta, thus allowing the thick proximal ejecta to mostly obscure the comparatively small local topography of CCRs.

The data for Linné, Piton B, and ‘piton b2’ showing the areal density of CCRs decreases exponentially with distance (starting at two crater radii). When exponential curves are fit to this data we find a preliminary trend showing that the rate of exponential decrease in areal packing density of CCRs with distance from the crater is faster for larger craters, although the larger craters also start with a higher initial value (Fig. 5 Inset). This result is perhaps surprising because around much larger craters (>20 km), CCRs are only found far away from the crater, where this trend might suggest they should be very sparse. We consider why CCRs are not found in the proximal ejecta blankets of much larger craters. A clear base hypothesis is that above a certain crater size a different process becomes dominant in the ejecta blanket suppressing the formation of CCRs. However, an alternate hypothesis that emerges from this data is that above a certain crater size the areal packing density of the ridges in the proximal ejecta blanket approaches 100% and thus the CCRs cease to appear as separate and identifiable features.

When we examine the Linné areal density data split into two geographic regions, east and west (Fig. 3, Fig. 5) we note that the western data is uniformly much denser than the eastern data. This is due at least in part to the significantly different sun angles on the measured NACs, however there may also be real differences in the distribution of CCRs. Regardless of the causes of the measured differences in the magnitude of areal density between eastern and western
Linné, the trend in areal density with distance from the crater rim follows the same pattern (increasing to a maximum at a distance of two crater radii and then decreasing) on both the east and west sides of the crater. While we observe similarity in the trend of how areal density varies with distance at this scale, when we compare the data from individual (1/12th of the ejecta blanket) wedges we find significant variations in the areal density curves, which cross, over and under each other. As an intermediate test of how much of the ejecta must be considered before local differences average out, we compared the curves for the northeast quarter and the southeast quarter. This comparison first shows that without the sun angle variation present in the east/west case the curves are dramatically closer to each other in value. However with this smaller data set we do see some small variation in the shapes of the curves. We posit that these results are due more to small local variations in the topography and ejected material being more expressed in a smaller data set than meaningful systematic differences in how areal density varies with distance. This is because systematic differences would likely show one quadrant or the other to have consistently higher values for areal density, which is not what we observe. As such, from our small sample of craters, we posit that around mare craters this process creates a distribution of CCRs that generally follows a simple trend in areal distribution, with local deviations.

3.3.3: Ridge Topography

CCRs are significant topographic features with those around Linné reaching at least 11 m in height as measured from a NAC DTM, which covers the central and western half of Linné’s ejecta blanket (Fig. 6). From our preliminary data it appears that the heights of these ridges generally decrease with increasing distance from the crater. Select CCRs were chosen for slope measurements based on the criteria of being visually fresh and sharp as well as physically
separated from other ridges on at least one side. DTM measurements show that the maximum slopes of the selected CCRs vary between 11° and 19° and that the slopes are often fairly even on both faces of the feature (Fig. 6). Additionally we observe that the topographic profiles of the ridge faces are usually roughly linear over most of their extent with rounding off to lower slopes only occurring near the tops and bottoms of the ridges (Fig. 6). These measured slopes are well below the angle of repose (expected for normal dune slip faces; \cite{Atwood-Stone2013}), which indicates either that these ridges have already experienced significant degradation or, more likely, that they formed below a critical slope angle.

There is an observed 8° variation in maximum steepness of the center sections of the slopes on the selected ridges. This could suggest differential application of the degradation process or a difference in their character as they were formed. We expect that differences in initial deposition are more likely for two reasons. First, this variation in slope is not correlated with either the heights of the ridges or with their distance from the crater, which is a good proxy for average clast size. Second, the ridges appear visually similar which suggests that they have experienced similar amounts of degradation, an idea supported by the fact that craters where CCRs have experienced significant degradation (e.g., Mösting C) have ridges that appear smoother and lower. If differential degradation was responsible for the variations in maximum slope we would expect that process to be preferentially acting more on some CCRs than others based on characteristics of the ridges like height or average clast size, which does not appear to be happening. We can thus state that CCRs form with slopes (roughly similar on both sides) that are in some, and possibly all, cases well below the angle of repose.

To examine the topography of CCRs around craters where DTMs are not present we used shadow measurements (Fig. 6). From the DTM at Linné we determined that the maximum slopes
of ridges, even with fresh sharp appearances, can be as shallow as 11º, which places certain constraints on using shadow measurements. First, we need NAC images whose solar incidence angles are greater than 80º, so that the observed shadows are certain to be cast away from the ridge. Second, it will probably be infeasible to take shadow measurements of CCRs that appear subdued or degraded, as these will likely have even lower slopes and could also have more rounding at the top of the ridge. Shadow measurements of select CCRs were taken at Piton B (using a NAC with solar incidence angle = 87º) and at the 3 km crater Encke X (using a NAC with solar incidence angle = 83º). At Piton B the tallest measured ridge was found to be a minimum of 24 meters high; this is a minimum because the measured shadow has been cast uphill, which foreshortens it and thus artificially decreases the calculated height of the ridge (Fig. 6). At Encke X there are two potential highest ridges: one is calculated to have a minimum height of 14 meters (again due to an uphill shadow); the other is calculated to have a maximum height of 21 meters (due in this case to a shadow cast downhill). While the terrain in these areas is broken up enough that the GLD100 (Global Lunar Database 100m resolution WAC DTM) does not have enough spatial resolution to determine precisely how steep the local slope is, the GLD100 can be used to roughly estimate it by adopting the local average slope. The tallest ridge at Piton B is estimated to be on a ~2.3° slope, which would change our calculated height to 43 meters. At Encke X the first ridge is estimated to be on a ~2.9° slope, which would change the calculated height to 20 meters. The second ridge at Encke X is estimated to be on a roughly level slope using the GLD100, despite its location around the crater, which means it is approximately 21 meters tall. In order to get more precise values we would need NAC DTMs for these areas. Our preliminary analysis shows that the heights of the tallest CCRs at each crater are positively
correlated with crater diameter. Additionally the heights of prominent ridges generally decrease away from the crater at both Piton B and Encke X.

3.4: Special Cases

The above results apply to craters that follow the fairly ideal case of CCR being relatively evenly distributed in azimuth around mare craters. While such examples are of primary importance in understanding these features, they are not the whole story. We have observed a number of craters that diverge from this standard case, which may be instructive in gaining a more complete picture of CCRs.

3.4.1: Encke X: Example of Suppression of CCR Formation by Melt-Rich Ejecta

At the mare crater Encke X, we mostly observe a fairly regular distribution of CCRs around the crater. However, in the northwest quadrant there is a significant wedge of low albedo material, which appears to be melt-rich ejecta, that completely lacks the CCRs found in the rest of the ejecta blanket (Fig. 7A). Thus it would seem that ejecta that is rich in melt may suppress the formation of CCRs. This likely results from the high melt fraction of the ejecta changing the flow regime from a dry granular flow to something with more internal cohesion. If this is the case than this result can be used to evaluate formation mechanisms.

3.4.2: Lassell D: Example of CCR Chains

Lassell D, a 2 km crater in the lunar mare, exhibits a very peculiar distribution of CCRs in its ejecta blanket. To the east the ridges are distributed fairly regularly, however to the west CCRs are mostly concentrated in two narrow arcs (Fig. 7B). We can tell that these arcs are
composed of CCRs, rather than being chains of secondary craters, because these features have the positive topography of ridges (Fig. 7B inset), although many of them are also associate with downrange troughs. Inside these arcs the CCRs appear grouped together as complex chains, whereas outside of them the ridges are almost non-existent. Similar chains of CCRs occur at other craters, though never so extensively as at Lassell D and without the corresponding zones of absence. We hypothesized that these chains might be caused by underlying topography and so we examined the GLD100 dataset around these craters. As expected, sometimes these chains are formed along a major break in the underlying slope. Conversely other CCR chains, notably those observed at Lassell D, are formed with no break in the underlying slopes and in fact are frequently formed over almost completely flat ground. Thus these odd chains of ridges at Lassell D would appear not to be related to the pre-existing topography and as such the reason for this distribution of CCRs is currently unknown.

3.4.3: ‘Lick Rim’: Example of Topographical Influence on CCR Distribution

One interesting example crater was formed right on the outer slope of the eastern rim of the 31 km mare crater Lick, which has a flat interior due to having been flooded by basaltic lava. This crater, ‘lick rim’ (see Table 1), has a notably asymmetrical distribution of CCRs: to the east we observe no ridges at all; and to the west, inside the walls of Lick, we observe a collection of ridges on the flat floor of the crater (Fig. 7C). ‘lick rim’ does not appear to be a significantly oblique impact, although ‘lick rim’s’ position on the rim of Lick would likely distort the characteristic shape and perhaps also the ejecta distribution of an oblique impact crater. We do not expect that obliquity played a role in this asymmetry, however the distorting effect of its position on the rim means that this cannot be completely ruled out. It is thus probable that the
geology or topography of Lick is responsible for this asymmetrical distribution of CCRs. Note that a greater drop in elevation from the west rim would produce higher velocity ejecta than to the east.

3.4.4: Mösting C: Example of Degraded Ridges

An important crater to examine in our data set when considering degradation of CCRs is Mösting C, a 4 km crater in the lunar mare. This crater has a distribution of CCRs in its ejecta blanket very similar to that found around Linné or Piton B; however unlike the sharply defined ridges frequently found around those craters, the CCRs at Mösting C are all wide, smooth and low mounds, which retain the elongated, and sometimes sinuous or criss-crossed, character of the more sharply defined CCR morphologies (Figs. 7D & 7E). As mentioned previously CCRs are found only around fresh lunar craters, which would imply a rapid degradation of these ridges. As such, the more subdued CCRs morphologies, seen here at Mösting C, may be indicative of a slightly older crater. If the differences in CCR morphologies are indicative of relative crater ages, then areal packing densities, as shown in Fig. 5, could be used to estimate the formation order of similarly sized craters, since older CCRs are wider and will thus cover proportionately more area.

Another feature of interest found at Mösting C are fields of relatively large boulders in the proximal ejecta (Fig. 7E). These boulders are found both over CCRs and in the low-lying areas between them. It does not appear that they are concentrated in one region or the other, perhaps suggesting that however CCRs are formed, the process has little impact on distribution of the largest ejecta clast sizes. Furthermore, while it is not unusual to see boulders on these ridges, we do not usually see such a dense grouping of them on a ridge crest as that in Fig. 7E.
We suggest two possible explanations for these overlying boulders: 1) That these boulders represent a later stage in ejecta deposition than the one in which the CCRs form. 2) That CCRs are created by the deposition of ejecta including large boulders and that perhaps at Mösting C we are observing slightly older CCRs, that now exposed their constituent boulders on the surface due to the extensive, but not complete, degradation of the CCRs around this crater. If this latter hypothesis is correct it would suggest that the erosive process responsible for the degradation of CCRs works preferentially on smaller clast sizes.

### 3.4.5: CCRs Around Highlands Craters

The more varied topography around highlands craters can affect CCRs in a number of ways. At the 4 km crater ‘alpha’ (see Table 1) we observe two distinct patterns of CCRs that appear to result from the topography. To the southwest, where the terrain is basically level, we observe a similar distribution of ridges as that noted around mare craters. To the northwest however, where the terrain is uphill, the CCRs are generally smaller and more sparsely distributed (Fig. 8A). The 2 km crater ‘gamma’ (see Table 1) also has two distinct patterns of CCRs potentially controlled by topography. To the southeast of ‘gamma’, where the terrain slopes uphill, we observe an especially densely packed area of ridges, partially shown in the Fig. 8B Inset, which is opposite to what we observed at ‘alpha’. To the northeast of ‘gamma’, which is a downhill slope, previous results [Morrison & Oberbeck, 1975] would predict a lack of CCRs. What we observe are two distinct sets of ridges: the first set are CCRs, although they are relatively small and sparse; and the second set of ridges run nearly radial or tangential to the crater, and may or may not be related to CCRs (Fig. 8B). A final highlands case to consider is the 8 km crater Stevinus A, which formed near, but not at, the edge of a much larger and
significantly degraded crater. Fairly close to Stevinus A we observe a set of large reasonably distributed CCRs as we might expect. Then moving further away at the edge of the larger crater we find a dense chain of sharply defined small ridges along the slope break of the rim of the crater. Finally, going down the ~19º slope inside the larger crater we observe some larger but subdued CCRs with prominent associated CCTs. From these observations of CCRs on slopes, that appear differently than those on level ground, it appears that topography does have a significant effect on how CCRs form. One thing we can say is that contrary to previous results [Morrison & Oberbeck, 1975] CCRs can form on opposite facing slopes, although they do not seem to form very well there.

3.4.6: Extra-Lunar CCRs

In order to better understand CCRs it would be very useful to see if and how these ridges are formed on other planetary bodies. This would help us understand what role gravity, and other specific characteristics of a planetary body, plays in forming CCRs. As part of our survey for craters that exhibit CCRs in their ejecta blankets, we have also been examining Mars using HiRISE (High Resolution Imaging Science Experiment) [McEwen et al., 2007] images and Mercury using MDIS (Mercury Dual Imaging System) [Hawkins et al., 2007] images.

On Mars, ejecta blankets of fresh craters are significantly complicated by ejecta facies specific to Mars and rapid modification by aeolian processes, which makes it difficult both to look for CCRs and to definitively identify ridges as CCRs when they are located. A couple of interesting examples are the 1 km crater Winslow and an unnamed 2 km crater we will refer to as ‘mars1’ (see Table 1). Both Winslow and ‘mars1’ have ridges that partially resemble the morphologies of subdued or degraded CCRs on the Moon (Fig. 9). However there some
differences in their distribution as they clump together in the first two crater radii outside the rim in a manner that is not quite analogous to what we observe as normal on the Moon. These ridges then almost completely disappear in the more distal portion of the ejecta blanket. As such these ridges around Winslow and ‘mars1’ may be CCRs that have been modified by Martian processes, or they may be the result of a different process. We also note that Mars’ regolith is often indurated, which could suppress or modify formation of CCRs.

On Mercury our search for CCRs is simpler as there is no atmosphere to complicate what ejecta features are found around craters, but image resolution is more limiting. Here, as in the lunar mare, we were looking for fresh craters by searching for those with sharply defined rims and bright ejecta. We found two such craters with fairly strong candidate CCRs in their ejecta blankets: a 3 km crater we will designate ‘490merc’ and a 4 km crater we will designate ‘770merc’ (see Table 1). Around both of these craters we observe numerous ridges that appear very similar to CCRs, with distributions that strongly resemble those seen around highlands craters (Fig. 9). Unfortunately we cannot study these CCRs in much detail as the best MDIS images for ‘490merc’ and ‘770merc’ only have resolutions of 11 m/pix and 15 m/pix, respectively. We expect that there are many more craters on Mercury with these features, however the relative scarcity of MDIS data coverage of the planet and further paucity of high-resolution images in the coverage that does exist makes the identification of CCRs challenging.

3.5: Assessment of Formation Hypotheses

Some observations of CCRs made in this work are incompatible with the previous ‘ballistic impact sedimentation and erosion formation hypothesis’ of Oberbeck et al. (1975). As a result we decided to test this existing hypothesis using ejecta scaling models [Housen et al.,
1983; Holsapple, 1993; Richardson et al., 2007]. For this test we consider CCRs formed at two crater radii (the distance with the highest packing density of CCRs) from the crater centers of Linné, Piton B, and ‘piton b2’. At these distances from the craters our scaling equations [Housen et al., 1983; Holsapple, 1993; Richardson et al., 2007] would indicate ejecta impact velocities of, respectively, ~48 m/s, ~75 m/s, and ~34 m/s, assuming 45° launch angles. These velocities are far too low for the ejecta to create secondary hypervelocity impact craters. While impacting ejecta will still cause erosion and ejection of secondary materials, tests performed by Hessen (2008) indicate that low velocity secondary impacts at 45° will launch almost all of their ejecta downrange from the primary crater. As such the above hypothesis, which requires significant quantities of secondary ejecta to travel back towards the primary crater, is problematic. Thus we discuss several new hypotheses for the formation of these features.

Here we outline three possible formation scenarios: 1) Once ejecta has impacted the ground, the ground surge might flow against a pre-existing topographic obstacle and form a deposit on the crater facing side. Features called ‘ejecta wakes’ are formed in this manner when ejecta builds up in front of, and partially flows around, a small pre-existing crater rim in the ejecta blanket. 2) In addition to pre-existing obstacles, the impact itself could create new topography: the shockwave that excavates a crater is known to continue outwards with decreasing energy. This seismic shock could preferentially reactivate pre-existing sub-surface fractures parallel to the shock front, causing uplift along fracture lines concentric to the crater. This uplift should occur before the arrival of the ejecta flow, which would then proceed to modify these new topographic features as described above. 3) Another possibility involves the interaction of shocks in the ejecta flow. Material flowing out of rocket nozzles can produce shockwave interference patterns that resemble ejecta features like herringbone structures and
possibly CCRs [Pimshtein, 2011]. Although near-crater ejecta travels at tens of meters per second, too slow to form classic shocks, shocks known as ‘hydraulic jumps’ do form (hydraulic jumps form in a shallow flowing layer of granular material when it is flowing faster than its ‘wave speed’) [Chanson, 2009]. It is possible that CCRs could form as a result of interference between shocks in different segments of the ejecta flow, or possibly via interaction of shocks with surface topography. In other words, CCRs may be antidunes.

3.6: Future Work

We will continue our survey for craters with CCRs, particularly extending our search to larger craters, so we can better understand the transition to very large craters that do not exhibit this facies. We will also be especially interested in expanding our catalog of highlands craters, so that we will have more data with which to study the effects of significant underlying slopes on CCR formation. We will create more mosaics and maps for different sizes of craters, which will improve our understanding of how the distribution and morphologies of the ridges changes under different conditions and for varying crater diameters. One interesting avenue for further study is examining how these features degrade over time, since they do appear to degrade relatively rapidly, only appearing around fairly fresh craters. This will require us to attempt to date some of the craters we are studying so that we can gain an understanding of how long it takes for different degradation states to be reached. Additionally we will be modeling ejecta flow to examine these hypotheses using discrete element methods, which are particularly suited to investigating the granular nature of ejecta flows. These further studies will aid us in evaluating alternative hypotheses for the formation of CCRs.
3.7: Figures & Tables

Figure 3.1: CCR morphology progression. Different CCR morphologies around the 5 km crater Piton B and approximate distance from the crater center in terms of crater radii, $C_R$, at which they are most commonly found. Images have been rotated so that the crater is to the left. The scale bars are all 100 m. See Supplemental Table 1 for NAC Image IDs.

Figure 3.2: Locations of craters with CCRs. Positions and relative diameters of 59 craters with CCRs plotted on the LROC WAC Global Mosaic (see Supplemental Table 2). Diameters range from 1-11 km. Green dots are craters where the NAC coverage is good enough to make a mosaic; red dots are other craters with well defined CCRs. Blue dots are craters with poorly defined/few ridges or poor NAC coverage.
Figure 3.3: Mosaic and map of Linné crater. A) LROC NAC mosaic of the 2 km lunar crater Linné and the CCRs in its ejecta blanket. B) Mapped outlines of the CCRs in the same region. CCRs mapped in blue are subdued in character and those mapped in green have a sharper morphology. The dashed blue box indicates the area where the NACs in the mosaic have unsuitable sun-angles, and thus the ridges measured in that area are less reliable. See Supplemental Table 1 for NAC Image IDs.
Figure 3.4: Proposed CCR interaction morphologies. An image from the ejecta blanket of Piton B, roughly 4 crater radii northeast of the crater center, showing examples of proposed CCR interaction morphologies. A and B show CCRs that intersect and cross each other. A and C show CCRs that we think formed almost on top of each other creating the appearance of a trough along the crest of a ridge. The blue arrows point to the centers of these troughs. North is up. See Supplemental Table 1 for NAC Image IDs.
Figure 3.5: CCR Areal density graph. The main graph shows the summed areas of all the mapped CCRs in a given ring (Fig. 3B) as a percentage of the total area of that ring. The inset graph shows the same data on a semi-log plot, along with exponential decay fits ($R^2 > 0.95$). These fits show that larger craters have more densely packed CCRs near the crater and also that their population of CCRs decays faster with increasing distance from the crater. ‘piton b2’ is the name we are using for an unnamed lunar crater very close to Piton B. Linné East and West show the breakdown of data to either side of the crater, this discrepancy is assumed to be due to differing incidence angles in the available NAC images.
Figure 3.6: Topographic Data. On the left are vertical profiles of CCRs from the ejecta blanket of Linné that were extracted from a NAC DTM. Inset figure of the DTM shows the position where each profile was taken. Profiles were taken with the zero point away from the crater, each profile is offset from the others, and the graphs have 6x vertical exaggeration. On the right is a NAC image of the crater Piton B with an 87º solar incidence angle, from which we can take shadow height measurements. Blue letters indicate the CCRs whose shadows we measured and the resulting heights of the ridges are in the box. These height values are minimums because the measured shadows are cast up the slope of the ejecta blanket. See Supplemental Table 1 for NAC Image IDs.
Figure 3.7: Special Cases CCRs. A) Melt-rich ejecta deposit at Encke X (roughly outlined in blue), bottom left shows a context map. B) Lassell D with CCR chains bounded with blue lines, upper left shows a close-up of a CCR in the chain, bottom right shows a context map. C) ‘Lick Rim’, a crater located on the eastern rim of Lick, with CCRs found only inside the walls of Lick. D) Area map of Mösting C showing the subdued ridges. E) Blow-up of a single subdued ridge at Mösting C with a set of boulders over part of it, which is typical for the ejecta blanket. North is up in all images. See Supplemental Table 1 for NAC Image IDs.
Figure 3.8: CCRs around highlands craters. The 4 km crater ‘alpha’ is shown in A, and the 2 km crater ‘gamma’ is shown in B. The NAC inset in B shows a zoomed in area of ridges. The colored insets are from the GLD100, scaled such that red is high elevation and blue is low elevation. The inset in A ranges from -2000m to -400m and the inset in B ranges from 3500m to 7000m in elevation relative to the mean Lunar elevation. The GLD100 insets show the exact same regions as the main images. North is up in both images. See Supplemental Table 1 for NAC Image IDs.
**Figure 3.9:** Extra-Lunar CCR possibilities. On the left is ‘490merc’ a 2800 m Mercurian crater shown in the images EN1034119486M & EN1034119490M (11 m/pix). Insets of three CCRs (A, B, C) are in the lower right of this image. On the right is ‘mars1’ a 2 km Martian crater shown in the image PSP_002204_1655 (25 cm/pix). The largest potential CCRs are found roughly one to two crater radii northwest of ‘mars1’. North is up in both images.
Table 3.1: Names, approximate diameters and locations of craters discussed in this paper. Lowercase names in single quotes denote the use names that we have assigned to craters without formal IAU designations. They are written this way to make them visually distinct from properly named craters.

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>D (km)</th>
<th>Long (E)</th>
<th>Lat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linné</td>
<td>Lunar Mare</td>
<td>2</td>
<td>11.8°</td>
<td>27.7°</td>
</tr>
<tr>
<td>Piton B</td>
<td>Lunar Mare</td>
<td>5</td>
<td>359.8°</td>
<td>39.3°</td>
</tr>
<tr>
<td>Mösting C</td>
<td>Lunar Mare</td>
<td>4</td>
<td>351.9°</td>
<td>-1.8°</td>
</tr>
<tr>
<td>Lassell D</td>
<td>Lunar Mare</td>
<td>2</td>
<td>349.5°</td>
<td>-14.6°</td>
</tr>
<tr>
<td>Encke X</td>
<td>Lunar Mare</td>
<td>3</td>
<td>319.7°</td>
<td>0.9°</td>
</tr>
<tr>
<td>‘piton b2’</td>
<td>Lunar Mare</td>
<td>1</td>
<td>359.7°</td>
<td>38.8°</td>
</tr>
<tr>
<td>‘lick rim’</td>
<td>Lunar Mare</td>
<td>3</td>
<td>53.4°</td>
<td>12.3°</td>
</tr>
<tr>
<td>Stevinus A</td>
<td>Lunar Highlands</td>
<td>8</td>
<td>51.6°</td>
<td>-31.8°</td>
</tr>
<tr>
<td>‘alpha’</td>
<td>Lunar Highlands</td>
<td>4</td>
<td>354.9°</td>
<td>-29.2°</td>
</tr>
<tr>
<td>‘gamma’</td>
<td>Lunar Highlands</td>
<td>2</td>
<td>212.5°</td>
<td>-24.9°</td>
</tr>
<tr>
<td>‘490merc’</td>
<td>Mercury</td>
<td>3</td>
<td>75.7°</td>
<td>45.6°</td>
</tr>
<tr>
<td>‘770merc’</td>
<td>Mercury</td>
<td>4</td>
<td>147.2°</td>
<td>28.4°</td>
</tr>
<tr>
<td>Winslow</td>
<td>Mars</td>
<td>1</td>
<td>59.2°</td>
<td>-3.7°</td>
</tr>
<tr>
<td>‘mars1’</td>
<td>Mars</td>
<td>2</td>
<td>38.6°</td>
<td>-14.2°</td>
</tr>
</tbody>
</table>
Chapter 4: A Topographic Examination of Crater Concentric Ridges

This chapter will be submitted as a paper in the very near future

Corwin Atwood-Stone, Veronica J. Bray, Sarah Sutton, and Alfred S. McEwen

Crater Concentric Ridges (CCRs) are common ejecta features of fresh craters between one and six kilometers in diameter on the moon. Despite being prominent features found around many craters, 77 in our catalog, CCRs have only been sparsely studied and are poorly understood. Using new high-resolution DTMs (Digital Terrain Models) of six craters and their ejecta, created from images taken by LROC NAC (Lunar Reconnaissance Orbiter Camera – Narrow Angle Camera), we examine these ridges in unprecedented detail. With this topographic data we characterize the range of morphologies of CCRs and consider how they are affected by pre-existing topography. Additionally, using maps created from LROC NAC images we analyze the distribution of these features around their host craters. With this data we then evaluate different hypotheses for the formation of these ridges.

4.1: Background & Introduction

Crater Concentric Ridges (CCRs) are topographic features commonly found in the ejecta blankets of small (1-10km) fresh craters on the moon. CCRs were previously known as ‘Lunar Concentric Dunes’ as a result of their physical similarity to dunes, however we have adopted the terminology of CCRs as more descriptive (Atwood-Stone et al., 2016). These features are elongated ridges oriented roughly concentrically to their host crater, which often have an arced shape with the bow of the arc pointed craterward (Howard, 1974). These ridges are most
commonly observed around craters in the Lunar maria. These ridges are found in ejecta blankets as close as 1.2 crater radii (Cr) to the crater center and extending out several crater radii from there (Morrison and Oberbeck, 1975). Moving outwards from the crater, CCRs generally get smaller and less densely packed. Their morphologies also change with increasing distance: from large subdued ridges, to classic CCR morphology, to ridges accompanied by a down-range trough [Fig. 1] (Morrison and Oberbeck, 1975). We will refer to this down-range trough morphology as Crater Concentric Troughs (CCTs).

Previous authors have hypothesized that CCRs formed as a result of ballistic impact sedimentation and erosion (Morrison and Oberbeck, 1975; Oberbeck et al. 1975). In this theory, secondary crater ejecta launched toward the primary crater interacts with the outflowing debris surge of the primary crater ejecta to deposit ridges. Accordingly, the CCTs are seen as chains of secondary craters and the source of the secondary ejecta. Our preliminary work (Atwood-Stone et al. 2016) cast doubts on this theory as a result of morphological details visible in new high-resolution data, primarily images from the Lunar Reconnaissance Orbiter Camera Narrow Angle Camera (LROC NAC) (Robinson et al., 2010).

In our preliminary work (Atwood-Stone et al., 2016) we showed that distribution and frequency of ridges around mare craters follows a set pattern, with the density of ridges peaking at two crater radii (Cr) from the crater center and decreasing outwards exponentially. Around highlands craters, CCRs were found to only form in some directions and to be significantly influenced by the underlying slope of the topography. This selective formation makes it much harder to find craters with ridges in the highlands, possibly suggesting that it is only observational bias that makes CCRs more common in the maria. Topographic investigation shows that these features can be up to a few tens of meters high, however their slopes were found
to be well below the angle of repose. Finally, these ridges were observed around craters on Mercury, suggesting that they may be a feature common to rocky airless bodies.

Here we are continuing and expanding upon our work analyzing CCRs with data from LRO, specifically considering these features using high-resolution DTMs. In particular we use this new data to consider three hypotheses for the formation of CCRs that were proposed in Atwood-Stone et al., 2016. In short these hypotheses postulated that CCRs may have formed by: interaction of ejecta with preexisting features, creation of topography via the subsurface shockwave of the impact, or shockwaves within the flowing ejecta forming remnant topographic features. The new topographic data allows us to consider the potential validity of these hypotheses.

4.2: Objectives & Methods

The main objective of this study is to fully characterize the three-dimensional morphologies of CCRs. A full understanding of their morphologies will allow us to better consider and evaluate the different hypotheses for CCR formation. In order to do this we utilized the database of fresh lunar craters with visible crater concentric ridges presented in Atwood-Stone et al. (2016) to identify candidate craters. Those craters with the best Lunar Reconnaissance Orbiter Camera (LROC, Robinson et al., 2007) Narrow Angle Camera (NAC) image coverage and existing viable stereo pairs were selected for this advanced morphological study.
4.2.1: Two-Dimensional Data Collection

In order to study the distribution and morphology of CCRs across full ejecta blankets, NAC mosaics of lunar craters and their surrounding ejecta were created using ISIS3 (Integrated Software for Imagers and Spectrometers; Keszthelyi et al., 2014). NAC images with incidence angles between 60° to 80° were used to ensure the proper amount of shadow to emphasize CCR topography without obscuring it. Mapping was completed for 8 craters [Table 1] from these mosaicked images using ArcMap 10 in order to quantitatively examine the distribution of these ridges. The eight study craters were chosen because they had the most complete patterns of ridges around them and represented a diverse range of crater diameters over the crater sizes noted to have CCRs by Atwood-Stone et al.,(2016). Mapping around all craters was divided into duodecants (wedges of the circular ejecta blanket equal to 1/12th of its area) in order to organize the data. Around each crater mapping was completed for those duodecants where the image quality was high enough to accurately map ridges. In those duodecants where image quality was not sufficient, CCRs were neither mapped nor measured in order to maintain sufficient data quality. By mapping only in complete radial segments data from different craters can be compared to each other without differences in quality image coverage affecting the results. We measured ground-surface area (A), length (l), width (w), and radial distance from crater center (D), of distinct CCRs around each crater.

Values derived from the above measurements included areal packing density (APD), Sinuosity (S) and curvature (C). Areal packing density describes the degree to which a given area is filled with CCRs and is a useful proxy for looking at how active the CCR forming process is at different craters and different distances from those craters. This areal density value was
calculated by dividing the total area of CCRs at a given range of distances from a crater by the total area of the ring represented by that range of distances [Fig. 2] (Atwood-Stone et al., 2016).

One last important 2D aspect of CCRs to consider statistically was their curvature. This was measured using the sinuosity index of the ridges in one radial wave of five different mapped craters. The sinuosity index measurement was borrowed from the fluvial geology community (García, 2015), which was calculated in this case as the length of the ridge along its crest divided by the linear distance between its endpoints. Thus a ridge with a value of one would be straight and one with a higher value would be more curved. One caveat of this particular measurement was that sinuosity index measurements could not be taken of ridges that had more than two endpoints.

4.2.2: Three-Dimensional Data Collection

We used five high resolution Digital Terrain Models (DTMs), generated from NAC stereo pairs, for topographic analysis of CCRs. One high-resolution DTM of Linné crater was provided by Arizona State University via the Planetary Data System. We also created four new DTMs (covering five relevant craters) at the University of Arizona to support this project [Table 1]. With a 10 microradian instantaneous field of view (IFOV), NAC pixel scale is nominally 50 cm from an orbital altitude of 50 km, with a 5 km swath width (Robinson et al., 2010). Images acquired from higher altitudes (up to 200 km) have correspondingly lower spatial resolution, but are still considered high resolution at 2 m per pixel. The DTMs we generated are at approximately four times the pixel scale of the source stereo images, and for consistency are created at either 2 m or 5 m per elevation post (pixel). LROC NAC stereo pairs are acquired on subsequent orbits, closely spaced in time to minimize illumination differences. We generated
these DTMs using pre- and post-processing routines in ISIS3, with photogrammetric bundle adjustment performed in the commercial software SOCET SET (BAE Systems). Stereo pairs are controlled first to each other using techniques similar to those described in Tran et al. (2010) and Henriksen et al. (2017). We use the autoTriangulation tool (Kilgallon et al., 2015) to adjust the stereo model to match laser altimetry from the Lunar Orbiter Laser Altimeter (LOLA), also on LRO (Smith et al., 2010) and boresight-aligned with LROC NAC. The resulting DTMs have a horizontal scale equivalent to their post spacing (e.g. 2 or 5 m), and a vertical precision estimated to be better than the horizontal post spacing (Henriksen et al., 2017), dependent on the stereo pair convergence angle and quality of relative image control. Absolute positional accuracy is related to the quality of the fit to LOLA, and is typically within 2 m vertically, and 10 m horizontally, which is within the tolerances of LOLA data (Henriksen et al., 2017). The source stereo images are then orthorectified to the DTM. Orthorectification minimizes displacements due to the original observation geometry, enabling accurate measurements to be made on the orthoimages. Ancillary products such as a shaded relief image and a slope map were also generated from the DTM.

Topographic profiles were taken from the DTMs to measure heights and slopes for numerous CCRs. Measurements were not taken for all ridges in the measured regions because in many cases the ridges are not sufficiently separated from topographic features to take an accurate profile. Separate height and slope values were taken for both faces of the ridges in order to examine any potential differences between the two faces of the CCRs. The two faces of these ridges that we are measuring are the interior and exterior faces, where interior refers to those faces generally oriented toward the crater and exterior refers to those oriented away from the crater. These measurements were complicated by the variation in height and slope along the
ridge, thus for each ridge height and slope were taken from a single profile through a portion of the ridge that appears to present a representative look at the whole. At a select number of ridges (chosen because they were separated from complex topography along their entire length) we took a number of profiles perpendicularly through the ridge along its entire length to determine if a single profile would be a fair representation of the whole. Since these measurements were taken consistently they are assumed to be reasonably accurate, especially in relation to each other; however there is a degree of human error inherent in this method. In order to have a consistent dataset, the slope was taken from a profile of the slope map of the DTM in the same place as the profile of the DTM itself. From these slope map profiles the slopes were quickly readable as the local maxima in the portion of the profile representing the center of each face.

After taking quantitative measurements to statistically analyze CCRs, the datasets were used to qualitatively examine the various morphologies expressed by these ridges. Using the NAC images we were able to examine a number of features of the ridges, such as how subdued they are, their shape, and whether they are associated with a down range trough. With the DTMs it was possible to examine how these morphological features appear in three dimensions. In order to achieve this we clipped out individual CCRs (or small subsets of them) and created full 3D representations of them using ArcScene 10 software. Beyond examining the morphology of these ridges in isolation it was also possible to examine how they interact and intersect with each other, and how they form in relation to the underlying topography. In addition to creating 3D insets of CCRs we also created a number of these insets at Linné and Piton B to examine the morphology of Crater Concentric Troughs (CCTs). Locations for these insets were chosen from the 2D images to represent the full range of CCTs, from those with clearly associated ridges to those that lacked an apparent ridge. These qualitative examinations help in considering different
ways in which these features could have formed, by defining a set of morphologies, which any hypothetical process must be able to replicate.

4.3: Results

In the course of our survey, encompassing Atwood-Stone et al., (2016) and this paper, we have discovered 76 craters with CCRs around them [Fig. 3]. Of these, 40 were within the maria and 34 within the lunar highlands. The remaining two examples were found in the border between these regions. Around the craters in the mare we usually observe ridges forming at all azimuths around the crater whereas in the highlands CCRs are observed only in some directions around craters but not in others. At some of the craters where CCRs are observed, like Linné, the CCRs are generally sharp and crisply defined, whereas at other craters, such as Mösting C, the ridges are more subdued and smoothed out. This difference in appearance of ridges from one crater to the next is likely a result of degradation due to different ages of craters. However, this difference in crater ages cannot be independently confirmed as all of our craters are quite fresh and if dated using crater counter would be within margins of error of each other. Similarly, crater evolution models would be problematic to employ as the d/D ratios, for all six craters for which we have DTMs, fall approximately between 0.23-0.24, which corroborates that these craters are very fresh but does not show enough variation for crater evolution models to accurately provide relative ages of these craters.

4.3.1: Two-Dimensional CCR Mapping Data

The areal packing density of mapped CCRs rises quickly to its highest value at 2 Cr and then falls off exponentially with increasing distance from the crater [Fig. 4]. This drop-off in
areal density is a result of the ridges becoming more dispersed and generally smaller further from the crater. A couple of the craters do peak further out, however we believe this is a result of issues with our data rather than differences in formation, as we will discuss later. The rate of exponential decay of the areal density of CCRs beyond 2 Cr (or more generally beyond the peak in the areal density graph) varies significantly between craters. The general trend that we can observe from our exponential fits of the data is that the areal packing density of CCRs decreases faster for larger craters.

In addition to measuring the dimensions of the mapped CCRs we also calculated the sinuosity index of ridges within a single duodecant for five of the mapped craters. The sinuosity values for all but two of these ridges varied between 1 and 1.5 [Fig. 5a], with most of the ridges falling near 1 and decreasing exponentially toward 1.5 as $e^{-7x}$. We also observe that the sinuosity index of CCRs has a slight tendency to decrease with distance from the crater [Fig. 5a], and a stronger tendency to increase with length [Fig. 5b].

4.3.2: Topography of CCRs

We measured heights and slopes of interior and exterior faces, and widths, for many of the ridges around five of the craters for which we have DTMs [Table 3]. Although we have data from five craters for the purposes of our discussion here we will be focusing on the two craters for which we have the most complete data: Linné and Piton B. Around these craters CCRs can reach significant heights, for example at the 2km crater Linné our tallest measured ridge is 22m, and at Piton B (5km) the tallest ridge measures 32m. Moving away from the crater the average height of the ridges gradually decreases out to 3 Cr [Fig. 6]. In fact the heights of these ridges will eventually decrease to zero further away from the craters, however our measurements from
the DTMs only extend out to 3 Cr, as past this measurable CCRs become scarce. In addition we can see from Figure 4 that the asymmetry in the heights of the interior and exterior faces of the ridges is systematic. At both Piton B and Linné we observed that the exterior face is, on average, a few meters taller than the interior face (due to the surrounding terrain being higher on the interior side). While this is statistically true on average, it is not the case for each individual CCR; in Figure 7 the maps show the locations of measured ridges marked by which face is taller, or if they are approximately equal in height. Furthermore as seen in Figure 4 the average heights of a larger crater like Piton B are consistently taller than those of a small crater such as Linné.

The slope angles of CCRs around Linné and Piton B generally range from 6° to 25° with a couple of outliers, one being as steep as 31° [Table 3]. Similarly to our observation of heights, exterior and interior slopes differ: the slopes of exterior faces at both Linné and Piton B are generally steeper than the interior faces [Fig. 6], although again this is only true on average and not for each individual CCR as shown in Figure 7. Unlike our observations of heights, the average steepness of slopes does not show a relation to either the size of the host crater, nor the distance from the crater.

In addition to statistically examining the heights and slopes of the ridges we also used the DTMs to study the individual morphologies of these features. To do this 3D insets [Fig. 8] were created for various ridges that have different expressions of what is described in Figure 1 as ‘Normal Ridges’. The proximal ‘Subdued Ridges’ of Figure 1 are difficult to show in a 3D figure (although one proximal ridge that is less subdued is shown in Figure 9g) and the ‘Ridges with Troughs’ will be described in detail in section 3.4. From these insets a variety of CCRs morphologies can be observed.
In Figure 8a there is an example of the classic crescent morphology of CCRs, but this shape is not universal. In many cases like Figures 8 b-c we observe ridges that are more linear or jagged in shape. The ridge seen in Figure 8b is also interesting because there is an apparent small crater breaking up the middle of the ridge: this could have occurred long after formation, but if it is the result of a secondary impact that would indicate the time frame for formation of these ridges. Sometimes these ridges also appear in groups, like those shown in Figure 8d. These ridges, which nearly touch, provide a clear example of how ridges might intersect with each other which can lead to conglomerate ridges where it is difficult to separate which sections were initially separate ridges. Even in the example shown here, where 3D detail shows them as clearly separate, in 2D images this appears as a single ridge with a triple point in the middle or even with different lengths constituting the longer ridge depending on the lighting. The ridges discussed thus far [Fig. 8 a-d] are from Linné and Piton B and appear fairly sharply defined in character. Specifically, the faces of these ridges appear fairly planar with a narrow ridge between them forming a roughly triangular cross-section. Contrast this appearance with that of the ridges in Figures 8e-f from Moltke crater which appear much more rounded and broad, exhibiting a cross-section closer to semicircular than triangular. An additional morphology noted is shown in Figure 8g, a set of long thin sinuous ridges that are tightly grouped together. This type of morphology is more common further out from the crater and often has CCTs associated with the CCRs, although they are hard to distinguish from the natural space between ridges.
4.3.3: Interaction With Pre-Existing Topography

The natural topography of CCRs can be influenced by the moonscape on which they form (e.g. Fig 7h). This pre-existing topography can take the form both of small, local topographic features or the large-scale complex topography observed in the lunar highlands. In both cases this topography can have significant effects on the resultant morphology of the CCRs forming on top of it. In order to study these effects we utilized 3D insets of DTMs like those in Figure 9, which shows CCRs in regions where there were clear, underlying topographic features.

One important type of underlying topography to consider is that of small, pre-existing craters as this is the most common topographic feature on the lunar surface. Furthermore CCRs are observed interacting with them in different and complex ways [Fig. 9]. In Figure 9a there is a CCR running through the middle of a small crater. The top of this ridge is a roughly the same elevation along its entire length, despite the fact that the depth of the underlying crater means that the middle of this ridge is quite tall while its ends outside of the crater are rather short. In a second type of example [Fig. 9 b-c] we again observe ridges that run across (or most of the way across) their respective craters. However in this case the ridges remain almost the same height along their entire length despite a drastic change in elevation – which is exactly the opposite of what we saw in Figure 9a. In the case of the two ridges intersecting a larger crater in Figure 9d we observe something different still. The ridge near the downrange rim of the crater looks like it might have small rise in topography inside the crater, the ridge closer to the middle completely disappears inside the craters. In a fourth case [Fig. 9e], which may show a degraded crater on a slope or just an anomalous drop in a slope, we see a ridge that runs from one side to the other of this depression. On at least one of the sides, and possibly both, it appears that the CCR has stopped just short of an unrelated topographic high, and while going into the depression the ridge
appears to bend forward. A similar effect is seen in the lower portion of Figure 8h, while in the upper portion of that figure the same ridge goes through a crater similarly to Figure 9c. In almost all of these cases the ridges remain coherent despite the significant underlying topography, and even when they do not they remain lined up on either side of the topographic feature.

The above small craters represent the predominant form of negative topography that ridges might form on. CCRs are also observed forming on underlying positive topography, although such features are significantly less common. For example, at Posidonius Y, there are a few, comparatively very large, pre-existing ridges that are found semi-radially to the crater. In Figure 9f we observe a CCR that formed on top of, and crossways to, one of these ridges. This CCR appears very subdued compared to others nearby that formed on flatter ground, and its curve forward appears to be the product of the topography on which it formed.

While the effect large scale underlying slopes have on the distribution and general size of CCRs has been examined in the literature (Atwood-Stone et al., 2016), here we want to examine how these slopes affect the morphology of individual CCRs. We observe that ridges forming on downhill slopes frequently take on specific morphological characteristics. In Figure 9g, which shows a ridge on the downslope of the crater rim at Linné, the CCR shows the classic arced morphology and is clearly much steeper on its downrange face – in fact its uprange face is quite shallow. Similarly in Figures 8 h-i, both of which are on a general downslope at Posidonius Y, we observe nicely arced ridges where the uprange face is comparatively shallow. In some cases, CCRs forming on these slopes accentuate the aspect of a shallow uprange slope to the point where that slope is level, or even slightly sloped down to the crest. It is true that statistically the downrange face is usually steeper in the general CCR population, however that difference is much greater on these downhill CCRs. The arced morphology described for these ridges on
downhill slopes is common in the general CCR population, however it appears almost constantly for these downhill CCRs.

Atwood-Stone et al. (2016) noted that CCRs forming on uphill slopes seem to be more common than their downhill counterparts. However the ridges themselves are often hard to discern, as the interior face of the ridge may not be much steeper then the underlying slope. In these cases however the down range trough is clearly noticeable [Fig. 10b]. Pronounced CCTs are almost always found with ridges on uphill slopes, which separates them significantly from the rest of the CCR population, where CCTs are only common for more distal ridges.

4.3.4: Troughs

An associated feature of some CCRs is a downrange Crater Concentric Trough, CCT. Examination in our 3D data has resulted in two qualitative observations of the general morphology of CCTs. First, in almost all cases where there is a clear ridge and trough pair, the base ground level immediately down range of the trough is significantly higher than the base ground level uprange of the ridge [Fig. 10 a-c]. In some cases the ground level just past the trough is nearly as high as the ridge itself. This high ground level does eventually (over a distance of several widths of the ridge-trough pair) descend to the normal base height.

CCTs are not observed without an accompanying CCR. Examination of the highest resolution data revealed small, but clearly present, ridges in the topographic data [Fig. 10d]. The situations where a CCR is not visible, in the topographic data, occur on significant uphill and downhill slopes. In these cases, where there is not level surroundings to compare to, we cannot always show that there is a ridge, but equally we cannot show the absence of one.
4.4: Discussion

The locations of CCR-bearing craters in our survey [Fig. 3] with 40 craters in the lunar mare and only 34 within the bounds of the much larger lunar highlands might suggest that CCRs are more common in the mare, which was the conclusion of earlier studies (Morrison and Oberbeck, 1975). However, our observations of these ridges instead suggest that they are likely equally common in both regions and that what our data shows is primarily observation bias arising from two distinct sources. The first is that few kilometer fresh craters are much easier to find in the maria, where they have bright halos of ejecta to advertise their presence, than they are in the highlands where they do not. As such determining which craters to search for CCRs around is significantly harder in the highlands. The second source of bias arises from the differences in distribution of CCRs around highlands craters; whereas at mare craters these ridges are found in a full pattern around the crater, in the highlands they are often only found in a limited number of directions. This becomes an issue because many of these craters are not heavily imaged by the NAC camera and so in many cases only a part of the crater’s ejecta blanket has a NAC image with appropriate viewing geometry. When this happens in the mare it is not an issue because the ridges are everywhere, but in the highlands they might be on the side of the crater and thus not be observed. As a further complication the more complicated topography of the highlands often casts shadows over significant regions of the ejecta blanket in the low sun images we require for this search, which can serve to further obscure the areas which actually contain CCRs.
4.4.1: Two-Dimensional CCR Mapping Data

The areal density curves [Fig. 4] that we calculated for our eight mapped craters in general show a peak at 2 Cr and an exponential drop-off with distance. However, as mentioned before, a few of the mapped craters have areal density curves that vary from this general picture. The curves at Encke X and Liebig J appear to peak further out at 2.5 Cr, however this appears to be the result of lighting issues in the available NACs rather than a real difference in the distribution of CCRs. In the images for these craters the proximal ejecta blanket appears washed out with light, which makes ridges difficult to locate and map. Furthermore, once past this peak the areal density curves at these craters have exponential drop-offs that fall right in line with the rest of the dataset. The data from the crater ‘epsilon’, which appears to peak even further out, has the same lighting issue, coupled with the small sample size of ridges at a 1 km crater. Another interesting feature of this dataset is that the curve for Mösting C peaks a little higher than Piton B, despite being almost a full kilometer smaller in diameter. Atwood-Stone et al. (2016) noted that peak areal density values varied with crater radii, which these data would contradict. The explanation for this discrepancy is that the ridges at Mösting C appear much more degraded than those at Piton B. In addition to making CCRs less distinct, this apparent degradation also makes them shorter and wider, which increases the area of individual ridges. Therefore our areal density curves vary not only with crater radii, but also with degradation, and thus apparent age of the craters. The consistent shape of the areal density curves that we observe thus appears to be a characteristic of CCRs which may help us evaluate formation processes of these ridges.

Degradation, and thus age, of the ridges also has a significant effect on the exponential fits of the areal density curves. Mösting C for example has a faster exponential decrease than would be expected for its size because of the state of its ridges. This is because degradation will
make smaller ridges more difficult to observe and map on NAC images faster than large ones. Since the furthest ridges from the crater are generally the smallest, they will disappear from the data, while the closer large ridges will get bigger, thus raising the apparent rate of exponential decrease. The data also shows that the rate of decrease is lower at Lichtenberg B than our trend would suggest. We suggest that this is largely a result of the ridges of this crater appearing exceptionally undegraded.

One interesting case to note when considering the distribution of CCRs around craters is Encke X (Atwood-Stone et al., 2016). This crater has a classic wedge shaped exclusion zone in the ejecta blanket which indicates an oblique impact. Inside the exclusion zone we observe no CCRs which indicates that ejecta flow is required for the formation of these ridges. Furthermore, at the margin of the zone the CCRs appear unusually oriented, possibly resulting from a velocity gradient in the ejecta near the border.

The sinuosity data that we measured, which shows that most CCRs have a sinuosity index close to 1, calls into consideration whether the ‘classic’ arced morphology described in previous works (Howard, 1974) is in fact common among these ridges. To analyze this we considered a set of quadratic curves of different sinuosity indexes [Fig. 5c] and saw how many of our measured CCRs had at least that much curvature. From the brown curve in Figure 5c we see that more than 80% of all CCRs have at least some visible curvature. Furthermore, the orange curve, which we would describe as sufficiently bent to qualify as having the ‘classic’ curved morphology, is less sinuous then 54% of all of the measured CCRs. Admittedly some of the more sinuous CCRs curve back and forth rather than forming a single arc, however the ‘classic’ arced morphology is still common enough to be usefully descriptive.
4.4.2: Topography of CCRs

From our measurements of heights and slopes of CCRs around craters with DTMs we can see that the topography of these ridges displays significant and systematic variations. This indications that topography will be just as important as planform morphologies in constraining the formation of these ridges. One feature of topography that does not appear to be systematic in variation is the distribution of ridges around the crater based on whether the interior or exterior face is taller or steeper [Fig. 7]. Aberrations from the norm in this respect are likely the results of local circumstances rather than a characteristic of general formation.

The measured slopes of these ridges, with the exception of a few outliers, are below the angle of repose that is observed for active dune faces (Atwood-Stone and McEwen 2013), which would suggest either that these ridges are already degraded or that they initially form below the angle of repose. Given the observed 19° variation in slopes we can say either that at least most of the CCRs form well below the angle of repose or alternatively there is a highly differential degradation process at work. We already know that CCRs are significantly and rapidly (on a geologic timescale) affected by degradation because these ridges are only observed at the freshest craters. However, given the visual similarity between the ridges at one crater and dissimilarity between ridges observed at different craters with different apparent amounts of degradation, it is highly unlikely that differential application of degradation is responsible for the range in slopes. Thus however these ridges form, they must form at a wide variety of slopes, and in most cases well below the angle of repose.

In considering why these ridges form with a variety of slopes, it is interesting to consider how those slopes vary with distance from the crater [Fig. 6], which is a proxy both for average clast sizes and ejecta velocities. However our observations suggest little to no correlation
between steepness of slope and distance from the crater. This would indicate that neither clast sizes nor ejecta velocity play a significant role in determining the shape of these ridges. One trend that we do observe is that the exterior slopes are generally steeper than the interior slopes which will constrain how these features form. This result contradicts that found in earlier work (Atwood-Stone et al., 2016) which observed slopes that were roughly equal on both sides of the ridge. The difference in these results is due to the highly limited sample size used by Atwood-Stone et al. [2016]. A final interesting feature found in our topographic measurements is a rough correlation between taller and steeper ridge faces. Taller ridges being steeper than short ones is not something that one would expect of topographic features in general, thus this observed correlation places a constraint on the formation of CCRs.

4.4.3: Interaction With Pre-existing Topography

The character of CCRs that form on pre-existing slopes and landforms can be significantly altered from the basic type found on flat plains. One particularly notable case of this is seen in the fields of ridges forming on the significant underlying slopes of the lunar highlands. Previous work (Atwood-Stone et al., 2016) showed that these slopes can have a significant, though inconsistent, affect on the distribution of these ridges. For example, at some craters ridges on uphill slopes would be smaller and more spread out than usual, while at others an uphill slope would result in a very compact set of ridges. In addition to this sort of previously described effect on the distribution of ridges, we have also observed that underlying topography can have a profound effect on the morphology of individual CCRs.

As discussed earlier one of the most common types of topography on the moon, small impact craters, appear to affect the morphology of CCRs in a variety of different ways. For
example the CCRs observed in Figures 9 a-c show very different interactions with the underlying crater. However this difference appears to result from the base size of the ridge compared to the underlying crater, namely that in Figure 9a the CCR is of comparable size to the underlying crater whereas in Figures 8 b-c the CCR is comparatively much smaller. In Figure 9d we observe CCRs interacting with a crater where the comparative size difference is even larger. One of those ridges completely disappears passing through the crater while the other has at most a faint trace inside. This is likely a continuation of the trend above to even larger size differences where the ridge has difficulty forming at the locally increased depth. It is important to note that we do not rule out the possibility that the crater postdates the ridges (which would very clearly explain why they are not seen inside it), however the apparent faint trace of one ridge would argue against this possibility. Another interesting affect is seen in Figure 9e where the ridge bends forward with the topography. This presents a significant difference from those ridges seen in Figures 9 a-c where the ridges remain fairly straight. This difference could result from those ridges forming in complete craters, which slope back up past the ridge, as opposed to the CCR in Figure 9e where the crater is formed on a slope and its downrange side is not observed. One interesting point to consider in regards to this topographic interaction is that one of the formation hypotheses in the literature (Melosh, 1989) is that CCRs could be the remnant uprange rims of pre-existing craters, whose downrange rims were eroded by ejecta flow. This hypothesis is no longer viable in light of these clearly observed interactions between ridges and pre-existing craters.

From these CCRs forming on underlying craters, as well as ridges observed to have formed on positive topography like at Posidonius Y [Fig. 9f], we can see that while small-scale topography clearly affects CCRs that form on it, these underlying features do not inhibit
formation. Furthermore, despite the underlying topography these ridges tend to remain coherent, or at least lined up in the case of Figure 9d. This indicates that the process forming them should be fairly large scale with a wide front, as opposed to small local affects coalescing in chains and influencing their neighbors.

In addition to altering the distribution patterns of CCRs the large-scale topographic slopes of the highlands are also observed to affect the morphology of individual CCRs. As we described earlier, those ridges forming on downhill slopes are far more likely than average ridges to take on an arced morphology [Fig. 9 g-i]. It may be that the additional gravitational force acting on ejecta flowing downhill helps to accentuate the classic arced morphology by moving the edges of the ridge faster than the center; analogous to the formation of barchan dunes. On underlying uphill slopes the observed association of CCTs almost always forming with ridges is likely a result of the geometry of the situation rather than a difference in formation method. Specifically, in many cases this trough will just be the observed separation between the crest of the ridge and the underlying uphill slope, thus mimicking the morphology of CCTs. However, in some cases we observe CCTs that are deeply incised into the uphill slope [Fig. 10b] which demonstrates considerable erosive potential.

4.4.4: Troughs

One interesting constraint on the formation of CCRs described by previous work (Morrison & Oberbeck, 1975; Atwood-Stone et al., 2016) is the existence of CCTs associated with the ridges. All potential hypotheses not only had to explain troughs associated with ridges, they also had to account for CCTs that form without an associated CCR. In fact, troughs formed without ridges was one of the key pieces of evidence for the ballistic impact sedimentation and
erosion process (Morrison and Oberbeck, 1975; Oberbeck et al. 1975). However, the formation constraint of troughs unaccompanied by ridges can now be removed due to our observations of these purported unaccompanied troughs. When we observe these troughs in the DTMs we find ridges associated with them that were not observable in the 2D dataset.

Our other major observation of CCTs made from our new 3D dataset was that the ground level downrange of a trough is often significantly higher than the ground uprange of its associated ridge. In order to account for these observations one of two situations must be true for the formation of CCRs. This high ground level past the ridge-trough pair could be pre-existing topography, and as such the ridge would have stalled coming up this small slope. This scenario appears plausible as we also often observe what appears to be one ridge that stalled right up against another, forming a double peaked ridge (Atwood-Stone et al., 2016), and furthermore ridge formation appears to be enhanced on uphill slopes (as compared to downhill slopes, not level areas), which could also result from stalling in reaction to topography. The second possible situation is that the broad rise of downrange of the rough was also formed with the CCR during the outflow of ejecta. This scenario is harder to support as it requires a far greater concentration of material in the discontinuous ejecta blanket than a freestanding ridge. However, we do not discount this possibility either; the lack of any clear morphology of these broad rises would argue against them being pre-existing topographic features, and thus both theories must be considered. One immediate result of this observation is that it contradicts the possibility that CCTs are concentric chains of secondary craters as is required by the ballistic impact sedimentation and erosion hypothesis (Morrison and Oberbeck, 1975; Oberbeck et al. 1975). This is because the amount of material in one of these broad rises if far larger than could have been excavated from the trough.
4.5: Assessment of Formation Hypotheses

In our preliminary work (Atwood-Stone et al., 2016) we concluded that the classic ballistic impact sedimentation and erosion hypothesis was not feasible based on high-resolution examination of the CCRs and the results of ejecta scaling models. Our further work, especially examining the 3D morphologies of the ridges, only serves to confirm this prior result. Additionally in that previous work we proposed three hypotheses that we would like to evaluate with regards to new data.

First, it was proposed that the ridges might result from the ground surge building up against topographic obstacles and flowing around them as an ejecta wake. In examining numerous CCRs in 3D we have generally not found evidence of topographic obstacles that the ridges might have interacted with. An exception to that is the more distant ridges with associated troughs which do have anomalous highs downrange of them, however given the lack of these highs where troughs do not exist it seems likely that they are either only responsible for the positions of more distant CCRs, or that they are a byproduct of the ridge and trough formation process. In addition, while the arced morphology that resembles an ejecta wake is common, it is far from universal and this hypothesis does little to explain some of the more complex morphologies that have been observed.

Second, we suggested that the shockwave from the impact might have created some topography, via reactivation of small subsurface fractures, for the ejecta to interact with, similar to the above interactions with pre-existing topography. This hypothesis has difficulty accounting for the variety of troughs observed in our 3D data. Specifically, ridges that form on a constant uphill slope with associated troughs that incise deeply into the slope are difficult to explain. This
is because a reactivated fracture could create topography to form a ridge, but it would be unlikely to leave the slope constant with a CCR in the middle of it, and it would not be able to cause a trough to be incised below the pre-existing topography. Another argument against this hypothesis comes from the crater 2D distribution of CCRs at Encke X. This crater, as mentioned earlier, was formed from an oblique impact, which caused an exclusion zone to be left in the ejecta blanket. If the shockwave hypothesis was accurate we should be able to see any topography created this way in that exclusion zone without any overlying ejecta forming CCRs from it. Since we do not, this hypothesis can be excluded from further consideration.

The third hypothesis we proposed was that the interaction of shocks in the ejecta flow, either between each other or with underlying topography, could have caused the formation of these ridges. This idea is very similar to how antidunes form at the base of supercritical river flows (Kennedy, 1963). Nothing in our observational data rules out this proposal, so it may describe how these ridges form. In the future we will be evaluating this hypothesis using discrete element modeling, specifically using the FDEM code (Atwood-Stone et al. 2017; Borzsonyi et al., 2009). To this end we will be comparing features produced in our 3D models to those observed and discussed in this paper.

Using 3D data from DTM s we have significantly expanded our knowledge of the morphologies of CCRs and their associated troughs. Additionally we have a better understanding of where these features are able to form and have a significant data set with which to consider and rule out different hypotheses for their formation. Furthermore this dataset will be invaluable for comparing to the morphologies of simulated features in considering formation methods.
4.6: Figures & Tables

**Figure 4.1:** CCR morphology progression. Images show CCRs from Piton B (4.7 km) in distance/morphology order. Distances are crater radii from the center of the crater. All images have been rotated so that Piton B is to the left, and all scale bars are 100m. Figure is copied from Figure 1 of Atwood-Stone et al. 2017.

**Figure 4.2:** A) LROC NAC Mosaic of the 2 km crater Linné and the CCRs in its ejecta blanket. B) Mapped outlines of the CCRs in the same region. CCRs mapped in light gray are subdued in character while those mapped in dark gray have a sharper morphology.
**Figure 4.3:** Positions and relative diameters of 77 craters with CCRs plotted on the LROC WAC Global Mosaic. Diameters range from 1-11 km with dot size indicating relative crater size. Green dots are craters where the NAC coverage is good enough to make a mosaic, red dots are craters with well defined CCRs which may be useful for study, blue dots indicate craters which either have poorly defined ridges, insufficient NAC coverage, or both. Modified from Figure 2 of Atwood-Stone et al. 2016.
Figure 4.4: Normalized areal packing density of CCRs as a function of distance around eight different craters ranging from one to five kilometers in diameter.
Figure 4.5: Graphs examining the sinuosity of CCRs around different craters. A) Shows the sinuosity indexes of CCRs at five different craters and how those values vary with distance from the crater. This graph and B share a legend for simplicity. B) Shows the sinuosity indexes for the same CCRs and how they vary with the length of the ridge. C) Shows different quadratic curves plotted between -10 and 10 and gives the sinuosity index for each of them. Each curve is artificially offset at x=0 from the others for ease of viewing. Additionally, the legend shows what percentage of measured CCRs have at least as much curvature as each displayed quadratic. To represent this same information graphically the horizontal lines in A and B correspond to the sinuosity index of each of these curves.
Figure 4.6: Height and slope trends of CCRs at Piton B and Linné. First we see that on average the CCRs at Piton B (4.7 km) are significantly taller than those at Linné (2.2 km) At both craters we observe that on average the heights of the exterior sides of the ridges are taller. Also at both craters we observe that on average the CCRs are tallest near the rim and gradually decrease in height outwards, this trend appears somewhat more pronounced for the exterior heights. For both craters the slopes of the exterior faces tend to be steeper, however distance from the crater and size of the crater does not appear to have a strong effect on the slopes of ridges. An effect of distance on slopes would be found for the closest ridges around the craters, described in Figure 1 as ‘Subdued Ridges’, which have lower slopes, however they tend to be so surrounded by interfering topography that is difficult to take useful profiles of them.
Figure 4.7: Hillshades produced from the Linné DTM such that the illumination is from the center of the crater. A: CCRs mapped by relative face slope, with the near equal category representing those ridges where both faces are within one degree of each other. B: The same ridges mapped by which face is taller, with the near equal category representing those ridges where the slopes of the faces are within one meter of each other. Axes are in meters.
Figure 4.8: Insets showing basic CCR morphologies in 3D detail. These are produced by laying synthetic hillshade images over topography from LROC DTMs. In all images there is 5x vertical exaggeration and the shadowed face of the ridge is away from the crater. For each inset we give the crater name, corner to corner distance in meters for scale and the approximate distance (in Cr) and direction of the CCR from the center of the crater. A) Linné: 430m: 2.8Cr S. B) Linné: 740m: 2.5Cr N. C) Piton B: 1460m: 2.3Cr E. D) Linné: 820m: 2.6Cr SW. E) Moltke: 1950m: 3.2Cr N. F) Moltke: 1091m: 3.9Cr N. G) Piton B: 1520: 4.9Cr N. H) Linné: 1030m: 3.2Cr N.
Figure 4.9: Insets showing CCR morphologies over underlying topography in 3D detail. These are produced by laying synthetic hillshade images over topography from LROC DTMs. In all images there is 5x vertical exaggeration and the shadowed face of the ridge is away from the crater. For each inset we give the crater name, corner to corner distance in meters for scale and the approximate distance (in Cr) and direction of the CCR from the center of the crater. A) Linné: 590m: 2.9Cr N. B) Posidonius Y: 830m: 3.1Cr S. C) Piton B: 1540m: 2.8Cr NE. D) Piton B: 2040m: 1.9Cr E. E) Linné: 640m: 2.9Cr SW. F) Posidonius Y: 610m: 2.7Cr E. G) Linné: 860m: 1.6Cr SW. H) Posidonius Y: 490m: 2.7Cr W. I) Posidonius Y: 680m: 2.6Cr W.
Figure 4.10: Insets showing CCR morphologies with accompanying troughs in 3D detail. These are produced by laying synthetic hillshade images over topography from LROC DTMs. In all images there is 5x vertical exaggeration and the shadowed face of the ridge is away from the crater. For each inset we give the crater name, corner to corner distance in meters for scale and the approximate distance (in Cr) and direction of the CCR from the center of the crater. A) Piton B: 1660m: 3.1Cr S. B) Piton B: 800m: 4.1Cr S. C) Piton B: 1600m: 3.1Cr S. D) Moltke: 2480m: 4.9Cr S.
Table 4.1: List of the data products created at 18 craters with CCRs, which comprise the primary study areas for this work. Additional information on location and size of each crater is also provided.

<table>
<thead>
<tr>
<th>Location</th>
<th>Mosaic</th>
<th>Map</th>
<th>DTM</th>
<th>Location</th>
<th>D (km)</th>
<th>Long (E)</th>
<th>Lat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linné</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Mare</td>
<td>2.2</td>
<td>11.8°</td>
<td>27.7°</td>
</tr>
<tr>
<td>Piton B</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Mare</td>
<td>4.7</td>
<td>359.8°</td>
<td>39.3°</td>
</tr>
<tr>
<td>Moltke</td>
<td>--</td>
<td>--</td>
<td>X</td>
<td>Mare</td>
<td>5.9</td>
<td>24.2°</td>
<td>-0.6°</td>
</tr>
<tr>
<td>Mösting C</td>
<td>X</td>
<td>X</td>
<td>--</td>
<td>Mare</td>
<td>3.8</td>
<td>351.9°</td>
<td>-1.8°</td>
</tr>
<tr>
<td>Lassell D</td>
<td>X</td>
<td>--</td>
<td>--</td>
<td>Mare</td>
<td>1.8</td>
<td>349.5°</td>
<td>-14.6°</td>
</tr>
<tr>
<td>Encke X</td>
<td>X</td>
<td>X</td>
<td>--</td>
<td>Mare</td>
<td>2.9</td>
<td>319.7°</td>
<td>0.9°</td>
</tr>
<tr>
<td>Posidonius Y</td>
<td>X</td>
<td>--</td>
<td>X</td>
<td>Mare</td>
<td>2.0</td>
<td>24.9°</td>
<td>30.0°</td>
</tr>
<tr>
<td>Lichtenberg B</td>
<td>X</td>
<td>X</td>
<td>--</td>
<td>Mare</td>
<td>4.9</td>
<td>298.5°</td>
<td>33.3°</td>
</tr>
<tr>
<td>Hell Q</td>
<td>X</td>
<td>--</td>
<td>--</td>
<td>Highlands</td>
<td>3.5</td>
<td>355.6°</td>
<td>-33.0°</td>
</tr>
<tr>
<td>Liebig J</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Mare</td>
<td>3.6</td>
<td>314.9°</td>
<td>-24.8°</td>
</tr>
<tr>
<td>‘piton b2’</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Mare</td>
<td>1.3</td>
<td>359.7°</td>
<td>38.8°</td>
</tr>
<tr>
<td>‘lick rim’</td>
<td>X</td>
<td>--</td>
<td>--</td>
<td>Mare</td>
<td>2.5</td>
<td>53.4°</td>
<td>12.3°</td>
</tr>
<tr>
<td>‘alpha’</td>
<td>X</td>
<td>--</td>
<td>--</td>
<td>Highlands</td>
<td>3.9</td>
<td>354.9°</td>
<td>-29.2°</td>
</tr>
<tr>
<td>‘beta’</td>
<td>X</td>
<td>--</td>
<td>--</td>
<td>Highlands</td>
<td>3.5</td>
<td>177.8°</td>
<td>-26.6°</td>
</tr>
<tr>
<td>‘gamma’</td>
<td>X</td>
<td>--</td>
<td>--</td>
<td>Highlands</td>
<td>1.9</td>
<td>212.5°</td>
<td>-24.9°</td>
</tr>
<tr>
<td>‘epsilon’</td>
<td>X</td>
<td>X</td>
<td>--</td>
<td>Mare</td>
<td>0.9</td>
<td>333.3°</td>
<td>26.6°</td>
</tr>
<tr>
<td>‘zeta’</td>
<td>X</td>
<td>--</td>
<td>--</td>
<td>Highlands</td>
<td>3.6</td>
<td>101.1°</td>
<td>4.6°</td>
</tr>
<tr>
<td>‘eta’</td>
<td>X</td>
<td>--</td>
<td>--</td>
<td>Mare</td>
<td>1.1</td>
<td>62.6°</td>
<td>18.3°</td>
</tr>
</tbody>
</table>
Table 4.2: Ranges and means of measured values for lengths, widths and areas of CCRs measured from NAC mosaics of eight craters. Units are meters and square meters as appropriate. Additionally at five of these craters we list calculated maximum and mean sinuosity index values for a subset of all mapped CCRs. In all cases the subset is the CCRs in a single 1/12th area wedge. At Piton B a single outlier is excluded for clarity.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>L Range</th>
<th>Mean L</th>
<th>W Range</th>
<th>Mean W</th>
<th>A Range</th>
<th>Mean A</th>
<th>SI - N</th>
<th>Max SI</th>
<th>Mean SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linné</td>
<td>1048</td>
<td>25-848</td>
<td>172</td>
<td>5-100</td>
<td>26</td>
<td>156-66194</td>
<td>5382</td>
<td>87</td>
<td>1.53</td>
<td>1.10</td>
</tr>
<tr>
<td>Piton B</td>
<td>330</td>
<td>84-2304</td>
<td>427</td>
<td>27-192</td>
<td>70</td>
<td>2193-354300</td>
<td>34419</td>
<td>76</td>
<td>1.39 (2.4)</td>
<td>1.10</td>
</tr>
<tr>
<td>Mösting C</td>
<td>218</td>
<td>54-2039</td>
<td>403</td>
<td>14-254</td>
<td>70</td>
<td>1095-326789</td>
<td>34752</td>
<td>45</td>
<td>1.47</td>
<td>1.08</td>
</tr>
<tr>
<td>Encke X</td>
<td>234</td>
<td>33-939</td>
<td>256</td>
<td>10-132</td>
<td>42</td>
<td>532-113927</td>
<td>13603</td>
<td>73</td>
<td>1.38</td>
<td>1.08</td>
</tr>
<tr>
<td>Lichtenberg B</td>
<td>860</td>
<td>45-1802</td>
<td>340</td>
<td>11-230</td>
<td>51</td>
<td>637-313343</td>
<td>22690</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Liebig J</td>
<td>157</td>
<td>133-1056</td>
<td>362</td>
<td>35-162</td>
<td>79</td>
<td>6801-118451</td>
<td>30977</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>'piton b2'</td>
<td>175</td>
<td>34-468</td>
<td>126</td>
<td>9-71</td>
<td>22</td>
<td>334-15217</td>
<td>3127</td>
<td>23</td>
<td>1.28</td>
<td>1.08</td>
</tr>
<tr>
<td>'epsilon'</td>
<td>190</td>
<td>28-442</td>
<td>92</td>
<td>5-35</td>
<td>16</td>
<td>309-5847</td>
<td>1601</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 4.3: Ranges and means of heights, slopes and widths of CCRs measured from DTMs of five craters. Units are meters and degrees as appropriate.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Interior H Range</th>
<th>Interior Mean H</th>
<th>Exterior H Range</th>
<th>Exterior Mean H</th>
<th>Interior S Range</th>
<th>Interior Mean S</th>
<th>Exterior S Range</th>
<th>Exterior Mean S</th>
<th>Width Range</th>
<th>Width Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linné</td>
<td>161</td>
<td>2-11</td>
<td>5</td>
<td>2-22</td>
<td>7</td>
<td>7-26</td>
<td>14</td>
<td>9-26</td>
<td>16</td>
<td>30-130</td>
<td>64</td>
</tr>
<tr>
<td>Piton B</td>
<td>227</td>
<td>3-26</td>
<td>11</td>
<td>4-32</td>
<td>14</td>
<td>6-27</td>
<td>14</td>
<td>6-31</td>
<td>16</td>
<td>70-330</td>
<td>130</td>
</tr>
<tr>
<td>Moltke</td>
<td>74</td>
<td>3-23</td>
<td>10</td>
<td>4-26</td>
<td>13</td>
<td>4-15</td>
<td>8</td>
<td>6-21</td>
<td>10</td>
<td>130-410</td>
<td>214</td>
</tr>
<tr>
<td>Liebig J</td>
<td>26</td>
<td>3-12</td>
<td>6</td>
<td>2-16</td>
<td>8</td>
<td>6-15</td>
<td>9</td>
<td>7-17</td>
<td>12</td>
<td>90-170</td>
<td>121</td>
</tr>
<tr>
<td>'piton b2'</td>
<td>25</td>
<td>1-11</td>
<td>3</td>
<td>1-17</td>
<td>4</td>
<td>2-11</td>
<td>6</td>
<td>3-14</td>
<td>7</td>
<td>30-80</td>
<td>54</td>
</tr>
</tbody>
</table>
Chapter 5: Crater Concentric Ridges Formed by Kelvin-Helmholtz Instabilities Between Ejecta and Regolith: A Simulated Experiment

This chapter will be submitted as a paper after the addition of the data from a few more simulations

Corwin Atwood-Stone, Jim McElwaine, Jim Richardson, Veronica J. Bray, & Alfred S. McEwen

Crater Concentric Ridges are topographic features of ejecta blankets oriented concentrically to fresh craters on the Moon that are roughly 1-5 km in diameter. We propose that these features are formed as the remnants of Kelvin-Helmholtz instabilities that form between the regolith and flowing ejecta. Using discrete element modeling we simulated crater ejecta around three lunar craters at different distances. Our simulations show that Kelvin-Helmholtz instabilities are formed between model regolith and flowing ejecta layers. When ejecta comes to a stop in these simulations topographic features in the results strongly resemble the observed topography of Crater Concentric Ridges on the Moon.

5.1: Background

5.1.1: CCR Background

Crater Concentric Ridges (CCRs) [Fig 1B] are topographic features found in the ejecta blankets of fresh lunar craters ranging in diameter from one to five kilometers (Morrison & Oberbeck, 1975; Atwood-Stone et al., 2016). These ridges—which were referred to as “Lunar Concentric Dunes” in the early literature—are oriented concentrically to their host crater and are classically described as having an arced shape, curving slightly outwards (Morrison & Oberbeck, 1975; Howard, 1974). Around mare craters these features appear starting at approximately 1.5 to
2 crater radii from the crater center and continue outwards for several crater radii, decreasing in areal density further from the crater (Morrison & Oberbeck, 1975; Atwood-Stone et al., 2016). These ridges appear in an apparently random but relatively even pattern all the way around their host craters [Fig 1A], except in ejecta exclusion zones formed during highly oblique impacts. Around highlands craters the distribution of these ridges is less evenly distributed and often asymmetrical, likely resulting from the significant underlying slopes that these craters form upon.

The morphology of these ridges follows a general trend with distance from the crater [Fig 1C]. Close to the crater these ridges take on a broad and subdued morphology. From about 1.5 to 3 crater radii from the center these ridges become more sharply defined and past this point ridges often have an accompanying trough, which follows the shape of the ridge on its downrange side. In the most distal locations the morphology of these troughs, which we will refer to as Crater Concentric Troughs (CCTs) appear accompanied by very minor ridges. CCRs can have sinuosity indexes ranging from 1 to 1.53 and in the more distal regions can sometimes appear as groups of long, sinuous ridges packed together. These ridges represent significant topography in the ejecta blankets of these craters, with heights ranging up to 32 meters for proximal ridges around larger craters. The slopes of these ridges are fairly variable but generally fall between 6° and 26°, and on average their downrange faces are steeper. In addition to solitary ridges, features are sometimes observed that appear to be two ridges that have formed almost on top of each other, such that they appear to be one larger ridge with a trough running down its center. (Atwood-Stone et al., 2016; 2018).

The early literature (Morrison & Oberbeck, 1975; Oberbeck et al. 1975)) concluded that these ridges were formed as a result of ballistic impact sedimentation and erosion; specifically
posing that they would form when secondary ejecta traveling back toward the crater would intersect with the outward flow of primary ejecta, thereby depositing a ridge. However more recent literature (Atwood-Stone et al., 2016; 2018) has disputed this primarily as a result of morphologies only visible in new, high resolution data sets; specifically the Lunar Reconnaissance Orbiter - Narrow Angle Camera (Robinson et al., 2010). The new observational work of Atwood-Stone et al. (2018) did not support other hypotheses, such as ejecta flow building up around pre-existing topography or topography being created via the seismic waves of the impact. In this paper we propose to develop the hypothesis that the topography of these ridges is formed as a result of a Kelvin-Helmholtz instability forming at the interface between the granular regolith and flowing ejecta layers.

5.1.2: Kelvin-Helmholtz Instabilities

A Kelvin-Helmholtz instability is a type of fluid-mechanical instability that forms at the boundary layer between two flowing fluids. In order for this type of instability to form there must be a difference in Froude number between two fluids with a discrete boundary. Typically there is a density differential between the two fluids, however a difference in velocity can also produce this effect. These instabilities form as a result of small perturbations in the initial boundary layer, specifically when a small portion of the slower fluid lies over an idealized planer boundary layer. The streamlines of the other fluid are slightly compressed as they move over this perturbation, causing the associated fluid to move faster as a result, thus lowering the pressure above the initial perturbation, causing it to grow. The same process happens in reverse on the other side of the boundary layer. Over time these perturbations grow larger and the velocity gradient across the boundary causes them to roll over in almost spiral-like waves. The resulting
series of roll-waves along this fluid boundary is the characteristic appearance of a Kelvin-Helmholtz instability. These instabilities are a common occurrence in nature, found in many places, ranging from the tops of clouds to the interface between the bands on Jupiter. (Kelvin, 1871; Miles, 1961; Thorpe 1971)

Typically Kelvin-Helmholtz instabilities have been described forming between layers of gasses or liquids; however it is possible for them to form at the interface between two granular 'fluids'. There have been both experimental and numerical studies examining this effect with granular particles flowing down an inclined plane. In these studies, two sets of granular particles would flow down the plane directly beside each other with one of them having been given a significantly higher initial velocity. These experiments showed the characteristic roll-waves of Kelvin-Helmholtz instabilities forming at the interface between these two flowing bodies of granular material. (Goldfarb et al., 2002; Ciamarra et al., 2005)

We propose that Kelvin-Helmholtz instabilities could form when crater ejecta flows over the lunar regolith. As a result of the ensuing roll-waves formed at the boundary layer, significant topography could be formed at the surface. We posit that CCRs are the topographic remnants of these roll-waves after the ejecta flow has come to a halt.

5.2: Methods

5.2.1: Fortran Discrete Element Method

In order to test the above hypothesis we need to model ejecta particles impacting into and flowing over a granular regolith layer. To do this we employed the Fortran Discrete Element Method (FDEM) code to run simulations of granular fluid interaction (Börzsönyi et al., 2009). Using the FDEM code we are able to create and observe the simulated flow of large numbers of
individual particles. The parameters of each of these particles are individually tracked throughout the simulation, including: all components of linear and angular velocities, and positions. All of these particles are tracked at very small time intervals as they move through the flow, and when they intersect with each other realistic collision and rebound physicals are applied. Thus using this code we are able to physically model the interactions between the ejecta and underlying regolith layer.

5.2.2: Excavation Flow Properties Model

In order to make useful and realistic models of ejecta using FDEM, we need to be able to input parameters into the simulations that correspond to the conditions where CCRs form on the Moon. To do this we have used the Excavation Flow Properties Model (EFPM) to calculate the likely properties of ejecta around three different craters which are known to have CCRs in their ejecta blankets: Linné, Liebig J, and Piton B. This semi-empirical code begins by using crater volume scaling relationships to approximate the size of an impactor based on crater size and surface properties. This is done following the general solution for transient crater volume scaling to simulate gravity and strength dominated crating regimes (Holsapple, 1993; Holsapple & Housen, 2007). This code next uses ejecta velocity scaling relationships (Richardson et al., 2007; Richardson, 2011) to compute surface ejection velocities from projectile and target material properties, impact parameters, and distance from the impact site. The solution thus calculated is applied to a discretized numerical model that represents the hydrodynamic streamlines of the excavation flow field (Maxwell & Siefert, 1974; Maxwell, 1977). This lets us compute the excavated mass and particle size distribution as a function of ejection velocity and distance from impact. Standard ballistic equations are then used to follow discrete ejecta masses from their
ejection sites to landing sites and calculate landing velocity and ejecta volume as a function of distance from the crater rim (Richardson, 2009). For our calculations we have used impact parameters from the three craters mentioned above and assumed certain values: a target strength of 15 MPa, an impact angle of 45°, and an impact velocity of 20 km/s.

5.2.3: Ejecta Simulation Set-Up

Using the FDEM code we created three sets of 54 models simulating crater ejecta impacting into lunar regolith and flowing over that surface. To do this we simulated a regolith floor as a thick layer of spherical simulation particles packed together and with a relatively level surface. This regolith layer, and the ensuing simulations, are created in a simulation space with solid vertical side boundaries 14.71 meters apart from each other in the y direction and with an x space 500 meters long with periodic boundary conditions. These 'periodic boundary' conditions allow the continuing flow of material to loop around the area that roughly, though not exactly, simulates the flow of material that would be coming into the area from the direction of the crater. This same regolith layer forms the base for all of the spherical particle simulations.

The simulations are initially set up with a highly dispersed field of ejecta particles starting 10 units above the regolith layer and with initial x and y velocities. The different parameters for these ejecta particles are set to simulate the ejecta from different craters and at different distances from those craters as calculated from the EFPM models discussed above. The initial parameters that characterize this ejecta are their x and y velocities, and how dispersed those particles initially are in vertical space. Specifically, our models are simulating ejecta from the ~2km crater Linné, the ~4km crater Liebig J, and the ~5km crater Piton B. At each of these craters we simulate ejecta at six different distances ranging from 1.5 to 4 crater radii from the
center of the crater at 0.5 crater radii intervals. Our simulations also model different ejecta depths as compared to our initial regolith layer with the number of ejecta particles totaling one-fifth, two-fifths, or three-fifths of the number of particles in the regolith layer. In fully covering the described phase space of variables for different craters, distances, and ejecta depths, we have run a total of 54 simulations.

In addition to these simulations using spherical particles, we performed a second set of simulations using model non-spherical particles in both the ejecta particles and regolith layer. These simulations are necessary because spherical particles do not maintain topography as well as non-spherical ones once they come to rest. To create non-spherical particles in the FDEM code, which is only programmed to run with spheres, attached three spherical particles together. Specifically we attach two particles to a third at right angles to each other, with these particles overlapping by half. While a group of ‘L’ shaped particles does not accurately represent real ejecta and regolith particles, it does encapsulate those particles’ non-spherical nature, which allows topography to be maintained in the end state of simulations. In all manners other than the shape of particles these simulations are identical to the first set of 54 simulations and fully cover the same phase space.

We also created a third and final set of 54 simulations adding a model impact crater to the regolith layer of the non-spherical particles. Small, pre-existing impact craters are features that will constantly be encountered by real ejecta on the Moon, and so it is an important component to add to our simulations. Furthermore they are important to consider because the Kelvin-Helmholtz instabilities that we hypothesize are the source of CCRs should be amplified and accentuated by perturbations, like pre-existing craters, between the two particle layers. Due to our narrow y-phase space we have modeled our pre-existing impact crater as a trough centered in
the regolith layer with a quadratic bottom, a depth of 7 meters, and width of 38 meters. This shape was simple to create and approximates the ~0.2 depth-diameter ratio of small, fresh lunar craters (McEwen et al., 2005; Daubar et al., 2014).

We initially set up our simulations in this configuration with a layer of ejecta particles flowing over an underlying regolith layer in order to test an earlier hypothesis that CCRs might form by a mechanism analogous to anti-dunes. Anti-dunes are fluvial morphologic features that form at the base of a supercritical fluid flow over an erodible granular base (Núñez-González and Martín-Vide, 2011). Thus our simulations were set up to test this hypothesis using the ejecta layer as our flowing fluid, albeit one granular in nature, and our regolith layer as an erodible base. However when we examined the results of our initial simulations we saw no evidence of any activity that resembled anti-dune formation, and in fact our simulations have continued to not show any evidence of anti-dunes. The results of these initial simulations clearly showed the formation of Kelvin-Helmholtz instabilities between the two layers and as such we moved on with the working hypothesis that these Kelvin-Helmholtz instabilities were related to the formation of crater concentric ridges.

5.2.4: Measurement of Mixing

One interesting aspect of the interaction between flowing ejecta and underlying regolith is the degree of mixing that occurs between the two sets of particles. In order to do this we consider all of the particles in the simulation to have a vertical rank based on the heights those particles had in the initial state of the simulation. The lowest particle was given a rank of one and the highest particle is given a rank of n, where n is the total number of particles in the simulation. Then at the final timestep we reranked all of the particles in both the ejecta and
regolith and calculate the root mean squared deviations in how the ranks of the particles changed. Thus if the ranking changes because ejecta and regolith particles are no longer strictly separated then the mixing of the system increases. This is represented numerically by the mixing index, which will equal zero when the particles are fully segregated and will equal one if the ejecta and regolith are perfectly mixed.

5.3: Results

5.3.1: Simulated Kelvin-Helmholtz Instabilities

In many of our ejecta simulations Kelvin-Helmholtz instabilities were quickly produced at the boundary between the flowing ejecta and the underlying regolith. However, these instabilities are not always produced at the same magnitude, or even at all. There are two factors apparent in our simulations that increase the size of the produced instabilities: initial velocity of falling ejecta, and relative depth of ejecta layer [Fig. 2]. Thus in simulations where the initial velocities were low or the simulated ejecta was relatively shallow, these features were smaller, or sometimes not present at all.

Another feature that significantly affects the morphology of these instabilities is the shape of the particles used in the simulations. In those simulations using spheres for particles the instabilities appear primarily as low-angle, diagonal spikes coming out of the flowing granular layer [Fig 3A]. The bottom portion of these spikes is formed of material initially from the regolith, which then ends up overlying the ejecta material of the next instability in the sequence. While this does result in a boundary layer that interleaves ejecta and regolith material, we do not see the standard roll-wave morphology characteristic of Kelvin-Helmholtz instabilities. In the simulations using L-shaped particles the instabilities are often initially formed in a way that
appears more in line with the roll-wave morphology [Fig 3B]. Furthermore the instabilities produced with non-spherical simulations are significantly larger. Then, as formation continues, the instabilities either elongate into spikes similar to those described above with spherical particles if velocities are high, or fail to truly roll over and end as a series of hills.

From our third set of simulations, those including a pre-existing crater in the regolith layer, we observe that the addition of this topography has a significant affect on the morphology of the instabilities. In all cases the significant perturbation to the shape of the boundary layer represented by this crater served as a formation catalyst for one of the instabilities in the simulation. Furthermore, in addition to always being the site where one of these instabilities begins to form, the instability is significantly larger and more accentuated than others in the same simulation or the simulation with corresponding parameters but no initial crater [Fig 3C]. Even in those simulations that do not otherwise show recognizable instabilities a single prominent feature will still occur starting at the crater.

After the initial formation of these instabilities they eventually collapse into topographic highs. The continuing flow of granular material over the surface then serves to erode or deposit material in a manner controlled by the presence of these topographic highs. The topographic features found in the final states of our simulations, which we describe in the next section, are thus the product of this erosion and deposition that is controlled by the initial topography of the Kelvin-Helmholtz instabilities.

5.3.2: Final Simulated Topography

In order to consider the phenomenon of crater concentric ridges in these simulations, the most important aspect to study is the final topography left when the granular flow comes to a
halt. As we alluded to above, our simulations that contained spherical particles leave significantly less topography in their final states than those with non-spherical particles, as spherical particles settle toward an even plain given enough time. What topography we do see in spherical particle simulations is comparatively muted, and since the real particles that would compose CCRs on the Moon are not perfectly spherical we will focus our following descriptions of resulting topography on those simulations using L-shaped particles.

In many of our simulations we observe coherent and measurable topographic features in the final state, however this is not true of all simulations. There is a tendency for those simulations that model conditions close to the crater, and thus with lower velocities, to produce final states that are more flat and featureless. However this tendency does not universally follow as some proximal simulations do record interesting topography and the simulation we produced with the least vertical relief in its final state occurred at 3.5 crater radii from its host crater. Other than observed smoother terrain and lower relief CCRs close to the host crater, and a couple of exceptions that we will describe later, the specific types of topography produced in a given simulation do not appear to correlate with the input parameters. It is notable that the presence of a pre-existing crater in the regolith layer drastically changes the appearance of the output topography of the simulation, although the nature of that change is not consistent from one simulation to the next.

In the final states of our simulations we’ve observed a number of different types of topographic features. The simplest type of topographic feature we observe is a solitary ridge in the ejecta field [Fig 4A]. In some cases these ridges can reach up to five meters high and have slopes ranging from 5 to 25 degrees. Further, these ridges have widths ranging from 50 to 150 meters out of the total 500 meter length of the simulation. Another type of feature we sometimes
observed is a row of small ridges lined up one after another [Fig 4B]. These ridges are typically at most 50 meters in width and tend to have heights and slopes slightly lower than those of the individual ridges previously described. A third type of ridge morphology that we observe is that of an apparent larger ridge with a shallow trough in its center, or two smaller ridges that are partially overlapping one another [Fig 4C]. All three morphologies are noted in the observational data of Atwood-Stone et al. (2016; 2018).

In addition to the positive topography of ridges we also observed negative topography like troughs in our simulations. In one example from the simulation 4 crater radii from Piton B with an initial crater in the regolith, the final topography shows a 300 meter wide and 5 meter deep trough with the rest of the simulation being a nearly flat plane [Fig 5A]. In addition to troughs that occur in isolation, we can also observe troughs that form directly downrange of a small ridge as in the case of the simulation 2.5 crater radii from Linné with an initial crater in the regolith layer. In that specific situation we see a roughly 50 meter wide and 2-3 meter tall ridge followed by a 4 meter deep, 100 meter wide trough [Fig 5B].

In a few of our simulations the final topography appears to be approximately a single wavelength of a sine wave over the entire 500 meter periodic boundary of our simulation [Fig 6A]. This appears to only occur in our most distal simulations, including the primary exception to our previous statement that simulations with spherical particles have very little final topography [Fig 6B]. There is one other type of topographic feature correlated to a specific set of initial parameters, namely simulations 1.5 crater radii from the host crater with an initial crater in the regolith. In these simulations we can see a single, fairly narrow ridge that occurs just past the placement of the initial pre-existing crater and in the final subsurface regolith layer we observe the frozen beginnings of a Kelvin-Helmholtz instability below this ridge [Fig 6C].
5.3.3: Ejecta-Regolith Mixing Trends

Another interesting feature of the final states of our simulations is the degree of mixing that occurs between the ejecta and regolith particles. The mixing that occurs in these simulations, largely as a result of the Kelvin-Helmholtz instabilities between the two layers, appears to depend upon two primary factors: the velocity of the ejecta, and the roughness of the initial regolith layer. As we can see in Figure 7 in all cases the mixing index increases approximately linearly with distance from the crater, and thus increased velocity. Furthermore we see that in most cases that with all other parameters being equal those simulations around larger craters, again indicating higher velocity, show a greater degree of mixing. The other factor that affects the mixing index calculated for these simulations is the roughness of the initial regolith layer. The least rough regolith layer that we have is that composed of spherical particles that are able to flow over each other comparatively easily without catching. In these low roughness simulations the degree of mixing is lower than those simulations with comparable parameters but greater roughness. The regolith layer with L-shaped particles is comparatively rougher and also exhibits a higher degree of mixing than the spherical particles. Finally the addition of a crater to the regolith layer adds further roughness to the simulation and in almost all cases those simulations with an initial crater have the highest mixing index of all simulations with comparable parameters.

5.4: Discussion

5.4.1: Kelvin-Helmholtz Instabilities

Our simulations have shown that Kelvin-Helmholtz instabilities can form between flowing ejecta and underlying regolith under certain conditions. A condition that significantly
affects their formation is the shape of the particles used in our simulations. Our data shows that simulations with non-spherical particles produce significantly larger instabilities and consequently tend to have more significant final topography. Unlike the particles in our simulations real lunar ejecta and regolith is composed of particles of a variety of shapes and a significant range of sizes. Given that a change from spherical to non-spherical particles produces significantly larger Kelvin-Helmholtz instabilities we would expect that ejecta flow composed of the diverse granular material found on the Moon should produce significantly larger instabilities, and likely larger topography as well.

Another factor that plays a significant role in altering the formation of Kelvin-Helmholtz instabilities between the ejecta and regolith is the presence of a pre-existing crater in our simulations. We posit that this effect is responsible for the irregular distribution of CCRs around their host craters. If the ejecta from a crater were landing on and flowing over a uniform plain then one would expect instabilities to form more or less continuously around the crater leaving behind a topography of concentric rings rather than the observed CCR morphologies. Instead pre-existing craters and other small topographic features cause frequent and irregular interruptions in this pattern producing ridges where they might otherwise not exist or inhibiting their formation when they otherwise would.

In our data we have additionally observed that Kelvin-Helmholtz instabilities form better under higher velocity conditions and at low enough velocities do not appear at all. This result is in agreement with observations of the moon that show that CCRs only form around craters that are sufficiently large (around one kilometer in diameter) (Atwood-Stone et al., 2016). Since smaller craters would have lower ejecta velocities our simulations suggest that the instabilities
would not be able to form, which provides a physical reason for the observed lower diameter bound for craters to host CCRs.

5.4.2: Simulated Topography and CCRs

As we have observed the Kelvin-Helmholtz instabilities in our simulations produce a number of topographic features in their end states. Many of these end state topographic features are of relatively low amplitude and are seen throughout our simulation set. We interpret this set of small amplitude features as most probably being the background noise of the simulated system. The features we have described above are those with larger amplitudes and which we thus interpret as being distinct from the background noise. In order to determine whether Kelvin-Helmholtz instabilities are responsible for the production of crater concentric ridges on the Moon we compared the described larger amplitude simulated topographic features to those measured by Atwood-Stone et al. 2016 & 2018. There are inherent limitations in the set-up of our simulations. The first is that the fixed 500 meter periodic length clearly limits the size of features that can be produced by our models. As a result, those simulations where the final topography appears as a single wave-like feature stretching the entire span of the simulation cannot be considered to be accurately sized features as they have taken on the dimensionality of the simulation space, although they do show that large features should be able to be produced by this method. Another inherent limitation of our simulations is the consistency of size and shape of all of our particles, which is quite different from real lunar material, which would exhibit a range of particulate sizes, and shapes. We posit that a more realistic range of simulated particles would be able to produce and maintain more topography. Continued simulations with a range of particle shapes and sizes would test this, but at the expense of significantly greater computing time. With
these caveats in mind, the topography produced in these simulations is qualitatively comparable to the measured topography of CCRs on the Moon.

There are several different observed CCR morphologies (Atwood-Stone et al. 2016, 2018), which we will be relating to those topographic features produced in our simulations [Fig. 1]. The simplest topographic feature observed in our simulations is the solitary ridge, which is directly comparable to those solitary CCRs measured on the moon [Fig 8]. Those ridges produced in our simulations are generally around the size of, or smaller than, the smallest CCRs and tend to have significantly lower slopes. However, as we noted above, the limited size of our simulation clearly limits the size of features that can be produced and particles of uniform shape and size will be less capable of maintaining steep topography. As such, these ridges are reasonable analogs for lunar CCRs. In our simulations we also found short chains of small ridges which are features that appear directly comparable to long, narrow CCRs which appear grouped one after another in the more distal regions of the ejecta blanket around real craters [Fig 9]. The third type of ridge morphology that we described in our simulations is that of an apparent larger ridge with a trough in its center, the same morphology of a large ridge with a shallow central trough is a commonly observed morphology of crater concentric ridges [Fig 10].

In addition to ridges we also observed troughs in the final topographic states of some of our simulations. Around lunar craters with CCRs the most distal portions of the ejecta blanket are characterized by troughs with the same planform morphology as CCRs, which are called crater concentric troughs (CCTs). While CCTs may be able to appear by themselves in the portions of the ejecta blanket furthest from the crater they are most commonly found directly downrange of a crater concentric ridge. These CCTs often appear isolated however detailed examination almost always reveals a small ridge uprange of the ridge (Atwood-Stone et al.,
It is possible that these simulations have a similarly minute and hard to discern uprange ridge. This same morphological association also appears in the topography of some of our simulations with a trough forming just downrange of a small ridge [Fig. 11]. Furthermore in neither our simulations nor real lunar topography are CCRs found downrange of a trough that does not also have a ridge up-range of it. As such the topography and morphologic associations between ridges and troughs in our simulations directly mirrors that measured from real CCRs on the moon.

A final topographic feature that we noted in the simulations designed to approximate the most proximal ejecta was that just past the position of an initial pre-existing crater a ridge would be found on the surface overlying the clear remains of the beginning of a Kelvin-Helmholtz instability. In real crater concentric ridge fields the highest areal density of ridges is found approximately two crater radii from the center of the crater with areal density decreasing outward in the ejecta blanket. However, inwards for a short distance from that two crater radii point, the frequency of ridges drops off sharply but does not immediately go to zero. We propose that the above simulated ridge morphology corresponds to the observed infrequent proximal ridges. This is because in only a relatively few places around an impact site would pre-existing craters of sufficient size exist to form ridges in this manner and that otherwise the ejecta velocities are too slow to form ridges. CCRs become more common past this distance from the crater because pre-existing craters are no longer required for their formation, although they can serve to enhance formation.
5.4.3: Mixing Trends

As we observed before, higher velocities and increased roughness of initial regolith layer are both factors that lead to increased mixing between ejecta and regolith particles in our simulations [Fig. 7]. Both of these results are generally what we would expect in real situations. Firstly, higher velocities of ejecta particles yield increased energy input into the system, which should generally lead to more chaotic and less stratified results. Secondly, the increased formation of Kelvin-Helmholtz instabilities plays a significant role in mixing of regolith and ejecta particles together at the boundary layer. As a result any effect that increases the amplitude of these instabilities (e.g. increased roughness) will increase the size of the mixed boundary layer. Lunar granular material is much more varied in size and shape than the granular material used in our simulations, and contains more pre-existing craters in any given area than we have modeled. Both of these effects should lead to more roughness in the real lunar regolith layer and as such we should expect a higher degree of mixing in real lunar samples than we observe in our simulations. Our simulations should therefore be considered a lower bound for mixing.

The observed mixing in our simulations provides an interesting comparison to the mixing that is observed between ejecta and target material around real craters. We have long known that ejecta does mix with underlying material, a phenomenon that is well studied and measured around Ries crater in Germany, where the mixed layer of ejecta and pre-existing target material is known as the Bunte Breccia (Hörz et al., 1983). This mixing occurs during the impact and outflow of ejecta known as ballistic sedimentation and erosion (Oberbeck, 1975). Our simulations suggest that the formation of Kelvin-Helmholtz instabilities between the ejecta and regolith may be an important factor in generating observed layers of mixed ejecta and regolith like the Bunte Breccia.
5.5: Conclusions

Our simulations of the ejecta environments around craters on the moon consistently show that Kelvin-Helmholtz instabilities are produced at the boundary between impacting ejecta and the regolith. Furthermore, as our simulations were changed to be more representative of lunar conditions (first by using non-spherical particles and then by adding pre-existing craters to the regolith) the formation of these Kelvin-Helmholtz instabilities was enhanced. As such, we conclude that Kelvin-Helmholtz instabilities can form on the Moon as ejecta flows over regolith, and can form the CCR and CCT morphologies observed in the ejecta blankets of craters 2-5 km in diameter.

The suite of topographic features present in the final states of our simulations are all features that are observed around real craters on the Moon as crater concentric ridges. Equally importantly the catalog of morphologic features of CCRs forming in the lunar mare does not include any features that are not present in our simulated topographic results. Although this pair of statements must be taken with the caveat that those features produced in our simulations are generally smaller and have lower slopes than those found in reality due to certain limitations of our system, they still demonstrate that CCR morphology can be created by Kelvin-Helmholtz instabilities. As such we have shown that Kelvin-Helmholtz instabilities forming between ejecta and regolith is a physically viable means of formation for crater concentric ridges on the moon.
5.6: Figures & Tables

**Figure 5.1:** Crater Concentric Ridges. A) The north-east quadrant of Linné crater’s ejecta blanket shown with LROC NAC images. In these images we see CCRs distributed around the crater. B) A 3D representation of a CCR from the ejecta blanket of Linné. This image is made from an artificial hillshade draped over topography taken from an LROC NAC DTM. This image has 5x vertical exaggeration and the crater is to the left of the ridge in this orientation. C) A progression of CCR morphologies shown via images taken from the ejecta blanket of Piton B related to the approximate distance those morphologies appear from the crater. Images are rotated so the crater is to the left and scale bars are all 100 meters. Fig. 1C is from Atwood-Stone et al, 2016.
Figure 5.2: Velocity and ejecta depth effects on Kelvin-Helmholtz Instabilities. All simulations are models from Linné at the same early timestep. A) is 4 Cr from the crater with thick ejecta. B) is 2 Cr from the crater with thick ejecta. C) is 4 Cr from the crater with thin ejecta. D) is 2 Cr from the crater with thin ejecta. As we can see those models with thicker ejecta or further from the crater (and thus with higher velocity ejecta) have higher amplitude Kelvin-Helmholtz instabilities. For these graphs (and all future figures of this style) the red particles are the regolith, the blue particles are the ejecta, there is a 3x vertical exaggeration and the axes are in units of meters.
Figure 5.3: Kelvin-Helmholtz instabilities between simulated ejecta and regolith. These model frames are taken from the same early timestep of simulations modeling conditions 3.5 crater radii from Linné using A) spheres, B) non-spherical particles and C) with a pre-existing regolith crater. In A) we see that the instabilities are relatively small and form low angle diagonal spikes. We also note that the regolith is significantly thicker than for the non-spherical particles – this is because while all simulations have the same number of spherical particles, in constructing the L-shaped particles those spheres overlap, yielding a thinner layer. In B) there are few larger instabilities that are at higher angles and roll over. In C) most of the instabilities appear the same as in B) except that the one second from the right which is both taller and wider, this is the ridge whose formation started at the pre-existing crater.
**Figure 5.4:** Ridges in final topography. A) Shows a 4 meter tall and over 100 meter wide ridge. This simulation is modeling conditions 2.5 crater radii from Piton B with L-shaped particles. B) shows a row of two 4 meter high 50 meter wide ridges, with some smaller ridges lined up to the right. This simulation is modeling conditions 3.5 crater radii from Linné with a pre-existing regolith crater. C) shows a ridge roughly 80 meters wide and 4 meters tall with a 2 meter deep trough in the middle. This simulation models conditions 1.5 crater radii from Liebig J with L-shaped particles.
Figure 5.5: Troughs in final topography. A) shows a 300 meter wide 4 meter deep trough with no associated ridge. This simulation is modeling conditions 4 crater radii from Piton B with a pre-existing regolith crater. B) shows a 100 meter wide 4 meter deep trough with a small ridge immediately to its left. This simulation is modeling conditions 2.5 crater radii from Linné with a pre-existing regolith crater.
Figure 5.6: Additional simulated topographic features. Both (A) and (B) show single sine wave-like ridges stretching the full width of the simulation. A) is modeling conditions 4 crater radii from Liebig J with L-shaped particles. B) is modeling conditions 4 crater radii from Linné with spherical particles. This simulation shows by far the most vertical relief of any of the spherical particle simulations we ran. C) shows a small ridge forming over the remnants of the Kelvin-Helmholtz instability that formed starting at the pre-existing crater, which is still visible in the regolith layer. This simulation is modeling conditions 1.5 crater radii from Piton B with a pre-existing regolith crater.
Figure 5.7: Degree of mixing between ejecta and regolith in our simulations. This graph shows the mixing index for all of our simulations organized by crater name and simulation type, and graphs that mixing against the distance from the crater.
**Figure 5.8:** Ridge morphology in simulations and topography. A) shows the same simulated ridge as in Fig 4A. B) shows topography from a ridge in the ejecta blanket of Linné with 3x vertical exaggeration to match the simulation. These features, although not exactly the same size, have very similar morphologies – suggesting that they may be formed similarly. C) is a shaded relief image of the ridge whose topography is shown in (B) and the line through the image is where the profile in (B) was taken.
Figure 5.9: Row of ridges morphology in simulations and topography. A) shows the same simulated row of ridges as in Fig 4B. B) shows topography from a row of ridges in the ejecta blanket of Piton B with 3x vertical exaggeration to match the simulation. These features, although not exactly the same size, have very similar morphologies – suggesting that they may be formed similarly. C) is a shaded relief image of the double ridge whose topography is shown in (B) and the line through the image is where the profile in (B) was taken. While often the rows of ridges are longer and more sinuous we could not show a good example of that here as this morphology tends to further from the ejecta blanket and the narrow DTM strips at Piton B and Linné do not happen to include any good examples.
Figure 5.10: Double ridge morphology in simulations and topography. A) shows the same simulated double ridge (or ridge with a trough in the middle) as in Fig 4C. B) shows topography from a double ridge in the ejecta blanket of Piton B with 3x vertical exaggeration to match the simulation. These features, although not exactly the same size, have very similar morphologies – suggesting that they may be formed similarly. C) is a shaded relief image of the double ridge whose topography is shown in (B) and the line through the image is where the profile in (B) was taken.
Figure 5.11: Ridge and trough morphology in simulations and topography. A) shows the same simulated ridge and trough as in Fig 5B. B) shows topography from a ridge and trough pair in the ejecta blanket of Piton B with 3x vertical exaggeration to match the simulation. These features, although not exactly the same size, have very similar morphologies – suggesting that they may be formed similarly. C) is a shaded relief image of the ridge and trough whose topography is shown in (B) and the line through the image is where the profile in (B) was taken.
Table 5.1: Values used in creating simulations. This set of values was used for the sphere, L-shaped particle and pre-existing crater simulations. In all simulations particles are one meter in radius, the regolith contains 26337 particles, and gravity is lunar surface gravity. Those simulations with a pre-existing crater actually have 204 fewer regolith particles as these were removed to make the simulated crater.

<table>
<thead>
<tr>
<th>Crater Simulated by Model</th>
<th>Modeled distance from crater center (C)</th>
<th>Initial X Velocity (m/s)</th>
<th>Y Velocity when ejecta impacts (m/s)</th>
<th>Duration of Impact (s)</th>
<th>Height of highest ejecta particle above regolith layer (m)</th>
<th>Fraction of ejecta particles compared to regolith particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linné</td>
<td>1.5</td>
<td>11.16</td>
<td>9.93</td>
<td>7.12</td>
<td>55.33</td>
<td>1/5</td>
</tr>
<tr>
<td>Linné</td>
<td>2.0</td>
<td>21.63</td>
<td>19.84</td>
<td>5.80</td>
<td>108.24</td>
<td>1/5</td>
</tr>
<tr>
<td>Linné</td>
<td>2.5</td>
<td>34.27</td>
<td>32.13</td>
<td>4.96</td>
<td>157.15</td>
<td>1/5</td>
</tr>
<tr>
<td>Linné</td>
<td>3.0</td>
<td>49.03</td>
<td>46.77</td>
<td>4.37</td>
<td>204.91</td>
<td>1/5</td>
</tr>
<tr>
<td>Linné</td>
<td>3.5</td>
<td>66.47</td>
<td>64.33</td>
<td>3.91</td>
<td>254.12</td>
<td>1/5</td>
</tr>
<tr>
<td>Linné</td>
<td>4.0</td>
<td>85.33</td>
<td>83.54</td>
<td>3.57</td>
<td>301.75</td>
<td>1/5</td>
</tr>
<tr>
<td>Linné</td>
<td>1.5</td>
<td>15.79</td>
<td>14.04</td>
<td>7.12</td>
<td>84.62</td>
<td>2/5</td>
</tr>
<tr>
<td>Linné</td>
<td>2.0</td>
<td>30.59</td>
<td>28.05</td>
<td>5.80</td>
<td>155.90</td>
<td>2/5</td>
</tr>
<tr>
<td>Linné</td>
<td>2.5</td>
<td>48.46</td>
<td>45.44</td>
<td>4.96</td>
<td>223.20</td>
<td>2/5</td>
</tr>
<tr>
<td>Linné</td>
<td>3.0</td>
<td>69.34</td>
<td>66.14</td>
<td>4.37</td>
<td>289.60</td>
<td>2/5</td>
</tr>
<tr>
<td>Linné</td>
<td>3.5</td>
<td>94.01</td>
<td>90.97</td>
<td>3.91</td>
<td>358.41</td>
<td>2/5</td>
</tr>
<tr>
<td>Linné</td>
<td>4.0</td>
<td>128.08</td>
<td>118.14</td>
<td>3.57</td>
<td>425.23</td>
<td>2/5</td>
</tr>
<tr>
<td>Linné</td>
<td>1.5</td>
<td>19.33</td>
<td>17.19</td>
<td>7.12</td>
<td>107.09</td>
<td>3/5</td>
</tr>
<tr>
<td>Linné</td>
<td>2.0</td>
<td>37.46</td>
<td>34.36</td>
<td>5.80</td>
<td>192.47</td>
<td>3/5</td>
</tr>
<tr>
<td>Linné</td>
<td>2.5</td>
<td>59.36</td>
<td>55.66</td>
<td>4.96</td>
<td>273.89</td>
<td>3/5</td>
</tr>
<tr>
<td>Linné</td>
<td>3.0</td>
<td>84.92</td>
<td>81.01</td>
<td>4.37</td>
<td>354.59</td>
<td>3/5</td>
</tr>
<tr>
<td>Linné</td>
<td>3.5</td>
<td>115.14</td>
<td>111.42</td>
<td>3.91</td>
<td>438.43</td>
<td>3/5</td>
</tr>
<tr>
<td>Linné</td>
<td>4.0</td>
<td>147.80</td>
<td>144.69</td>
<td>3.57</td>
<td>519.98</td>
<td>3/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>1.5</td>
<td>11.56</td>
<td>10.13</td>
<td>10.67</td>
<td>61.12</td>
<td>1/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>2.0</td>
<td>23.27</td>
<td>21.19</td>
<td>8.31</td>
<td>151.53</td>
<td>1/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>2.5</td>
<td>37.81</td>
<td>35.34</td>
<td>6.93</td>
<td>230.77</td>
<td>1/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>3.0</td>
<td>55.07</td>
<td>52.49</td>
<td>6.00</td>
<td>306.77</td>
<td>1/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>3.5</td>
<td>75.21</td>
<td>72.83</td>
<td>5.31</td>
<td>382.78</td>
<td>1/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>4.0</td>
<td>98.17</td>
<td>96.31</td>
<td>4.79</td>
<td>459.51</td>
<td>1/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>1.5</td>
<td>16.35</td>
<td>14.32</td>
<td>10.67</td>
<td>105.88</td>
<td>2/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>2.0</td>
<td>32.90</td>
<td>29.97</td>
<td>8.31</td>
<td>224.45</td>
<td>2/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>2.5</td>
<td>53.46</td>
<td>49.98</td>
<td>6.93</td>
<td>332.15</td>
<td>2/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>3.0</td>
<td>77.88</td>
<td>74.24</td>
<td>6.00</td>
<td>437.14</td>
<td>2/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>3.5</td>
<td>106.36</td>
<td>102.99</td>
<td>5.31</td>
<td>543.04</td>
<td>2/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>4.0</td>
<td>138.83</td>
<td>136.20</td>
<td>4.79</td>
<td>650.44</td>
<td>2/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>1.5</td>
<td>20.02</td>
<td>17.54</td>
<td>10.67</td>
<td>140.22</td>
<td>3/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>2.0</td>
<td>40.30</td>
<td>36.70</td>
<td>8.31</td>
<td>280.41</td>
<td>3/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>2.5</td>
<td>65.48</td>
<td>61.21</td>
<td>6.93</td>
<td>409.94</td>
<td>3/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>3.0</td>
<td>95.38</td>
<td>90.92</td>
<td>6.00</td>
<td>537.17</td>
<td>3/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>3.5</td>
<td>130.26</td>
<td>126.14</td>
<td>5.31</td>
<td>666.01</td>
<td>3/5</td>
</tr>
<tr>
<td>Piton B</td>
<td>4.0</td>
<td>170.03</td>
<td>166.81</td>
<td>4.79</td>
<td>796.95</td>
<td>3/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>1.5</td>
<td>11.37</td>
<td>10.00</td>
<td>9.28</td>
<td>59.75</td>
<td>1/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>2.0</td>
<td>22.44</td>
<td>20.46</td>
<td>7.35</td>
<td>133.36</td>
<td>1/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>2.5</td>
<td>36.23</td>
<td>33.87</td>
<td>6.17</td>
<td>200.01</td>
<td>1/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>3.0</td>
<td>52.64</td>
<td>50.16</td>
<td>5.37</td>
<td>264.73</td>
<td>1/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>3.5</td>
<td>71.64</td>
<td>69.32</td>
<td>4.77</td>
<td>329.33</td>
<td>1/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>4.0</td>
<td>93.12</td>
<td>91.24</td>
<td>4.31</td>
<td>394.19</td>
<td>1/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>1.5</td>
<td>16.08</td>
<td>14.14</td>
<td>9.28</td>
<td>98.19</td>
<td>2/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>2.0</td>
<td>31.74</td>
<td>28.94</td>
<td>7.35</td>
<td>195.65</td>
<td>2/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>2.5</td>
<td>51.24</td>
<td>47.90</td>
<td>6.17</td>
<td>286.60</td>
<td>2/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>3.0</td>
<td>74.44</td>
<td>70.93</td>
<td>5.37</td>
<td>376.20</td>
<td>2/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>3.5</td>
<td>101.32</td>
<td>98.03</td>
<td>4.77</td>
<td>466.31</td>
<td>2/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>4.0</td>
<td>131.69</td>
<td>129.03</td>
<td>4.31</td>
<td>557.18</td>
<td>2/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>1.5</td>
<td>19.69</td>
<td>17.32</td>
<td>9.28</td>
<td>127.70</td>
<td>3/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>2.0</td>
<td>38.87</td>
<td>35.44</td>
<td>7.35</td>
<td>243.44</td>
<td>3/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>2.5</td>
<td>62.75</td>
<td>58.67</td>
<td>6.17</td>
<td>353.04</td>
<td>3/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>3.0</td>
<td>91.17</td>
<td>86.87</td>
<td>5.37</td>
<td>461.74</td>
<td>3/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>3.5</td>
<td>124.09</td>
<td>120.06</td>
<td>4.77</td>
<td>571.42</td>
<td>3/5</td>
</tr>
<tr>
<td>Liebig J</td>
<td>4.0</td>
<td>161.28</td>
<td>158.03</td>
<td>4.31</td>
<td>682.24</td>
<td>3/5</td>
</tr>
</tbody>
</table>
Chapter 6: Conclusions & Future Work

6.1: Conclusions

In the course of this work I have used the topography of Martian sand dunes to demonstrate that the granular angle of repose does not depend on gravitational acceleration. Further, I have used high resolution LROC NAC imagery to significantly expand our knowledge of the morphology of Crater Concentric Ridges (CCRs) and the circumstances under which they form. Additionally, I have produced a catalog of 77 lunar craters with CCRs when only a few were known before and have also found these features on Mercury using MESSENGER data. Using DTMs I have further been able to characterize the topography of these ejecta features. Using this high-resolution observational data I have disproved the old ballistic sedimentation and erosion hypothesis for their formation by showing that certain features of CCRs, specifically their downrange troughs, do not appear as would be predicted by this hypothesis. Additionally my observational data contradicts the possibility that CCRs form as the build-up of ejecta against pre-existing topography by showing that these ridges form in locations where pre-existing topography would not have been available to create them. Furthermore the absence of CCRs in the exclusion zone of Encke X, despite the well-formed pattern of them found on either side of this zone clearly demonstrates that any hypotheses not involving the impacting and flowing ejects are not viable.

Using discrete element modeling I have simulated the flow of crater ejecta over regolith in order to understand how these features do form. From the results of my simulations I have posited and supported the hypothesis that CCRs are formed as a result of Kelvin-Helmholtz instabilities forming between the ejecta and regolith. In addition our simulations also show a
lack of evidence that would support a previous hypothesis that CCRs might have formed in a manner analogous to anti-dunes. While the current results are promising they are not from exhaustive tests and I would hope to expand these results in the future.

6.2: Future Work

When creating simulations to this point I have been able to test the topographic profiles of real CCRs against simulated results, but at this time it has not been possible to fully consider their complex planform morphologies due to the narrow simulation widths that I accepted in order to reduce processor time. Thus, it would be very useful to run simulations with parameters already shown to produce significant topographic results in a much wider simulation space to see if ridges that curve and intersected with each other, like CCRs on the moon, can be created.

Another aspect of CCRs that I was not able to test was the different ways that they form on pre-existing uphill and downhill slopes, which would be essential to the understanding of formation of CCRs in the lunar highlands. I have not created simulations with these slopes because the periodic nature of our boundary conditions, adopted to ensure continuing ejecta flow in a relatively small simulation does not allow for a vertical discontinuity between one boundary and the other. In order to test formation on these up- and downhill slopes I would want to run simulations with a significantly longer phase space in the x direction which would allow for a significant pre-existing hill in the regolith layer while still having the initial height of the regolith layer at either periodic boundary be the same.

In addition, the exponential decrease in areal density of CCRs moving away from the host crater would be a very instructive aspect of CCRs to test with simulations. In order to do this I would need a very large simulation space representing the entire length of a slice of the
crater’s ejecta blanket with continuously variable ejecta fluxes and velocities. This type of simulation would be very processor intensive, but if feasible would be an even better way of testing CCR formation on up and down hill slopes as periodic boundaries would not be required.

I would also be interested in examining how CCRs form over a regolith with a more realistic distribution of pre-existing impact craters. In order to do this I can take the topography from an LROC-NAC DTM of a relatively uninteresting region of the lunar mare and mold our granular regolith layer to match that topography. If the above extended simulations yield results matching topographic CCR data from the moon this will provide strong support for the conclusion that CCRs are formed via Kelvin-Helmholtz instabilities. On the other hand if these results do not match observational lunar data they will hopefully provide clues to other formation hypotheses to consider.

6.3: Future Application

Crater Concentric Ridges are far from the only type of ejecta morphology, even on the Moon, and I believe many of the other classes of ejecta morphologies could be profitably studied with these same simulation techniques. Ejecta facies on the Moon are observed change type for different sizes of craters. Around craters in the 20 to 200km diameter range a series of facies grading from concentric hummocky ridges and troughs close to the crater to features similar to CCRs to radial ridges (Melosh, 1989). Using simulation parameters calculated to match the ejecta of larger craters the formation of these topographic features can hopefully be simulated and examined. It would be especially interesting to determine if the middle distance ejecta facies for these larger craters is in fact causally related to CCRs. One alteration that will have to be made to the simulations in order to examine the distal radial ridge facies will be to use a much
wider phase space in the simulations as evidence of radial ridges would not be apparent in a narrow simulation space.

On Mars the presence of a thin atmosphere, volatiles, and subsurface ice are responsible for an entirely different set of facies than those known on airless bodies like the Moon. These facies often described as forming as a result of fluidized ejecta include rampart craters (Wohletz & Sheridan, 1983), double-layer ejecta (Weiss & Head, 2013), and multi layer ejecta (Vijayan et al., 2014). The FDEM code that I have been using in this work can be tuned to include an atmosphere and interstitial fluids between the particles which should allow this environment to be simulated. Models could then be run using parameters for the ejecta of relevant Martian craters and tuning the values of the interstitial fluid to evaluate hypotheses for these different Martian ejecta facies.
References


