IMPACT IMPACTS ON THE MOON, MERCURY, AND EUROPA

A dissertation submitted to the graduate division of the University of Hawai'i at Mānoa in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

 in

GEOLOGY AND GEOPHYSICS

March 2020

By Emily S. Costello

Dissertation Committee:

Paul G. Lucey, Chairperson S. Fagents B. Smith-Konter N. Frazer P. Gorham

© Copyright 2020 by Emily S. Costello All Rights Reserved This dissertation is dedicated to the Moon, who has fascinated our species for millennia and fascinates us still.

Acknowledgements

I wish to thank my family, who have loved and nourished me, and Dr. Rebecca Ghent for opening the door to planetary science to me, for teaching me courage and strength through example, and for being a true friend. I wish to thank my advisor, Dr. Paul Lucey for mentoring me in the art of concrete impressionism. I could not have hoped for a more inspiring mentor. I finally extend my heartfelt thanks to Dr. Michael Brodie, who erased the line between "great scientist" and "great artist" that day in front of a room full of humanities students - erasing, in my mind, the barrier between myself and the beauty of physics.

Abstract

In this work, I reconstitute and improve upon an Apollo-era statistical model of impact gardening (Gault et al. 1974) and validate the model against the gardening implied by remote sensing and analysis of Apollo cores. My major contribution is the modeling and analysis of the influence of secondary crater-forming impacts, which dominate impact gardening. Secondary craters are formed when debris that has been launched by the collision of an object from space with the surface of a body falls back onto the surface with sufficient energy to produce a crater. Interest in secondary craters and their importance in the evolution of the surfaces of Solar System bodies was re-inspired by a study of the secondary craters of Mars' Zunil crater (McEwen et al. 2005), which shocked many in the cratering community for being so large, far-flung, and numerous. Similarly, studies of Jupiter's icy moon Europa's surface showed that most craters that are < 1 km in diameter are secondary craters (Birehaus et al. 2001; 2005). Secondary impacts appear to be significant drivers of changes at the uppermost surface on bodies across the solar system. I apply my model of impact gardening due to secondary impacts to explore the implications of impact gardening on the Moon, Mercury, and Europa, with a specific interest in the implications of impact gardening on the distribution and evolution of water ice resources in the solar system.

Table of Contents

Acknow	ledgeme	ents	iv
Abstrac	t		v
List of 7	Fables .	· · · · · · · · · · · · · · · · · · ·	iii
List of I	Figures		ix
Chapter	1: Intr	oduction	1
Chapter	2: The	mixing of lunar regolith: Vital updates to a canonical model \ldots .	15
2.1	Introdu	uction	16
2.2	Model		18
	2.2.1	The Poisson Expression	18
	2.2.2	Flux and Crater Scaling	26
	2.2.3	Overturn as a Function of Time	28
	2.2.4	Production Functions	34
2.3	Overtu	rn: The Lunar Case	35
	2.3.1	Lunar Primaries	37
	2.3.2	Lunar Secondaries	41
	2.3.3	Validating Overturn Calculations	15
	2.3.4	Lunar Micrometeorites	51
2.4	Conclu	sions	55
Chapter	·3: Imp	act gardening as a constraint on the age, source, and evolution of ice	
on M	ercury a	and the Moon	75

3.1	Introduction		
3.2	Gardening Model: Updates to the treatment of cumulative craters		78
3.3	Valida	tion: Gardening regolith on the Moon	88
	3.3.1	Validation of the secondary crater production function	88
	3.3.2	Validation of gardening model	88
	3.3.3	The timescale for validity of the Poisson model for secondaries	92
3.4	Result	s	94
	3.4.1	Gardening ice and regolith on the Moon and Mercury	94
	3.4.2	The ancient lunar flux and regolith thickness as a constraint on	
		primordial ice.	97
3.5	Discus	sion \ldots	101
	3.5.1	The age of ice deposits on Mercury.	101
	3.5.2	The sources of water delivered to the Moon and Mercury	105
	3.5.3	Ice on the Moon	107
3.6	Conclu	usions	112
Chapter	:4: The	e Formation and Gardening of Europa's "Regopag"	128
4.1	Introd	uction	129
4.2	2 Methods		131
	4.2.1	Modeling the production of icy regolith or "regopag." \ldots	131
	4.2.2	Modeling impact gardening	133
	4.2.3	Modeling secondary impacts	133
	4.2.4	The impact rate at Europa	135
4.3	Result	s	138
4.4	Discus	sion \ldots	138
	4.4.1	The depth profile of irradiated material	138
	4.4.2	Lateral transport and regolith/regopag depth	141
	4.4.3	Gardening crater rays and plume deposits.	142

4	.4.4	The thermal and radiation process that make regopag distinct from	
		silicate regolith	4
4.5 C	Conclu	sions	6
Chapter 5	: Con	clusion $\ldots \ldots 15$	53

List of Tables

2.1	Values for λ from solutions to the cumulative Poisson equation at 10, 50, and	
	99% probability.	60
2.2	A list of parameters and definitions used to convert impactor size to crater	
	size	61
2.3	Equations used with equation numbers and descriptions	62
3.1	Impactor size to crater size scaling parameters parameters from material	
	published online by Holsapple (2003) and from Table 1 in Williams et al.	
	(2014), which supersede the values in Table 1 of Holsapple (1993). * The	
	impactor density for rocky secondaries, following Costello et al., (2018). **	
	The impactor density for icy secondaries.	87
3.2	Overturn depths are calculated using Equation (8) for $n \ge 1$ overturns at	
	99% probability and using the material properties listed in Table 3.1 and in	
	hard ice given rocky and icy secondary impactors.	97
4.1	A preliminary summary of the depth of influence and timescale for different	
	impact, radiation, and thermal processes on Europa that includes the results	
	of this work	145

List of Figures

1.1	On the left is a scanning electron microscope image of a crater that is only	
	microns in diameter discovered on a grain of lunar regolith (from Heiken et	
	al. 2012 p. 304). On the right, we see Eratosthenes crater and the curvature	
	of the Moon (Apollo 17 Crew, NASA). The craters share a strikingly similar	
	morphology despite the orders of magnitude that separate them in size and	
	imply similar orders of magnitude in the size range of objects striking the	
	Moon	1
1.2	Apollo 12 astronaut Alan Bean leaves footprints in the fluffy impact-	
	generated lunar regolith as he takes a drill tube core sample (AS12-49-7243).	3
1.3	Apollo 16 deep drill core 60009 with a gradient from dark, space weathered	
	regolith to light, pristine regolith with depth. Impact gardening churns	
	surface material to depth and material that was at depth to the surface	4
2.1	The geometry underpinning the Poisson expression	19
2.2	In this work and the model presented by Gault et al. (1974), the fate of	
	material experiencing an impact is simplified by the assumption that the	
	truncated volume of a transient crater volume is overturned as shown. Distal	
	craters of diameter D_c must impact some fraction of a crater diameter c away	
	from surface point Q in order to overturn subsurface point U	20

- 2.3 Craters that form on the perimeter of the shaded area must have a diameter D_c or greater to disturb point Q. Craters larger than Dc can strike beyond the shaded region and still disturb point U. Thus, the cumulative distribution of all craters of diameter D_c to $D_{MAX} \gg D_c$ will contribute to overturn. . . 23
- 2.4 The Neukum production function, Hartman production function and Equation 2.42 are generally in good agreement at the lower limit of validity, on the order of 100m craters. We may be overestimating the number of 200 m to 1 km diameter craters and underestimating the number of craters larger than 1km. We use the coefficients reported by Ivanov et al. (1999, 2001) to calculate the Neukum production function. We calculate Equation 2.42 using the lunar regolith values in Appendix Table 2 and the flux values reported by Brown et al. (2002).

2.8 Overturn calculations for at least one overturn event at 50 and 99% probability. Our results with primaries only predict overturn that is similar to the overturn predicted by Gault et al. (1974); however, the inclusion of secondaries increases the rate of overturn by several orders of magnitude. 44

2.10 We compare the mixing rates calculated by this model at 50% and 99% probability to the reworking rate presented by Morris (1978) and Blanford et al. (1980). Gault et al. (1974) and our calculations using only the flux of primary impactors show mixing that is too shallow at all timescales. Mixing due to secondaries is much more intense. We see 300 to 10,000 overturn events occurring at depths and over timescales consistent with the reworking calculated form the Apollo cores. The statistics of this model suggest that any specific core that shows evidence of 15 cm overturn is highly unlikely to be due to a primary and that the depth profile of any surface-correlated material in the top meter of regolith is dominantly controlled by overturn due to secondary impacts.

48

50

- 2.11 The mixing due to secondaries calculated by this model is consistent with the thorough reworking of the top 3 cm of regolith reasoned by Speyerer et al. (2016) from observations of splotches in LROC temporal pairs, the elimination of 20cm deep cold spots over one to two hundred thousand years, and the erasure of 1 m deep rays over about a billion years. Note that as the number of overturn events increases, the difference between 50 and 99% probability shrinks. At 10,000 overturn events, the difference is negligible.

53

- 2.14 a) Overturn driven by both the small meteorite flux described by Grün et al. (1985) and the flux of larger meteorites described by Brown et al. (2002) and a comparison to the reworking calculated by Morris (1978) and Blanford et al. (1980). b) A comparison of the Brown et al (2002) flux, Grün et al. (1985) flux, and the best fit we calculated for the Grün et al. (1985) flux (Equation 2.61). The best fit we calculated for the Grün et al. (1985) data begins to differ significantly from the Grün et al. (1985) lunar flux model at meteorite diameters of about 1 mm. That is overturn at about 1cm. As meteorites increase in size, the flux model dips towards an agreement with Brown et al. (2002). Even with significantly higher overturn due to small meteorites in the top 1 cm of regolith, overturn calculations that only consider the impact of primaries fail to describe the reworking depth and rate calculated from Apollo cores.
- 3.1 The geometry of the model following Figure 2 of Costello et al., (2018). The scaling value h is the fraction of the crater diameter, D_c , that has been excavated by a cratering event. The scaling value c is controlled by the shape of the crater bowl and describes the distance at which a crater must strike (in terms of crater diameter) in order to overturn a point at depth. 84

3.2	Craters that are larger than diameter D also affect a surface point following	
	Figure 3 of Costello et al. (2018)	85

3.4 All overturn contours plotted here represent the deepest depth overturned at least one time over the time interval on the x-axis with 99% probability. The model results using the size frequency distribution of small albedo anomalies observed in LROC temporal pairs (Speyerer et al., 2016) (solid black line) fits exceedingly well against the reworking of surface-correlated space weathering products in the top meter of regolith calculated from Apollo cores by Morris 1978 and Blanford et al., (1980) and our model results using assumptions about the production of secondary impacts. The model results using a secondary impact flux derived from the Brown et al., (2002) flux of primary impacts fits both the LROC reworking rate and the reworking observed in Apollo cores. Compared to the results of Costello et al., (2018) (grey dot-dashed line plotted following the results shown in Figure 4 of Costello et al., (2018)), the updates to the model decrease the rate of overturn at small scales by changing the magnitude and power law slope of the overturn function. 92

- The results of Morris et al. (1978) and Blanford et al. (1980) represent 3.5the reworking depth generally; however, the effects of reworking observed in Apollo cores is variable. a) We capture the stochasticity of gardening by varying the model with probability. At various probabilities, our model is consistent with the reworking demonstrated by the work from Morris (1978) and Blanford et al., (1980), the reported 2 to 3 cm of gardening in 80,000 years from Speyerer et al., (2016) based on observations of the size-frequency of albedo anomalous splotches, the homogenization of Al^26 in the top few centimeters of regolith over timescales less than 1 Myr (Fruchter et al. 1976; 1977; 1978), the results of Nishizumi et al. (2019), who found an event 50 kyr ago overturned about 25 cm of material in Apollo 17 string drill tube 7002-7009, the fading of themophysical anomalies dubbed "cold spots" observed in LRO Diviner data extend to the sensing limit of the diurnal skin depth (20 cm) and are no older than about 1 Myr (Williams et al., 2018). b) The data presented by Morris represents the "in situ reworking depth", which describes the depth that has seen the surface at least one time over some time interval. Our model results match the Morris (1978) and Blanford et al. (1980) in situ reworking rates, predicting between one and one hundred overturns have excavated material to the depth and over the timescale.
- 95

3.6 Gardening due to secondary impacts on the Moon in ice and in regolith shown in "cores" that have dimensions of depth and probability. Contours are calculated by solving the cumulative Poisson equation (Equation 2) for various probabilities and inputting the appropriate λ into Equation 13. We do not include calculations below our reasonable timescale limit of 100 kyr. For our calculation of gardening in an icy target (a, b and c) we show a region where the true in situ reworking depth likely exists, driven by both icy (solid line) and rocky (dotted line) secondary crater-forming impactors.

- 3.8 Impact gardening on the Moon and Mercury and regolith and ice due to icy and rocky secondary impactors. Gardening is more efficient on the Moon than Mercury at the depth scale analyzed here (< 10 m), and gardening is more efficient in ice than in regolith on both planetary bodies. 100

- 3.10 The depth of an ice deposit in the absence of losses or transport after deposition if it were supplied at the rate calculated by Moses et al., (1999) and impact overturn depth contours for impact gardening in regolith and in hard ice due to icy and rocky secondary impactors on Mercury (Equations 16 and 18). Gardening mixes incrementally built-up deposits formed from continuous sources faster that they are supplied. 108

- 4.2 Illustration of the regopag thickness model. We calculate the total volume excavated by craters and set that volume equal to the volume of a thin spherical shell. The thickness of the spherical shell is the reported regopag thickness.
- 4.3 The crater production rate on Europa. The vertical error in the our plot of the Bierhaus et al. crater count data, which is considered complete down to 200 m craters, comes from assumptions about the surface age. We calculate fits to the cratering rate implied by the Bierhaus et al. crater count data for surface ages of 1 Myr (the minimum time it would take for tectonic features to have formed: Howell et al 2018), 10 Myr, and 200 Myr. The models of crater production do not suffer the same uncertainty in age scaling predicting some number of craters form per annum based on the number and scale of impacts per annum. Our models for the number of secondaries produced by both the Case A and Case B primary impact flux fit the cratering rate implied by the Bierhaus crater counts for surface ages between 10 and 200 Myr. 137

4.5	We calculate the impact gardening rate on Europa at 50% probability using	
	the cratering rate implied by the Bierhaus et al. crater counts and our	
	modeled secondary impact cratering rates. We predict the impact gardening	
	zone extends to 10 to 50 cm depth	140
4.6	The probability distribution of gardening with depth.	140

Chapter 1

Introduction



Figure 1.1 On the left is a scanning electron microscope image of a crater that is only microns in diameter discovered on a grain of lunar regolith (from Heiken et al. 2012 p. 304). On the right, we see Eratosthenes crater and the curvature of the Moon (Apollo 17 Crew, NASA). The craters share a strikingly similar morphology despite the orders of magnitude that separate them in size and imply similar orders of magnitude in the size range of objects striking the Moon.

Objects over twelve orders of magnitude in size encounter the Earth and Moon during their orbit around the Sun. Evidence of these encounters is written in craters, which despite the orders of magnitude that separate their size, maintain a strikingly similar morphology. Craters that are microns across that have been discovered in individual grains of soil returned from the Moon (Figure 1.1, left) share a similar shape to the craters we can see through binoculars when we look up at our nearest celestial neighbor on a clear night (1.1, right). The Earth's atmosphere and active surface have prevented the formation of some craters (as objects burn up on entry) and erased much of the record of impacts over geologic time; however, the Moon has no atmospheric shield and its surface is shaped primarily by impacts. Over billions of years, impacts have pulverized rock and blanketed the surface of the Moon in fine-grained regolith. When Apollo astronauts walked on the surface of the Moon, their boots made prints in the regolith (e.g. Figure 1.2), showing its unique fluffy texture.

After regolith has formed, subsequent impacts churn buried regolith to the surface and surface regolith to depth in a processes called "impact gardening." Evidence of impact gardening is visible in cores returned by the Apollo program, where a gradient of dark, space weathered regolith, transitions into bright unweathered regolith with increasing depth (e.g. Figure 1.3).Unfortunately, models for the depth and effects of impact gardening on the lunar regolith under-predict the effects visible in the Apollo cores by several orders of magnitude, with particular severity at < 10 cm depth scales and < 1 Myr timescales (Gault et al. 1974; Arnold 1975). Further contradicting the models, before-and-after images returned by the Lunar Reconnaissance Orbiter Narrow Angle Camera (LRO NAC) over its decade-long mission show an accumulation of meter-scale albedo anomalies that have been interpreted to be the result of small impacts, which garden the top few centimeters of lunar regolith globally over 100 kyr timescales.

Impact gardening is the process by which impacts redistribute surface material, removing material from depth and re-depositing it near the surface. Gardening is also called "mixing" or "overturn" (e.g. Gault et al. 1974, Arnold 1975) that complicates what might be an otherwise distinct stratigraphic arrangement of materials with depth by repeatedly and stochastically inverting the depth-distribution of materials. Gault et al. (1974) presented a pioneering regolith mixing model predicated on the assumption that impact flux is a probabilistic process that obeys the Poisson distribution (Gault et al. 1972; Gault et al. 1974). In Gault et al. (1974), regolith overturn is defined to occur when a point at depth has been influenced by an impact event (Figure 1). Their model mathematically describes the frequency with which material at that depth is affected by an impact, and transported



Figure 1.2 Apollo 12 astronaut Alan Bean leaves footprints in the fluffy impact-generated lunar regolith as he takes a drill tube core sample (AS12-49-7243).



Figure 1.3 Apollo 16 deep drill core 60009 with a gradient from dark, space weathered regolith to light, pristine regolith with depth. Impact gardening churns surface material to depth and material that was at depth to the surface.

from depth to the near-surface. The success rate of overturning events is presented by Gault et al. as a function of input parameters: time, impact flux, and crater scaling. These parameters, together with a statistical method based on Poisson law and the stochastic impact flux describe the rate and probability of overturn at depth as a function of time.

The Gault et al. (1974) model has had significant and ongoing influence on the the understanding and impact of planetary regoliths (Arnold 1975; Spencer, 1987; Harmon 2001; Schorghofer et al. 2016a; Hirabayashi et al. 2016; Huang et al. 2017) and analyses of the reworking depth of surface exposure effects in Apollo cores (Morris 1978, Blanford et al. 1980). However, key model parameters such as impact flux and the relationship between crater size and meteorite and target material properties have not been updated since the 1974 study, nor has the model been customized to objects other than the Moon. Building on the legacy of the Gault et al. (1974) model, we have reproduced the probabilistic approach of Gault et al. 1974 and built on the model, extending its inputs to include newer data and generalizing the target and impactor properties. We used the updated model to describe gardening on the Moon and demonstrated its use with updated input values and cratering efficiency laws and validating the results (Costello et al. 2018). The updated model separately treats flux and crater efficiency so that the model can be applied to any object and flux. Updates include crater scaling from Holsapple (1993), separately treats gravity and strength scaled craters, uses a parabolic crater profile (Melosh 1989; Pilkington and Grieve, 1992; Chappelow and Sharpton, 2002; Chappelow, 2013) and an adaption that allows the model to accept any crater size frequency distribution that follows a power law (e.g. Hartman, 1984; Hartman, 1999). In our application to the Moon, we input the wellconstrained contemporary impact flux from Brown (2002) and target and impactor material properties comprising density (Jeanloz and Ahrens, 1978, Grun et al. 1985, Ceplecha et al. 1998, Kiefer et al. 2012), yield strength, and porosity (Holsapple, 2003).

Finally, and most importantly, I include the effects of secondary impactors on regolith overturn as had been suggested but not included by Gault et al. Understanding of the intensity of secondary cratering has evolved since 1974, with scale and effect revealed by studies of impact ejecta (e.g. Vickery 1986, 1987; Cintala and McBride 1995) and observations of martian (McEwen et al. 2005, Preblich et al. 2007) and lunar craters (Allen 1979; Bart and Melosh, 2007; Robinson et al. 2015, Speyerer et al. 2016). When compared to the reworking rates calculated from analysis of Apollo cores (e.g. Morris 1979; Blanford et al 1980) and implied by the rate at which lunar surface features such as rays disappear into background regolith, models of impact gardening that only include a primary impact flux fail to keep up at all depths and timescales (Gault et al. 1974; Arnold 1975). When considering impact processing at the meter and smaller scale, secondaries are critical. Whether driven by primaries or secondaries, the analytic model simplifies to a prediction of reworking that proceeds through a column of regolith following a power law function of time.

An important feature of the Gault et al. model is in its analytic nature. This overturn model can serve as a computationally inexpensive vanguard for future exploration on impact gardening. Results can be used to identify important parameters for more detailed study, for example, in the lunar case, we see that secondaries have a profound effect on the evolution of lunar regolith and call for more detailed analysis. For far less computational cost than a single run of a sophisticated Monte Carlo simulation (e.g. Arnold 1975; Crider & Vondrak, 2003; Huang et al. 2017), the analytic model can yield a large number of results, providing deep insights into the fundamental drivers of overturn in seconds. The relative ease with which the model can be deployed makes it a useful tool in the exploration of the Moon and beyond. A particular strength of the generalized approach presented in my updated model is that it allows the opportunity to describe the impact gardening rate on any airless body. In this work, I pay respect to the rich heritage of lunar science by revisiting the model by Gaul et al. (1974), and facilitate the extension of this Apollo-era vision across the Solar System.

My first target is the poles of the Moon and Mercury. The Moon and Mercury both have polar regions in permanent shadow that provide hospitable conditions for preservation of volatiles (Urey et al. 1967; Watson et al. 1962; Vasavada et al. 1999; Paige et al. 2010; Paige et al., 2013). On Mercury, all surfaces and shallow subsurfaces cold enough to preserve ice against sublimation show strong evidence of the presence of ice (Paige et al. 2013) and there are ice deposits that are meters thick (e.g. Slade et al. 1992; Harmon et al. 1994; Lawrence et al. 2013). However, ice on the Moon is less conspicuous. Workers have found limited traces of water ice (e.g. Nozette et al. 1996; Colaprete et al. 2010; Zuber et al 2012; Hayne et al. 2015; Li et al. 2017) but the Moon does not have extensive polar surface or shallow buried ice deposits like Mercury. The cause of the discrepancy between the abundance of near-surface ice between the Moon and Mercury remains a mystery, however, Marchi et al. (2005) showed that the modern flux of large impactors of diameters 1 cm - 100 m is about ten times lower on Mercury than it is on the Moon. This will cause a difference in the depth and rate of regolith overturn, and impact gardening may be the cause of the difference in ice distribution.

Europa is an icy body of astrobiological importance and the destination of a new multiple flyby mission (Europa Clipper, launch in 2023) and landed mission concepts. Two previous remote sensing visits to Europa, from the Voyager and Galileo spacecraft, sparked wonder and debate about the unique morphologic features, chemistry, and astrobiological potential of this icy satellite of Jupiter. Europa's surface is composed of water ice and salts and it is thought that a liquid water ocean hides kilometers below the solid ice shell (Kivelson et al. 2000). We also know that the surface of Europa is young relative to its heavily cratered neighbor-moons Ganymede and Callisto, and mysterious linea and chaos terrains could suggest relatively recent or ongoing large-scale resurfacing. We also know that the surface is heavily irradiated by Jupiter's ionosphere, so much so that biolomolecules exposed to the surface would be destroyed. Impact gardening redistributes irradiated material to depth and draws pristine material and potential biolomolecules upwards to the dangerous radiation at the surface. I model impact gardening on Europa to identify surface-subsurface transport rates, and modification and preservation timescales in support of the hope to discover evidence of life, and characterize the icy regolith material remote sensing senses and a lander would sample on Europa.

References

Arnold, J. R. (1975). Monte Carlo simulation of turnover processes in the lunar regolith.In Lunar and Planetary Science Conference Proceedings (Vol. 6, pp. 2375-2395).

Bart, G. D., & Melosh, H. J. (2007). Using lunar boulders to distinguish primary from distant secondary impact craters. Geophysical Research Letters, 34(7).

Bierhaus, E. B., Chapman, C. R., & Merline, W. J. (2005). Secondary craters on Europa and implications for cratered surfaces. Nature, 437(7062), 1125.

Bierhaus, E. B., Chapman, C. R., Merline, W. J., Brooks, S. M., & Asphaug, E. (2001).

Pwyll secondaries and other small craters on Europa. Icarus, 153(2), 264-276.

Bierhaus, E. B., Chapman, C. R., & Merline, W. J. (2000, October). Secondary cratering on Europa. In Bulletin of the American Astronomical Society (Vol. 32, p. 1067).

Brown, P., Spalding, R. E., ReVelle, D. O., Tagliaferri, E., & Worden, S. P. (2002). The flux of small near-Earth objects colliding with the Earth. Nature, 420(6913), 294.

Blanford, G. E. (1980). Cosmic ray production curves below reworking zones. In Lunar and Planetary Science Conference Proceedings (Vol. 11, pp. 1357-1368).

Chappelow, J. E. (2013). Simple impact crater shape determination from shadows. Meteoritics & Planetary Science, 48(10), 1863-1872. Chappelow, J. E., & Sharpton, V. L. (2002). An improved shadow measurement technique for constraining the morphometry of simple impact craters. Meteoritics Planetary Science, 37(4), 479-486.

Ceplecha, Z., Borovička, J., Elford, W. G., ReVelle, D. O., Hawkes, R. L., Porubčan, V., & Šimek, M. (1998). Meteor phenomena and bodies. Space Science Reviews, 84(3-4), 327-471.

Colaprete, A., Schultz, P., Heldmann, J., Wooden, D., Shirley, M., Ennico, K., ... & Goldstein, D. (2010). Detection of water in the LCROSS ejecta plume. Science, 330(6003), 463-468.

Costello, E. S., Ghent, R. R., & Lucey, P. G. (2018). The mixing of lunar regolith: Vital updates to a canonical model. Icarus, 314, 327-344.

Crider, D. H., & Vondrak, R. R. (2003). Space weathering of ice layers in lunar cold traps. Advances in Space Research, 31(11), 2293-2298.

Fruchter, J. S., Rancitelli, L. A., & Perkins, R. W. (1976, April). Recent and longterm mixing of the lunar regolith based on Na-22 and Al-26 measurements in Apollo 15, 16, and 17 deep drill stems and drive tubes. In Lunar and Planetary Science Conference Proceedings (Vol. 7, pp. 27-39).

Fruchter, J. S., Rancitelli, L. A., Laul, J. C., & Perkins, R. W. (1977). Lunar regolith dynamics based on analysis of the cosmogenic radionuclides Na-22, Al-26, and Mn-53. In Lunar and Planetary Science Conference Proceedings (Vol. 8, pp. 3595-3605).

Gault, D. E., Hörz, F., Brownlee, D. E., & Hartung, J. B. (1974). Mixing of the lunar regolith. In Lunar and Planetary Science Conference Proceedings (Vol. 5, pp. 2365-2386).

Gault, D. E., Hörz, F., & Hartung, J. B. (1972). Effects of microcratering on the lunar surface. In Lunar and Planetary Science Conference Proceedings (Vol. 3, p. 2713).

Hammel, H. B., Wong, M. H., Clarke, J. T., de Pater, I., Fletcher, L. N., Hueso, R., ... & Simon-Miller, A. A. (2010). Jupiter after the 2009 impact: Hubble Space Telescope imaging of the impact-generated debris and its temporal evolution. The Astrophysical Journal Letters, 715(2), L150. Hapke, B. (2001). Space weathering from Mercury to the asteroid belt. Journal of Geophysical Research: Planets, 106(E5), 10039-10073.

Harmon, J. K. (1997). Mercury radar studies and lunar comparisons. Advances in Space Research, 19(10), 1487-1496.

Harmon, J. K., Perillat, P. J., & Slade, M. A. (2001). High-resolution radar imaging of Mercury's north pole. Icarus, 149(1), 1-15.

Hartmann, W. K. (1977). Relative crater production rates on planets. Icarus, 31(2), 260-276.

Hartmann, W. K. (1984). Does crater "saturation equilibrium" occur in the solar system? Icarus, 60(1), 56-74.

Hartmann, W. K. (1999). Martian cratering VI: Crater count isochrons and evidence for recent volcanism from Mars Global Surveyor. Meteoritics & Planetary Science, 34(2), 167-177.

Hawke, B. R., Blewett, D. T., Lucey, P. G., Smith, G. A., Bell, J. F., Campbell, B. A.,& Robinson, M. S. (2004). The origin of lunar crater rays. Icarus, 170(1), 1-16.

Hayne, P. O., & Aharonson, O. (2015). Thermal stability of ice on Ceres with rough topography. Journal of Geophysical Research: Planets, 120(9), 1567-1584.

Heiken, G., Vaniman, D., & French, B. M. (Eds.). (1991). Lunar sourcebook: A user's guide to the Moon. CUP Archive.

Hirabayashi, T., Minton, D. A., Melosh, H. J., Milbury, C., Huang, Y. H., & Soderblom,J. M. (2016, March). Equilibrium State in Impact-Generated Porosity on a Lunar Surface.In Lunar and Planetary Science Conference (Vol. 47, p. 2491).

Holsapple, K. A. (1993). The scaling of impact processes in planetary sciences. Annual review of earth and planetary sciences, 21(1), 333-373.

Holsapple, K. A. (2003). Theory and equations for "Craters from Impacts and Explosions". St. Louis, MO: Washington University.

Hörz, F., Schneider, E., Gault, D. E., Hartung, J. B., & Brownlee, D. E. (1975). Catastrophic rupture of lunar rocks: A Monte Carlo simulation. Earth, Moon, and Planets, 13(1), 235-258.

Huang, Y. H., Minton, D. A., Hirabayashi, M., Elliott, J. R., Richardson, J. E., Fassett,C. we., & Zellner, N. E. (2017). Heterogeneous Impact Transport on the Moon. Journal ofGeophysical Research: Planets.

Hueso, R., Pérez-Hoyos, S., Sánchez-Lavega, A., Wesley, A., Hall, G., Go, C., ... & Korycansky, D. G. (2013). Impact flux on Jupiter: From superbolides to large-scale collisions. Astronomy & Astrophysics, 560, A55.

Ivanov, B. A. (2001). Mars/Moon cratering rate ratio estimates. Space Science Reviews, 96(1), 87-104.

Kivelson, M. G., Khurana, K. K., Russell, C. T., Volwerk, M., Walker, R. J., & Zimmer,C. (2000). Galileo magnetometer measurements: A stronger case for a subsurface ocean atEuropa. Science, 289(5483), 1340-1343.

Lawrence, D. J., Feldman, W. C., Goldsten, J. O., Maurice, S., Peplowski, P. N., Anderson, B. J., ... & Rodgers, D. J. (2013). Evidence for water ice near Mercury's north pole from MESSENGER Neutron Spectrometer measurements. Science, 339(6117), 292-296.

Li, S., Lucey, P., & Milliken, R. (2017). Water in Pyroclastic Deposits and Cold Traps on the Moon: Possible Resources for Future Exploration. LPI Contributions, 2041.

Lucey, P.G., D.T. Blewett, G. J. Taylor, & B.R. Hawke, Imaging the maturity of the lunar surface, J. Geophys. Res, 105, E8, 20297-20305, 2000

Marchi, S., Morbidelli, A., & Cremonese, G. (2005). Flux of meteoroid impacts on Mercury. Astronomy & Astrophysics, 431(3), 1123-1127.

McEwen, A. S., Preblich, B. S., Turtle, E. P., Artemieva, N. A., Golombek, M. P., Hurst, M., ... & Christensen, P. R. (2005). The rayed crater Zunil and interpretations of small impact craters on Mars. Icarus, 176(2), 351-381. McEwen, A. S., & Bierhaus, E. B. (2006). The importance of secondary cratering to age constraints on planetary surfaces. Annu. Rev. Earth Planet. Sci., 34, 535-567. Neukum, G., Ivanov, B. A., & Hartmann, W. K. (2001). Cratering records in the inner solar system in relation to the lunar reference system. In Chronology and evolution of Mars(pp. 55-86). Springer, Dordrecht.

Melosh, H. J. (1989). Impact cratering: A geologic process. Research supported by NASA. New York, Oxford University Press (Oxford Monographs on Geology and Geophysics, No. 11), 1989, 253 p., 11.

Melosh HJ, Kendall J, Horgan B, Johnson BC, Bowling T, Lucey PG, Taylor GJ. South Pole–Aitken basin ejecta reveal the Moon's upper mantle. Geology. 2017 Dec 1;45(12):1063-6.

Morris, R. V. (1978). In situ reworking/gardening/of the lunar surface-Evidence from the Apollo cores. In Lunar and Planetary Science Conference Proceedings (Vol. 9, pp. 1801-1811).

Nakamura, Y., J. Dorman, F. Duennebier, D. Lammlein, & G. Lathan 1975. Shallow lunar structure determined from the passive seismic experiment. Moon 13, 3–15.

Neukum, G. (1983). Meteoritenbombardement und datierung planetarer oberflachen. Habilitation Dissertation for Faculty Membership, Ludwig Maximilianis Univ.

Neukum, G., Ivanov, B. A., & Hartmann, W. K. (2001). Cratering records in the inner solar system in relation to the lunar reference system. In Chronology and evolution of Mars (pp. 55-86). Springer Netherlands.

Nozette S, Lichtenberg CL, Spudis P, Bonner R, Ort W, Malaret E, Robinson M, Shoemaker EM. The Clementine bistatic radar experiment. Science. 1996 Nov 29;274(5292):1495-8.

Ohtake, M., K. Uemoto, Y. Yokota, T. Morota, S. Yamamoto, R. Nakamura, J. Haruyama, T. Iwata, T. Matsunaga, & Y. Ishihara (2014), Geologic structure generated by large-impact basin formation observed at the South Pole-Aitken basin on the Moon, Geophys. Res. Lett., 41, 2738–2745, doi:10.1002/2014GL059478.

Paige, D. A., Siegler, M. A., Harmon, J. K., Neumann, G. A., Mazarico, E. M., Smith,D. E., ... & Solomon, S. C. (2012). Thermal stability of volatiles in the north polar region of Mercury. Science, 1226265.

Paige, D. A., Siegler, M. A., Zhang, J. A., Hayne, P. O., Foote, E. J., Bennett, K. A., ... & Foote, M. C. (2010). Diviner lunar radiometer observations of cold traps in the Moon's south polar region. science, 330(6003), 479-482.

Pappalardo, R. T., Vance, S., Bagenal, F., Bills, B. G., Blaney, D. L., Blankenship, D.
D., ... & Leisner, J. S. (2013). Science potential from a Europa lander. Astrobiology, 13(8), 740-773.

Pasckert JH, Hiesinger H, van der Bogert CH. Lunar farside volcanism in and around the South Pole–Aitken basin. Icarus. 2018 Jan 1;299:538-62.

Petro, N. E., and C. M. Pieters (2006), Modeling the provenance of the Apollo 16 regolith, J. Geophys. Res., 111, E09005, doi:10.1029/2005JE002559.

Pilkington, M., & Grieve, R. A. F. (1992). The geophysical signature of terrestrial impact craters. Reviews of Geophysics, 30(2), 161-181. Allen, C. C. (1979). Large lunar secondary craters: Size-range relationships. Geophysical Research Letters, 6(1), 51-54.

Preblich, B. S., McEwen, A. S., & Studer, D. M. (2007). Mapping rays and secondary craters from the Martian crater Zunil. Journal of Geophysical Research: Planets, 112(E5).

Prettyman, T. H., Yamashita, N., Castillo-Rogez, J. C., Feldman, W. C., Lawrence, D. J., McSween, H. Y., ... & Marchi, S. (2016, March). Elemental composition of Ceres by Dawn's Gamma Ray and Neutron Detector. In Lunar and Planetary Science Conference (Vol. 47, p. 2228).

Quaide W. L. & Oberbeck V. R (1975) Development of the mare regolith: Some model considerations. The Moon, 13, 27–55.

Robinson, M. S., Boyd, A. K., Denevi, B. W., Lawrence, S. J., McEwen, A. S., Moser,D. E., ... & Wagner, R. V. (2015). New crater on the Moon and a swarm of secondaries.Icarus, 252, 229-235.

Sánchez-Lavega, A., Wesley, A., Orton, G., Hueso, R., Perez-Hoyos, S., Fletcher, L. N., ... & Simon-Miller, A. (2010). The impact of a large object on Jupiter in 2009 July. The Astrophysical Journal Letters, 715(2), L155.

Schorghofer, N. (2016a). Predictions of depth-to-ice on asteroids based on an asynchronous model of temperature, impact stirring, and ice loss. Icarus, 276, 88-95.

Schorghofer, N., Mazarico, E., Platz, T., Preusker, F., Schroeder, S. E., Raymond, C. A., & Russell, C. T. (2016b). The permanently shadowed regions of dwarf planet Ceres. Geophysical Research Letters, 43(13), 6783-6789.

Slade, M. A., Butler, B. J., & Muhleman, D. O. (1992). Mercury radar imaging: Evidence for polar ice. Science, 258(5082), 635-641.

Shoemaker, E. M. (1962). Interpretation of lunar craters. Physics and Astronomy of the Moon, 283-359.

Shoemaker, E. M. (1965). Preliminary analysis of the fine structure of the lunar surface in Mare Cognitum. In The Nature of the Lunar Surface (p. 23).

Singer, K. N., McKinnon, W. B., Gladman, B., Greenstreet, S., Bierhaus, E. B., Stern, S. A., ... & Bray, V. J. (2019). Impact craters on Pluto and Charon indicate a deficit of small Kuiper belt objects. Science, 363(6430), 955-959.

Speyerer, E. J., Povilaitis, R. Z., Robinson, M. S., Thomas, P. C., & Wagner, R. V. (2016). Quantifying crater production and regolith overturn on the Moon with temporal imaging. Nature, 538(7624), 215.

Urey, H. C. (1967). Water on the Moon. Nature, 216(5120), 1094-1095.

Vasavada, A. R., Paige, D. A., & Wood, S. E. (1999). Near-surface temperatures on Mercury and the Moon and the stability of polar ice deposits. Icarus, 141(2), 179-193.

Vaughan WM, Head JW. Impact melt differentiation in the South Pole-Aitken basin: Some observations and speculations. Planetary and Space Science. 2014 Feb 1;91:101-6.

Vickery, A. M. (1986). Size-velocity distribution of large ejecta fragments. Icarus, 67(2), 224-236.

Vickery, A. M. (1987). Variation in ejecta size with ejection velocity. Geophysical Research Letters, 14(7), 726-729. Chicago

Vondrak, R. R., & Crider, D. H. (2003). Ice at the lunar poles: That the Moon harbors ice at high latitudes is well known. The source of that water, however, may come as something of a surprise. American Scientist, 91(4), 322-329.

Watson, K., Murray, B. C., & Brown, H. (1962). The stability of volatiles in the Solar System. Icarus, 1(1-6), 317-327.

Zahnle, K., Schenk, P., Levison, H., & Dones, L. (2003). Cratering rates in the outer Solar System. Icarus, 163(2), 263-289.

Zuber, M. T., Head, J. W., Smith, D. E., Neumann, G. A., Mazarico, E., Torrence, M.
H., ... & Melosh, H. J. (2012). Constraints on the volatile distribution within Shackleton crater at the lunar south pole. Nature, 486(7403), 378-381.

Chapter 2

The mixing of lunar regolith: Vital updates to a canonical model

Note: This chapter was published in 2018 in the journal Icarus 314, 327-344, as "The mixing of lunar regolith: Vital updates to a canonical model." with co-authors R.R. Ghent and P.G. Lucey.

Abstract

In this work we update the regolith mixing model presented by Gault et al. (1974), including new input values and reworking key parameters. Much as Gault et al. did, we present a way to calculate the rate at which lunar regolith is overturned at depth. The model describes a mixing front that proceeds downward from the surface following a power-law function of time. Our most important update is the inclusion of secondary impacts. Our calculations show that secondaries are necessary to produce the reworking rate inferred from the depth distribution of surface-correlated material in Apollo cores (Fruchter et al. 1977; Morris 1978; Blanford et al. 1980), from the rate at which splotches rework the top 3 cm of regolith (Speyerer et al., 2016), and from the rate at which Diviner cold spots (Bandfield et al., 2013) and crater rays (Pieters et al. 1985; Hawke et al. 2004; Werner and Medvedev, 2010) are reworked into background regolith. Overturn calculations that only consider the impact of primaries fail to describe observed reworking rates at all depths and timescales. We conclude that secondary impacts dominate mixing in the top meter of lunar regolith.

2.1 Introduction

Each time an object impacts a planetary body, material is excavated from depth and deposited in the proximity as an ejecta deposit. Impacting objects can be micron-sized grains of cosmic dust, kilometer-sized asteroids, or any of all twelve orders of magnitude in between. The size distribution of objects that strike the Moon is largely stochastic, governed by mutual impacts and the power laws of pulverization (Strom et al. 2005; Malhotra et al. 2015). Impacting objects generate craters correlated to the impactor size, velocity, and material properties of the impactor and target (e.g. Schmidt and Holsaple, 1980; Holsapple and Schmidt, 1982; Schmidt and Housen, 1987; Holsapple, 1993). The power-law size distribution of impactors and the well-constrained relationship between impactor size and crater size allow statistical modeling of regolith evolution, including impact gardening.

Impact gardening is the process by which impacts redistribute regolith material, removing grains from depth and re-depositing them near the surface. Gardening is also called ?mixing? or ?overturn? (e.g. Gault et al. 1974, Arnold 1975) because it muddles the otherwise distinct stratigraphic arrangement of materials with depth by repeatedly and stochastically inverting the depth-distribution of materials. Explorations of the impact-driven evolution of regolith have continued to provide insight into the depth profiles of cosmic ray tracks, volatile elements, abundance of cosmogenic radionuclides, percentages of different lithologic components, and grain size distributions (e.g. Fruchter et al. 1976; Fruchter et al. 1977; Morris 1978; Blanford et al. 1980; Crider and Vondrak, 2003; Vondrak and Crider, 2003; Heiken et al. 2012; Hurley et al. 2012). Each study contributes to our understanding of the process and consequences of impact gardening and its wider influence on lunar stratigraphy, the lifetime of rays and other surface features such density and albedo anomalies, and the burial, exposure, and break down of volatiles and rocks.

Gault et al. (1974) presented a pioneering regolith mixing model predicated on the assumption that impact flux is a probabilistic process that obeys the Poisson distribution (Gault et al. 1972; Gault et al. 1974). In Gault et al. (1974), regolith overturn is defined

to occur when a point at depth has been influenced by an impact event. Their model mathematically describes the frequency with which material at that depth is affected by an impact, and transported from depth to the near surface. The success rate of overturning events is presented by Gault et al. as a function of core input parameters: time, impact flux, and crater scaling. These parameters, together with a statistical method based on Poisson law and the stochastic impact flux describe the rate and probability of overturn at depth as a function of time.

The Gault et al. (1974) model has had significant and ongoing influence on the development of regolith evolution models (Arnold 1975; Spencer, 1987; Harmon 2001; Schorghofer et al. 2016; Hirabayashi et al 2016; Huang et al. 2017) and analyses of the reworking depth of surface exposure effects in Apollo cores (Morris 1978, Blanford et al. 1980). However, key parameters such as impact flux and the relationship between meteorite properties and crater size have not been updated since the 1974 study. Building on the legacy of the Gault et al. (1974) model, we present a refreshed approach to the overturn of lunar regolith, in which we explicitly rework and update the key parameters originally included in the model: crater scaling and the flux of crater-forming impactors.

Finally, and most importantly, we include the regolith overturn effects of secondary impacts. Gault et al. (1974) noted the inclusion of secondaries as an important future addition to the model; in this study we follow through on that suggestion. Since 1974, our understanding of the intensity of secondary cratering has evolved, with scale and effect revealed by recent studies of impact ejecta (e.g. Vickery 1986, 1987; Cintala and McBride 1995) and observations of martian (McEwen et al. 2005, Preblich et al. 2007) and lunar craters (Allen 1979; Bart and Melosh, 2007; Robinson et al. 2015, Speyerer et al. 2016). Largely due to the inclusion of secondaries, we calculate a rate of mixing that is much higher than that predicted by Gault et al. (1974) at all depths and timescales. The high secondarydriven reworking rate is in better agreement with several validating cases, including the depth-density profile of surface maturity indicators and the rate at which surface features with well-constrained depth and longevity such as rays and cold spots (Bandfield et al. 2014)
are mixed into the background. The scale of the improvement suggests that secondaries play a compelling role in the evolution of lunar regolith.

2.2 Model

The Gault et al (1974) model and the work we present here are predicated on the assumption that overturn follows a Poisson probability distribution with time that is functionally dependent on the flux of meteoritic impacts and the size of the craters that those impacts produce. The key components of the model are 1) a Poisson expression that describes the theoretical success-rate of a point at depth being inside the excavated volume of a crater over a time interval and 2) a crater production function that describes the cumulative number of craters of a certain diameter that form per unit area per unit time. The Poisson expression shown here is effectively unaltered from that put forth by Gault et al. (1974). We present a review of it here for clarity. We then describe an updated and more explicit treatment of crater scaling and geometry and refresh crater efficiency input parameters based on observations and experiments conducted since 1974.

2.2.1 The Poisson Expression

The probability function for the Poisson distribution describes the probability of observing n events over a time interval:

$$P_d(n;\lambda) = \frac{\exp(-\lambda)(\lambda)^n}{n!}$$
 for $n = 0, 1, 2...$ (2.1)

where n is the number of events and λ is the average number of events per interval. The cumulative probability function describes the probability that at least n events have occurred and takes the form:

$$P_{c}(n;\lambda) = \sum_{i=1}^{n} \frac{\exp(-\lambda)(\lambda)^{i}}{i!} = 1 - P_{d}(n)$$
(2.2)

Using Equation 2.2, one can compute the probability that at least n events will occur if the average number of events per interval is some value λ . Tables of λ values have been calculated numerically for situations where n successful events occur at 10, 50, and 99% probability. A table in Molina (1942) documents numerically derived values for λ for the range $0 \le n \le 153$. Gault et al. (1974) numerically derived values for λ in the range $153 \le n \le 10^6$, with order of magnitude steps in between. Values for λ at 10, 50, and 99% probability that are used to calculate overturn in this work can be found in Table 2.1.

In the following section, we present the geometric derivation of the Poisson expression used by Gault et al. (1974) to describe the number of times a point at depth is successfully overturned by a crater-forming impact per unit area and unit time on the Moon and include important steps and reasoning.



Figure 2.1 The geometry underpinning the Poisson expression.

To begin, we imagine a simplistic geometric vision of some planetary surface where all possible points of impact exist in a round-edged square (Figure 2.1). There is some point Q on the round edged square surface and some point U directly below (Figure 2.2). By considering the probability the sub-surface point U within the simple geometric scheme will



Figure 2.2 In this work and the model presented by Gault et al. (1974), the fate of material experiencing an impact is simplified by the assumption that the truncated volume of a transient crater volume is overturned as shown. Distal craters of diameter D_c must impact some fraction of a crater diameter c away from surface point Q in order to overturn subsurface point U.

or will not be disturbed by an impact event, we can present overturn as a function of the Poisson-derived average number of events, λ , and time, t.

Let us geometrically define the planetary surface. An overturn-able point Q exists somewhere inside or on the boundary of a square with side s and area, $A_{Square} = s^2$. The square is surrounded by a rounded square band such that $A_{Band} = 4rs + \pi r^2$. To illustrate the purpose of the band, imagine point Q is directly on one corner of the square (see the star in Figure 2.1). The rounded band describes the additional area inside which a crater of radius r could form and still influence some point within the square. When we consider a planetary surface, the square model surface (A_{Square}) is much larger than the radius of any crater; thus, the band will effectively disappear. For now, it allows some useful geometric manipulation. $A_{Surface}$ describes the geometry of the total planetary surface area:

$$A_{Surface} = A_{Square} + A_{Band} \tag{2.3}$$

$$= s^2 + 4rs + \pi r^2 \tag{2.4}$$

In order for an impact event with effective excavation radius r to excavate Q, the epicenter of impact must be within a circle of radius r and area, $A_{\circ} = \pi r^2$. Any object that strikes within A_{\circ} with excavation radius r will excavate point Q. Any circular crater whose epicenter of impact is within the square, along the boundary of the square, in the band, or on the boundary of the band <u>could</u> excavate point Q. The probability that a surface point Q within $A_{Surface}$ remains undisturbed by one random cratering event of radius r is written as follows:

$$P_u(1) = \frac{[Total Area] - [Disturbed Area]}{[Total Area]}$$
(2.5)

$$= \frac{A_{Surface} - A_{\circ}}{A_{Surface}} \tag{2.6}$$

$$= \frac{s^2 + 4rs + \pi r^2 - \pi r^2}{s^2 + 4rs + \pi r^2}$$
(2.7)

$$= \frac{(s^2 + 4rs)}{(s^2 + 4rs + \pi r^2)} \tag{2.8}$$

The number of times, N_Q , that point Q is overturned by an impact can be expressed as a function of time t by defining $N_Q = \frac{[Total \ number \ of \ excavations]}{[Unit \ Area][Unit \ Time]}$ such that the total number of overturns that occur, n, is written:

$$n = N_Q(A_{Surface})t = N(s^2 + 4rs + \pi r^2)t$$
(2.9)

The probability that at least one random cratering event of radius r <u>disturbs</u> point P is the following:

$$P_c(1) = 1 - P_u = \frac{\pi r^2}{s^2 + 4rs + \pi r^2}$$
(2.10)

and the probability of at least n random events out of a total of m events excavating a point U is a binomial probability:

$$P_c(n) = \frac{m!}{n!(m-n)!} P_d(n)^n (1 - P_d(n))^{m-n}$$
(2.11)

where P_c is the cumulative probability of being overturned at least n times and P_d is the differential probability of being overturned exactly n times. As the total number of impact events increases, the above equation can be approximated using the Poisson exponential:

$$P_c(n) = \frac{exp(-mP_d(1))(mP_d(1))^n}{n!}$$
(2.12)

With total number of events $m = n = N(s^2 + 4rs + \pi r^2)t$ so that $mP_d(1) = \lambda$, the above equation reduces to the following:

$$P_c = \frac{exp(-\lambda)(\lambda)^n}{n!} \tag{2.13}$$

where we arrive again at Equation (1): the Poisson distribution.

As the goal of this rumination on Poisson statistics and geometry is to relate the frequency at which a point is excavated by a crater to a function of variable time, we return to the geometry presented in Figure (2.1) and note that the probability a point Q remains undisturbed by n impacts is the following:

$$P_u(n) = \left[\frac{(s^2 + 4rs)}{(s^2 + 4rs + \pi r^2)}\right]^n \tag{2.14}$$

The surface area of the Moon is much larger than the area of most impact craters $(s \gg r)$. As s increases, the total number of events we must consider, n, increases. This is tied to a key assumption of Poisson probability: the probability of an event occurring in a region is proportional to the size of the region. If we consider a larger area, the total number of



Figure 2.3 Craters that form on the perimeter of the shaded area must have a diameter D_c or greater to disturb point Q. Craters larger than Dc can strike beyond the shaded region and still disturb point U. Thus, the cumulative distribution of all craters of diameter D_c to $D_{\text{MAX}} \gg D_c$ will contribute to overturn.

impacts we count increases proportionally:

$$\begin{array}{lll}
P_u(n) &=& \lim_{\substack{s \to \infty \\ n \to \infty}} \left[\frac{(s^2 + 4rs)}{(s^2 + 4rs + \pi r^2)} \right]^n$$
(2.15)

$$= \lim_{s \to \infty} \left(\frac{A}{B}\right)^{N_Q t B} \tag{2.16}$$

$$= \lim_{s \to \infty} \left[\left(1 + \frac{\pi r^2}{A} \right)^{-1} \right]^{N_Q t B}$$
(2.17)

by letting $A = s^2 + 4rs$ and $B = A + \pi r^2$. Because $s \gg r$, the term inside the round brackets can be approximated using the binomial series expansion.

$$\simeq \lim_{s \to \infty} \left[\left(1 - \frac{\pi r^2}{A} \right) \right]^{NtB}$$
(2.18)

Now, using the binomial approximation of the whole expression we show the following:

$$\simeq \lim_{s \to \infty} \left[1 - N_Q t B\left(\frac{\pi r^2}{A}\right) + \Theta(NtB)^2 \right]$$
(2.19)

The sum of the smaller terms from the approximation, $\Theta(N_Q t B)^2$, goes to zero. We rearrange Equation (14) into the following:

$$= \lim_{s \to \infty} \left[1 - N_Q t (A + \pi r^2) \left(\frac{\pi r^2}{A} \right) \right]$$
(2.20)

$$= \lim_{s \to \infty} \left[1 - N_Q t \pi r^2 - N_Q t \left(\frac{\pi r^2}{A}\right)^2 \right]$$
(2.21)

and we note that as A goes to infinity, the term $N_Q t \left(\frac{\pi r^2}{A}\right)^2$ goes to zero. Equation 2.21 can be approximated such that:

$$\begin{aligned}
P_u(n) &\equiv P_u \simeq e^{-N_Q \pi r^2 t} = e^{-\lambda} \\
\stackrel{s \to \infty}{\underset{n \to \infty}{\longrightarrow}}
\end{aligned} \tag{2.22}$$

where $P_u(n)$ is the probability of a surface point Q remaining undisturbed by craters of diameter D_c which are produced in a time interval t by a flux (number per unit area and time) of stochastically impacting bodies. The average number of events, λ , can be written:

$$\lambda = N_Q \pi r^2 t \tag{2.23}$$

Rearranged, we discover the number of disturbances per unit time and area is functionally dependent upon the Poisson-derived average number of events, λ , per unit time and the

size of crater:

$$N_Q(D_c) = \frac{4\lambda}{\pi D_c^2 t} \tag{2.24}$$

Any crater larger than D_c up to $D_{MAX} \gg D_c$ must also excavate point Q (Figure 2.3); therefore we calculate the cumulative distribution of crater radii of diameter D_c and larger that affect the point Q:

$$N_Q(\ge D_c) = \int_{D_{\text{MAX}}}^{D_c} \frac{4\lambda}{\pi D_c^2 t} dD \qquad (2.25)$$

$$\approx \frac{4\lambda}{\pi D_c t} \tag{2.26}$$

where $N_Q (\geq D_c)$ is the cumulative number of craters per area time that could influence surface point Q and λ represents the average number of events from a cumulative Poisson distribution.

Now consider a point at depth, U, located some smaller fraction of the crater depth, dH, directly below point Q (Figure 2.2). If we consider the top third of a crater is overturned by excavation (Melosh 1989), then $d = \frac{1}{3}$. Because of the curvature of the side of a crater, a distal crater of diameter D_c , must impact within cDc of the surface point P to excavate the subsurface point U. To calculate the value of c, we arrive at the first of our updates: crater geometry. While Gault et al. (1974) modeled craters as spherical caps, we model paraboloid craters (Melosh 1989; Pilkington and Grieve, 1992; Chappelow and Sharpton, 2002; Chappelow, 2013). From the geometry of a paraboloid; we have: $c = \frac{1}{2}\sqrt{1-d} = \frac{1}{2}\sqrt{\frac{2}{3}} \approx 0.41$ (Figure 2.2). In summary, the general form of the Poisson Expression is written:

$$N_U(n \ge D_c) = \frac{4\lambda}{\pi c^2 D_c t} \tag{2.27}$$

where $N_U(n \ge D_c)$ is the cumulative number of craters greater than or equal to diameter D_c that overturn the buried point U per area time, λ is the cumulative Poisson distributionderived average number of events per interval, D_c is crater diameter, c is a scalar that comes from crater bowl geometry and the depth considered excavated, and t is time. The expression relates the cumulative number of successful overturns to the average number of events per interval, a value for which we have convenient tables, and time.

2.2.2 Flux and Crater Scaling

In the previous section, we showed that the value $N_U (\geq D_c)$ represents the cumulative number of overturns per unit area and unit time based on a Poisson distribution of overturning events. To relate this probabilistic expression to the rate at which material is overturned by any input distribution of primary or secondary impactors on the Moon, we explore the flux of impactors onto the lunar surface and the size and shape of craters they produce. We take the crater scaling laws presented by Holsapple (1993) to describe the relationship between impactor size and crater size, and assume an average set of impactor and target properties, velocity and impact geometry. In addition, we assume that the flux, or cumulative number of impacting objects of a certain diameter, D_m , per unit area and unit time follows a power law:

$$N_F(\ge D_m) = aD_m^b \tag{2.28}$$

where $N(\geq D_m)$ is the cumulative number of meteorites of diameter $\geq D_m$ impacting per unit area, a is the y-axis intercept, and b is the slope of the $\log(N)$ vs. $\log(D_m)$ plot. By contrast, Gault et al. (1974) employed a power-law representation of the mass distribution of material colliding with the surface of the moon. This is a superficial difference. Both the Gault et al. (1974) model and our updated version assume spherical impactors of uniform density; meteorite mass and diameter are interchangeable with a few simple calculations. We use the size distribution of flux to minimize mass-to-diameter scaling assumptions when combining flux and the crater scaling laws of Holsapple (1993).

The following discussion of crater scaling relationships is a twofold update to that presented by Gault et al. (1974). First, we widen the model's parameter space by including a treatment of target and projectile properties not addressed by Gault. Second, future modeling is facilitated by our explicit inclusion of parameters as variables so that non-lunar values can be used for other planetary objects. Using these cratering laws we can explore overturn that is driven by various impactor types with various velocities on surfaces with a variety of scientifically interesting material properties, e.g. regular regolith, melt ponds, and porous ejecta blankets.

A great deal of work has been done in the exploration of crater scaling (e.g. Gault and Wedekind, 1978; Schmidt and Holsaple,1980; Holsapple and Schmidt, 1982; Schmidt and Housen, 1987; Holsapple, 1993). Studies suggest that the size and shape of a crater can be described as a function of the material parameters of both impactor and target, impact velocity, and impact angle.

From Holsapple (1993), the transient crater volume, V_t , is a function of the diameter of a crater, D_c , or crater depth, H, and has the following form:

$$V_t = \left(\frac{D_c}{2K_r}\right)^3 = \left(\frac{H}{K_d}\right)^3 \tag{2.29}$$

Crater depth, H, can be presented as a fraction of the crater diameter, D_c by re-arranging equation (2.29):

$$H = \frac{K_d}{2K_r} D_c \tag{2.30}$$

Assuming spherical impactors of uniform density, we manipulate the transient crater volume presented by Holsapple (1993) into the following function in terms of impactor diameter, D_m :

$$V_t(D_m) = f[D_m v_f^{\mu} \rho_t^{\nu}, \rho_m, Y, g]$$
(2.31)

$$= K_1 \left(\frac{\pi D_m^3 \rho_m}{6\rho_t}\right) \left\{ \left(\frac{g D_m}{2v_f^2}\right) \left(\frac{\rho_m}{\rho_t}\right)^{\frac{1}{3}} + K_2 \left[\left(\frac{Y}{\rho_t v_f^2}\right)^{\frac{2+\mu}{2}} \right] \right\}^{\frac{-3\mu}{2+\mu}}$$
(2.32)

where K_r , K_d , K_1 , and K_2 are empirically derived scalars that depend on the target material, ρ_m is the density of the impactor, ρ_t is the target bulk density, g is the gravity of the target object, Y is the target yield strength, μ is an empirically derived scalar that depends on the target porosity, and v_f is the final velocity of the object upon impact. Equation 2.32 is a special case where the exponential scaling of target density $\nu = 1/3$. Holsapple and Schmidt (1982) showed that momentum scaling and energy scaling both give $\nu = 1/3$, and Holsapple (1993) accepts that it is likely a good general value.

2.2.3 Overturn as a Function of Time

Using equations 2.32 and 2.29, we take the following relationship between crater diameter, D_c , and meteorite diameter, D_m , with notation simplified for future manipulation:

$$D_c = \delta \left\{ \gamma D_m^3 \left[\epsilon D_m + \alpha \right]^\beta \right\}^{\frac{1}{3}}$$
(2.33)

where $\alpha = K_2\left(\left(\frac{Y}{\rho_t v_f^2}\right)^{\frac{2+\mu}{2}}\right), \ \beta = \frac{-3\mu}{2+\mu}, \ \delta = 2K_r, \ \gamma = \frac{K_1 \pi \rho_m}{6\rho_t}, \ \text{and} \ \epsilon = \left(\frac{g}{2v_f^2}\right) \left(\frac{\rho_m}{\rho_t}\right)^{\frac{1}{3}}.$

Crater size relationships differ based on which scaling parameters are dominant. The lithostatic pressure at a depth equivalent to the projectile radius, whichmust be overcome for excavation to occur is $g\frac{D_m}{2}$, where D_m is the diameter of the impactor. For small D_m , the effective target yield strength, $Y \gg g\frac{D_m}{2}$, and so dominates the crater size scaling. We denote such craters as 'strength regime' craters. Conversely, for large D_m , $g\frac{D_m}{2}/ggY$, and the gravity term dominates the scaling, leading to 'gravity regime' craters.

We combine the expressions for crater scaling, flux, and the Poisson expression to generate an expression that describes the rate of overturn as a function of time. The following steps lead to the analytic model of overturn: First, solve Equation 2.33 for meteorite diameter, D_m ; second, replace D_m in the flux expression (Equation 2.28) with the result of the previous step to state the cumulative impact flux as a function of crater diameter; third, set the result of the previous step equal to the Poisson expression (Equation 2.27 ($N_F(\geq D_c) = N_U(\geq D_c)$)); fourth, solve for D_c ; and finally, solve for the depth fraction of crater diameter considered overturned using Equation 2.30 and the definition of overturn depth from Figure 2.2; $dH = d \frac{K_d}{2K_r} D_c$. The depth fraction of crater diameter that is overturned is $\approx \frac{1}{10}D_c$ for $dH = \frac{1}{3}H$ (Melosh 1989), and where K_r and K_d are consistent with the material properties of lunar regolith (see Table 2.2). To calculate overturn in the strength regime we first recall that $\epsilon = \left(\frac{g}{2v_f^2}\right) \left(\frac{\rho_m}{\rho_t}\right)^{\frac{1}{3}}$ and $\alpha = K_2\left(\left(\frac{Y}{\rho_t v_f^2}\right)^{\frac{2+\mu}{2}}\right)$. If the gravity term, ϵD_m , is much less than the strength term, α , we can ignore the gravity term, ϵD_m , in Equation 2.33;

$$D_c = \delta \left\{ \gamma D_m^3 \left[\alpha \right]^\beta \right\}^{\frac{1}{3}}$$
(2.34)

First we solve the above for D_m as a function of D_c :

$$D_m = \frac{D_c}{\delta(\gamma \alpha^\beta)^{\frac{1}{3}}} \tag{2.35}$$

Second, we replace D_m in the flux expression (Equation 2.28) with the result of the above:

$$N(D_c) = a \left\{ \frac{D_c}{\delta(\gamma \alpha^\beta)^{\frac{1}{3}}} \right\}^b$$
(2.36)

Third, we set $N_F(\geq D_c) = N_U(\geq D_c)$ by setting the result of the previous step equal to the Poisson expression (Equation 2.27):

$$a\left\{\frac{D_c}{\delta(\gamma\alpha^\beta)^{\frac{1}{3}}}\right\}^b = \frac{4\lambda}{\pi c^2 D_c t}$$
(2.37)

Fourth, we solve the above for D_c :

$$D_c = \left\{ \frac{4\lambda \left[\delta(\gamma \alpha^\beta)^{\frac{1}{3}} \right]^b}{ac^2 \pi t} \right\}^{\frac{1}{b+1}}$$
(2.38)

Finally, we consider the depth fraction of a crater diameter to calculate depth of overturn, Λ , as a function of time in the strength regime:

$$\Lambda = d \frac{K_d}{2K_r} \left\{ \frac{4\lambda \left[\delta(\gamma \alpha^\beta)^{\frac{1}{3}} \right]^b}{ac^2 \pi t} \right\}^{\frac{1}{b+1}}$$
(2.39)

This expression describes the depth of overturn Λ , as it is driven by a flux of impactors as a function of material properties of impactor and target, a Poisson-derived success-rate, and time in the strength regime. To calculate overturn in the gravity regime we note that if the gravity term is much greater than the strength term ($\epsilon D_m \gg \alpha$), then we can ignore the strength term, α , in Equation 2.33;

$$D_c = \delta \left\{ \gamma D_m^3 \left[\epsilon D_m \right]^\beta \right\}^{\frac{1}{3}}$$
(2.40)

We now solve the above for D_m :

$$D_m = \left[\frac{D_c}{\delta(\gamma\epsilon^\beta)^{\frac{1}{3}}}\right]^{\frac{3}{3+\beta}}$$
(2.41)

Second:

$$N(D_c) = a \left\{ \left[\frac{D_c}{\delta(\gamma \epsilon^{\beta})^{\frac{1}{3}}} \right]^{\frac{3}{3+\beta}} \right\}^b$$
(2.42)

Third:

$$a\left\{\left[\frac{D_c}{\delta(\gamma\epsilon^\beta)^{\frac{1}{3}}}\right]^{\frac{3}{3+\beta}}\right\}^b = \frac{4\lambda}{\pi c^2 D_c t}$$
(2.43)

Fourth:

$$D_c = \left\{ \frac{4\lambda \left[\delta(\gamma \epsilon^{\beta})^{\frac{1}{3}} \right]^{\frac{3b}{3+\beta}}}{ac^2 \pi t} \right\}^{\frac{3+\beta}{3b+3+\beta}}$$
(2.44)

Finally, we consider the depth fraction of a crater diameter to calculate the rate depth of overturn, Λ , as a function of time in the gravity regime:

$$\Lambda = d \frac{K_d}{2K_r} \left\{ \frac{4\lambda \left[\delta(\gamma \epsilon^\beta)^{\frac{1}{3}} \right]^{\frac{3b}{3+\beta}}}{ac^2 \pi t} \right\}^{\frac{3+\beta}{3b+3+\beta}}$$
(2.45)

To describe the point where strength regime transitions to gravity regime, we define the critical meteorite size where $\frac{\epsilon D_m}{\alpha} = 1$:

$$C = \frac{\alpha}{\epsilon} = \frac{K_2\left(\left(\frac{Y}{\rho_t v_f^2}\right)^{\frac{2+\mu}{2}}\right)}{\left(\frac{g}{2v_f^2}\right)\left(\frac{\rho_m}{\rho_t}\right)^{\frac{1}{3}}}$$
(2.46)

Impacting material that has a diameter larger than C generates gravity-scaled craters. Impactors smaller than C generate strength-scaled craters. Again, using parameters consistent with primary impact cratering in lunar regolith (Table 2.2), the critical meteorite diameter $C \approx 0.05$ m. We derive a corresponding quantity, C_{Λ} , that describes the critical depth where we change from strength-scaling to gravity-scaling. To calculate C_{Λ} we solve for the depth fraction of equation (2.33) using $D_m = C$.

$$C_{\Lambda} = \frac{K_d}{2K_r} \delta \left\{ \gamma C^3 \left[\epsilon C + \alpha \right]^{\beta} \right\}^{\frac{1}{3}}$$
(2.47)

When the calculated depth of overturn, Λ , is greater than C_{Λ} , we use Equation 2.45; and when overturn depth is less than C_{Λ} we use Equation 2.39. In Section 3 we use the parameters listed in Table 2.2 and find $C_{\Lambda} = 0.60$ m for primary craters. Craters that overturn material less than 0.60 m depth are strength-scaled. Craters that overturn material more than 0.60 m depth are gravity-scaled. Note that we have calculated this strength/gravity transition using the relatively weak yield strength of lunar regolith (see Table 2.2) and that gravity dominated craters in low strength media can be very small (e.g. Wünnemann et al., 2011); thus, a decimeter-scale transition is reasonable.

The above calculations translate the impact of an object characterized by some size, velocity, and density parameters into a surface with yet more characteristic parameters into the size of a crater. One important additional impact parameter can control crater efficiency: the angle of impact. Gault and Wedekind (1978) performed a comprehensive series of hypervelocity experiments, firing rounds of aluminum and pyrex spheres into non-cohesive quartz sand and granite at velocities ranging from 3.6 to 7.2 km s⁻¹. Their results

show that impact angle affects crater efficiency as:

$$D_{\theta} = D_c \sin^{\frac{\xi}{3}}(\theta) \tag{2.48}$$

where θ is the impact angle from the horizontal, D_{θ} is the diameter of a crater formed by low angle impact, D_c is the diameter of crater formed by a normal impact, $\xi = 1$ for particulate targets, and $\xi = 2$ for granite targets. Particulate targets are approximate for scaling in the gravity regime and granite targets are approximate for scaling in the strength regime. Calculating the cratering efficiency of low angle impacts using Equation 2.48 is equivalent to taking the vertical component of impact velocity $(v_f sin(\theta))$ in cratering laws like those of Holsapple (1993) (e.g. Chapman and McKinnon, 1986). We take the form from Equation 2.48 because it makes the treatment of impact angle more obvious in the final presentation of overturn. Impact experiments show that secondaries are more likely to impact at shallow angles (e.g. Schultz et al. 2007) and that primaries which impact at shallow angles produce more secondaries (Shoemaker, 1962; Oberbeck, 1975; Anderson et al. 2003; McEwen and Bierhaus, 2006). Because impact angle has implications for the discussion of secondary cratering, the explicit inclusion of impact angle in the overturn equation facilitates future investigation of the role secondaries play in the evolution of regolith.

In summary, overturn, Λ , is a function that describes the frequency at which a point at depth is part of the truncated volume of a crater produced on a planetary surface over a time interval t, as predicted by a Poisson distribution-derived average number of events per interval, λ . Simplifying the notation in equations (2.39) and (2.45), we see that this model predicts an overturn front that proceeds to depth with time following a power-law:

$$\Lambda(t,\lambda) = \begin{cases} \eta_s t^{\zeta_s} & \text{if } \Lambda < C_\Lambda \text{ and } b < -1, \\ \eta_g t^{\zeta_g} & \text{if } \Lambda > C_\Lambda \text{ and } b < \frac{(\beta+3)}{3} \end{cases}$$
(2.49)

where Λ is the depth of overturn in meters, t is time, C_{Λ} is the transition point between strength and gravity scaling from Equation 2.47, and b is the power index of the flux of impactors from Equation 2.28. The values η and ζ are derived from the treatment of crater scaling and are expanded below:

$$\eta_s = \sin^{\frac{2}{3}}(\theta) \frac{dK_d}{2K_r} \left\{ \lambda \frac{4 \left[\delta(\gamma \alpha^\beta)^{\frac{1}{3}} \right]^b}{ac^2 \pi} \right\}^{\frac{1}{b+1}}$$
(2.50)

$$\zeta_s = -\left(\frac{1}{b+1}\right) \tag{2.51}$$

$$\eta_g = \sin^{\frac{1}{3}}(\theta) \frac{dK_d}{2K_r} \left\{ \lambda \frac{4 \left[\delta(\gamma \epsilon^\beta)^{\frac{1}{3}} \right]^{\frac{3b}{3+\beta}}}{ac^2 \pi} \right\}^{\frac{3+\beta}{3b+3+\beta}}$$
(2.52)

$$\zeta_g = -\left(\frac{3+\beta}{3b+3+\beta}\right) \tag{2.53}$$

where θ is the impact angle from the horizontal, λ is a Poisson-derived value for the average number of events (see section 2.1), d and c are scalars defined by the crater bowl geometry and depth excavated (see the end of section 2.1) and where the remaining variables are defined earlier in this section and summarized in Tables 2.2 and 2.3.

A serendipitous consequence of our updated treatment of crater scaling is an extended range of values for the power index of flux, b, for which the model is valid. The power-law slope of the overturn front, ζ , is a function of b in the strength regime, and in the gravity regime, a function of b and $\beta = \frac{-3\mu}{2+\mu}$, where μ is a porosity parameter. To make physical sense ζ must be positive; i.e. a shallow point is more likely to be overturned than a deep point. This gives a limited range of values for the power index of the size distribution of flux, b, over which the model can realistically describe overturn. If the power index of the size distribution of impactors, b, is too close to 0, ζ will be negative and the model ceases to make physical sense. Although this restriction was not addressed in Gault et al. (1974), their model and another analytic overturn model presented by Blake and Wasserberg (1975) suffer from the same constraints on the sign of ζ . Upon simplification of Equation 15 from Gault et al. (1974) to the form $\Lambda = \eta_{\text{Gault}} t^{\zeta_{\text{Gault}}}$:

$$\zeta_{\text{Gault}} = \frac{-\beta'}{(\gamma' + 2\beta')} \tag{2.54}$$

where β' is always positive and is controlled by material properties (Vedder 1972; Gault 1974) and γ' is the dimensionless power index of the mass distribution of flux. The Gault et al. model can only describe overturn due to a mass distribution of flux such that $0 \leq \frac{-\beta'}{(\gamma'+2\beta')}$. For their treatment of micrometeorites, $(m < 10^{-7.5}g)$, Gault et al. (1974) presented the values: $\beta' = 0.352$ (Vedder 1972) and $\gamma' = -0.45$ (Gault et al. 1974). Using equation (2.54), we see that for micrometeorites, $\zeta_{\text{Gault}} = -1.385$. The negative valued power index does not make physical sense and should not have been used to calculate a reasonable description of overturn if documentation of the Gault et al. model is correct. In comparison, our updated model can accept a size distribution power index of flux as shallow as $b \leq -1$ in the strength regime. In the gravity regime, and where porosity parameter μ is consistent with lunar regolith (see Table 2.2), our model reasonably describes overturn where $b \leq -0.51$. While η_{Gault} can not be reproduced from the documentation presented in Gault et al. (1974), we interpret η_{Gault} to be on the order of 10^{-5} based on our calculations using the information presented by Gault et al. (1974), Wedekind and Gault, (1974), and the overturn curve presented in Morris (1978).

2.2.4 Production Functions

Gault et al. (1974) did not have the benefit of decades of crater counts and crater production studies carried out since 1974. As opposed to combining flux and crater scaling as Gault did, one could calculate overturn due to any crater production function. Given a production function, we can derive a simple form to describe overturn. Consider a power law size frequency distribution of the form:

$$N_{SFD}(\ge D_c) = uD_c^v \tag{2.55}$$

where $N_{SFD}(\geq D_c)$ is the cumulative number of craters of diameter $\geq D$ per unit area time, *i* is a constant that depends on *N*, and *j* is the power law exponent, or slope of the $\log(N)$ vs. $\log(D)$ plot.

Any size frequency distribution of the above form can be set equal to the Poisson expression (Equation (2.27)) and solved for the overturned depth fraction of the crater diameter to yield the following overturn function:

$$\Lambda_{SFD} = dH \left(\frac{4\lambda}{u\pi c^2 t}\right)^{\frac{1}{\nu+1}} \tag{2.56}$$

where u and v are described by the power law in Equation (2.55).

In Figure 2.4 we see that the production function for gravity regime craters (Equation (2.42)) that we derive by combining the power law flux presented by Brown et al. (2002) and the crater scaling laws of Holsapple (1993) produces a curve that is comparable to the piece-wise power law Hartmann production function (Hartmann, 1984; Hartman, 1999), and the eleventh order polynomial Neukum production function (Neukum, 1983; Ivanov et al. 1999, 2001). If one wants to understand overturn at depths of one meter and shallower, it is important to note that the Neukum and Hartmann production functions describe relatively large craters and should not be extrapolated downward. The Neukum production function is valid down to 250 m craters (Ivanov et al., 2008) and Hartmann down to 300 m craters (Hartmann and Gaskell, 1997). These craters are too large and therefore too rare to have significant influence on the global reworking of the top meter of regolith in the past billion years.

2.3 Overturn: The Lunar Case

To apply the updated model to the lunar case, we explore the flux of materials onto the surface of the moon and the material properties of the lunar regolith. Table 2.2 summarizes the material properties of regolith that we use for this version of the model. Since 1974, our understanding of the modern flux of meteoritic impactors has substantially improved,



Figure 2.4 The Neukum production function, Hartman production function and Equation 2.42 are generally in good agreement at the lower limit of validity, on the order of 100m craters. We may be overestimating the number of 200 m to 1 km diameter craters and underestimating the number of craters larger than 1km. We use the coefficients reported by Ivanov et al. (1999, 2001) to calculate the Neukum production function. We calculate Equation 2.42 using the lunar regolith values in Appendix Table 2 and the flux values reported by Brown et al. (2002).

having been informed by observations of microcraters in spacecraft and Apollo samples (e.g. Flavill et al. 1978; McDonnell and Allison, 1981), bolide flashes and fireballs in the Earth's atmosphere (Brown et al. 2002; Ceplecha et al. 1998; Halliday et al. 1996), impact flashes on the Moon (Suggs et al. 2014), near earth object populations (Rabinowitz et al. 2000) and observations of newly formed craters and other visible symptoms of impact (Speyerer et al. 2016). In this study we explore the flux of three varieties of crater-forming impactors: 1) Primary impactors that are larger than micrometeorites and smaller than 1km asteroids, $(1 \text{ cm} < D_m < 1\text{km})$; 2) Very small and micrometeorite primary impactors $(10^{-7} \text{ cm} < D_m < 1 \text{ cm})$; and 3) Secondary impactors formed as constituents of primary impact ejecta. We assume each variety of impactor follows a power law size distribution as described by Equation 2.28.

2.3.1 Lunar Primaries

On the Moon, overturn occurs when objects impact the lunar regolith. To model the rate of overturn in the lunar case we constrain the flux of material from space onto the lunar surface, the velocity and angle at which these materials impact, and the material properites of these primary impactors and the lunar regolith target. To inform the power law size distribution of impacting objects larger than micrometeorites and smaller than 1km asteroids, we look to the bolide flash observations presented by Brown et al. (2002). The power-law flux of impactors down to about 1cm in diameter derived from these observations is in good agreement (within error) with lunar flash observations (Ortiz et al. 2006; Suggs et al, 2014). For impactors between 1 and 10 meters in diameter, the Brown et al. (2002) flux is also in good agreement with observations from Spacewatch (Rabinowitz et al, 2000), infrasound/acoustic bolide observations (Morbidelli et al, 2002).

Brown et al. (2002) observations are relevant for meteors smaller than 10m. Large meteors are exceedingly rare and are seldom observed over the last century of direct observation. The meteorite which caused the bolide flash over Chelyabinsk in 2013 was estimated to have been 16 to 21 m in diameter (Brown et al 2013). At this size, it was the largest extraterrestrial object to enter the Earth's atmosphere since the 1908 Tunguska event (Whipple, 1930; Ben-Menahem, 1975; Sekanina, 1998), generated the largest bolide flash ever observed by infrasound sensors (Pichon et al. 2013; de Groot and Hedlin, 2014), and is classified by the Brown et al. (2002) power law as a once-in-a-century event. To justify extrapolating the Brown et al. (2002) power-law upwards to meteorites 10m and larger, we cross-reference other flux indicators. The Brown et al, (2002) flux extrapolated upward is consistent with the flux of meteorites derived from the survey of tens-of-meter

asteroids near-Earth asteroids (Werner et al. 2002). Similarly, the upwardly extrapolated Brown et al. (2002) power-law when combined with the Holsapple (1993) cratering efficiency laws is generally consistent with the production of craters of diameter on the order of 100 km predicted by Neukum et al. (2001) and Hartmann (1984; 1999) (Figure 2.4).

The most likely angle at which a meteorite will strike the Moon is $\theta = 45^{\circ}$. It can be shown (Shoemaker 1962) that regardless of the gravitational field of a target planet, the differential probability that a meteoroid from an isotropic flux impacts at an angle between θ and $\theta + d\theta$ is

$$dP(\theta) = 2sin\theta cos\theta d\theta \tag{2.57}$$

From the integral of the above equation it can be shown that more than 75% of all impacts occur at angles where $\theta = 20^{\circ}$ to 70°. The probability a meteorite strikes a glancing blow at $\theta < 5^{\circ}$ is only about 0.75%. Right in the middle of the probability distribution, $\theta = 45^{\circ}$ is the most likely impact angle and a satisfying first-order approximation for the angle of impact for almost all primary impacts. In the following calculations for overturn in the lunar case, we take $\theta = 45^{\circ}$.

To calculate overturn due to primary impactors, we take values from Brown et al. (2002) and normalize to the surface of the Moon, such that $a = 7.25 \times 10^{-14}$ and b = -2.7. The impact velocity of these meteorites is taken to be 20 km s⁻¹: a velocity equal to that used to calibrate the Brown et al. (2002) results. Meteorite density can be assumed to be between 2 and 3 g cm⁻³ based on a summary of a wealth of meteoroid studies (Grün et al. 1985). This places the effective meteoroid density we model somewhere between ordinary and carbonaceous chondrites: $\rho_m = 2.5 \text{g cm}^{-3}$ (Grün et al. 1985; Ceplecha et al. 1998). Using the values in Tables 2.1 and 2.2 and λ values for at least one overturn event at 50% probability (Molina 1942), we compute the following function for the overturn of lunar



Figure 2.5 As the number of overturn events increases, the difference between 10, 50 and 99% probability becomes negligible. Figure (a) shows how values for λ converge at high n values. On the right, we present our calculations of overturn due to primaries with the same axes as Figure 9 in Gault et al. (1974). Here too, as number of turns increases the difference between reworking at different probabilities shrinks. This statistical feature is intuitive: the relative difference between 10,000 and 10,001 turns is smaller than the difference between 1 and 2 turns.

regolith due to primary impactors:

$$\Lambda_P = \begin{cases} 7.07 \times 10^{-7} \ t^{0.59} & \text{if } \Lambda < C_{\Lambda} = 0.60, \\ 1.58 \times 10^{-5} \ t^{0.44} & \text{if } \Lambda > C_{\Lambda} = 0.60 \end{cases}$$
(2.58)

where Λ describes the depth of overturn in meters and t is in years. The turning point between strength and gravity regime, C_{Λ} , is calculated from Equation 2.47 using the material properties for lunar regolith in Table 2.2. We plot overturn calculations due to a flux of primary impactors in Figures 2.5 and 2.6. Figure 2.5b has the same axes as Figure 9 from Gault et al (1974): number of turns vs. depth holding time constant. The shape of the



Figure 2.6 Holding λ constant, we calculate reworking depth as a function of time. As the number of turns increases, the difference between 10, 50 and 99% probability (dotted, dashed, solid lines) shrinks in a manner similar to Figure 2.5b.

contours in Figure 2.5b are similar to the contours in Figure 9 of Gault et al. (1974) because they are controlled by the Poisson-derived average number of events, λ , a parameter both models have in common. In figure 2.5 we see that as the number of turns increases, overturn at 10, 50 and 99% probabilities converge. This is intuitive, as the relative difference between 10,000 and 10,001 turns is smaller than the difference between 1 and 2 turns. In Figure 2.6 we hold the cumulative number of overturns at one and take λ values for some probability (i.e. the top row of Table 2.1) to present an overturned depth as a function of time. In the following sections, we will plot our calculations with axes of reworking depth and time, similar to Figure 2.6.

2.3.2 Lunar Secondaries

To calculate overturn driven by secondaries, we must first constrain their global flux, effective density and impact velocity. We construct a secondary flux based on the work of Shoemaker (1965) and McEwen et al. (2005), assuming each primary described in the Brown et al. (2002) primary flux produces 10^5 secondaries and the maximum secondary block size is 5% of the parent primary size. These assumptions give a flux that follows a power law where $a = 7.25 \times 10^{-9}$ and b = -4. The size distribution of secondary impactors used in this work is similar to that estimated by Speyerer et al. (2016) for the flux of secondary splotches: b = -4.14. The secondary flux that we use in these calculations is on the conservative end of the predictions from McEwen et al.'s 2005 study of Zunil crater, which estimates a size frequency power index of -5 for 10^7 of the 10^8 secondary craters generated per primary impact (see Table 4 of McEwen et al. 2003). Melosh (1984) shows that if a primary meteorite impacts with velocity in the range of 1 to 31 km s⁻¹ (recall we model 20 km s⁻¹ primary impacts), the maximum prompt spall velocity is 0.5 to 1.5 km s⁻¹. In keeping with previous efforts to be relatively conservative in treating the effects of secondaries, for this version of the model we assume that each secondary impactor strikes the lunar surface at a velocity of 0.5 km s^{-1} . This secondary impact velocity is chosen somewhat arbitrarily; however, when the model is tested for sensitivity to impact velocity, it is shown to be a relatively weak parameter in overturn (Figure 2.7a).

The density of secondary impactors can be roughly estimated from Apollo samples. Lunar rock 60025,36 is a ferroan anorthosite with a bulk density between 2200 and 2240 kg m⁻³ (Jeanloz and Ahrens, 1978). Sample 12051,19 is much denser low titanium basalt with a bulk density of 3270 ± 50 kg m⁻³ (Kiefer et al. 2012). For this version of the model, we average the bulk density of all of the non-meteoritic lunar samples reported in Table 1 of Kiefer et al. (2012) and set the density of secondary impactors, $\rho_m = 2780$ kg m⁻³.

This density assumption is a flimsy assumption and presents the opportunity for sensitivity testing. An average of Apollo samples can not realistically represent the density of all secondary impactors. Some variation in density should be expected for impacts into highlands versus maria. As shown in Figure 2.7b, we calculated overturn holding all other variables constant where secondary impactor density was 1000 kgm⁻³ and 4000 kgm⁻³, approximately ± 1000 kgm⁻³ of the density assumed from lunar samples. From this figure it is clear that impactor density is a reassuringly weak parameter in overturn.

One additional assumption has been glossed over in this discussion of secondaries: impact angle. For the above calculations of overturn driven by secondaries, we propagate an earlier assumption that $\theta = 45^{\circ}$ satisfactorily describes the angle of most impacts. This assumption does not hold in the case of secondaries. Intuition and impact studies show that secondaries are much more likely to impact at shallower angles than primaries (e.g. Schultz et al. 2007). To test the model sensitivity to impact angle we hold all other parameters constant and calculate overturn where all secondaries impact at $\theta = 45^{\circ}$ and where all secondaries impact at $\theta = 10^{\circ}$. From this comparison (Figure 2.7c), we see that the model is weakly sensitive to angle of impact. This is reassuring. For the time being, one need not delicately constrain the distribution of secondary impact angles.

The model is dominantly sensitive to the flux of impactors, as is demonstrated in Figure 2.7c. We hold all other values constant and vary only the power index of impact flux. While each flux reaches a meter after about a hundred million years, the steeper flux will excavate depths less than a meter much faster than a shallow impact flux. Our assumed flux of secondaries has a power index of b = -4, and while a steeper power index (e.g. -5 to -7 as suggested by McEwen et al., (2003)) will have significant influence at short timescales, it will not have a strong effect at the deepest depths and longest timescales.

Confident our weakest assumptions will not significantly alter the results, we calculate the rate of overturn using the values for secondary impact cratering in lunar regolith from Table 2.2, and λ values for at least one overturn event at 50% probability (Molina 1942):

$$\Lambda_S = \begin{cases} 4.07 \times 10^{-3} t^{0.33} & \text{if } \Lambda < 0.60, \\ 9.58 \times 10^{-2} t^{0.26} & \text{if } \Lambda > 0.60 \end{cases}$$
(2.59)



Figure 2.7 To test model sensitivity to parameters used in the treatment of secondary impacts, we hold all other values constant and calculate the overturned depth due to secondary impactors for one overturn at 50% probability where: a) impact velocity, v_f , is 0.5ms^{-1} or 0.005ms^{-1} ; b) the impactor density, ρ_m , is 4000 kgm⁻³ or 1000 kgm⁻³, c) the impact angle, θ , is 45° or 10°; and d) where the power index of impact flux, b, is -2.5, -4, or -8. These tests show that the model is weakly sensitive to impact velocity, angle, and the density of the impactor. The model is significantly more sensitive to size distribution of the impact flux, as represented by the power index.

In Figure 2.8 we compare the results of Gault et al. (1974), the calculations of overturn driven by primaries, and calculations of overturn driven by secondaries at 50 and 99% probability. Secondaries appear to have a very strong effect.



Figure 2.8 Overturn calculations for at least one overturn event at 50 and 99% probability. Our results with primaries only predict overturn that is similar to the overturn predicted by Gault et al. (1974); however, the inclusion of secondaries increases the rate of overturn by several orders of magnitude.

In Figure 2.9, we show the overturn driven by secondary impactors at 99% probability that we calculate using the values summarized in the Tables 2.1 and 2.1 and include a conceptual illustration of what these calculations mean. The overturn front where n = 1turn represents the boundary below which material is undisturbed by impacts, and above which material is disturbed. At shallower depths disturbance is more intense, displaying more prominent symptoms for reworking, as surface-correlated materials such as nanophase iron and cosmogenic radionuclides are transported to depth and the measurable fraction of



Figure 2.9 Here we plot the overturn driven by secondary impactors as a function of time (a, b). This figure illustrates how the overturn front represents the lower boundary of overturn. All points at shallower depth than the front are overturned n times or more over the same time interval. Figure c illustrates an imaginary core taken to 10 m depth. Regolith in the imaginary core has been exposed to the overturn driven by secondary impacts for 1Gyr and exhibits the symptoms of impact gardening.

fresh to space-weathered material shifts. The column on the right of Figure 2.9 illustrates an imaginary core drilled to 10 m depth and how a billion years of secondary impacts might show evidence of different levels of overturn in a regolith depth profile.

2.3.3 Validating Overturn Calculations

Apollo Samples

To validate our calculations we explore whether or not the large effect of secondaries is reflected in measurements of reworking (Figures 2.8 and 2.10). The studies of Apollo drill cores presented by Morris (1978) and Blanford et al. (1980) both assume an in situ maturation zone in the top 1 mm of regolith where material accumulates nanophase FeO, cosmic tracks, and other surface-correlated maturity indicators. These mature components are subsequently churned into the underlying regolith by impacts. The vertical extent to which these mature materials have been shuffled into the underlying regolith via overturn is the reworking depth. Morris (1978) and Blanford et al. (1980) assessed Apollo core samples, identified zones with maturity characteristics distinguishable from soil material immediately below or above, and presented a reworking depth by noting the bottom of that zone.

To calculate the vertical extent and timescale of reworking, Morris (1978) measured the depth profile of ferromagnetic resonance index I_s /FeO in Apollo 15 and 17 deep drill cores and correlated these results to the emplacement history of the Apollo 15 and 17 landing sites. Blanford et al. (1980) compiled reworking data based on nuclear track densities. Both datasets suggest that reworking progresses with time following a power-law function of time, and Morris (1978) presented the following best fit expression:

$$\Lambda_{Morris} = 4.39 \times 10^{-5} t^{0.45} \tag{2.60}$$

where Λ_{Morris} is the reworking depth in meters and t is in years. In Figures 2.10 and 2.11 we compare our predicted reworking rates at 50 and 99% probability to the Morris (1978) reworking rate best-fit (Equation 2.60).

Gault et al. (1974) included only the effect of primaries in their calculations. Figure 2.10 shows that overturn calculated using only the flux of primaries is too shallow and infrequent at all timescales compared to the reworking rates calculated by Morris (1978) and Blanford et al. (1980), even for a single overturn event at 50% probability, which does not describe extensive reworking. With secondaries included, we see thorough reworking consistent with the datapoints presented by Morris (1978) and Blanford et al. (1980).

In addition, the timescale calculated by Gault et al. and our model with only primary impacts considered is much too long to account for the observed depth-distribution of ²⁶Al. The shallowest data point from Morris (1978) is at 3 cm and unlike the other data points, it is not based on the abundance of nanophase iron. The point at 2-3 cm depth represents

the extent of the homogenous distribution of cosmogenic radionuclide ²⁶Al in Apollo 15 and 16 deep drill cores calculated by Fruchter et al. (1977). An earlier study of the depth profile of ²⁶Al in Apollo double drive tube 12025 (Rancitelli et al. 1971) showed a similar result: thorough mixing in the top 2-3 cm of the lunar surface. The production rate of ²⁶Al undisturbed by overturn is well constrained by theoretical calculations from solar and galactic proton intensities and energy spectra (Reedy and Arnold, 1972; Rancitelli et al. 1971) and sample measurements (Finkel et al. 1971; Rancitelli et al. 1971, Fruchter et al. 1976). When the depth density of ²⁶Al in cores is decoupled from the undisturbed production rate, it is clear that the global homogenization of ²⁶Al to about 2-3 cm depth is driven by overturn (Fruchter et al. 1976; Fructer et al. 1977, 1978). ²⁶Al has a short half-life, and the million year timescale of the Morris (1978) data point is an upper limit.

Overturn due only to primary impacts is much too infrequent and shallow to produce the thorough mixing implied by the depth distribution of 26 Al in the Apollo cores. It takes a flux of primary impactors hundreds of millions of years to reach 3 cm depth just once with 50% probability. The homogeneous distribution of 26 Al suggests many more than one overturn event has occurred in less than a million years. The flux of secondary impacts appears to be much more effective, thoroughly reworking the regolith at 2-3 cm in less than a million years: a rate consistent with inferences from 26 Al in the Apollo cores.

Surface Features

Calculations with primaries only also fail to account for the reworking rates suggested by observations of lunar surface features at various depths and timescales. Studies of albedobright Copernican rays using Earth-based radar, Lunar Orbiter images, and Clementine UV/VIS maps (Pieters et al. 1985; Hawke et al. 2004; Werner and Medvedev, 2010) describe the depth and longevity of crater rays. Copernican rays last, by definition, about 1Gy and can be as deep as 10 meters (Hawke et al. 2001). Figure 2.11 shows that our calculations are consistent with erasure over this timescale, and suggest that the top 2-3



Figure 2.10 We compare the mixing rates calculated by this model at 50% and 99% probability to the reworking rate presented by Morris (1978) and Blanford et al. (1980). Gault et al. (1974) and our calculations using only the flux of primary impactors show mixing that is too shallow at all timescales. Mixing due to secondaries is much more intense. We see 300 to 10,000 overturn events occurring at depths and over timescales consistent with the reworking calculated form the Apollo cores. The statistics of this model suggest that any specific core that shows evidence of 15 cm overturn is highly unlikely to be due to a primary and that the depth profile of any surface-correlated material in the top meter of regolith is dominantly controlled by overturn due to secondary impacts.

meters of regolith are overturned at least once in a billion years by secondaries at 50% probability, and the top meter is overturned to 99% probability at least once.

Cold spots, anomalously low density regions around young fresh craters (Bandfield et al. 2014), have been discovered in data returned by the Diviner Lunar Radiometer (Paige et al. 2010a, Paige et al. 2010b). Thermal modeling suggests that these density anomalies are at least 10-20 cm thick (Vasavada et al. 2012; Hayne et al. 2013; Bandfield et al. 2014) and size frequency distributions suggest cold spots are ephemeral, persisting on the order of 100,000 years (Williams et al. 2016a, 2016b, 2017). In Figure 2.11, we show that in 100,000 years, our model calculates at least one overturn event has taken place at the maximum depth to which Diviner can sense the existence of cold spots. Provided each new impact

does not make a new cold spot of significant thickness, mixing will eliminate cold spots over the timescale we expect. Regolith overturn may not be required to erase a cold spot; rather, compaction from secondary impacts may alter the depth-density profile, and equilibrating the fluffy cold spot anomalies with the background regolith. Whether by compaction or overturn, it is sufficiently clear that primary impacts alone are too infrequent to fade cold spots.

Another observation of recent lunar impact activity is the presence of "splotches" which appear in Lunar Reconaissance Orbiter Camera (LROC) temporal pairs. Splotches are approximately circular bright or dark features that range in size from 30 m down to LROC's 1 m detection limit. Splotches are reflectance changes that have appeared during operation of the LRO mission, and therefore indicate ongoing surface modification (Speverer et al. 2016). A recent study uses the size distribution and frequency of splotches to reason that the top 2-3cm of regolith are thoroughly mixed in about 80,000 years (Speyerer et al. 2016). In Figure 2.11, we see that our calculations are consistent with this estimate, and suggest the top 2-3cm of regolith is thoroughly reworked by being overturned at least 100 times by secondaries in 80,000 years. The splotch production rate derived by Speyerer et al. (2016) is based on temporal image pairs collected 0.5 to 3.4 years apart. If splotches are secondaries, then the Speyerer et al. (2016) splotch mixing rate is based only on the production of secondaries by small (; 100 m) primary craters and is not representative of the secondary splotch production of larger, rarer impacts. If larger impacts that have not yet been observed create more secondaries (e.g. McEwen et al 2003), and more secondary splotches, then the mixing due to secondary splotches in the top 2-3 cm will be even more thorough.

There is vertical scatter in the ray, cold spot and splotches data points in Figure 2.11 relative to the model. Here again we encounter the issue of 'thorough' reworking. How many overturn events does it take to homogenize ²⁶Al? How many to eliminate a ray? How many overturn events are required to thoroughly rework? The story is complicated further by remaining unknowns in the physics of the creation and reworking of splotches, cold spots,

and rays. Cold spots are density anomalies. Different mechanisms such as compaction likely assist in the dispatch of a cold spot, while compaction holds little sway in explosively mixing away a ray. Gaps remain in our understanding of the processes at work; however, it should be evident from the production rate, depth, and longevity of these surface features that the flux of primary impacts alone could not produce splotches or erase cold spots and rays. Using the impact flux applied here, the effect of primaries only overtakes those of secondaries well beyond 4.5 Gyr. To first order, we can conclude that the overturn driven by secondaries on the top meter of regolith are significant. The exact magnitude of the overturn, whether it is one or ten thousand events, is a topic for future exploration.



Figure 2.11 The mixing due to secondaries calculated by this model is consistent with the thorough reworking of the top 3 cm of regolith reasoned by Speyerer et al. (2016) from observations of splotches in LROC temporal pairs, the elimination of 20cm deep cold spots over one to two hundred thousand years, and the erasure of 1 m deep rays over about a billion years. Note that as the number of overturn events increases, the difference between 50 and 99% probability shrinks. At 10,000 overturn events, the difference is negligible.

2.3.4 Lunar Micrometeorites

One of the main results of Gault et al. (1974) was the presence of a mixing layer in the top mm of regolith. This mixing layer was characterized by extreme rates of overturn and was driven by a flux of micrometeorites six orders of magnitude greater than the flux of larger objects from space. Since 1974, a wealth of studies have been conducted in an effort to constrain the flux of micrometeorites onto the surface of the Moon.

Constraints on the flux of micrometeorites come from two main lines of evidence: first, the presence of zap-pits on lunar rocks, which have been known since the first rocks were returned from the Moon (Hörz and Hartung 1971; Bloch et al. 1971; Schneider et al. 1973); and second, damage to spacecraft. Grün et al. (1985) present a comprehensive flux model for meteorites smaller than about 1 cm that is based on spacecraft data from Pegasus and Explorer (Whipple, 1967; Hörz et al. 1975; Naumann, 1966), the meteoroid detector on board the Helios spacecraft (Grün et al. 1980), Pioneers 8 and 9 (Berg and Gerloff, 1971; McDonnell, 1978), HEOS-2 (Hoffmann et al. 1975a, b), and Helios (Gruin et al. 1980), and the size distribution of lunar microraters observed on lunar rock samples (Morrison and Zinner, 1977; Morrison and Clanton, 1979).

We assume all micrometeoroid impactors are spherical, have an effective density of 2.5 kg cm^{-3} , and impact velocity 20 km s^{-1} ; our velocity and density assumptions are consistent with those used by Grün et al. (1985) to derive flux from pit populations in lunar rocks. From the data presented in Table 1 in Grün et al. (1985), we use a non-linear least squares method to calculate the power law best fit to the cumulative size distribution of meteorites that impact the lunar surface per meter per year:

$$N_{\rm Grün} = 1.53 \times 10^{-12} D_m^{-2.64} \tag{2.61}$$

where N is in units of cumulative number per meter year, and, again, D_m is meteorite diameter. In Figure 2.12 we see that for meteorite diameters 1 cm and larger, the Grün et



Figure 2.12 In this comparison of the size distribution of flux from Grün et al. (1985) and Brown et al. (2002), we observe that the flux of micrometeorites is governed by a power-law that is similar to the flux of larger meteorites, even down to tens of nanometer particles of dust. The Grün et al. (1985) lunar flux model displays some waviness; although there is a discontinuity between the best fit we calculated and the Brown et al. (2002) power-law, the Grün et al. (1985) lunar flux model is in excellent agreement with Brown et al. (2002) where meteorites are 1cm in diameter and larger.

al. (1985) lunar flux model is in excellent agreement with the Brown et al. (2002) flux. At smaller diameters, the Grün et al. (1985) flux is within an order of magnitude higher.

Let us note that as the size of meteorites shrinks, the concept of overturn increasingly fails to describe the real physical processes at work. Although we have a power law of flux that is valid down to tens of nanometers, these particles will not overturn regolith on impact. The model presented here describes the frequency with which a point at depth is component in the excavated volume of a crater. In larger size regimes, where the target is generally particulate, we describe the inversion of regolith as a metaphor for gardening. In contrast, material that is struck by a micrometeorite experiences a different energy partitioning regime, where more energy is spent as heat than kinetic overturn (Anders et al. 2012).



Figure 2.13 We calculate the rate of overturn driven by the flux of micrometeorites from Grün et al (1985). Hardness is not a very strong parameter in the model. The depth considered excavated is stronger, but does not drive orders of magnitude changes in overturn. The sensitivity to the depth considered overturned dH is asymmetrical because of crater geometry rules we outline in Section 2.1 (Figure 2.2). As the depth considered overturned increases, fewer distal craters successfully overturn a point at depth. If the depth considered overturned is shallow, more distal craters can successfully overturn the point at depth.

For this treatment of overturn driven by the flux of very small impactors, we assume that any impactor that is about a micron or larger could reasonably overturn regolith. With this assumption, despite the physical reality issues, we calculate the overturn rate driven by micrometeorites using the Grün et al. (1985) flux and the material parameters for regolith from Table 2.2 input to the overturn function in the strength regime, Equation 2.39. The following represents the overturn rate driven by primary micrometeorites for at least one
overturn occuring at 50% probability:

$$\Lambda_M = 2.52 \times 10^{-6} t^{0.61} \tag{2.62}$$

where Λ_M represents the overturn depth as a function of time, t, in units of meters and years. Because energy partitioning at this small scale likely alters the distribution of material provenance in an impact, this analysis presents an opportunity to test the model sensitivity to the magnitude of the depth considered overturned, dH (see Figure 2.2). In Figure 2.13 we compare the overturn rate where $d = \frac{1}{2}, \frac{1}{3}$, and $\frac{1}{6}$ in regular regolith and in hard rock. It is surprising how insensitive the model is to this parameter, but let us recall from section 2.1: The Poisson Expression, that the deeper we consider excavation, the closer distal impacts of the same diameter must strike to excavate a point at depth ($c = \frac{1}{2}\sqrt{1-d}$). The inverse geometric relationship between depth and proximity damps model response to these parameters. This test shows that although small simple craters may be shallower than larger simple craters (Stopar et al. 2017; Mahanti et al. 2018), the overturn model is relatively insensitive to how we define overturn depth and crater depth-diameter ratios.

In Figure 2.14 we plot our calculated overturn driven by the largest small meteorites described by Grün et al. (1985) (D_m up to 10 cm) and compare to the overturn driven by the Brown et al. (2002) primary flux. Our overturn calculations using the flux of small primaries falls off at overturn depths on the order of 1 cm (Figure 2.14a). Figure 2.14 and previous discussion of secondary impacts show that flux is clearly the strongest driving parameter in this model and the fall off of overturn at 1 cm depth is a result of a fall in the number of meteorites 1 mm and larger. The best fit we calculated to the Grün et al. (1985) lunar flux model (Equation 2.61) begins to significantly overestimate the number of meteorites starting around 1 mm. For meteorites larger than 1 mm, the primary flux of falls off from Grün et al. (1985) to the flux from Brown et al. (2002) (Figure 2.14b). Even with the higher flux of small meteorites from Grün et al. (1985), the overturn driven by primary



Figure 2.14 a) Overturn driven by both the small meteorite flux described by Grün et al. (1985) and the flux of larger meteorites described by Brown et al. (2002) and a comparison to the reworking calculated by Morris (1978) and Blanford et al. (1980). b) A comparison of the Brown et al (2002) flux, Grün et al. (1985) flux, and the best fit we calculated for the Grün et al. (1985) flux (Equation 2.61). The best fit we calculated for the Grün et al. (1985) data begins to differ significantly from the Grün et al. (1985) lunar flux model at meteorite diameters of about 1 mm. That is overturn at about 1cm. As meteorites increase in size, the flux model dips towards an agreement with Brown et al. (2002). Even with significantly higher overturn due to small meteorites in the top 1 cm of regolith, overturn calculations that only consider the impact of primaries fail to describe the reworking depth and rate calculated from Apollo cores.

impacts only is too shallow at all timescales to produce the reworking rate calculated from Apollo cores (Morris 1978; Blanford et al. 1980).

2.4 Conclusions

Using the core concepts presented by Gault et al. (1974) we present a generalized model that describes the rate and probability a point at depth experiences overturn as a function of time. By using material parameters consistent with lunar regolith and impact flux, we calculate the rate and probability of overturn in the lunar case. Compared to the overturn rate driven by the modern flux of primaries, overturn due to secondaries is in much better agreement with the Morris (1978) reworking rate and the depth-distribution of ²⁶Al measured in Apollo cores. This is especially true at short timescales and shallow depths. Further, overturn due to secondaries better describes the rate at which surface features such as splotches rework the regolith and the rate at which cold spots and rays are reworked into the background. We conclude from these comparisons that secondaries are the dominant driver of overturn in the top meter of lunar regolith.

Superficially, calculations of overturn driven by micrometeorites could be improved by using the dust flux from studies of LADEE and LDEF data (e.g. Meshishnek et al. 1993; Horanyi et al. 2015; Szalay and Horanyi, 2016). More fundamentally, future incarnations of our model should include cratering laws and energy-partitioning that are designed specifically to describe micro-impacts. Another fundamental issue remains unaddressed in this treatment of micrometeorite overturn: the effects of micro-secondaries. Zook et al. (1984) impact experiments show that the pitting observed in lunar samples is probably dominated by high-speed secondary impacts and not by primary meteoroid impacts.

Evidence of mixing does not discriminate between primaries, secondaries, slumping, jetting or astronaut footprints. The depth-distribution of surface correlated materials observed in Apollo cores and the rate at which cold spots and rays disappear are the result of a complicated system of mixers. Determining the relative influence of each mixing driver is important for future modeling of regolith evolution. Here we have treated only one kind of regolith mixing: vertical excavation form cratering events. Because the mixing rates we predict with a flux of secondary impacts included are reasonable, one could argue that the vertical mixing of regolith is dominantly driven by secondary distal ejecta that produce secondary craters. Inferences about lateral transport and horizontal mixing are currently beyond the scope of this model; however, by better constraining the treatment of secondaries, we may be able to investigate mixing in three dimensions and compare our results to lateral mixing models (e.g Huang et al. 2017) in the future.

The treatment of secondaries used in this work could be improved to first order by a piece-wise power law or polynomial re-casting of flux as well as a treatment of the velocity and impact angle distributions of secondary projectiles. Recall that in this work we crudely assume that all secondaries impact the lunar surface at 0.5 km s⁻¹, the minimum in the range of maximum spall velocities (Melosh, 1984). By working in the ejecta size-velocity relationships presented by Vickery (1987), Cintala et al. (1999), Nakamura and Fujiwara (2001), Hirase et al (2004), and Hirata and Nakaumra (2006) this model could include a treatment of the strong negative relationship between fragment size and velocity. Revisions to the size distribution and velocity of secondary impactors and the interrelationship between these parameters will likely force the rate of secondary-driven overturn down. Even if these corrections push overturn orders of magnitude lower, going from 100,000 to 10 overturn events in the top 3 cm of regolith would still be a reasonable indicator of thorough reworking and in better agreement with the Morris (1978) data than primary-driven overturn.

Thinking of secondaries in terms of their dependent relationship on primaries casts a pall of uncertainty on the fundamental assumption that impacts follow a Poisson distribution. The spatial distribution of secondaries is inextricably linked to primary impacts. The flux of secondaries onto the Moon is not uniformly distributed; rather, the likelihood a point is overturned by a secondary impact is largely dependent on proximity to the primary impact crater. Even proximity is no guarantee when secondary-forming ejecta fall in clusters, spokes, and rays (Schultz and Gault 1985, Vickery 1986; Melosh 1989; Kadono et al. 2015) and shallow angle primary impacts display an asymmetric ejecta distribution (Gault and Wedekind, 1978). In addition to the relationship between size, velocity, and impact angle, secondaries are also controlled by the location of their parent primary impact. The size distribution and density of secondary impactors is location dependent; a primary impactor that strikes the maria will produce a different size and density distribution of secondaries than an impactor that strikes the highlands. Regardless of location, any primary impactor that is too small to pierce the regolith layer will be accompanied by a different distribution of secondary craters than a crater that excavates blocks of basaltic melt or mare. These concerns call for an existential reassessment of the statistics used by this model for secondary impacts.

The power of the Gault et al. model is in its analytic nature. This overturn model can serve as a computationally inexpensive vanguard for future exploration of impact gardening. Results can be used to identify important parameters for more detailed study; for example, in the lunar case, we see that secondaries have a profound effect on the evolution of lunar regolith and call for more detailed analysis. For less computational cost than a single run of a sophisticated Monte Carlo model dedicated to the exploration of regolith evolution (e.g. Oberbeck et al. 1973; Oberbeck 1975; Arnold 1975; Borg et al. 1976; Duraud et al. 1975; Crider and Vondrak, 2003; Vondrak and Crider, 2003; Huang et al. 2017), this analytic model can yield a large number of results providing deep insights into the fundamental drivers of overturn in seconds. The ease with which the model can be deployed makes it a useful tool in the exploration the Moon and beyond. A particular strength of the generalized approach presented here is that it allows the opportunity to describe the impact gardening rate to first order on any airless body. In this work we pay respect to the rich heritage of Lunar science by revitalizing the model by Gault et al. (1974), and facilitate the extension of this Apollo-era vision across the solar system.

Appendix

Values Used in this Manuscript						
$\pmb{\lambda}$: the average number of events per interval from the Cumulative Poisson Distribution						
<i>n</i> : the	Percent Probability					
number of events	10%	50%	99%			
1	0.105	0.693	4.605			
2	0.530	1.678	6.638			
3	1.102	2.674	8.406			
4	1.742	3.672	10.05			
6	3.150	5.670	13.11			
8	4.655	7.670	16.00			
10	6.221	9.670	18.87			
20	14.53	19.67	31.85			
30	23.33	29.67	44.19			
40	32.11	39.67	56.16			
10 ²	87.42	99.67	1.247 x 10 ²			
3 x 10 ²	2.780 x 10 ²	2.997 x 10 ²	3.418 x 10 ²			
10 ³	9.596 x 10 ²	9.997 x 10 ²	1.075 x 10 ³			
3 x 10 ³	2.930 x 10 ³	3.000 x 10 ³	3.129 x 10 ³			
10 ⁴	9.872 x 10 ³	1.000 x 10 ⁴	1.023 x 10 ⁴			
3 x 104	2.978 x 10 ⁴	3.000 x 10 ⁴	3.041 x 10 ⁴			
10 ⁵	9.959 x 10 ⁴	1.000 x 10 ⁵	1.007 x 10 ⁵			
3 x 10 ⁵	2.993 x 10⁵	3.000 x 10 ⁵	3.013 x 10⁵			
106	9.9687 x 10⁵	1.000 x 10 ⁶	1.002 x 10 ⁶			

Table 1

Table 2.1 Values for λ from solutions to the cumulative Poisson equation at 10, 50, and 99% probability.

	Parameter Description	Values Used in this Manuscript (m yrs kg)			
		Primaries	Secondaries	Micrometeorites	
а	Magnitude of the cumulative impact flux.	6.3 x 10 ⁻¹¹	7.25 x 10⁻ ⁹	1.53 x 10 ⁻¹²	
b	Power index of the cumulative impact flux.	-2.7	-4	-2.64	
Vf	Final impact velocity.	5.7 x 10 ¹¹	1.6 x 10 ¹⁰	5.7 x 1011	
ρm	Density of the impacting body.	2500	2780	2500	
θ	Impact angle. (degrees)	45			
С	Proximity scalar for overlapping craters	0.41			
d	Fraction of crater depth considered overturned.	1/3			
g	The gravity of the planetary body.	1.61 x 10 ¹⁵			
i	Magnitude of the cumulative crater production.	-			
j	Power index of the cumulative crater production.	-			
Crat onlin Willi in Ta	er scaling parameters from material published ne (Holsapple, 2003) and from Table 2 in ams et al. (2014), which supersede the values able 1 of Holsapple (1993).	Lunar Regolith	Soft Sand	Hard Rock	
<i>K</i> ₁	Empirically derived crater scaling parameter.	0.132	0.132	0.095	
K2	Empirically derived crater scaling parameter.	0.26	0	0.257	
Kr	Empirically derived crater scaling parameter.	1.1	1.4	1.1	
K _d	Empirically derived crater scaling parameter.	0.6	0.35	0.6	
μ	Empirically derived crater scaling parameter that varies by target porosity.	0.41	0.41	0.55	
Y	Target yield strength. (MPa)	0.01	0	10	
$ ho_t$	Target density.	1500	1700	3200	
С	The strength / gravity crater scaling transition impactor size (calculated using lunar values).		0.05		
Cл	The strength / gravity crater scaling transition depth (calculated using lunar values).	0.6			

Table 2

Table 2.2 A list of parameters and definitions used to convert impactor size to crater size.

Summary of Important Functions	Important Equations	Eqn. No.
The cumulative number of overturning events per area time from the Poisson distribution .	$N_U(\ge D_c) = \frac{4\lambda}{\pi c^2 D_c t}$	(27)
The cumulative number of impactors per area time from flux .	$N_F(\ge D_m) = aD_m^b$	(28)
The cumulative number of events per interval from the Poisson distribution .	$V_t(D_m) = K_1 \left(\frac{\pi D_m^3 \rho_m}{6\rho_t}\right) \left\{ \left(\frac{gD_m}{2v_f^2}\right) \left(\frac{\rho_m}{\rho_t}\right)^{\frac{1}{3}} + K_2 \left[\left(\frac{Y}{\rho_t v_f^2}\right)^{\frac{2+\mu}{2}} \right] \right\}^{\frac{-3\mu}{2+\mu}}$	(32)
The strength / gravity crater scaling transition impactor diameter.	$C = \frac{\alpha}{\epsilon}$	(46)
The strength / gravity crater scaling transition depth.	$C_{\Lambda} = \frac{K_d}{2K_r} \delta \left\{ \gamma C^3 \left[\epsilon C + \alpha \right]^{\beta} \right\}^{\frac{1}{3}}$	(47)
Overturn as a function of time in the gravity and strength regime.	$\Lambda(t,\lambda) = \begin{cases} \eta_s t^{\zeta_s} & \text{if } \Lambda < C_\Lambda \text{ and } b < -1, \\ \eta_g t^{\zeta_g} & \text{if } \Lambda > C_\Lambda \text{ and } b < \frac{(\beta+3)}{3} \end{cases}$	(49)
The magnitude of overturn in the strength regime.	$\eta_s = \sin^{\frac{2}{3}}(\theta) \frac{dK_d}{2K_r} \left\{ \lambda \frac{4 \left[\delta(\gamma \alpha^\beta)^{\frac{1}{3}} \right]^b}{ac^2 \pi} \right\}^{\frac{1}{b+1}}$	(50)
The power index of overturn in the strength regime.	$\zeta_s = -\left(\frac{1}{b+1}\right)$	(51)
The magnitude of overturn in the gravity regime.	$\eta_g = \sin^{\frac{1}{3}}(\theta) \frac{dK_d}{2K_r} \left\{ \lambda \frac{4 \left[\delta(\gamma \epsilon^\beta)^{\frac{1}{3}} \right]^{\frac{3b}{3+\beta}}}{ac^2 \pi} \right\}^{\frac{3+\beta}{3b+3+\beta}}$	(52)
The power index of overturn in the gravity regime	$\zeta_g = -\Big(rac{3+eta}{3b+3+eta}\Big)$	(53)
The number of craters per area time from a crater production function.	$N_{SFD} (\ge D_c) = u D_c^v$	(55)
Overturn as a function of time from a size frequency distribution of craters.	$\Lambda_{SFD} = dH \left(\frac{4\lambda}{u\pi c^2 t}\right)^{\frac{1}{v+1}}$	(56)
	$\alpha = K_2 \left(\left(\frac{Y}{\rho_t v_f^2} \right)^{\frac{2+\mu}{2}} \right)$	-
Variables defined to economize	$\beta = \frac{-3\mu}{2+\mu}$	-
crater scaling parameters and simplify the algebra that produces the overture function	$\delta = 2K_r$	-
uie overturn function.	$\gamma = \frac{K_1 \pi \rho_m}{6\rho_t}$	-
	$\epsilon = \big(\frac{g}{2v_f^2}\big)\big(\frac{\rho_m}{\rho_t}\big)^{\frac{1}{3}}$	-

Table 3

Table 2.3 Equations used with equation numbers and descriptions.

References

Allen, C.C., 1979. Large lunar secondary craters: size-range relationships. Geophys. Res. Lett. 6 (1), 51–54.

Anders, C., Bringa, E.M., Fioretti, F.D., Ziegenhain, G., Urbassek, H.M., 2012. Crater formation caused by nanoparticle impact: a molecular dynamics study of crater vo- lume and shape. Phys. Rev. B 85 (23), 235440.

Anderson, J.L., Schultz, P.H., Heineck, J.T., 2003. Asymmetry of ejecta flow during oblique impacts using three-dimensional particle image velocimetry. Journal of Geophysical Research: Solid Earth 108 (E8). http://dx.doi.org/10.1029/ 2003JE002075.

Arnold, J.R., 1975. A monte carlo model for the gardening of the lunar regolith. Earth Moon Planets 13 (1), 159–172.

Bandfield, J.L., Song, E., Hayne, P.O., Brand, B.D., Ghent, R.R., Vasavada, A.R., Paige, D.A., 2014. Lunar cold spots: granular flow features and extensive insulating materials surrounding young craters. Icarus 231, 221–231.

Bart, G.D., Melosh, H., 2007. Using lunar boulders to distinguish primary from distant secondary impact craters. Geophys Res Lett 34 (7), L07203. http://dx.doi.org/10. 1029/2007GL029306.

Ben-Menahem, A., 1975. Source parameters of the siberian explosion of june 30, 1908, from analysis and synthesis of seismic signals at four stations. Phys. Earth Planet. Inter. 11 (1), 1–35.

Berg, O., Gerloff, U., 1971. More than two years of micrometeorite data from two pioneer satellites. Space Research XI. pp. 225–235.

Blake, M.L., Wasserburg, G., 1975. Cratering and cosmogenic nuclides. Geophys. Res. Lett. 2 (11), 477–479.

Blanford, G., 1980. Cosmic ray production curves below reworking zones. Proceedings of the Conference on Lunar and Planetary Science. 11. pp. 1357–1368.

Bloch, M., Fechtig, H., Gentner, W., Neukum, G., Schneider, E., 1971. Meteorite impact craters, crater simulations, and the meteoroid flux in the early solar system. Proceedings of the Conference on Lunar and Planetary Science. 2. pp. 2639.

Borg, J., Comstock, G., Langevin, Y., Maurette, M., Jouffrey, B., Jouret, C., 1976. A monte carlo model for the exposure history of lunar dust grains in the ancient solar wind. Earth Planet. Sci. Lett. 29 (1), 161–174.

Brown, P., Assink, J., Astiz, L., Blaauw, R., Boslough, M., Borovička, J., Brachet, N., Brown, D., Campbell-Brown, M., Ceranna, L., et al., 2013. A 500-kiloton airburst over chelyabinsk and an enhanced hazard from small impactors. Nature 503 (7475), 238–241.

Brown, P., Spalding, R., ReVelle, D., Tagliaferri, E., Worden, S., 2002. The flux of small near-earth objects colliding with the earth. Nature 420 (6913), 294.

Ceplecha, Z., Borovička, J., Elford, W.G., ReVelle, D.O., Hawkes, R.L., Porubčan, V., Šimek, M., 1998. Meteor phenomena and bodies. Space Sci. Rev. 84 (3–4), 327–471.

Chapman, C.R., McKinnon, W.B., 1986. Cratering of planetary satellites. IAU Colloq. 77: Some Background about Satellites. pp. 492–580.

Chappelow, J., 2013. Simple impact crater shape determination from shadows. Meteorit. Planet. Sci. 48 (10), 1863–1872.

Chappelow, J.E., Sharpton, V.L., 2002. An improved shadow measurement technique for constraining the morphometry of simple impact craters. Meteorit. Planet. Sci. 37 (4), 479–486.

Cintala, M.J., Berthoud, L., Hörz, F., 1999. Ejection-velocity distributions from impacts into coarse-grained sand. Meteorit. Planet. Sci. 34 (4), 605–623.

Cintala, M.J., McBride, K.M., 1995. Block distributions on the lunar surface: a comparison between measurements obtained from surface and orbital photography. NASA-TM- 104804, NAS 1.15:104804, S-782, NIPS-96-07702. NASA Johnson Space Center, Houston, TX, United States.

Crider, D., Vondrak, R., 2003. Space weathering of ice layers in lunar cold traps. Adv. Space Res. 31 (11), 2293–2298. Duraud, J., Langevin, Y., Maurette, M., Comstock, G., Burlingame, A., 1975. The simulated depth history of dust grains in the lunar regolith. Proceedings of the Conference on Lunar and Planetary Science. 6. pp. 2397–2415.

Finkel, R., Arnold, J., Imamura, M., Reedy, R., Fruchter, J., Loosli, H., Evans, J., Delany, A., Shedlovsky, J., 1971. Depth variation of cosmogenic nuclides in a lunar surface rock and lunar soil. Proceedings of the Conference on Lunar and Planetary Science. 2. pp. 1773.

Flavill, R., Allison, R., McDonnell, J., 1978. Primary, secondary and tertiary microcrater populations on lunar rocks effects of hypervelocity impact microejecta on primary populations. Proceedings of the Conference on Lunar and Planetary Science. 9. pp. 2539–2556.

Fruchter, J., Rancitelli, L., Evans, J., Perkins, R., 1978. Lunar surface processes and cosmic ray histories over the past several million years. Proceedings of the Conference on Lunar and Planetary Science. 9. pp. 2019–2032.

Fruchter, J., Rancitelli, L., Laul, J., Perkins, R., 1977. Lunar regolith dynamics based on analysis of the cosmogenic radionuclides na-22, al-26, and mn-53. Proceedings of the Conference on Lunar and Planetary Science. 8. pp. 3595–3605.

Fruchter, J., Rancitelli, L., Perkins, R., 1976. Recent and long-term mixing of the lunar regolith based on na-22 and al-26 measurements in apollo 15, 16, and 17 deep drill stems and drive tubes. Proceedings of the Conference on Lunar and Planetary Science. 7. pp. 27–39.

Gault, D., Hörz, F., Brownlee, D., Hartung, J., 1974. Mixing of the lunar regolith. Proceedings of the Conference on Lunar and Planetary Science. 5. pp. 2365–2386.

Gault, D.E., Hörz, F., Hartung, J.B., 1972. Effects of microcratering on the lunar surface. Proceedings of the Conference on Lunar and Planetary Science. 3. pp. 2713.

Gault, D.E., Wedekind, J.A., 1978. Experimental studies of oblique impact. Proceedings of the Conference on Lunar and Planetary Science. 9. pp. 3843–3875. de Groot-Hedlin, C.D., Hedlin, M.A., 2014. Infrasound detection of the chelyabinsk meteor at the usarray. Earth Planet. Sci. Lett. 402, 337–345.

Grün, E., Pailer, N., Fechtig, H., Kissel, J., 1980. Orbital and physical characteristics of micrometeoroids in the inner solar system as observed by helios 1. Planet. Space. Sci. 28 (3), 333–349.

Grün, E., Zook, H., Fechtig, H., Giese, R., 1985. Collisional balance of the meteoritic complex. Icarus 62 (2), 244–272.

Grün, E., Zook, H.A., Fechtig, H., Giese, R.H., 1985. Collisional balance of the meteoritic complex. Icarus 62 (2), 244–272.

Halliday, I., Griffin, A.A., Blackwell, A.T., 1996. Detailed data for 259 fireballs from the canadian camera network and inferences concerning the influx of large meteoroids. Meteorit. Planet. Sci. 31 (2), 185–217.

Harmon, J.K., Perillat, P.J., Slade, M.A., 2001. High-resolution radar imaging of mercury's north pole. Icarus 149 (1), 1–15.

Hartmann, W.K., 1984. Does crater saturation equilibrium occur in the solar system? Icarus 60 (1), 56–74.

Hartmann, W.K., 1999. Martian cratering vi: crater count isochrons and evidence for recent volcanism from mars global surveyor. Meteorit. Planet. Sci. 34 (2), 167–177.

Hartmann, W.K., Gaskell, R.W., 1997. Planetary cratering 2: studies of saturation equi- librium. Meteorit. Planet. Sci. 32 (1), 109–121.

Hawke, B.R., Blewett, D., Lucey, P., Smith, G., Bell, J., Campbell, B., Robinson, M., 2004. The origin of lunar crater rays. Icarus 170 (1), 1–16.

Hayne, P., Ghent, R., Bandfield, J., Vasavada, A., Siegler, M., Greenhagen, B., Williams, J.-P., Paige, D., 2013. Formation and evolution of the moon's upper regolith: con- straints from diviner thermal measurements. Proceedings of the Conference on Lunar and Planetary Science. 44. pp. 3003.

Heiken, G., Vaniman, D., French, B.M., 1991. Lunar Sourcebook: A user's Guide to the Moon. CUP Archive.

Hirabayashi, M., Minton, D.A., Fassett, C.I., 2017. An analytical model of crater count equilibrium. Icarus 289, 134–143.

Hirase, Y., Nakamura, A.M., Michikami, T., 2004. Ejecta size-velocity relation derived from the distribution of the secondary craters of kilometer-sized craters on mars. Planet. Space Sci. 52 (12), 1103–1108.

Hirata, N., Nakamura, A.M., 2006. Secondary craters of tycho: size-frequency distributions and estimated fragment size-velocity relationships. J. Geophys. Res. Planets 111 (E3).

Hoffman, H.-J., Fechtig, H., Grün, E., Kissel, J., 1975. Temporal fluctuations and anisotropy of the micrometeoroid flux in the earth-moon system measured by heos 2. Planet. Space Sci. 23 (6), 985–991.

Hoffmann, H.-J., Fechtig, H., Grün, E., Kissel, J., 1975. First results of the micrometeoroid experiment s 215 on the heos 2 satellite. Planet. Space Sci. 23 (1), 215–224.

Holsapple, K., 1993. The scaling of impact processes in planetary sciences. Annu. Rev. Earth Planet. Sci. 21 (1), 333–373.

Holsapple, K., 2003. Theory and equations for craters from impacts and explosions. St. Louis, MO: Washington University.

Holsapple, K., Schmidt, R., 1980. On the scaling of crater dimensions: 1. Explosive pro- cesses. J. Geophys. Res. Solid Earth 85 (B12), 7247–7256.

Holsapple, K., Schmidt, R., 1982. On the scaling of crater dimensions: 2. Impact processes. J. Geophys. Res. Solid Earth 87 (B3), 1849–1870.

Horanyi, M., Szalay, J., Kempf, S., Schmidt, J., Grün, E., Srama, R., Sternovsky, Z.,
2015. A permanent, asymmetric dust cloud around the moon. Nature 522 (7556), 324–326.
Hörz, F., Brownlee, D., Fechtig, H., Hartung, J., Morrison, D., Neukum, G., Schneider,
E., Vedder, J., Gault, D., 1975. Lunar microcraters: implications for the micrometeoroid complex. Planet. Space Sci. 23 (1), 151–172.

Hörz, F., Hartung, J., Gault, D., 1971. Micrometeorite craters on lunar rock surfaces.
J. Geophys. Res. 76 (23), 5770–5798.

Huang, Y.-H., Minton, D.A., Hirabayashi, M., Elliott, J.R., Richardson, J.E., Fassett, C.I., Zellner, N.E., 2017. Heterogeneous impact transport on the moon. J. Geophys. Res. Planets 122, 1158–1180. http://dx.doi.org/10.1002/2016JE005160.

Hurley, D.M., Lawrence, D.J., Bussey, D.B.J., Vondrak, R.R., Elphic, R.C., Gladstone, G.R., 2012. Two-dimensional distribution of volatiles in the lunar regolith from space weathering simulations. Geophys. Res. Lett. 39 (9), L09203. http://dx.doi.org/10. 1029/2012GL051105.

Ivanov, B., 2008. Size-frequency Distribution of Asteroids and Impact Craters: Estimates of Impact Rate. Catastrophic Events Caused by Cosmic Objects. Springer, pp. 91–116.

Ivanov, B., Neukum, G., Wagner, R., 1999. Impact craters, nea, and main belt asteroids: size-frequency distribution. Proceedings of the Conference on Lunar and Planetary Science. 30.

Ivanov, B., Neukum, G., Wagner, R., 2001. Size-frequency distributions of planetary impact craters and asteroids. Collisional Processes in the Solar System. Springer, pp. 1–34.

Jeanloz, R., Ahrens, T.J., 1978. The equation of state of a lunar anorthosite-60025. Proceedings of the Conference on Lunar and Planetary Science. 9. pp. 2789–2803.

Kadono, T., Suzuki, A., Wada, K., Mitani, N., Yamamoto, S., Arakawa, M., Sugita, S., Haruyama, J., Nakamura, A., 2015. Crater-ray formation by impact-induced ejecta particles. Icarus 250, 215–221.

Kiefer, W.S., Macke, R.J., Britt, D.T., Irving, A.J., Consolmagno, G.J., 2012. The density and porosity of lunar rocks. Geophys Res Lett 39 (7), L07201. http://dx.doi.org/10. 1029/2012GL051319.

Le Pichon, A., Ceranna, L., Pilger, C., Mialle, P., Brown, D., Herry, P., Brachet, N., 2013. The 2013 russian fireball largest ever detected by ctbto infrasound sensors. Geophys. Res. Lett. 40 (14), 3732–3737.

Mahanti, P., Robinson, M., Thompson, T., Henriksen, M., 2018. Small lunar craters at the apollo 16 and 17 landing sites-morphology and degradation. Icarus 299, 475–501.

McDonnell, J., 1978. Microparticle studies by space instrumentation. Cosmic Dust. (A78- 38226 16-90) Chichester, Sussex, England and New York, Wiley-Interscience, pp. 337-426.

McDonnell, J., Allison, R., 1981. Lunar microcrater records: where is the cometary efflux? Proceedings of the Conference on Lunar and Planetary Science. 12. pp. 682–684.

McEwen, A.S., Bierhaus, E.B., 2006. The importance of secondary cratering to age constraints on planetary surfaces. Annu. Rev. Earth Planet. Sci. 34, 535–567.

McEwen, A.S., Preblich, B.S., Turtle, E.P., Artemieva, N.A., Golombek, M.P., Hurst, M., Kirk, R.L., Burr, D.M., Christensen, P.R., 2005. The rayed crater zunil and interpretations of small impact craters on mars. Icarus 176 (2), 351–381.

Melosh, H., 1984. Impact ejection, spallation, and the origin of meteorites. Icarus 59 (2), 234–260.

Melosh, H.J., 1989. Impact Cratering: A Geologic Process. Oxford University Press. Research supported by NASA. New York, (Oxford Monographs on Geology and Geophysics, No. 11) 253 p. 11.

Meshishnek, M., Gyetvay, S., Paschen, K., Coggi, J., 1993. Long duration exposure facility (ldef) experiment m0003 meteoroid and debris survey. NASA. Langley Research Center, LDEF: 69 Months in Space. Second Post-Retrieval Symposium, Part 2. pp. 357–415.

Molina, E.C., 1942. Poisson's exponential binomial limit: Table i – individual terms, table ii – cumulated terms. Oxford, England: Van Nostrand.

Molina, R.J., 1966. The near-earth meteoroid environment. Calibration of Pegasus and Explorer XXIII Detector Panels, NASA Tech. Rep. TR R-321.

Morbidelli, A., Jedicke, R., Bottke, W., Michel, P., Tedesco, E., 2002. From magnitudes to diameters: the albedo distribution of near earth objects and the earth collision ha- zard. Icarus 158 (2), 329–342. Morris, R., 1978. In situ reworking/gardening/of the lunar surface-evidence from the apollo cores. Proceedings of the Conference on Lunar and Planetary Science. 9. pp. 1801–1811.

Morrison, D., Clanton, U., 1979. Properties of microcraters and cosmic dust of less than 1000 a dimensions. Proceedings of the Conference on Lunar and Planetary Science. 10. pp. 1649–1663.

Morrison, D., Zinner, E., 1977. 12054 and 76215-new measurements of interplanetary dust and solar flare fluxes. Proceedings of the Conference on Lunar and Planetary Science. 8. pp. 841–863.

Nakamura, A., Fujiwara, A., 1991. Velocity distribution of fragments formed in a simulated collisional disruption. Icarus 92 (1), 132–146.

Neukum, G., 1983. Meteoritenbombardement und datierung planetarer oberflachen. Habilitation Dissertation for Faculty Membership, Ludwig Maximilianis University.

Neukum, G., Ivanov, B.A., Hartmann, W.K., 2001. Cratering records in the inner solar system in relation to the lunar reference system. Space Science Reviews 96 (1-4), 55–86.

Oberbeck, V., Quaide, W., Mahan, M., Paulson, J., 1973. Monte carlo calculations of lunar regolith thickness distributions. Icarus 19 (1), 87–107.

Oberbeck, V.R., 1975. The role of ballistic erosion and sedimentation in lunar stratigraphy. Rev. Geophys. 13 (2), 337–362.

Ortiz, J., Aceituno, F., Quesada, J., Aceituno, J., Fernandez, M., Santos-Sanz, P., Trigo- Rodriguez, J., Llorca, J., Martin-Torres, F., Montanes-Rodriguez, P., et al., 2006. Detection of sporadic impact flashes on the moon: implications for the luminous efficiency of hypervelocity impacts and derived terrestrial impact rates. Icarus 184 (2), 319–326.

Paige, D., Foote, M., Greenhagen, B., Schofield, J., Calcutt, S., Vasavada, A., Preston,
D., Taylor, F., Allen, C., Snook, K., et al., 2010a. The lunar reconnaissance orbiter diviner
lunar radiometer experiment. Space Sci. Rev. 150 (1–4), 125–160.

Paige, D.A., Siegler, M.A., Zhang, J.A., Hayne, P.O., Foote, E.J., Bennett, K.A., Vasavada, A.R., Greenhagen, B.T., Schofield, J.T., McCleese, D.J., et al., 2010b. Diviner

lunar radiometer observations of cold traps in the moon's south polar region. Science 330 (6003), 479–482.

Pieters, C.M., Adams, J.B., Mouginis-Mark, P.J., Zisk, S.H., Smith, M.O., Head, J.W., McCord, T.B., 1985. The nature of crater rays: the copernicus example. J. Geophys. Res. Solid Earth 90 (B14), 12393–12413.

Pilkington, M., Grieve, R., 1992. The geophysical signature of terrestrial impact craters. Rev. Geophys. 30 (2), 161–181.

Preblich, B.S., McEwen, A.S., Studer, D.M., 2007. Mapping rays and secondary craters from the martian crater zunil. J. Geophys. Res. Planets 112 (E5), E05006. http://dx. doi.org/10.1029/2006JE002817.

Rabinowitz, D., Helin, E., Lawrence, K., Pravdo, S., 2000. A reduced estimate of the number of kilometre-sized near-earth asteroids. Nature 403 (6766), 165.

Rancitelli, L., Perkins, R., Felix, W., Wogman, N.A., 1971. Erosion and mixing of the lunar surface from cosmogenic and primordial radio-nuclide measurements in apollo 12 lunar samples. Proceedings of the Conference on Lunar and Planetary Science. 2. pp. 1757.

Reedy, R., Arnold, J., 1972. Interaction of solar and galactic cosmic-ray particles with the moon. J. Geophys. Res. 77 (4), 537–555.

ReVelle, D.O., 1997. Historical detection of atmospheric impacts by large bolides using acoustic-gravity waves. Ann. N. Y. Acad. Sci. 822 (1), 284–302.

Robinson, M.S., Boyd, A.K., Denevi, B.W., Lawrence, S.J., McEwen, A.S., Moser, D.E., Povilaitis, R.Z., Stelling, R.W., Suggs, R.M., Thompson, S.D., et al., 2015. New crater on the moon and a swarm of secondaries. Icarus 252, 229–235.

Schmidt, R.M., Housen, K.R., 1987. Some recent advances in the scaling of impact and explosion cratering. Int. J. Impact Eng. 5 (1–4), 543–560.

Schneider, E., Storzer, D., Hartung, J., Fechtig, H., Gentner, W., 1973. Microcraters on apollo 15 and 16 samples and corresponding cosmic dust fluxes. Proceedings of the Conference on Lunar and Planetary Science. 4. pp. 3277. Schorghofer, N., Mazarico, E., Platz, T., Preusker, F., Schroeder, S.E., Raymond, C.A., Russell, C.T., 2016. The permanently shadowed regions of dwarf planet ceres. Geophys. Res. Lett. 43 (13), 6783–6789.

Schultz, P.H., Eberhardy, C.A., Ernst, C.M., A'Hearn, M.F., Sunshine, J.M., Lisse, C.M., 2007. The deep impact oblique impact cratering experiment. Icarus 191 (2), 84–122.

Schultz, P.H., Gault, D.E., 1985. Clustered impacts: experiments and implications. J. Geophys. Res. Solid Earth 90 (B5), 3701–3732.

Sekanina, Z., 1998. Evidence for asteroidal origin of the tunguska object. Planet. Space Sci. 46 (2), 191–204. 343

Shoemaker, E.M., 1962. Interpretation of lunar craters. Kopal, Z. (Ed.), Physics and Astronomy of the Moon Academic Press. New York, New York, pp. 283–359.

Shoemaker, E.M., 1965. Preliminary analysis of the fine structure of the lunar surface in mare cognitum. Proceedings of the International Astronomical Union Colloquium. 5. Cambridge University Press, pp. 23–77.

Spencer, J.R., 1987. Thermal segregation of water ice on the galilean satellites. Icarus 69 (2), 297–313.

Speyerer, E.J., Povilaitis, R.Z., Robinson, M.S., Thomas, P.C., Wagner, R.V., 2016. Quantifying crater production and regolith overturn on the moon with temporal imaging. Nature 538 (7624), 215–218.

Stopar, J.D., Robinson, M.S., Barnouin, O.S., McEwen, A.S., Speyerer, E.J., Henriksen, M.R., Sutton, S.S., 2017. Relative depths of simple craters and the nature of the lunar regolith. Icarus 298, 34–48.

Strom, R.G., Malhotra, R., Ito, T., Yoshida, F., Kring, D.A., 2005. The origin of planetary impactors in the inner solar system. Science 309 (5742), 1847–1850.

Strom, R.G., Malhotra, R., Xiao, Z.-Y., Ito, T., Yoshida, F., Ostrach, L.R., 2015. The inner solar system cratering record and the evolution of impactor populations. Res. Astron. Astrophys. 15 (3), 407–434.

Suggs, R., Moser, D., Cooke, W., Suggs, R., 2014. The flux of kilogram-sized meteoroids from lunar impact monitoring. Icarus 238, 23–36.

Szalay, J.R., Horanyi, M., 2016. Lunar meteoritic gardening rate derived from in situ ladee/ldex measurements. Geophys. Res. Lett. 43 (10), 4893–4898.

Vasavada, A.R., Bandfield, J.L., Greenhagen, B.T., Hayne, P.O., Siegler, M.A., Williams, J.-P., Paige, D.A., 2012. Lunar equatorial surface temperatures and regolith proper- ties from the diviner lunar radiometer experiment. J. Geophys. Res. Planets 117 (E12), E00H18. http://dx.doi.org/10.1029/2011JE003987.

Vedder, J.F., 1972. Craters formed in mineral dust by hypervelocity microparticles. J. Geophys. Res. 77 (23), 4304–4309.

Vickery, A., 1986. Size-velocity distribution of large ejecta fragments. Icarus 67 (2), 224–236.

Vickery, A.M., 1987. Variation in ejecta size with ejection velocity. Geophys. Res. Lett. 14 (7), 726–729.

Vondrak, R.R., Crider, D.H., 2003. Ice at the lunar poles: that the moon harbors ice at high latitudes is well known. the source of that water, however, may come as something of a surprise. Am. Sci. 91 (4), 322–329.

Werner, S.C., Harris, A., Neukum, G., Ivanov, B., 2002. The near-earth asteroid size frequency distribution: a snapshot of the lunar impactor size—frequency distribution. Icarus 156 (1), 287–290.

Werner, S.C., Medvedev, S., 2010. The lunar rayed-crater population characteristics of the spatial distribution and ray retention. Earth Planet. Sci. Lett. 295 (1–2), 147–158.

Whipple, F.J.W., 1930. he great Siberian meteor and the waves, seismic and aerial, which it produced. Quart. J. Roy. Meteorol. Soc. 56, 287–304.

Whipple, F. L., 1967. On Maintaining the Meteoritic Complex. SAOSpecial Report 239, 1.

Williams, J., Bandfield, J., Ghent, R., Greenhagen, B., Paige, D., 2016. Anisotropic impact cratering on the moon observed in the lunar cold spot crater population. AGU Fall Meeting Abstracts.

Williams, J.-P., Bandfield, J., 2016. Lunar cold spots and crater production on the moon. AAS/Division for Planetary Sciences Meeting Abstracts. 48.

Williams, J.-P., Bandfield, J., Paige, D., Greenhagen, B., Speyerer, E., Ghent, R., 2017.
A recent, large multi-impact event on the moon. Proceedings of the Conference on Lunar and Planetary Science. 48.

Williams, J.-P., Pathare, A.V., Aharonson, O., 2014. The production of small primary craters on mars and the moon. Icarus 235, 23–36.

Wünnemann, K., Nowka, D., Collins, G., Elbeshausen, D., Bierhaus, M., 2011. Scaling of impact crater formation on planetary surfaces: insights from numerical modeling. Proceedings of the 11th Hypervelocity Impact Symposium. 20. Fraunhofer Verlag, pp. 1-16.

Zook, H., Lange, G., Grun, E., Fechtig, H., 1984. Lunar primary and secondary microcraters and the micrometeoroid flux. Proceedings of the Conference on Lunar and Planetary Science. 15. pp. 965–966.

Chapter 3

Impact gardening as a constraint on the age, source, and evolution of ice on Mercury and the Moon

Note: This chapter is in press at the Journal of Geophysical Research: Planets, with co-authors R.R. Ghent, P.G. Lucey and M Hirabayashi.

Abstract

We update an analytic impact gardening model (Costello et al., 2018) to calculate the depth gardened by impactors on the Moon and Mercury and assess the implications of our results for the age, extent and source of water ice deposits on both planetary bodies. We show that if the water presently on the Moon has a primordial origin, it may have been 4-15 m thick. If ice deposits are buried, they may be as shallow as 3 cm or as deep as 10 m and provide a gradient of probability for ice gardened into a column. Our calculations for gardening on Mercury show that thermal lag deposits will be reworked into the background over 200 Myr, and, thus, the most recent large-scale deposition of ice on Mercury must have occurred no more than 200 Myr ago. We also find that gardening mixes incremental layers of ice with underlying regolith and prevents the growth of pure ice deposits by continuous supply. We conclude that ice deposits on the Moon and Mercury are likely the result of sudden and voluminous deposition.

3.1 Introduction

The poles of the Moon and Mercury both have locations permanently shielded by topography from sunlight inside of which temperatures are low enough to allow the presence of water ice that can persist for billions of years against sublimation. The similarity ends there. The poles of Mercury are unambiguously ice-rich while the poles of the Moon are largely dry. Earth-based radar observations revealed charismatic radar-bright regions in permanently shadowed regions (PSRs) near Mercury's north and south poles that showed reflectivity and polarization properties that were more like the icy objects of the outer solar system than the rocky Moon or the rest of Mercury (Slade 1992; Harmon and Slade 1992; Harmon et al., 1994; Harcke, 2005). In 2011 NASA's MErcury Surface, Space Environment, GEochemistry, and Ranging (MESSENGER) mission entered orbit around Mercury and explored the composition of the radar-bright regions. MESSENGER neutron spectra showed elevated hydrogen at Mercury's north pole, and Lawrence et al. (2013) concluded that the radar-bright regions were deposits of nearly pure water ice. On Mercury, every surface and shallow subsurface location that is cold enough to preserve water ice from sublimation shows radar backscatter enhancements (Vasavada et al., 1999; Chabot et al., 2013; Paige et al., 2013) and deposits are thought to be up to 30 m thick (Eke et al., 2017; Deutsch et al., 2018; Susorney et al., 2019).

In contrast, the search for ice on the Moon is ongoing and results have been comparatively dry, showing that the Moon is relatively ice-free compared to Mercury. It has long been postulated that lunar PSRs could hold water ice (Urey 1952; Watson et al. 1962). Neutron spectroscopy observations from both the Lunar Prospector Neutron Spectrometer (LPNS) and the Lunar Exploration Neutron Detector (LEND) instrument on board the Lunar Reconnaissance Orbiter (LRO) have shown elevated hydrogen at the poles to their sensing depth of about a meter; however, neutron spectroscopy is sensitive only to the presence of hydrogen, not its molecular bonds (e.g. Feldman et al., 2000; Miller 2012; Boynton 2012). It is unknown if the H anomalies are a signature of molecular

water. Strong evidence for the presence of water ice in the sub-surface came from the Lunar Crater Observation and Sensing Satellite (LCROSS) mission, which upon crashing into a PSR inside the south polar crater, Cabeus, produced a volatile-rich plume and data showed that the regolith at Cabeus may have a water concentration of $\sim 5\%$ by mass (Colaprete et al., 2010). Earth-based and orbital radar observations of the lunar poles have shown indications for circular polarization ratio anomalies inside PSRs that could indicate buried ice, but these experiments conclusively show that extensive ice deposits like those seen on Mercury are not present on the Moon (Stacy et al., 1997; Nozette et al., 2001; Neish et al., 2011; Thomson et al., 2012; Fa and Cai 2013; Campbell et al., 2006; Spudis et al., 2013). At the surface, evidence of patchy surface water that covers roughly 10% of the total PSR area has been presented by workers using LRO Lunar Orbiter Laser Altimeter (LOLA) reflectance measurements, LRO Lyman Alpha Mapping Project (LAMP) UV spectra, and Chandravan Moon Mineral Mapper (M3) infrared spectra, coupled with temperature data from the LRO Diviner thermal radiometer (e.g. Zuber et al., 2012; Hayne et al., 2015, Fisher et al., 2016, Milliken and Li 2016; Li et al., 2018). A statistical approach by Rubanenko et al., (2019) concluded that craters in the south lunar polar region have relatively low depth-diameter ratios and suggested that the shallowing is caused by buried ice; however, because of the statistical nature of the work, they could not identify individual shallowed candidate carters and the mystery of why there might be an asymmetric distribution of water by any source between the north and south poles remains a mystery and concern. While the Moon's poles are not completely dry, the limited distribution and quantity of water ice are in stark contrast with Mercury's extensive icy deposits.

The differences in the water concentrations at the poles of the Moon and Mercury may be explained by luck or age. The Moon's ice may be the ancient relic of Mercury-like ice deposits formed by volcanic outgassing or cometary impacts (Siegler et al., 2016; Needham & Kring, 2017) or simply the steady accumulation of water formed from solar wind-implanted hydrogen (Crider and Vondrak 2000; Crider and Vondrak 2002; Liu et al., 2012; Hurley & Benna 2018). In contrast, Mercury may have gotten lucky recently - struck by a statistically anomalous comet or water-bearing asteroid no more than 300 Myr ago that left Mercury's surface scarred by the crater Hokusai and its poles full of water ice (Ernst et al. 2018). In addition to age or luck, Mercury's ice evolves over time differently from the Moon's. Marchi et al. (2005) showed that the flux of 1 cm to 100 m diameter meteorites is about an order of magnitude lower at Mercury than at the Moon. These impactors and the secondary craters that they generate are the dominant impact gardeners of the top few meters of material on the Moon and Mercury. A possible scenario is that the Moon once had Mercury-like ice deposits that have been pulverized, exposed to significant loss, and mixed with underlying regolith by a more intense meter-scale impact environment.

Impacts continue to shape the surfaces of the Moon and Mercury. The effects of impact gardening on the regolith of both bodies have been studied since the Apollo era (e.g. Gault et al., 1974; Cintala 1992; Costello et al., 2018). What affects the regolith must also affect polar ice deposits. In the present study we update and extend our impact gardening model (Costello et al. 2018) that calculates the depth excavated and overturned by impacts as a function of time to investigate the effects of impact gardening on ice at the poles of the Moon and Mercury. Our model is validated by the lunar case and includes a treatment of secondary impacts, which are critically important for understanding regolith overturn from the surface to meter scale depths (McEwen et al., 2005; McEwen & Bierhaus, 2006; Speyerer et al., 2016; Costello et al., 2018). We compare our impact gardening model predictions to observations of the distribution of ice and ice-related features on both planets to constrain their age, source, and evolution over time.

3.2 Gardening Model: Updates to the treatment of cumulative craters.

Costello et al. (2018) presented an analytical model that describes the frequency with which a point at depth is included in the excavated volume of a crater with some probability by modeling cratering as a marked homogeneous Poisson process, which were first applied to the problem of impact gardening by Gault et al., (1974). In this paper, we update the marked homogeneous Poisson process model by Costello et al., (2018) by revising a flaw in the treatment of the cumulative impactor distribution, which results in a more accurate prediction of impact overturn (the process by which impacts mechanically churn the regolith) driven by small crater sizes. Here, we detail the differences between the current treatment and that of Costello et al., (2018), and discuss the implications for the predictions of each treatment. We begin by following Equation (23) of Costello et al., (2018), which was constructed using a geometric argument such that when a reference area is large, the average number of cratering events can be approximated as the following equation:

$$\lambda = N\pi \frac{(cD)^2}{4}t\tag{3.1}$$

where N is the total number of craters emplaced of constant diameter D that form per area and time, t is time, and c is a scaling factor for a new crater of D to disturb a point along the center point of an existing crater of diameter D_c at depth hD (Figure 3.1). The average number of events, λ , is unitless. Values for λ come from solutions to the cumulative Poisson probability equation:

$$P = 1 - \sum_{n=0}^{n} \frac{e^{-\lambda} \lambda^n}{n!} \tag{3.2}$$

for combinations of λ and the cumulative number of times, n, newly emplaced craters disturb at a given area over time. The values for λ used in this work can be found in Table 1 of Costello et al., (2018). Equation (1) is the same expression derived and used in Costello et al., (2018).

Here, we revise our model to correctly treat the effects of craters larger than a reference diameter D_c , which also influence our reference point (Figure). Costello et al (2018) solved equation (1) for N, the total number of craters per area per unit time, and integrated over diameter D to capture the effects of craters larger than reference diameter D_c . This leads to an expression with units of craters per length, rather than area, per time. Here, instead, we express Equation (1) in discrete form as

$$\lambda = tc^2 \left(\Delta N_1 \frac{\pi D_1^2}{4} + \Delta N_2 \frac{\pi D_2^2}{4} + \dots + \Delta N_{MAX} \frac{\pi D_{MAX}^2}{4} \right)$$
(3.3)

where ΔN_i is the number of emplaced craters with a diameter $D_i (\geq D_c)$ per area per time, *i* is an index up to the number MAX, and cD_c is the distance at which a crater must strike in order to overturn a point at depth (Figure 3.1). The sum of ΔN_i over different crater sizes is equal to the total number of emplaced craters at all sizes. This expression recognizes that the distribution of craters varies as a function of crater size (e.g. Hirabayashi et al., 2018), and the sum gives the total number of emplaced craters at all sizes. We then write Equation (3) in continuous form:

$$\lambda = \left| tc^2 \int_{D_c}^{D_{MAX}} \frac{\pi D^2}{4} \frac{dN_c}{dD} dD \right|$$
(3.4)

where N_c is the cumulative crater production function and has units of number per unit area and time. The average number of events per interval, λ , is an inherently positive interval scale quantity and the direction of our integration does not matter. Whether we begin counting large craters and finish counting small or begin small and finish large, the cumulative number of craters will be equal; to capture the inherent positivity of numberspace, we include absolute values around the right-hand-side of the equation. We include absolute values and adhere to the classical calculus understanding of Equation (4), deviating from the standard assumption that a cumulative crater distribution is always positive (Appendix I of Crater Analysis Techniques Working Group, 1979) such that the model is prepared to explore distributions that change with crater size, should future workers wish to sub-divide it.

The effect of the Costello et al., (2018) treatment is an overprediction of the depth overturned by impacts for very young ages and small crater sizes (due to the incorrect exponent of the N vs. t curve). The cumulative number of small craters are more likely to be affected by a wider range of craters, thus, the Costello et al. (2018) results for shallow gardening are effected by the error. In contrast, the predicted overturn depths for older ages and large crater sizes were generally unaffected (Figure 3.3). However, the uncertainty associated with the slope of the crater production function is large for small craters; consequently, the Costello et al. (2018) model gave generally consistent results with empirical data. The remainder of the Costello et al. (2018) mathematical treatment, and the main result outlined in the paper - the idea that the gardening effects of secondary impacts are necessary to describe observations of reworking on the Moon - stand as published.

Crater production functions (CPFs) represent the number of craters of a given diameter that form on an area per unit time (e.g. Crater Analysis Techniques Working Group, 1979; Neukum, 1983; Ivanov et al., 2001; 2002). We use CPFs in their cumulative form, which give the number of craters of diameter D and larger that form on an area per unit time (Crater Analysis Techniques Working Group, 1979). Let us assume that craters produced on planetary bodies follow a cumulative power law size frequency distribution:

$$N_c = uD^v \tag{3.5}$$

where u and v are the parameters that control the shape of the CPF. The shape parameter u is always positive and has units of craters per $[L]^{2+v}$ and time. The shape parameter v is a dimensionless power index and is usually negative i.e. there are usually more small craters than large craters. We solve for λ by substituting Equation (5) into Equation (4):

$$\lambda = \left| \frac{\pi t c^2}{4} \frac{u v}{v + 2} \left[D_c^{v+2} - D_{MAX}^{v+2} \right] \right|$$
(3.6)

 D_{MAX} is defined as a crater size much larger than the minimum crater diameter (D_c) required to overturn to a certain depth (Figure), and may be the maximum crater diameter observed on a considered planetary body. When v < -2 (a common crater frequency power index is ~ -3), as $D_{MAX} \rightarrow \infty$ the D_{MAX} term in Equation (6) goes to zero, and the expression is simplified. We solve Equation (6) for D_c :

$$D_c = \left| \left[\left(\frac{v+2}{vu} \right) \left(\frac{4\lambda}{\pi t c^2} \right) \right]^{\frac{1}{v+2}} \right|$$
(3.7)

and the resulting Equation (7) gives the frequency a surface point is interacted with craters D_c and larger following a Poisson distribution and where, at the surface, c = 1. When we calculate overturn depth, c < 1 because craters must strike closer to a given point to excavate a point a depth (see Figure 3.1).

We define the depth of overturn (Λ) as a fraction of crater diameter (Figure 3.1):

$$\Lambda = hD_c \tag{3.8}$$

where h is the dimensionless excavation depth-fraction of crater diameter. Substituting Equation (7) into Equation (8), we arrive at the final form of the analytic model for the depth of impact gardening:

$$\Lambda = \left| h\left[\left(\frac{v+2}{vu}\right) \left(\frac{4\lambda}{\pi t c^2}\right) \right]^{\frac{1}{v+2}} \right|$$
(3.9)

where Λ is the depth of overturn as a function of time. This simple analytical function takes in the parameters for a cumulative power law flux, $(N_c = uD^v)$ and a cumulative Poisson distribution-derived average number of events (λ) and gives us the minimum frequency with which a point at the depth Λ is in the excavated volume of a crater. We can read Equation (9) as follows: Material at Λ depths has been brought to the surface by impacts that have occurred at least *n* times given the value for λ determined by a given probability, which is available in Table 1 of Costello et al. (2018). In its simplest form, the overturn function follows a power law function of time:

$$\Lambda = At^{-B} \tag{3.10}$$

where

$$A = \left| h \left[\left(\frac{v+2}{vu} \right) \left(\frac{4\lambda}{c^2 \pi} \right) \right]^{\frac{1}{v+2}} \right|$$
(3.11)

and

$$B = \frac{1}{v+2} \tag{3.12}$$

The power index of the reworking depth (B) must be negative and v must be < -2 for the model to describe physical reality - small, shallowly overturning impacts are more likely than large, deeply overturning impacts. Fortunately, most predictions of CPFs for secondary craters, which dominate the mechanical churning of the uppermost meter or so, have relatively steep power indices (~ -4 e.g. McEwen et al., 2005, Bierhaus et al., 2005; Speyerer et al., 2016), satisfying the requirement that v be < -2.

Costello et al. (2018) modeled a CPF from a power-law impact flux and scaling laws for the size of a crater given impactor momentum and the material properties of the target. Equations (38) and (42) in Costello et al. (2018) describe the production function from the impact flux and the scaling to crater size using the scaling laws presented in Holsapple (1993). The lithostatic pressure at a depth equivalent to the projectile radius, which must be overcome for excavation to occur, is $\rho g R_m$, where R_m is the impactor radius, g is gravity, and ρ is the density of the target. For small impactors, the effective target yield strength is greater than $\rho g R_m$, and the scaling from impactor size to crater size is in the strength regime. For large impactors, the gravity term is much greater than the target yield strength and the scaling from impactor size to crater size in the gravity regime. The shape parameters u and v for the CPF can be calculated for impacts in the strength and gravity regime in terms of impact flux, Holsapple (1993) scaling from impactor size to crater size, and the Poisson expression as follows per Costello et al. (2018) Equations (33-45):



Figure 3.1 The geometry of the model following Figure 2 of Costello et al., (2018). The scaling value h is the fraction of the crater diameter, D_c , that has been excavated by a cratering event. The scaling value c is controlled by the shape of the crater bowl and describes the distance at which a crater must strike (in terms of crater diameter) in order to overturn a point at depth.



Figure 3.2 Craters that are larger than diameter D also affect a surface point following Figure 3 of Costello et al. (2018).

$$u = \begin{cases} \sin(\theta)^{\frac{2}{3}} a \left[\frac{1}{\delta(\gamma\alpha^{\beta})^{1/3}}\right]^{b} & \text{in Strength Regime} \\ \sin(\theta)^{\frac{1}{3}} a \left[\frac{1}{\delta(\gamma\epsilon^{\beta})^{1/3}}\right]^{\frac{3b}{3+\beta}} & \text{in Gravity Regime} \end{cases}$$
(3.13)

where $\alpha = K_2\left(\left(\frac{Y}{\rho_t v_f^2}\right)^{\frac{2+\mu}{2}}\right)$, $\beta = \frac{-3\mu}{2+\mu}$, $\delta = 2K_r$, $\gamma = \frac{K_1 \pi \rho_m}{6\rho_t}$, $\epsilon = \left(\frac{g}{2v_f^2}\right)\left(\frac{\rho_m}{\rho_t}\right)^{\frac{1}{3}}$, following Costello et al. (2018), and where K_r , K_d , K_1 , and K_2 are empirically derived scalars that depend on the target material (and where K_2 is more typically defined inside a power of $(2 + \mu)/2$, e.g. Holsapple 1993), ρ_m is the density of the impactor, ρ_t is the target bulk density, g is the gravity of the target object, Y is the target yield strength, μ is an empirically derived scalar that depends on the target porosity, and v_f is the final velocity of the object upon impact. A method to calculate the strength-gravity transition depth can be found in Costello et al., (2018). When we plot overturn as a function of time we will see a kink at the strength-gravity transition where the overturn function changes slope and magnitude following Equation (13) (see Figures 3.3 or 3.4). Although aesthetically messy with abundant parameters, our model offers control of these input parameters and allows the comparison of predicted reworking depths in targets that are rocky or icy.

Estimates of production functions from crater counts risk errors at small scales from resolution limits, human error, contamination by secondary impacts, and erasure if craters are in equilibrium (e.g. Minton et al., 2019). When craters are in equilibrium, "craters of the given size are being produced at the same rate at which they are being destroyed" (Gault 1970). It is impossible to calculate the number of craters that form on a surface over a time interval if those craters are in equilibrium using observations of the surface alone. Our method of using a size-frequency distribution of impacting bodies (e.g. the bolide flux presented by Brown et al (2002), which is valid down to meteorite sizes of ~ 1 cm) and the scaling from impactor size to crater size provides a way to 'see through' crater equilibrium.

We update the depth fraction of crater diameter that is overturned (h) to capture the relatively shallow depth-diameter of low energy secondary craters $(d/D \approx 0.2)$, where d is

Table 3.1 Impactor size to crater size scaling parameters parameters from material published online by Holsapple (2003) and from Table 1 in Williams et al. (2014), which supersede the values in Table 1 of Holsapple (1993). * The impactor density for rocky secondaries, following Costello et al., (2018). ** The impactor density for icy secondaries.

	/ (/			1	U U		
K_1	K_2	K_d	K_r	μ	$Y (dynes cm^{-2})$	$\rho_t \ ({\rm g \ cm^{-3}})$	$\rho_i \ ({\rm g} \ {\rm cm}^{-3})$
0.132	0.26	1.1	0.6	0.41	1×10^5	1.5	2.7^{*}
0.095	0.351	1.1	0.6	0.55	1.5×10^5	0.93	0.93^{**}
	K_1 0.132 0.095	$\begin{array}{c ccc} K_1 & K_2 \\ \hline 0.132 & 0.26 \\ 0.095 & 0.351 \end{array}$	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	K_1 K_2 K_d K_r μ Y (dynes cm ⁻²) 0.132 0.26 1.1 0.6 0.41 1×10^5 0.095 0.351 1.1 0.6 0.55 1.5×10^5	K_1 K_2 K_d K_r μ Y (dynes cm ⁻²) ρ_t (g cm ⁻³) 0.132 0.26 1.1 0.6 0.41 1×10^5 1.5 0.095 0.351 1.1 0.6 0.55 1.5×10^5 0.93

the final crater depth; e.g. Melosh 1989; McEwen et al., 2005; Bierhaus et al., 2010) and assume that only the top half of a crater is excavated such that: $h = 0.02 \times 0.5 = 0.04$ (assuming only half of a crater depth is overturned following Speyerer et al., 2016). We also inherit the scaling parameter c from Costello et al. (2018), which describes the distance craters must form along the center point of an existing crater of diameter D at depth hDto overturn, given as fraction of crater diameter: $c = 1/2\sqrt{1-h} = 0.41$ (see Figure 3.1; Costello et al. 2018).

We use the secondary production model published in Costello et al., (2018). Costello et al., (2018) used the results from the McEwen et al., (2005) study of Mars' Zunil crater and the work of Shoemaker (1965) to model the production of secondary craters by a primary flux. Following Costello et al., (2018), we assume that every primary impact produces one hundred thousand secondary impacts: if the impact flux has the shape: ad^b , where d is the impacting fragment diameter and the secondary flux parameter $a_{\text{Secondary}} = a_{\text{Primary}} \times 10^5$. The secondary flux power index is $b_{\text{Secondary}} = -4$ (following Table 4 of McEwen et al., 2005). To produce a secondary crater production function we process the flux of secondary fragments through the Holsapple (1993) scaling from impactor size to crater size, assuming that all secondary impactors strike the surface at an average velocity of 0.5 km s⁻¹ (Melosh 1985; Vickery 1986) and the material properties defined in Table 3.1.

3.3 Validation: Gardening regolith on the Moon.

3.3.1 Validation of the secondary crater production function.

We test the validity of our assumptions about the scaling from impactor size to crater size, material properties, and the production of secondary crater by calculating gardening due to the crater production observed by the LRO Camera (LROC) over the last decade (Speyerer et al., 2016). The observed crater production function by Speyerer et al., (2016) is free from assumptions about material properties, secondary flux, and impact velocity because values for u and v are taken from the size-frequency distribution of observed meter-scale surface albedo anomalies that appeared over the decade LRO has been in orbit. We plot the crater production function, Equation (5), using shape parameters from the observed distribution of splotches ($u = 1.25 \times 10^{-5}$ and v = -4.14 in units of meters and years; these values are reported in the Methods section of Speyerer et al., 2016) and our parameter-intensive model for the production of secondaries (Equation 13) and note the similarity between these two production functions (Figure 3.3). Some debate remains about whether albedo anomalous "splotches" observed by LROC are primary or secondary in nature (Speyerer et al., 2016); however, the relatively good fit between our secondary production model and the reported production of splotches suggests that the splotches are indeed secondary.

3.3.2 Validation of gardening model.

Our model for the gardening of regolith by primary and secondary craters yields a curve that represents the deepest depth that has been disturbed at least n times with some probability following the cumulative Poisson distribution over a time interval. Canonically, the vertical extent of the percolation of surface-correlated materials has been called the "in situ reworking depth" (see Morris (1978) and this depth defines the lower limit of the "in situ reworking zone" which has an upper limit being the very surface. The number of overturns implied by an in situ reworking depth is a minimum of at least one overturn. More than one overturn can occur in the reworking zone.



Figure 3.3 We plot the cumulative frequency of our modeled secondaries following the method of Costello et al. (2018) and assuming craters are in the strength regime and forming in regolith and compare to the production of splotched reported by Speyerer et al., (2016). The scaling from apparent to transient diameter changes very little and the functions fit well.
We model the in situ reworking depth and zone using our overturn model at high probability. In Figure 3.4 we compare the model results produced by the updated model presented here, the results of Costello et al. (2018), and the in situ reworking depth observed in Apollo cores (Morris 1978; Blanford et al. 1980). To calculate the colored contours we solve Equation (9) with values for u and v calculated using Equations (13) and (13) (which include assumptions about material properties, gravity, velocity, impact angle, and the scaling from impactor size to crater size) for impacts into lunar regolith and the flux of secondary impactors produced by a lunar-scaled Brown et al. meteorite flux (2002). We assume that the modern flux captured by Brown et al., (2002) has been stable for the last 1 Gyr (e.g. Neukum et al., 2001; Huang et al., 2018). The countours labeled "LROC CPF" are calculated using crater production function values for u and v following values reported in Speyerer et al., (2016) for the production of splotches and scaled to transient crater diameter by a factor of 0.84 (Melosh 1989: Methods section of Speverer et al., 2016). The gardening from splotches are calculated using only the observed size-distribution of craters and are free from assumptions about material properties or gravity of the target, the velocity, angle of impact or material properties of impactors or pi-crater scaling.

The lunar in situ reworking depth we calculate using our model for secondary production using lunar regolith material properties (Table 3.1), a modeled secondary impact flux produced by the primary impact flux following Brown et al., (2002), for $n \ge 1$ at 99% probability, is plotted as a red line in Figure 3.4 and is written explicitly as follows:

$$\Lambda = \begin{cases} 3.94 \times 10^{-5} t^{0.5} & \text{in Strength Regime} \\ 7.35 \times 10^{-4} t^{0.35} & \text{in Gravity Regime} \end{cases}$$
(3.14)

where t is in units of years and Λ is in units of meters.

The overturn depth function for $n \ge 1$ at 99% probability calculated using the CPF from Speyerer et al., (2016 is written:

$$\Lambda = 3.45 \times 10^{-5} t^{0.47} \tag{3.15}$$

and is also plotted in Figure 3.4 as a solid black line. The relatively good fit between these two calculations follows the good fit between the input production functions (Figure 3.3).

Morris (1978) and Blanford et al., (1980) calculated the depth of the in situ reworking zone by analyzing the depth distribution of surface-correlated space weathering products (I_s/FeO, cosmic ray tracks, and cosmogenic radionuclides e.g. Fruchter et al., 1976; 1977; 1978) in Apollo drill cores. Upon publication of Morris (1978), no impact gardening model could fit the predicted reworking rate (Arnold 1975; Gault et al., 1974; see Figure 2 of Morris (1978)) even given low probability, likely because these models did not include gardening due to secondary impacts. The absence of secondary impacts was noted as a likely cause of the misfit by Morris (1978). Morris (1978) somewhat arbitrarily ascribed a 50% probability to his calculations of the in situ reworking depth, reasoning that impact gardening is a stochastic process and noting the absence of further models or observational constraints.

Our model, which includes secondary impacts, and our model of mixing driven by splotches fit using high probability 99% probability of at least 1 overturn, Figure 3.3). We also see a gradient in the frequency of overturn that fits the variable overturn seen within the in situ reworking zone, with greater frequency at shallower depths. After 500 Myr of gardening, a core that samples the top meter would show an in situ reworking depth of less than a meter, with an in situ reworking zone, where frequent churning has distributed space weathering products into the top 10 cm or so. Most of the Apollo cores have on the order of ten distinct layers - for example, the 236-cm-deep Apollo 15 sample 15001-15006 has 42 distinct textural units (Heiken et al., 1973, 1976), Apollo 12 sample 12025-12028 has 10 (e.g. Fryxell and Heiken, 1974) and concentrations of nano-phase iron, a space weathering product, are typically concentrated in the top 10 cm (Lucey et al., 2006); however, investigations of grain size and sorting within layers and the depth-distribution of space weathering products tell a story of frequent overturns and a complicated history of mixing (e.g. Morris et al 1979; Lucey et al., 2006; Huang et al. 2017). The fit of our models at high probability and the reasonable gradient in the number of turns we predict compared to the in situ reworking zone analysed by Morris (1978) and Blanford et al. (1980)



Figure 3.4 All overturn contours plotted here represent the deepest depth overturned at least one time over the time interval on the x-axis with 99% probability. The model results using the size frequency distribution of small albedo anomalies observed in LROC temporal pairs (Speyerer et al., 2016) (solid black line) fits exceedingly well against the reworking of surfacecorrelated space weathering products in the top meter of regolith calculated from Apollo cores by Morris 1978 and Blanford et al., (1980) and our model results using assumptions about the production of secondary impacts. The model results using a secondary impact flux derived from the Brown et al., (2002) flux of primary impacts fits both the LROC reworking rate and the reworking observed in Apollo cores. Compared to the results of Costello et al., (2018) (grey dot-dashed line plotted following the results shown in Figure 4 of Costello et al., (2018)), the updates to the model decrease the rate of overturn at small scales by changing the magnitude and power law slope of the overturn function.

support the notion that the work by Morris (1978) may be more representative of global impact gardening than the author gave himself credit. Still, as Morris (1978) stated, a direct and rigorous treatment in which values of reworking depth for various probability levels and number of overturns are determined awaits a much larger database of cores and experiments.

3.3.3 The timescale for validity of the Poisson model for secondaries.

Awaiting a more compete dataset, our updated model for the depth of impact gardening using the LROC CPF and the model results calculated from the flux of secondary impactors fit both one another and the in situ reworking depths calculated from analysis of Apollo cores by Morris (1978) and Blanford et al., (1980). The fit validates our model for the 1 Myr to 500 Myr timescale over which the Apollo core analysis is representative of the in situ reworking depth.

To calculate the secondary flux we assumes that the modern primary impact flux captured by Brown et al. (2002) at the Moon has been stable over the last 1 Gyr (e.g. Neukum et al., 2001; Huang et al., 2018); however, recent work suggests that there may have been an order of magnitude uptick in the flux about 200 Myr ago (Mazrouei et al., 2019). Variations in the impact flux translate directly to variations in the rate of impact gardening. Our model does not currently take in representations of the flux over time that are more sophisticated than a power law; however, given the relatively good fit between the reworking rate over the last 1 Gyr calculated from Apollo cores and our model calculations (Figure 3.4), the power law appears to be a reasonable approximation.

Primary crater formation is a Poisson processes, and generally satisfy the assumptions: 1) craters are uniformly distributed over the surface and through time; and 2) the formation of one crater does not affect the probability of the formation of another. Secondary impacts are not a Poisson process, having a spatial and temporal distribution that is existentially linked to their parent primary impact; however, over long timescales, secondaries become approximately like a Poisson point process. We explore the minimum length of time over which we can comfortably use our model of secondaries as an approximate Poisson process by exploring the timescale over which secondaries begin to behave like a Poisson point process as validated by observations of the effects of gardening in samples and remote sensing observations.

Speyerer et al. (2016) reported a reworking rate of 2 to 3 cm every 80,000 years, which was consistent with the homogeneous distribution of cosmogenic Al^{26} in Apollo cores observed by Fruchter et al., 1976; 1977; 1978). Our gardening calculations are consistent with this shallow and short-timescale gardening at 50% probability, validating our model for secondary gardening down to the hundreds-of-thousands of years and centimeter scale. Recent work by Nishizumi et al. (2019) studying an Apollo 17 drill core 70009-70001 shows an excavation event down to ~ 25 cm occurred about 500 kyr ago. While other cores show that the whole Moon has not been gardened to such depths over hundreds of thousands of years, our model predicts that the Apollo 17 drill core is not wildly anomalous, and suggests that if probability can be linked to spatial coverage, then 5-10% of the lunar surface may have been similarly gardened. The Diviner lunar radiometer experiment on board LRO has also observed ephemeral thermophysical anomalies around young craters that fade over 100 to 1 Myr years are at least as thick as the diurnal skin depth: 20 cm (Hayne et al. 2017; Williams et al. 2018). While gardening by secondaries may be only one contributor to the as yet unconstrained mechanisms that destroy cold spots, we see the in situ reworking zone driven by secondaries effecting the total volume of the cold spot at least once at 3 to 20% probability over the timescale of 100 kyr to 1 Myr. We plot our model solved at various probabilities and with these validating observations in Figure 3.5.

We conclude the that secondaries behave like a Poisson point process after about 100 kyr and our model is valid over timescales on and above that order of magnitude. This is not to say that the modeling of secondary impacts as a Poisson point process is without its faults, and we will explore the limitations introduced by this treatment in the discussion section; however, the model fit with observational data suggests that these issues minimally interfere with our predictions at timescales at and above about 100 kyr.

3.4 Results

3.4.1 Gardening ice and regolith on the Moon and Mercury.

With a model validated by the lunar case, we proceed to explore the extent and rate of impact gardening on the Moon and Mercury in both regolith and in ice over timescales between 80,000 and 1 Gyr (Figures 3.6 and 3.7). As described in the previous section, we model overturn on the Moon using the primary impactor flux from Brown et al. (2002) scaled to the Moon and the secondary impacts they produce following the method in Costello



Figure 3.5 The results of Morris et al. (1978) and Blanford et al. (1980) represent the reworking depth generally; however, the effects of reworking observed in Apollo cores is variable. a) We capture the stochasticity of gardening by varying the model with probability. At various probabilities, our model is consistent with the reworking demonstrated by the work from Morris (1978) and Blanford et al., (1980), the reported 2 to 3 cm of gardening in 80,000 years from Speyerer et al., (2016) based on observations of the size-frequency of albedo anomalous splotches, the homogenization of Al^26 in the top few centimeters of regolith over timescales less than 1 Myr (Fruchter et al. 1976; 1977; 1978), the results of Nishizumi et al. (2019), who found an event 50 kyr ago overturned about 25 cm of material in Apollo 17 string drill tube 7002-7009, the fading of themophysical anomalies dubbed "cold spots" observed in LRO Diviner data extend to the sensing limit of the diurnal skin depth (20 cm) and are no older than about 1 Myr (Williams et al., 2018). b) The data presented by Morris represents the "in situ reworking depth", which describes the depth that has seen the surface at least one time over some time interval. Our model results match the Morris (1978) and Blanford et al. (1980) in situ reworking rates, predicting between one and one hundred overturns have excavated material to the depth and over the timescale.

et al. (2018). We apply this model to Mercury by using the flux of 1 cm - 100 m objects from Marchi et al. (2005). We vary the material property inputs of Equations (12) and (13) using values in Table 3.1 and use the relative gravity of the Moon and Mercury, which control the scaling from impactor size to crater size.

For this study, we make two simplifying assumptions: 1) all craters scale following the Holsapple (1993) scaling laws; and 2) the material being gardened is either pure hard ice or pure regolith. Some workers have shown that transient crater scaling between impactor size and crater size in cold water ice scales like rock in the gravity regime (Turtle and Pierazzo, 2001; McKinnon and Parmentier, 1986; Chapman and McKinnon, 1986). Yet other models and impact experiments suggest that impactor size to crater size scaling may be different in water ice, with differences made more intense as material properties such as porosity evolve with time (Bierhaus & Schenk 2010; Fendyke et al. 2013; Yasui et al. 2017; Michikami et al. 2017; Prieur et al. 2017; Kurosawa and Takeda 2019). As ice, regolith, and rocks are bombarded, broken, and mixed, the porosity, yield strength, and density of the target evolve with time in poorly constrained ways. We simplify, using the two examples of hard ice and regolith because their material parameters are provided by Holsapple (1993) and are self-consistent with the scaling laws we also take from Holsapple (1993). Including a sophisticated treatment of icy crater scaling and time-dependent surface evolution are beyond the scope of this study.

Overturn functions plotted in Figure 3.8 are summarized in Table 3.2 and plotted in Figure 3.8 for comparison. For overturn in hard ice on both the Moon and Mercury we assume that secondary impactors have the density of ice or rocks (Table 3.1). Secondaries are more likely to be composed of the same material as the target because of the relatively limited area over which secondaries are strewn, especially at the sub-meter scales we are modeling, and Mercury's icy poles are not covered in rocky regolith ejecta; however, the majority of the Moon and Mercury are not icy and it is possible that non-local rocky secondaries are making craters in polar ice deposits. The scale of a crater is dependent on the density and yield strength of both the target and impactor. Icy impactors garden

	Overturn Depth (Λ)		
	Regolith Target Rocky Secondaries	Hard Ice Target	
		Icy Secondaries	Rocky Secondaries
Moon (Strength Regime) Moon (Gravity Regime)	$\begin{array}{l} 3.94\times10^{-5}\ t^{0.5}\\ 7.35\times10^{-4}\ t^{0.32} \end{array}$	$\begin{array}{c} 6.97\times 10^{-5} \ t^{0.5} \\ 2.44\times 10^{-3} t^{0.32} \end{array}$	$\begin{array}{c} 1.45\times 10^{-4} \ t^{0.5} \\ 3.90x\times 10^{-3} \ t^{0.32} \end{array}$
Mercury (Strength Regime) Mercury (Gravity Regime)	$\begin{array}{c} 2.45\times 10^{-5} \ t^{0.5} \\ 4.13\times 10^{-4} \ t^{0.32} \end{array}$	$\begin{array}{l} 4.33\times 10^{-5} \ t^{0.5} \\ 1.34\times 10^{-3} \ t^{0.32} \end{array}$	$\begin{array}{l} 8.99\times 10^{-5} \ t^{0.5} \\ 2.92\times 10^{-3} \ t^{0.32} \end{array}$

Table 3.2 Overturn depths are calculated using Equation (8) for $n \ge 1$ overturns at 99% probability and using the material properties listed in Table 3.1 and in hard ice given rocky and icy secondary impactors.

less efficiently than rocky impactors due to their lower density and yield strength relative to rocky impactors. By modeling gardening driven by both rock and icy secondaries we present bounds for the upper (all rocky secondaries) and lower (all icy secondaries) limits for gardening at the poles. These limits appear as solid (all icy) and dotted (all rocky) contours bounding a shaded region where the true in situ reworking depth contour, which is likely driven by a mix of rocky and icy secondaries exists in Figures 3.6 and 3.7, which illustrate the depth of gardening on the Moon and Mercury respectively. We compare gardening on the Moon and Mercury in Figures 3.6, 3.7, and 3.8. The figures illustrate two simple and important results: 1) impact gardening at the depth scale modeled here (< 10 meters) is more intense on the Moon than on Mercury by a factor of ~ 2 ; and 2) On both the Moon and Mercury, hard ice is gardened more efficiently than regolith.

3.4.2 The ancient lunar flux and regolith thickness as a constraint on primordial ice.

The Moon may have had extensive Mercury-like ice deposits that have been destroyed or churned into underlying regolith by impact gardening. To explore this hypothesis and the evolution of lunar ice, we investigate the minimum thickness of lunar ice deposits would have to have been initially to have been gardened into underlying regolith.



Figure 3.6 Gardening due to secondary impacts on the Moon in ice and in regolith shown in "cores" that have dimensions of depth and probability. Contours are calculated by solving the cumulative Poisson equation (Equation 2) for various probabilities and inputting the appropriate λ into Equation 13. We do not include calculations below our reasonable timescale limit of 100 kyr. For our calculation of gardening in an icy target (a, b and c) we show a region where the true in situ reworking depth likely exists, driven by both icy (solid line) and rocky (dotted line) secondary crater-forming impactors.



Figure 3.7 Gardening due to secondary impacts on Mercury in ice and in regolith shown in "cores" that have dimensions of depth and probability. Contours are calculated by solving the cumulative Poisson equation (Equation 2) for various probabilities and inputting the appropriate λ into Equation 13. Shaded regions in sub-figures (c) and (f) indicate the depth of "micro-cold traps" and thermal lag deposits respectively. We do not include calculations below our reasonable timescale limit of 100 kyr. For our calculation of gardening in an icy target (a, b and c) we show a region where the true in situ reworking depth likely exists, driven by both icy (solid line) and rocky (dotted line) secondary crater-forming impactors.



Figure 3.8 Impact gardening on the Moon and Mercury and regolith and ice due to icy and rocky secondary impactors. Gardening is more efficient on the Moon than Mercury at the depth scale analyzed here (< 10 m), and gardening is more efficient in ice than in regolith on both planetary bodies.

To investigate the effects of gardening on ice deposits that may be older than the Copernican era, we assume that the thickness of mare regolith of known surface age can constrain the unknown thickness of polar ice deposits of the same age. Over the last 3.5 Gyr, impacts have pulverized mare basalts into a regolith layer that is about 3 m thick (Nakamura et al., 1975; Fa & Wieczorek 2012; Fa et al., 2014; 2015; Bart 2014). In Figure 3.9 we extend our model for gardening beyond the Copernican era and explore how thick an ancient pure ice deposit must have been to have been completely penetrated by impacts. We assume that a model for $n \ge 10$ overturns at 99% probability, represents the relatively uniform production of 3 m of mare regolith. We then assume that $n \ge 1$ overturns have also affected polar ice deposits to a greater depth proportional to the greater efficiency of cratering in ice. Under these assumptions, model results indicate that a deposit that is 3.5 Gyr old would have to have initially been 4 - 15 m thick to be gardened into underlying regolith (Figure 3.9).

3.5 Discussion

3.5.1 The age of ice deposits on Mercury.

After 1 Gyr of bombardment, impact gardening is extremely unlikely to have touched the bottom of a 4 to 8 m thick ice deposit on Mercury, let alone deposits greater than 10 m thick (Figure 3.7a). Our gardening calculations at this multi-meter scale do not rule out the possibility that Mercury's extensive ice deposits are older than 1 Gyr.

Shielding by thermal lag.

Many of Mercury's radar-bright ice deposits are covered by a layer of low-reflectance material that has been interpreted to be the carbonaceous leftovers of ice that has sublimated or "thermal lag" (Crites et al. 2013; Neumann et al. 2013; Paige et al. 2013; Syal et al. 2015; Delitsky et al. 2017). MESSENGER neutron data and thermal models show that these low albedo lag deposits are up to 10 - 30 cm thick (Paige et al. 2013;



Figure 3.9 The higher ancient impact flux simulated using the depth of mare regolith. We model impact gardening in regolith and ice for $n \ge 1$ and $n \ge 10$ overturns at 99%. If we assume that between 1 and 10 overturn events in the model transforms mare basalt into regolith, then we can assume that between 1 and 10 overturns have also affected polar ice deposits to a greater depth proportional to the greater efficiency of cratering in ice.

Lawrence et al 2013), and images indicate that the low-reflectance deposits directly overlie ice deposits, terminating sharply at the boundary of radar-bright regions (Chabot et al. 2014).

Impact gardening over the scale of tens of millions of years will only turn up more lag deposit, gardening the first few decimeters of material at Mercury's poles (Figures 3.7e and 3.7f). Some impacts will dig deeper; for example, we predict that there is a 50% chance that ice buried under ~ 20 cm of thermal lag will have been excavated once over 10 Myr. Much as Apollo core 7002-7009 showed an anomalously young deeply penetrating impact (Nishizumi et al 2019; Figure 3.5), rare, larger impacts on Mercury may penetrate the lag and exhume small amounts of ice onto the surface, causing observed variations in surface brightness among thermal lag regions (Chabot et al., 2013; 2014; Deutsch et al., 2016). Quantitatively linking the efficiency of lag-penetrating impacts and up-sampling of ice at low model probability and the surface albedo variations awaits a more complete dataset. We can comfortably conclude that shielding by thermal lag further extends the potential lifetime on Mercury's polar ice deposits against gardening. Our model predicts that low-albedo thermal lag deposits may not only shield the ice deposits they overlie from sublimation (Paige et al. 2013), but also take the brunt of impact gardening.

Age constraints from surface ice.

There are locations where temperatures are cold enough that sublimation could not build up a protective blanket of lag and where ice is exposed directly to the surface (Paige et al. 2013; Deutsch et al., 2017). Surface ice is exposed to non-thermal loss processes including sputtering by solar wind plasma, UV, impact vaporization and mechanical gardening that churns protected ice upwards to the relatively hostile surface (e.g. Farrell et al. 2019). If exposed ice deposits on Mercury were billions of years old and never developed a shield of thermal lag, they would have succumbed to non-thermal losses. The presence of surface ice implies that the ice deposits on Mercury may indeed be young. Thermal modeling by Rubanenko et al. (2018) hypothesized the presence of "micro-cold trap" surface ice deposits existing in sub-meter regions of permanent shadow that may only be a few decimeters thick. The relative efficiency of gardening in ice makes these small unprotected deposits particularly vulnerable and we predict that if they exist, micro cold trap ice deposits would be thoroughly gardened over 10 Myr timescales (Figure 3.7c).

Constraints on the age of Mercury's ice from low albedo deposits that are not radar-bright.

There also are PSR locations somewhat farther from the poles of Mercury where the surface has low albedo compared to surrounding regolith but is not radar-bright. It is thought that these locations once harbored ice deposits that have since succumbed to thermal sublimation (Paige et al. 2013; Chabot et al. 2019). If thermal lag at these locations is underlain by regolith, impact gardening will mix them into background regolith over time, much as gardening does to lunar surface features. We assume that the thermal lag deposits are 10-30 cm thick (Paige et al. 2013; Lawrence et al. 2013) and have similar material properties to the surrounding regolith to calculate the depth reached by overturn. In order for us to still be able to observe the low surface albedo anomalies today, they must be too young to have been worked into background regolith by gardening. We predict that it would take less than 200 Myr to mix 30-cm thermal lag underlain by regolith into the background (Figure 3.7f). Thus, if the albedo-dark deposits are the thermal lag of a sublimated ice deposit, the initial deposition of ice must have occurred no more than 200 Myr ago. The 100 Myr timescale we predict for the gardening of Mercury's lag deposits is three orders of magnitude above the 100 kyr minimum timescale above which our model for secondary impact gardening is valid, so we can be relatively certain of our prediction that Mercury's most recent large scale deposition of ice occurred no more than 200 Myr ago.

Because of its extensive and optically immature rays (Braden & Robinson, 2013; Neish et al., 2013), it has been suggested that Hokusai crater (57.7°N, 16.8°E) formed in the Kuiperian time-stratigraphic system, and has an upper limit age of 100 to 300 Myr (Banks

et al., 2017). Our gardening calculations support the narrative of Hokusai as a source for Mercury's most recent large scale ice delivery, by showing that the most recent emplacement must have occurred no more than 200 Myr ago.

3.5.2 The sources of water delivered to the Moon and Mercury.

Surface ice is subject to intense gardening over short timescales (Figures 3.7c and 3.7c). The relatively high rate of impact gardening near the surface means that the deposition rate of ice has a major impact on its survival. Ice deposits formed from the steady accumulation of thin layers of water ice from water-bearing meteorites (e.g. Moses et al., 1999) or solar wind implantation (e.g. Crider and Vondrak, 2000) are more vulnerable to the destructive effect of impacts near the surface. Although thin deposits are vulnerable, gardening quickly loses efficiency at depth. A 10 cm thick ice deposit is exponentially more durable against gardening than a 1 cm deposit.

Moses et al., (1999) assumed a dust flux at Mercury of $1\pm 0.8 \times 10^{10}$ g yr⁻¹ that contains a water mass fraction of roughly 10%. They assume 63% of the dust flux mass remains on the planet after an impact and 5.15% of the water survives migration to the poles. This produces a cumulative delivery of 0.8 to 20 m of ice to Mercury's poles over 3.5 Gyr with a linear continuous deposition rate of 2.29×10^{-10} to 5.79×10^{-9} m yr⁻¹. Modeling by Ong et al. (2010) shows that about 6.5% of a cometary impact into the Moon is retained, so the lower end of the retention percent used by Moses et al. (1999) is more likely. Other studies of comet impacts have shown that retention of meteoritic water depends strongly on impact velocity and impact angle - slower and more oblique impacts have less energetic volatile plumes, more of which remain gravitationally bound (Pierazzo and Melosh, 2000; Gisler et al., 2006; Ong et al., 2010; Stewart et al., 2011; Prem et al., 2015). At Mercury, micrometeorites have a high average impact velocity relative to meteorites larger than ~ 1 g (Cintala, 1992; Marchi et al., 2005), and their vapor plumes are less likely to be low energy enough for water to remain gravitationally bound. Considering these factors, we should think of the Moses et al., (1999) supply as a generous estimate.

We compute the depth that an ice deposit would be in the absence of any losses if it were supplied by meteorites at the generous rate calculated by Moses et al., (1999) and compare it to the overturn depth we calculate, plotting them together in Figure 3.10. Let us imagine $\sim 4 \text{ mm}$ of ice accumulates on a patch of ground in a PSR over about 1 Myr. Our model suggests that that patch of ground is gardened to at least 2 centimeters depth over the same time interval, overturning an order of magnitude more material than the continuous source was able to accumulate. Smaller time steps and thinner deposits are even more vulnerable to the power law efficiency of gardening. The incremental layers built up over time by continuous sources are mixed with underlying regolith faster than they can accumulate, thwarting the growth of a pure ice deposit like those seen at Mercury's poles (e.g. Butler et al., 1993). We conclude from this exercise that pure, many meters-thick ice deposits on Mercury could not have been built over billions of years from continuous sources because impact gardening mixes incrementally built up ice layers with underlying regolith faster than continuous sources can supply them. In contrast, we can not similarly rule out the possibility that lunar ice, which appears to be well mixed with regolith (e.g. Colaprete et al., 2010), may be continuously supplied.

In the previous section we concluded that the presence of albedo-dark lag underlain by regolith implies near-surface ice on Mercury has a maximum age of about 200 Myr. Over 200 Myr, even the un-gardened and generous estimate of the amount of water supplied to the poles by wet meteorites (Moses et al., 1999) provides only enough water for a deposit that is a few millimeters thick (Figure 3.7). If Mercury's pure ice deposits are indeed less than 200 Myr old, even in the absence of gardening, the continuous supply calculated by Moses et al., (1999) could not have made them. The relatively young predicted age of Mercury's most recent ice delivery and the durability of thick deposits in comparison to intensely gardened thin deposits indicate that the sources of ice at the poles of Mercury were voluminous and suddenly delivered, such as a single or a series of large comet impacts. We do not rule out the possibility that Mercury's polar deposits were formed from multiple exogenous and endogenous sources, so long as those sources were relatively sudden and voluminous; e.g. an ancient volcanic outgassing (e.g. Butler et al., 1993) was supplemented by large cometary depositions (e.g. Ernst et al. 2018) with invisible layering of thermal lag at thicknesses below the resolution of radar remote sensing.

While we do not have similar age constraints on lunar ice deposits, the relative durability of thick deposits against gardening supports the theory of a voluminous and sudden source for lunar ice as well. Farrell et al., (2019) concluded that ice on the surface of the Moon may only be stable for < 2 kyr, suggesting an extremely turbulent near surface environment and spelling doom for thin layers of continuously delivered ice. If the Moon does indeed have pure ice deposits that are buried (e.g. Rubanenko et al., 2019), such deposits would have had to have grown and survived gardening at the surface for some time before their burial, and, like Mercury's deposits, could not have been continuously supplied. Thus, we conclude that a sudden and voluminous source of lunar polar water delivery, such as a volcanic outgassing (e.g. Needham & Kring, 2017), is more likely than continuous supply.

3.5.3 Ice on the Moon.

Gardening is more efficient on the Moon than on Mercury (Figure 3.8) due to the higher flux of 1 cm - 100 m primary impactors at the Moon (Marchi et al., 2005); however, despite the greater efficiency, gardening would never have penetrated the entirety of a Mercury-like deposit on the Moon if that deposit was < 1 Gyr old. Even a 5 m thick deposit that was emplaced 1 Gyr ago would not have been gardened in its entirety and should still appear radar-bright. If the Moon ever had Mercury-like deposits they must have been ancient (e.g. Needham & Kring, 2017; Deutsch et al., 2019), and therefore subject to the orders of magnitude higher impact environment before the Copernican era or buried.

The fate of primordial surface ice.

We explored the idea of thick primordial deposits in Section 4.2, and were able to present a rough estimate of the minimum thickness a surface deposit must have been to have been gardened to its interface with the regolith: 4-15 m. The results suggest that the Moon may



Figure 3.10 The depth of an ice deposit in the absence of losses or transport after deposition if it were supplied at the rate calculated by Moses et al., (1999) and impact overturn depth contours for impact gardening in regolith and in hard ice due to icy and rocky secondary impactors on Mercury (Equations 16 and 18). Gardening mixes incrementally built-up deposits formed from continuous sources faster that they are supplied.

well have had ancient Mercury-like deposits that were initially thicker than 10 m which have since succumbed to gardening, which are now so thoroughly mixed with regolith that they are invisible to radar (e.g. Butler et al., 1993; Colaprete et al., 2010).

Our results come from assumptions about the relationship between regolith growth and gardening, but that relationship is itself a subject of ongoing investigation. Hirabayashi et al (2018) modeled the growth of regolith from high energy primary impacts, not the secondary impacts that we model here, and had model results in good agreement with the regolith depths sensed by Apollo 15 seismic experiments (Nakamura et al. 1975). It is thought that regolith production is driven by high energy impacts (e.g. Oberbeck et al 1973; Quaide & Oberbeck 1975; Hirabayashi et al. 2018), by micrometeorite abrasion (e.g. Hörz et al. 1974), and/or thermal fatigue (e.g. Molaro & Byrne 2012; Delbo et al. 2014; Molaro et al 2015; Molaro et al. 2017) to varying and yet unknown degrees, while gardening is driven mostly by frequent low energy secondary impacts. If the secondary impacts that we model do not possess enough energy to produce 3 m of mare regolith, then the impact flux must have been more than an order of magnitude more intense than that modeled here, ancient ice deposits would have had to be much thicker, and thicker deposits mean a greater mass is demanded from any delivery mechanism. A better understanding of the relationship between regolith production and mechanical churning would improve our ability to derive the initial thickness of ice deposits from the depth of similar-aged regolith and interpret model results.

Our results suggest that the top meter or so of Mercury is less reworked than the top meter of the Moon. The relatively slower processing of the top few meters of Mercury's surface is consistent with observations that ice deposits on Mercury have a sharp boundary with their surroundings (e.g. Chabot et al. 2014); however, studies suggest that Mercury has thicker regolith than the Moon (Kreslavsky & Head 2015) and that craters degrade faster on Mercury than on the Moon (Fassett et al. 2017). Again, we run into the uncertain relationship between impact gardening and regolith formation. We look forward to seeing what the Bepi-Colombo mission to Mercury reveals about the small impactor flux at Mercury and the results of continuing studies of the relationship between impacts, regolith growth, and crater degradation. For now, we proceed under the assumption that the Marchi et al. (2005) flux of 1 cm to 100 m objects is correct and is indeed driving the relatively slow gardening of Mrcury's top meter.

The depth to buried ice.

If instead of extensive Mercury-like surface deposits, ancient lunar ice was buried under meters of regolith (e.g. Rubanenko et al., 2019), and if cohesive ice deposits exist at depths between 1 and 10 m, the surface ice we observe may be the result of secondary impact gardening up-sampling that ice during the Copernican era. Our gardening calculations at high probability give a lower limit on the depth of up-sampled ice. Any shallower than our calculations, and buried ice would have been gardened in the in situ reworking zone. We predict that gardening could efficiently up-sample ice when it is touched by the in situ reworking depth; thus, ice may be buried between 1 cm and 3 m deep (from interpretation of Figures 3.4 and 3.6). Such shallow deposits should be visible to radar; however, the radar remains dark.

The observed surface ice may be the result of rare, relatively large impacts which penetrate a deep regolith layer. We can investigate this possibility by exploring the depth to ice using lower probability in the model. We performed a similar exercise using lower probability to explore the mixing history of Apollo core 70002-70009 (Nishizumi et al., 2019) and the fading of cold spots (Williams et al., 2018) in section 3.1. If we accept that gardening at 10% probability accounts for the observed surface ice, buried ice may be between 10 cm and approaching 10 m deep (Figures 3.5 and 3.6). How so much regolith was deposited over the purported buried ice deposits while similarly-aged pyroclastic deposits such as those at Aristarchus remain spectrally distinct at the surface (e.g. Lucey et al., 1986) remains an open question.

While Figures 3.6 and 3.7 and the gradient of probability that they illustrate could be interpreted to be representative of the depth to ice on the Moon and Mercury, we caution the reader that interpretation of model results at low probability introduces both known and unknown unknowns. While the vertical and temporal gardening that our model predicts is in comfortable agreement with several validating observations of the vertical and temporal extent of gardening on the Moon, interpretation from spatial dimensions introduces uncertainty. If we wish to rigorously investigate the observed spatial distribution of surface ice and link it to probability of overturn, we would need to qualify our model with more observational data to illustrate the validity or invalidity of its results for similar applications. We do not know what areal fraction of the lunar surface has a mixing history similar to the Apollo core 70002-70009, or what physical processes fade cold spots, let alone that gardening 10%, 50% or 100% of a cold spot volume fades it and therefore can not use these as rigorously validating or invalidating cases for the spatial distribution implied by lower percent probability in the model.

One known unknown that we are particularly cautious of is the implications of our model dimensions. Between Equations (1) and (3) of this work, we reduce the dimensionality of our marked homogeneous point process intensity function from four (two spatial dimensions, time, and one mark) down to two (time and depth/mark) using the geometry of the problem (Figure) and the assumption that the distribution of points and marks are independent. Reducing the dimensionality of a model in this way may make the model blind to pertinent physical phenomena. For example, Minton et al., (2019) presented both an analytic and a numerical approach to modeling surface degradation by crater equilibrium. Their analytic model had only one dimension: mark. When comparing their analytic results and numerical results, they found the the analytic model could not have predicted the significant effects of spatial parameters such as crater ray width, which were not reduced and apparent in their computationally expensive numeric model. Similarly, we should approach the computationally efficient yet dimensionally reduced models presented in this work and by Costello et al., (2018) and Gault et al., (1974) with caution when trying to understand the influence and implications of spatial phenomena beyond the vertical dimension, such as the patchy surface distribution of water, pending further qualification from observations,

cores, and experiments that investigate the physical and spatial effects of frequent small scale impacts.

We encounter another issue with our analytic model for secondary cratering when we consider the dynamism of ice on the uppermost lunar surface. Farrell et al. (2019) performed calculations that suggest that what little surface ice exists on the Moon remains on the surface for < 2 kyr, and that the surface environment may be extremely dynamic. Impact gardening by secondaries must play some role int he dynamism; however, the 1 kyr timescale is well below our reasonable limit for treating secondaries as a Poisson process, and, in its present form, our model can contribute little of value to understanding the evolution of these most ephemeral deposits.

In the future it will be valuable to develop the models used in this work further. By updating the model we may be able to avoid reducing dimensions and constrain the shallowest and most ephemeral impact gardening. An improved model for secondary crater production that can accommodate differences in the production of secondaries driven by the material properties of the body (e.g. ice vs. silicate worlds), gravity, and velocity of impacts may also significantly improve these results, especially as we explore further beyond the Moon (e.g. Bierhaus et al., 2018).

3.6 Conclusions

The updated model fit well with the extent of impact gardening in Apollo cores (Morris 1978; Blanford et al. 1980), and calculated from the size frequency distribution of albedoanomalous splotches in LROC temporal pairs (Speyerer et al. 2016). The fit between our secondary crater production model and the production of albedo anomalies observed in LROC temporal pairs from Speyerer et al (2016), or splotches, implied that the splotches are indeed secondary cratering phenomena. We validated the impact gardening model for the Moon in regolith for timescales between 100 kyr and 500 Myr. With a validated model in hand, we modeled the gardening of hard ice and regolith on the Moon. Ancient polar ice would have been subject to a similar impact flux as mare basalt, and because mare basalts were pulverized into ~ 3 m of regolith, ice at the poles must have been gardened to a similar or greater depth based on the relative efficiency of cratering in ice compared to rock and regolith. We tracked the relatively higher efficiency of gardening in ice and conclude that if ice was emplaced in lunar polar PSRs 3.5 Gyr ago, the deposits may have been 4-15 m thick.

Unlike the Moon, Mercury's present ice is abundant. While our model can not rule out an ancient origin for Mercury's deep deposits directly from gardening because of their extensive depth and shielding by thermal lag, the presence of surface ice suggests a recent delivery. We can further constrain the age of Mercury's most recent large-scale delivery of ice by modeling the gardening of lower latitude albedo-dark features that have been interpreted to be the remains of ice deposits that have sublimated. Because we still observe these albedo-dark features, they must not yet have been gardened into background regolith and we predict that the ice that preceded them must have been emplaced no more the 200 Myr ago. This timescale is consistent with the Hokusai impactor being the most recent large-scale delivery of water (Ernst et al., 2018).

Moses et al., (1999) calculated a generous estimate for the amount of water delivered to Mercury's poles by continuous supply. Even this generous estimate of the continuous delivery of water from micrometeorites only emplaces several millimeters of ice over 200 Myr. Ice deposits from continuous supply take time to grow - and during that time they are subject to intense small-scale impact gardening. It is unlikely that significant ice deposits on either the Moon or Mercury are the result of a continuous supply of water. Prompt and voluminous sources such as cometary impact are exponentially more durable against gardening. The ice observed on the Moon and Mercury is therefore more likely to have had a prompt and voluminous source or sources (e.g. large cometary impacts, such as the Hokusai impact on Mercury less than 200 Myr ago (Ernst et al., 2018)), or voluminous ancient volcanic outgassing (e.g. Kerber et al., 2009; Needham & Kring, 2017) to withstand intense small-scale gardening.

We conclude that the difference between the water distribution at the poles of the Moon and Mercury is driven by luck and gardening. Mercury was struck in the last 200 Myr by a rare and large water-bearing object that deposited a significant amount of water. Mercury may already have had extensive ice deposits built up from other cometary impacts and/or a primordial outgassing that had not been significantly gardened due to the relatively lower impact flux of 1 cm to 100 m objects (Marchi et al., 2005). Over the last billion years, Mercury's ice deposits have only needed to contend with a modern flux that is gentle relative to both the ancient and modern lunar flux, and are widely shielded from gardening and surface loss processes by decimeter-scale thermal lag deposits. Although the gardening rate is higher on the Moon, if a Mercury-like mass of water had been placed on Moon during the Copernican era, its remains should still be radar-bright today. Instead, we observe a comparatively dry Moon. In the future, the differences between the poles of the Moon and Mercury will likely become even more pronounced, as gardening continues to contribute to the depletion of what ice remains on the Moon and only scratches the surface of Mercury's extensive deposits.

Acknowledgments

Work described in this paper was sponsored in part by the National Aeronautics and Space Administrations Lunar Reconnaissance Orbiter project under a contract to the University of California at Los Angeles, David A. Paige, Principal Investigator and by support from a Bullard Fellowship Award through the University of Hawaii. M.H. acknowledges support from Auburn University's Intramural Grant Program. We give special thanks to David Minton (Purdue University) and Ya-Huei Huang (Massachusetts Institute of Technology), whose expert advice on modeling cratering processes greatly improved this work. All of the data produced and plotted in this work can be reproduced using the equations and parameters provided.

References

Banks, M. E., Xiao, Z., Braden, S. E., Barlow, N. G., Chapman, C. R., Fassett, C. I., & Marchi, S. S. (2017). Revised constraints on absolute age limits for Mercury's Kuiperian and Mansurian stratigraphic systems. Journal of Geophysical Research: Planets, 122, 1010 1020. https://doi.org/10.1002/2016JE005254

Bart, G. D. (2014). The quantitative relationship between small impact crater morphology and regolith depth. Icarus, 235, 130-135.

Bierhaus, E. B., Chapman, C. R., & Merline, W. J. (2005). Secondary craters on Europa and implications for cratered surfaces. Nature, 437(7062), 1125-1127.

Bierhaus, E. B., & Schenk, P. M. (2010). Constraints on Europa's surface properties from primary and secondary crater morphology. Journal of Geophysical Research: Planets, 115(E12).

Bierhaus, E. B., McEwen, A. S., Robbins, S. J., Singer, K. N., Dones, L., Kirchoff, M. R., & Williams, J. P. (2018). Secondary craters and ejecta across the solar system: Populations and effects on impact?crater?based chronologies. Meteoritics & Planetary Science, 53(4), 638-671.

Blanford, G. E. et al. (1980). Cosmic ray production curves below reworking zones. In Lunar and Planetary Science Conference Proceedings (Vol. 11, pp. 1357-1368).

Boynton, W. V., Droege, G. F., Mitrofanov, I. G., McClanahan, T. P., Sanin, A. B., Litvak, M. L., ... & Harshman, K. (2012). High spatial resolution studies of epithermal neutron emission from the lunar poles: Constraints on hydrogen mobility.Journal of Geophysical Research: Planets,117(E12). Braden, S. E., & Robinson, M. S. (2013). Relative rates of optical maturation of regolith on Mercury and the Moon. Journal of Geophysical Research: Planets, 118, 19031914. https://doi.org/10.1002/jgre.20143

Brown, P., Spalding, R. E., ReVelle, D. O., Tagliaferri, E., & Worden, S. P. (2002). The flux of small near-Earth objects colliding with the Earth. Nature, 420(6913), 294.

Butler, B.J., Muhleman, D.O., Slade, M.A., (1993). Mercury: Full-disk radar images and the detection and stability of ice at the north pole. J. Geophys. Res. 98, 15003-15023.

Butler, B. J. (1997). The migration of volatiles on the surfaces of Mercury and the Moon. Journal of Geophysical Research: Planets, 102(E8), 19283-19291.

Campbell, D. B., B. A. Campbell, L. M. Carter, J.-L. Margot, and N. J. S. Stacy (2006), No evidence for thick deposits of ice at the lunar south pole, Nature, 443(7), 835 837, doi:10.1038/nature05167.

Chabot, N. L., Ernst, C. M., Harmon, J. K., Murchie, S. L., Solomon, S. C., Blewett,D. T., & Denevi, B. W. (2013). Craters hosting radar-bright deposits in Mercury's northpolar region: Areas of persistent shadow determined from MESSENGER images. Journalof Geophysical Research: Planets, 118(1), 26-36.

Chabot, N. L., Ernst, C. M., Denevi, B. W., Nair, H., Deutsch, A. N., Blewett, D. T., ... & Harmon, J. K. (2014). Images of surface volatiles in Mercury's polar craters acquired by the MESSENGER spacecraft. Geology, 42(12), 1051-1054.

Chapman, C. R., & McKinnon, W. B. (1986). Cratering of planetary satellites. In IAU Colloq. 77: Some Background about Satellites (pp. 492-580).

Cintala, M. J. (1992). Impact-induced thermal effects in the lunar and Mercurian regoliths. Journal of Geophysical Research: Planets, 97(E1), 947-973.

Colaprete, A., Schultz, P., Heldmann, J., Wooden, D., Shirley, M., Ennico, K., ... & Goldstein, D. (2010). Detection of water in the LCROSS ejecta plume. science, 330(6003), 463-468.

Costello, E. S., Ghent, R. R., & Lucey, P. G. (2018). The mixing of lunar regolith: Vital updates to a canonical model. Icarus, 314, 327-344.

Colaprete, A., Schultz, P., Heldmann, J., Wooden, D., Shirley, M., Ennico, K., ... & Goldstein, D. (2010). Detection of water in the LCROSS ejecta plume. Science, 330(6003), 463-468.

Crater Analysis Techniques Working Group. "Standard techniques for presentation and analysis of crater size-frequency data." Icarus 37.2 (1979): 467-474.

Crider, D. H., & Vondrak, R. R. (2000). The solar wind as a possible source of lunar polar hydrogen deposits. Journal of Geophysical Research: Planets, 105(E11), 26773-26782.

Crider, D. H., & Vondrak, R. R. (2002). Hydrogen migration to the lunar poles by solar wind bombardment of the Moon. Advances in Space Research, 30(8), 1869-1874.

Crider, D., & Killen, R. M. (2005). Burial rate of Mercury's polar volatile deposits. Geophysical research letters, 32(12).

Crites, S. T., Lucey, P. G., & Lawrence, D. J. (2013). Proton flux and radiation dose from galactic cosmic rays in the lunar regolith and implications for organic synthesis at the poles of the Moon and Mercury. Icarus, 226(2), 1192-1200.

Deutsch, A. N., Head, J. W., Chabot, N. L., & Neumann, G. A. (2018). Constraining the thickness of polar ice deposits on Mercury using the Mercury Laser Altimeter and small craters in permanently shadowed regions. Icarus, 305, 139-148.

Delbo, M., Libourel, G., Wilkerson, J., Murdoch, N., Michel, P., Ramesh, K. T., ... & Marchi, S. (2014). Thermal fatigue as the origin of regolith on small asteroids. Nature, 508(7495), 233.

Delitsky, M. L., Paige, D. A., Siegler, M. A., Harju, E. R., Schriver, D., Johnson, R. E., & Travnicek, P. (2017). Ices on Mercury: Chemistry of volatiles in permanently cold areas of Mercury's north polar region. Icarus, 281, 19-31.

Deutsch, A. N., Head III, J. W., & Neumann, G. A. (2019). Analyzing the ages of south polar craters on the Moon: Implications for the sources and evolution of surface water ice. Icarus, 113455. Deutsch, A. N., Head, J. W., Chabot, N. L., & Neumann, G. A. (2018). Constraining the thickness of polar ice deposits on Mercury using the Mercury Laser Altimeter and small craters in permanently shadowed regions. Icarus, 305, 139-148.

Deutsch, A. N., Neumann, G. A., & Head, J. W. (2017). New evidence for surface water ice in small scale cold traps and in three large craters at the north polar region of Mercury from the Mercury Laser Altimeter. Geophysical Research Letters, 44(18), 9233-9241.

Deutsch, A. N., Chabot, N. L., Mazarico, E., Ernst, C. M., Head, J. W., Neumann, G. A., & Solomon, S. C. (2016). Comparison of areas in shadow from imaging and altimetry in the north polar region of Mercury and implications for polar ice deposits. Icarus, 280, 158-171.

Eke, V. R., Lawrence, D. J., & Teodoro, L. F. (2017). How thick are Mercury's polar water ice deposits?. Icarus, 284, 407-415.

Ernst, C. M., Chabot, N. L., & Barnouin, O. S. (2018). Examining the potential contribution of the Hokusai impact to water ice on Mercury. Journal of Geophysical Research: Planets, 123(10), 2628-2646.

Fa, W., Zhu, M. H., Liu, T., & Plescia, J. B. (2015). Regolith stratigraphy at the Chang'E-3 landing site as seen by lunar penetrating radar. Geophysical Research Letters, 42(23), 10-179.

Fa, W., Liu, T., Zhu, M. H., & Haruyama, J. (2014). Regolith thickness over Sinus Iridum: Results from morphology and size-frequency distribution of small impact craters.Journal of Geophysical Research: Planets,119(8), 1914-1935.

Fa, W., & Cai, Y. (2013). Circular polarization ratio characteristics of impact craters from Mini-RF observations and implications for ice detection at the polar regions of the Moon. Journal of Geophysical Research: Planets, 118(8), 1582-1608.

Fa, W., & Wieczorek, M. A. (2012). Regolith thickness over the lunar nearside: Results from Earth-based 70-cm Arecibo radar observations. Icarus, 218(2), 771-787. Farrell, W. M., Hurley, D. M., Poston, M. J., Hayne, P. O., Szalay, J. R., & McLain, J. L. (2019). The Young Age of the LAMPobs erved Frost in Lunar Polar Cold Traps. Geophysical Research Letters.

Fassett, C. I., Crowley, M. C., Leight, C., Dyar, M. D., Minton, D. A., Hirabayashi, M., ... & Watters, W. A. (2017). Evidence for rapid topographic evolution and crater degradation on Mercury from simple crater morphometry. Geophysical Research Letters, 44(11), 5326-5335.

Feldman, W. C., Lawrence, D. J., Elphic, R. C., Barraclough, B. L., Maurice, S., Genetay, I., & Binder, A. B. (2000). Polar hydrogen deposits on the Moon. Journal of Geophysical Research: Planets, 105(E2), 4175-4195.

Fendyke, S., Price, M. C., & Burchell, M. J. (2013). Hydrocode modelling of hypervelocity impacts on ice. Advances in Space Research, 52(4), 705-714.

Fisher, E. A., Lucey, P. G., Lemelin, M., Greenhagen, B. T., Siegler, M. A., Mazarico,
E., ... & Paige, D. A. (2017). Evidence for surface water ice in the lunar polar regions
using reflectance measurements from the Lunar Orbiter Laser Altimeter and temperature
measurements from the Diviner Lunar Radiometer Experiment. Icarus, 292, 74-85.

Fruchter, J., Rancitelli, L., Evans, J., Perkins, R., 1978. Lunar surface processes and cosmic ray histories over the past several million years. Proceedings of the Conference on Lunar and Planetary Science. 9. pp. 2019 2032.

Fruchter, J., Rancitelli, L., Laul, J., Perkins, R., 1977. Lunar regolith dynamics based on analysis of the cosmogenic radionuclides na-22, al-26, and mn-53. Proceedings of the Conference on Lunar and Planetary Science. 8. pp. 3595-3605.

Fruchter, J., Rancitelli, L., Perkins, R., 1976. Recent and long-term mixing of the lunar regolith based on na-22 and al-26 measurements in apollo 15, 16, and 17 deep drill stems and drive tubes. Proceedings of the Conference on Lunar and Planetary Science. 7. pp. 27 39. Fryxell R. & Heiken G. (1974) Preservation of lunar core samples: Preparation and interpretation of threedimensional stratigraphic sections. Proc. Lunar Sci. Conf. 5th, pp. 935.966.

Gault, D. E., Hörz, F., Brownlee, D. E., & Hartung, J. B. (1974). Mixing of the lunar regolith. In Lunar and Planetary Science Conference Proceedings (Vol. 5, pp. 2365-2386).

Gault, D. E. (1970). Saturation and equilibrium conditions for impact cratering on the lunar surface: Criteria and implications. Radio Science, 5(2), 273-291.

Ghent, R. R., Hayne, P. O., Bandfield, J. L., Campbell, B. A., Allen, C. C., Carter, L. M., & Paige, D. A. (2014). Constraints on the recent rate of lunar ejecta breakdown and implications for crater ages. Geology, 42(12), 1059-1062.

Hawke, B. R., Blewett, D. T., Lucey, P. G., Smith, G. A., Bell, J. F., Campbell, B. A.,& Robinson, M. S. (2004). The origin of lunar crater rays. Icarus, 170(1), 1-16.

Gisler, G. R., Weaver, R. P., & Gittings, M. L. (2006, March). Energy partitions in three-dimensional simulations of the Chicxulub meteor impact. In 37th Annual Lunar and Planetary Science Conference (Vol. 37).

Harcke, L. J. (2005). Radar imaging of solar system ices (No. UMI-31-71807). Stanford University.

Harmon, J. K., & Slade, M. A. (1992). Radar mapping of Mercury: Full-disk images and polar anomalies. Science, 258(5082), 640-643.

Harmon, J. K., Slade, M. A., Velez, R. A., Crespo, A., Dryer, M. J., & Johnson, J. M. (1994). Radar mapping of Mercury's polar anomalies. Nature, 369(6477), 213.

Hartmann, W. K. (1984). Does crater saturation equilibrium occur in the solar system?. Icarus, 60(1), 56-74.

Hartmann, W. K. (1999). Martian cratering VI: Crater count isochrons and evidence for recent volcanism from Mars Global Surveyor. Meteoritics & Planetary Science, 34(2), 167-177.

Hayne, P. O., Hendrix, A., Sefton-Nash, E., Siegler, M. A., Lucey, P. G., Retherford,K. D., ... & Paige, D. A. (2015). Evidence for exposed water ice in the Moon's south

polar regions from Lunar Reconnaissance Orbiter ultraviolet albedo and temperature measurements. Icarus, 255, 58-69.

Heiken G. H., McKay D. S., & Fruland R. M. (1973) Apollo 16 soils: Grain size analysis and petrography. Proc. Lunar Sci. Conf. 4th, pp. 251-265.

Heiken G. H., Morris R. V., McKay D. S., & Fruland R. M. (1976) Petrographic and ferromagnetic resonance studies of the Apollo 15 deep drill core. Proc. Lunar Sci. Conf. 7th, pp. 93-111.

Hiesinger, H. V., Van Der Bogert, C. H., Pasckert, J. H., Funcke, L., Giacomini, L., Ostrach, L. R., & Robinson, M. S. (2012). How old are young lunar craters?. Journal of Geophysical Research: Planets, 117(E12).

Hirabayashi, M., Howl, B. A., Fassett, C. I., Soderblom, J. M., Minton, D. A., & Melosh,
H. J. (2018). The role of breccia lenses in regolith generation from the formation of small,
simple craters: Application to the Apollo 15 landing site. Journal of Geophysical Research:
Planets, 123(2), 527-543.

Holsapple, K. A. (1993). The scaling of impact processes in planetary sciences. Annual review of earth and planetary sciences, 21(1), 333-373.

Holsapple, K. A. (2003). Theory and equations for Craters from Impacts and Explosions.St. Louis, MO: Washington University.

Hörz, F., Schneider, E., & Hill, R. E. (1974). Micrometeoroid abrasion of lunar rocks-A Monte Carlo simulation. In Lunar and Planetary Science Conference Proceedings (Vol. 5, pp. 2397-2412).

Huang, Y. H., Minton, D. A., Hirabayashi, M., Elliott, J. R., Richardson, J. E., Fassett,C. I., & Zellner, N. E. (2017). Heterogeneous impact transport on the Moon. Journal ofGeophysical Research: Planets, 122(6), 1158-1180.

Huang, Y. H., Minton, D. A., Zellner, N. E., Hirabayashi, M., Richardson, J. E., & Fassett, C. I. (2018). No change in the recent lunar impact flux required based on modeling of impact glass spherule age distributions. Geophysical Research Letters, 45(14), 6805-6813. Hurley, D. M., & Benna, M. (2018). Simulations of lunar exospheric water events from meteoroid impacts. Planetary and Space Science, 162, 148-156.

Ivanov, B. A., Neukum, G., & Wagner, R. (2001). Size-frequency distributions of planetary impact craters and asteroids. In Collisional processes in the solar system (pp. 1-34). Springer, Dordrecht.

Ivanov, B. A., Neukum, G., Bottke, W. F., & Hartmann, W. K. (2002). The comparison of size-frequency distributions of impact craters and asteroids and the planetary cratering rate. Asteroids III, 1, 89-101.

Kerber, L., J. W. Head, S. C. Solomon, et al., Explosive volcanic eruptions on mercury: Eruption conditions, magma volatile content, and implications for interior volatile abundances, Earth and Planetary Science Letters, 285 (3), 263 271, 2009.

Kurosawa, K., & Takada, S. (2019). Impact cratering mechanics: A forward approach to predicting ejecta velocity distribution and transient crater radii. Icarus, 317, 135-147.

Kreslavsky, M. A., & Head, J. W. (2015, March). A thicker regolith on Mercury. In Lunar and Planetary Science Conference (Vol. 46, p. 1246).

Lawrence, D. J., Feldman, W. C., Goldsten, J. O., Maurice, S., Peplowski, P. N., Anderson, B. J., ... & Rodgers, D. J. (2013). Evidence for water ice near Mercury's north pole from MESSENGER Neutron Spectrometer measurements. Science, 339(6117), 292-296..

Li, S., Lucey, P. G., Milliken, R. E., Hayne, P. O., Fisher, E., Williams, J. P., ... & Elphic, R. C. (2018). Direct evidence of surface exposed water ice in the lunar polar regions. Proceedings of the National Academy of Sciences, 201802345.

Li, L., & Mustard, J. F. (2000). Compositional gradients across mare highland contacts: Importance and geological implication of lateral transport. Journal of Geophysical Research: Planets, 105(E8), 20431-20450.

Liu, Y., Guan, Y., Zhang, Y., Rossman, G. R., Eiler, J. M., & Taylor, L. A. (2012).
Direct measurement of hydroxyl in the lunar regolith and the origin of lunar surface water.
Nature Geoscience, 5(11), 779.

Lucey, P., Korotev, R. L., Gillis, J. J., Taylor, L. A., Lawrence, D., Campbell, B. A., ... & Mendillo, M. (2006). Understanding the lunar surface and space-Moon interactions. Reviews in Mineralogy and Geochemistry, 60(1), 83-219.

Marchi, S., Morbidelli, A., & Cremonese, G. (2005). Flux of meteoroid impacts on Mercury. Astronomy & Astrophysics, 431(3), 1123-1127.

Mazrouei, S., Ghent, R. R., Bottke, W. F., Parker, A. H., & Gernon, T. M. (2019). Earth and Moon impact flux increased at the end of the Paleozoic. Science, 363(6424), 253-257.

McEwen, A. S., Preblich, B. S., Turtle, E. P., Artemieva, N. A., Golombek, M. P., Hurst, M., ... & Christensen, P. R. (2005). The rayed crater Zunil and interpretations of small impact craters on Mars. Icarus, 176(2), 351-381.

McEwen, A. S., & Bierhaus, E. B. (2006). The importance of secondary cratering to age constraints on planetary surfaces. Annu. Rev. Earth Planet. Sci., 34, 535-567.

McKinnon, W. B., & Parmentier, E. M. (1986). Ganymede and Callisto. In Satellites (pp. 718-763).

Melosh, H. J. (1989). Impact cratering: A geologic process. Research supported by NASA. New York, Oxford University Press (Oxford Monographs on Geology and Geophysics, No. 11), 1989, 253 p., 11.

Michikami, T., Hagermann, A., Morota, T., Haruyama, J., & Hasegawa, S. (2017). Oblique impact cratering experiments in brittle targets: Implications for elliptical craters on the Moon. Planetary and Space Science, 135, 27-36.

Miller, R. S. (2012). Statistics for orbital neutron spectroscopy of the Moon and other airless planetary bodies. Journal of Geophysical Research: Planets, 117(E12).

Milliken, R. E., & Li, S. (2017). Remote detection of widespread indigenous water in lunar pyroclastic deposits. Nature Geoscience, 10(8), 561.

Minton, D. A., Fassett, C. I., Hirabayashi, M., Howl, B. A., & Richardson, J. E. (2019). The equilibrium size-frequency distribution of small craters reveals the effects of distal ejecta on lunar landscape morphology. Icarus, 326, 63-87. Molaro, J., & Byrne, S. (2012). Rates of temperature change of airless landscapes and implications for thermal stress weathering. Journal of Geophysical Research: Planets, 117(E10).

Molaro, J. L., Byrne, S., & Langer, S. A. (2015). Grain scale thermoelastic stresses and spatiotemporal temperature gradients on airless bodies, implications for rock breakdown. Journal of Geophysical Research: Planets, 120(2), 255-277.

Molaro, J. L., Byrne, S., & Le, J. L. (2017). Thermally induced stresses in boulders on airless body surfaces, and implications for rock breakdown. Icarus, 294, 247-261.

Morris, R. V. (1978). In situ reworking/gardening/of the lunar surface-Evidence from the Apollo cores. In Lunar and Planetary Science Conference Proceedings (Vol. 9, pp. 1801-1811).

Morris R. V., Lauer H. V. Jr., & Gose W. A. (1979) Characterization and depositional and evolutionary history of the Apollo 17 deep drill core. Proc. Lunar Planet. Sci. Conf. 10th, pp. 1141-1157.

Moses, J. I., K. Rawlins, K. Zahnle, and L. Dones, External sources of water for mercury's putative ice deposits, Icarus, 137(2), 197 221, 1999.

Nakamura, Y., Dorman, J., Duennebier, F., Lammlein, D., & Latham, G. (1975).
Shallow lunar structure determined from the passive seismic experiment. The Moon, 13(1-3), 57-66.

Needham, D. H., & Kring, D. A. (2017). Lunar volcanism produced a transient atmosphere around the ancient Moon. Earth and Planetary Science Letters, 478, 175-178.

Neish, C. D., Bussey, D. B. J., Spudis, P., Marshall, W., Thomson, B. J., Patterson, G. W., & Carter, L. M. (2011). The nature of lunar volatiles as revealed by Mini RF observations of the LCROSS impact site. Journal of Geophysical Research: Planets, 116(E1).

Neish, C. D., Blewett, D. T., Harmon, J. K., Coman, E. I., Cahill, J. T. S., & Ernst, C.
M. (2013). A comparison of rayed craters on the Moon and Mercury. Journal of Geophysical Research: Planets, 118, 2247 2261. https://doi.org/10.1002/jgre.20166 Neukum, G. (1983). Meteoritenbombardement und datierung planetarer oberflachen. Habilitation Dissertation for Faculty Membership, Ludwig-Maximilians-Univ.

Nishiizumi, K., Welten, K.C., Caffee, M.W., 2019. Recent Deposition and Mixing History of the Apollo 17 Drill Core 70009-70001. Presented at the Lunar and Planetary Science Conference, p. 2277.

Nozette, S., Spudis, P. D., Robinson, M. S., Bussey, D. B. J., Lichtenberg, C., & Bonner,
R. (2001). Integration of lunar polar remote sensing data sets: Evidence for ice at the lunar south pole. Journal of Geophysical Research: Planets, 106(E10), 23253-23266.

Oberbeck, V. R., Quaide, W. L., Mahan, M., & Paulson, J. (1973). Monte Carlo calculations of lunar regolith thickness distributions. Icarus, 19(1), 87-107.

Ong, L., Asphaug, E. I., Korycansky, D., & Coker, R. F. (2010). Volatile retention from cometary impacts on the Moon. Icarus, 207(2), 578-589.

Paige, D. A., Siegler, M. A., Harmon, J. K., Neumann, G. A., Mazarico, E. M., Smith,D. E., ... & Solomon, S. C. (2013). Thermal stability of volatiles in the north polar region of Mercury. Science, 1226265.

Paige, D. A., Siegler, M. A., Zhang, J. A., Hayne, P. O., Foote, E. J., Bennett, K. A., ... & Foote, M. C. (2010). Diviner lunar radiometer observations of cold traps in the Moon's south polar region. science, 330(6003), 479-482.

Pierazzo, E., & Melosh, H. J. (2000). Melt production in oblique impacts. Icarus, 145(1), 252 261. https://doi.org/10.1006/icar.1999.6332

Prem, P., Artemieva, N. A., Goldstein, D. B., Varghese, P. L., & Trafton, L. M. (2015). Transport of water in a transient impact-generated lunar atmosphere. Icarus, 255, 148-158.

Prieur, N. C., Rolf, T., Luther, R., Wünnemann, K., Xiao, Z., & Werner, S. C. (2017). The effect of target properties on transient crater scaling for simple craters. Journal of Geophysical Research: Planets, 122(8), 1704-1726.

Quaide, W., & Oberbeck, V. (1975). Development of the mare regolith: Some model considerations. The Moon, 13(1-3), 27-55.
Rubanenko, L., Venkatraman, J., & Paige, D. A. (2019). Thick ice deposits in shallow simple craters on the Moon and Mercury. Nature Geoscience, 12(8), 597-601.

Rubanenko, L., Mazarico, E., Neumann, G. A., & Paige, D. A. (2018). Ice in Micro Cold Traps on Mercury: Implications for Age and Origin. Journal of Geophysical Research: Planets, 123(8), 2178-2191.

Shoemaker, E.M., 1965. Preliminary analysis of the fine structure of the lunar surface in mare cognitum. Proceedings of the International Astronomical Union Colloquium. 5. Cambridge University Press, pp. 23 77.

Siegler, M. A., Miller, R. S., Keane, J. T., Laneuville, M., Paige, D. A., Matsuyama, I., ... & Poston, M. J. (2016). Lunar true polar wander inferred from polar hydrogen. Nature, 531(7595), 480.

Slade, M. A., Butler, B. J., & Muhleman, D. O. (1992). Mercury radar imaging: Evidence for polar ice. Science, 258(5082), 635-641.

Speyerer, E. J., Povilaitis, R. Z., Robinson, M. S., Thomas, P. C., & Wagner, R. V. (2016). Quantifying crater production and regolith overturn on the Moon with temporal imaging. Nature, 538(7624), 215-218.

Spudis, P. D., Bussey, D. B. J., Baloga, S. M., Cahill, J. T. S., Glaze, L. S., Patterson,
G. W., ... & Ustinov, E. A. (2013). Evidence for water ice on the Moon: Results for
anomalous polar craters from the LRO Mini RF imaging radar. Journal of Geophysical
Research: Planets, 118(10), 2016-2029.

Stacy, N. J. S., Campbell, D. B., & Ford, P. G. (1997). Arecibo radar mapping of the lunar poles: A search for ice deposits. Science, 276(5318), 1527-1530.

Stewart, B. D., Pierazzo, E., Goldstein, D. B., Varghese, P. L., & Trafton, L. M. (2011). Simulations of a comet impact on the Moon and associated ice deposition in polar cold traps. Icarus, 215(1), 1 16. https://doi.org/10.1016/j.icarus.2011.03.014

Susorney, H. C., James, P. B., Johnson, C. L., Chabot, N. L., Ernst, C. M., Mazarico,
E. M., ... & Kinczyk, M. J. (2019). The thickness of radar-bright deposits in Mercury's northern hemisphere from individual Mercury Laser Altimeter tracks. Icarus, 323, 40-45.

Syal, M. B., Schultz, P. H., & Riner, M. A. (2015). Darkening of Mercur's surface by cometary carbon. Nature Geoscience, 8(5), 352.

Thomson, B. J., Bussey, D. B. J., Neish, C. D., Cahill, J. T. S., Heggy, E., Kirk, R. L., ... & Ustinov, E. A. (2012). An upper limit for ice in Shackleton crater as revealed by LRO Mini RF orbital radar. Geophysical Research Letters, 39(14).

Turtle, E. P., & Pierazzo, E. (2001). Thickness of a Europan ice shell from impact crater simulations. Science, 294(5545), 1326-1328.

Urey, H.C. (1952) The Planets: Their Origin and Development (Yale Univ Press, New Haven, CT).

Vasavada, A. R., Paige, D. A., & Wood, S. E. (1999). Near-surface temperatures on Mercury and the Moon and the stability of polar ice deposits. Icarus, 141(2), 179-193.

Vickery, A. M. (1986). Size-velocity distribution of large ejecta fragments. Icarus, 67(2), 224-236.

Watson, K., Murray, B. C., & Brown, H. (1962). The stability of volatiles in the solar system. Icarus, 1(1-6), 317-327.

Yasui, M., Schulson, E. M., & Renshaw, C. E. (2017). Experimental studies on mechanical properties and ductile to brittle transition of ice silica mixtures: Young's modulus, compressive strength, and fracture toughness. Journal of Geophysical Research: Solid Earth, 122(8), 6014-6030.

Zuber, M. T., Head, J. W., Smith, D. E., Neumann, G. A., Mazarico, E., Torrence, M.
H., ... & Melosh, H. J. (2012). Constraints on the volatile distribution within Shackleton crater at the lunar south pole. Nature, 486(7403), 378.

Chapter 4 The Formation and Gardening of Europa's "Regopag"

Note: This chapter will be submitted pending co-author notes to the Journal of Geophysical Research: Planets with co-authors C.B. Phillips, R.R. Ghent, and P.G. Lucey.

Abstract

The top vertical meter of Europa is hidden under the optical surface seen by remote sensing, which is sensitive only to the top microns to millimeters, and lateral meters are obscured by the resolution of current datasets; however, we can investigate Europa's invisible meters through our understanding of the processes that act on the surface. Impacts mobilize material in the top meter, breaking up consolidated ice and churning buried materials upwards in a process called "impact gardening." Material that is exposed to the near-surface is altered by hypervelocity micrometeoroid impacts, charged particles, and segregating and sintering thermal processes. We model the rate and extent of impact gardening and compare our results to these other agents of change acting at Europa's uppermost surface. Our impact processing calculations describe the formation of about 10 m thick layer of fine grained ice material or "regopag" over the whole surface on Europa, and show that pristine material that has never seen radiation at the surface resides more than half a meter below the optical surface.

4.1 Introduction

Europa is an icy body of astrobiological importance and the destination of a new multiple flyby mission (Europa Clipper, launch in 2023) and landed mission concepts. Two previous remote sensing visits to Europa, from the Voyager and Galileo spacecraft, sparked wonder and debate about the unique morphologic features, chemistry, and astrobiological potential of this icy moon of Jupiter. The top vertical meter of Europa is hidden under the optical surface seen by remote sensing, which is sensitive only to the top microns to millimeters, and meters are obscured by the resolution of current datasets; however, we can investigate Europa's invisible meters through our understanding of the processes that act on the surface.

Because Europa is airless, and therefore vulnerable to impacting objects at scales from microns to tens of kilometers, its surface may be similar to the Moon. Energetic impacts by micron-diameter dust, many kilometer-diameter objects, and bodies of every order of magnitude in between have bombarded the Moon for billions of years, shattering bedrock and producing 10-20 m thick regolith (e.g. Nakamura et al. 1982; McKay et al. 1991). These publications define the lunar regolith as being dominated by material of size < 1 cm, with only occasional and relatively rare surface and buried boulders. Lunar regolith soil samples have a mean particle size of about 75 μ m (e.g. Haskin et al. 1991). The global surface of the Moon is blanketed in regolith, from the Greek "rhegos-" meaning blanket, and "lithos-" meaning stone.

We introduce an etymological sister to regolith: "regopag" from the Greek "pagos-" meaning ice or salt evaporite deposit, to highlight the conceptual similarity, but distinguish the dominantly water ice impact-generated fragmental material that likely blankets Europa and other airless icy worlds. The regopag has also previously been called "icy regolith;" however, as we learn more about the ice-bearing poles of the Moon and Mercury and icerock transitional bodies such as Ceres, "icy regolith" may also imply ice particles mixed into silicate regolith, while regopag is existentially shaped by thermal and radiolytic processes (e.g. Ip et al. 1998; Nordheim et al. 2018; Molaro et al. 2019) in ways that silicate regolith



Figure 4.1 Galileo Image s0426272378 (6 m/px), which shows a ridge that has been sheared by a fault, exposing a cross-section and a one or two pixel wide layer of bright material blanketing the surface.

and regolith-ice mixtures are not. Despite the differences we have introduced a new word to communicate, the regopag on Europa, like the Moon's regolith, will have formed through years of energetic impacts and acts as a fluffy blanket over the surface.

Photometric experiments that suggest that the uppermost surface of Europa is covered in fine-grained and loosely packed material with high porosity (e.g. Nelson et al. 2018). High-resolution images of Europa's surface from the Galileo mission show a surface that is "softened," but texturally dominated by tectonic processes and mysterious chaos terrains at the kilometer scale. Galileo image number s0426272378 shows a ridge that has been sheared by a fault, revealing a cross section of the ridge that appears to have a thin bright layer at its margin with the uppermost surface (Fig. 4.1). This layer, which is nearly hidden within one or two pixel of Galileo's remote imaging, would have to be at least 6 m thick to be visible in the image (Phillips et al. 2017). Could this be the impact generated regopag?

Models of the thickness and evolution of the impact-generated lunar regolith have been used and developed since the Apollo era. One such model is the analytic model published by Gault et al. (1974), which quantifies the frequency with which impacts excavate material to a certain depth as a function of time. The Gault et al. (1974) model under-predicted the impact gardening that produced the observed depth-distribution of space weathering products (which darkens regolith that has been exposed to the surface) observed in Apollo cores (e.g. Morris 1978); however, a revival of the Gault model by Costello et al. (2018) included the gardening driven by secondary impacts and provided an excellent fit that could quantitatively describe the impact processing of the upper few meters of regolith for timescales over 100 thousand years. We adapt the Costello et al. (2018) model of impact processing of the Moon to quantitatively investigate the impact processing of the surface of young, icy Europa, to determine the effects of impacts in time and space on Europa's hidden meters and the thickness of its impact generated regopag.

4.2 Methods

4.2.1 Modeling the production of icy regolith or "regopag."

We model the growth of a layer of regopag on Europa to the first order by calculating the total volume excavated by impact craters as a function of time, and assuming a uniform distribution of ejecta across the surface of Europa. We calculate the thickness of the regopag layer by calculating the thickness of a thin spherical shell of volume equal to volume excavated by impact craters and inner-radius equal to the radius of Europa.

$$V_{ejecta} = V_{shell} = 4\pi r^2 h \tag{4.1}$$

where r is the radius of Europa and h is the thickness of the thin spherical shell of regopag.

The volume of ejecta excavated by craters can be calculated using the size distribution of crater-forming impacts and a cylindrical approximation of the excavated zone. We assume that the crater production function follows a power law size frequency distribution:

$$N = uD^v \tag{4.2}$$

where N is the cumulative number of craters of transient diameter D that form per area and time, and u and v are parameters that control the magnitude and slope of the power law respectively. Only about the top 1/3 of the crater volume is ejected, while the rest of the material is compressed, brecciated, or, in the case of hypervelocity impacts, melted or vaporized. Craters are also typically 1/10 as deep as they are wide. The volume of the excavated zone of a crater with diameter D can be approximated as a cylinder with height equal to 1/3 the crater depth:

$$V = \frac{\pi}{120} D^3$$
 (4.3)

We solve for D in equation (3) and replace D in equation (2) with the result to calculate the size-frequency distribution of excavated volumes as a function of time. The total volume excavated by craters over a time interval t can then be approximated by summing the volume excavated by the distribution of craters that form on the surface:

$$V_{ejecta} = t \int_{V_1}^{V_2} N(V) dV$$

= $t \int_{V_1}^{V_2} u \left(\frac{120V}{\pi}\right)^{\frac{v}{3}} dV$
= $t u \left(\frac{120}{\pi}\right)^{\frac{v}{3}} \left(\frac{3}{v+3}\right) \left(V_2^{\frac{v+3}{3}} - V_1^{\frac{v+3}{3}}\right)$ (4.4)

where V_1 and V_2 are arbitrary small and large volumes respectively, where u and v are shape parameters from the crater production function, and t is time. Using these expressions, we solve for h in equation (1) to estimate the thickness of the regopag as it grows over time:

$$h = \frac{tu}{4\pi r^2} \left(\frac{120}{\pi}\right)^{\frac{v}{3}} \left(\frac{3}{v+3}\right) \left(V_2^{\frac{v+3}{3}} - V_1^{\frac{v+3}{3}}\right)$$
(4.5)

where r is the radius of Europa.

4.2.2 Modeling impact gardening.

Impact gardening mobilizes material in the top meter, churning buried materials upwards. We calculate the impact gardening rate on Europa using the analytic model published by Costello et al, (2018). The model takes in a crater production function (equation 1) and calculates the frequency a point at depth is in the excavated volume of a crater as a function of time. The analytic model takes the form:

$$\Lambda = h \left[\left(\frac{v+2}{uv} \right) \left(\frac{4\lambda}{\pi t c^2} \right) \right]^{\frac{1}{v+2}}$$
(4.6)

where Λ is the gardening depth, t is a time interval, h is the dimensionless depth fraction of crater diameter, u and v are from the crater production function (Eqn. 1), λ is the cumulative Poisson distribution-derived average number of events per interval, and c is a dimensionless scaling parameter that accounts for overlapping craters. For details on the derivation of the model, we refer to Costello et al. (2018) and the followup paper: Costello et al. (2020). Ultimately, this expression allows us to calculate the depth that has been in the excavated volume of craters as a function of time. The model has been able to reproduce the depth distribution of space weathering products observed in Apollo cores, and the timescale over which ephemeral lunar surface features are gardened into background regolith (Costello et al., 2018).

4.2.3 Modeling secondary impacts.

Models of regolith mixing that do not include the effects of secondary impacts underestimate the rate of gardening by orders of magnitude. A critical update introduced by Costello et al. (2018) was the inclusion of secondary impacts. Following Costello et al. (2018), we assume that every primary impact that strikes Europa produces one hundred thousand secondary impacts. If the impact flux has the shape ad^b , where d is the diameter of the impacting object and the secondary flux parameter $a_{\text{Secondary}} = a_{\text{Primary}} \times 10^5$. The secondary flux power index is $b_{\text{Secondary}} = -4$ (following Table 4 of McEwen et al., 2005). To produce a



Figure 4.2 Illustration of the regopag thickness model. We calculate the total volume excavated by craters and set that volume equal to the volume of a thin spherical shell. The thickness of the spherical shell is the reported regopag thickness.

secondary crater production function we process the flux of secondary fragments through the Holsapple (1993) scaling from impactor size to crater size following the method in Costello et al. (2018, Eqn. 32).

4.2.4 The impact rate at Europa.

Our models take in a crater production function (Eqn 1) that describes the size-frequency distribution of craters formed on a surface per unit area and time. We model impact processing using either a crater production function constructed from observations and crater counts or a crater production function synthesized from the flux of objects from space and assumptions about impactor diameter to crater diameter scaling. Costello et al. (2020) found that the gardening calculated using the observed and synthesized crater production functions fit both one another and the gardening observed in Apollo cores. Although in our assessment of gardening on Europa we lack the ground-truth allowed by the Apollo cores, we should expect a similar agreement between craters counted and craters modeled on Europa.

Bierhaus et al. (2001; 2005; hereafter "Bierhaus et al. crater counts") performed extensive crater counts using high-resolution Galileo data. Their crater counts can be considered complete down to about 200 m diameter craters. Unlike the Moon, the relatively young surface of Europa has not yet reached crater saturation at this scale (where every point on the surface has been struck by a 200 m crater-forming impact at least one time); however it must have been below image resolution. We assume the shape of the crater production function implied by the Bierhaus crater counts holds down to 1 m craters. This extrapolation is reasonable, as the size distribution of craters over this scale has a relatively stable shape on the Moon (e.g. Speyerer et al. 2016); however, because Europa is icy rather than rocky and is struck by a different impactor population there may be surprises revealed by the imager on board Europa Clipper.

In our effort to model the production of small craters on Europa, we look first to the primary impact rate. Dynamic models agree that Jupiter comets dominate the impactor population (Zahnle et al. 1998; Levison et al. 2000; Zahnle et al 2003). The Levison et al. (2000) dynamic model and the Zahnle et al (2003) "Case B" size frequency distribution, which should have been representative of the flux at Neptune have been used by other workers to be representative of the small primary impactor flux at Europa (e.g. Tsuji et al. 2016) because of agreement with recent impact flash observations (Hueso et al. 2013).

We identify two possible scenarios for the cratering rate at Europa to use in our modeling:

- Case A: We assume that the cratering rate at Europa can be represented by Zahnle et al. (2003) "Case A". We model a crater production function for secondary craters using the Case A primary flux predicted by Zahnle et al. (2003) using the method described in section 2.3.
- Case B: We assume, as Tsuji et al. (2016) did, that the cratering rate at Europa can be represented by the Zahnle et al. (2003) "Case B" and Levison et al. (2000) dynamic model. We also model the secondary flux produced by this relatively higher impact rate following the method outlined in section 2.3.

Fig. 4.3 illustrates the collection of knowledge and models that we use to understand the cratering rate on Europa. The vertical error in the our plot of the Bierhaus et al. crater count data comes from assumptions about the surface age. Let us image that we have counted 10 craters on a surface. If we assume that surface is 1 Myr old, the 10 craters we counted imply a cratering rate of 10 craters per Myr. If instead the surface is 1 Gyr old, the 10 craters we counted imply a much lower cratering rate: 10 craters per Gyr. The models of crater production do not suffer the same uncertainty because they are not scaled from surface age. The models predict some number of craters form per annum based on the number and scale of impacts per annum. Both the Case A and Case B modeled secondary production functions appear to fit the Bierhuas et al. crater counts where the assumed surface age is between 10 and 200 Myr. Costello et al. (2020) showed that that the secondary crater production model for the Moon fit the observed production of meter scale albedo anomalies on the Moon (Speyerer et al., 2016), and it is reassuring that the



Figure 4.3 The crater production rate on Europa. The vertical error in the our plot of the Bierhaus et al. crater count data, which is considered complete down to 200 m craters, comes from assumptions about the surface age. We calculate fits to the cratering rate implied by the Bierhaus et al. crater count data for surface ages of 1 Myr (the minimum time it would take for tectonic features to have formed: Howell et al 2018), 10 Myr, and 200 Myr. The models of crater production do not suffer the same uncertainty in age scaling - predicting some number of craters form per annum based on the number and scale of impacts per annum. Our models for the number of secondaries produced by both the Case A and Case B primary impact flux fit the cratering rate implied by the Bierhaus crater counts for surface ages between 10 and 200 Myr.

model again appears to fit observations here regardless of the use of the Case A or Case B primary impact flux.

4.3 Results

We use the method described in Section 2.2 to calculate the thickness of a thin spherical shell of inner radius equal to the radius of Europa and with volume equal to the volume ejected by impacts into a hard ice target (Fig. 4.4). We integrate over crater sizes from 1 m to 45 km, assuming that craters smaller than 1 m mostly eject material that is already regopag. Our results show that the contribution of primary impactors is negligibly small. Despite lower energy, secondary impacts are so frequent that their ejecta is the dominant contributor to the regopag. We predict on the order of 10 m of regopag accumulates on a 10 Myr old surface. This is in the same order of magnitude as the depth implied by the Galileo image s0426272378 cross-section.

Once regopag is formed, it is churned by frequent smaller impacts. We calculate the depth of impact gardening using the method outlined in Section 2.2 and the cratering rates identified in Section 2.3 and show the results in Fig. 4.5. Just like on the Moon, impact gardening is shallower than the regolith/regopag depth. We calculate that the top 10 cm to 1 m of Europa globally is thoroughly mixed. Some regions have been more thoroughly gardened. We plot the depth-distribution of impact gardening depth with probability in Fig. 4.6. Though rarely found on Europa, some regions may have a mixing zone as deep as 10 m.

4.4 Discussion

4.4.1 The depth profile of irradiated material.

In previous work the impact gardened mixing depth has been called the "in situ reworking zone", implying that material in this zone is so frequently overturned by impacts that it might as well be on the surface (Morris 1978). Apollo cores show a systematic decrease of



Figure 4.4 We calculate the thickness of a spherical shell of volume equal to the volume ejected by carters over a time interval shown on the x-axis. Primary impacts contribute a relatively small volume while secondary impacts excavate much more. We integrate craters between 1 m and 45 km in diameter, assuming that smaller craters mostly excavate material that is already regopag. We predict on the order of 10 m of regopag has accumulated over Europa's surface age.



Figure 4.5 We calculate the impact gardening rate on Europa at 50% probability using the cratering rate implied by the Bierhaus et al. crater counts and our modeled secondary impact cratering rates. We predict the impact gardening zone extends to 10 to 50 cm depth.



Figure 4.6 The probability distribution of gardening with depth.

space weathering products with depth, and the Costello et al. model for gardening on the Moon reproduces the depth distribution exceedingly well. Like Apollo cores, Fig. 4.6 shows the decreasing probability of finding surface-correlated material at a given depth as it has been transported by impact gardening. The top 20 to 30 cm of regopag on Europa are likely saturated with radiolytic products and any material in this zone spends a significant amount of calendar time at the uppermost surface. We should expect spatial heterogeneity in the depth distribution of surface correlated products, just as there is spatial heterogeneity in the depth distribution observed in the Apollo cores; however, if we are searching for biomolecules that have never been irradiated at the surface, we conclude that we must look deeper than 50 cm, where gardening has had a 99% probability of churning regopag to the surface over the surface age of Europa.

4.4.2 Lateral transport and regolith/regopag depth.

On the Moon, lateral transport of material is less efficient than vertical transport (Langevin & Arnold 1977; Costello et al. 2018; Huang et al. 2017). On the Moon, impacts and lateral mixing have smeared the boundary between dark basaltic mare and bright plagioclase anorthosite highlands in a 4-5 km mixing region and some Apollo mare samples include up to 20% highlands material (Heiken et al. 1991); however, it has taken billions of years of large ray-forming impacts to marginally blur these regions (e.g. Huang et al. 2017). Extensive pyroclastic deposits such as the Aristarchus pyroclastic deposit are spectrally and thermophysically distinct at the surface (e.g. Allen et al. 2012) and their presence implies that even billions of years of lateral transport does not move enough material to bury them. While pyroclastic glass is found in Apollo samples across the sampled surface, it is thought to have been transported to these locations by much greater than 50 km and/or basin-forming impacts (Huang et al. 2017; Xie & Zhu 2016; Haskin et al. 2003; Oberbeck 1975). There are no visible craters on the surface of Europa that are this size.

The surface of the Moon is two to four orders of magnitude older than Europa and has had two to four orders of magnitude more time to encounter those large meteorites whose impacts drive the limited lateral transport we observe. We reason that lateral transport of material due to impacts on Europa is too slow to be important at the meter scale except in the special case of those restricted regions that have been influenced by the rays of a large crater such as Pwyll. The negligible contribution of primary impacts to the regopag depth (Fig. 4.4) supports the supposition that lateral transport of primary ejecta is limited. All of this is not to say that future studies of lateral transport on Europa following, for example, the work of Huang et al. (2017) or Xie & Zhu (2016), would not be illuminating or useful, only that such a study would need to focus on the ejecta of Europa's largest craters and that lateral transport is not a globally influential process. Another important implication of the relatively slow rate of lateral transport on Europa is that local material anomalies of interest will not be dispersed by impacts, even in trace amounts, across the entire surface of Europa.

4.4.3 Gardening crater rays and plume deposits.

Costello et al. (2018; 2020) validated the model of gardening on the Moon by exploring the implications of gardening model results for the erasure of lunar surface features, including crater rays. Lunar rays are charismatic albedo anomalies that splay radially away from a young crater, presenting an albedo contrast with background material. The contrast can be the result of material differences (e.g. highland anorthosite regolith rays on a mare basalt regolith background) or maturity (e.g. un-space weathered material excavated and thrown over space weathered material). Rayed craters on the Moon are less than 1 Gyr old; and older craters have had their rays faded into background regolith by a combination of impact gardening and space weathering by solar wind and micrometeoroid impacts. Rays are thought to be 1 m - 10 m thick, depending on the distance from and size of their parent crater (McGetchin et al. 1973; Hawke et al. 2004). Costello et al. (2018) showed that gardening due to secondary impacts could erase rays that are 1 m thick over 1 Gyr.

Europan crater rays are as charismatic as rays on the Moon, and yet more mysterious in nature and evolution. Europa's second largest crater, Pwyll (45 km diameter), displays extensive rays that are bright against reddened and darkened underlying material. Europan rays like those that surround Pwyll may be conceptually similar to lunar maturity rays, where fresh material is thrown over material that has been chemically and physically altered by exposure to the surface environment. In Europa's case, the surface ice would be radiolyzed and possibly colored over time by endogenic sulfur from Io (e.g. Eviatar et al. 1981; Alvarellos et al. 2008). Not all craters on Europa have bright rays. Niamh (5 km in diameter), for example, has dark rayed ejecta - the origin and nature of which is not yet understood; however, despite the persistent mystery of the formation mechanisms and nature of Europa rays, one fact is indisputable: not all craters on Europa have rays, which implies some form of erasure over time. At the 20 km scale, the difference between the cratering rate from Cases A and B from Zahnle et al. (2003) are negligible, and both predict one ¿ 20 km crater forms every 2 Myr. Three ¿ 20 km diameter rayed craters have been identified on the observed half Europa: Pwvll, Manannán, and Taliesin. Following the logic presented in Phillips et al. (2000) we reason that if such craters form once every 2 Myr (or once every 4 Myr on half of Europa), then Pwyll, Manannán, and Taliesin may have formed over 12 Myr and rays must therefore fade over a lifetime on that order.

Over 12 Myr, we calculate impact gardening on the order of 10 cm (Fig. 4.5) and up to 1 m in limited regions (Fig. 4.6). If Europan cratering follows similar laws to cratering on the Moon, then ejecta from Pwyll is 1 m thick 100 km from the rim (10 crater radii away; McGetchin et al. 1973). If gardening, radiolysis and Iogenic alteration behave together in a similar way that gardening and space weathering erase rays on the Moon, gardening would not be able to erase a 1 m thick ray until more than 100 Myr had passed. The gardening depth we calculate (about 10 cm in 10 Myr) is too shallow to account for the erasure rate of meter thick rays over only 12 Myr.

There are no observable plume deposits on Europa; however, if they are similar in thickness to rays they will also fade over 12 Myr. If this is true, then no new plume has formed on the observed surface over the last 12 Myr. Unless Pwyll, Manannán, and Taliesin, are anomalously young, it is unlikely that their crater rays are simply a bright fine-grained frost (Chapman and McKinnon, 1986), as they would be disrupted by impact gardening over short timescales. Similarly, a millimeter thick plume deposit would be vulnerable to the orders of magnitude faster and more intense impact gardening at the millimeter scale and would be extremely ephemeral.

4.4.4 The thermal and radiation process that make regopag distinct from silicate regolith.

The regopag is affected by thermal and radiation processes in ways that silicate regolith is not. Impact processes are just one act in a circus of sublimation ablation, thermal segregation, sintering, sputtering, and irradiation. The surface of Europa is extremely active and, as was noted by Phillips et al. (2000): sputtering erosion alone may erode the top meter of regopag over only 10 Myr (Ip et al. 1998), meaning regopag from crater ejecta may be sputtered as quickly as it is produced. If thermal processes or sputtering erosion dominated the erasure of crater rays, then we should observe spatial variation in ray fading that reflects latitudinal variation in temperature (e.g. Spencer et al. 1999; Hobley et al. 2018) and spatial variation in radiation dose (Nordheim et al., 2018). There is no evidence of a spatial dependance for crater rays or ray fading: Pwyll's rays splay outward with equal brilliance towards and away from the equator; however, exploring the finer scale brightness changes in ray material as a probe of erasure mechanisms is an exciting prospect of the global high resolution images that will be provided by Europa Clipper.

High resolution images of targets like the exposed cross-section shown in Fig. 4.1 and its 6 to 12 meter wide bright layer would also provide valuable evidence for the thickness and evolution of the regopag. By targeting ridges that have been cross cut by younger faults and taking images at a shallow view angle, we would take advantage of the unique tectonic activity on Europa and the views of the subsurface it provides us that are unavailable on bodies like the Moon. High resolution images would also provide a tool for exploring regopag depth through techniques that have been used to explore regolith depth on the Moon. Specifically, some craters have large blocks of rock in their ejecta that are visible in

	Process	Depth Scale	Time Scale	Reference
Impacts	Gardening	10 cm to 1 m	Power law with time. ~3 cm Myr ⁻¹	This Work
	Regopag	> 10 m	Power law with time. ~1 m Myr ⁻¹	
Charged Particles	Sputtering Erosion	Leading/trailing asymmetry. 0.2-2 µm	~2 × 10 ⁻² m Myr ^{-1*} 1 m per 10 Myr ^{**}	*Cassidy et al. (2013); Hobley et al. (2018) **Ip et al. (1998)
	Radiation Dose	Varies spatially. Up to 1 m penetration.	See Fig. 16 of * and Fig. 3 of **	*Cooper et al. (2001); **Nordheim et al. (2018)
Thermal Processes	Sublimation Ablation	Varies by temperature. 0 to 15 m	Varies by temperature. 0 - 3 x 10 ⁻⁷ m yr ⁻¹	Hobley et al. (2018); Hand et al. (2019)
	Thermal segregation	Varies by temperature. ?	Varies by grain size and may be suppressed by sputtering* ?	*Spencer et al. (1987)
	Sintering	Varies by temperature. µm to ?	Timescale depends on grain size and temperature. See Fig. 15 of *	*Molaro et al. (2019)

Table 1: A preliminary summary of the depth of influence and timescale for different impact, radiation, and thermal processes on Europa that includes the results of this work.

Table 4.1 A preliminary summary of the depth of influence and timescale for different impact, radiation, and thermal processes on Europa that includes the results of this work.

LRO images. Some craters do not. Where craters have ejected blocks they have penetrated the regolith. By identifying how large craters must be to excavate rocks we can probe the regolith depth (e.g. Bart et al. 2011). A survey of the ejecta of Europa's craters at high resolution could yield similar insights into the depth of the regopag.

While we wait for data from Europa Clipper, we can integrate our understanding of the processes that form and shape the regopag. In Table 4.4.4 we summarize the depth and timescale of charged particle and thermal processes as they have been described in literature and of the impact process that we presented here. This table should be expanded and elaborated. Sputtering, for example, has been shown to produce a tenuous water exosphere over Europa and Ganymede (e.g. Planiaki et al. 2012); however not all sputtered volatiles are lost to space, some will migrate. Impact gardening forces the migration of everything, with no preference for volatility or albedo. How efficient are these processes in relation to one another? How do they affect the surface texture and albedo? Do impacts on Europa produce amorphous water agglutinates like the glassy agglutinates that bind regolith grains on the Moon? Do grains of regopag accumulate amorphous coatings from impact vapor? Does impact vapor play a role in addition to radiation and thermal processes in the dominantly amorphous water observed on the surface of Europa (e.g. Hansen & McCord 2004)? Do impacts facilitate sintering by providing fine grained material and an increased temperature? Does sintering or gardening act faster? What is the radiation dose received by regopag as a function of depth in the presence of impact gardening?

4.5 Conclusions

- We introduce a new term to describe the impact generated fine grained material that blankets icy worlds: "regopag". The regopag is altered by thermal and radiolytic processes in ways that silicate regolith is not; however, both regopag and regolith form from repeated impacts.
- The icy regolith or "regopag" on Europa is ¿ 10 m thick.

- Most of the lunar regolith can be attributed to relatively high energy impacts (e.g. Oberbeck 1975; Hirabayashi et al. 2018). Our treatment of regopag growth was exploratory and could be improved with more robust modeling and qualification with direct observations.
- Secondary impacts dominantly contribute to regopag production on Europa.
- The top 10-50 cm of Europa's surface regopag is thoroughly mixed and there may be locations where the mixing zone extends to 10 m depth. If we wish to discover biomolecules that have never been exposed to surface radiation, we must look deeper than 50 cm. Impact gardening alone can not explain the fading of crater rays over 12 Myr.
- Global high resolution images of Europa will provide valuable validation and exploration tools. We will be able to searching high resolution images of the ejecta of Europa's small craters for ice-boulders as a probe of regopag depth, its spatial variation, and the evolution of impact generated surface texture. Europa's active surface provides some unique targets for imaging such as crater rays and cross-cut ridges like those in the Galileo image s0426272378, which are of particular value for the exploration of the regopag and its evolution in the presence of impacts, thermal processes and radiation.
- While we wait for Europa Clipper and a landed mission to arrive, we should combine our knowledge of the impact, thermal, and radiation processes that alter Europa's surface as a system.

Acknowledgements

This work was supported and facilitated by a summer internship at the National Aeronautics and Space Administration Jet Propulsion Laboratory Summer Internship Program and a Solar System Workings grant. All of the data plotted can be reproduced using the equations and parameters provided or in the referenced literature.

References

Allen, C. C., Greenhagen, B. T., Donaldson Hanna, K. L., & Paige, D. A. (2012). Analysis of lunar pyroclastic deposit FeO abundances by LRO Diviner. Journal of Geophysical Research: Planets, 117(E12).

Alvarellos, J. L., Zahnle, K. J., Dobrovolskis, A. R., & Hamill, P. (2008). Transfer of mass from Io to Europa and beyond due to cometary impacts. Icarus, 194(2), 636-646.

Bart, G. D., Nickerson, R. D., Lawder, M. T., & Melosh, H. J. (2011). Global survey of lunar regolith depths from LROC images. Icarus, 215(2), 485-490.

Bierhaus, E. B., Chapman, C. R., & Merline, W. J. (2005). Secondary craters on Europa and implications for cratered surfaces. Nature, 437(7062), 1125.

Bierhaus, E. B., Chapman, C. R., Merline, W. J., Brooks, S. M., & Asphaug, E. (2001).Pwyll secondaries and other small craters on Europa. Icarus, 153(2), 264-276.

Cooper, J. F., Johnson, R. E., Mauk, B. H., Garrett, H. B., & Gehrels, N. (2001). Energetic ion and electron irradiation of the icy Galilean satellites. Icarus, 149(1), 133-159.

Costello, E. S., Ghent, R. R., & Lucey, P. G. (2018). The mixing of lunar regolith: Vital updates to a canonical model. Icarus, 314, 327-344.

Costello, E. S., Ghent, R. R., M. Hirabayashi, & Lucey, P. G. (2020). Impact gardening as a constraint on the age, source, and evolution of ice on Mercury and the Moon. JGR: Planets.

Eviatar, A., Siscoe, G. L., Johnson, T. V., & Matson, D. L. (1981). Effects of Io ejecta on Europa. Icarus, 47(1), 75-83.

Gault, D. E., Hörz, F., Brownlee, D. E., & Hartung, J. B. (1974). Mixing of the lunar regolith. In Lunar and Planetary Science Conference Proceedings (Vol. 5, pp. 2365-2386).

Haskin, L. A., Moss, B. E., & McKinnon, W. B. (2003). On estimating contributions of basin ejecta to regolith deposits at lunar sites. Meteoritics & Planetary Science, 38(1), 13-33.

Heiken, G. H., Vaniman, D. T., & French, B. M. (1991). Lunar sourcebook-A user's guide to the moon. Research supported by NASA,. Cambridge, England, Cambridge University Press, 1991.

Hirabayashi, M., Howl, B. A., Fassett, C. I., Soderblom, J. M., Minton, D. A., & Melosh,
H. J. (2018). The role of breccia lenses in regolith generation from the formation of small,
simple craters: Application to the Apollo 15 landing site. Journal of Geophysical Research:
Planets, 123(2), 527-543.

Hobley, D. E. J., Moore, J. M., Howard, A. D. & Umurhan, O. M. Formation of metrescale bladed roughness on Europa's surface by ablation of ice. Nat. Geosci. 11, 901–904 (2018).

Holsapple, K. A. (1993). The scaling of impact processes in planetary sciences. Annual review of earth and planetary sciences, 21(1), 333-373.

Huang, Y. H., Minton, D. A., Hirabayashi, M., Elliott, J. R., Richardson, J. E., Fassett,
C. I., & Zellner, N. E. (2017). Heterogeneous impact transport on the Moon. Journal of
Geophysical Research: Planets, 122(6), 1158-1180.

Hueso, R., Pérez-Hoyos, S., Sánchez-Lavega, A., Wesley, A., Hall, G., Go, C., ... & Korycansky, D. G. (2013). Impact flux on Jupiter: From superbolides to large-scale collisions. Astronomy & Astrophysics, 560, A55.

Ip, W. H., Williams, D. J., McEntire, R. W., & Mauk, B. H. (1998). Ion sputtering and surface erosion at Europa. Geophysical research letters, 25(6), 829-832.

Jaumann, R., Brown, R. H., Stephan, K., Barnes, J. W., Soderblom, L. A., Sotin, C., ... Wagner, R. (2008). Fluvial erosion and post-erosional processes on Titan. Icarus, 197(2), 526-538.

Langevin, Y., & Arnold, J. R. (1977). The evolution of the lunar regolith. Annual Review of Earth and Planetary Sciences, 5(1), 449-489. Lebreton, J. P., Witasse, O., Sollazzo, C., Blancquaert, T., Couzin, P., Schipper, A. M., ... & Kazeminejad, B. (2005). An overview of the descent and landing of the Huygens probe on Titan. Nature, 438(7069), 758.

Lorenz, R. D., Lopes, R. M., Paganelli, F., Lunine, J. I., Kirk, R. L., Mitchell, K. L., ... & Miyamoto, H. (2008). Fluvial channels on Titan: initial Cassini RADAR observations. Planetary and Space Science, 56(8), 1132-1144.

Levison, H. F., Duncan, M. J., Zahnle, K., Holman, M., & Dones, L. (2000). Planetary impact rates from ecliptic comets. Icarus, 143(2), 415-420.

McEwen, A. S., Preblich, B. S., Turtle, E. P., Artemieva, N. A., Golombek, M. P., Hurst, M., ... & Christensen, P. R. (2005). The rayed crater Zunil and interpretations of small impact craters on Mars. Icarus, 176(2), 351-381.

McGetchin, T. R., Settle, M., & Head, J. W. (1973). Radial thickness variation in impact crater ejecta: Implications for lunar basin deposits. Earth and Planetary Science Letters, 20(2), 226-236.

Melosh, H. J. (1985). Ejection of rock fragments from planetary bodies. Geology, 13(2), 144-148.

Melosh, H. J. (1989). Impact cratering: A geologic process. Research supported by NASA. New York, Oxford University Press (Oxford Monographs on Geology and Geophysics, No. 11), 1989, 253 p., 11.

Molaro, J. L., Choukroun, M., Phillips, C. B., Phelps, E. S., Hodyss, R., Mitchell, K.L., ... & Meirion-Griffith, G. (2019). The microstructural evolution of water ice in the solar system through sintering. Journal of Geophysical Research: Planets, 124(2), 243-277.

Morris, R. V. (1978). In situ reworking/gardening/of the lunar surface-Evidence from the Apollo cores. In Lunar and Planetary Science Conference Proceedings (Vol. 9, pp. 1801-1811).

Nakamura, Y., Latham, G. V., & Dorman, H. J. (1982). Apollo lunar seismic experiment—Final summary. Journal of Geophysical Research: Solid Earth, 87(S01), A117-A123. Nelson, R. M., Shkuratov, Y., Boryta, M., Hapke, B. W., & Vandervoort, K. (2018, July). Understanding Europa's surface texture from remote sensing photopolarimetry. In 42nd COSPAR Scientific Assembly (Vol. 42).

Nordheim, T. A., Hand, K. P., & Paranicas, C. (2018). Preservation of potential biosignatures in the shallow subsurface of Europa. Nature Astronomy, 2(8), 673.

Oberbeck, V. R. (1975). The role of ballistic erosion and sedimentation in lunar stratigraphy. Reviews of Geophysics, 13(2), 337-362.

Plainaki, C., Milillo, A., Mura, A., Orsini, S., Massetti, S., & Cassidy, T. (2012). The role of sputtering and radiolysis in the generation of Europa exosphere. Icarus, 218(2), 956-966.

Phillips, C. B., McEwen, A. S., Hoppa, G. V., Fagents, S. A., Greeley, R., Klemaszewski,
J. E., ... & Breneman, H. H. (2000). The search for current geologic activity on
Europa. Journal of Geophysical Research: Planets, 105(E9), 22579-22597.

Phillips, C. B., & Molaro, J. L. (2017, March). Europa's Surface Properties and Processes. In Lunar and Planetary Science Conference (Vol. 48).

Spencer, J. R., Tamppari, L. K., Martin, T. Z., & Travis, L. D. (1999). Temperatures on Europa from Galileo photopolarimeter-radiometer: nighttime thermal anomalies. Science, 284(5419), 1514-1516.

Spencer, J. R. (1987). Thermal segregation of water ice on the Galilean satellites. Icarus, 69(2), 297-313.

Tsuji, D., & Teanby, N. A. (2016). Europa's small impactor flux and seismic detection predictions. Icarus, 277, 39-55.

Vickery, A. M. (1986). Size-velocity distribution of large ejecta fragments. Icarus, 67(2), 224-236.

Xie, M., & Zhu, M. H. (2016). Estimates of primary ejecta and local material for the Orientale basin: Implications for the formation and ballistic sedimentation of multi-ring basins. Earth and Planetary Science Letters, 440, 71-80. Zahnle, K., Schenk, P., Levison, H., & Dones, L. (2003). Cratering rates in the outer Solar System. Icarus, 163(2), 263-289.

Zahnle, K., Dones, L., & Levison, H. F. (1998). Cratering rates on the Galilean satellites. Icarus, 136(2), 202-222.

Chapter 5

Conclusion

In this dissertation I derived, expanded upon, and adapted an analytic model of impact gardening to calculate the extent to which and timescale over which impact gardening alters the surfaces of the Moon, Mercury, and Europa. The dissertation supports the following key scientific findings:

- Secondary impacts dominate over primary impacts in the impact gardening of planetary surfaces.
- Micrometeoroids overturn the top few milimeters of lunar soil with extreme frequency.
- The reconstituted, expanded upon, and adapted impact gardening model based on Gault et al. (1974) is validated for the Moon against the gardening implied by analysis of Apollo cores and interpretation of remote sensing data sets (Chapters 1 and 2).
- The model is dominantly sensitive to variation in the slope of the input cumulative crater production function. It is also sensitive to impact velocity. It is relatively weakly sensitive to material properties of the target that control crater size such as density and yield strength.
- Impact gardening is more efficient on the Moon than on Mercury.
- Gardening is more efficient in ice than in regolith.
- Lunar ice may be billions of years old and have previously been > 10 m thick.

- Mercury's most recent large-scale deposition of ice occurred no more than 200 Myr ago.
- The sources of ice on the Moon and Mercury are likely sporadic and voluminous rather than continuous.
- The differences between the Moon and Mercury will likely only become more distinct, as gardening exposes what little ice remains on the Moon to loss and only scratches the surface of Mercury's extensive deposits.
- On Europa, primary impacts produce a layer of regopag that is > 10 cm thick.
- Secondary impacts churn the top 10 cm to 1 m of Europa's regopag, and we will have to dig at least half a meter deep to find abundant material that has never been radiolytically altered.