Landslide scaling across the Solar System

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Abstract

The scaling of landslides provides important insights into the processes that drive them. On Earth, the distribution of landslide areas has inverse power law scaling for small areas and power law scaling for large areas. This distribution has been linked to the different source mechanisms that occur in the unconsolidated, homogenous soil layer vs. in deeper, heterogenous rock layers. The same distribution has been observed on different bodies in the Solar System, including Mars, the Moon, and Mercury. The differences between the observed distributions on these bodies has been attributed to variations in gravity, subsurface fluids, ice, topography, and geology. In this paper, I map landslide areas on Vesta and compare the scaling there to other bodies. I argue that gravity is not the major factor controlling landslide area scaling and instead that, on heavily cratered surfaces, the distribution of crater sizes is the most important factor.

Introduction

Landslides are fundamental surface processes that play an important role in sediment transport and landscape evolution. One approach to better understand their properties is the study of landslide catalogs; collections of mapped landslides in a particular region. This allows for the examination of how, for example, landslide volume scales with area or landslide frequency varies with size. This method has been used extensively for landslides on Earth, both for specific time periods (e.g. landslides triggered by a specific earthquake or storm) and geographic regions (Brunetti et al., 2009; Frattini and Crosta, 2013; Malamud et al., 2004; Stark and Hovius, 2001; Tebbens, 2020). Landslide scaling has allowed scientists to characterize the different processes that are responsible for terrestrial landslides as well as predict the occurrence rates of hazardous events.

With the advent of high-resolution imagery, we have observed landslides on many non-Earth bodies, including the Moon, Mars, Venus, Mercury, and various asteroids including Vesta and Ceres (Brunetti et al., 2015; Crosta et al., 2018; Parekh et al., 2021). For some of these locations, researchers have used mapping techniques developed on Earth to create landslide catalogs. Examining the difference in landslide scaling relations across these bodies gives us a way to study the impact of gravity, the atmosphere, subsurface fluids, and the geologic environment on landslide properties.

In this paper, I map the areas of previously identified landslides on Vesta. I compare this catalog to datasets from Earth, the Moon, Mars, and Mercury. I then examine the extent to which the differences in landslide scaling between these bodies is due to gravity vs. topography by comparing the scaling of landslides to the scaling of impact craters.

Data

Mercury

Researchers have mapped landslides on crater slopes on Mercury (Brunetti et al., 2015). They used imagery from the Mercury Dual Imaging System (MDIS; 250 m/pixel). A digital elevation model (DEM) was not available for Mercury when they conducted their study. They compiled a catalog of 58 landslides in 38 craters.

Earth

I use a catalog containing 11,000+ landslides from Washington State. The Washington State Geologic Survey has mapped landslides throughout the state to better understand the risks they pose to people and infrastructure (Washington Geological et al., 2017). To identify and map landslides they used orthoimagery and DEM's generated from lidar data (max of 2 m/pixel) collected by aerial surveys. This catalog is an example of high-resolution terrestrial landslide mapping.

The Moon

Similarly to Mercury, landslides have been mapped on crater slopes on the Moon (Brunetti et al., 2015). Their study only considered landslides over 10^6 m^2. To identify and map landslides, they used imagery from the Wide Angle Camera on the Lunar Reconnaissance Orbiter Camera (100 m/pixel), as well as a global DEM (100 m grid size). They found 60 landslides in 35 craters.

Mars

Thanks to the availability of high resolution imagery, researchers have undertaken a project to globally map landslides on Mars (Crosta et al., 2018). They analyzed the planet over latitudes from –60° to +60° and only mapped landslides greater than 10^5 m^2. To globally identify landslides, they used imagery from the High Resolution Stereo Camera on Mars Express (18 m/pixel), the Mars Orbital Camera (1.5–12 m/pixel), and the Context Imager (5–6 m/pixel), as well as 400 m gridded topography from the Mars Orbital Laser Altimeter (MOLA). To locally map landslides, they used HiRISE imagery (0.3 m/pixel) and DEM's from HRSC (50–150 m grid size) and MOLA (463 m grid size) when the HRSC-derived DEM was not available. Their final catalog contains 3,000+ landslides.

Vesta

Previous researchers have identified landslides on Vesta (Parekh et al., 2021). However, they only recorded location, maximum length, and total drop, and did not measure areas. They used imagery from the Dawn Low Altitude Mapping Orbit (LAMO; ~20 m/pixel) as well as a DEM (92 m/pixel).

Methods

Mapping landslide areas on Vesta

I started with the locations identified by previous researchers (Parekh et al., 2021) and used the same imagery and DEM that they used. I found that most landslides were on crater slopes. The sharp shadows, especially in the north, limited my mapping coverage. While mapping I tried to follow the procedures outlined in (Slaughter et al., n.d.) for identifying landslide scarps and deposits. However, the poor resolution made this difficult. I also saw some examples where it appeared that newer landslide deposits were sitting on top of an older slide form. I did not map these because I felt I lacked the resolution to disambiguate each individual slide. In total, I was able to determine areas for 42 out of the 85 slides given in the supplemental information for the paper. I also mapped the areas of the 40 craters in which these landslides occurred using the same methods.

Estimating probability density functions of landslide areas

A common technique when analyzing landslide catalogs is to examine the relationship between landslide frequency and area (Malamud et al., 2004; Stark and Hovius, 2001). Let A be the landslide area. Then a probability density function $p(A)$ is defined such that the probability of a landslide occurring within a range of areas $A_{\min}$ to $A_{\max}$ is given by

$$Pr[A_{\min} \leq A \leq A_{\max}] = \int_{A_{\min}}^{A_{\max}} p(A) dA.$$

This probability density function can be estimated from the finite samples in a landslide catalog using kernel density estimation. I used the implementation in the Python library scikit-learn with a Gaussian kernel and Scott's method for estimating the bandwidth. Due to the wide range of landslide areas, I performed the kernel density estimation in log space.

Results

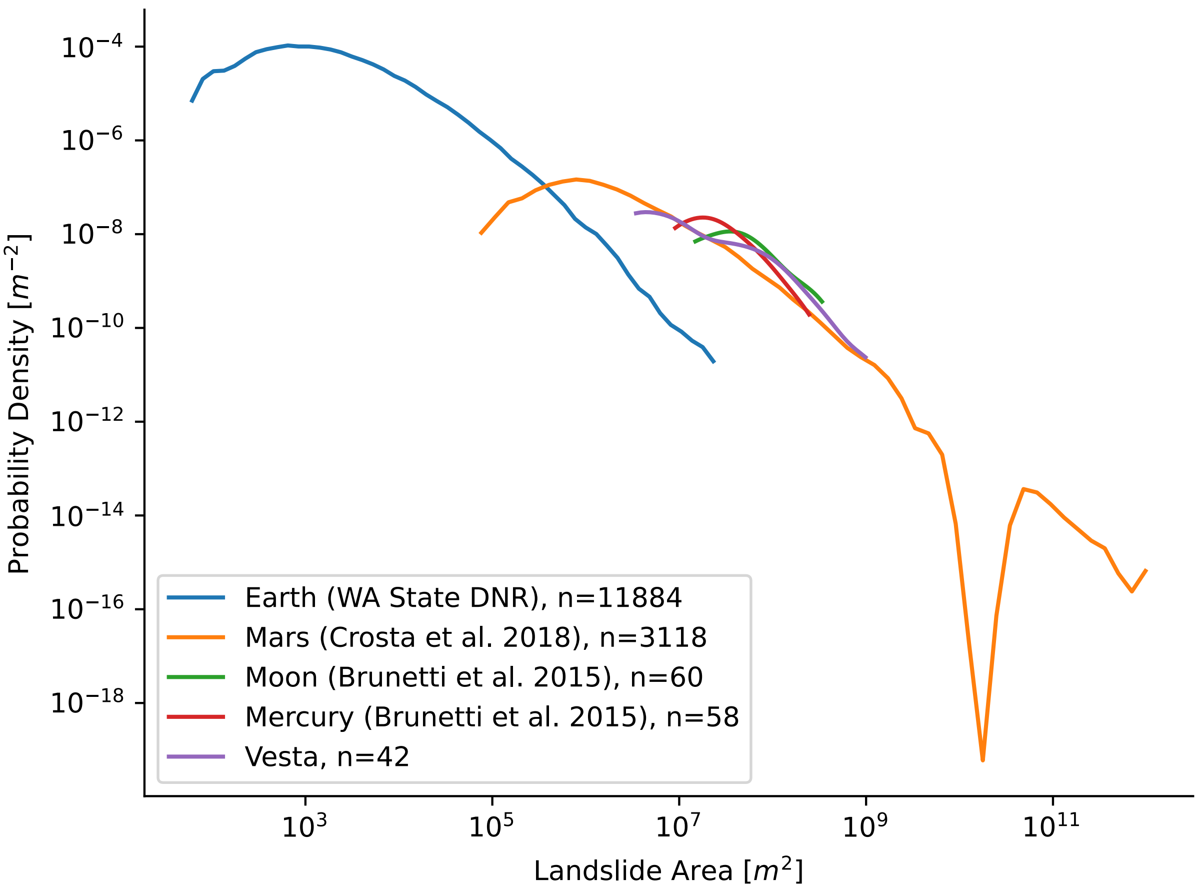

Figure 1: Area probability density functions for landslide catalogs on Earth, Mars, the Moon, Mercury, and Vesta. All bodies except for Vesta show a well-defined rollover above the catalog's minimum resolution. The gap in the Mars catalog's distribution from ~10^{10}–10^{11} m^2 is due to an absence of measured events within those areas.

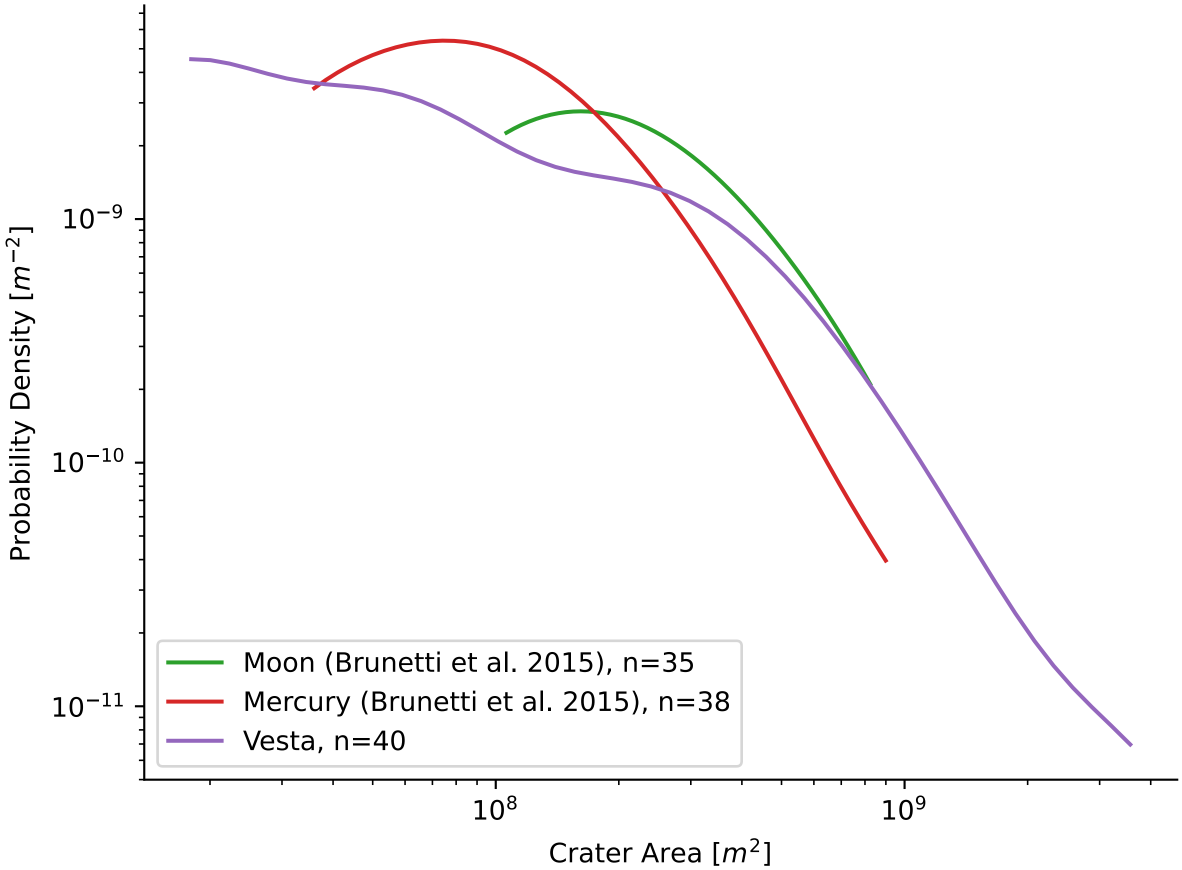

Figure 2: Area probability density functions for craters on the Moon, Mercury, and Vesta. The crater areas for Mercury and the Moon are calculated from diameters given in (Brunetti et al., 2015). Crater areas on Vesta mapped using the same imagery and DEM as for landslides.

Discussion

Prototypical probability-area relationship

Various hypotheses have been put forward to explain the probability-area relationship that is typically observed in terrestrial landslide catalogs (shown in Figure 3). Originally, the rollover was thought to be an artifact of the mapping resolution (Stark and Hovius, 2001). However, further studies have shown that this rollover appears to occur at areas larger than the mapping resolution, and thus represents a real phenomenon. One popular model that explains rollover was derived by lab experiments where slides were induced in a sandbox by a vibrating bed (Katz and Aharonov, 2006). This model posits that there are two different populations of landslides: 1. Those that occur in the upper, homogenous soil layer and 2. Those that are large enough to enter heterogenous rock layers. A landslide in the first population will naturally expand to incorporate the entire soil layer, leading to a characteristic landslide area that scales with the soil depth. The size of landslide in the second population is controlled by the variability in the local geology — bedding planes, fractures, weak layers — and thus scales with a power law distribution. Combining these two populations gives the observed frequency-area relationship with different scaling for small and large landslides.

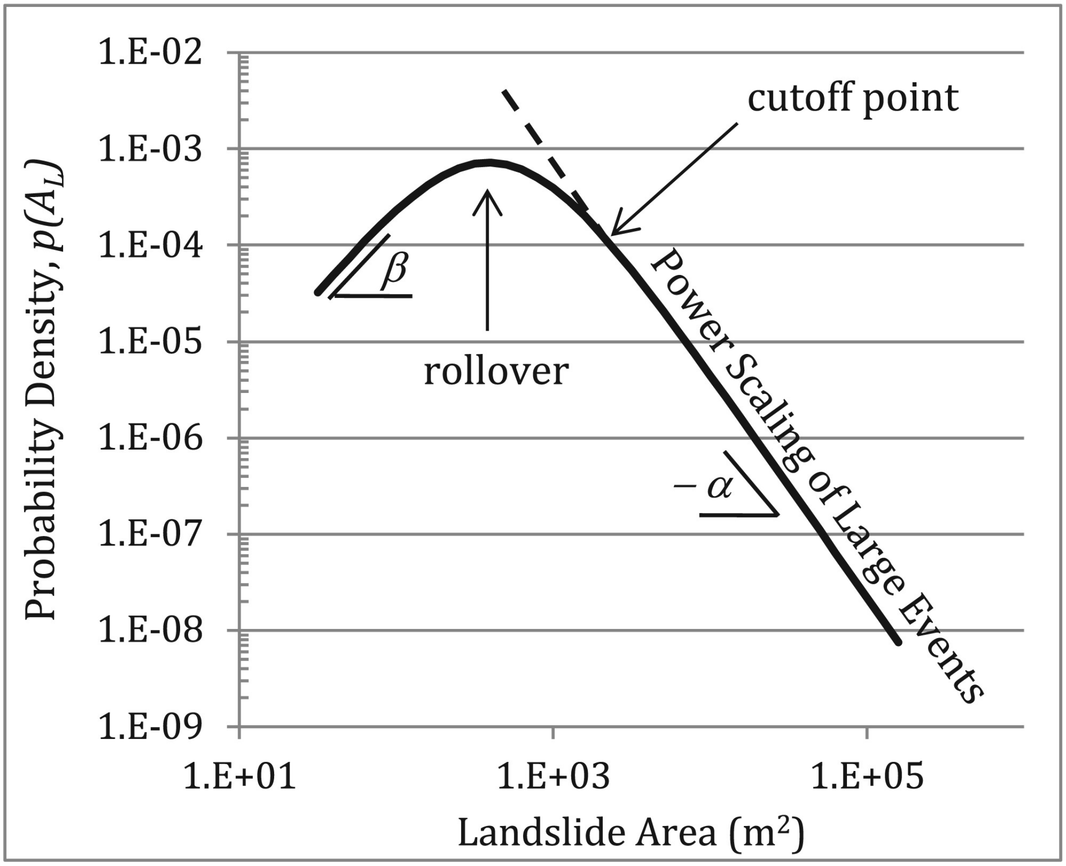

Figure 3: Typical landslide probability-area relationship, taken from (Tebbens, 2020). Below the rollover point there is an inverse power-law scaling where slides become exponentially more likely with area. At the rollover point the probability of a landslide peaks — this area is called the characteristic size. Beyond this point the distribution approaches power law scaling where slides become exponentially less likely with area. The cutoff point refers to the area after which the distribution is well approximated by a power law.

Lack of a rollover point in Vesta's catalog

Figure 1 shows that the probability density function estimated from Vesta's catalog lacks a clear rollover point, as the conceptual model predicts and as is seen for every other body. However, I believe that my catalog does not have enough coverage to capture the true distribution of landslides on Vesta. More landslides will need to be mapped to accurately determine the rollover point on Vesta (if one exists) and how it compares with other bodies.

Role of gravity

Researchers have pointed towards the reduced gravity on Mars (3.71 m/s^2 vs. 9.81 m/s^2 on Earth) as a factor for why its rollover point (~10^6 m) is so much higher than observed on Earth (~10^3 m) (Crosta et al., 2018). This makes sense, as reduced gravity can allow for a larger drop to develop, and landslide runout (and area) scales with drop. Additionally, reduced gravity may allow material flows to travel farther. However, the role of gravity is less clear when looking at the landslide catalogs from Mercury, the Moon, and Vesta. These three bodies have a wide range of gravities: 3.7 m/s^2 on Mercury, 1.62 m/s^2 on the Moon, and 0.22 m/s^2 on Vesta. Their mapped landslide areas, on the other hand, overlap, from roughly 10^7–10^9 m^2. The rollover points on Mercury and the Moon are different — 1.49×10^7 vs. 4.09×10^7 m^2 — but are much closer than observed for Earth and Mars. This indicates that gravity may not be the primary driver in differences in landslide scaling on these bodies.

Role of topography

On Earth, researchers have linked landslide area scaling to scaling of topography as well as depth-dependent material strength (Frattini and Crosta, 2013). This work focused on the fractal topography created by drainage networks in mountainous regions on Earth. Unlike on Earth, cratering has a large impact on the topography of Mercury, the Moon, and Vesta. All the mapped landslides from Mercury and the Moon, and most of the slides on Vesta, occurred in craters. Perhaps the distribution of crater sizes controls landslide areas.

Figure 2 shows the probability density functions for crater areas on these bodies. The distributions for Mercury and the Moon strongly resemble those for landslide area; they both have inverse power law scaling for small areas, a rollover point, and then power law scaling for large areas. The rollover points for crater areas are, respectively, roughly 1.40×10^8 and 3.31×10^8 m^2. The ratio of the rollover points on the Moon vs. Mars is 2.36 for crater area and 2.73 for landslide area. This similarity suggests that the differences in rollover between these two bodies could be explained by the difference in crater sizes instead of gravity. Additionally, while there is no clear rollover point, the distribution of the probability density function for Vesta's craters looks very similar to the one for landslides. These results also suggest that the different scaling for small and large events may not be due to homogenous vs. heterogenous layers but could instead be explained by the distribution of crater sizes.

Conclusions

When comparing Earth, the Moon, Mars, and Mercury, there does not appear to be a clear relationship between the rollover point of landslide area probability density functions and gravity. My mapped catalog of landslides on Vesta was likely too incomplete to for me to observe a clear rollover point. However, I observed a similar range of landslide areas on Vesta as on the Moon and Mercury. On the heavily cratered bodies lacking atmospheres, the probability density function of crater size appears to be roughly a constant multiple of the probability density function of landslide area, suggesting that crater topography is the primary control on landslide areas on these bodies.

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