Global Drivers of Lunar Rockfall

V. T. Bickel[1,2], A. Jordan[2], A. Manconi[2], S. Loew[2], and U. Mall[1], [1]Max Planck Institute for Solar System Research, Goettingen, Germany (bickel@mps.mpg.de), [2]ETH Zurich, Zurich, Switzerland.

Introduction: Rockfalls are boulders or blocks that detach from an elevated source region and roll, bounce, or slide downslope. These features were first discovered on the Moon in pre-Apollo Lunar Orbiter images – more than 50 years ago [e.g. 1]. Recent work has shown that rockfalls are abundant across the surface of the Moon and that their spatial distribution is heterogeneous: the vast majority of rockfalls are located in impact structures and the highest spatial densities are associated with young, Copernican craters [2]. Here, rockfalls are either initiated through propagation of impact-generated fracture networks (long-term driver) or directly triggered (induced or ejected) by small-scale impact events (short-term driver). Impact events of various scales are probably one of the reasons why even the oldest, pre-Nectarian terranes still host rockfall [2]. Interestingly, less than ~1% of all rockfalls are located in the proximity of tectonic features. The above observations indicate that impact processes play an important role in rockfall occurrence, acting as long- and short-term drivers, over billions of years [2].

Despite these recent findings our understanding of lunar rockfalls remains incomplete. Are there other important global-scale / local-scale or long-term / short-term drivers of lunar rockfalls? Where and how to they operate? What can these drivers tell us about the endo- and exogenic activity of the Moon and other airless bodies?

Here we use a deep learning-generated, global rockfall map [2,3] in combination with multiple global, geophysical datasets to find answers to these questions.

Methods: We use a global catalog created by [2] that holds 136,610 rockfalls and correlate its entries (using QGIS) with a total of 17 geophysical maps, specifically: minimum and maximum surface temperature; daily surface temperature gradient; effective albedo; solar thermal onset; thermal conductivity [4]; surface roughness; nightside albedo; topographic elevation, slope, and aspect; free-Air and Bouguer gravity anomalies; radial tidal displacement [5]; and the locations of the 28 recorded shallow Apollo-era moonquake epicenters [6,7], as well as the locations of wrinkle ridges and lobate scarps. We extract the value of each map for each rockfall location - effectively characterizing the regions that host rockfalls – and compare these distributions to each map's background distribution, with the intention to find discrepancies between the distributions that enable us to better understand potential underlying physical processes.

Long-term drivers: We discover that rockfalls tend to be located in regions with: 1) large thermal gradients, 2) high thermal conductivity, 3) increased surface roughness, 4) steep slope angles, and 5) large tidal displacement values. We also find that the majority of rockfalls are 6) located on equator-facing slopes (see Figure 1 and 2). Interestingly, rockfalls tend to be more abundant on E- and W-facing slopes at higher latitudes (see Figure 2). We do not observe any obvious qualitative relation between rockfall abundance, and the distribution of tectonic features, i.e., we do not find evidence that tectonic activity acts as long-term driver of lunar rockfall.

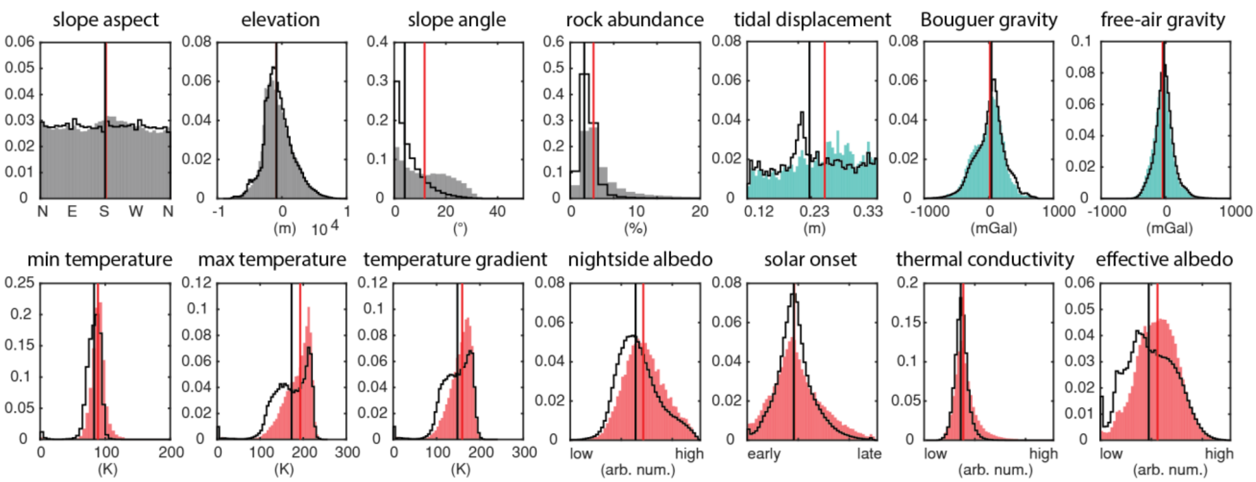

Figure 1. Comparison of rockfall (colored) and background (black line) normalized distributions for slope aspect, elevation, slope angle, rock abundance (all dark gray), tidal displacement, Bouguer and free-air gravity anomalies (all cyan), daily minimum & maximum temperature, daily temperature gradient, nightside surface albedo, solar thermal onset delay, thermal conductivity, and effective albedo (all red). The red vertical line represents the rockfall median, the black vertical line the background median.

Our observations show that the Sun plays a major role in driving rockfall occurrence on the Moon, breaking down exposed bedrock via thermal fatigue as time passes, particularly in young, steep source regions (such as Copernican craters) that face the equator, i.e., that receive large amounts of solar radiation and thus experience large thermal gradients. Our observations also suggest that tidal displacement could have an impact on fracture propagation and rockfall occurrence, although more data is required to substantiate this initial observation.

The reason for the pronounced rotation of the dominant rockfall orientation to E-W on slopes at high latitudes is currently unclear, but could be related to the solar-induced peak interior and surface stresses that occur on boulders in the local morning and afternoon [8]; as the effective albedo decreases towards the poles, this effect could become more pronounced. Besides that, the recently proposed, E-W trending (at high latitudes), near-surface stress field of the Moon [7] might influence the rockfall aspect distribution as well.

Short-term drivers: Exploring the catalog derived by [2] we observe numerous rockfalls across the surface of the Moon that have either been induced or ejected by small-scale impact events, i.e., we confirm the important role of meteoritic impacts as global short-term driver of rockfall as described by previous work [2]. In addition, we note that the role of impacts as a short-term driver appears to be increasingly important in older terranes which host shallow slopes and fewer rock outcrops/boulders. We do not find evidence that the lunar seismicity as recorded during the Apollo-era acts as a short-term driver of rockfall. We note that this observation is not conclusive, as the Apollo-era seismic monitoring duration (~7 a) differs substantially from the survivability of rockfall tracks (~1.5 – 35 Ma, e.g. [9]). In steep, young, exposed source regions, solar-driven thermal fatigue might act as short-term driver as well.

Conclusion: We conduct the first comprehensive, global-scale study of lunar long- and short-term drivers by fusing deep learning-generated and existing geophysical datasets. We argue that daily temperature cycles and meteoritic impacts are the dominant long- and short-term drivers of rockfalls on the Moon, potentially supported by meteoritic micro-bombardment and apparently independent of the geomorphic context. We do not find evidence that seismic activity has been an important, global-scale long- and short-term driver of rockfalls in the Moon's recent geologic past, but note that seismicity might play a role in the proximity of tectonic features [7]. The findings of this study show that the presence of rockfalls – or mass wasting features in general – is not necessarily connected to geologically recent or present-day tectonic activity, but can have other drivers. For example, on Mars, solar-driven thermal fatigue has been identified as an important global-scale driver of rockfalls as well [10], increasing our confidence in our results.

Future remote sensing and ground-based missions to the Moon, such as a global, long-lived, lunar geophysical network, would allow us to test our current hypotheses about lunar rockfall and mass wasting processes.

References: [1] H.J. Hovland and J.K. Mitchell (1973) *The Moon, 6.* [2] V.T. Bickel et al. (2020) *Nature Communications*, *11*. [3] V.T. Bickel et al. (2018) *IEEE TGRS*, *57.* [4] B. Moseley et al. (2020) *The Planetary Science Journal*, *1.* [5] R. Thor et al. (2020) *Journal of Geodesy, in press.* [6] Y. Nakamura et al. (1979) LPSC 10th. [7] T.R. Watters et al. (2019) *Nature Geoscience*, *12.* [8] J.L. Molaro et al. (2017) *Icarus*, *294*. [9] D. Hurwitz and D.A. Kring (2016) *Earth and Planet. Sci. Letters*, *436*. [10] P.-A. Tesson et al. (2020) *Icarus*, *342.*

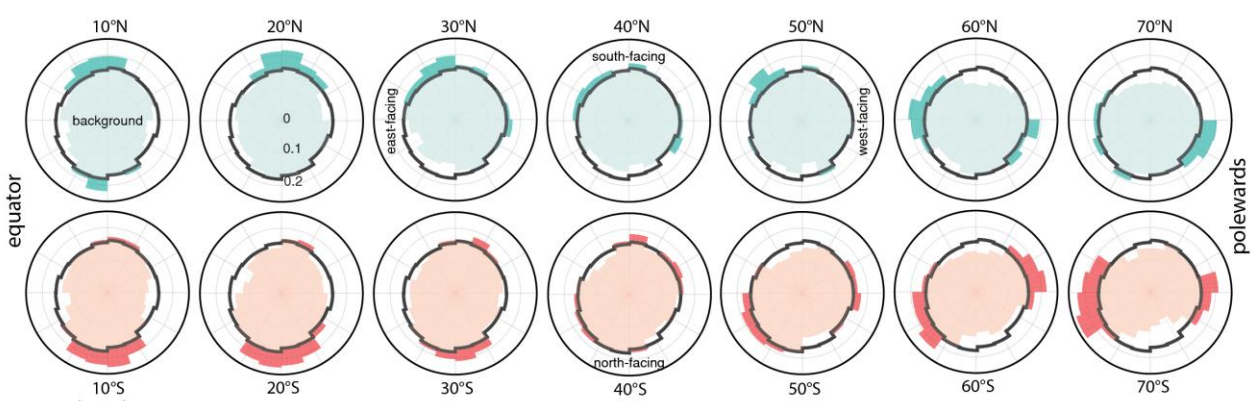

Figure 2. Normalized rockfall and background slope aspect distribution as function of latitude (polar histograms), in 10°N/S bins, for the northern (top, cyan) and southern (bottom, red) hemisphere, from the equator (left) towards the poles (right). The background distribution is indicated with a black line. N-facing is up, S-facing is down, W-facing is right, E-facing is left.