AI + LROC BIG DATA = THE FIRST GLOBAL MAP OF LUNAR ROCKFALLS

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Introduction: NASA's Lunar Reconnaissance Orbiter mission (LRO) returned more than 2 million high-resolution (NAC) images of the lunar surface. This big data archive contains a large amount of valuable, yet undiscovered information about the erosional state of the Moon. One feature revealed in this dataset is lunar rockfalls, a landslide type that occurs when boulders fall, jump, and roll from topographic highs to topographic lows (Fig.1). The current assumption is that the drivers of lunar rockfalls are moon-quakes, impact-induced shaking, and thermal fatigue [e.g. 1,2]. Therefore, the spatial distribution of rockfalls might be indicative of the Moon's recent endo- and exogenic activity. However, the distribution of rockfalls across the lunar surface is currently unknown. A Deep Learning-powered approach [3] has been applied in combination with advanced cloud computing capabilities to search for rockfalls in the full LRO NAC image archive, creating the first global and consistent rockfall map of the Moon.

Methods: In a previous step, a Convolutional Neural Network (CNN) has been trained to detect and map rockfalls in NAC images [3]. In the present work, this CNN has been implemented in an automated mapping pipeline that consists of 1) an image selection algorithm, 2) download and preprocessing routines, 3) the CNN, and 4) postprocessing routines. The NAC data are accessed through NASA JPL's Moon Trek application programming interface (api). The selection of NAC images is based on their spatial resolution, solar incidence angle, and overlap with neighboring images. After CNN-processing, the diameter of each detected rockfall is estimated based on the size of its regression-derived bounding box [3]. The pipeline with the embedded CNN has been used to scan more than 250,000 NAC images and more than 64 Tpixel or 7.5 TB of data, achieving nearly complete spatial coverage between 85°N and 85°S. Coverage is limited by increasingly difficult illumination conditions at higher latitudes. Two local and nine Google Cloud instances were used to process the data, using 30 CPUs and 15 GPUs. The access to the cloud infrastructure was granted by NASA's Frontier Development Lab (and its sponsors), as well as a Google Cloud Academic Research grant.

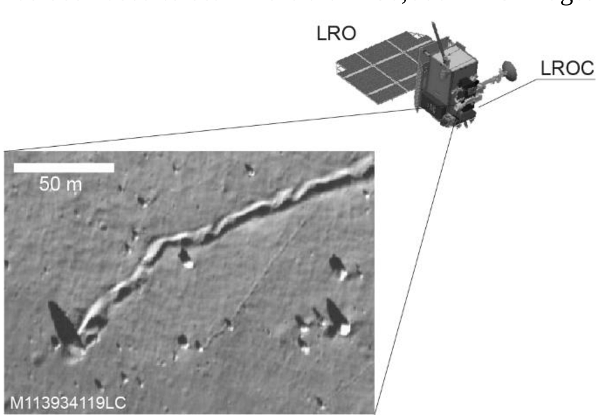

Fig. 1. | Lunar rockfalls: A picture of rockfalls with tracks taken by LRO (detail of NAC M113934119LC).

Preliminary results: The applied CNN identified 136,610 rockfalls on the lunar surface (Fig.2). The majority of rockfalls are located in highland regions (91%), while their distribution over the near and farside, as well as northern and southern hemisphere are relatively well balanced. The background spatial density is 2 rockfalls per 1° by 1° quadrangle, while the peak density (125 rockfalls per 1° by 1° quadrangle) has been measured in the Bürg crater, lunar nearside. Other remarkable high-density rockfall clusters are Crookes, Milne N/L, Aristoteles, Atlas, Pasteur D, and Tsiolkovsky craters, as well as the Montes Rook and Cordillera regions. In general, the majority of rockfalls appear to be situated in craters and basins, but some clusters lie in graben (e.g. Vallis Alpes) and pyroclastic vents (e.g. west of Baily crater). Interestingly, the spatial distribution of rockfalls within certain craters is heterogeneous, potentially indicating oblique impacts. The estimated diameters of rockfalls range from ~3 to ~25 m, with the majority of diameters lying between ~7 and ~10 m (Fig.2).

Preliminary conclusions: While the analysis of this dataset is ongoing, the preliminary results indicate that the main driver of lunar rockfalls are impacts and impact-induced fracture networks. The derived global rockfall map might also help to localize recent seismic activity on the surface of the Moon and might inform landing site selection for future geophysical surface payloads. This work demonstrates the power of AI-enabled methods to optimize the scientific return from rapidly growing data archives. The trained CNN will soon be available on NASA JPL's Moon Trek platform (trek.nasa.gov/moon/).

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References: [1] Kumar et al. (2016) *JGR: Planets 121*,147–179. [2] Xiao et al. (2013) EPSL 376,1-11. [3] Bickel et al. (2018) *IEEE TGRS, 57(6)*, 3501-3511.

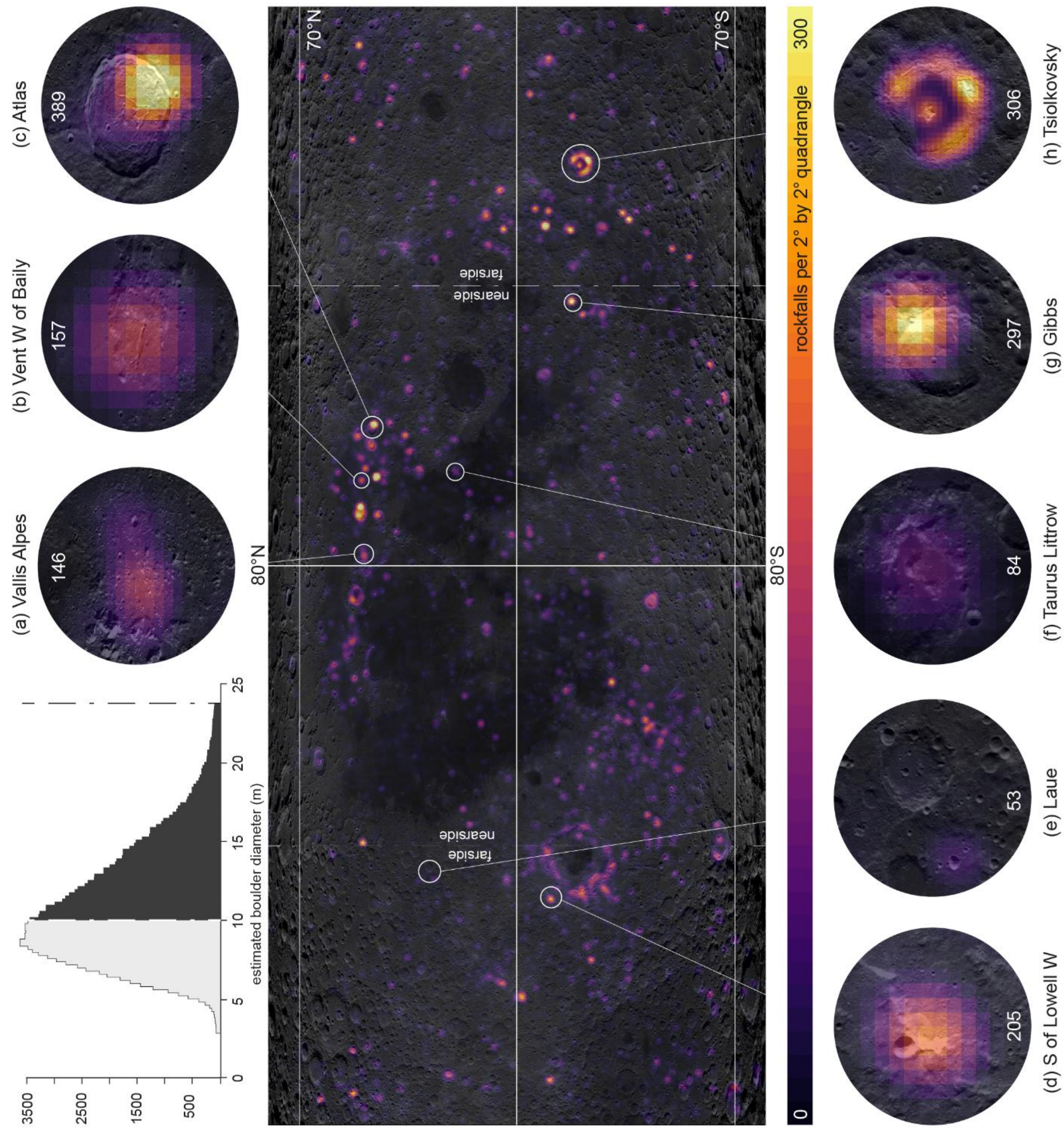

Fig. 2. | Lunar global rockfall map: Heatmap of the mapped lunar rockfalls in an equirectangular projection (80°N to 80°S). The majority of rockfalls appears to cluster in impact craters and basins. Due to the difficult illumination conditions at higher latitudes, the number of detected rockfalls in these regions will be lower. White circles indicate details that are shown in the insets, highlighting the spatial rockfall density and distribution in different geomorphic contexts, such as craters (c,e,g,h), graben (a), pyroclastic vents (b), etc.; the number indicates the maximum number of rockfalls per 2° by 2° quadrangle per region. Insets d) and g) feature impact-induced rockfalls that are directly driven by a small, impacting body. The histogram shows the distribution of the estimated rockfall diameters on the Moon; the white part of the histogram indicates a potential bias of the CNN for boulders < ~10m, as rockfalls with smaller diameters are harder to detect than rockfalls with larger diameters. Due to the limitations of the spatial resolution of the used sensor (NAC), eventually a cutoff is reached and rockfalls smaller ~3m can't be detected anymore. This limitation would also affect a human operator, however.