Counting 90 million craters on Mars to find the source of meteorites

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Counting 90 million craters on Mars to find the source of meteorites

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Introduction: Martian meteorites are the only samples from the Red Planet available for in-depth laboratory analyses. More than 280 pieces of 152 unique samples, originating from at least 11 source craters, are curated in the world's collections [1]. Ejection ages, based on cosmic ray exposure (CRE), vary from 0.7 to 20 Myr [2-4]. The ejection sites are still unknown, despite several previous propositions [5-7], motivated by the significance of establishing a link between the crystallization ages, and the chemical and mineralogical properties of these samples with surface geology.

Secondary impact craters, the key to identify the meteorites ejection sites: The formation of an impact crater generates debris ejected with speeds above and below the escape velocity on Mars (5 km/s). The fraction of ejecta material with a velocity higher than the escape velocity may get through the Martian atmosphere and into the interplanetary space. Numerical simulations suggest that impact events capable of producing such fragments would form craters larger than ~3 km in diameter on the Martian surface [8-9]. Material with a velocity lower than 5 km/s falls back to the surface in a radial pattern or rays around the primary source crater and forms secondary craters with a maximum size of about 2 to 5% of the primary crater diameter [10-12]. These secondaries are shallower than those formed by primary impacts and are rapidly eroded. Typically, a secondary crater of 100 m in diameter would be completely erased in about 50 Myr. Therefore, the occurrence of radial patterns of small secondaries is a diagnostic feature of young primary craters [6,13-14]. The use of high-resolution imagery would allow the identification of such small craters, but manual mapping of the tens of millions of secondary impact craters constellating the surface of Mars is not feasible.

Machine learning approach to identify small craters on high-resolution images: We adapted an automated Crater Detection Algorithm (CDA) [15] to identify craters smaller than 1 km in diameter across the entire surface of Mars. The algorithm was trained using High-Resolution Imagery System Experiment (HiRISE) images (25 cm/pixel) and applied on the global Context Camera (CTX) mosaic [16] (6 m/pixel), thus generating a database of more than 90 million detections (Figure 1).

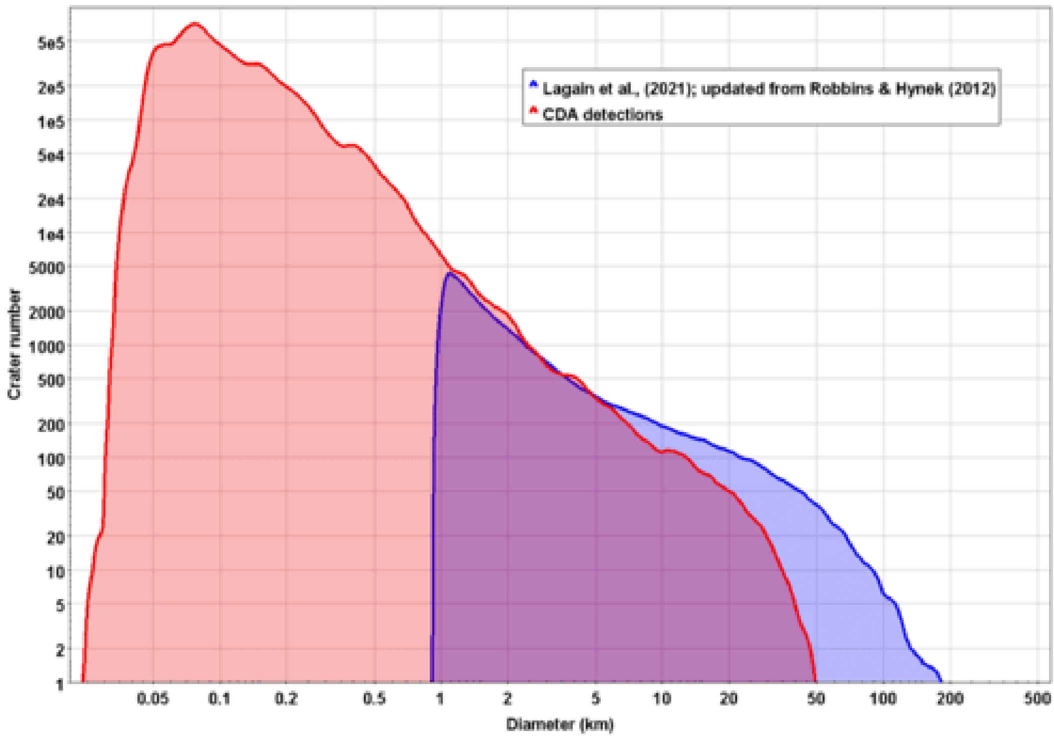

Figure 1: Crater Size-Frequency Distribution of the automatic crater database (in red) compared to the manual catalogue (in blue) from [11-12].

We evaluated the performance of our model against ~1000 impact craters >60 m (10 pixels in diameter on CTX imagery) manually mapped on 6 different geological units, thus constituting the ground truth (GT). For craters > 100 m in diameter, it results in an average true positive detection rate (or *recall*) of more than 80% and an average precision of 96%. The diameter estimation derived from our model is within 25% of uncertainty compared to our ground truth (Figure 2), which is within the expected human performance [17].

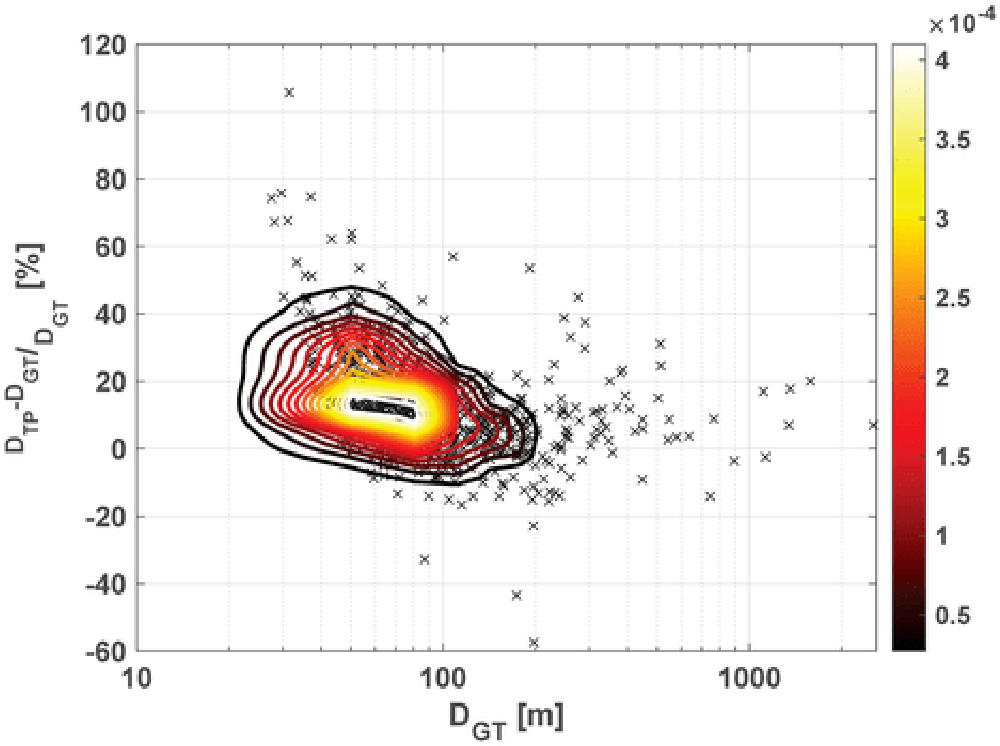

Figure 2: Comparison between the difference in the diameter of craters estimated by the CDA and the ground truth (black crosses). The kernel density estimator shows that detections larger than 100m are estimated within 25% of uncertainties compared to manually identified impact craters.

The ejection site of a group of Martian meteorites: We analyzed the spatial and size distribution of craters smaller than 300 m by computing a crater density map from this dataset. The figure 3 presents the results obtained by combining three density maps with red, green, and blue channels corresponding to local crater density (in a 0.05° grid) for three diameter size ranges, in order of decreasing range of diameter, respectively 150 < D < 300 m, 75 < D < 150 m and < 75 m. Using this map, we identified 19 secondary ray systems associated with large and recent primary craters (Figure 3).

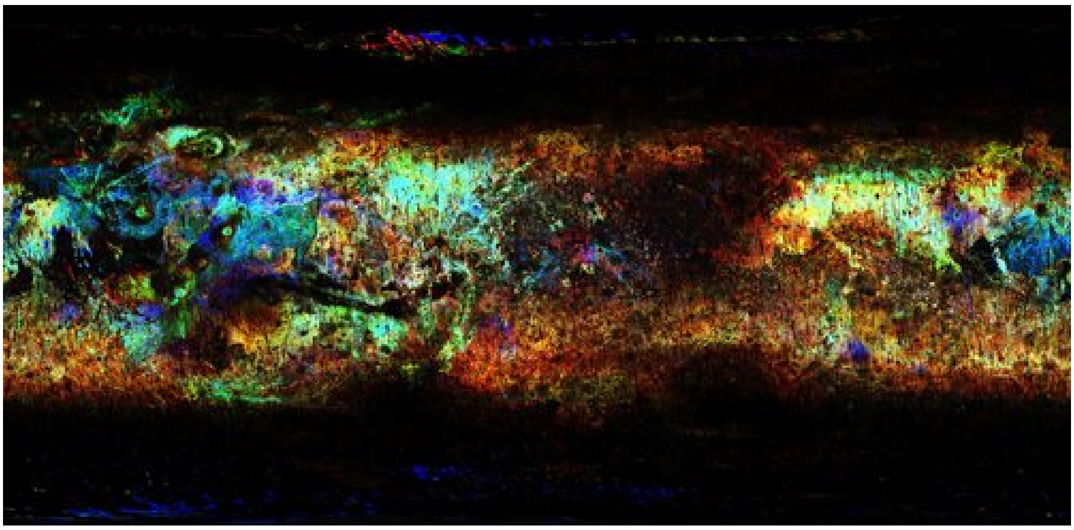

Figure 3: Density map of craters < 300 m in diameter (89,054,458 entries). Colors indicate crater

densities of specific diameter ranges (see text for details).

Using crater counts on the ejecta blanket of each of those 19 impact craters and their surrounding terrains, we derived respectively the model age of those impacts and the age of the impacted material. Those results are compared with the ejection age of Martian meteorites as well as their crystallization ages. We found that two craters, both located in the Tharsis volcanic province, are the most likely source of depleted Shergottites launched ~1 Myr ago [3]. Considering the magmatic ages and the petrogenesis of these samples, this implies that a major thermal anomaly deeply rooted in the mantle under Tharsis was active over most of the geological history of the planet, and has sampled a depleted mantle that has retained geochemical signatures of Mars' early history.

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