THE THARSIS MANTLE SOURCE OF DEPLETED SHERGOTTITES REVEALED BY 90 MILLION IMPACT CRATERS. A. Lagain[1]*, G. K. Benedix[1], K. Servis[1,2], D. Baratoux[3], L.-S. Doucet[4], A. Rajšic[1], H. A. R. Devillepoix[1], P. A. Bland[1], M. C. Towner[1], E. K. Sansom[1] and K. Miljković[1]. [1]Space Science and Technology Centre, Curtin University, Perth, Australia; [2]CSIRO - Pawsey Supercomputing Centre, Kensington WA, Australia; [3]Géosciences Environnement Toulouse, University of Toulouse, CNRS & IRD, France; [4]Earth Dynamics Research Group, TIGeR, School of Earth and Planetary Sciences, Curtin University, Perth, WA, Australia. (anthony.lagain@curtin.edu.au).

Introduction: Martian meteorites are the only samples from the Red Planet available for in-depth laboratory analyses. More than 307 pieces of 166 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 [2-3]. The ejection sites are still unknown, despite several previous propositions [4-6], motivated by the significance of establishing a link between the crystallization ages, and the chemical and mineralogical properties of these samples with surface geology. Here, we use a machine learning approach to pinpoint the crater source of a group of martian meteorites: the depleted shergottites launched 1.1 Ma ago [2].

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 [7-8]. 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 [9-10]. 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 [11-12]. 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) [13-14] 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 [15] (6 m/pixel), thus generating a database of more than 90 million detections.

We evaluated the performance of our model against ~1000 impact craters >60 m (10 pixels in diameter on CTX imagery) manually mapped on six 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, which is within the expected human performance [15].

The ejection sites 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 $D < 75$ m. Using this map, we identified 19 secondary ray systems associated with large and recent primary craters, potentially source of martian meteorites (Figure 1). We estimate that the population of craters larger than 7 km in diameter and formed over the last 10 Ma (17 craters out of 19) is complete.

Tharsis, the source region of the depleted shergottites launched 1.1 Ma ago: 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 the depleted shergottites ejected 1.1 Ma ago from the surface as well as their crystallization ages (ranging between 330 and 570 Ma, with one specimen, NWA 7635, that is 2.4 Ga old) [2]. Two impact craters located on the Tharsis province matches with the ages constraints of this group of meteorites: Tooting ($D \approx 30$ km) and 09-00015 ($D \approx 20$ km) craters (green diamonds on Figure 1). Considering the angle of the impact that has formed Tooting crater, its size, the presence of volatiles in the target, and the age of the underlying target material (~1.77 Ga old, within error of the crystallization age of NWA 7635), we conclude that Tooting crater is the most likely source of this group of meteorites, although 09-00015 cannot be ruled out.

Implications and perspectives: Considering that olivine phenocrysts in the ol-phyric depleted shergottites are in near-equilibrium with their parental melt, the potential mantle temperature (Tp) can be estimated from 1714 to 1835 °C [17-18]. These high Tp values defines an adiabatic gradient that crosses the martian mantle solidus at depth > 1000 km, indicating that melting potentially started in the transition zone marked by the appearance of ringwoodite, or even lower, close to the core/mantle boundary. These data support a hot-spot origin for the formation of the parental magma of these meteorites. The link between the depleted shergottites and the Tharsis dome suggests that Amazonian volcanic activity (since 2.4 Gyr until 330 Myr ago, at a minimum) related to the Tharsis bulge formed above the superplume are sourced deep in the mantle since that time, and by extrapolation, perhaps since the beginning of the Tharsis formation.

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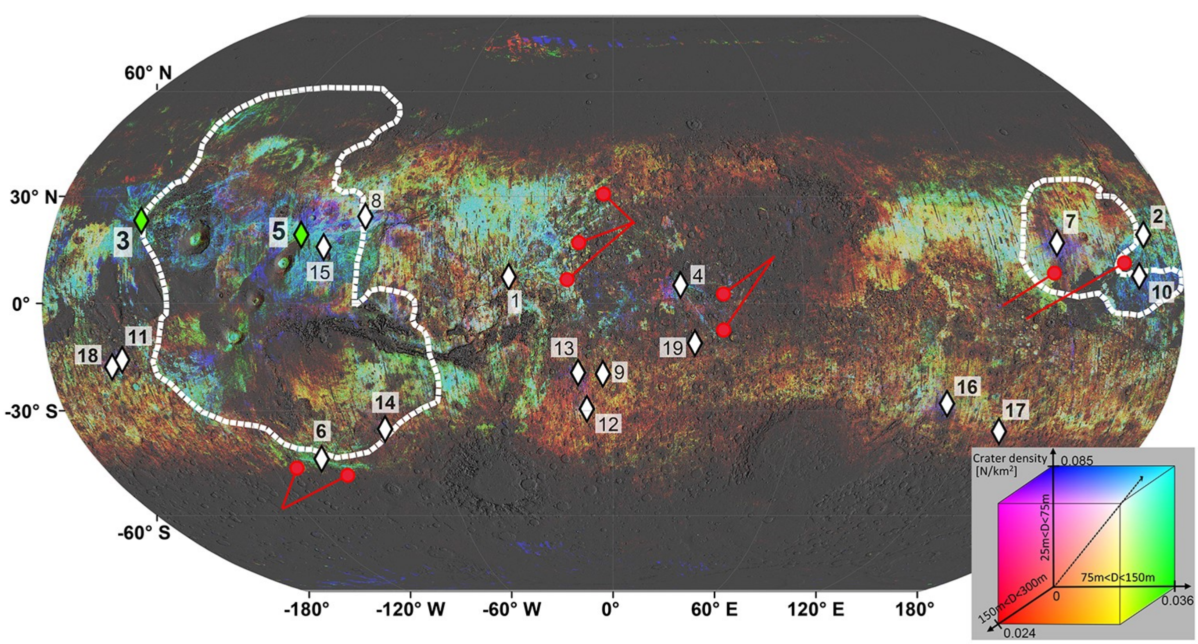

Figure 1: Crater density map of 90 million impact craters detected by the CDA. Red arrows highlight some secondary crater ray systems. Diamonds are the 19 young impact craters associated with secondary craters. See Ref 16 for the name and location of those craters. Labels 3 and 5 represents Tooting and 09-00015 craters respectively.