The Tharsis mantle source of depleted shergottites revealed by 90 million impact craters

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The only martian rock samples on Earth are meteorites ejected from the surface of Mars by asteroid impacts. The locations and geological contexts of the launch sites are currently unknown. Determining the impact locations is essential to unravel the relations between the evolution of the martian interior and its surface. Here we adapt a Crater Detection Algorithm that compile a database of 90 million impact craters, allowing to determine the potential launch position of these meteorites through the observation of secondary crater fields. We show that Tooting and 09-000015 craters, both located in the Tharsis volcanic province, are the most likely source of the depleted shergottites ejected 1.1 million year ago. 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 until recently geochemical signatures of Mars’ early history.
Martian meteorites are the only samples from the Red Planet available for laboratory analyses. More than 307 pieces of 166 unique samples, originating from at least 11 source craters, are curated in the world’s collections. Ejection ages, based on cosmic ray exposure (CRE), vary from 0.7 to 20 Myr. The ejection sites are still unknown, despite several previous propositions, motivated by the significance of establishing a link between the crystallization ages, and the chemical and mineralogical properties of these samples with surface geology. Martian meteorites comprise five broad petrological categories: shergottites, nakhlites, chassignites, ALH 84001 and NWA 7034 and related pairs. The shergottites are the most represented in terms of mass and number of specimens in collections. Based on the concentration of rare earth elements (REE) and isotopic compositions, this group is subdivided into three distinct geochemical classes: depleted, intermediate and enriched. REE patterns are inherited from the mantle source from which the rocks crystallized and subsequent magmatic processes such as fractional crystallization.

The age of ejected depleted shergottites cluster around a value of 1.1 ± 0.2 Myr. This suggests that they were ejected as sub-meter rock boulders by a single meteoritic impact. Although it would be possible that a rock sampled at a given place by a meteoritic impact had been previously transported by other processes (such as a previous impact with no evidence of shock), we will assume here that the rocks were generated at the impact location by magmatic processes. This group includes basaltic and poikilitic textures but is largely dominated by olivine-phryic shergottites and is characterized by a common depletion in REE. Crystallization ages range from ~330 Myr to ~570 Myr for 11 specimens, whereas NWA 7635 is ~2.4 Gyr old. The temporary controversy regarding the significance of much older Uranium–Plumb ages for some of these samples is now being settled. The hypothesis according to which the Mojave impact crater, located in old Noachian terrains, might be the source of all shergottites can now be discarded. The variability of crystallization ages and peak shock pressures reported for this group of depleted shergottites launched 1.1 Myr ago imply that a wide diversity of volcanic rocks was ejected from different geological units exposed at the surface of Mars or at shallow depths.

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 on Mars 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. A portion of the material ejected with a velocity lower than 5 km/s (accounting for atmospheric deceleration) falls back to the surface in a radial pattern or rays around the primary source crater and forms secondary craters. Secondary craters reach a maximum diameter of about 2–5% of the primary crater diameter. For instance, a 30 km crater would typically form secondaries smaller than 1 km diameter. These secondaries are shallower than those formed by primary impacts and are rapidly eroded. Considering an average depth/diameter for these craters of ~0.116 and an Amazonian (<3 Ga) crater obliteration rate of 100 km/yr14, a secondary crater of 100 m in diameter would be erased in 50 Myr (erosion of half of the depth and infilling of the other half). Therefore, the occurrence of radial patterns of small secondaries associated with a primary crater is a diagnostic feature of a recent impact. Thus, the crater source of depleted shergottites launched 1.1 Myr ago should be associated with abundant small secondaries, in the ~10–300 m-size range. Identification of rayed craters is possible using images in the thermal infrared domain, but this approach is hampered by image resolution (100 m/pixel) and dust coverage (about half the Martian surface would remain not accessible by this technique). Existing databases of impact craters on Mars do not cover the range of diameters (less than 1 km) that are relevant to find radial patterns of secondaries associated with primary craters <30 km. The use of high-resolution imagery would address this issue, but manual mapping of the tens of millions of secondary impact craters constituting the surface of Mars is not feasible.

In this work we adapt a Crater Detection Algorithm (CDA) to detect craters <1 km on the whole surface of Mars. We build a database of 90 million impact craters and identify secondary crater rays system to locate the crater candidates responsible of the ejection of martian meteorites. We show that Tooting and 09-000015 craters are the most likely source of the depleted shergottites ejected 1.1 Ma ago. We discuss the relationship between this group of meteorites and the Tharsis volcanic province, where these two craters are located. We infer the presence of a major thermal anomaly, deeply rooted in the mantle, under the Tharsis dome. This thermal anomaly has sampled a depleted mantle over most of the geological history of Mars.

### Results

#### Machine learning approach to pinpoint the meteorite crater sources

We retrained a Convolutional Neural Network (Methods, subsection The Crater Detection Algorithm) to identify craters down to 25 m in diameter across the entire surface of Mars. The algorithm was trained using High-Resolution Imaging Science Experiment (HiRISE) images (25 cm/pixel) and applied on the global Context Camera (CTX) mosaic (5 m/pixel), thus generating a database of ~90 million detections (Methods, subsection Application to the CTX global mosaic and evaluation, Supplementary Table 1 and Supplementary Figs. 1–4). To visualize secondaries, and therefore recent primary of different sizes, the density of secondaries for three ranges of sizes (150 < D < 300 m, 75 < D < 150 m and <75 m) are represented as a map (Figs. 1 and 2) using, respectively, the red, blue and green channels (Methods, subsection Crater Density map computation, and Supplementary Fig. 5). The distribution of detections >300 m are not examined as the presence of large secondaries is not a discriminant factor for the (young) age of the primary crater. A careful survey of this map allowed the identification of 19 secondary ray systems associated with large and recent primary craters (Fig. 1).

#### The ejection site of the depleted shergottites

The ages of these 19 young impacts are determined using manual crater counts (excluding secondaries) on their ejecta blanket (Methods, subsection Model age derivation and uncertainties) and are used to test the completeness of the survey presented here: these 19 impact craters may represent the complete record of large and recent impact craters on the surface of Mars. Despite the inherent lack of small craters on several ejecta blanket that might bias the formation model age of those craters (Methods, subsection Model age derivation and uncertainties), we found that the 17 craters larger than 7 km in diameter and younger than 10 Myr old plot on an 8.2 ± 2 Myr isochron (Supplementary Fig. 6 and Supplementary Table 2). There is only 9% of chance that a crater larger than 7 km was missed according to Poisson uncertainties and primary crater production function. This suggests that the use of secondaries as a criteria to identify recent craters is valid and that the identified crater population larger than 7 km formed in the last ~10 Myr is complete. Thus, the visualization of 90 million craters counted using the automatic detection approach allows us to reduce the number of potential source craters of the Martian
Anderson crater (label 7) and 09-00015 (label 5) are highlighted in green and their rays of secondaries are shown on Fig. 2a and b respectively. Red arrows point some secondary crater rays and readers are invited to visit http://craters.computation.org.au/ and http://HIVE.curtin.edu.au/research/CDA-94M-release for high-resolution versions of the map. Background: MOLA shaded relief (http://bit.ly/HRSC_MOLA_Blend_v0), projection: Robinson. a Legend of the crater density map shown on panel a. Each dimension of the colorcube corresponds to the crater density (number of craters per km²) of specific diameter ranges (blue: 25–75 m, green: 75–150 m and red: 150–300 m).

Among the 19 craters with small secondaries, only two craters, Tooting (Fig. 2a) and 09-000015 (Fig. 2b), have model ages compatible with the range of crystallization ages of the depleted shergottites (Fig. 3). They are both located on volcanic terrains interpreted as stacking of lava flows with thicknesses of up to a few kilometres in some places and associated with Tharsis’ dome activity, the largest volcanic province on Mars. We note that Tooting crater is the only one that matches both ejection and crystallization ages. Based on our crater counts on Tooting’s ejecta blanket, its formation model age is estimated to be ~1 Myr, while our counts on the surrounding ground gives a model age of ~308 ± 41 Myr. Moreover, accounting for large craters around Tooting that have been filled-up by recent volcanic activity, an Early Amazonian model age can be derived (1.77±0.69 Gyr). Although not discriminant, this age matches within error the crystallization age of NWA 76353 (Fig. 3 and Supplementary Figs. 7 and 29) and might represent a minimum age of older volcanic episodes that have been subsequently covered by younger Amazonian lavas.

To further restrict the number of candidate crater sources for the depleted shergottites launched 1.1 Myr ago, their crystallization ages (~330 Myr–570 Myr and ~2.4 Gyr) are compared to the ages of terrains surrounding each crater. This approach assumes that crater counts on the area surrounding the crater source may provide the age of the volcanic episode comparable to the crystallization age of the meteorite. Surrounding terrain model ages have been derived for all impact craters using the recently revised Mars crater catalogue, compiled manually and complete down to 1 km, completed for higher precision by manual mapping of smaller craters if necessary (Methods, subsection Model age derivation and uncertainties). Model ages obtained for different impact cratering rates, ranging between a factor of 2 around the reference impact flux over the last ~3 Gyr were also estimated (Methods, subsection Influence of impact cratering rate uncertainties on model ages, Fig. 3, and Supplementary Table 2).

Fig. 1 Crater density map of Mars. a Density map of craters <300 m in diameter (89,054,458 entries), resolution 0.05°/px. Colours indicate crater densities of specific diameter ranges (alternatively, supplementary Fig. 5 presents the crater density for each band separately). The diamonds identify 19 potential crater candidates (D > 3 km) for the launch of Martian meteorites (see Supplementary Table 2 for the size, location and model age of those craters), identified from radial patterns of secondary crater rays (D < 300 m). White dashed lines represent the contour of the Tharsis dome (at the left) and Elysium (at the right). Tooting (label 3) and 09-000015 (label 5) are highlighted in green and their rays of secondaries are shown on Fig. 2a and b respectively. Red arrows point some secondary crater rays and readers are invited to visit http://craters.computation.org.au/ and http://HIVE.curtin.edu.au/research/CDA-94M-release for high-resolution versions of the map. Background: MOLA shaded relief (http://bit.ly/HRSC_MOLA_Blend_v0), projection: Robinson. b Legend of the crater density map shown on panel a. Each dimension of the colorcube corresponds to the crater density (number of craters per km²) of specific diameter ranges (blue: 25–75 m, green: 75–150 m and red: 150–300 m).
Fluidized morphologies (as well as 09-000015), indicating the presence of subsurface volatiles that increase the spallation volumes by as much as 10\%\(^9\). This crater also presents an asymmetric distribution of secondary craters rays, a feature not seen in 09-000015 and its rays system extends at least up to 1500 km from the crater, i.e. up to 100 crater radii (Fig. 2a). This is more than 1000 km farther than previously noted\(^7\). The forbidden zone (zone lacking secondaries) observed on Fig. 2a confirms an oblique impact\(^23\). Based on the morphological evidence of the crater\(^7,23\) and numerical simulations\(^24\), the angle of entry of the impactor that formed Tooting crater ranged between 30° and 50° from the surface. Numerical models\(^24\) suggest that such an oblique impact would enhance the fraction of ejected debris reaching escape velocity, all other parameters being equal. For instance, the ejected mass from a 45° impact is more than 7 times greater than for a vertical impact\(^24\).

Regarding the surface environment, analysis of volatiles in impact melt pockets of the Tissint meteorite shows post-magmatic and pre-impact low alteration by subsurface water, which equilibrated with the present-day atmosphere\(^25\). Both the lobate morphology of the ejecta of Tooting and the flow textures in its inner wall\(^26\), interpreted to be sediments remobilized by water seeping, argue for the existence of subsurface reservoirs of volatiles at the time of impact. Microscopic evidence for recent subsurface reservoirs of water on Mars can thus be linked to surface morphology.

**Discussion**

Long-lived (\(^{147}\)Sm-\(^{143}\)Nd, \(^{87}\)Rh-\(^{87}\)Sr, \(^{176}\)Lu-\(^{177}\)Hf, \(^{183}\)Re-\(^{188}\)Os, \(^{233,238}\)Pa-\(^{232}\)Th, \(^{206,207,208}\)Pb) and short-lived (\(^{146}\)Sm-\(^{142}\)Nd, \(^{182}\)Hf-\(^{182}\)W) isotopic composition of the depleted shergottites\(^4\) indicate, respectively, that they sampled a highly depleted mantle formed early in Mars history, during the differentiation of the Martian magma ocean (MMO), \(-4.5\) Gyr ago\(^6,27\). In addition, considering that olivine phenocrysts in the ol-phryic depleted shergottites are in near-equilibrium with their parental melt, the potential mantle temperature (Tp) can be estimated from 1714 to 1835 °C\(^28,29\). This is hotter than estimates from situ rock analyses in Gusev (1300°–1500 °C), Meridiani (1400 °C) or Gale crater (1250–1500 °C)\(^28–30\). On Earth, the broad range of potential mantle temperatures reflects the diversity of mantle melting environment, such as hot spots or large igneous provinces above mantle plume, mid-oceanic ridges or fluid-enhanced melting at subduction zones. The high Tp inferred from ol-phryic depleted shergottites defines an adiabatic gradient that crosses the Martian fertile mantle (primary) solidus\(^28,31\) at depth >1000 km (Fig. 4a). This indicates that melting potentially started in the transition zone, marked by the appearance of γ-spinel (ringwoodite) or below in the lower mantle. However, direct comparison between these Tp and a fertile mantle solidus, with Mg\# of 0.75–0.77, can be tenuous as the latter would melt at lower temperature\(^32\), with respect to a depleted mantle source characterized by higher Mg\# of 0.85–0.86\(^33\). Nevertheless,
experimental results show that the composition of melt extracted from a fertile mantle at 8 and 10 GPa match the high magnesium content of some depleted shergottites, which is consistent with melting starting at least 10 GPa, i.e. at the bottom of the upper mantle (Methods, subsection Potential mantle temperature and depth of melting).

These data support a hot-spot origin for the formation of the parental magma of these meteorites with a partially molten hot section of the mantle forming relatively early in the history of Mars. The most accepted explanation for the origin of the Tharsis volcanic province is the superplume hypothesis, with the onset of a large thermal anomaly deeply rooted in the mantle since the multi-stage crystallization of the M MO, ~20 Myr after the accretion. In absence of plate tectonics, this abnormally hot mantle would produce shield volcanoes fed by a single or multiple plumes (Fig. 4b) that have builded-up Tharsis at least over the last ~4 Gyr. The Early Noachian stage of the Tharsis growth is thought to have been intense (50 × 10^6 – 100 × 10^6 km^3) in the Martian interior are anomalously hot, which might induce melting potentially occurs below 10 GPa (1), within the transition zone (2) and possibly down to the core-mantle boundary (3), i.e. between ~800 and ~1600 km. b Schematic cross-section of Mars below the Tharsis dome, showing the Tharsis superplume beneath the crust as well as the depth range of melting for the parental magmas of the depleted shergottites and potential melts pathways (red dashed lines). Structure of the Martian interior and layers thicknesses are inferred from SEIS (Seismic Experiment for Interior Structure) data on board of the InSight lander olivine, opx orthopyroxene, cpx clinopyroxene, gt garnet, ringwoodite, wad wadsleyite, maj majorite, mw magnesio-wustite.

The CDA was initially trained on Thermal Emission Imagery System (THEMIS) Day IR images (100 m/pix) covering 1762 impact craters ≥1 km in diameter from the Mars crater database. To detect smaller impact craters and thus be able to identify rays of sub-kilometre-sized secondary craters, higher resolution datasets, such as HiRISE (High-Resolution Imaging Science Experiment) and CTX (Context Camera) are necessary. The high degree of detail found in these datasets makes the current training for the CDA inefficient due to the presence of decameter to hectometer-sized circular structures that are not of impact origin. This include landscapes within field of view exhibiting circular features or structures formed by the erosion, essential to include in the training dataset to avoid detecting them. Retraining the algorithm is therefore essential to accurately detect impact craters smaller than 1 km in diameter.

The Crater Detection Algorithm has been previously described in detail. The key features are summarized here followed by a description of the adaptation achieved for the purpose of this study.

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impact craters as small as 25 m. The mosaic covers about 99% of the surface of Mars between 88°S and 88°N of latitudes. Each of the 15840 tiles composing the mosaic measures 4880 square km, of which just 89,054,458 are smaller than 300 m in diameter and used to analyse the spatial crater distribution presented on Fig. 1a.

To statistically validate the results, we manually mapped ~2000 craters using CTX imagery on different types of terrains and compared them to the CDA’s results. Supplementary Table 1 shows how many craters have been manually identified for each terrain as well as the number of true positive (TP), false detection or false positive (FP) and missed craters or false negative (FN) for different diameter ranges from >60 m. We cannot guarantee the validity of the manually mapped crater population <60 m and the associated metrics due to the resolution of the image. We calculated the true positive rate (or recall) defined as $T_P = \frac{TP}{TP + FN}$, and F1 score combined both metrics using the harmonic mean of the recall and precision, thus allowing to punish extreme values. From this, the average precision, recall and F1 are higher than 0.75 for craters larger than 70 m in diameter except on highlands and at high latitudes (>50°) where the metrics are lower than 0.75 but always above 0.55. Detections at mid and high latitudes (>50°) are of the lowest quality compared to those closer to the equator, mostly due to the degraded morphology of impact craters. We note that merging the metrics between each type of terrains (last column of Supplementary Table 1) is not representative of the overall performance of our CDA on the whole surface of Mars since it is not normalized by the fraction of the surface represented by each type of terrains. For example, aprons, impact or high latitudes constitute a minor fraction of the surface. Also the total recall and F1, accounting for craters <60 m (Supplementary Table 1) are an estimation if the manually mapped craters are complete down to the smallest crater detected by the CDA. This is certainly the case, mostly due to the resolution of the image and those values cannot be used for evaluating the performance of the algorithm.

We also evaluated the precision of the diameter estimation among true positive detections (913 across all terrains considered in this evaluation test). Supplementary Figure 2 shows the percentage difference between the diameter estimated by the CDA ($D_{\text{CDA}}$) and the diameter manually measured based on ground truth ($D_{\text{GT}}$). We observe an increase in the overestimation with the decrease in crater size due to the resolution of the image. This is especially true for craters <50 m. For craters larger than 100 m in diameter and except rare instances at high latitudes, the CDA estimates crater size with errors as much as 25%. For craters <1 km in diameter. Significant physical properties variability between ejecta deposit, composed of brecciated and unconsolidated material, and the underlying rocks are expected. However, the thickness of the ejecta blanket of a 10 km Layered Ejecta Rampart Sinuous crater does not exceed a dozen meters and is up to a few kilometers thick. The crater density in that area also varies with the volcanism following the formation of small impact craters on those ejecta blanket, typically larger than a few hundred meters in diameter, is therefore represented by the underlying rocks. Primary impact craters size used to derive model ages shall be dominated by the physical properties of the underlying rocks, rather than of the ejecta. We therefore neglect ejecta layer properties effects on the crater SFD used to derive the model ages we present in this study.

The statistical effect of small counting area and/or sparse number of craters used to derive model ages of a planetary surface has been widely discussed in the literature. While crater counts performed on areas larger than 100 km² are less sensitive to statistical bias due to the stochastic nature of the cratering record, the accuracy of the model ages decrease with decreasing count area size. This source of uncertainty is partially attenuated thanks to the use of the Poisson timing analysis technique that allows meaningful model age estimates, even in the case where a unit on Mars does not exhibit any craters. The crater density in that area also varies with the volcanism following the formation of small impact craters on those ejecta blanket, typically larger than a few hundred meters in diameter, is therefore represented by the underlying rocks. Primary impact craters size used to derive model ages shall be dominated by the physical properties of the underlying rocks, rather than of the ejecta. We therefore neglect ejecta layer properties effects on the crater SFD used to derive the model ages we present in this study.

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Influence of impact cratering rate uncertainties on model ages. Uncertainties of model ages derived from crater counts have been widely discussed in the literature. The impact cratering rate over the last 3 Gyr is assumed to be high but is poorly constrained to the lack of kilometic craters younger than 3 Gyr old. Also, the $R_{\text{bolide}}$ (factor used to convert the Lunar chronology to Mars) has been derived from direct observations of the crater population and dynamical considerations of asteroid and comets population. One of the largest source of uncertainty is the estimation of the respective contribution of cometary materials to the cratering record on the Moon and on Mars. Model age
code availability

The Crater Detection Algorithm code supporting the findings in this study is available upon request from the corresponding author A.L. The numerical impact crater formation were made using the iSALE shock physics hydrocode. At present, iSALE is not fully open source. Application for use of iSALE can be made via https://code.igo-benchmark.org. Any recent stable release can be used to reproduce the data presented. We used the IDL 5.2 software (L3Harris geospatial https://www.l3harrisgeospatial.com/Software- Technology/IDL) to run the disetSta II software available at https://geofabrics.berlin.de/en/geo/fachrichtungen/planet/softwarealgorithms and the ESRI’s ArcGIS 10.8.1 software suite (ESRI https://www.esri.com/en-us/arcgis/about-arcgis/overview) and Matlab (https://au.mathworks.com/products/matlab.html) to produce the maps.

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Data availability

Correspondence and material requests should be addressed to Anthony Lagain at anthony.lagain@gmail.com. Remote sensing data (HRIRSE and CTX imagery) are available at http://murray-lab.caltech.edu/CTX/ctxls/ and at http://murray-lab.caltech.edu/Mars2020/. The crater density map presented on Fig. 1a is available at high resolution at http://HIVE.curtin.edu.au/research/CDA-94M-release and at http://craters.computation.org.au/. The algorithm training dataset that support the findings of this study is available in Zenodo with the identifier: https://doi.org/10.5281/zenodo.5514313. Derived data supporting the findings of this study are available within the paper, the Supplementary Information file, in Supplementary Data, and from the corresponding author A.L. on request. Source data are provided with this paper.
ADACS, and CSIRO. Raw data were generated at Pawsey Supercomputing Centre. We thank Wesley Lamont and the Curtin Hub for Immersive Visualization and eResearch (HIVE) for their help in the visualization of our crater detection having allowed the best use of our algorithm.

**Author contributions**

A.L. and G.K.B. are responsible for study conceptualization. K.S. adapted and retrained the CDA under A.L. guidance. A.L. performed the CDA evaluation, crater counts, age measurements, impact flux simulation, density map computation and secondary rays survey. D.B., L.S.D. and A.L. interpreted the potential mantle temperature data. A.R. and K.M. performed iSALE impact crater modelling. H.A.R.D., E.S. and M.T. helped with data handling and some aspects of the crater density map computation. A.L., G.K.B., D.B., L.S.D. and P.B. were involved in data interpretation. A.L. wrote the manuscript, with contributions, review and editing from all co-authors.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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