LINKING MARTIAN METEORITES TO THEIR SOURCE CRATERS: NEW INSIGHTS.

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Introduction: As the only samples available for laboratory study, the >100 known martian meteorites provide invaluable information on the formation, differentiation, and geologic evolution of Mars. These predominantly igneous samples span the majority of Mars history, with a bias (attributable to the sample delivery method) towards Amazonian ages: the augite-rich shergottites ~2400 Ma [1, 2]; the nakhlites and chassignites ~1300 Ma [3]; and the youngest shergottites 575-175 Ma [3, 4]. Ejection ages indicate that the martian meteorites were produced by ≤8 impact events between 0.7 and 20 Ma [3]. Attempts at identifying the source craters for these meteorites using spectral matching [e.g., 5, 6] have met with limited success, primarily because the youngest igneous terrains (e.g., Tharsis) are largely obscured by dust [e.g., 7]. The study by [8] was among the first integrated approaches to this problem; however, these authors assumed ages of 4.1-4.3 Ga for the shergottites, a postulation which has since been proven incorrect [e.g., 9]. The identification of rayed craters – indicative of high ejection velocities and young ages – on predominately Amazonian igneous surfaces has provided the best potential candidates [10]; however, since the visibility of rays depends on thermal contrast [10], the list of such craters are few and limited.

Here we utilize existing remotely-sensed datasets coupled with new modeling of the meteorite delivery process to “rule in” or “rule out” candidate source craters from among a database of the best-preserved craters on Amazonian igneous terrains.

Approach: As indicated from ejection ages, the martian meteorite source craters are young, <20 Ma [3], and likely very well-preserved. We use the occurence of primary crater-fill deposits (i.e., pitted impact melt-bearing deposits) as a criterion for crater preservation [11, 12], in addition to the presence of thermally contrasted ejecta or rays. This approach yields a database of >200 fresh craters from across the Martian surface, over a variety of terrain types and ages (based on [11, 12]). We have integrated these fresh craters into a Microsoft Access database which tabulates the crater size, freshness, geological unit, and other relevant information for each crater. The database can be queried based on any number of constraints, such as surface unit age and type, and permissible range of crater sizes based on impact modeling (see below). Other constraints will be implemented in future, including the matching of meteorite reflectance spectra [e.g., 13] to those obtained from dust-free surfaces exposed by recent (<20-year) impacts [14]. The result is a list of potential source craters for each of a selection of martian meteorites.

Modeling: Following [15], we use the iSALE shock physics code to simulate the dwell times and peak pressures reached during the ejection of material at greater than escape velocity from a Mars-like basaltic target following a vertical (90°) impact at 13.1 km/s (see [16] for details). Numerical simulations track dwell time (the time the rock spends at high pressure) during impact ejection; model results are co-inverted for inferred peak pressure and dwell time to give a range of permissible impactor sizes, which are then converted to impact crater diameters based on the formulation of [17]. Notably, the model results provide constraints on pre-impact burial depth. We selected four martian meteorites for which dwell times and bulk peak shock pressure have been determined, and which cover the range of petrologic types, Amazonian ages, and conditions and timing of impact ejection (Table 1).

Results: Application of the model to the four martian meteorites results in a range of impactor sizes for each with the expected correlation between impactor size and dwell time (Table 1). We have adjusted the lower limit of crater diameter obtained from modeling by 50%, on the basis that a (more common) 45° impact angle will result in a smaller crater diameter. We consider craters with diameters below the minimum for Martian meteoroid ejection determined by [18] to be unlikely sources, and use an effective lower limit of 2.5 km diameter instead. In the case of NWA 8159, results are considered an upper limit as described in [16]. The maximum modeled crater diameter for Tissint is not consistent with results from shock petrography [19]. Indeed, the likelihood of a >100 km diameter crater having an age of <20 Ma is low, and thus we expect most potential craters to be relatively small.

Cross-reference of the range of permissible crater diameters with our crater database, and selecting for Amazonian-age igneous units and the best-preserved craters, results in a relatively small number of possible craters for each meteorite (Table 1). Most potential craters are <30 km diameter, with only one 73 km diameter, consistent with expectations that large, young craters are rare. We have identified a subset of six previously unmapped craters from among these for more detailed mapping, for the purpose of further assessing them as potential martian meteorite sources.

Table 1. Ages, conditions of impact ejection, and modeling results for selected martian meteorites

			Model input		***Model output***				
Meteorite	**Crystallization age (Ma)**	**Ejection age (Ma)**	**Dwell time (ms)**	**P, bulk (GPa)**	**Burial depth (m)**	**Impactor radius (m)**	**Crater diameter range (model; km)**	**Effective crater diameter range (km)[b]**	**N[c]**
Zagami	177 ± 3	2.92 ± 0.15	10	22-23	<6	781-1250	22-33	11-33	8
Tissint	574 ± 20	0.7 ± 0.3	10-20	≥ 29-30	<50	685-7692	20-164	10-164	12
Chassigny	1340 ± 50	11.3 ± 0.6	1-10	26-32	<25	63-3824	2.4-89	2.5-89	17
NWA 8159	2370 ± 250	0.9 ± 0.1	100[a]	15-23	<25	<7250[a]	<156[a]	2.5-156	17

Notes: See [16] for data sources. [a] Considered an upper limit. [b] Crater diameter range adjusted for 45° impact angle, and probable lower limits (see text). [c] Number of candidate craters in the effective crater diameter range in Amazonian igneous terrains.

Eight of the craters are candidates for all four meteorites; however, it is unlikely that all four of these meteorites were derived from the same crater. For example, Tissint and NWA 8159 are both members of a group of 12 geochemically-depleted shergottites which share a ~1 Ma ejection age and which span ~2 billion years of Mars igneous history [1, 2]; included in this group is NWA 7635, a ~2400 Ma, augite-rich shergottite similar to NWA 8159 [1, 2]. The common ejection ages of these rocks has been used to argue for their derivation from the same ejection site, from a stack of sequential, layered lava flows [2], with NWA 7635 and NWA 8159 (as the oldest lavas) at the base. However, our results indicate that NWA 8159 had a pre-impact burial depth of at most 25 m (Table 1). If NWA 8159 and NWA 7635 were the lowermost flows in the stack, it is difficult to envision as many as ten younger flows within a depth of only 25 m; even if oblique impact effects are considered (in which the excavation depth is greater in the downrange direction), the petrography of the shergottites is inconsistent with crystallization in thin (< ~5 m) flows. This discrepancy can be reconciled if the augite-rich shergottites NWA 7635 and NWA 8159 are derived from their own impact crater, distinct from the other depleted shergottites. In this case, the common ~1 Ma ejection age of the depleted shergottites and the augite-rich shergottites is fortuitous (but furthermore, is consistent with a larger number of smaller craters occurring at ~1 Ma).

Our results for the Zagami meteorite – among the youngest at 177 Ma – illustrate the potential implications of linking martian meteorites to their source igneous units. Our modeled maximum pre-impact burial depth for Zagami is 6 m, consistent with derivation of Zagami from a thin lava flow; given its young crystallization age, and the relatively low effusive rate of late Amazonian Mars volcanism, it is unlikely that the Zagami source flow has been covered by more recent lava flows. Thus, if we can identify the source crater for Zagami, we will be able to effectively determine the absolute age of a lava flow on Mars for the first time (in advance of Mars Sample Return). The linking of the martian meteorites – having known crystallization ages – to their source igneous units has the potential to assist in reducing the uncertainties in the cratering chronology of Mars, especially for mid- to late-Amazonian terrains where the age estimates may be on the order of 2-3 times their actual radiometric ages [20].

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