Continued Use of Exogenic Materials found on Mars as Planetary Research Tools
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Introduction: As demonstrated by the Mars Exploration Rover (MER) and Mars Science Laboratory (MSL) missions, meteorites, micrometeorites and other exogenic (non-indigenous) materials comprise a non-trivial fraction of martian surface materials. These materials have been accumulating throughout geologic time in an environment with high preservation potential. Meteorites found on Mars generally have compositional equivalents in curated collections on Earth – in this sense they can be used as geochemical standards because each individual meteorite group has narrow and well-known ranges of variation in major and trace elements, isotopes, mineralogy and texture. The current inventory of confirmed and candidate meteorites identified at the Spirit, Opportunity, and Curiosity rover landing sites, as both serendipitous finds and formal science campaign targets, numbers at least 55, including 15 noted officially by the Meteoritical Society (Ashley *et al.* 2011; Ashley *et al.* 2009; Gattacceca *et al.* 2019; Lasue *et al.* 2020; Meslin *et al.* 2019; Wiens *et al.*, 2017; Ruff *et al.* 2006; Schröder *et al.* 2010; Schröder *et al.* 2008)[1]. All have been altered since arrival on Mars by a variety of physical and chemical environmental processes. Factors that inform an evolving paradigm of Mars as a planet open to ongoing input of outside material include: 1) soil chemistry having several percent chondritic component (Yen *et al.* 2006); 2) the martian meteorite, polymict regolith breccia NWA 7034 also having a chondritic component (Goderis *et al.*, 2016); 3) work addressing recent impacts (e.g., Daubar *et al.* 2014); and 4) suspicions concerning unconstrained chondritic, cometary, or IDP influences as possible contributors to organic anomalies in MSL's Sample Analysis at Mars (SAM) measurements (e.g., Eigenbrode *et al.,* 2018; Freissinet *et al.,* 2015). Encounters with these exogenic materials are anticipated in future roving missions on Mars, and we encourage their examination *in-situ* for the scientific purposes outlined below.

Background: Far from being mere curiosities, exogenic materials found on Mars have proven useful in augmenting our understanding of 1) chemical and physical weathering processes with associated implications for mineral-water interactions (Ashley *et al.,* 2011; Fleischer *et al.,* 2010; Schröder *et al.,* 2010; Schröder *et al.,* 2008), 2) Amazonian chemical weathering rate estimates (Schröder *et al.,* 2016); 3) atmospheric density models (Beech and Coulson 2010; Chappelow and Golombek 2010; Chappelow and Sharpton 2006); 4) atmospheric fragmentation and production of strewnfields (Fleischer *et al.,* 2011; Schröder *et al.*, 2010); 5) thermal infrared behavior of dust on reflective metal surfaces (Ashley *et al.*, in preparation); 6) soil chemistry (Yen *et al.,* 2019; Yen *et al.,* 2006); and 7) statistical relevance of type-frequency distributions (e.g., Johnson *et al.,* 2020; Meslin *et al.,* 2019). Analog and modeling studies have also investigated microbial colonization and biosignature preservation in chondritic meteorites (Tait *et al.,* 2020; Tait *et al.,* 2014; Tait *et al.,* 2017) and micrometeorites (Tomkins *et al.,* 2019). Most of these efforts have been supported through mission-related, NASA ROSES, and university research funding.

MER demonstrated that a decade-long plan does not necessarily encompass the full duration of a roving Mars mission. With this in mind, the next decade could see extended mission operations for Curiosity, Perseverance and ExoMars that span portions of the 2023-2032 Survey. This white paper endorses integration of several overlapping and evolving Mars science disciplines to investigate exogenic materials. An abbreviated list of important areas of

[1] At the time that the previous white paper on this topic was submitted to the PSDS, 11 confirmed and candidate meteorites had been identified on Mars. The current inventory thus represents a 400% increase.

investigation using exogenic materials include, a) aqueous and mechanical surface weathering processes, providing insights into climate evolution; b) explaining discrepancies in meteorite type-frequency distributions with anticipated abundances; c) atmospheric evolution, with Noachian-Hesperian atmospheric oxygen trapped in micrometeorites, d) potential for contamination to Mars Sample Return (MSR) regolith and sedimentary rock samples intended to address geology and biosignatures of rover landing sites; and e) potential for astrobiological relevance. Some of these and other topics will be examined in the specific problem set addressed below.

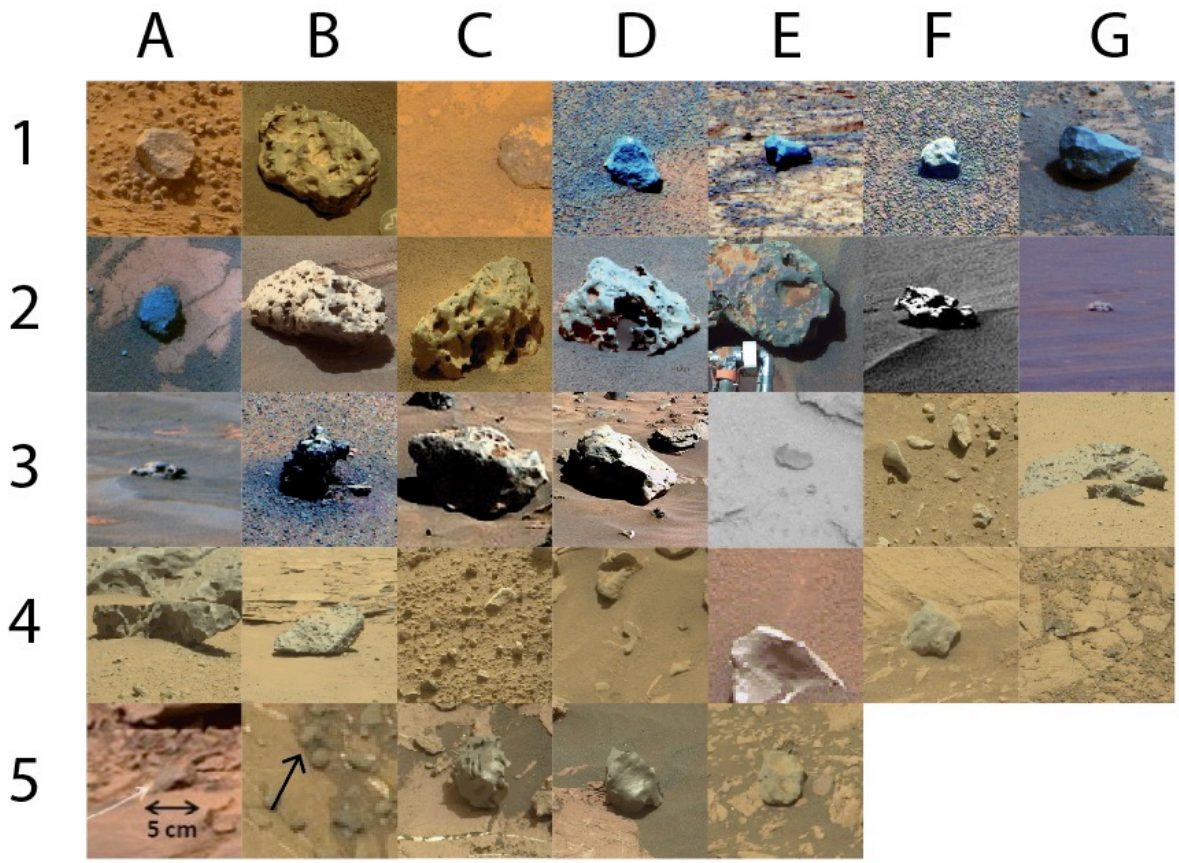

Figure 1. This incomplete list shows the official and field names or sols of meteorite candidates from NASA rovers Opportunity, Spirit and Curiosity. The * indicates an official name in the Meteoritical Society database. A1 MP 002* (Barberton), B1 Meridiani Planum (MP) 001* (Heatshield Rock), C1 MP 003* (Santa Catarina), D1 Joacaba, E1 Mafra, F1 Paloma, G1 MP 004* (Santorini), A2 MP 005* (Kasos), B2 MP 006* (Block Island), C2 MP 007* (Shelter Island), D2 MP 008* (Mackinac Island), E2 Oilean Ruaidh, F2 Ireland, G2 Bingag Cave, A3 Dia Island, B3 Canegrass, C3 Alan Hills, D3 Zhong Shan, E3 MSL Sol 397, F3 Babrongan #10, G3 Aeolis Palus (AP) 002*, A4 AP 003*, B4 AP 001*, C4 CC_BT_0686a #7, D4 Crystal Spring#7, E4 MSL Sol 898, F4 Cottonwood, G4 Tintic#1, A5 MSL Sol 1160, B5 Omusati, C5 Aeolis Mons (AM) 001*, D5 AM 002*, E5 Normandien.

Specific problems to be addressed:

1. *Amazonian/Hesperian surface weathering processes.* Meteorite weathering on Earth obscures their pre-atmospheric chemistries, textures, mineralogies, and histories. However, their weathering on Mars helps clarify environmental interactions and exposure histories in their find environments, which is highly important to Mars science. Extremely low water/rock ratios and cold conditions means that weathering operates slowly in the current epoch on Mars. Nonetheless, all meteorites found so far have weathered in a variety of ways, including oxidation, acidic corrosion, sculpting by wind abrasion, and/or fragmentation. Exogenic materials weather differently (both chemically and mechanically) compared to rocks indigenous to Mars, and their weathering on Earth is reasonably well understood. Weathered meteorites are highly susceptible to aqueous alteration because their high-temperature and reduced mineral compositions make them chemically reactive in oxidizing environments. Moreover, while some meteorite types show signs of pre-terrestrial aqueous alteration, the majority are unaltered prior to arrival on a planetary surface. Hence these rocks represent a unique suite of control samples for characterizing both aqueous and physical weathering processes on Mars, and therefore address water occurrence and behavior, calibration of climate models, and associated astrobiological questions. With reasonable estimates of surface residence times, variations in weathering rates might be assessed by noting changes in weathering products among different specimens on the same martian surface.

2. *Where are the chondrites?* Of the 55 meteorites found on Mars, the strong majority are irons. The near absence of stony meteorites (which comprise ~94% of Earth's inventory) is significant, and likely to be only partially the result of operational sampling bias; survivability of larger samples may be a function of composition. The fact that all chondritic meteorites so far identified on the surface are small (e.g., Lasue, *et al.*, 2019), in concert with remote sensing of at least one candidate for active chondritic disintegration from weathering (B3 in Figure 1; Ashley *et al.*, 2015b), suggest fragmentation may explain the discrepancy. Disintegration and dispersal may progress by oxidation of metallic iron grains in stony meteorites, which is commonly observed in desert environments on Earth, although this tends to increase the find rate on Earth. However, complete fragmentation upon impact with the surface due to insufficient aerobraking in the thin atmosphere may also explain the size bias and apparent lack of stony meteorites. Catastrophic fragmentation in the atmosphere during passage can also occur before impact to produce strewnfields. A large field of cobbles near the Cabo Anonimo promontory along the NNW rim of Victoria crater at Meridiani Planum are a possible example of a meteorite strewnfield on Mars (Ashley *et al*., 2009; Fleischer *et al*., 2011; Schroder *et al*., 2016; Figure 2). They contain either one or both types of metallic iron in the form of kamacite, or iron sulfide in the form of troilite (both meteoritic minerals), in addition to other ferrous and ferric iron phases. The ferric iron is most likely a product of chemical alteration (Schröder et al., 2010). Many thousands of small fragments resulting from such processes would be easily overlooked by rover surveys because their size, angular shapes and dust coating would make them difficult to distinguish from martian rocks. These hypotheses require confirmation by targeted examination of smaller samples. Meteorites can also occur within proximal and distal impact ejecta material, be present as lag deposits after ejecta deflation (Schröder *et al.* 2016), or become entrained within regolith. Our understanding of martian surface processes will not be complete until it can explain the abundance of different meteorite types on the surface.

3. *Mineral-water interactions from ice contact or from burial?* Iron meteorites exhibit morphologies and coatings that suggest complex post-fall exposure histories related to recent climate effects near the martian equator, where all three rovers are located due to engineering constraints. Among the more conspicuous weathering features for the irons are 1) differential erosion of internal mineralogy (either kamacite plates, or taenite/schreibersite lamellae), revealing Widmanstätten patterns, 2) discontinuous iron oxide coatings interpreted as a sign of water interaction, and 3) the effects of cavernous weathering, which often penetrate to rock interiors (see Figure 3 for examples of some of these features). Martian surface processes required to account for these features include atmospheric ablation, surficial aeolian scouring, acidic corrosion, and microfilm aqueous alteration. Cross-cutting relationships between exposed Widmanstätten patterns and oxide coatings (see Figure 3g), in concert with patterns of recent coating removal, indicate recent interaction with water or hydrogen peroxide (Ashley *et al*., 2011). However, it is not clear whether these processes occurred during burial from ripple migration (which should produce microenvironments of enhanced humidity within pore space volumes), or from ice interaction during periods of high obliquity. Refining these hypotheses is clearly important for understanding the climate history of Mars, and possibly useful for calibrating climate models. Similar encounters at the Jezero crater and Oxia Planum landing sites will extend the range of this type of study to >18° north.

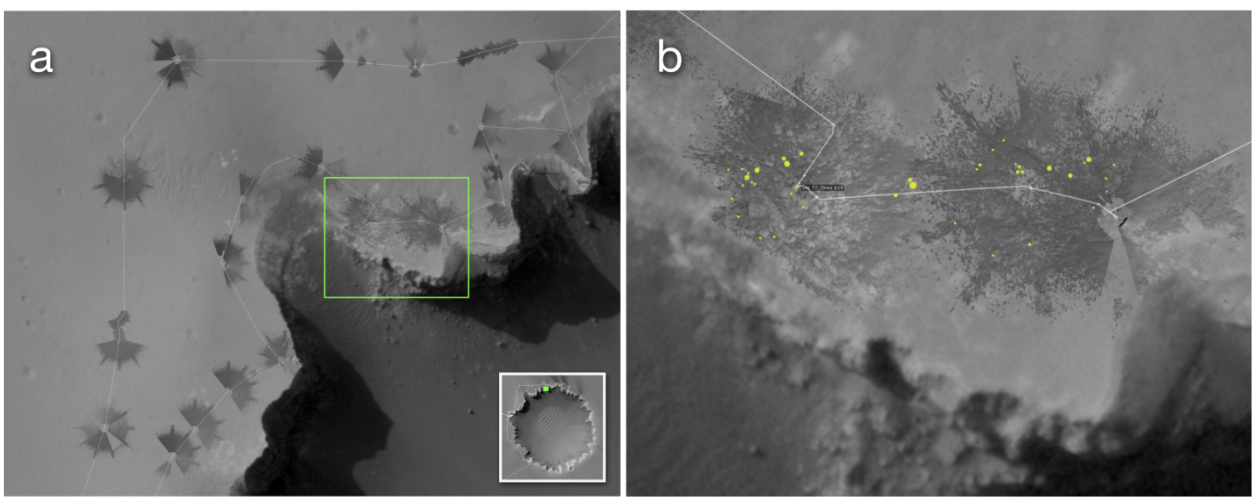

Figure 2. HiRISE frames showing North-northwest rim of 800m-diameter Victoria crater (inset 3a) and Cabo Anonimo promontory (green box) at Meridiani Planum where the Santa Catarina cobble field is located, with Opportunity rover traverse localization. Dark grey patches are seam-corrected, orthorectified Navcam mosaics reprojected to an overhead perspective and georeferenced to a HiRISE basemap. True-diameter measurements for each cobble are represented where visible in 3b (yellow dots), but are limited to the Navcam coverage. Helicopter image reconnaissance would help inform this type of distribution by reducing areal discontinuity.

4. *Potential exogenic contamination of regolith and sedimentary rock samples*. In addition to the possibility for forward bio-contamination from Earth and cross-contamination between samples on a sample caching mission, efforts should be made to avoid *in-situ* organic carbon, geochemical, and mineralogical contamination during collection of indigenous samples for any MSR mission. The need for careful control of contamination has been understood since

before Pathfinder (e.g., Flynn and McKay, 1990), and is probably best summarized by Yen et al. (2006): *"… establishing the likelihood that sample return missions will collect meteoritic rather than martian material is essential in developing mission strategies."* Because Perseverance and ExoMars will be the first mission assets designed for sample return, understanding contamination issues is critical to preserving sample integrity. Soils analyzed *in-situ* at three rover landing sites suggest planet-wide similarity in composition (Yen *et al.,* 2019), and a strong meteoritic component is concluded to explain high nickel concentrations (Yen *et al.,* 2006). This can be used to track exogenic input. Exogenic heterogeneity may occur locally due to variations in abundance of fragmented meteorites from high-velocity primary impacts (Golombek *et al.*, 2006), or from weathering as noted above.

5. *MSR Samples of accident; Hesperian aged atmosphere and solar system inventories*. Small chondritic fragments may easily become incorporated in soil samples, contributing both organic and inorganic material. With regolith and sedimentary rocks being likely sampling targets for MSR (e.g., Beaty *et al.* 2019), sampling of small meteorite fragments, micrometeorites and/or extraterrestrial chromites is unavoidable. I-Type micrometeorites are altered to iron oxide phases upon atmospheric entry, trapping upper atmospheric oxygen as part of the new mineral structure. This has been demonstrated with Archean-aged micrometeorites on Earth (Tomkins *et al.* 2016), and allows for oxygen isotopic data to be extracted (Pack *et al.* 2017). If found on Mars within dated sediments, such data could provide pivotal information about the atmosphere during shifting climate episodes. Based on terrestrial sampling of dunes where ~220 micrometeorites per kg were found (Tomkins *et al.* 2019), extrapolating to a 15 g sampling core on Mars would result in ~2-3 micrometeorites per core, but the abundance is expected to be far higher than this due to the much greater age of the martian surface, and limited degree of weathering on Mars. In addition, chromites are some of the most mechanically resistant minerals in chondrites, surviving as detrital grains inside sedimentary rocks. With older rocks on Mars, study of returned extraterrestrial chromites could foster a better understanding of the fluxes and types of meteorite parent bodies shortly after the LHB, as well as reveal potential extinct parent body types. Thus, micrometeorites and extraterrestrial chromites should be recovered from martian sedimentary samples, especially those targeted for dating, and may provide the only direct measurement of the Hesperian atmosphere during the crucial environmental transition to the Amazonian if materials dating to that interval can be returned to Earth.

6. *Meteorite concentrations along-traverse and between sites.* As mentioned, several dozen candidate meteorites have been recognized during existing rover mission traverse navigation, including a large inventory recognized in MSL data. Apparent variations in the local abundances of meteorites between different rover missions, or within the same mission, have raised speculative hypotheses as to whether this reflects more than operational sampling bias (Wellington *et al.* 2019; Meslin *et al.* 2019; Ashley *et al.*, 2015b). While the various size-reduction mechanisms mentioned in 2) above represent potential explanations, vertical (as a lag deposit) or horizontal (via glacial transport) concentration mechanisms may also be possibilities. In the latter scenarios, simply establishing meteorite abundance may thus contribute to an understanding of surface processes within the local environment.

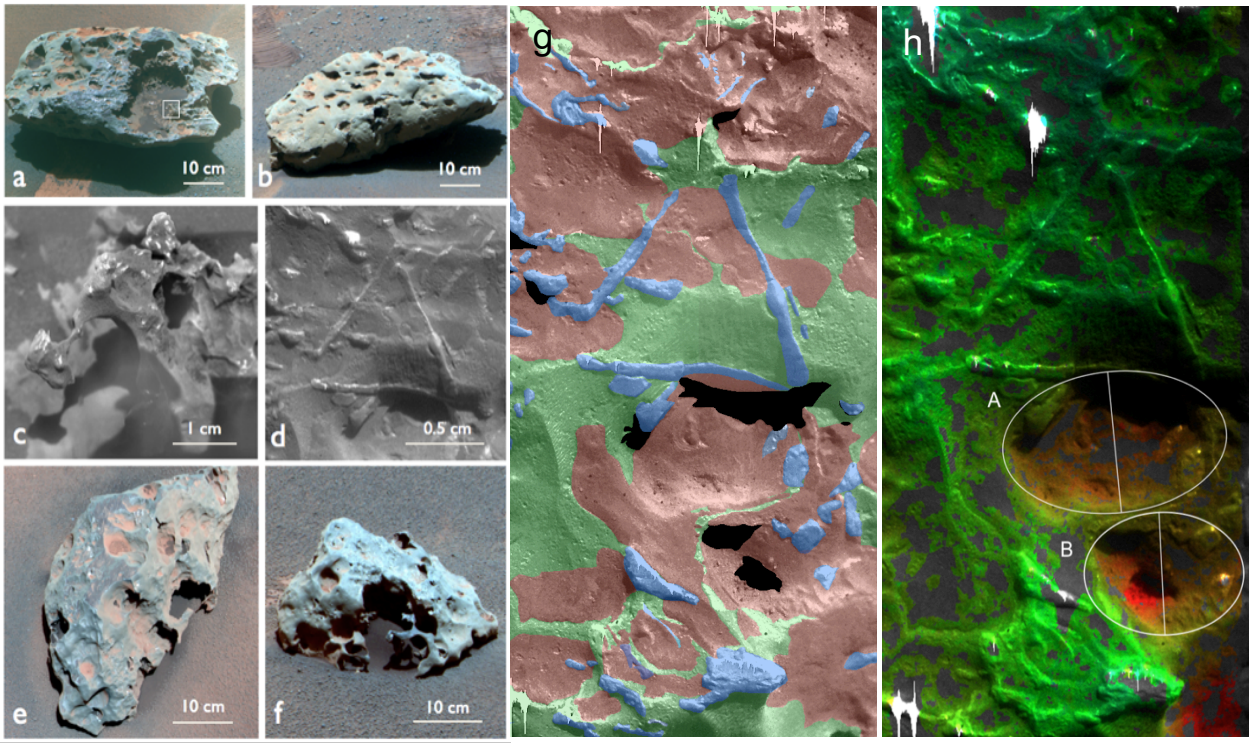

Figure 3. Examples of acidic corrosion, iron oxidation, aeolian sculpting, and cavernous excavation of metal on Mars. Figures 1a and 1b false color Pancam images show the north and south sides of MP 006 (aka Block Island), respectively. Note large, cavernous pit on western (right) third of 1a. The small square highlights the Veterans Park Microscopic Imager (MI) target area (partial mosaic presented as 1c), collected on Opportunity Sol 1979. 1d is a detail of a MI mosaic from MP 006, showing Widmanstätten pattern and heterogeneous coating (darker grey-toned areas). Features have weathered differentially from either mechanical erosion or aqueous alteration. Coatings are topographically lower than kamacite plates. This, combined with their chemistry (which is unlike that of their substrate), demonstrates the coating to be a weathering product and not a fusion crust. Figures 1e and 1f show MP 007 and MP 008 iron meteorites, respectively. Figure 1g shows the micro-mapping of crosscutting oxide coatings with the Widmanstätten features of MP 006. Figure 1h is a micro-digital elevation model produced with stereo frames showing morphometric measurement of suspected regmaglypts (A & B ellipses), which covey information on the macro-scale freshness of the surface. Micro-scale vertical measurements confirm post-fall exposure to water.

Instrumentation considerations. For Perseverance rover extended mission work, particulate meteoritic influence on soil and rock chemistry must be identified chemically using PIXL (for elevated Ni, Cu, MgO abundance, and high Mg/Si ratios), SHERLOC and SuperCam LIBS/Raman fluorescence datasets, while macroscale meteorites await serendipitous detection during traverse. Both single-frame and stereo imagers are suitable for remotely sensing the morphology and color anomalies of rock and regolith targets. All images with high to moderate compression are useful for characterizing meteorite morphology, texture, and conducting weathering assessments. Multispectral imaging from Mastcam-Z will permit bandpass ratios and spectral characteristics useful for identifying (possibly even in an automated way) iron meteorites (e.g., Johnson *et al.*, 2020). SHERLOC data will help to confirm organic material

from carbonaceous chondrites. Ideally, diagnostic morphologic anomaly characterizations require a 360º circumnavigation (as was done for MP 006 at Meridiani Planum (Ashley *et al.,* 2011)), but more realistic assessments rely on Mastcam-Z stereo pairs, multispectral imaging, micro-imaging, and decorrelation stretches in color frames with fewer images. The nature of each assessment should be determined on a case-by-case basis as target uniqueness is established by the science and operations teams. Perseverance rover helicopter (Ingenuity) reconnaissance for suspected strewnfield identification may serendipitously identify such deposits (see possible example in Figure 2), or these may even be targeted if considered a reasonable use case for this asset. RIMFAX (Perseverance) and WISDOM (ExoMars) ground penetrating radar would be particularly useful to address key questions concerning burial of irons in the vicinity of impact structure ejecta blankets (see Schröder *et al*., 2016).

Operational considerations. As discussed, exogenic material studies must rely heavily on data collected by rover mission teams. Many of these observations, especially follow-on investigations from initial serendipitous finds, will compete with other high priority science and mission goals. Strategies to provide the highest science return for both meteorite studies and other science goals may be achievable by well-timed remote sensing planning coordination. An emphasis should be placed on mid-field spectral imaging at and near sites with expected revisit opportunities (during a "walkabout," or initial characterization of a local area). Early remote sensing acquisition when a rover is located at a site with a significant expected dwell time (such as during sampling campaigns) may be prime opportunities to identify targets of interest for these and other studies.

Additional studies. Space constraints prohibit a full presentation of research topics that can be approached by the study of exogenic materials on other planetary surfaces. The reader is directed to the Visions and Voyages 2013-2022 white paper for further thoughts on this subject, many of which remain relevant for 2023-2032, and include 1) compositional variations among main-belt asteroids; 2) improving understanding of impact processes (this work to be pursued in concert with results from the NASA InSight mission efforts to detect recent impacts through seismic energy, or bolide occurrence using auxiliary payload sensors and cameras; Daubar *et al*., 2018); 3) atmospheric density fluctuations; and 4) unanticipated applications: V&V_Exogenics_2011. The role of space weather and heliophysics in the fate of exogenic materials on Mars is another area of potentially fruitful interdisciplinary interest (e.g., Hassler *et al*., 2017). As a final note, in addition to the value to astrobiological and geochemical/isotopic research noted above, sample return of a sufficiently weathered chondritic target massive enough to avoid movement during drilling may also serve as an age-datable geochemical standard for examining mineral-water interactions and weathering of other samples in a sample cache. Moreover, a sample of organics from a carbonaceous chondrite could provide insights on the origin, lines of evolution, and preservation pathways of sulfur-bearing organic compounds, such as those observed by SAM in Gale crater sediments. These questions warrant an in-depth community discussion on chondritic sample return to objectively gauge costs and merits.

References for this white paper are hosted at the MEPAG DSPSA white paper website: https://mepag.jpl.nasa.gov/reports/decadal2023-2032/References-Martian_Exogenic_Materials.pdf.