THE STUDY OF EXOGENIC ROCKS ON MARS—AN EVOLVING SUBDISCIPLINE IN METEORITICS

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History is replete with entertaining anecdotes of meteorites found and lost on Earth. That chronicle has recently been expanded to include the exotic saga of meteorite search, discovery, and assessment on another planet using roving spacecraft. The inventory of confirmed and candidate meteorites on Mars currently stands at a minimum of 21 finds from three widely separated rover landing sites (Table 1). Using a combination of remote sensing and direct-measurement instruments on Opportunity and Spirit (Mars Exploration Rovers, MERs), and most recently on Curiosity (Mars Science Laboratory, MSL), a morphologic and chemical database has been compiled for this suite of rocks. Finding nonindigenous materials on Mars forces us to rethink meteoritical definitions and language (for example, to avoid confusion about whether the term *Martian meteorites* refers to meteorites found on Mars or to the SNC meteorite association). Here we will refer to these rocks as Martian finds.

THEORY

Martian finds provide new ways to address a variety of science topics (e.g. Chappelow and Sharpton 2006; Yen et al. 2006; Chappelow and Golombek 2010; Ashley et al. 2011a). For example, the reactive metallic iron in most meteorites provides clues to aqueous alteration that indigenous rocks do not. This is significant for the purpose of assessing weathering processes near the Martian equator (where the Mars rovers are conveniently located). On Earth, weathering is a serious nuisance to the study of a meteorite's preterrestrial history (e.g. Velbel 2014). On Mars the effects of mineral–water interactions permit the probing of aqueous geologic scenarios and related paleoclimate/habitability questions. Moreover the occurrence of meteorite falls throughout Mars' history means that some falls (if their residence times can be determined) may assist understanding of subtle reactions related to the low water–rock ratios of more recent (Amazonian age) climate situations—a valuable tool for Mars science (e.g. Kraft et al. 2014).

A reference library of thermal emission spectra for fresh and weathered meteorites was prepared to assist with the detection and evaluation of weathering effects using the miniature thermal emission spectrometers (Mini-TES) on the MER rovers (Ashley and Wright 2004). The approach was based on the weathering behavior of ordinary chondrites in Antarctica, a Mars-analog environment. Current understanding of meteorite delivery mechanisms and inner Solar System dynamical models predicts that meteorite-type proportions on Mars would approximate those found on Earth, where some 94 percent are stony (chondrite and achondrite) varieties.

OBSERVATIONS

As with most discoveries in the planetary sciences, some observations confirm theory while others raise baffling questions. For example, to date not a single chondritic meteorite has been identified on Mars, and the suite is dominated instead by large (30–200 cm) iron–nickel meteorites (see Table 1). A selection bias probably results from the nature of meteorite survival, preservation, and the built-in mission requirements that tend to overlook small rocks, but identifying this lost population would solve an important mystery (Ashley et al. 2015). Mini-TES was indeed useful for identifying the first meteorites found on another planet, but not in the manner anticipated. Steve Ruff, of Arizona State University's Mars Space Flight Facility, recognized that the spectrum measured for Heat Shield Rock at Meridiani Planum was similar to the spectrum of the Martian sky. Only a metallic object has the reflectivity to produce these spectra, and so a meteorite was suspected and later confirmed (Schröder et al. 2008). Zhong Shan and Allan Hills, located in Gusev Crater on the opposite side of the planet, were identified in a similar way. Subsequent iron discoveries were identified based on morphology, mineralogy, texture, luster, and chemistry. Other anomalies are found among the stony-iron candidates. They are brecciated and contain varying amounts of kamacite (an Fe–Ni alloy) and troilite (FeS), but they do not resemble known meteorite varieties (Schröder et al. 2010). They may represent either a type of meteorite not found in Earth-based collections or some species of impact breccia that preserves materials from the impacting bolide. If meteoritic, the rocks are probably members of a single-fall strewn field. Further studies are underway. The tendency for most irons to be found in groups is also almost certainly an indication of specimens being members of common falls ("pairing" in meteoritics vernacular).

Overall, the observed effects of weathering in Martian finds are complex and are likely combinations of relic/fossil components and products of contemporary processes. Our knowledge of each rock depends on how complete rover reconnaissance has been on a case-by-case basis, which is largely a function of mission priorities at each time of discovery. Unknown residence times for the meteorites complicate the difficulty of sorting out their Martian histories. The irons tend to present rounded and pitted morphologies with enlarged hollows and sculpted surfaces that are likely the result of eolian abrasion (Fig. 1). However the intensities of these features vary among specimens and even within the same specimen, from virtually unmodified to cavernously excavated. This is consistent with some terrestrial examples, where similar morphologies led Buchwald to

Table 1 LIST OF METEORITE CANDIDATES FOUND ON MARS. The Opportunity discoveries were on Meridiani Planum while the Spirit and Curiosity finds were in Gusev and Gale craters, respectively.

Meteorite	Rover	First sol encountered	Type (suspected or confirmed)	Instrumentation employed
Barberton	Opportunity	121	stony-iron	PancamNavcam
Heat Shield Rock*	Opportunity	339	IAB complex iron	MTES/Pancam/APXS/MB/MI
Allan Hills	Spirit	858	iron	MTES/Pancam/Navcam
Zhong Shan	Spirit	858	iron	MTES/Pancam/Navcam
Santa Catarina	Opportunity	1034	stony-iron	MTES/Pancam/APXS/MB/MI
Joacaba	Opportunity	1046	stony-iron	MTES/Navcam
Mafra	Opportunity	1151	stony-iron	MTES/Navcam
Paloma	Opportunity	1190	stony-iron	MTES/Navcam
Santorini	Opportunity	1713	stony-iron	Pancam/APXS/MB/MI
Kasos	Opportunity	1889	stony-iron	Pancam/APXS/MB/MI
Block Island	Opportunity	1961	IAB complex iron	Pancam/APXS/MB/MI
Shelter Island	Opportunity	2022	IAB complex iron	Pancam/APXS/MB/MI
Mackinac Island	Opportunity	2034	iron	PancamNavcam
Oileán Ruaidh	Opportunity	2368	iron	PancamNavcam
Ireland	Opportunity	2374	iron	PancamNavcam
Bingag Cave	Opportunity	2642	iron	PancamNavcam
Dia Island	Opportunity	2642	iron	PancamNavcam
Canegrass	Opportunity	3346	unknown	PancamNavcam
Lebanon	Curiosity	634	iron	Mastcam/ChemCam RMI
Lebanon B	Curiosity	634	iron	Mastcam/ChemCam RMI
Littleton	Curiosity	634	iron	Mastcam/ChemCam RMI

* Official name: Meridiani Planum (Connolly et al. 2006)

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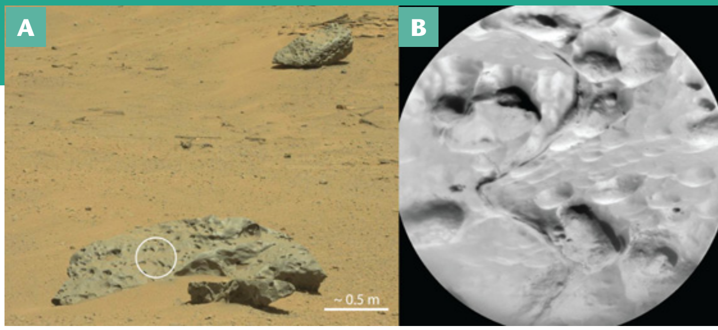

Figure 1 (**A**) Released images of Lebanon, Lebanon B, and Littleton taken by Curiosity's Mastcam on MSL sol 640 in Gale Crater. (**B**) A ChemCam Remote Micro-Imager view of the circled area in (A). Note the deep incision, the scalloped and polished surface, and the enlarged hollows. Images courtesy of NASA/JPL/LANL

speculate on the role of sulfuric acid produced when troilite nodules are exposed to water on Earth (Buchwald 1975); indeed, this mechanism is the preferred explanation for many (but not all) of the hollows observed on the Martian examples. Thus, separating eolian scouring effects from the effects of acidic corrosion is not always straightforward.

Comparing finds among sites can be a qualitative but thought-provoking pastime. Four of the Meridiani irons exhibit Widmanstätten patterns and iron oxide/oxyhydroxide coatings, while six show signs of cavernous weathering (see Schröder et al. 2008; Johnson et al. 2010; Ashley et al. 2011b; Fleischer et al. 2011). None of these features are obvious in the images of Gale Crater irons, where meteorite surfaces appear more polished (Fig. 1). Many reasons are possible for this, of course, including differences in residence time and incomplete reconnaissance by the rovers, as well as actual differences in site-specific weathering processes. Other features are unique to individual samples. Lebanon (see Table 1 for the locations of the meteorites) shows deep incision, presumably along internal weaknesses. Shelter Island shows large-scale differential mass removal, and Mackinac Island appears to have been hollowed to its core. The upper surface of Block Island presents a gaping pit decorated along its rim with delicate and highly angular protrusions (Fig. 2). Clearly a large mass of unknown mineralogy has been removed from its metal groundmass.

A beautiful sequence of events is recorded on Block Island, Shelter Island, and Oileán Ruaidh. The presence of acid-etched (or more likely sandblasted) Widmanstätten patterns (Fig. 2d) confirms postfall surface modification. The presence of iron oxide / oxyhydroxide coatings in crosscutting relationships with these features (Fig. 2d) shows that they too occurred after fall. They must therefore be a weathering product rather than fusion crusts produced during atmospheric flight. Finally, clear indications of rust destruction in the current epoch show that

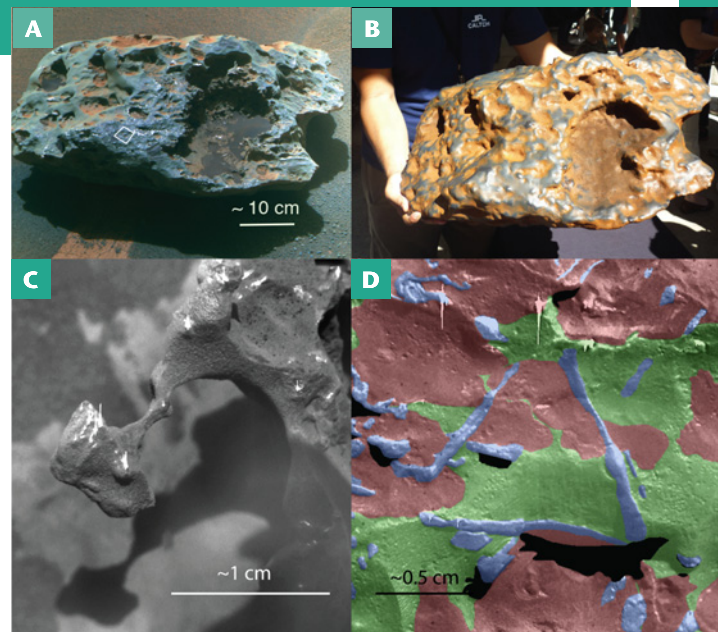

Figure 2 The Block Island meteorite found by Opportunity on Meridiani Planum on sol 1961. (**A**) The outline shows the Microscopic Imager (MI) mosaic area shown in D; north is toward the lower left. (**B**) A full-scale, resin 3-D print of Block Island prepared by Kris Capraro of JPL from a geometric model using Pancam images collected at six circumferential rover standoff positions around the meteorite. (**C**) A hammerhead-shaped metal protrusion together with its shadow along the rim of Block Island's conspicuous pit. (**D**) Map of the MI mosaic area in (A). Blue indicates Widmanstätten pattern (may be taenite or schreibersite lamellae), red is iron oxide/oxyhydroxide coating, green is bare metal, and black is shadow. Images courtesy of NASA/JPL/MIPL/Pancam/MI

simple exposure to the small amount of oxygen in the Martian atmosphere is insufficient to produce the coating and that water (probably ice) was therefore involved. Moreover, it means that this exposure was recent, because otherwise the relatively soft coatings would have been removed by wind abrasion. Thus, we have recent rust formation by water at the Martian equator alternating with periods of eolian scouring (see Ashley et al. 2011b for further details). The most off-the-shelf explanation is one involving obliquity cycling where water ice is brought to equatorial latitudes every few hundred thousand years. An alternate hypothesis involves ripple migration (now dormant; Golombek et al. 2010) over the meteorites on comparable timescales, where frost forms on meteorite surfaces while buried (e.g. Yen et al. 2005). Future studies will seek to differentiate between these competing theories.

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