Putative Indigenous Carbon-Bearing Alteration Features in Martian Meteorite Yamato 000593

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Abstract

We report the first observation of indigenous carbonaceous matter in the martian meteorite Yamato 000593. The carbonaceous phases are heterogeneously distributed within secondary iddingsite alteration veins and present in a range of morphologies including areas composed of carbon-rich spheroidal assemblages encased in multiple layers of iddingsite. We also observed microtubular features emanating from iddingsite veins penetrating into the host olivine comparable in shape to those interpreted to have formed by bioerosion in terrestrial basalts. Key Words: Meteorite—Yamato 000593—Mars—Carbon. *Astrobiology* 14, 170–181.

1. Introduction

THE MARTIAN METEORITES represent samples of the martian regolith that were ejected from the planet as a consequence of bolide impact events that have occurred over the last 20 million years (Nyquist *et al.*, 2001). Radiometric crystallization ages determined for individual meteorites indicate they formed across much of the martian geological record, from as recently as 165 million years ago (Shergotty) to as long as 4.1 billion years ago (ALH84001) (Nyquist *et al.*, 2001). Martian meteorites are principally mafic or ultramafic. Nearly all those that have been studied in microscopic detail, however, exhibit evidence of at least transient interaction with aqueous fluids, such as the presence of secondary mineral assemblages and evaporitic deposits present within veins and internal fracture surfaces. Several main mineral phases associated with these secondary alteration features include iddingsite, carbonates, sulfates, halite, and various clay minerals (Gooding and Wentworth, 1987; Gooding *et al.*, 1988, 1991; Wentworth and Gooding, 1988a, 1988b, 1990, 1991; Wentworth and McKay, 1999; Greenwood, 2000; Wentworth *et al.*, 2001; Treiman, 2005). Other minor phases include sulfides (Treiman *et al.*, 1993; Wentworth *et al.*, 1998; Treiman, 2005), ferric oxides (Treiman *et al.*, 1993; Treiman, 2005) and ferrihydrite (Treiman and Gooding, 1991; Treiman, 2005). While the exact physical environment under which these minerals formed and the composition of the alteration fluid are not well constrained, a martian origin can be established based on isotopic grounds

(Imae *et al.*, 2002) and through microstratigraphic relationships between the secondary phases and the fusion crust (*e.g.*, Wentworth and Gooding, 1990; Treiman and Goodrich, 2002). The lack of extensive alteration of primary minerals such as olivine suggests secondary mineral formation during evaporation of brine-like solutions (Gooding and Wentworth, 1991; Bridges and Grady, 2000; Bridges *et al.*, 2001) at low temperatures (< 150°C) and over relatively short periods of time (Wentworth *et al.*, 2005). The abundance of secondary minerals in different meteorites ranges from ~0.2 to 2 vol %, being highest in the nakhlites (*e.g.*, Nakhla and Lafayette) at ~2 vol % (Bridges and Grady, 1999, 2000) and in ALH84001 at ~1 vol % (Mittlefehldt, 1994).

Yamato 000593 (henceforth Y000593) was discovered in 2000 at the Yamato Glacier in Antarctica by the Japanese Antarctic Research Expedition. Based on oxygen isotope data (Imae *et al.*, 2002) and mineralogy (Mikouchi *et al.*, 2002, 2003; Imae *et al.*, 2003a, 2003b; Misawa *et al.*, 2003a, 2003b), it belongs to the nakhlite subgroup of the martian meteorites. The meteorite represents a fragment of a larger fall and has been paired with the Yamato 000749 and Yamato 000802 meteorites (Misawa *et al.*, 2003a). Together, these meteorites compose a whole rock mass of ~15 kg (Meyers, 2003; Misawa *et al.*, 2003a). Mineralogically, Y000593 is an unbrecciated igneous rock consisting mainly of coarse-grained crystals of augite and olivine with minor plagioclase, pyrrhotite, apatite, fayalite, tridymite, and magnetite (Imae *et al.*, 2003b; Mikouchi *et al.*, 2003). Evidence of interaction with aqueous fluids is substantiated

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by carbonate phases and clay-rich iddingsite veins containing amorphous silica-rich material, possibly a gel or opaline-like phase, also present in the matrix (Spencer *et al.*, 2008a, 2008b). Because iddingsite alteration veins in Y000593 are truncated at the fusion crust, it appears likely that they formed prior to atmospheric entry and hence have a martian origin (Treiman and Goodrich, 2002). Additional evidence of interaction of Y000593 with aqueous fluids includes the presence of microtubular features or microtunnels emanating from iddingsite veins and penetrating into the surrounding olivine crystals. Because olivine is a reactive mineral, exposure to aqueous fluids results in the epitactic and/or topotactic nucleation of iddingsite within wedge-shaped etch channels, which results in a typical lamellar structure observed in partly altered olivine grains (Eggleton, 1984; Smith *et al.*, 1987). The observed microtunnels, however, display curved, undulating shapes consistent with bioalteration textures observed in basaltic glasses (Fisk *et al.*, 1998, 2006; Furnes *et al.*, 2001; Preston *et al.*, 2011).

Previous reports describe tunnel features and their associated mineralogy in Nakhla. However, no investigation has yet been reported for similar features in Y000593 and compared to Nakhla. For the first time, we describe features called microtunnels associated with iddingsite veins in Y000593. Additionally, we also report the presence of indigenous organic matter occurring as heterogeneous carbon-rich areas in iddingsite veins and carbon-bearing spheroidal features interleaved between layers of iddingsite.

2. Methods

Optical identification of secondary phases in a 25.4 mm round polished thin section of Y000593 was performed by using a Nikon 120 microscope equipped with a digital camera. Series of images were taken over a range of focal distances and combined with ImageJ¹ software to give extended depth-of-field images through the depth of the section. After optical imaging, a conductive carbon surface coating <1 nm thick was applied to the thin section to enable chemical characterization with a JEOL 6340F field emission scanning electron microscope (FE-SEM) equipped with an IXRF System energy-dispersive X-ray spectrometer (EDS) that allows detection of light elements including carbon. A range of acceleration voltages and beam currents were used to determine the optimum conditions for imaging and analysis. The optimum voltage and current for backscatter, secondary electron, and lower secondary imaging were determined to be 15 kV at 10 μ A. Individual (point) spectra were collected by using 6.5, 10, and 15 kV with an analysis spot size ranging from $\sim$ 0.1 to 1 μ m.

A polished petrographic thin section of LEW87051, an Antarctic achondrite recovered from the ice by a US team in 1987 (Mason, 1989), was prepared under identical conditions to that of Y000593 to serve as a control. While the provenance of LEW87051 is uncertain (Warren and Kallemeyn, 1990), the oxygen isotopic ratios exclude a martian origin. This meteorite is classified as an angrite² composed

predominantly of large magnesium-containing olivine grains ($\sim$ Fo₈₀) embedded within a fine-grained ground-mass of euhedral laths of anorthite intergrown with clinopyroxene and magnesium-poor olivine crystals (up to $\sim$ Fo₁₀₀) (McKay *et al.*, 1990). Its terrestrial residence time based on ¹⁴C radiochronology is estimated to be $\sim$ 50 thousand years (Eugster *et al.*, 1991), which is nearly identical to that for Y000593 (Nishiizumi and Hillegonds, 2004). LEW87051 weighs $\sim$ 0.6 g (Eugster *et al.*, 1991), only $\sim$ 0.004% of that of Y000593 at $\sim$ 13.7 kg. The difference in weights between the two meteorites and consequently greater surface area to volume of LEW87051 implies effects of terrestrial contamination³ or weathering⁴ are likely to be more pronounced in LEW87051. While not recovered from the same blue ice field, LEW87051 provides a useful means to evaluate whether our observations of Y000593 could be a product of its residence time in Antarctica.

A chip of Y000593 (from allocated split Y000593,80) $\sim$ 2 mm in size was attached to a 12.7 mm aluminum pin mount with conductive carbon tape before being sputter-coated with a thin (<1 nm) layer of platinum to enable charge dissipation during FE-SEM/EDS analysis. Imaging was performed at 15 kV, while EDS analyses were performed at 6.5 and 10 kV; the lower kilovolt value allows for improved detection of light elements ($Z < 9$).

3. Results

Optical images of the Y000593 thin section show an extensive network of brown/orange iddingsite veins hundreds of microns in length that cross-cut fractured olivine crystals. Extending out approximately perpendicular from a large fraction of the veins are iddingsite-filled tunnels typically $\geq 0.5 \mu$ m in width and tens of microns in length (Fig. 1). In addition to the large-width ($\geq 0.5 \mu$ m) tunnels, approximately a third of the veins show threadlike microtunnels of iddingsite that range from $\sim$ 100 to 200 nm in width and $\sim$ <1 to 4 μ m in length (Figs. 1 and 2). The majority of microtunnels display curved and/or sigmoidal (S-shaped) morphologies (Fig. 2). EDS spectra show that the host olivine contains approximately equimolar $\sim$ Si:Fe, while the adjacent iddingsite is strongly iron-enriched with respect to silicon (Fig. 3). A layer of silica $\sim$ 2 μ m in width rims a portion of the iddingsite vein (Fig. 1). EDS spectrum of silica shows Si > Fe compared to that for both olivine and iddingsite (Fig. 3). Two representative EDS spectra of iddingsite show its heterogeneous nature at the submicron scale; one contains major carbon, calcium, and manganese consistent with the presence of mixed cation carbonate (Fig. 3), while the other contains major carbon with little to no calcium or manganese, indicating the carbon may be independent of carbonate.

Y000593 chips revealed close-packed spheroidal structures encased within and surrounded by multiple layers of iddingsite-like compositions (Fig. 4). Structures ranged in

¹ImageJ is a public domain, Java-based image processing program developed at the National Institutes of Health.

²Angrites have been described as an unusual group of ancient basaltic igneous meteorites formed $\sim$ 4.55 billion years ago (Floss *et al.*, 2003).

³Terrestrial contamination of meteorites can be of anthropogenic and/or naturogenic origin and occurs after impact and during subsequent handling and storage.

⁴Weathering includes *in situ* physical, chemical, and/or biological alteration of original meteorite components.

FIG. 1. (A) Low-magnification scanning electron microscope/backscattered electron (SEM/BSE) view of a polished thin section of Y000593. Expanded views of regions enclosed by green and red boxes are shown in (B) and (C), respectively. Running diagonally across the image from top to bottom is a dark epoxy-filled vein crossing fractured crystals of olivine and augite (gray). (B) Optical image of region enclosed by green box in (A), showing characteristic red-brown iddingsite alteration of the silicates at the vein interface. (C) SEM/BSE view of the region enclosed by the red box in (A), the detailed structure of the alteration edges including tunnels and microtunnels. The four circles indicate the locations that the point EDS spectra in Fig. 3 were obtained from. The blue inset box indicates the location of the high-magnification region shown in Fig. 2.

diameter from ~ 100 to 500 nm and are enriched in carbon relative to the underlying host mineral phases and surrounding iddingsite (Fig. 4).

LEW87051 was characterized by identical techniques and instrumentation used for Y000593. Minor rusty or oxidized phases are present, presumably as a consequence of Antarctic weathering, while LEW87051 showed no evidence of iddingsite or silica alteration phases. Furthermore, there were no observations of microtunnels extending from fractures and veins (Fig. 5).

4. Discussion

Terrestrial iddingsite was first described in 1893 as a mixture of hydrous non-aluminous silicates of iron, magnesia, and soda pseudomorphous with olivine phenocrysts having a bright orange-yellow color (Lawson, 1893). Its composition and mineralogy has remained imprecise, since it lacks a definite chemical composition and therefore cannot be regarded as a simple submicroscopic intergrowth of two or more well-characterized minerals. It is best defined

FIG. 2. High-magnification SEM/BSE view of the region in the blue box shown in Fig. 1C. Undulating, sigmoid-shaped microtunnels emanate from the iddingsite vein and penetrate into olivine. They are filled with iddingsite and range from ~ 1 to $3 \mu\text{m}$ in length and ~ 0.1 to $0.2 \mu\text{m}$ in width.

as a complex mineral assemblage⁵ where it can be envisioned to represent the continuous transformation of an iron-bearing olivine crystal as it passes through various stages of structural and chemical change in the presence of liquid water at both elevated (300–450 K; Tomasson and Kristmannsdottir, 1972) and lower temperatures (< 300 K) given sufficiently long time frames (Zolensky *et al.*, 1988). Typical iddingsite veins show regular etching in the form of lamellar fissures formed during the opening of fractures and cleavage planes in olivine; these fissures display a pattern of wedge-shaped or sawtooth borders resulting from the crystallographically controlled dissolution of the olivine crystal structure (Eggleton, 1984; Smith *et al.*, 1987). Smectite produced by weathering of olivine contains aluminum and potassium introduced from another source.

Iddingsite in the nakhlites has long been interpreted as pre-terrestrial (Wentworth and Gooding, 1989; Gooding *et al.*, 1991; Romanek *et al.*, 1998; Treiman, 2005) and provided the first laboratory evidence for indigenous liquid water and a martian hydrosphere (Wentworth and Gooding,

1988a, 1989; Gooding *et al.*, 1991; Karlsson *et al.*, 1992; Treiman *et al.*, 1993; Romanek *et al.*, 1998). Isotopic dating suggests the iddingsite formation in Nakhla iddingsite occurred ~ 600 million years ago (Swindle *et al.*, 2000), either in a single event or through episodic aqueous exposure over a short time interval (Swindle and Olson, 2004). Iddingsite veins in Y000593 appear to be consistent in both composition and mineralogy to veins in other nakhlites (Wentworth and McKay, 1999; Treiman, 2005; Fisk *et al.*, 2006; McKay *et al.*, 2006). Observations from Y000593 show microtunnels radiating from the edges of iddingsite vein into host olivine (Figs. 1 and 2). Unlike typical sawtooth etch fissures in the alteration zone, undulating microtunnels display curved and/or sigmoid-shaped threadlike morphologies similar in size and shape to those in terrestrial silicates interpreted as being formed by bioweathering processes (Fisk *et al.*, 1998, 2006; Furnes *et al.*, 2004; Fisk and McLoughlin, 2013). Microtunnels may have initially been hollow but now are filled with iddingsite. It is noteworthy that similar microtunnels emanating from iddingsite veins have also been described within Nakhla (Gooding *et al.*, 1991; Fisk *et al.*, 2006). Features are also consistent with a recently reported library of bioerosion textures in terrestrial basalts (Fisk and McLoughlin, 2013).

The surface of Mars has received a significant contribution of abiotic organic matter derived from exogenous sources (Bland and Smith, 2000) and through planetary processes (Chang, 1993). However, current robotic *in loco parentis* investigations of martian surface regolith have yet to provide any definitive evidence for carbonaceous matter. Nevertheless, it is worth remembering that only the Viking 1 and 2 lander missions carried molecular analysis packages specifically designed to detect organic matter (Biemann *et al.*, 1976, 1977; Biemann, 1979). The failure of the Viking landers to conclusively identify the presence of any simple organic species in surface soils (Biemann *et al.*, 1976, 1977; Biemann, 1979) is now generally, although not

⁵Iddingsite consists of a matrix composed of coarse and fine-grained smectite-type phyllosilicates with heterogeneously distributed fine-grained crystalline and amorphous components. The crystalline grains include hematite, goethite, maghemite, ferrihydrite, carbonates, and sulfates; the amorphous phases include silica and carbonaceous matter, as described herein. Iddingsite has been proposed to form by aqueous weathering of basalt in which the olivine crystal structure is diffused with water resulting in the dissolution and oxidation of structural components and concomitant leaching of elements. The phyllosilicate matrix is formed through the incorporation of Al and Na introduced from outside the olivine. Mg is dissolved out of the olivine structure and is replaced by H^+ , resulting in a distorted olivine structure with weakened inter-element bonds resulting in the slow release of Si and Fe. Diffusion of O may be a limiting factor for Fe-oxide formation because it may control the formation of soluble species $\text{Fe}(\text{OH})_2^+$, which has been suggested as precursor nuclei for Fe oxides including goethite and hematite (Smith *et al.*, 1987; Taylor, 1987).

FIG. 3. SEM/EDS spectra of select regions shown by green circles in Fig. 1. (A) Olivine host matrix with a significant Fe peak indicating an intermediate composition between fayalite and forsterite end members. (B) Silica-rich band along the olivine fracture surface showing depletion of Fe and enrichment of Al compared to the adjacent host olivine. (C) Iddingsite Regions 1 and 2 illustrating the significant heterogeneity in carbon abundance and cation variability of the iddingsite at the micron scale. Note that the use of epoxy-embedding medium for thin-sample preparation makes it difficult to wholly exclude the contribution of epoxy to observed carbon abundances; this was minimized by acquiring spectra from alteration regions that were contiguous at the scale of the analysis spot and showed no observable surface fracturing or porosity.

necessarily satisfactorily, explained as the result of UV photocatalytic oxidation combined with an unusual and highly oxidizing surface soil chemistry (Oro and Holzer, 1979; Zent and McKay, 1992; Yen *et al.*, 2000). The 2012 Mars Science Laboratory Curiosity has a suite of analytical tools associated with the Sample Analysis at Mars (SAM) instrument, which can measure the nature of organic matter within the near-surface of Mars. To date, the results from the SAM analyses show that indigenous organic content on Mars is yet to be determined (Leshin *et al.*, 2013; Ming *et al.*, 2013).

In contrast, many of the martian meteorites contain detectable organic compounds with measured abundances typically between 10 and 200 ppm (Wright *et al.*, 1986; Grady *et al.*, 1994; Romanek *et al.*, 1994; Bada *et al.*, 1998; Jull *et al.*, 2000; Sephton *et al.*, 2002; Steele *et al.*, 2012). The problem is that each studied martian meteorite also contains some terrestrial organic compounds or contaminants, so the challenge is to discriminate the terrestrial organics from those purported to be martian. Spatial association (McKay *et al.*, 2011) and isotopic analyses (Jull *et al.*, 2000) have been used previously to establish a martian heritage for some of these organics. For example, in a recent report by McKay *et al.* (2011), regions of carbon-rich matter in Nakhla were encased within iddingsite and salt crystals and interpreted as having a martian origin. Investigations by Jull *et al.* (2000) of Nakhla in which $\delta^{13}\text{C}$ and $\delta^{14}\text{C}$ isotope analysis procedures were used discovered that a significant amount (70–80%) of both the acid-soluble and insoluble carbonaceous matter in this meteorite was indigenous. Sephton *et al.* (2000, 2002) have subsequently reported the presence of indigenous high-molecular-weight organic matter in Nakhla by using solvent extraction in combination with flash-pyrolysis gas chromatography–mass spectrometry; they observed a suite of isotopically distinct ($\delta^{13}\text{C}$) aromatic and C_n -alkyl aromatic hydrocarbons.

The Y000593 iddingsite assemblage displays chemical and mineral heterogeneity at the submicron scale (Fig. 3C; Iddingsite Regions 1 and 2), consistent with previous observations of martian iddingsite (*e.g.*, Wentworth and Gooding, 1988b, 1989; Gooding *et al.*, 1991; Treiman, 2005). Iddingsite spectrum of Region 1 (Fig. 3C; also see Fig. 1) shows $\text{Fe} \geq \text{Si}$ with minor calcium, magnesium, manganese, and carbon, indicating the presence of abundant iron oxides and mixed cation carbonate. By comparison, an iddingsite spectrum of Region 2 (Fig. 3C; also see Fig. 1) shows $\text{Si} > \text{Fe}$ and major carbon with very minor calcium and magnesium, indicating the presence of few iron oxides and little, if any, carbonate. The presence of major carbon and lack of corresponding cations is consistent with the occurrence of organic matter embedded in iddingsite. EDS analysis of the polished thin section of Y000593 revealed some carbon-rich areas heterogeneously distributed throughout the iddingsite veins. These carbon-rich areas do not appear to be spatially associated with specific morphological or mineralogical features.

In contrast, analysis of Y000593 chips revealed submicrometer-sized spheroids enriched in carbon relative to the underlying host olivine and some regions of iddingsite (Fig. 4). Preliminary selected area electron diffraction analysis of the underlying layer revealed only silicate compositions; therefore, the carbon enrichment is not likely

FIG. 4. (A) SEM view of spheroidal features embedded in a layer of iddingsite. Locations of EDS spectra of the spherules and background are given by the red and blue circles, respectively. (B) EDS spectra of spherules (red) and background (blue). The spherules are enriched ~ 2 fold in carbon compared to the background. (C) SEM view of spherulitic features encased in both an upper (false-colored orange) and lower layer of iddingsite.

FIG. 5. (A) Optical image of typical features found within a thin section of achondritic non-martian meteorite LEW87051. No iddingsite veins were detected, and no microtunnels extending from fractures were observed. (B) Optical view of a thin section of martian meteorite Y000593 showing extensive iddingsite-rich alteration veins. Both views were taken at the same magnification. Both meteorites were recovered from Antarctica and exposed to similar environmental conditions.

bound to carbonate. These structures were observed embedded in between multiple layers of iddingsite (Fig. 4); and the spatial association of carbon-rich areas and spheroids with the iddingsite indicates these features formed either prior to, or contemporaneously with, the iddingsite in which they are encapsulated. This suggests that, like the iddingsite, they also formed on Mars. We note that indigenous organic matter in martian samples has been arguably confirmed from multiple meteorites by numerous independent research groups (Jull *et al.*, 1999, 2000; Sephton *et al.*, 2000, 2002), with the most recent report in 2011 describing carbon-rich features spatially associated with iddingsite and salt crystals in the martian meteorite Nakhla (McKay *et al.*, 2011).

Martian meteorites Y000593 and Nakhla have experienced strikingly different environmental conditions after their impact with Earth. The former was collected as a find in Antarctica after a ~50-thousand-year residence time and the latter as a sighted fall in Egypt recovered and quickly placed in a museum after its fall. The observation that these two meteorites exhibit similar microtunnel features despite the very different terrestrial landing environments and post-recovery histories strongly argues that the microtunnels are not the result of terrestrial contamination and instead were formed during an aqueous alteration on Mars. For example, while some contact with wet ground cannot be excluded for Nakhla, its terrestrial exposure history was many orders of

magnitude less than that of Y000593. While Antarctic meteorites undergo some terrestrial weathering, non-martian Antarctic meteorite LEW87051 showed no evidence of iddingsite or silica alteration phases, nor were any of the microtunnels observed extending from fractures and veins (Fig. 5A). Again, the presence of these microtunnels and iddingsite veins in Y000593 (Fig. 5B) and their absence in LEW87051, coupled with the presence of similar iddingsite veins and microtunnels in Nakhla, is strong evidence that they were not formed during terrestrial weathering but were formed on Mars.

This is the first report of purported indigenous carbonaceous matter in martian meteorite Y000593. This matter is embedded within spherules encased in layers of iddingsite compositions and embedded within iddingsite veins presumably formed by the action of liquid aqueous fluids on Mars (Gooding *et al.*, 1991). Both the spherules and microtunnel features formed either prior to, or contemporaneously with, iddingsite and hence have a martian origin. It is possible the carbonaceous matter has an abiotic origin or origins derived from exogenous (cometary/asteroidal/interplanetary dust) sources (Flynn and McKay, 1989, 1990; Flynn, 1993, 1996) and/or through planetary process including magmatic and impact-generated gases (Zolotov and Shock, 1998, 1999). Alternatively, the spherules and associated carbonaceous matter may have biogenic origins because spherulitic features are similar in both size ($\sim 0.1\text{--}0.5\ \mu\text{m}$) and shape to known terrestrial fossilized microbes reported in the range of $0.13\text{--}0.55\ \mu\text{m}$ (Folk and Chafetz, 2000; Brignon *et al.*, 2008). The presence and distribution of carbon-rich areas with tunnel erosion patterns in iddingsite imply this matter is relatively insoluble, consistent with the geopolymer kerogen (Kim *et al.*, 2006). While detailed analyses of carbonaceous matter are outside the scope of this paper, given abundant sample amounts, future analysis in which techniques more destructive to the sample are used (*e.g.*, mass spectrometry) may provide deeper insight into the nature of the carbon.

The Y000593 microtunnels are remarkably similar in morphology to bioerosion textures found in terrestrial Fe-Mg silicates described by Fisk *et al.* (2006), Preston *et al.* (2011), and Furnes *et al.* (2004). The microtunnels are inconsistent with alteration channels produced by the crystallographically controlled abiotic dissolution of olivine (Eggleton, 1984; Smith *et al.*, 1987). Fisk *et al.* (2006) suggested common features of biotic alteration include the following: tunnels that emerge from a glass or mineral surface that has been in contact with water, a host mineral or glass replaced with hydrous minerals, dark brown to black boundary between the glass and fracture-filling clay, uniform tunnel size and shape in a single sample, uniform tunnel diameter along the length of the individual tunnel, and localized, nonuniform distribution of tunnels along fractures or mineral edges. We suggest that the microtunnels in Y000593 display all the aforementioned characteristics.

Previous studies of terrestrial glass and olivine samples interpreted the presence of tunnels and microtunnels to be of biogenic origin (Fisk *et al.*, 1998, 2006; Furnes *et al.*, 2004; Preston *et al.*, 2011). This interpretation is greatly strengthened by the presence of DNA in some of these terrestrial features (Fisk *et al.*, 1998, 2006). Similar DNA fluorescence experiments performed by Fisk *et al.* (2006) on microtunnels in Nakhla did not detect DNA. As noted ear-

lier, however, the nakhlites appear to have been subjected to aqueous alteration during a period as old as 600 million years ago. Therefore, if martian DNA were introduced into the tunnel structure of nakhlites at that time, its instability during weathering and aging would likely preclude its survival in present-day samples.

Previous studies reveal that a combination of SEM and EDS can be used to differentiate between mineralized carbonate and organic matter by analyzing composition and texture (Toporski *et al.*, 2000; Toporski and Steele, 2007; McKay *et al.*, 2011). Specifically, the composition of carbonate requires the presence of cations (*e.g.*, Mg, Ca, Mn, or Fe) to balance the CO_3^{2-} anion. Therefore, the relative abundances of the cations can be detected by EDS and should correlate to carbon in carbonaceous material. If no cations are detected by EDS to correlate with carbon, one may consider the possibility of this material existing in the organic in phase. Furthermore, observed textures such as stringlike membranous material, tubular features, honeycomblike networks of material are inconsistent with typical mineral-carbonate structures and, in correlation with compositional observations, may indicate organic material. However, we note that when both phases are intermixed, such as may be the case in Y000593, differentiating between these phases is complex. Due to the often limited sample size for meteoritic and lunar materials, SEM and EDS are well-established nondestructive analytical methods that are frequently utilized to characterize extraterrestrial samples (Heiken *et al.*, 1972; Wentworth and McKay, 1987; Toporski *et al.*, 2000; McKay *et al.*, 2011; Ross *et al.*, 2011; Ruzicka *et al.*, 2012).

5. Summary and Conclusions

The martian meteorite Y000593 contains two distinctive sets of features associated with the martian-derived iddingsite. The tunnel and microtunnel structures are typically found in olivine along the margins of mineralogically complex iddingsite veins. These microtunnels contain areas of enhanced carbon abundance that, in some cases, are not associated with common carbonate cations and therefore are interpreted as carbonaceous material, perhaps similar to kerogen. The second set of features consists of nanometer- to micrometer-sized spherules sandwiched between layers of indigenous iddingsite and distinct from carbonate and the underlying silicate layer. Similar spherules have also been described in Nakhla (Gibson *et al.*, 2001). EDS spectra of the Y000593 spherules show that they are significantly enriched in carbon compared to the nearby surrounding iddingsite layers. A striking observation is that these two sets of features in Y000593, recovered from Antarctica after about ~ 50 -thousand-year residence time, are similar to features found in Nakhla, an observed fall collected shortly after landing. We cannot exclude the possibility that the carbon-rich regions in both sets of features may be the product of abiotic mechanisms; however, textural and compositional similarities to features in terrestrial samples, which have been interpreted as biogenic, imply the intriguing possibility that the martian features were formed by biotic activity.

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Author Disclosure Statement

For all authors listed, no competing financial interests exist

Abbreviations

BSE, backscattered electron; EDS, energy-dispersive X-ray spectrometer or spectrometry; FE-SEM, field emission scanning electron microscope or microscopy; SAM, Sample Analysis at Mars; SEM, scanning electron microscope or microscopy; Y000593, Yamato 000593.

References

- Bada, J.L., Glavin, D.P., McDonald, G.D., and Becker, L. (1998) A search for endogenous amino acids in martian meteorite ALH84001. *Science* 279:362–365.
- Biemann, K. (1979) The implications and limitations of the findings of the Viking organic analysis experiment. *J Mol Evol* 14:65–70.
- Biemann, K., Oro, J., Toulmin, P., III, Orgel, L.E., Nier, A.O., Anderson, D.M., Flory, D., Diaz, A.V., Rushneck, D.R., and Simmonds, P.G. (1976) Search for organic and volatile inorganic compounds in two surface samples from the Chryse Planitia region of Mars. *Science* 194:72–76.
- Biemann, K., Oro, J., Toulmin, P., III, Orgel, L.E., Nier, A.O., Anderson, D.M., Flory, D., Diaz, A.V., Rushneck, D.R., and Simmonds, P.G. (1977) The search for organic substances and inorganic volatile compounds in the surface of Mars. *J Geophys Res* 82:4641–4658.
- Bland, P.A. and Smith, T.B. (2000) Meteorite accumulations on Mars. *Icarus* 144:21–26.
- Bridges, J.C. and Grady, M.M. (1999) A halite-siderite-anhydrite-chlorapatite assemblage in Nakhla: mineralogical evidence for evaporites on Mars. *Meteorit Planet Sci* 34: 407–415.
- Bridges, J.C. and Grady, M.M. (2000) Evaporite mineral assemblages in the nakhlite (martian) meteorites. *Earth Planet Sci Lett* 176:267–279.
- Bridges, J.C., Catling, D.C., Saxton, J.M., Swindle, T.D., Lyon, I.C., and Grady, M.M. (2001) Alteration assemblages in martian meteorites: implications for near-surface processes. *Space Sci Rev* 96:365–392.
- Brigmon, R.L., Morris, P., Smith, G., Dilek, Y., Furnes, H., and Muehlenbachs, K. (2008) Evaporite microbial films, mats, microbialites and stromatolites. In *Links between Geological Processes, Microbial Activities & Evolution of Life*, edited by Y. Dilek, H. Furnes, and K. Muehlenbachs, Springer, Dordrecht, pp 197–235.
- Chang, S. (1993) Prebiotic synthesis in planetary environments. In *The Chemistry of Life's Origins*, edited by J.M. Greenberg, C.X. Mendoza-Gómez, and V. Pirronellos, Kluwer Academic Publishers, Dordrecht, pp 259–299.
- Eggerton, R.A. (1984) Formation of iddingsite rims on olivine: a transmission electron microscope study. *Clays Clay Miner* 32:1–11.
- Eugster, O., Michel, T., and Niedermann, S. (1991) (Pu-244)-Xe formation and gas retention age, exposure history, and terrestrial age of angrites LEW86010 and LEW87051—comparison with Angra DOS Reis. *Geochim Cosmochim Acta* 55:2957–2964.
- Fisk, M. and McLoughlin, N. (2013) Atlas of alteration textures in volcanic glass from the ocean basins. *Geosphere* 9:317–341.
- Fisk, M.R., Giovannoni, S.J., and Thorseth, I.H. (1998) Alteration of oceanic volcanic glass: textural evidence of microbial activity. *Science* 281:978–980.
- Fisk, M.R., Popa, R., Mason, O.U., Storrie-Lombardi, M.C., and Vicenzi, E.P. (2006) Iron-magnesium silicate bioweathering on Earth (and Mars?). *Astrobiology* 6:48–68.
- Floss, C., Crozaz, G., McKay, G., Mikouchi, T., and Killgore, M. (2003) Petrogenesis of angrites. *Geochim Cosmochim Acta* 67:4775–4789.
- Flynn, G.J. (1993) Organic matter on the early surface of Mars: an assessment of the contribution by interplanetary dust [abstract 1248]. In *24th Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Flynn, G.J. (1996) The delivery of organic matter from asteroids and comets to the early surface of Mars. *Earth, Moon, Planets* 72:469–474.
- Flynn, G.J. and McKay, D.S. (1989) An assessment of the meteoric and meteoritic contributions to dust on Mars [LPI technical report 89-01]. In *MECA Workshop on Dust on Mars III*, Lunar and Planetary Institute, Houston, pp 23–25.
- Flynn, G.J. and McKay, D.S. (1990) An assessment of the meteoritic contribution to the martian soil. *J Geophys Res* 95:14497–14509.
- Folk, R.L. and Chafetz, H.S. (2000) Bacterially induced microscale and nanoscale carbonate precipitates. In *Microbial Sediments*, edited by R. Riding and S.M. Awramik, Springer, Berlin.
- Furnes, H., Staudigel, H., Thorseth, I.H., Torsvik, T., Muehlenbachs, K., and Tumyr, O. (2001) Bioalteration of basaltic glass in the oceanic crust. *Geochemistry, Geophysics, Geosystems* 2, doi:10.1029/2000GC000150.
- Furnes, H., Banerjee, N.R., Muehlenbachs, K., Staudigel, H., and de Wit, M. (2004) Early life recorded in archaic pillow lavas. *Science* 304:578–581.
- Gibson, E.K., McKay, D.S., Thomas-Keptra, K.L., Wentworth, S.J., Westall, F., Steele, A., Romanek, C.S., Bell, M.S., and Toporski, J. (2001) Life on Mars: evaluation of the evidence within martian meteorites ALH84001, Nakhla, and Shergotty. *Precambrian Res* 106:15–34.
- Gooding, J.L. and Wentworth, S.J. (1987) Calcium carbonate and calcium sulfate in martian meteorite EETA79001. In *Planetary Geology and Geophysics Program Report, 1986*, NASA, Washington, DC, pp 158–159.
- Gooding, J.L. and Wentworth, S.J. (1991) Origin of “white druse” salts in the EETA790001 meteorite [abstract 1229]. In *22nd Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Gooding, J.L., Wentworth, S.J., and Zolensky, M.E. (1988) Calcium carbonate and sulfate of possible extraterrestrial origin in the EETA 79001 meteorite. *Geochim Cosmochim Acta* 52:909–915.
- Gooding, J.L., Zolensky, M.E., and Wentworth, S.J. (1991) Aqueous alteration of the Nakhla meteorite. *Meteoritics* 26:135–143.

- Grady, M.M., Wright, I.P., Douglas, C., and Pillinger, C.T. (1994) Carbon and nitrogen in ALH 84001. *Meteoritics* 29:469.
- Greenwood, J.P. (2000) Modified sulfur isotopic compositions of sulfides in the nakhlites and Chassigny. *Geochim Cosmochim Acta* 64:1121–1131.
- Heiken, G., McKay, D.S., and Clanton, U.S. (1972) Preliminary stratigraphy of regolith at Apollo 15 site. *Transactions American Geophysical Union* 53:1038.
- Imae, N., Okazaki, R., Kojima, H., and Nagao, K. (2002) The first nakhlite from Antarctic. In *33rd Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Imae, N., Ikeda, Y., Kojima, H., and Stansbery, E. (2003a) Igneous petrogenesis of Yamato nakhlites. In *34th Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Imae, N., Ikeda, Y., Shinoda, K., Kojima, H., and Iwata, N. (2003b) Yamato nakhlites: petrography and mineralogy. *Antarctic Meteorite Research* 16:13–33.
- Jull, A.J.T., Beck, J.W., Burr, G.S., Gilmour, I.A., Sephton, M.A., and Pillinger, C.T. (1999) Isotopic evidence for abiotic organic compounds in the martian meteorite, Nakhla. *Meteorit Planet Sci* 34(Supplement):A60.
- Jull, A.J.T., Beck, J.W., and Burr, G.S. (2000) Isotopic evidence for extraterrestrial organic material in the martian meteorite, Nakhla. *Geochim Cosmochim Acta* 64:3763–3772.
- Karlsson, H.R., Clayton, R.N., Gibson, E.K., and Mayeda, T.K. (1992) Water in SNC meteorites: evidence for a martian hydrosphere. *Science* 255:1409–1411.
- Kim, D., Lai, H.-T., Chilingar, G., and Yen, T. (2006) Geopolymer formation and its unique properties. *Environ Geol* 51:103–111.
- Lawson, A.C. (1893) *The Geology of Carmelo Bay*, Bulletin of the Department of Geology of the University of California, Vol. 1, The University, Berkeley, p 31.
- Leshin, L.A., Mahaffy, P.R., Webster, C.R., Cabane, M., Coll, P., Conrad, P.G., Archer, P.D., Atreya, S.K., Brunner, A.E., Buch, A., Eigenbrode, J.L., Flesch, G.J., Franz, H.B., Freissinet, C., Glavin, D.P., McAdam, A.C., Miller, K.E., Ming, D.W., Morris, R.V., Navarro-González, R., Niles, P.B., Owen, T., Pepin, R.O., Squyres, S., Steele, A., Stern, J.C., Summons, R.E., Sumner, D.Y., Sutter, B., Szopa, C., Teinturier, S., Trainer, M.G., Wray, J.J., Grotzinger, J.P., and the MSL Science Team. (2013) Volatile, isotope, and organic analysis of martian fines with the Mars Curiosity rover. *Science* 341, doi:10.1126/science.1238937.
- Mason, B. (1989) Sample LEW 87051. *Antarctic Meteorite Newsletter* 12:15.
- McKay, D.S., Clemett, S.J., Thomas-Keprta, K.L., Wentworth, S.J., Gibson, E.K., Jr., Robert, F., Verchovsky, A.B., Pillinger, C.T., Rice, T., and van Leer, B. (2006) Observation and analysis of *in situ* carbonaceous matter in Nakhla: part I [abstract 2251]. In *37th Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- McKay, D.S., Thomas-Keprta, K.L., Clemet, S.J., Gibson, E.K., Le, L., Rahman, Z., and Wentworth, S.J. (2011) Organic carbon features identified in the Nakhla martian meteorite [abstract 2673]. In *42nd Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- McKay, G., Crozaz, G., Wagstaff, I., Yang, S.R., and Lundberg, L. (1990) A petrographic, electron microprobe study of mini-angrite Lewis Cliff 87051 [abstract 1393]. In *21st Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Meyers, C. (2003) Yamato 000593/749/802. *Mars Meteorite Compendium* XXII:1–5.
- Mikouchi, T., Koizumi, E., Monkawa, A., Ueda, Y., and Miyamoto, M. (2002) Comparative mineralogy of the new nakhlite Yamato 000593 with other nakhlite martian meteorites. In *Antarctic Meteorites XXVII*, papers presented to the 26th Symposium on Antarctic Meteorites, National Institute of Polar Research, Tokyo.
- Mikouchi, T., Koizumi, E., Monkawa, A., Ueda, Y., and Miyamoto, M. (2003) Mineralogy and petrology of Yamato 000593: comparison with other martian nakhlite meteorites. *Antarctic Meteorite Research* 16:34–57.
- Ming, D.W., Archer, P.D., Jr., Glavin, D.P., Eigenbrode, J.L., Franz, H.B., Sutter, B., Brunner, A.E., Stern, J.C., Freissinet, C., McAdam, A.C., Mahaffy, P.R., Cabane, M., Coll, P., Campbell, J.L., Atreya, S.K., Niles, P.B., Bell, J.F., III, Bish, D.L., Brinckerhoff, W.B., Buch, A., Conrad, P.G., Des Marais, D.J., Ehlmann, B.L., Fairén, A.G., Farley, K., Flesch, G.J., Francois, P., Gellert, R., Grant, J.A., Grotzinger, J.P., Gupta, S., Herkenhoff, K.E., Hurowitz, J.A., Leshin, L.A., Lewis, K.W., McLennan, S.M., Miller, K.E., Moersch, J., Morris, R.V., Navarro-González, R., Pavlov, A.A., Perrett, G.M., Pradler, I., Squyres, S.W., Summons, R.E., Steele, A., Stolper, E.M., Sumner, D.Y., Szopa, C., Teinturier, S., Trainer, M.G., Treiman, A.H., Vaniman, D.T., Vasavada, A.R., Webster, C.R., Wray, J.J., Yingst, R.A., and the MSL Science Team. (2013) Volatile and organic compositions of sedimentary rocks in Yellowknife Bay, Gale Crater, Mars. *Science* 343, doi:10.1126/science.1245267.
- Misawa, K., Kojima, H., Imae, N., and Nakamura, N. (2003a) The Yamato nakhlite consortium. *Antarctic Meteorite Research* 16:1–12.
- Misawa, K., Shih, C.-Y., Wiesmann, H., Nyquist, L.E., and Stansbery, E. (2003b) Crystallization and alteration ages of the antarctic nakhlite Yamato 000593 [abstract 1556]. In *34th Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Mittlefehldt, D.W. (1994) ALH84001 cumulate orthopyroxene: a previously unappreciated martian meteorite [abstract 1456]. In *25th Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Nishiizumi, K. and Hillegonds, D.J. (2004) Exposure and terrestrial histories of new Yamato lunar and martian meteorites. *National Institute of Polar Research Tokyo, Antarctic Meteorites XXVIII*:60–61.
- Nyquist, L.E., Bogard, D.D., Shih, C.-Y., Greshake, A., Stöffler, D., and Eugster, O. (2001) Ages and geologic histories of martian meteorites. *Space Sci Rev* 96:105–164.
- Oro, J. and Holzer, G. (1979) The photolytic degradation and oxidation of organic compounds under simulated martian conditions. *J Mol Evol* 14:153–160.
- Preston, L.J., Izawa, M.R.M., and Banerjee, N.R. (2011) Infrared spectroscopic characterization of organic matter associated with microbial bioalteration textures in basaltic glass. *Astrobiology* 11:1–15.
- Romanek, C.S., Grady, M.M., Wright, I.P., Mittlefehldt, D.W., Socki, R.A., Pillinger, C.T., and Gibson, E.K., Jr. (1994) Record of fluid-rock interactions on Mars from the meteorite ALH84001. *Nature* 372:655–657.
- Romanek, C.S., Perry, E.C., Treiman, A.H., Socki, R.A., Jones, J.H., and Gibson, E.K., Jr. (1998) Oxygen isotopic record of silicate alteration in the SNC meteorite Lafayette. *Meteorit Planet Sci* 33:775–784.
- Ross, D.K., Thomas-Keprta, K.L., Rahman, Z., Wentworth, S.J., and McKay, D.S. (2011) FE-SEM, FIB and TEM study of surface deposits on Apollo 15 green glass volcanic

- spherules [abstract 2203]. In *42nd Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Ruzicka, A., Hutson, M., Floss, C., and Hildebrand, A. (2012) Large silica-rich igneous-textured inclusions in the Buzzard Coulee chondrite: condensates, differentiates, or impact melts? *Meteorit Planet Sci* 47:1809–1829.
- Sephton, M.A., Gilmour, I., Wright, I.P., de Leeuw, J.W., Grady, M.M., and Pillinger, C.T. (2000) High molecular weight organic matter in Nakhla [abstract 1786]. In *31st Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Sephton, M.A., Wright, I.P., Gilmour, I., de Leeuw, J.W., Grady, M.M., and Pillinger, C.T. (2002) High molecular weight organic matter in martian meteorites. *Planet Space Sci* 50:711–716.
- Smith, K.L., Milnes, A.R., and Eggleton, R.A. (1987) Weathering of basalt: formation of iddingsite. *Clays Clay Miner* 35:418–425.
- Spencer, L.M., McKay, D.S., Gibson, E.K., Thomas-Keptra, K.L., Wentworth, S.J., and Clemett, S.J. (2008a) Observation and analysis of martian meteorite Y000593: evidence of biosignatures. *Meteorit Planet Sci* 43(Supplement):5114.
- Spencer, L.M., McKay, D.S., Thomas-Keptra, K.L., Wentworth, S.J., and Clemett, S.J. (2008b) Observation and analysis of martian meteorite Y000593: evidence for biosignatures [abstract 1680]. In *39th Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Steele, A., McCubbin, F.M., Fries, M., Kater, L., Boctor, N.Z., Fogel, M.L., Conrad, P.G., Glamoclija, M., Spencer, M., Morrow, A.L., Hammond, M.R., Zare, R.N., Vicenzi, E.P., Siljeström, S., Bowden, R., Herd, C.D., Mysen, B.O., Shirey, S.B., Amundsen, H.E., Treiman, A.H., Bullock, E.S., and Jull, A.J. (2012) A reduced organic carbon component in martian basalts. *Science* 337:212–215.
- Swindle, T.D. and Olson, E.K. (2004)⁴⁰Ar–³⁹Ar studies of whole rock nakhlites: evidence for the timing of formation and aqueous alteration on Mars. *Meteorit Planet Sci* 39:755–766.
- Swindle, T.D., Treiman, A.H., Lindstrom, D.J., Burkland, M.K., Cohen, B.A., Grier, J.A., Li, B., and Olson, E.K. (2000) Noble gases in iddingsite from the Lafayette meteorite: evidence for liquid water on Mars in the last few hundred million years. *Meteorit Planet Sci* 35:107–115.
- Taylor, R.M. (1987) Non-silicate oxides and hydroxides. In *The Chemistry of Clays and Clay Minerals*, edited by A.C.D. Newman, Mineralogical Society Monograph No. 6, Longmans, London.
- Tomasson, J. and Kristmannsdottir, H. (1972) High temperature alteration mineral and thermal brines, Reykjanes, Iceland. *Contrib Mineral Petrol* 36:123–134.
- Toporski, J. and Steele, A. (2007) Observations from a 4-year contamination study of a sample depth profile through the martian meteorite Nakhla. *Astrobiology* 7:389–401.
- Toporski, J.K.W., Steele, A., Westall, F., Griffin, C., Whitby, C., Avei, R., and McKay, D.S. (2000) Electron microscopy studies, surface analysis and microbial culturing experiments on a depth profile through martian meteorite Nakhla [abstract 1636]. In *31st Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Treiman, A. (2005) The nakhlite meteorites: augite-rich igneous rocks from Mars. *Chemie der Erde/Geochemistry* 65: 203–270.
- Treiman, A.H. and Gooding, J.L. (1991) Iddingsite in the Nakhla meteorite: TEM study of mineralogy and texture of pre-terrestrial (martian?) alterations. In *54th Annual Meeting of the Meteoritical Society*, Lunar and Planetary Institute, Houston, p 231.
- Treiman, A.H. and Goodrich, C.A. (2002) Pre-terrestrial aqueous alteration of the Y-000593 and Y-000749 nakhlite meteorites. In *27th NIPR Symposium on Antarctic Meteorites*, National Institute of Polar Research, Tokyo, pp 166–167.
- Treiman, A.H., Barrett, R.A., and Gooding, J.L. (1993) Pre-terrestrial aqueous alteration of the Lafayette (SNC) meteorite. *Meteoritics* 28:86–97.
- Warren, P.H. and Kallemeyn, G.W. (1990) Geochemistry of the LEW87051 angrite and other basaltic achondrites [abstract 1658]. In *21st Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Wentworth, S.J. and Gooding, J.L. (1988a) Calcium carbonate in Nakhla: further evidence for pre-terrestrial secondary minerals in SNC meteorites. *Meteoritics* 23:310.
- Wentworth, S.J. and Gooding, J.L. (1988b) Chloride and sulfate minerals in the Nakhla meteorite [abstract 1640]. In *19th Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Wentworth, S.J. and Gooding, J.L. (1989) Calcium carbonate and silicate “rust” in the Nakhla meteorite [abstract 1605]. In *20th Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Wentworth, S.J. and Gooding, J.L. (1990) Pre-terrestrial origin of “rust” in the Nakhla meteorite [abstract 1672]. In *21st Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Wentworth, S.J. and Gooding, J.L. (1991) Carbonate and sulfate minerals in the Chassigny meteorite. *Meteoritics* 26:408.
- Wentworth, S.J. and McKay, D.S. (1987) Glasses in ancient and young Apollo 16 regolith breccias: populations and ultra Mg-prime glass. In *18th Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston, pp 67–77.
- Wentworth, S.J. and McKay, D.S. (1999) Weathering and secondary minerals in the Nakhla meteorite [abstract 1946]. In *30th Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Wentworth, S.J., Thomas-Keptra, K.L., Taunton, A.E., Velbel, M.A., and McKay, D.S. (1998) Possible weathering features in ALH 84001 [abstract 1793]. In *29th Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Wentworth, S.J., Velbel, M.A., Thomas-Keptra, K.L., Longazo, T.G., and McKay, D.S. (2001) Weathering of martian evaporites [abstract 2108]. In *32nd Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.
- Wentworth, S.J., Gibson, E.K., Velbel, M.A., and McKay, D.S. (2005) Antarctic Dry Valleys and indigenous weathering in Mars meteorites: implications for water and life on Mars. *Icarus* 174:383–395.
- Wright, I.P., Carr, R.H., and Pillinger, C.T. (1986) Carbon abundance and isotopic studies of Shergotty and other shergottite meteorites. *Geochim Cosmochim Acta* 50:983–991.
- Yen, A.S., Kim, S.S., Hecht, M.H., Frant, M.S., and Murray, B. (2000) Evidence that the reactivity of the martian soil is due to superoxide ions. *Science* 289:1909–1912.
- Zent, A.P. and McKay, C.P. (1992) Chemical reactivity of the martian soil. In *MSATT Workshop on Chemical Weathering on Mars*, Lunar and Planetary Institute, Houston, pp 41–42.

- Zolensky, M., McSween, H.Y., Jr., and Matthews, M.S. (1988) Aqueous alteration. In *Meteorites and the Early Solar System*, edited by J.F. Kerridge, University of Arizona Press, Tucson, pp 114–143.
- Zolotov, M. and Shock, E. (1999) Abiotic synthesis of polycyclic aromatic hydrocarbons on Mars. *J Geophys Res* 104: 14033–14050.
- Zolotov, M.Y. and Shock, E.L. (1998) Abiotic synthesis of hydrocarbons on Mars: theoretical modeling of metastable equilibria [abstract 956]. In *Martian Meteorites: Where Do We Stand and Where Are We Going?* Lunar and Planetary Institute, Houston.

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