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Evaluation of meteorites as habitats for terrestrial microorganisms: Results from the Nullarbor Plain, Australia, a Mars analogue site

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Abstract

Unambiguous identification of biosignatures on Mars requires access to well-characterized, long-lasting geochemical standards at the planet's surface that can be modified by theoretical martian life. Ordinary chondrites, which are ancient meteorites that commonly fall to the surface of Mars and Earth, have well-characterized, narrow ranges in trace element and isotope geochemistry compared to martian rocks. Given that their mineralogy is more attractive to known chemolithotrophic life than the basaltic rocks that dominate the martian surface, exogenic rocks (e.g., chondritic meteorites) may be good places to look for signs of prior life endemic to Mars. In this study, we show that ordinary chondrites, collected from the arid Australian Nullarbor Plain, are commonly colonized and inhabited by terrestrial microorganisms that are endemic to this Mars analogue site. These terrestrial endolithic and chasmolithic microbial contaminants are commonly found in close association with hygroscopic veins of gypsum and Mg-calcite, which have formed within cracks penetrating deep into the meteorites. Terrestrial bacteria are observed within corrosion cavities, where troilite (FeS) oxidation has produced jarosite [$KFe_3(SO_4)_2(OH)_6$]. Where terrestrial microorganisms have colonized primary silicate minerals and secondary calcite, these mineral surfaces are heavily etched. Our results show that inhabitation of meteorites by terrestrial microorganisms in arid environments relies upon humidity and pH regulation by minerals. Furthermore, microbial colonization affects the weathering of meteorites and production of sulfate, carbonate, Fe-oxide and smectite minerals that can preserve chemical and isotopic biosignatures for thousands to millions of years on Earth. Meteorites are thus habitable by terrestrial microorganisms, even under highly desiccating environmental conditions of relevance to Mars. They may therefore be useful as chemical and isotopic "standards" that preserve evidence of life, thereby providing the possibility of universal

context for recognition of microbial biosignatures on Earth, Mars and throughout the solar system.

1. Introduction

One of the greatest hurdles to identifying extra-terrestrial life is the ambiguity inherent to detection of biosignatures in poorly understood geochemical settings, such as the martian surface. Ideally, a well-characterized, sterile geochemical standard could be deployed to the surface of Mars that, if colonized and inhabited by putative martian microorganisms, would give unambiguous signatures of microbial modification. Conveniently, the mineralogical, elemental and isotopic characteristics of chondritic meteorites — which make up 87% of our extraterrestrial population of meteorites on Earth — have been carefully constrained by extensive study (Farquhar et al., 2007; Jarosewich, 1990). The exogenic rocks are not to be confused with the martian meteorites (e.g., shergottite, nakhlite, and chassignite types, as well as ALH 84001 and NWA 7034 and pairs) which are crustal rocks from Mars that have fallen to Earth. Unless explicitly stated, we discuss chondritic meteorites that have fallen to Mars or Earth. Chondrites contain sulfide minerals and FeNi alloys that support terrestrial sulfur- and iron-oxidizing microorganisms under laboratory conditions (Gronstal et al., 2009). Chondritic meteorites (carbonaceous chondrites in particular) also contain soluble organic compounds and minerals that can support heterotrophic microorganisms (Mautner, 1997). For instance, bioavailable phosphorus, nitrogen and chromium are found within meteorites in apatite group minerals [$Ca_5(PO_4)_3(OH,F,Cl)$], schreibersite [$(Fe,Ni)_3P$] (Pasek and Lauretta, 2008) and carlsbergite (CrN) (Harries et al., 2015).

Microbial sulfur cycling causes stable isotope fractionation and produces alteration minerals with distinctive isotopic signatures (Canfield, 2001) that can be readily distinguished from those observed in unaltered ordinary and enstatite (i.e., low-Ca pyroxene) chondrites (Figure 1). Comparatively little is known about the stable sulfur isotope signatures of martian rocks and how the planet’s complex history could have affected sulfur isotope fractionation

(Farquhar et al., 2000; Farquhar et al., 2010). Our understanding of martian sulfur cycling comes from studies of the SNC (Shergottite, Nakhlite, Cassignite) meteorites, which are samples of the martian crust that were ejected during from Mars during impact events. Large differences in $\delta^{34}S$ values have been reported for the different classes of SNC meteorites (Farquhar et al., 2000). Even within the Nakhlite sub-types there is (1) $\delta^{34}S_{(means)}$ = -6.1 – 1.5 ‰ variation of the means (using pyrrhotite and pyrite) in $\delta^{34}S$ values between meteorites (Greenwood et al., 2000), (2) $\delta^{34}S_{(S.Phases)}$ =0.93 – 2.03 variation between different sulfur-bearing phases within a single meteorite (Nakhla) (Farquhar et al., 2000), and (3) $\delta^{34}S_{(Nakhla)}$ = -1.7 – 4.9 variation within grains of the same phase (pyrrhotite) within one meteorite (Nakhla) (Farquhar et al., 2007; Greenwood et al., 2000). This heterogeneity, combined with poor constraints on the evolution of the martian sulfur cycle, could make unambiguous detection of stable sulfur isotopic biomarkers difficult. Given these points, we suggest that chondritic meteorites may be excellent standards for the detection of past or present life at planetary surfaces.

However, before sulfur isotope analysis can be established as a tool for exobiology discovery, there must be a compelling case for microbes to colonize and inhabit meteorites in the first place. This work will establish the mineral behaviour and micro-environments of meteorites, that would aid microbes in their survival. In addition to redox sensitive elements, such as carbon, sulfur and iron, which can be harnessed for metabolism and/or biomass production, microorganisms require a source of water. Earth's deserts, such as the Nullarbor Plain in Australia, are valued as Mars analogues because of their aridity. They are also commonly explored for meteorites because the scarcity of water slows weathering, improving preservation of their original size and composition (Bland et al., 2006). However, if the scarcity of bioavailable water in terrestrial deserts poses a challenge to Earth life; it may be a problem for theoretical life in the arid martian surface and subsurface.

Hygroscopic minerals such as sulfates, halides, perchlorates, carbonates, Fe-oxyhydroxides and smectites naturally adsorb atmospheric water vapor to crystal surfaces and accommodate H_2O within their crystal structures. It has been speculated that this mineral behavior could provide a source of water to desiccation-resistant microorganisms on Mars (Davila et al., 2008). Davila et al. (2008) have demonstrated that deliquescence of halite (NaCl) provides sufficient water to sustain endolithic cyanobacteria under the desiccating conditions of the hyperarid Atacama Desert in South America. Furthermore, reactions amongst hygroscopic minerals are known to occur at or below their deliquescence relative humidities (RH), and can thus maintain nutrient cycling in the absence of detectable liquid water, even at temperatures much less than 0°C (Wilson and Bish, 2011, 2012). In this way, hygroscopic minerals may allow survival of putative microorganisms within the shallow martian subsurface (Benison and Karmanocky, 2014; Mohlmann and Thomsen, 2011). Meteorites commonly contain hygroscopic sulfates, carbonates, Fe-oxyhydroxides and smectites by virtue of weathering of primary sulfides, FeNi alloys and silicate minerals (Bland et al., 2006; Velbel, 2014; Zurfluh et al., 2013). The porosity of chondritic meteorites (Consolmagno et al., 2008), and elevated phosphorus concentrations relative to many common rock compositions are also expected to facilitate colonization by contaminant microorganisms. Combined, these traits suggest meteorites may be excellent refuge habitats for microorganisms in environmentally hostile conditions.

Chondritic meteorites are fragments of planetesimal parent bodies that formed over 4.5 billion years ago during the birth of our solar system, but never underwent further accretion to form planets. As such, their formation predates the emergence of life on Earth and they are sterile when they fall to the surfaces of Earth, Mars and other solar system bodies. Thus, any microorganisms detected in chondritic meteorites will be endemic to the planet and local environment in which the meteorite fell. This means that the biological study of meteorites is similar to “first colonizer” research from recent basaltic lava flows in Iceland (Kelly et al., 2014). Kelly et al. (2014) showed that these lavas were colonized by low diversity microbial colonies, including chemolithotrophic taxa, within 3–5 months post eruption. Being comprised chiefly of olivine, pyroxene and plagioclase feldspar, basaltic rocks on Earth and Mars are chemically and mineralogically similar to chondritic meteorites. Thus meteorites may represent a more easily colonized refuge on the surface of Mars for theoretical chemlithotrophic organisms adapted to basaltic substrates. The weathering profiles of meteorites can create points of ingress for endolithic microorganisms to take advantage of a diversity of microhabitats. As such, we might expect to find that microorganisms colonize pore spaces or voids (i.e., cryptoendoliths) as well as fissures and cracks (i.e., chasmoendoliths) within meteorites.

We collected fragments of chondritic meteorites from the Nullarbor Plain, an arid Eocene limestone karst in southern central Australia (Webb and James, 2006), to examine whether they interact in a detectable way with Earth’s biosphere under Mars-analogous conditions. A subset of meteorite samples were glutaraldehyde-fixed in the field for later imaging of microorganisms endemic to the Nullarbor Plain using a Field Emission Gun Scanning Electron Microscope (FEG-SEM). Another subset of samples were collected for an independent 16S rRNA gene phylogenetics study of microbial populations, the results of which can be found in Tait et al. (2017). Secondary minerals were identified, and their abundances quantified, using powder X-Ray Diffraction (XRD). The extent to which these weathering products adsorb atmospheric water vapor was measured using a water sorption analyzer. Stable and radiogenic carbon isotope data were used to determine the origin of Mg-calcite as either a weathering product that could form in any CO_2-rich planetary atmosphere, such as that of Earth or Mars, or contamination from Eocene Nullarbor Limestone. Our results provide confirmation that terrestrial microorganisms commonly colonize and inhabit meteorites in one of the most arid environments on Earth. Furthermore, they leave behind an assemblage of alteration minerals that is ideally suited to preservation of fossil, organic molecular and isotopic biosignatures within ordinary chondrites.

2. Methods

2.1 Meteorite Sample Description

Meteorites were recovered from the Nullarbor Plain during Monash University's 2013–2015 annual recovery expeditions. Full meteorite descriptions can be found on *The Meteoritical Bulletin Database* and all samples are curated within the collection of the School of Earth, Atmosphere and Environment at Monash University. For petrological classification methods see Tait et al. (2014); Van Schmus and Wood (1967), for shock classification see Stoffler et al. (1991), and for weathering classification see Wlotzka (1993); Zurfluh et al. (2016). Weathering grade in meteorites reflects terrestrial alteration of the original mineralogical composition since falling to Earth. Meteorites and soil samples were collected aseptically using gloves washed in 70% ethanol, and sterile bags/falcon tubes to prevent contamination by microorganisms other than those endemic to the Nullarbor Plain.

Ooldea 002 is a fragmented 1.3-kg L5 chondrite that was found in nine partially buried pieces. The sample is lightly shocked (S2) and exhibits a complete metal/sulfide (W4) alteration profile. *Ooldea 005* is a 144-g H5 chondrite that is broken into blocks with a partial fusion crust. The sample is moderately shocked (S3) with moderate alteration (W3). *Ooldea 007* is a single H3 stone weighing 135 g, exhibiting moderate shock (S3) and complete metal alloy and sulfide alteration (W4). *Ooldea 009* is a H6 chondrite consisting of two pieces that jigsaw fit together, with a total mass of 47 g. The sample exhibits light shock (S2) and heavy alteration (W3). *Watson 015* is a 457-g H4 chondrite that was found in two pieces, with 2/3rds coverage by fusion crust. The sample is lightly shocked (S2) and exhibits complete alteration of the metal alloy and sulfide grains (W4). *Watson 017* is a 1.8-kg H5 chondrite that was found in over 100 pieces with two main masses. The meteorite is moderately shocked (S3) and has moderate alteration (W3).

2.2 *Powder X-ray Diffraction*

Mineralogical characterization of meteorites focused on alteration products within networks of pores and fractures, which would be accessible to microorganisms endemic to the Nullarbor Plain. An off-white precipitate commonly develops within these fractures, infilling them as veins that can be up to several hundreds of μm in thickness. The mineralogical composition of vein samples from three meteorites, Ooldea 002, Watson 015, and Ooldea 007, was determined using powder X-ray Diffraction (XRD), which required breaking the meteorites along existing planes of weakness to expose their interior surfaces. Vein material was mechanically extracted from meteorites, homogenized in an agate mortar and pestle under anhydrous ethanol, and dried in a fume hood. Samples were stored under ambient temperatures and relative humidities typical for Melbourne, Australia.

Mineral identification and semi-quantitative phase analysis were carried out in the Monash X-ray Platform using a Bruker D8 Advance X-Ray Diffractometer. Patterns were collected using a Cu X-ray tube (operated at 40 kV and 40 mA) over a 2θ range of 3 – 80° with a step size of 0.02°/step and a dwell time of 3 s/step. Due to their small size, samples were mounted as ethanol slurries onto a zero-background silicon plate for analysis. Mineral phases were identified using the Powder Diffraction File 2 (PDF-2) database available from the International Centre for Diffraction Data (ICDD) using the DIFFRAC^{plus} EVA v.2 software program (Bruker AXS). Estimates of phase abundances were obtained by Rietveld refinement (Bish and Howard, 1988; Hill and Howard, 1987; Rietveld, 1969) using the program Topas v.4.2 (Bruker AXS). The resulting Rietveld refinements provide a semi-quantitative measure of phase abundance owing to collection of patterns from thin films of hand-ground powder, mounted on a zero-background silicon plate. XRD patterns collected in this way exhibit the effects of non-ideal particle size statistics and preferred orientation on some phases, which can result in higher R_{wp} values (see Table 1 for results).

We used the abundance of quartz found within meteorite fractures to estimate the amount of terrestrial mineral contamination derived from Nullarbor regolith. This value can be used to estimate contamination because quartz is not an abundant primary phase in chondritic meteorites, and thus must be terrestrial in origin (Hezel et al., 2006). The abundances of all mineral phases found in both the regolith and meteorite samples were scaled, based on the amount of quartz in the sample, to estimate the amount of contamination in each sample. These estimations should only be considered rough guidelines (see Table 1 for results).

2.3 Stable and Radiogenic Isotope Geochemistry

Samples of vein material from three meteorites (Ooldea 002, Ooldea 007, Watson 015) and three samples of Nullarbor Limestone were analyzed for their ^{14}C concentrations using the Single Stage Accelerator Mass Spectrometer (SSAMS) at the Australian National University (ANU) (Fallon et al., 2010). Ooldea 002 failed to produce a result. Stable carbon isotopic data were collected from the same six samples by Isotope Ratio Mass Spectrometry (IRMS) at Monash University (MU). The δ^{13}C compositions are given relative to Vienna Pee Dee Belemnite

(VPDB). These techniques were used to determine the origin of the carbonate in the meteorite (i.e., Karst limestone vs. meteorite weathering), and assess the influence of contamination.

2.4 *Water Sorption Isotherms*

Water sorption isotherm experiments were carried out in the Department of Materials Engineering at MU using a gravimetric CISORP Water Sorption Analyzer (manufactured by CI Electronics; methods modified from Morgan et al. (2015)). Samples were exposed to ambient pressure at a constant temperature of 20°C, which was chosen for overlap between equatorial to southern mid-latitude summer temperatures on Mars (~ -23.2 – 26.9°C (McEwen et al., 2011)) and ambient conditions in the Nullarbor Desert (-4.5 – 48.7°C; measured from Cook weather station, SA, #018110, (Years 1920-2010), Bureau of Meteorology)). A diurnal cycle of relative humidity (RH) was simulated by increasing RH from 10 to 90% and then allowing it return to 10% RH (in 10% increments). Samples were allowed to equilibrate with atmospheric RH at each step before the instrument automatically began the next humidity increment. Scales were calibrated to 20°C prior to commencement of the experiment and each of the samples analyzed weighed approximately 100 mg.

2.5 *Scanning Electron Microscopy*

Biological samples for SEM were collected aseptically and field-fixed with filter-sterilized (0.1 μm) solution of 0.1%$_{(aq)}$ glutaraldehyde. Samples were then dehydrated using a traditional graded ethanol series (50%, 70%, 90% and 100% x3) and critical point dried using a Bal-Tec CPD 030. Back Scattered Electron (BSE) and Secondary Electron Images (SEI) were collected from Pt-coated samples using a JEOL 7001F FEG-SEM at the Monash Centre for Electron Microscopy.

The microscope was operated in BSE, SEI and Energy Dispersive X-ray Spectroscopy (EDS) modes using varying accelerating voltages, ranging from 1–15 kV, with a working distance of 10 mm.

3. Results

3.1 Stable and Radiogenic Isotopes

Nullarbor Limestone samples (n=3) gave ^{14}C-depleted F_m (Fraction Modern) values between 0.0015 and 0.0034 and $\delta^{13}C$ values between -7.20 and -6.09 ‰, (Figure 2). Two meteorite vein samples, identified as carbonate-bearing, gave much greater F_m values of 0.8458 ± 0.25 and 0.3967 ± 0.65 that correspond to calibrated ^{14}C ages of 7490 ± 140 cal BP (Ooldea 007) and 1410 ± 25 cal BP (Watson 015). The meteorite veins gave $\delta^{13}C$ values of -0.70 ‰ (Ooldea 007) and 3.60 ‰ (Watson 015). No stable or radiogenic isotope results could be obtained for the Ooldea 002 vein sample because of its small size and relatively low carbonate content (Table 1).

3.2 Mineralogy and Sorption Behavior of Vein Material

Ordinary chondritic meteorites contain primarily olivine [$(Mg,Fe)_2SiO_4$], low-Ca pyroxene [$(Mg,Fe)SiO_3$], high-Ca pyroxene [$Ca(Mg,Fe)Si_2O_9$], plagioclase [$(Na,Ca)(Al,Si)_4O_8$], apatite [$Ca_5(PO_4)_3(F,Cl,OH)$], troilite [FeS], and taenite and kamacite [FeNi] alloys. Weathering products found in the fractures of our samples were found to be predominantly Mg-calcite [$(Ca,Mg)CO_3$] and gypsum [$CaSO_4 \cdot 2H_2O$], with minor goethite [α-FeO(OH)] and smectites. Aeolian quartz [SiO_2] and orthoclase [$KAlSi_3O_8$] were found in some fractures (Table 1). Because quartz is not found in ordinary chondrites, its abundance in each meteorite was used to estimate the relative amount of contamination (as a percentage by weight) introduced from the

Nullarbor Plain (Table 1). This also provides a relative measure of the extent to which contamination by Nullarbor sediment might have provided a mechanism for ingress of terrestrial microorganisms; as microbes may either be attached to detritus or by themselves, both resulting in penetration along meteorite fractures.

Water sorption analyses indicate that vein material extracted from meteorites can gain up to 3.0 % of its mass in sorbed H_2O as humidity increases (Figure 3). The hysteresis observed in desorption isotherms indicates that these admixtures of hygroscopic minerals tend to retain more H_2O at a given RH than was initially sorbed. Desorption curves cross the paths of adsorption curves for all samples, resulting in a negative mass change at low RH.

Light microscopy and SEM imaging provides further information about the spatial distribution of hygroscopic alteration phases relative to fractures and pores in meteorites. Figures 4A and B show that Fe^0, Fe^{2+} and S^{2-} in FeNi alloy and troilite near the cores of weathered meteorites have been oxidized to Fe^{3+}- and SO_4^{2-}-bearing minerals, including jarosite [$KFe_3(SO_4)_2(OH)_6$] (Figure 5). Contrastingly, near the exterior of each meteorite, these primary minerals are typically less weathered. Large cracks, caused by the crystallization pressure of hydrated sulfate minerals, can be seen to increase the permeability of the remainder of the meteorite with respect to this corrosion cavity (Figure 5).

3.3 Mineral–Microbe Associations

In addition to fracture porosity, extensively weathered meteorites possess 50 – 1000 µm diameter voids that are produced by corrosive removal of FeNi alloys and/or troilite. These are commonly found at depths > 1–3 mm beneath their fusion crusts. Like the fracture networks, these corrosion cavities are also coated with hygroscopic alteration minerals, and biofilms line the interiors of some, but not all voids (Figures 6, 7). Indeed, we found a surprisingly high level of microbial colonization and diversity in meteorite fractures: 10–20 µm thick biofilms, inhabited by a range of morphologically distinct terrestrial microorganisms, commonly cover extensive regions of Mg-calcite veins (Figure 6A). Microbial community composition/structure of Nullarbor ordinary chondrites is described in detail in (Tait et al., 2017). Additionally, in the course of our sampling we glutaraldehyde-fixed cells in the process of — or having recently completed — binary cell division (e.g., diplobacilli and diplococci, Figures 6A and 7B,C). The surface of Mg-calcite vein material is commonly obscured by a layer of extracellular polymeric substances (EPS) (Figure 6), which are commonly generated by microorganisms and consist predominantly of polysaccharides and proteins. The process of chemical fixation and dehydration, combined with exposure to vacuum during electron microscopy work, results in a volume change to the EPS that causes the residual material to appear deflated, torn, and filamentous (Dohnalkova et al., 2011). The EPS has peeled back in places to reveal strongly degraded and pitted scalenohedral calcite (Figure 6B,C). Also observed in the Mg-calcite/gypsum veins were microbes that had been covered by a nanocrystalline precipitate, but this feature could also be produced by dehydration of gram-negative cell envelopes (Figure 6B). Figure 8 in particular shows a close spatial relationship between biofilms (i.e., cells and EPS) and corroded high-Ca pyroxene.

4. Discussion

4.1 Fingerprinting the Origin of Carbonate Veins

The calibrated ^{14}C ages for vein material indicate the minimum amount of time that meteorites have been on the Nullarbor Plain. Based on these values, Watson 015 and Ooldea 007 have been interacting with Earth's biosphere for a minimum of 1410 ± 25 to 7490 ± 140 years, respectively. These meteorites were selected for study owing to the outward appearance of cracking (which would indicate the presence of interior vein material). The weathering grade assigned to both meteorites is W4 (on a scale from W1 – W6 (Wlotzka, 1993)). Weathering grade is commonly used as a proxy for the duration of time a meteorite spent on Earth's surface; but, in the case of the Nullarbor, weathering rates are thought to be more variable owing to climatic change in the region over time (Bland et al., 2000; Jull et al., 2010), thus a residency age based on weathering grade alone is not applicable.

Values of $F_m > 1$ uniquely identify uptake of modern atmospheric carbon into minerals. Additionally, stable carbon isotopic fractionation factors can be used to predict the range of $\delta^{13}C$ values expected for a mineral forming in isotopic equilibrium with atmospheric CO_2. Calculated values of $\delta^{13}C_{calcite}$ for calcite precipitation in equilibrium with atmospheric CO_2 were obtained using a $\delta^{13}C_{CO2}$ value of –8.31‰. This value was assumed for the modern atmosphere in the Nullarbor Desert based on data from Kermadec Island (Keeling et al., 2005). The stable carbon isotopic fractionation factor, $\Delta^{13}C_{calcite\text{-}CO2(g)}$, of Deines and others (1974) was used for this calculation over the range of temperatures relevant to the Nullarbor Plain (see above). The resulting values of $\delta^{13}C_{calcite}$ were used to designate a field for carbonate precipitation from the modern atmosphere in Figure 2.

The depleted ^{14}C signature of Nullarbor Limestone is consistent with their identification as Eocene in age (15–25 Ma). Contrastingly, the meteorite vein material from Watson 015 gives $\delta^{13}C$ and F_m values consistent with equilibrium precipitation of calcite from the modern (or recent) atmosphere (Figure 2). Thus, the Mg-calcite from meteorite fractures likely formed via reaction between carbonic acid in rainwater with primary Ca- and Mg-bearing minerals such as plagioclase and clinopyroxene that exist within the meteorites. The $\delta^{13}C$ and F_m values for Ooldea 007 plot outside the modern equilibrium field. We interpret this as a mixing curve resulting from contamination of the meteorite samples by Nullarbor Limestone. This would indicate most of the carbonate in this sample is derived from weathering of the meteorites by reaction with Earth's atmosphere, and a smaller fraction from externally remobilized limestone. Thus, carbonate alteration, which is hygroscopic and can preserve textural, isotopic and fossil biosignatures, would still form by interaction of ordinary chondrites with a CO_2-bearing atmosphere, such as that on Mars, in the absence of limestone.

4.2 Hygroscopic Vein Minerals and Water Cycling

XRD analysis shows that the vein material contains four hygroscopic minerals: gypsum, a smectite, goethite and Mg-calcite. Mg-carbonate minerals have been found previously within veins in meteorites collected from Antarctica (Jull et al., 1988; Long et al., 1989; Velbel, 1988). It is an important observation that carbonate alteration of meteorites can occur under Antarctic temperature conditions because these more closely reflect the climate on Mars. Each of the hygroscopic phases found in the Nullarbor meteorites exhibits distinct H_2O sorption behavior; however, we have treated them together because they form a hygroscopic admixture within the veins.

As with the surface of Mars (Savijärvi, 1995), atmospheric RH on the Nullarbor Plain decreases with increasing daytime temperature and increases during the cooler nights. Application of these conditions to the hygroscopic vein material consistently results in a negative mass change in which the desorption isotherm crosses the sorption isotherm at the lowest RH values. This mass loss most likely results from the loss of crystallographic H_2O from gypsum during a partial phase transition to bassanite [$CaSO_4 \cdot {\sim}0.5H_2O$] or anhydrite [$CaSO_4$]. Although neither bassanite nor anhydrite was found during XRD analysis, three possibilities exist that could account for this disparity: (1) Bassanite and/or anhydrite did form at low RH, but quickly rehydrated to produce gypsum in Melbourne's more humid atmosphere prior to analysis, (2) the abundances of the lower hydrates of Ca-sulfate were below the detection limits of our XRD under the operating conditions we used, or (3) anhydrate/bassanite never formed, because the interiors of the meteorites always had a moderate to high RH.

The samples of vein material gained 1.0 – 3.0 % of their mass in H_2O at a peak RH value of 90 %. Furthermore, under moderate RH conditions the vein material retained as much as 0.5 wt.% of sorbed H_2O under conditions of declining RH. The variation in the sorption behavior of meteorite vein material (Figure 3) likely results from differences in the relative proportions of hygroscopic minerals (Table 1). Vein material that forms within meteorites thus attracts atmospheric H_2O vapor to its surface and retains it under most RH conditions. This would serve to buffer atmospheric RH, leading to development of a 'humidity oasis' within the fracture systems in meteorites (i.e., humidity is higher inside meteorites as external humidity drops, providing a source of water for further weathering and support of microbes).

4.3 Generation of Veins and Porosity within Meteorites

The creation of veins and porosity in the meteorites is controlled by the removal of FeNi and FeS from the system, causing reaction-driven cracking as the new Fe-oxides can have up to a three fold increase in volume from their original starting materials, and resulting in the generation of fracture networks. (Ashley and Velbel, 2000; Bland et al., 2006). This progressive weathering feature probably reflects: (1) uptake of water by capillary action followed by (2) rapid evaporation of water from the exterior during the hot and arid daytime. The greater extent of weathering deep within the meteorites relative to their surfaces (Figure 4) supports the idea that weathering is driven by capillary transport of water. During the day adsorbed water to mineral surfaces around the exterior of the meteorite is boiled off, where as water vapor internally is trapped leading to a heterogeneous weathering profile. Oxidative dissolution of FeNi alloy, troilite and silicate minerals would then increase porosity by transfer of mass into fractures (to form the veins), which are widened and extended by the crystallization pressure of hydrous weathering products. An example can be seen in Figure 5, where FeNi and FeS have been oxidized and mass has been removed from the system along cracks; Fe-oxyhydroxides and jarosite remain. Jarosite, which forms in low pH conditions, is known to have the capacity to preserve molecular biosignatures (Preston et al., 2011).

4.4 Colonization of Veins and Pore Networks by Contaminant Microorganisms

Terrestrial contaminant microorganisms have colonized some but not all of the voids left by the weathering of FeNi alloys and troilite; they are also found on hygroscopic vein material. This variability in habitation likely relates to permeability changes during progressive weathering whereby not all cavities would be continuously accessible to environmental microorganisms (i.e., alteration products may fill existing cavities, or reaction-driven cracking results in opening up new areas of the meteorite).

Figure 8 shows a close spatial relationship between biofilms and corroded high-Ca pyroxene, which is texturally similar to silicate dissolution features observed by Gibson et al. (1983), implying that, as in other environments (Jones, 2010), microbes promote weathering to generate secondary minerals that favor environmental regulation. Coupled weathering of troilite, plagioclase, high-Ca pyroxene and olivine (driven either abiotically or by acidophilic bacteria) provides a mechanism by which SO_4^{2-}, Fe^{3+}, Ca^{2+} Mg^{2+} and K^+ are mobilized for precipitation of goethite, gypsum, and jarosite beneath biofilms in corrosion cavities (Figures 7). These minerals indicate a low-pH microenvironment, which is favored by some Fe- and S-oxidizing bacteria, and thus may preserve stable C, O, and S isotope signatures that are indicative of metabolism (e.g., Figure 1). Other evidence of habitation, detectable even in the absence of cells, comes in the form of pitting on grains of high-Ca pyroxene and scalenohedral Mg-calcite. Identical textures have been observed previously in calcite and are known to reflect acid dissolution of the mineral by microorganisms to regulate pH (Steinhauer et al., 2010). There remains a possibility that these dissolution textures in the silicates and carbonates textures are similar to those found in abiotic weathering of martian SNC meteorites in Antarctica (Velbel, 2016), perhaps a product of dissolved carbonic acid in rainwater. However, unlike the Antarctic SNC meteorites this etching texture does not show up in thin-section analysis, which would indicate wide-spread abiotic alteration. What is observed is a localized etching (i.e., dissolution textures), in tight proximity to the biofilms. Additionally, these dissolution textures have yet to be observed in the absence of microbes, within our meteorite samples. This is hard to explain with specimen wide abiotic processes. The strong spatial relationship to films, localized frequency, and textures identical to other biotic examples (Gibson et al., 1983; Steinhauer et al., 2010), make us confident this dissolution is biogenic in nature. The EPS covering grains of scalenohedral calcite in our samples form drapes of a smooth, semi-transparent (transparent to the electron beam at ~15 kV) material. It peels back in places to reveal filamentous structures within the fixed and dehydrated EPS that remain attached to underlying cells, similar to the filamentous behavior of EPS dehydration described by Dohnalkova et al. (2011). The EPS appears to begin peeling from the apices of scalenohedral calcite grains, which results in isolated patches of EPS left draped over calcite surfaces (Figure 2 C). The EPS covering the high-Ca pyroxene (Figure 8) has a different morphology than that coating calcite grains, in that it has a mottled surface texture rather than being dominated by filaments, and some cells within the EPS are flattened. The composition of thin layers of EPS was impossible to determine with EDS because the electron beam interacts with both the EPS and the underlying mineral substrate; however, it is most likely composed of polysaccharides (Donlan, 2002). One possible function of EPS in chondritic meteorites, other than nutrient cycling, is as a store for water. Retention and adsorption of water vapor by EPS is a valuable property that has previously been reported to be used by hypolithic cyanobacteria in the Atacama Desert (Azua-Bustos et al., 2011). Just as alteration minerals in chondritic meteorites adsorb water to their surfaces during periods of high RH, EPS could also help the microbial community retain water in the arid Nullarbor Plain.

Carbonate minerals, such as the Mg-calcite in veins, can form in circumneutral to alkaline microenvironments, even under bulk acidic conditions (Fernández-Remolar et al., 2012). Also, carbonate minerals are known to preserve organic biomolecules (e.g., phenols associated with lignin) for millions of years in stalagmites from the Nullarbor Plain (Blyth et al., 2010), and by extension, could offer the same preservation potential within meteorites. Of further relevance to biomarker preservation is the observation that the surfaces of some microbes in the Mg-calcite/gypsum veins appear to be covered by a nanocrystalline precipitate (Figure 6B). Such coatings are thought to play an important role in fossilization and biopreservation of microbial cells within terrestrial settings (Williams et al., 2015) and may be relevant to the search for life on Mars and other planets. However, this feature is ambiguous and could also result from dehydration of gram-negative cell envelopes, which are relatively thin compared to those of gram-positive cells, during the fixation process.

Chondritic meteorites are sterile when they fall to planetary surfaces and weather to produce the ‘trinity’ of biopreservation minerals: (1) carbonates for isotopic, organic molecular and fossil preservation (Blyth et al., 2010; Power et al., 2011), (2) smectites for preservation of organic molecules (Gaines et al., 2005), and (3) sulfates for isotopic, organic and fossil preservation (Benison and Karmanocky, 2014; Szynkiewicz et al., 2012). Thus, in addition to lending themselves to habitation (contamination) by environmental microorganisms under Mars relevant conditions, such as those in the Nullarbor Plain, chondrites also provide ideal conditions to preserve evidence of past life.

4.5 Practicality of Finding Meteorites on Mars

Rover missions have identified more than 23 iron and/or stony-iron meteorites on the surface of Mars (Ashley et al., 2011b), including some achondrites (Schröder et al., 2016). As of yet there are no confirmed chondritic meteorites that have been found on Mars, although candidates have been proposed, based on weathering profiles (Ashley et al., 2015). This low chondritic population could be related to survival of stony meteorites requiring shallow atmospheric entry (~10°–30°) and masses <100 kg (Chappelow and Sharpton, 2006). However, cratering records indicate that the surface of Mars receives 1.7 – 2.8 times more meteoritic material than that of Earth (JeongAhn and Malhotra, 2015; Shoemaker, 1977). Furthermore, the mean residence time for meteorites during the martian wet period which occurred 2–3 b.y.a. has been estimated to be on the order of 10^9 years (Bland and Smith, 2000). This is comparable to the slowest estimations for current Amazonian weathering rates of stony meteorites on Mars (Schröder et al., 2016), which also estimates $>10^9$ year long residencies. Consequently, chondritic meteorites should be plentiful on the surface of Mars, particularly given the absence of a planet wide resurfacing mechanism such as tectonics. Thus, it could be that no chondritic meteorites have been reported on Mars owing to difficulties with visual identification and their low mission priority (Ashley, 2015).

The most distinctive feature of meteorites, which provides the best criterion for finding them on Mars, is their fusion crusts. The fusion crust of a chondritic meteorite is a smooth, full or partial covering of quenched silicate melt with thumb-sized divots, called regmaglypts, and is the product of melting and ablation during atmospheric entry (Thaisen and Taylor, 2010). However, chondritic meteorites on Earth — given enough time — lose their distinctive fusion crusts to oxidative weathering, revealing fresh material underneath. It is unlikely that the fusion crust would survive the eons of time some meteorites may have been resident on the surface; other textures should be relied on for identification (see below).

Given similar oxidative weathering pathways on Mars and Earth, finding reddish-brown chondritic meteorites on the reddish-brown surface of Mars may be difficult. There are three additional features, in addition to fusion crusts, that may facilitate identification of chondritic meteorites on Mars. (1) Mg-carbonate efflorescences may protrude from cracks in the surfaces of chondritic meteorites. This is a common feature of meteorites recovered from Antarctica, a better analog to Mars than the Nullarbor Plain. Most of these efflorescences form after collection, a consequence of being stored in warmer atmospheres with higher relative humidities (Jull et al., 1988; Velbel, 1988). Given the complex history of the martian water cycle and the impact of Milankovitch cycles, periods of increased water vapor pressures in the martian atmosphere could generate similar efflorescences, and as a consequence also record information about atmospheric evolution on Mars (Ashley et al., 2011b). Such distinctive surface features may be present on martian chondrites, making visual identification easier. (2) The chondritic weathering profile is quite unique. As reduced iron phases oxidize, they create secondary weathering products with higher molecular volumes. This leads to the formation of cracks that cross cut the meteorite resulting in mass wasting of thin flakes of material from the meteorite. It is common on Earth to find flakes of chondritic material spread across a small area (e.g., < 1 m^2), resulting in tightly grouped paving around the main mass of a meteorite. This weathering pattern may be used to find meteorites on Mars as well as Earth (Ashley et al., 2015). (3) The prevailing wind on Mars has resulted in aeolian erosion of surface features and rocks, including preferential erosion of softer materials. This process could expose chondrules and grains of metals and sulfides beneath the fusion crusts of meteorites, which would be visibly different from textural features of surrounding rocks (Ashley et al., 2011b).

It is likely that meteorites may have fallen into shallow crater lakes only to be buried in further sediment. Indeed bomb-sags from volcanic eruptions have been found on Mars (Manga et al., 2012); under a past thicker atmosphere meteorites might create similar structures in wet sediment. Such outcrops could potentially show “fossil meteorites” similar to those found in Ordovician limestone in Sweden (Schmitz et al., 1996). Given the higher fluxes during the Hesperian/Amazonian transition than today (Carr and Head, 2010), outcrops of past lake beds may also be worth investigating for chondritic material.

Given the complex weathering histories of meteorites on Mars identifying them requires a systematic approach. It may be possible to develop a machine learning algorithm to search for these features, or create a citizen science website (e.g., *Moon Zoo, Planet Four, Stardust@Home etc.*) in order to leverage human pattern recognition on a large scale to search for meteorites on Mars, from a backlog of images. Once a list of candidate textures have been established from the backlog, these could be tested by the rovers when candidates present themselves in order to “ground truth” and develop a robust meteorite recognition program.

5. Implications

5.1 Robotic Investigation of Meteorites to Assess Merit of Sample Return

There are currently two active rovers on Mars: Mars Exploration Rover (MER) “Opportunity” and Mars Science Laboratory (MSL) “Curiosity”. More robotic missions are planned, which will lead to robotic and/or human return of martian material to Earth within the next few decades. Meteorites are already being discussed as possible sample return candidates for abiotic reasons (Ashley et al., 2011a)(e.g., meteorites could record lower atmospheric evolution within their weathering products, and include meteorite specimens that don't exist within Earth’s collections, etc.). However, the astrobiology argument put forward by this body of work has not yet been considered, and could add further argument to meteorite sample return from the surface of Mars. If chondrites are to be considered among the specimens selected on sample return missions, robotic exploration must first show that: (1) confirmed chondritic meteorites are present on Mars, (2) they have merit as past or present habitats for hypothetical microorganisms on Mars, and (3) meteorites are recoverable within the bounds of the engineering constraints placed on sample return missions.

The MER contains a suite of instruments aimed at exploring questions of habitability, including Pancam, Navcam, Mini-TES (Miniature Thermal Emission Spectrometer), APXS (Alpha Particle X-Ray Spectrometer), MB (Mossbauer Spectrometer), and MI (Microscopic Imager). All of these instruments have been employed in tandem for the identification of iron and stony-iron, and howardite–eucrite–diogenite (HED) meteorites on Mars (Ashley et al., 2011b; Schröder et al., 2016).

The Mastcam and ChemCam’s RMI (Remote Micro-Imager) on Curiosity have also been used in identifying iron meteorites at Gale Crater (Ashley, 2015). Curiosity also has the ability to vaporize rocks for chemical identification using ChemCam, which may be the easiest method to survey small candidate chondritic meteorites. Curiosity’s SAM (Sample Analysis at Mars), which contains a Gas Chromatograph Quadrupole Mass Spectrometer and a Tunable Laser

Spectrometer, could also be used to assess the habitability of meteorites. If a discovered meteorite has visible efflorescences (or is marked by cracks where sulfate and carbonate minerals may be hidden), drilling that material for analysis with the SAM instrument may reveal organic biomolecules produced by putative organisms preserved within alteration minerals inside the meteorite.

The CheMin instrument, which is an XRD/XRF on Curiosity, could be used (as we have done in our experiments using XRD) to identify chondritic meteorites and their secondary weathering products. However, there remain two operational difficulties to using this instrument with regards to meteorites: (1) if the meteorite is too small, the drill required for sampling may slip and (2) if the meteorite is too large, the "inside out" weathering profile and "humidity oasis" shown by our terrestrial investigations may result in the illusion of an un-weathered rock if only the surface can be sampled. If this weathering mechanism also happens on Mars, and the drill is too shallow, it may not access the weathered and thus habitable region of a large chondrite, providing a false negative.

The current generation of rovers has the capacity to establish the habitability potential of meteorites on Mars. Once this is established, their potential for sample return can be properly assessed with respect to other sample return priorities.

5.2 A Model for Microbial Colonization and Habitation of Chondrites on Earth and Mars

Our SEM results show that terrestrial microorganisms commonly colonize and inhabit ordinary chondrites from the Nullarbor Plain, Australia. This represents an important first step in establishing that chondritic materials on Mars and other planetary surfaces might also support putative microbial communities and provide a robust record of past or present mineral–microbe interactions. Follow up studies should investigate the longevity of preservation of organic biomolecules and stable isotopic biosignatures in ordinary chondrites.

Chondritic meteorites offer a combination of factors favoring microbial life in arid environments: (1) a mineralogical source of energy and nutrients, (2) provision of water, (3) shielding from UV light and ionizing radiation, (4) temperature moderation, (5) humidity regulation, and (6) accessible and chemically regulated microhabitats (cracks and voids). Basalt, which covers most of the surface of Mars, is deficient in all ways relative to meteorites, save for UV shielding, and has a broad range in stable sulfur isotope values (Figure 1; Farquhar et al. (2007)) that could potentially mask isotopic biosignatures.

We can extrapolate our terrestrial observations of microbial colonization and habitation of meteorites in the Nullarbor Plain to the surface of Mars (Figure 9). In this model, water vapor and molecular oxygen in the martian atmosphere plus or minus biogeochemical processes oxidize the FeNi alloys and sulfide minerals within a meteorite. This produces hygroscopic minerals such as Fe-oxyhydroxides, sulfates, carbonates and smectites. These in turn buffer the relative humidity inside the meteorite by adsorbing water vapor to mineral surfaces at night and releasing it during the warmer day. This humidity oasis enhances the weathering of primary phases, such as silicates and phosphates, releasing more cations for uptake by any potential biofilms. Microhabitats form over a range of pH conditions from acidic to circumneutral, enabling colonization by a diversity of hypothetical microorganisms. Putative martian microbes may continue to ingress the meteorite via the regolith, or transient water flow. Should these putative martian microorganisms be chemotrophic and adapted to xerophilic conditions, they could survive within the relatively humid environment inside meteorites. Thus, meteorites have potential to act as a refuge long enough for the microbes to alter the geochemistry of the substrate in a recognizable manner before ultimately succumbing to the hostility of the martian surface.

The most primitive life forms on Earth are believed to be chemolithotrophic. If a martian biosphere exists, or existed, it stands to reason that it would also be chemolithotrophic, but perhaps located deep underground where it is still warm (Michalski et al., 2013). Today, oxidative weathering would be slower, and sorption of water of lesser magnitude, on Mars than on the Nullarbor Plain due to the lower partial pressures of water vapor and molecular oxygen (Maltagliati et al., 2011). Due to the long residence time of meteorites on Mars, estimated to be on the order of 10^9 years (Bland and Smith, 2000), some meteorites presently on the surface of Mars could have sampled a putative surface biosphere during the Amazonian/Hesperian transition at ~3 Ga (Carr and Head, 2010). Meteorites found on older land surfaces (i.e., the martian highlands) may provide more scientific value than those on a younger surface given the upper age limit for their residency. Furthermore, transient surface brines, such as those suggested to be responsible for the recurring slope lineae within craters (Ojha et al., 2015), could vector currently living microorganisms from a near-surface biosphere into the refugia of more recently fallen meteorites, making meteorites prime targets for future sample return missions to Mars.

6. Conclusions

Our study has shown that stony meteorites on Earth contain a ‘trinity’ of biopreservation minerals (e.g., smectites, sulfates, and carbonates) that are known to preserve organics and stable isotopic biosignatures for millions of years. We have also shown that the hygroscopic alteration minerals in meteorites adsorb water vapor from the atmosphere to their crystal surfaces and that microorganisms appear to colonize these minerals preferentially, suggesting they are using this hygroscopy to obtain water in the arid Nullarbor Plain. These microorganisms were also found to be dissolving primary silicate and secondary carbonate minerals within the meteorites, showing that biota contribute to the alteration of meteorites. Furthermore, indications of microbially mediated alteration of meteorites is commonly preserved and detectable.. Endolithic microbes are known to colonize rocks and soils at Earth's surface; thus, it is unsurprising that terrestrial microorganisms commonly colonize stony meteorites. Unlike terrestrial rocks, meteorites have unique value as substrates for microbial growth: as remnants of the primordial solar system, they are used extensively as isotopic standards (e.g., VCDT) and geochemical baselines (e.g., CI normalization). The relatively homogeneous composition of meteorites makes them indispensable to understanding geological and environmental processes. This 'standard'-like property of meteorites makes them ideal 'witness plates' for microbially mediated alteration. Consequently, meteorites on Mars could become an invaluable resource for astrobiological exploration, particularly since existing rover missions are capable of sampling and analyzing meteorites for signs of some biomarkers that we have identified. Meteorite residence times can date back to the Hesperian when Mars was warm and wet, potentially recording a snapshot of a putative martian biosphere from that time. Meteorites represent a readily accessible habitat that is made of a solar-system-wide standard material; thus, they can be used to reduce ambiguity in detecting signs of life on the surface of Mars.

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Author Contributions

This project was conceived, designed and executed by A.W.T. with input from S.A.W. and A.G.T. A.W.T led the writing of the paper and construction of figures, under the supervision and S.A.W and A.G.T. Significant feedback with regards to methodology, techniques and interpretation was given by S.A.W, A.G.T, E.J.G and G.S. Radiogenic isotope data were collected by S.F. All authors contributed to the discussion, interpretation and writing.

Table 1 | Abundances of minerals in vein material by Rietveld refinement.

Official Name	Ooldea 002	Watson 015	Ooldea 007	Ooldea Regolith
Type	L5	H4	H3	-
Weathering grade	W4	W4	W4	-
Mineral	Ooldea 002 (wt.%)	Watson 015 (wt.%)	Ooldea 007 (wt.%)	Ooldea Regolith (wt.%)
kaolinite	5.7		8.6	17.4
illite	33.4			11.9
magnesite	0.5			
orthoclase	0.6		0.9	10.6
oligoclase	5.8		2.1	5.7
goethite	2.5	3.8	1.5	0.5
gypsum	0.6	24.6	6.1	
calcite	38.0	60.0	52.4	0.8
quartz	12.8	8.9	28.4	53.2
high-Ca pyroxene		2.7		
totals	100.0	100.0	100.0	100.0
*Contamination (wt.%)**	18.9	16.7	53.4	-
R_{wp} (%)	11.4	11.7	11.0	16.7

* Contamination is based on the quartz content in the vein material, scaled to the Ooldea regolith (see methods).

Figure Captions:

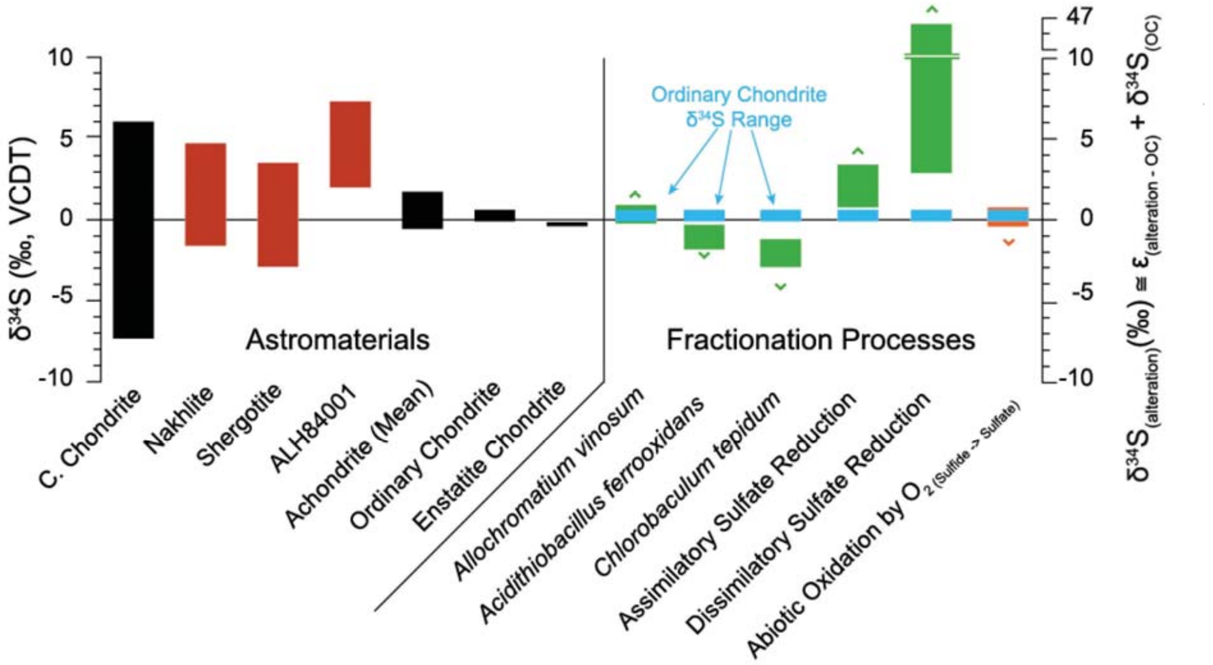

Figure 1 | Suitability of astromaterials for detection of biological $\delta^{34}S$ signatures. The left hand side shows $\delta^{34}S$ ranges of sulfur-bearing phases in astromaterials. The right hand side plots predicted $\delta^{34}S$ ranges of secondary minerals (alteration) in ordinary chondrites (OC) affected by some common sulfur oxidising/reducing organisms and abiotic processes. Isotopic fractionation by terrestrial organisms far exceeds the range of $\delta^{34}S$ values found in ordinary (blue) and enstatite chondrites, but is largely within the range found in SNC meteorites. See (Farquhar et al., 2007; Greenwood et al., 1997) and references therein for astromaterial values and (Balci et al., 2007; Brabec et al., 2012; Canfield, 2001; Pisapia et al., 2007) for values pertaining to fractionation processes.

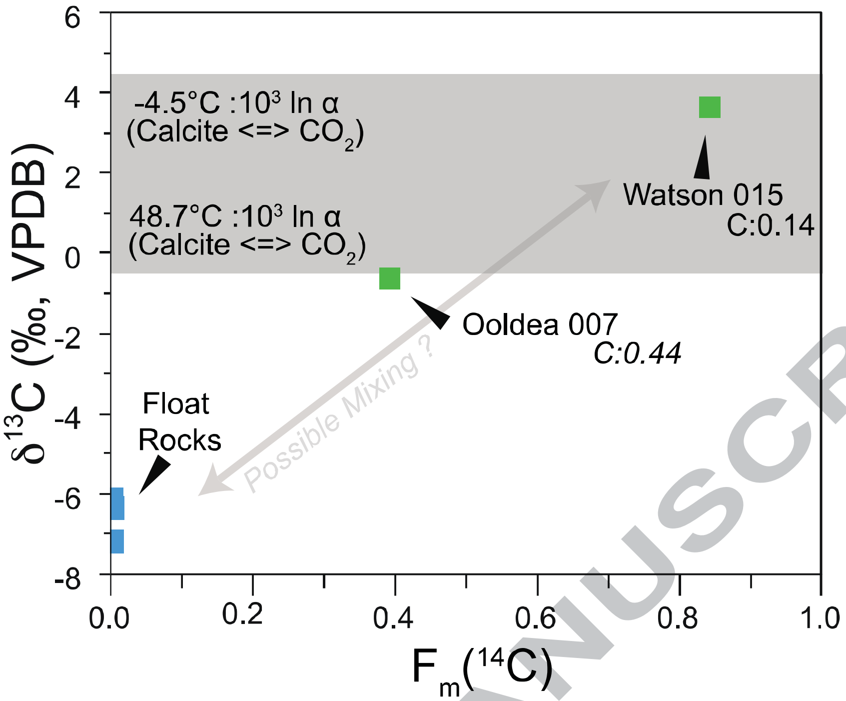

Figure 2 | Vein-carbonate origin and potential contamination. Values of δ^{13}C versus F_m (^{14}C) are plotted here for meteorite vein material and Nullarbor limestone. δ^{13}C values for calcite precipitating in equilibrium with atmospheric CO_2 gas (grey box), are calculated over the typical range of temperatures recorded in the Nullarbor using the fractionation factors of Deines et al. (1974). The estimated proportion of contamination (c), from windblown dust and limestone, is given for each meteorite analysed.

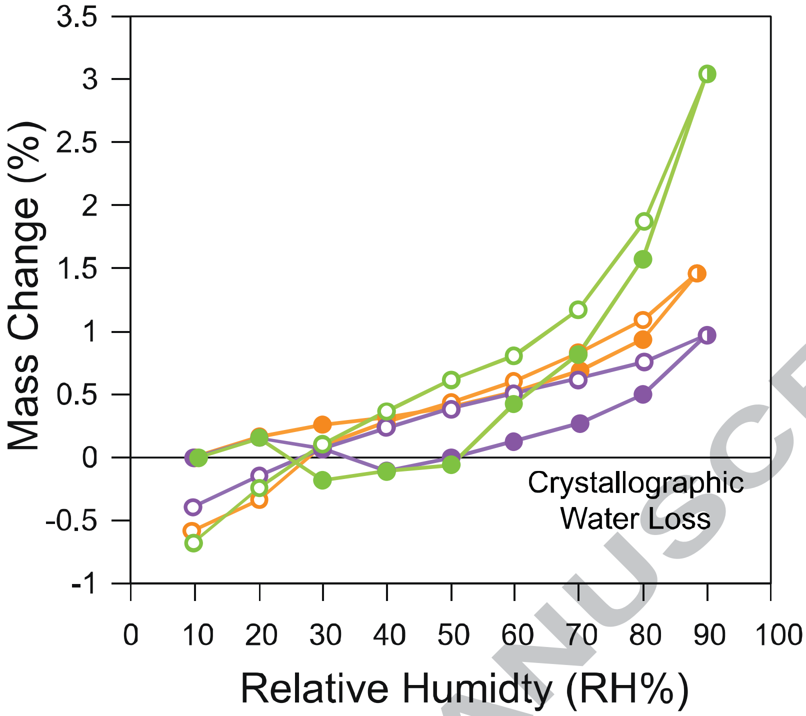

Figure 3 | Adsorption isotherms for vein material. Green = Ooldea 002 (L5, W4), orange = Watson 015 (H4, W4), purple = Ooldea 007 (H3, W4). Filled circles denote sorption steps and empty circles denote desorption.

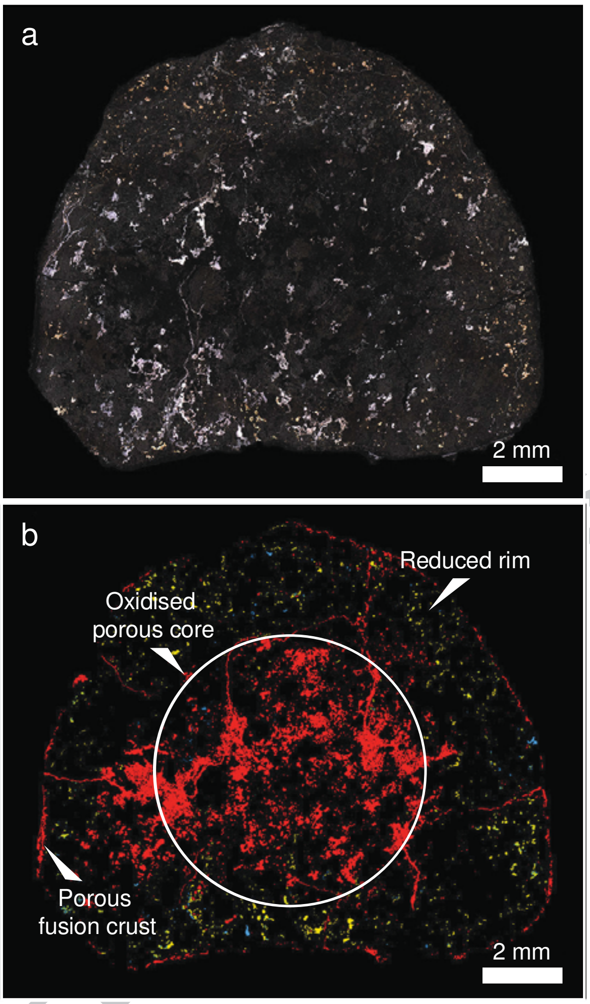

Figure 4 | Humidity oasis. Original and processed reflected light images of the Ooldea 009 (H6, S3, W3) chondrite. Phases and voids were determined by scaling the LUT (Look up table), and were then artificially colored. **(a)** Original reflected light image. **(b)** Processed image shows void spaces (red) in the centre of Ooldea 009. The reduced rim contains unoxidised troilite (yellow) and FeNi alloy (blue).

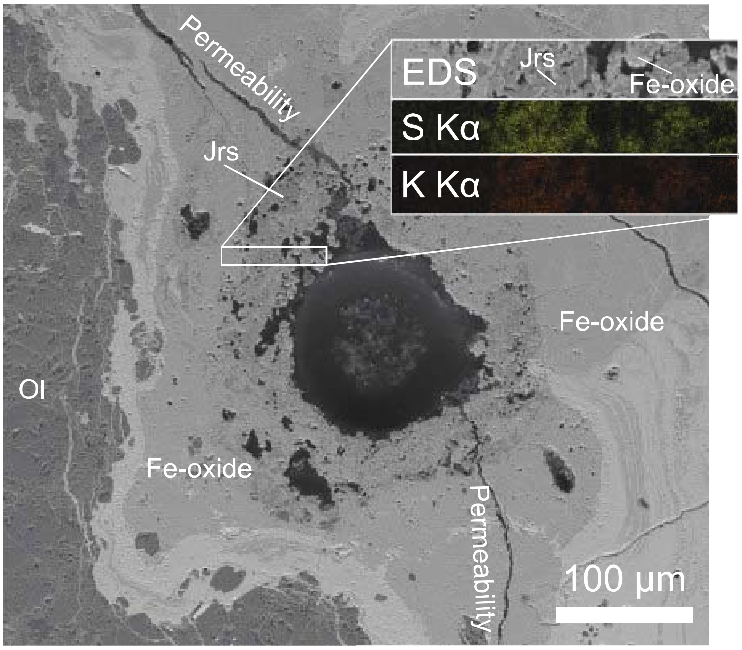

Figure 5 | Jarosite in corrosion cavity. Backscattered Electron (BSE) image and S and K Kα Energy Dispersive Spectroscopy (EDS) maps (inset) of a corrosion cavity inside the Ooldea 005 ordinary chondrite. FeNi and FeS have been oxidised and removed from the system along cracks, leaving behind Fe-oxyhydroxides and jarosite (Jrs).

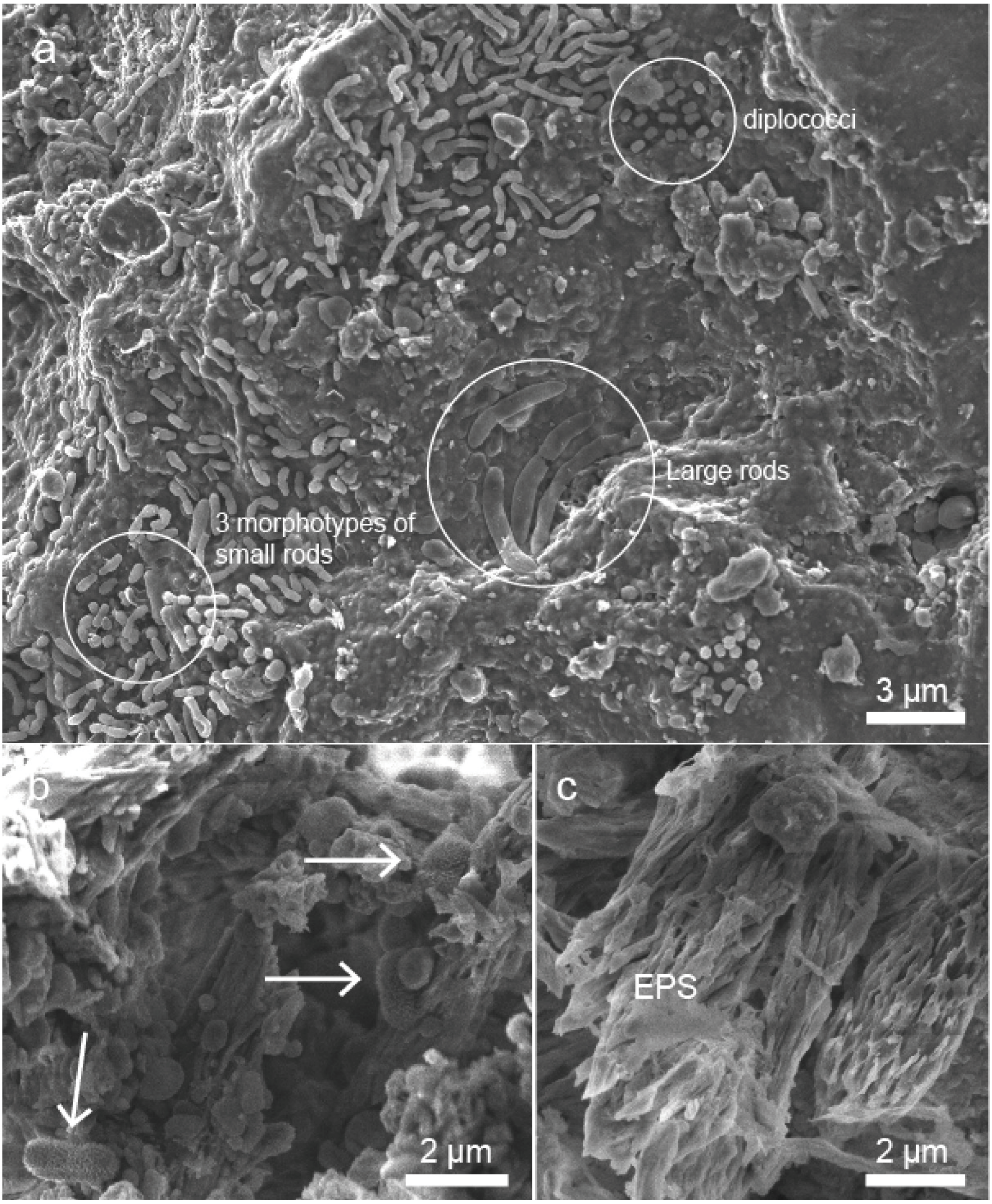

Figure 6 | Chasmoendolithic biofilm and calcite etching. FEG-SEM micrographs of **(a)** carbonate vein material in Ooldea 007 hosting a bacterial biofilm contaminant, composed of several, morphologically distinct prokaryotes (highlighted in circles). **(b)** At higher magnification, we see bacteria (arrows) with a fuzzy surface, this is either a mineral precipitate or folded gram-negative cell envelopes. The appearance of pitted and etched scalenohedral calcite suggests that the bacteria contaminants are promoting the dissolution of carbonate. **(c)** Heavily etched scalenohedral calcite was particularly visible where the sample dehydration process had peeled the exopolymer (EPS) off of the surface, e.g., Watson 017.

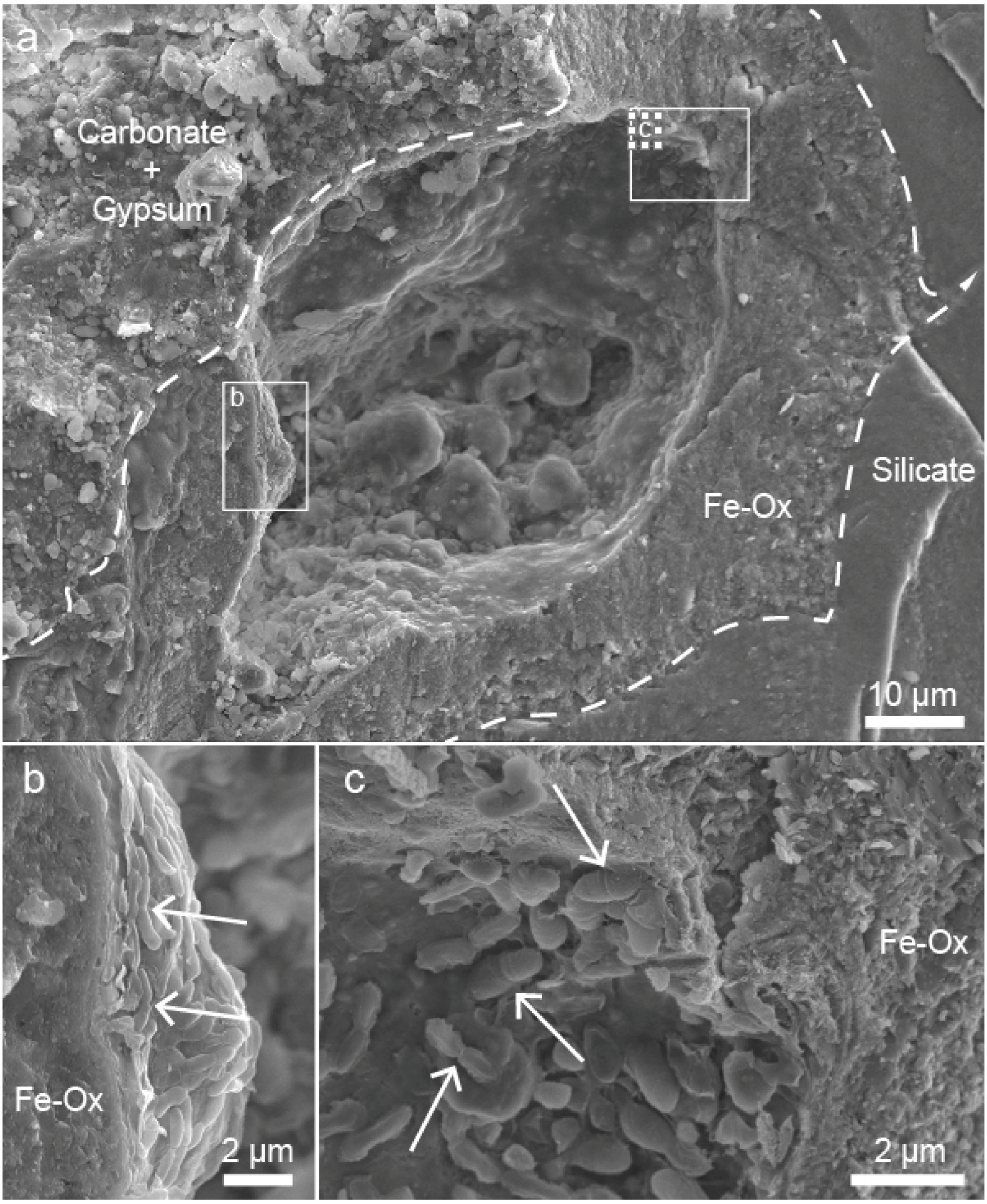

Figure 7 | Cryptoendolithic biofilm. Continued growth of biofilm (within Ooldea 007) has resulted in the formation of corrosion cavities. Note the 'soft texture' of the inside of the corrosion pit **(a)**, which is consistent with the presence of exopolymer. Energy dispersive spectroscopy demonstrated the presence of iron oxide proximal to a carbonate vein, which may have aided corrosion. Representative high magnification images (boxes 'b' and 'c') reveal the presence of bacteria undergoing cell division (arrows) lining the corrosion pit.

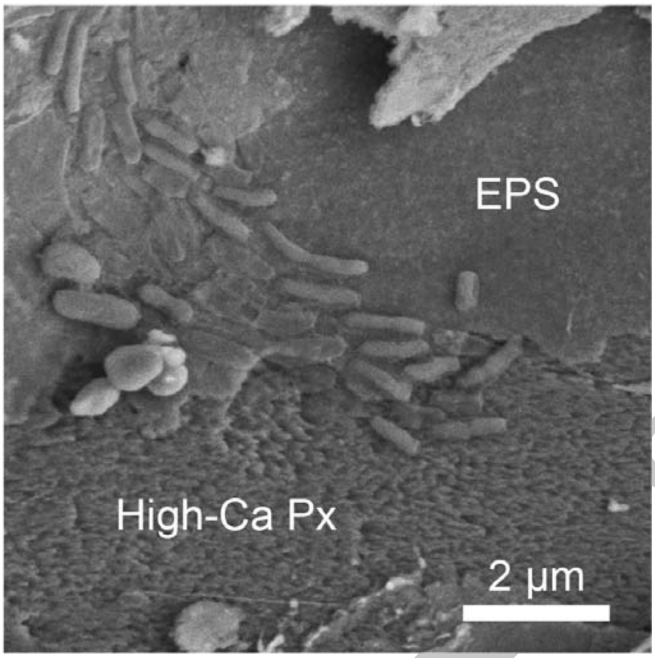

Figure 8 | Biologically-mediated silicate etching. FEG-SEM micrograph of Watson 017 highlighting the occurrence of high-Ca pyroxene overlain by EPS and bacteria, possessing a ‘sawtooth’ dissolution texture (Gibson et al., 1983) demonstrating that bacterial biofilms are also linked to silicate weathering.

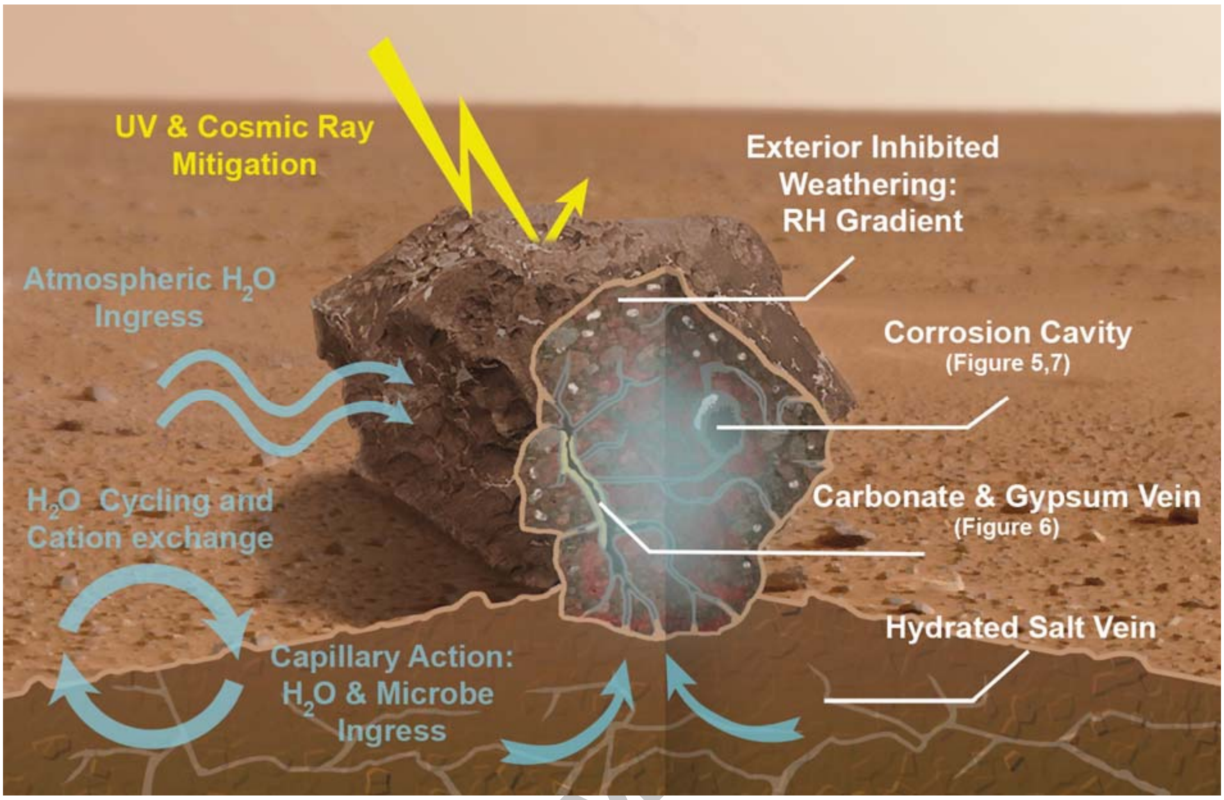

Figure 9 | Meteorite habitat model for Mars. This model shows the key properties of a meteorite habitat on Mars.

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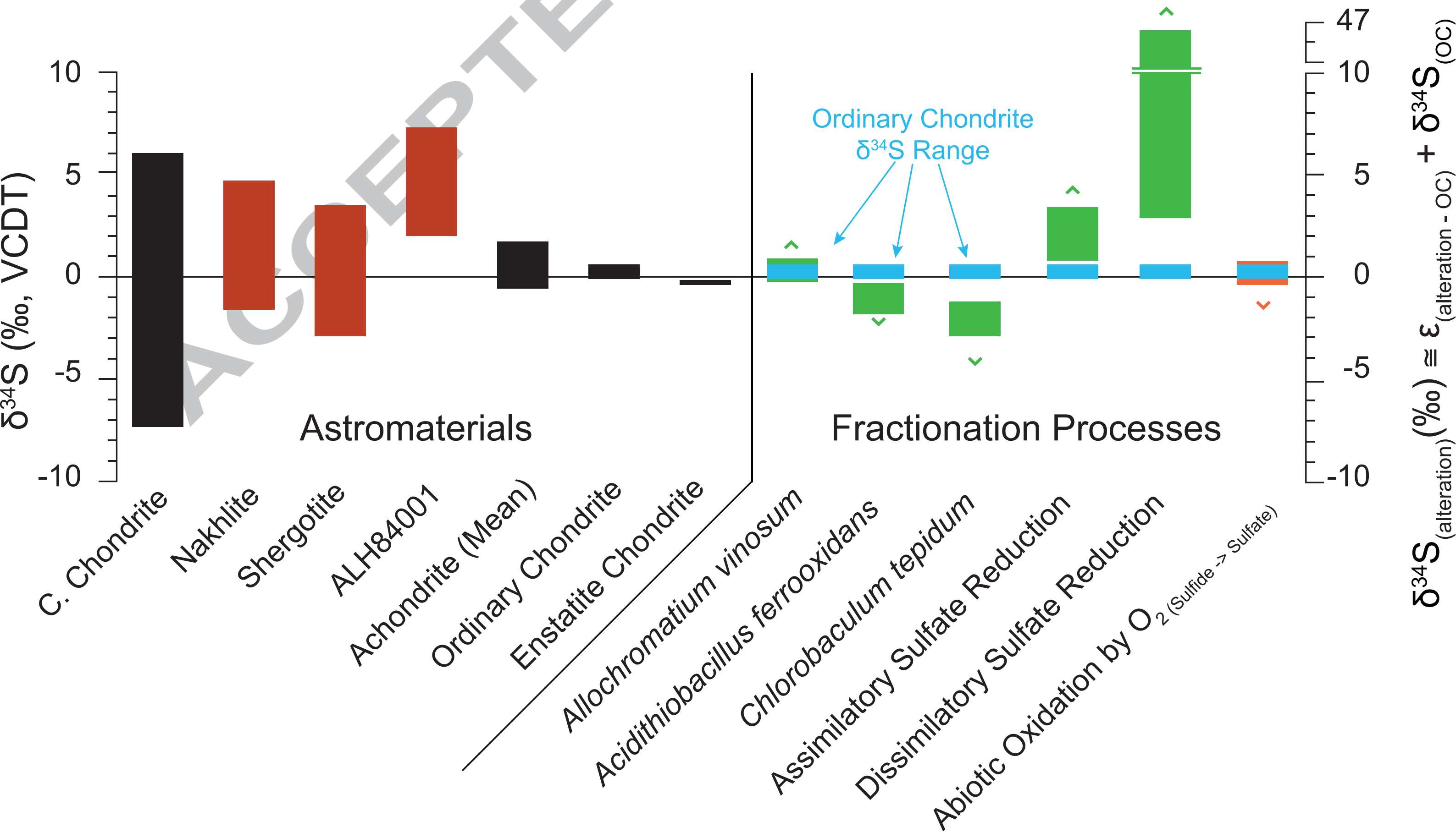
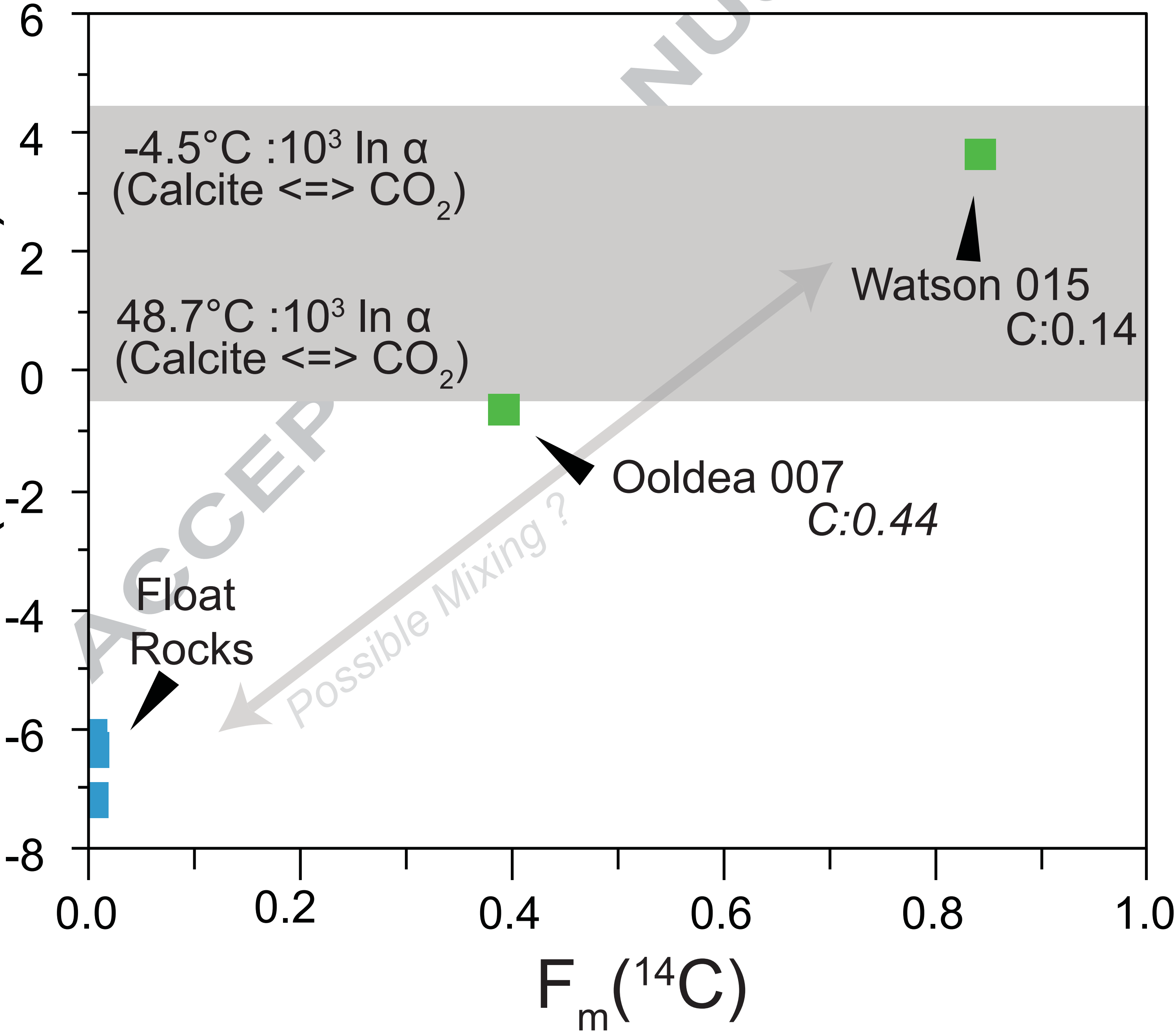

δ34S (‰, VCDT)
10
5
0
-5
-10
Astromaterials
C. Chondrite
Nakhlite
Shergotite
ALH84001
Achondrite (Mean)
Ordinary Chondrite
Enstatite Chondrite
Ordinary Chondrite δ34S Range
Fractionation Processes
Allochromatium vinosum
Acidithiobacillus ferrooxidans
Chlorobaculum tepidum
Assimilatory Sulfate Reduction
Dissimilatory Sulfate Reduction
Abiotic Oxidation by O2 (Sulfide -> Sulfate)
47
10
5
0
-5
-10
$\delta^{34}S_{(alteration)}(‰) \cong \varepsilon_{(alteration - OC)} + \delta^{34}S_{(OC)}$


6
4
2
0
-2
-4
-6
-8
0.0
0.2
0.4
0.6
0.8
1.0
δ13C (‰, VPDB)
Fm(14C)
-4.5°C :10³ ln α
(Calcite <=> CO2)
48.7°C :10³ ln α
(Calcite <=> CO2)
Watson 015
C:0.14
Ooldea 007
C:0.44
Float
Rocks
Possible Mixing ?

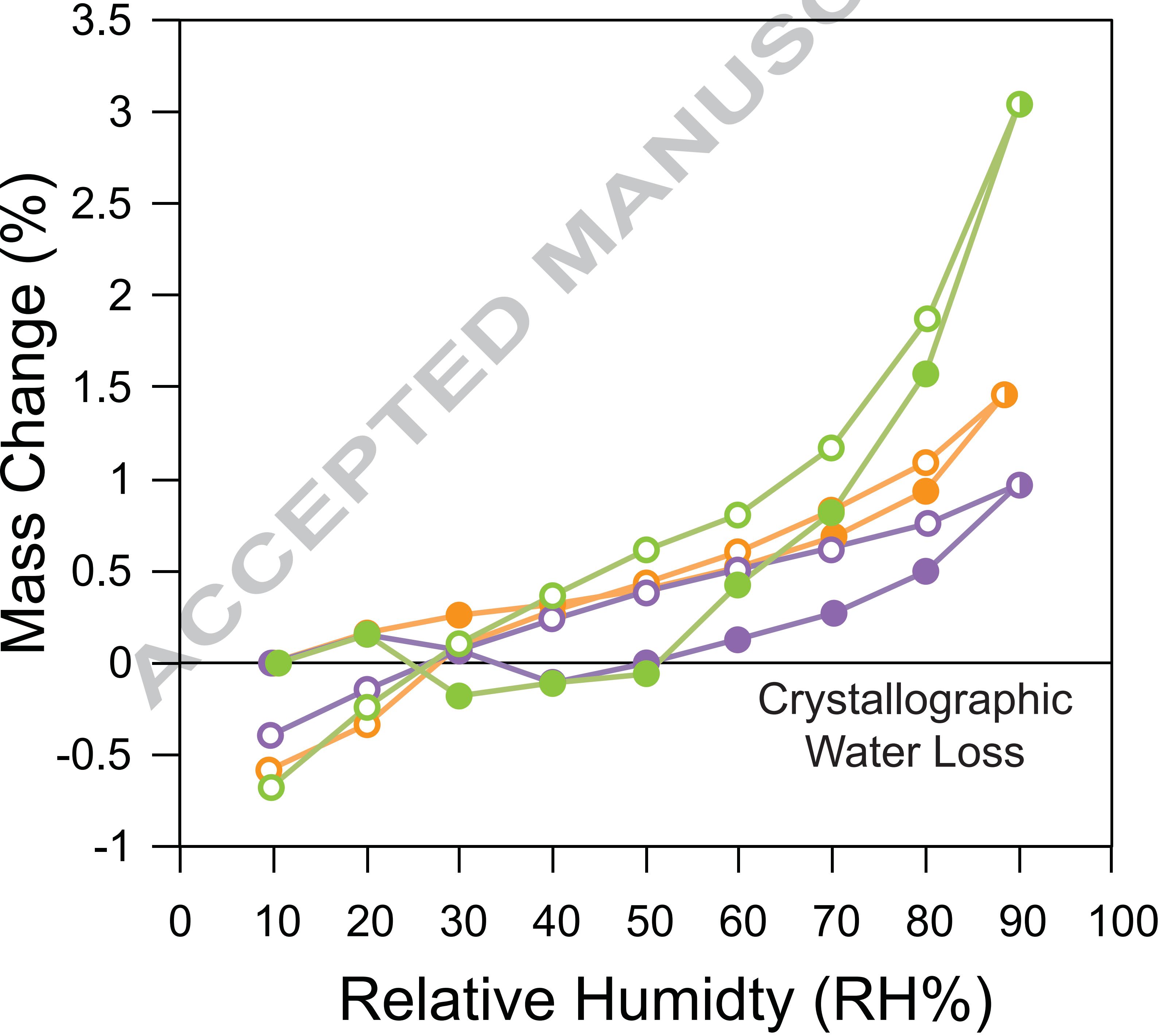
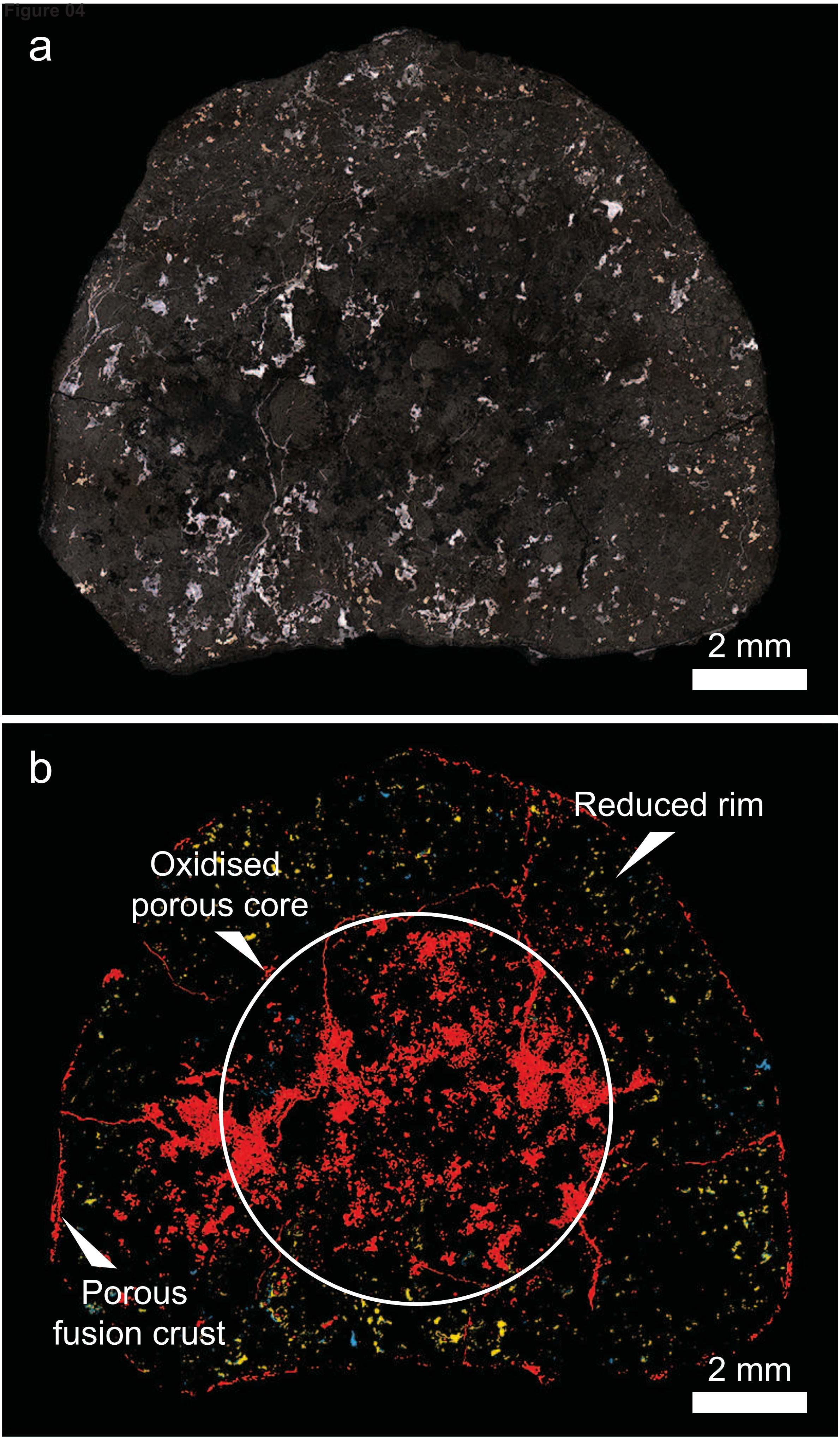
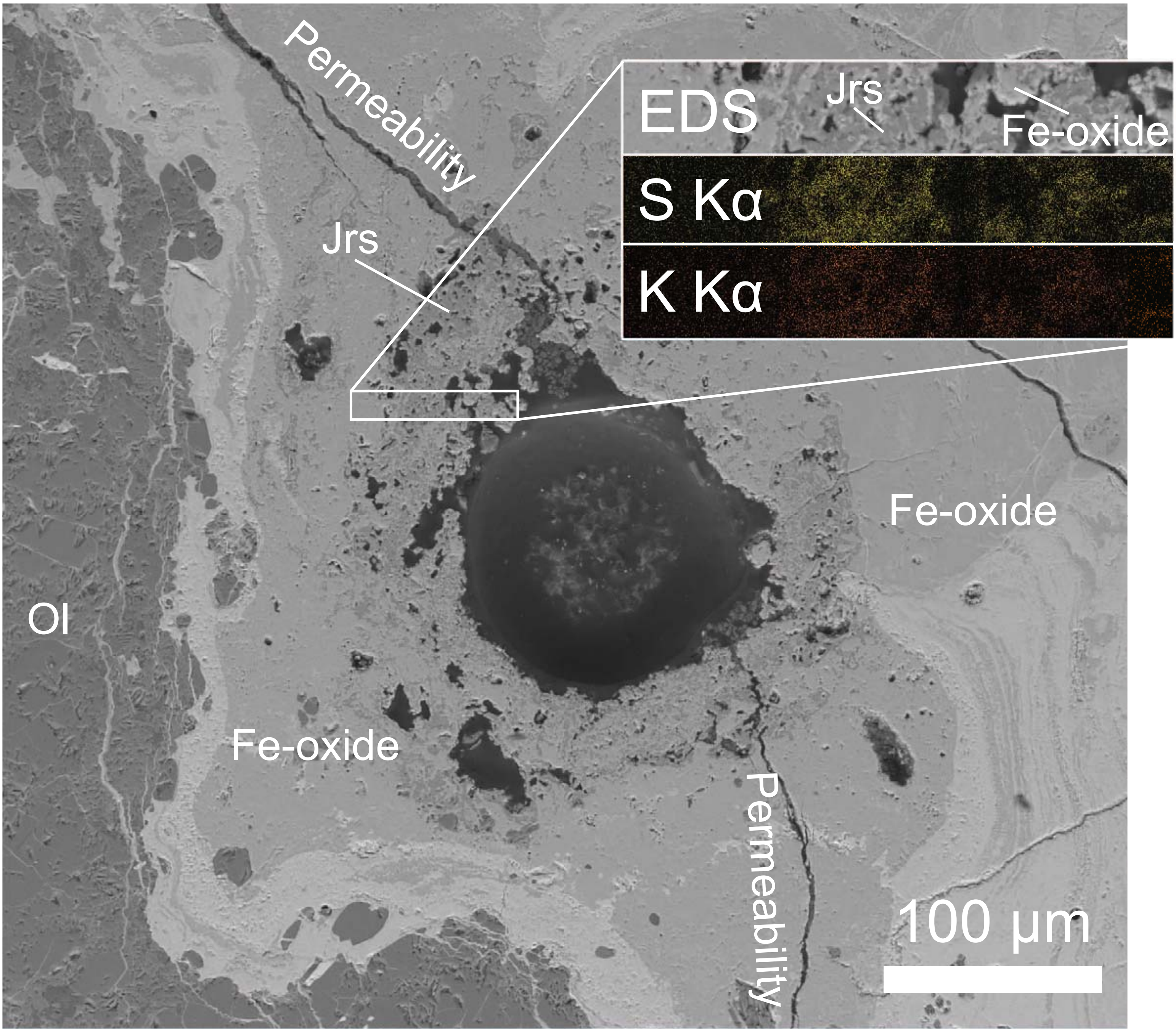
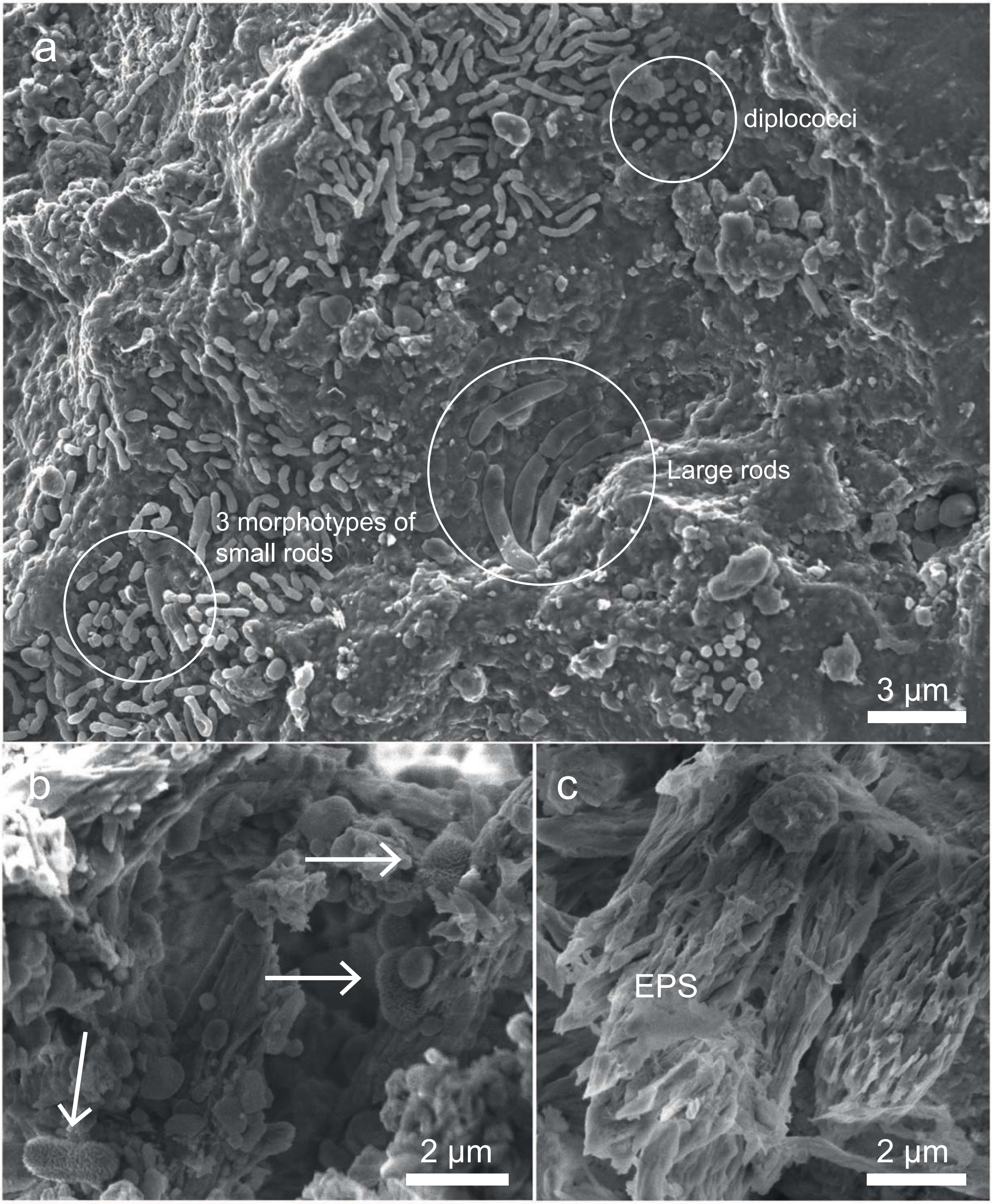
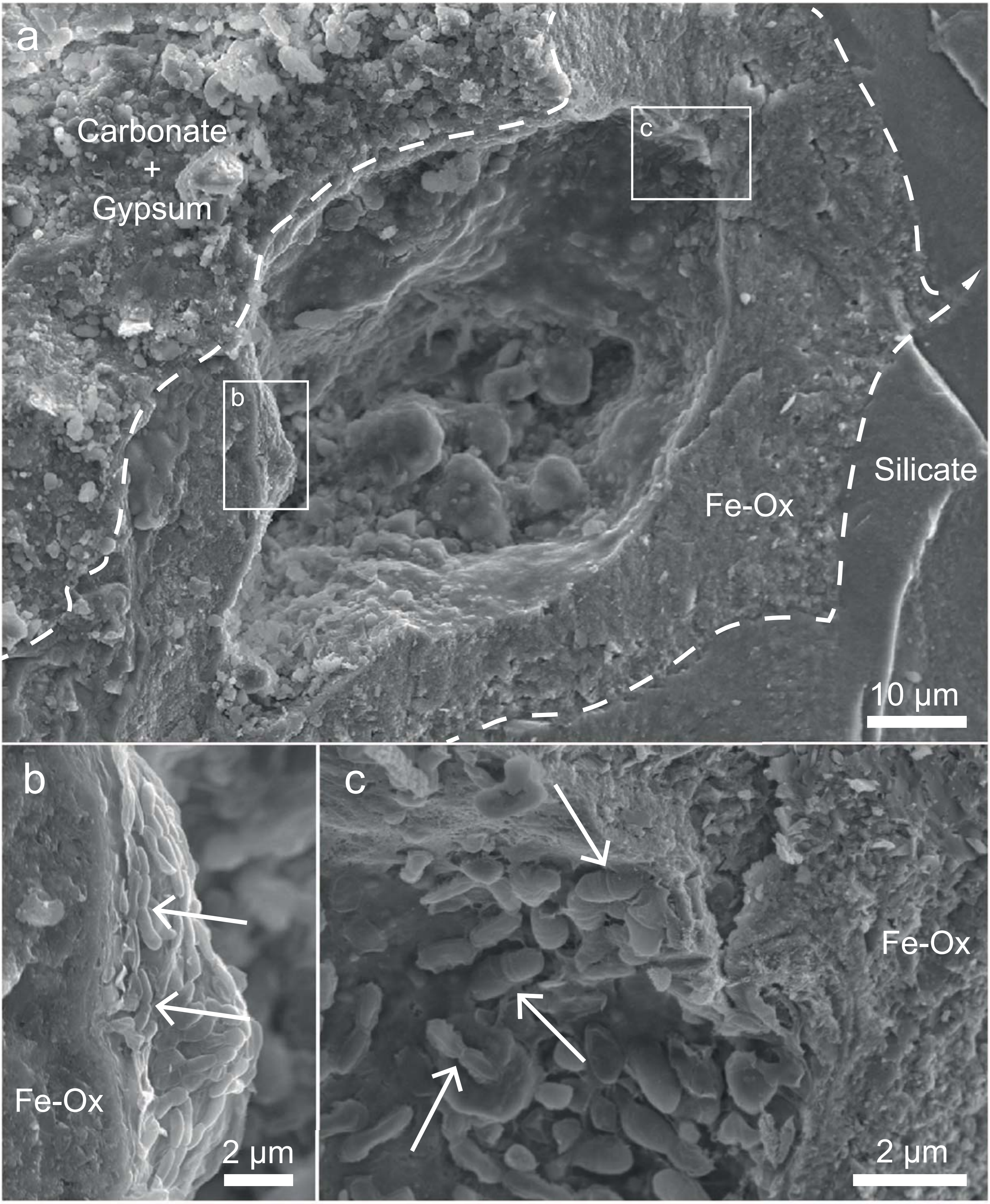

3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
Mass Change (%)
0
10
20
30
40
50
60
70
80
90
100
Relative Humidty (RH%)
Crystallographic
Water Loss

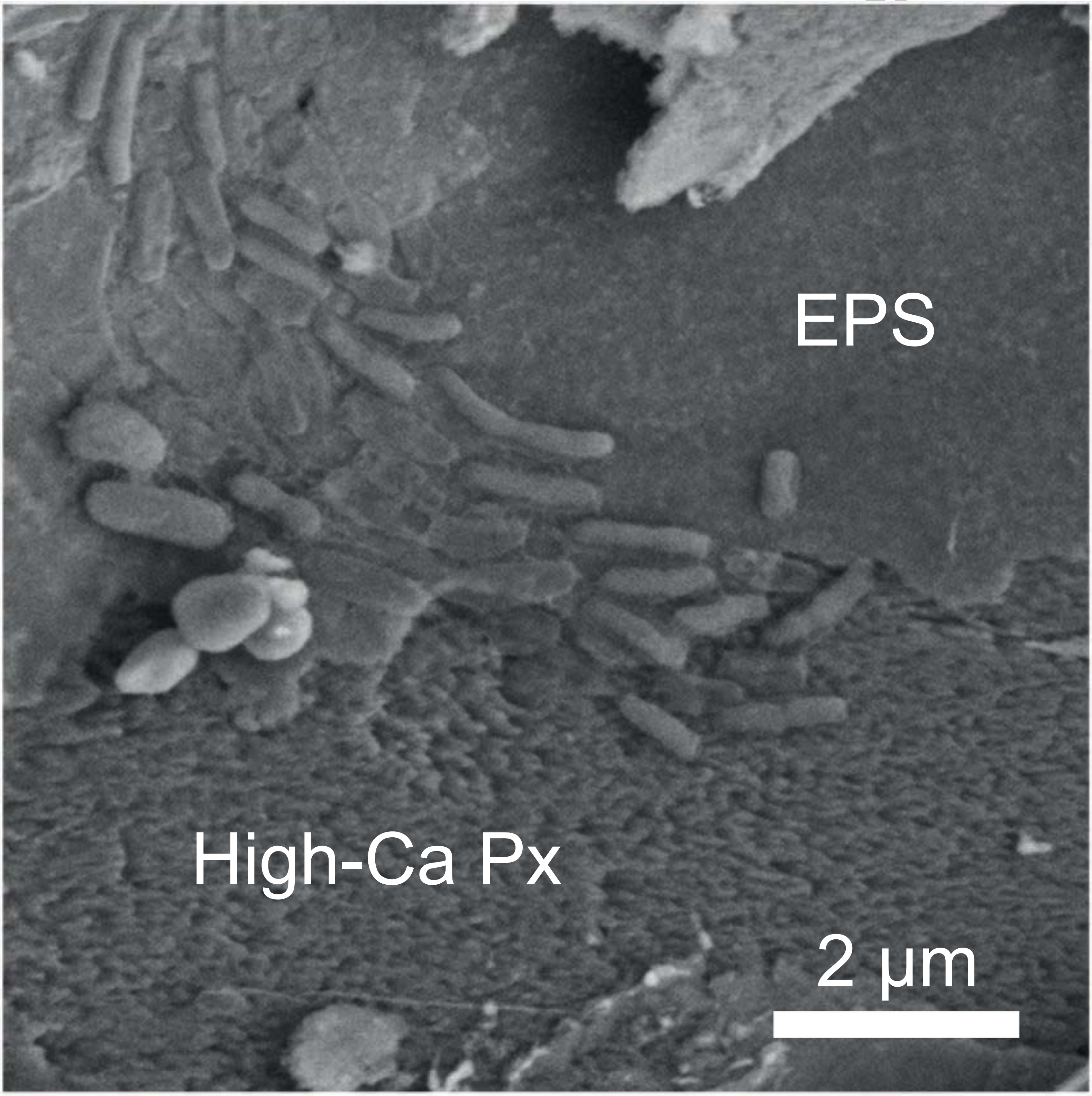
Figure 04


a
2 mm
b
Reduced rim
Oxidised porous core
Porous fusion crust
2 mm


Permeability
Jrs
EDS
Jrs
Fe-oxide
S Kα
K Kα
Fe-oxide
Ol
Fe-oxide
Permeability
100 µm


a
diplococci
Large rods
3 morphotypes of
small rods
3 µm
b
2 µm
c
EPS
2 µm


a
Carbonate
+
Gypsum
c
b
Silicate
Fe-Ox
10 µm
b
Fe-Ox
2 µm
c
Fe-Ox
2 µm


EPS
High-Ca Px
2 µm

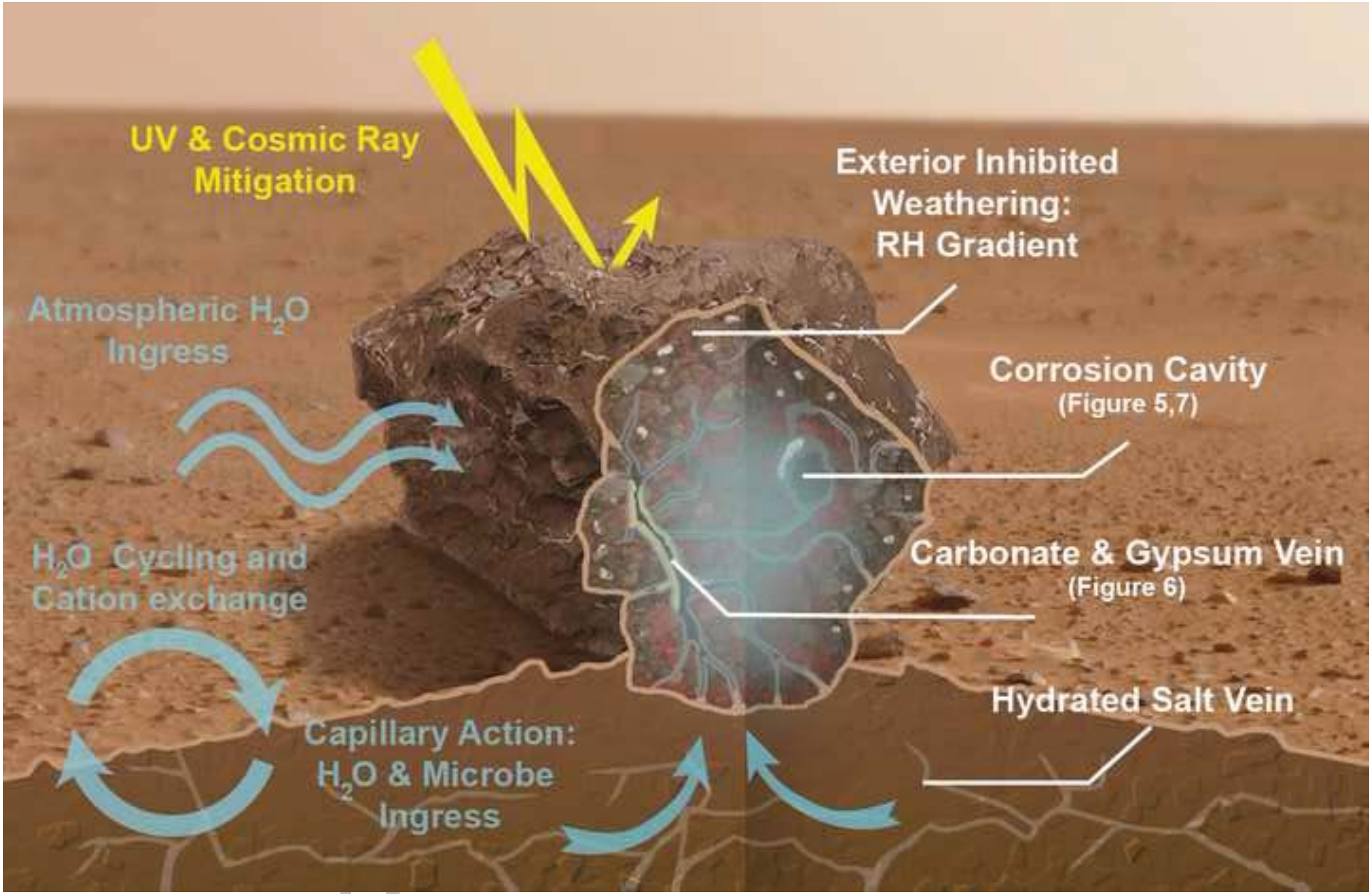

UV & Cosmic Ray Mitigation
Exterior Inhibited Weathering: RH Gradient
Atmospheric H_2O Ingress
Corrosion Cavity (Figure 5,7)
H_2O Cycling and Cation exchange
Carbonate & Gypsum Vein (Figure 6)
Hydrated Salt Vein
Capillary Action: H_2O & Microbe Ingress

Table 1 | Abundances of minerals in vein material by Rietveld refinement.

Official Name	Ooldea 002	Watson 015	Ooldea 007	Ooldea Regolith
Type	L5	H4	H3	-
Weathering grade	W4	W4	W4	-
Mineral	Ooldea 002 (wt.%)	Watson 015 (wt.%)	Ooldea 007 (wt.%)	Ooldea Regolith (wt.%)
kaolinite	5.7		8.6	17.4
illite	33.4			11.9
magnesite	0.5			
orthoclase	0.6		0.9	10.6
oligoclase	5.8		2.1	5.7
goethite	2.5	3.8	1.5	0.5
gypsum	0.6	24.6	6.1	
calcite	38.0	60.0	52.4	0.8
quartz	12.8	8.9	28.4	53.2
high-Ca pyroxene		2.7		
totals	100.0	100.0	100.0	100.0
*Contamination (wt.%)**	18.9	16.7	53.4	-
R_{wp} *(%)*	11.4	11.7	11.0	16.7

* Contamination is based on the quartz content in the vein material, scaled to the Ooldea regolith (see methods).