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ASTROBIOLOGY

Indicators and Methods to Understand Past Environments from ExoMars Rover Drills

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Abstract Great advances are expected during the analysis of drilled material acquired from 2 m depth by ExoMars rover, supported by the comparison to local context, and the joint use of different instruments. Textural information might be less detailed relatively to what is usually obtained at outcrops during classical geological field work on the Earth, partly because of the lack of optical imaging of the borehole wall and also because the collected samples are crushed. However sub-mm scale layering and some other sedimentary features might be identified in the borehole wall observations, or in the collected sample prior to crushing, and also at nearby outcrops. The candidate landing sites provide different targets and focus for research: Oxia Planum requires analysis of phyllosilicates and OH content, at Mawrth Vallis the layering of various phyllosilicates and the role of shallow-subsurface leaching should be emphasized. At Aram Dorsum the particle size and fluvial sedimentary features will be interesting. Hydrated perchlorates and sulphates are ideal targets possibly at every landing sites because of OH retention, especially if they are mixed with smectites, thus could point to even ancient wet periods. Extensive use of information from the infrared wall scanning will be complemented for geological context by orbital and rover imaging of nearby outcrops. Information from the context is especially useful to infer the possible action of past H_2O. Separation of the ice and liquid water effects will be supported by cation abundance and sedimentary context. Shape of grains also helps here, and composition of transported grains points to the weathering potential of the environment in general. The work on Mars during the drilling and sample analysis will provide brand new experience and knowledge for future missions.

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Introduction

Reconstructing past conditions on Mars is important for astrobiology and, to this purpose, subsurface drilling is expected to provide a significant leap forward. This work is a synopsis, focusing on geological features that are expected to be observed when the ExoMars (EXM) rover will drill in the subsurface, searching for both textural biosignatures and organic compounds (Bost et al. 2013, 2015). The observations can potentially provide new information in order to infer past environmental conditions on the planet. Therefore, this is a pro-active study to prepare for this mission by assembling potential observations that can support the interpretation of past and recent environments on Mars. We overview the links between potential observations of different instruments and support them with the current understanding of Mars, i.e. on how the knowledge on the regional context supports the interpretation. Firstly, the methods are outlined ("Methods" section) that the rover could use during exploration. Secondly ("Results" section), the potentially observed features are listed, i.e. structural, particle size and shape, and compositional issues. Thirdly, the "Discussion" section gives an overview on how such observations could point to certain geological facies and ancient physicochemical conditions, and also which are the expectations for the EXM landing sites. This sequence of presentation almost follows the expected argumentation using the results gained during the mission: assembling separate information from different detectors toward reconstructing the ancient environments. In the "Conclusions" section, while summarising our findings, we provide estimations of the importance of having a geological context in order to reach a proper interpretation. This work was compiled under the COST TD 1308 action ("ORIGINS") that aims to realize trans-domain research in astrobiology. Paleo-environmental reconstruction is a multi-disciplinary activity as mineralogists, chemists, and physicists have towork together with geologists and biologists to estimate whether ancient conditions did support life on Mars or not.

The ESA EXM rover is planned to land on an old and/or sedimentary terrain to investigate it with various instruments. Although such a terrain is expected to also contain rocks excavated from a large depth, mostly loose or cemented material will be finally sampled. In depths of down to 2 m, small-scale sedimentary features such as particle shape, grain size distribution, and compositional indicators will be investigated, as well as the mineralogical composition, especially that of phyllosilicates (Bibring et al. 2006; Poulet et al. 2005) and bound OH content in sulphates and weathered silicates (Rice et al. 2013). These features are representative of past water action and environmental variations (see later in the "Indication of water and ice", "Hydration level" and "Compositional issues" chapters). These can be detected with the EXM rover and, as a result, provide constraints to past environmental conditions, especially those related to the formation of phyllosilicates in the Noachian era at the candidate landing sites.

It is clear that a detailed analysis of the Martian regolith is necessary in order to understand the context and proceed to correct interpretations. Besides earlier remote analyses of the landing sites, the rover will closely inspect the outcrops (including the use of small sized impact craters in general to estimate the existence and location of strongly indurated shallow subsurface layer, Kereszturi 2012) to study subsurface characteristics, which will be used to rank the potential locations for drilling. A good registration of the local geological setting, apart from selecting drilling locations with a potential, can also provide background for discussions and interpretations. The detailed characterization of the landing sites is presented in the section "Expectations at EXM rover landing sites".

Methods

This review is based on a careful selection of published results that are deemed reliable, and they were evaluated from the point of view of the instruments' capability. These pieces of information were fused in order to identify target sedimentary features that support and improve the planning of future research strategies. We use the term "paleo-environmental indicator" to geological features that may facilitate identification of environmental processes and past conditions. The instrumental setup and their analytical capabilities are summarized in Table 1.

The target analysis will start from distance (PanCam, ISEM), continued from nearby before the drill (CLUPI), during the drill (MaMISS), of the fine (CLUPI), and crushed fine (CLUPI, MicrOmega, RLS, MOMA). PanCam (Panoramic camera) provides a surface context of the sedimentary setting, and cm scale textural information such as layering or cementation of pebbles, similarly to Curiosity in Gale crater (Williams et al. 2013) at nearby outcrops. The

Table 1 EXM instruments evaluated in this work (Arevalo et al. 2012, Brinckerhoff 2012; Bost et al. 2015; De Angelis et al. 2014; Griffiths et al. 2006; Hill et al. 2011; Jaumann et al. 2010; Josset et al. 2012; Pilorget and Bibring 2013; Rull et al. 2011). Although WISDOM and ADRON are also indicated, but this work focuses on the instruments listed in the upper seven rows

Detector	Wavelength range/method	Spatial resolution	Ideal target types
PanCam (WAC, HRC)	Optical: 0.400–1.1 μm	1.2/0.2 from 200 m distance	Surface outcrops and lithology, general Composition
ISEM	Infrared:1.15–3.3 μm	Pencil beam, 1° filed of view	Outcrop compositional analysis
CLUPI	Optical	Down to 7 μm/pixel at 10 cm distance (distance dependent)	Morphology of target rocks, including sedimentary structures and drilled fines
MaMISS	0.4–2.2 μm (20 nm wavelength resolution, reflection mode)	0.1 mm (along profile, in line scan analysis)	Mineral composition and distribution in the borehole wall
MicrOmega (infrared spectrometer)	0.9–3.5 μm continuous, 0.5–0.9 μm at few wavelengths	20 μm	Mineral identification, characteristics of certain particles of the sample
Raman Laser Spectrometer (RSL)	150–3800 cm^{-1} (2.5 μm resolution), excitation by 532 nm laser	2.5 μm	Organics, mineral products and Indicators of biological activities, abiotic organics from meteorites and disordered carbonaceous material, hydrated phases, various minerals of the sample
MOMA	1064 nm Nd:YAG laser for desorption and pyrolysis oven with gas chromatograph and ion trap	No (sampling interval from drilling)	Organics, various volatiles, elemental composition of the sample
WISDOM	Radar pulses between 500 MHz – 3 GHz	cms vertically	Subsurface structure, water ice content
ADRON	Neutron spectrometer for 0.001 eV–100 keV	Meter scale according to rover's movement	OH content of shallow subsurface

ISEM (Infrared Spectrometer for ExoMars) mounted on the mast will provide remote compositional data in order to select ideal locations for detailed inspection. It is also capable of identifying hydrous minerals. During the drilling process, MaMISS (Mars Multispectral Imager) will illuminate the borehole wall and will spectrally analyse the reflected light through a hard transparent sapphire window on the driller, in order to identify the subsurface distribution of minerals. It is expected to reveal possible features of the original strata by rotationally scanning the borehole wall, producing both vertical and horizontal profiles. CLUPI (Close-UP Imager) can provide images of sedimentary structures of uncrushed rock surfaces and micro-scale photos of the fines produced by the drill and later by the crushing station. The crushing station will produce powder from the acquired sample (grain size depends on material properties and crushing time, tests suggest to be around the range of 100 μm; Schulte et al. 2012b) erasing the sedimentary context and potential biomorphic structures, but making certain instrumental analysis easier (see later). The MicrOmega infrared spectrometer and the RLS (Raman spectrometer) will scan the crushed and flattened power, and the MOMA (Mars Organics Molecule Organiser) will scan/pyrolize the powder of crushed material to identify minerals, hydrated phases and organics. The sample will be acquired from the bottom of the borehole, which is not necessarily the same with that accumulated as a cone of drill debris on the surface. Unfortunately, borehole wall could not be recorded as an outcrop (the sampled grains in their original environment), although some textural information on the collected material by PanCam and CLUPI for context, and on the drill wall by MaMISS could be gained. A general picture should be built from separated information from different instruments, where the context from PanCam and radar (WISDOM) analysis are also important beforehand.

Hypothetic Martian biomorphic signatures are important targets, which might appear at different spatial scales (Westall et al. 2015), also might be small (Foucher and Westall 2009; Westall et al. 2011) and the crushing could destroy them. Tests (Foucher et al. 2014a) suggest that integration of results of more instruments is necessary for interpretation to compensate the loss of textural information because of during the crushing process (Foucher et al. 2014b). Shifting and broadening of Raman peaks is also expected in crushed regolith samples, the signal/noise ratio will decrease (Foucher et al. 2013) and the fluorescence will increase (Foucher et al. 2011). The difficulty of identifying carbonaceous biogenic fossils is demonstrated for precambrian rocks (Foucher et al. 2015). These blind tests suggest that the joint interpretation of results from different instruments is necessary to reach firm conclusion.

Results

The potentially important targeted features are summarized below using Earth analogues for structural features (i.e., layers, concretions), for geometrical features (i.e., grain size and shape), and for mineralogical information (i.e., chemical composition, OH content). Among them, special emphasis is given on the hydrous minerals, because these are sensitive environmental indicators.

Structural Features

The EXM instrumental setup is restricted in optically identifying structural features since only the MaMISS scans will be available from the borehole walls, and the spatial density of the data points as well as the scanning strategy (e.g., density and spatial distance of tracks) is limited. Even though the layers could be identified correlating compositional and particle size/shape trends with those observed in the laboratory, the sampling interval is still a limiting factor in identifying layers. In theory the bedding, ripple marks, mud cracks, or even cross-bedding could be identified at cm scale, although they require detailed information from the borehole wall scans, and comparing the sample before and after crushing might help. Moulds are also candidate targets to look for. The Opportunity rover identified similar features in sulphate-rich rocks at the Meridiani Planum. These exhibited plate-shaped voids left behind after soluble evaporitic minerals were removed from the strata (Herkenoff et al. 2004). Their morphology is compatible with the triclinic phase of hydrous magnesium sulfate $MgSO_4 \cdot 11H_2O$ (Peterson and Wang 2006).

Ice and sand (sediment) wedges are thought to be frequent on Mars, inferred from polygonal features appearing on the surface. The size range of such wedge casts may be on the meter scale; thus, it seems improbable to identify them even if the drill crosses one. Among the sedimentary deformational features, cm-scale ones may also exist at periglacial terrains, but their identification is still difficult in borehole wall scans, except if they show a characteristic textural contrast between the base sediment and the material of the wedge filling.

Past hydrothermal systems could produce veining, like it was observed by Curiosity (Arvidson et al. 2014), which could be a target for PanCam in outcrops. CLUPI could contribute in such observation by analyzing crusted or mantled grains (surrounded by later formed secondary minerals, like for example identified at Haughton-crater, Northern Canada by Osinski and Spray 2001), and also as crushed parts of earlier drilled veins using MicrOmega, comparing the shape and composition of lithic fragments. Detailed search for micro-volume voids in minerals should be made, as they could provide geochemical information for the origin and evolution of hydrothermal systems. To perform such a task analogue tests with crushed veins or crusted grains would help to see ideal ways how to use parallel high-resolution chemical, mineralogical and morphological analysis.

Particle Size and Shape

Aeolian sediments include well-sorted grains with 0.7–2.2 μm size (Kahre et al. 2008). Fluvial sediments are less sorted, and glacial and mass-wasted ones are strongly diverse, although electrostatic adhesion could increase the size of agglomerated grains (Mazumder et al. 2004). The shape of individual particles and their size distribution provide information as sphericity of grains is in connection with transport distance and transport modes on Earth (Wentworth 1919, 1922; Inman 1949; Friedman 1979). Sediment particle size distribution has not been analysed on Mars yet, thus Earth analogues may provide some constraints here. Based on terrestrial analogues, the size distribution curves of aeolian sediments might show several superposed peaks (multimodal) beside a dominant one. The largest peak is in general characteristic for well sorted aeolian particles with short to medium duration/distance of transport. Two-grain size-distribution parameters are being widely used to characterize the transport medium and the travelling distance on Earth: the median and the standard deviation (Blott and Pye 2001). These parameters can be hopefully roughly estimated despite the fact that the measured size distributions will certainly be disturbed by the crushing station (Schulte et al. 2012a).

Important differences compared to Earth include: (1) the probable lack, or subordinate role of quartz; and (2) the dominant role of other, slightly less refractory and harder minerals of basaltic rocks, such as olivine, magnetite, ulvospinel, and ilmenite. On Mars, wind is likely to be the main agent for recent particle sorting, but older fluvial conglomerates with coarser and wider grain size distributions could indicate fluvial origin (Newsom et al. 2015) in chrono-sequences.

The sample preparation influences the results, as the crushing station alters the size distribution (although mainly separates aggregates into original grains), the spatial context will be lost (although fragments might hold superpositional relations as mantled grains or vein fragments surrounded by host rock fragments). The change of particle size effects the measurement, especially spectral peaks (King and Clark 1989). Using Raman analysis intensity increases usually as grain size decreases (Pellow-Jarman et al. 1996), carbonaceous material might be easier to identify in trace amount in powder (Lopez-Reyes et al. 2013), while shifting and broadening of peaks (Weber et al. 1993) might also appear in connection with crystal size change too, but this effect is partly material specific. The intensity of laser also matters, and the irradiance for RLS is set to 0.8–1.2 kW/cm^2 not to damage oxides, hydroxides and organics (Rull et al. 2013). The particle size effect for infrared analysis is complex as larger particles might be agglomeration of smaller ones (especially for clays), but in general the decreasing particle size produces decreasing band strength (Cooper and Mustard 1999), possibly influencing the interpretation of MicrOmega's results.

Indication of Water and Ice

Morphological observations of drilled grains, including shape plus size distribution (and their vertical change) could help to identify whether water or ice served as a transport media in the past. The variations in water content could be divided into physical and mineralogical/chemical reasons. The observation of the physical variations will be difficult since most instruments are expected to characterise only crashed samples. In classical Earth sciences, features related to frost action are used to identify changes of ice in the shallow subsurface (e.g., ice and sand/sediment wedges, ice lenses, polygons, patterned grounds, sorted objects). When crossing such features, analyzing the vertical section of the drill core only particle size trends (and in ideal cases some morphological characteristics) could be identified, but the instrumental facility of EXM is not ideal for such observations.

Humidity-related aggregate formation under the Martian conditions was observed by Phoenix, where adsorption produced aggregates of the regolith that fell into pieces by desiccation in the scoop. Similar behaviour will likely be recognizable in the drilled samples of ExoMars, depending on how long the target sample will be observed after coring. Ancient water in the form of ice might be incorporated into the sediments as pure ice lens/wedges, easily identifiable with the MaMISS instrument by the spectral signature of ice, while in parallel strong mineral signatures are not expected to be present. Ice bodies of recent age exist in the middle and high latitude regions based on excavations of fresh impact craters (Byrne et al. 2009). Older and buried ice layers cannot however be excluded in the low latitude region. Although the Martian cryosphere is extremely old, ice with Ga age is not expected at low latitudes in depths of 2 m.

Hydration Level

Minerals containing significant quantities of water, which are exotic on Earth, might be however present on Mars. Minerals capable of water up-taking, such as Mg- and Ca-sulphates, chlorides, and phyllosilicates, are present on the surface of Mars in an abundance of 8–25 %

(Clark and Hart 1981), and they could change their hydration state under the climatic changes that possibly took place in the Amazonian period (Carter et al. 2005). Major influencing factors include the cold and rare atmosphere, diffusion barriers (duricrust) in the shallow subsurface (Bish 2003), as well as thermal inertia and hydroscopicity. Hydration/dehydration is poorly understood in cold environments that are characterized by low water/rock ratio (Harvey et al. 2006; e.g. small liquid amounts with many mineral grains), and also with salts that formed earlier that may have experienced later changes. In this respect the important minerals are summarized below.

Fe and Mg sulphates: threshold conditions (humidity and temperature) for their hydration and dehydration (Jänchen and Brettschneider 2011) partly overlap with recent climatic changes, but the daily hydration cycle is weak. Highly hydrated $MgSO_4{\cdot}nH_2O$ minerals might form under the Amazonian temperature regime at low latitudes, if ice had ever existed there. Such minerals (epsomite, hexahydrite) may be preserved till today (Vaniman et al. 2005). Several sulphates (including blödite, ($Na_2Mg(SO_4)_2{\cdot}4H_2O$), kainite, ($MgSO_4{\cdot}KCl{\cdot}2.75H_2O$), polyhalite, ($K_2Ca_2Mg(SO_4)_4{\cdot}2H_2O$)) that contain structural water probably do not dehydrate under the current Martian surface conditions (Bish and Scanlan 2006). Also jarosite ($KFe_3(SO_4)_2{\cdot}(OH)_6$) is thermodynamically stable today (Forray et al. 2004) besides other hydrous ferric sulphates (Hasenmueller and Bish 2005). Under cold conditions and in the presence of water ice, highly hydrated phases like meridianiite, $MgSO_4{\cdot}11H_2O$ might form (Leftwich et al. 2013), which however melts incongruently above 2 °C to 70 % epsomite ($MgSO_4{\cdot}7H_2O$) and 30 % H_2O (Peterson and Wang 2006).

Gypsum ($CaSO_4{\cdot}H_2O$ system) could also occur as dehydrated or rehydrated (Weitz et al. 2013). Acid fog models and laboratory experiments suggest that gypsum might form during the interaction of JSC-1 simulant material and H_2SO_4 down to 255 K (Berger and Ayang-Nzamé 2014). Bassanite ($CaSO_4{\cdot}0.5(H_2O)$) forms from gypsum very slowly under the current Martian conditions, and its rehydration to gypsum occurs only in saturated water environments. Bassanite hydration produces gypsum in the presence of ice, thus bassanite and water ice are not expected to occur together (Robertson and Bish 2013). If anhydrite ($CaSO_4$) exists, it is easily converted to bassanite. Gypsum and bassanite might form from the mixture of Ca-smectites and Mg-sulfates by cation exchange under a changing relative humidity (Wilson and Bish 2011).

Hydrated Mg-perchlorate is stable under the current conditions on Mars. Deliquescence relative humidity (DRH) of Na-perchlorate increases with decreasing temperature (51 % at 273 K to 64 % at 228 K), thus under cold, almost saturated conditions (e.g. mixed with water ice) it might form even today, although 228 K is close to the sublimation temperature of water ice. The DRH of the hydrated Mg-perchlorate also increases with decreasing temperature, from 42 % at 273 K to 64 % at 223 K. But the efflorescence relative humidity (transition into solid state) is lower: 13 % and 19 % for $NaClO_4$ and $Mg(ClO_4)_2$ respectively in wide temperature ranges; thus, if once they got hydrated they tend to keep their humidity in dry conditions as well (Gough et al. 2011).

Smectites could hold H_2O molecules in partially dehydrated phases (Carey and Bish 1996; 1997) even in the current conditions. Mg-clays characteristically form in neutral to alkaline conditions, and might indicate extended duration of aqueous conditions and/or high water/rock ratios. For example Ca-smectites retain interlayer H_2O even at 0 % relative humidity (Bish et al. 2002) and hydrated perchlorates imply H_2O-rich conditions previously. *Zeolites* might form by alteration of hydrovolcanic basaltic ash and palagonites (Golden et al. 1993). Simulations suggest, for example that clinoptilolite could stay highly hydrated even under current Martian conditions (Fialips et al. 2005).

In general, *different hydration states* provide information on the past conditions. Subsurface hydration states are might be incompatible with the atmospheric conditions; thus substantial change is expected in the hydration state after drilling. Hydrated phases are almost resistant to daily temperature/humidity fluctuations (Robertson and Bish 2012) on Mars. For instance, gypsum is difficult to dehydrate today.

Concluding, hydration states may provide indications for a wetter and possibly somewhat warmer past climate compared to those that prevails today. Dehydration slows down in cold environments (Wang 2012), thus Mg-sulfates that formed earlier could still be hydrated. Water ice might exist at middle latitude terrains at obliquity >45° (it might have formed in the last 4–5 Myr ago; Richardson and Wilson 2002). Vertical variations of the hydration level in the drill hole thus provide crucial information on wet/icy past climates.

Compositional Issues

Phyllosilicates are among the most important targets for the primary landing site as they form under water action with certain range of past pH, temperature and wet duration – although the effectivity of weathering and volume of produced clays are influenced by the grain size too. While early surface liquid flow has been proposed to explain the origin of these minerals, the exhumation of phyllosilicates at impact craters is also considered compatible with a shallow subsurface origin (Ehlmann et al. 2011). Trends in elemental distribution could provide insights into their formation and later alteration. Even more recently the widespread occurrence of weathering sequences from orbital data (Al-rich kaolinites above and Fe/Mg smectites below) with the estimated ages suggest that surface liquids existed on Mars inthe Noachian (Carter et al. 2015) and contributed in the formation of phyllosilicates. Beside these weathering related possibilities phyllosilicates might also form by magmatic fractionation (Meunier et al. 2012).

Compositional trends were reconstructed/inferred for Meridiani Planum from non-uniform deposition and/or migration of mobile magnesium-sulfates (Clark et al. 2005). The upward sulphate and downward chloride migration point to temporal variations in pH and water/rock ratio caused by evaporation from the liquid-saturated sediment. Layer specific appearance of vugs (McLennan et al. 2005) might be produced by dissolution of $MgCl_2$, or by the declining water table that resulted in NaCl leaching. Cation content of phyllosilicates also refers to their formation conditions: the higher solubility and mobility of Mg compared to Fe and Al suggests that Mg-clay may indicate aqueous conditions (Léveillé 2012).

The paragenesis of clays and other minerals could point to differences in formation conditions, where Martian meteorites could also improve the estimations (Chatzitheodoridis et al. 2014). Observations from EXM will help to clarify the complex picture of various model scenarios on the role of temperature, pH, available oxidizing agents and CO_2 partial pressure on phyllosilicate formation, and also selecting from the possible multiple routes to produce Fe/Mg-smectites. Modelling of weathered basaltic materials' evaporation suggests early formation of nontronite and magnetite (Chevrier 2009), where nontronite indicates oxidizing conditions at various temperatures, while at reducing conditions the temperature has stronger control, and nontronite forms only <50 °C. Above that, it is replaced by saponite, at higher temperature serpentine and chlorite are characteristic. At high CO_2 partial pressure kaolinite replaces nontronite under low temperature. Another set of models using paragenesis of phyllosilicates, amorphous silica, sulphates (identified by Spirit rover) is compatible with acid weathering of even older phyllosilicates. For Mawrth Vallis region similar modelled acid leaching of mixed phyllosilicates produces kaolinite overlaying montmorillonite that caps Fe/Mg-smectites (Altheide et al. 2010). The water/rock ratio also matters, as high w/r values produces Al-phyllosilicates and amorphous silica, while elevated CO_2 pressure supports the formation of carbonates instead of smectite (Catalano 2013), and oxic weathering prefers producing Mg-saponite with nontronite. The analysis of these minerals together with the sedimentary information provides input whether the given environment was a fast flowing river dominated, or slowly seeping shallow subsurface water dominated.

The MicrOmega and the Raman instruments are expected to assist in the identification of phyllosilicates and the determination of their type. Although the 2 m long drill might not be enough to profile the expected sequence of upper Al clays and lower Fe/Mg clays, the comparison of several drill profiles at different stratigraphic locations might help to at least distinguish between weathering by surface vs. weathering by subsurface liquids, if topography and stratigraphy are well known.

Discussion

With the instruments onboard ExoMars, research work should focus on issues that would lead to the identification of signatures of past climatic variations. On the Martian surface, sedimentation rates were in general decreased after the Noachian/Hesperian transition; thus, substantial masses of sediments are expected to be accumulated during long periods of time in the Amazonian era, or by major events such as fast floods or mass movements. Indicators of such events is likely to be the coarser grain size distributions should be, distinguished by airborne dust from their more uniform small, and well-sorted particle size.

Particle size and shape may also give insights into transport processes. The maximum size of well-sorted particles of aeolian origin could suggest wind strength and atmospheric density variations, although possible agglomeration of smaller particles is more dependent on electrostatic forces, which must be better understood and should be taken into consideration during data interpretation (Kok and Renno 2005). The chemical and mineralogical composition of the eroded and transported particles could provide information, both on the source areas and the scale of transport distances. Although the knowledge of the heterogeneity of source of transported materials for Mars is still poor, except certain potential locations composed of salt particles. For that purpose, temporal variations along the vertical strata would be a useful indicator. In the absence of the mechanically and chemically resistant quartz in the mineralogy of Mars, the most resistant components of basalts (that could be identified by MicrOmega and Raman methods) are minerals such as olivine, magnetite, ulvospinel, and ilmenite.

Vertical trends are expected in the oxidation level and therefore also variations in the concentration of possible organic material constituents, mainly controlled by parameters such as gradients of the surface UV dose, the oxidizing chemistry (Stoker and Bullock 1997), and possibly, decreasing with depth by ionizing radiation (Dartnell et al. 2007a). The on-board instruments are capable of detecting these variations in mineral composition. Especially the comparison of hydration levels of the same mineral(s) collected at different drill depths would assist in separating the layers that indicate different formation conditions, as described in the following paragraphs.

Hydrated minerals are of high importance, although for the firm identification of the existence of *past water*, hydration is not enough without other, mainly textural information (Mustard et al. 2008). For example, grains that are rounded could provide such information, although this is relevant mainly for larger grains (e.g. gravels), which however are not expected to be easily seen after drilling. Other possibilities come from the sedimentary issues, such as fine-layered depositional features—although here the separation from ice related deposition and hydration could be difficult. The presence of water weathered clays might help but their formation requires specific temperature and pH. Imbrication could also point to fluvial deposition, but also here the limited information on the borehole walls (because of their small size) might cause problems. Optical appearance of the lithology like in an outcrop can not be acquired, although the infrared data from MaMISS could show several features. Thus the regional context provides useful information here (for example drilling into a fluvial fan or in channels running toward depressed depositional area).

Among the hydrated minerals, Mg-sulfates and perchlorates tend to keep their hydration state under dry conditions because of kinetic effects (Vaniman et al. 2004b). But if a certain layer (earlier surface horizon) was exposed to elevated temperatures and dry conditions (such as today's equatorial locations), this layer might dehydrate. Because of the cold, rare atmosphere on Mars, and since the diffusion between hydrated phases is limited, the hydration state of buried minerals could be preserved and may indicate their formation conditions. *Pure ice* layers might also be present in a buried form, although should be avoided because of safely issues (gas exhalation by fast ice sublimation). Such shallow ice layers were identified only at middle and high latitudes (Byrne et al. 2009), but the presence of similar layers cannot be excluded at low latitude, possibly formed during even earlier climatic cycles.

Beside the hydration by deposited ice, *eutectic freezing of brines* could also take place. Such layers are likely made of sulphates, chlorides, and perchlorates. The finely grained eutectic intergrowths (Rieck et al. 2005), the specific lamellae and the matrix around rods of ice-I are indicative of liquid state before eutectic freezing (McCarthy et al. 2007), but might be difficult to be observed because they are small and could be easily destroyed during sample acquisition. Thus, indirect argumentation is required to separate highly hydrated phases formed by freezing of bulk brines from solid ice. The high abundance of water over the stoichiometric composition could be such an indicator. Another possibility is the Na/Mg ratio in perchlorates that could roughly point to the formation conditions. Joint occurrence of epsomite and water ice probably points to melting, but the produced water ice could easily further sublimate.

Composition of mineral assemblages could be affected by the co-presence of certain minerals; for example, smectites suppress the deliquescence of Mg-sulfate, and the coexistence of these two minerals may buffer the relative humidity in porous voids, and produce phases with hydration level inconsistent with the atmospheric conditions (Wilson and Bish 2012). Thus, joint occurrence of sulphates and smectites are good indicators of important targets. Dehydration of $MgSO_4{\cdot}nH_2O$ systems might take place at substantially slower rates if smectites are present at the same location (Table 2).

The importance of drilling with access to 2 m depth can be related to avoid the *organic disintegration* effects from surface such as: UV radiation from, with a penetration depth in the mm scale inside the volume of samples; diffusion of oxidants that are produced on the surface, with penetration depths in the cm-dm scale; and, particle radiation, with penetration depths in the meter scale (Dartnell et al. 2007b). Less destroyed remnants of earlier organic molecules are expected below 2 m or at sites that were exhumed only recently. In a hypothetical set of strata, originally with a vertically homogeneous concentration of organics, a trend is expected and might also be observed between the concentration and the complexity of the organics in correlation with the depth and the concentration of the identified oxidants in the given layers. Here, the diversity observed by MOMA, Raman, and MicrOmega is expected to provide an

Table 2 Observable parameters for ExoMars rover instruments

Detector	Parameters that are relevant to processes	Extrapolated conditions
Outcrop wall, drilled cores and fines		
CLUPI	Petrography, layering, particle size distribution of grains above 30–50 μm before crushing, shape of these grains, homogeneity in colour of certain grain size range, possible bio-sedimentary structures, biosedimentary, biogenic morphological structures	Indication of sedimentary origin, level of sorting by the wind, transport method and related energy, vertical change of wind's role, existence of hydrothermal dissolution/deposition
MaMISS	Thick veins in sediments, layering, large vugs, IR spectral data on composition, OH content, mineral identification, bulk ice identification if exists separately	Rough formation conditions (pH, temperature, W/R ratio, oxidizing conditions), content of original and later uptake of water
Crushed material		
MicrOmega	Grain scale characterization of minerals, identification of pyroxene and olivine, ferric oxides, hydrated phyllosilicates, sulphates (epsomite, hexahydrite), carbonates, organics and OH content	Formation conditions, accessible H_2O, grain "types" and composition →transport, depositional and later alteration, estimation of pH, temperature, W/R ratio, oxidizing conditions
MOMA	Mineral identification: oxides, hydroxides, organics, carbonates, level of crystallinity; automatic scanning and targeted scanning	Identification of astrobiology relevant organics
Raman	Mineral and organics identification, OH content estimation, mineral structural issues	Formation conditions, later alteration, organic preservation, wet conditions

important insight into the interpretation of the distribution of the organics, while putting them in a spatial context and might give information on the potential layers that carry the organics. The role of particle irradiation on the Raman observability of certain organisms has been already analysed in laboratory, when simple bacteria showed substantial decrease of Raman peak intensity from cellular carotenoids along with increased dose (Dartnell et al. 2013).

Expectations at EXM Rover Landing Sites

Among the four candidate sites (Vago et al. 2014; Loizeau et al. 2015) Oxia Planum (18.20°N, 335.45°E) was selected as the primary landing site for the 2018 mission. There is a basin at the outlet of the Coogoon Valles system, an area which is an eroded, old highland terrain with outflow channels and sediments. The exposures of layered Fe/Mg phyllosilicates suggest ancient water action, while at certain locations the dark, possibly volcanic, material has been eroded only recently (~100 million years). The aqueous conditions of this area along with the fine-grained sediments are potential hosts for preserved microorganisms from the early era of Mars. For the 2020 launch window, in addition to Oxia Planum, a second site, to be selected between Aram Dorsum and Mawrth Vallis, they are considered below.

Aram Dorsum (7.9°N, 348.8°E) shows flat toped sinuous ridges as remnants of long term (and not catastrophic) fluvial activity, they were emphasized by relief inversion (Sefton-Nash et al. 2015) and surrounded by polygonized marginal material. The whole stratum is partly overlain by ejecta and later sediments. The middle Noachian aged, recently exhumed (300–100 Ma) aggradational river system might left behind coarse grained sediments. For organic material preservation probably the finer grained inter-channel (flood-plain) deposits are better (Balme et al. 2015). At several locations the lack of evidence for hydrated minerals might be caused by dust cover that should be taken into account for planning the drills' location. Great variety of particulate material is expected with depositional signatures of flowing liquid, where shape and size distribution of grains are important, especially at the outcrops of the inverted channels. Between them at the floodplain area the fine scale material might show elevated occurrence with possible enhanced preservation of organics.

Mawrth Vallis region (22°N, 342°E) is an altered phyllosilicate rich area with bright, indurated, high thermal inertia (Loizeau et al. 2006)) clay minerals that are often present at plateau-like old and eroded units, which were sculpted by a large outflow channel (Carter et al. 2015). The Fe-rich nontronite is located at the bottom, the Al-rich phyllosilicates at the top of the vertical sequence (Loizeau et al. 2007), together with some kaolinite and hydrated silica (Bishop et al. 2007). The altered, occasionally >100 m or thick unit is capped by a dark, up to 10 m thick probably volcanic layer. The expected aqueous, moderate pH, low temperature conditions inferred for the clay formation are favourable for astrobiology. The mineralogy provides information on the ancient weathering process, including the possible leaching that produced Al-rich phyllosilicates from Fe/Mg-rich ones in the shallow subsurface or in surface water. Phyllosilicates also support the preservation of organics, although it is difficult to extract organics from them.

Based on orbital neutron spectrometry data, water content in the top 1–2 m of the regolith may reach 10 % at equatorial terrains and is probably bound in clays or zeolites (Vaniman et al. 2004a, b). A good candidate/proxy is the $MgSO_4 \cdot nH_2O$ system where, based on experiments relevant to Martian conditions, hexahydrite, gypsum, and starkeyite are the expected minerals. At the primary EXM landing site 4–7 % H_2O water equivalent hydrogen abundance is present at the top 2 m of regolith (Feldman et al. 2004) with small annual variation in bound water content (Kuzmin et al. 2006) including two elevated periods around Ls = 90 and 280. The annual difference might influence adsorption properties of fine dust and affect the appearance of the powder coming out from the drill.

Smectites are suggested to form in the shallow subsurface by water percolation in the Noachian period (Ehlmann et al. 2011; Ehlmann 2013, Mangold et al. 2007). Thus, the expected long term subsurface water percolation most probably has altered all grains, also capable to be observed and analysed by the MicrOmega instrument. Hesperian sulphates are mainly surface evaporates, thus evaporation, eutectic freezing, and salt formation might have occurred. The stability of gypsum is close to the current Martian surface conditions and this mineral can be formed in areas with prolonged occurrence of 100 % relative humidity (probably bulk water ice).

Conditions suitable for the formation of micro-volumes of *liquid water* at low latitude in Gale crater were recently identified with night-time hydration of perchlorate grain surfaces (Martín-Torres et al. 2015). This daily water cycle might influence the behaviour of perchlorates during drilling, and especially the extracted sample powders, thus the results of certain measurements (especially the OH content) should be corrected for this effect, implying that exact meteorological data are required during the work of ExoMars. Hydrated perchlorates were already identified by Curiosity in Gale crater (Archer et al. 2014), and they are also expected at the EXM landing site.

The joint usage of instruments could be further exploited on several investigations, especially the results from the MaMISS and the MicrOmega instruments can be combined very well, as the first provides IR data on the original setting and the second provides high resolution data on the powdered material with gain scale information (size and shape together with composition). MaMISS can be used to integrate the results spatially (i.e., which grain type came from which layer) before the crushing and mixing process. Beside the direct sample analysis, the results of WISDOM (cm-resolution subsurface geological investigation) and ADRON (sub-surface water and hydrated minerals) instruments that will cover the landing site is also planned to identify subsurface OH contents, and target the drill. The knowledge on the sedimentary setting, with the added advantage provided by the WISDOM instrument (Ciarletti 2009), will helps in integrating the orbital observations in a stratigraphic analysis in order to optimise the drilling investigations by comparing the dielectric properties based on density, hardness, and porosity of the different locations. In the same way, ADRON will provide information on the subsurface ice content and hydration analysis before drilling, and gives possibility for the ranking between different locations regarding the subsurface OH content. In the ideal case, daily or especially annual hydration changes could be observed that will improve the interpretation of the OH content of the shallow subsurface.

Although during the drilling process the target materials might dehydrate, at low drill speeds and with low temperatures maintained during coring, it is probable that at least detectable quantities of the original OH content of the minerals will be preserved. Measurements should be taken “right after” the drilling operation (in seconds to minutes) and also on longer time periods (days to weeks) in order to demonstrate the effect. Here, the weather monitoring of the nearby surface platform of the lander could provide the required correction data. The sampling procedure is already developed accordingly, aiming to the minimisation of possible OH losses (Schulte et al. 2010) by transferring the sample from the drill onto the Core Sample Handling Mechanism in less than 15 min. There, PanCam and CLUPI will image the sample and immediately ingest it into the rover’s Analytical Laboratory Drawer (ALD) at the end of the sol. Thus, the sample will be protected inside the rover overnight (Baglioni 2014). The sample crushing is planned to take place immediately in the next early morning, when temperatures are still below −40 °C, thus OH and organic content are expected to be preserved. During drilling, the minerals at the rim of the drill rock cylinder are expected to be influenced more than those in the middle of the cylinder (but here if bulk ice is present, rapid water ice sublimation might produce an upward gas jet), while crushing will influence the volume of sample, thus investigation to minimize and further understand the consequences are underway (Baglioni et al. 2013; Magnani et al. 2010). As high water ice content might cause a risk for the drilling process, such locations should be avoided.

Based on the neutron spectrometry data, the drill will certainly cross the OH-containing part of the strata. The borehole walls can be desiccated after drilling; however, to gain a solid understanding of its possible role in changing the hydration state during the processing just like the reactions of the oxidants, some more testing is required. Thus the change in dehydration in the sample and the borehole wall (subsequent MaMISS scans) should be correlated.

Lessons Learned from the Curiosity Rover

Recent results from the Curiosity rover on the regolith and the rock outcrops of the Gale crater provided significant insight into the observational possibilities for the EXM rover. Using the morphological analysis of MAHLI, a bimodal grain size distribution was found, suggesting a related bimodal transport with active deflation (Minitti 2013). Using MastCam and MAHLI images, millimetre-sized nodules were found in the Sheepbed member of the Yellowknife Bay formation (Stack 2014), and these early formed concretions suggest that groundwater played and important role in the diagenesis at this location. The analyzed rocks were Na- and Al-rich mugearite and alkali-rich basalt, with a wide range of Fe, Mn, K content. They could be volcanic and/or volcanoclastic re-deposited rocks, with signatures of weathering and element concentration in certain minerals (Schmidt et al. 2014). Using only the ChemCam instruments, existence of orthopyroxene and palagonite-like materials, range of ferric and ferrous components were identified (Johnson et al. 2015), providing examples how surface multispectral survey helps to separate different potential targets for drill. ChemCam also provided examples for composition-based grain scale separation between materials (Cousin et al. 2015), what is of great potential for MicrOmega.

Among the H_2O and OH bearing components phyllosilicate(s), bassanite, akaganeite, sulphides, and amorphous materials were identified by Curiosity (Ming 2014; Vaniman et al. 2014), beside sulphates, sulphides, iron-oxides or hydroxides. Carbonates and possibly organics have been produced by pyrolysis (Leshin 2013). Careful interpretation of any organics, especially chlorinated ones, is required in the future as perchlorates react with organics at elevated temperature, producing new compounds. Laboratory tests show low molecular weight organic matter reacts at lower temperatures relatively to high molecular weight compounds (Sephton et al. 2014). Perchlorates will also play a unique and important role in the analysis of EXM (Carrier and Kounaves 2014), and their role will decrease downwards during the drilling process.

Combining morphological and compositional observations, the pebble rich conglomerates and lacustrine mudstones suggest ancient wet conditions in Gale crater (Vasavada et al. 2014). Fractures filled with calcium sulphate veins (gypsum, anhydrite, bassanite) were formed by relatively non-acidic circulating fluids (Nachon et al. 2014) from such liquids that persisted well after sedimentation and lithification. This mineral assemblage suggests chemical disequilibrium conditions (with carbonates of alkaline and sulphates of acidic conditions, Archer et al. 2014). Curiosity's work provided a good example on how different in-situ observations could be integrated to identify the past occurrence of an ancient natural pH and low salinity lake with materials of variable redox states, which existed for tens of thousands years (Grotzinger et al. 2014). Many similar observations and conclusions could be reached by the EXM rover as well.

Conclusions

Comparing the expected paleo-environment indicators and EXM rover's capabilities, the following observations are relevant (main topics of expected discoveries are emphasized with bold). During drilling various **structural features** may be intersected, however the available data during this activity might not be enough to recognize all of them. Basic sedimentary structures (i.e., layering and lamination) are the easiest to observe in optimal MaMISS scans. Using the acquired particles' characteristics, such identification also seems possible but it is likely to be limited by the applied sampling interval.

Information gained on the grain morphology, size distribution and the mineralogy together provides insight into the formation, transport, and deposition of the given material. **Aeolian and water flow transported** grains could be separated by their size and shape. The separation of weathering before or after the deposition is difficult with restricted textural information. Here, the joint interpretation of high resolution optical and infrared imaging surveys, and comparison of the grains to each other, might provide **hints on the sequence of events**, together with the regional geological context.

Table 3 Overview how to extrapolate from observations by various instruments (1st column) to processes and past environment types (2-7th columns) of past conditions. The focus should be on identifying vertical differences for each parameters (grain size, OH content). Abbreviations: comp. – composition, heterog. – heterogeneous or heterogeneity, homog. – homogeneous or homogeneity, surf. – surface). Light gray shading marks the two expected environments which might emerge periodically by orbital tilt driven recent climatic changes, and dark shading mark the environment with the long duration of expected habitability conditions together with organic preservation. It is important to note that to detect organics some burial might help much and such burial could be surface location type independent

Processes and environments/ instrument	Fluvial	Subsurface water	Bulk ice	Aeolian	Mass movements	Information on transport distance, source
MaMISS	Layering/gradation with different particle size	Hydrated state, different OH content according to layering	Hydrated state, different OH content according to layering	Characteristic particle size below spatial resolution	Large spatial heterogeneity	
CLUPI	Rounded grains even at large diameter	Abundant weathered ingredients at sub-grain scale	Sublimation till (highly heterogeneous dry grains)	Single max. in grain size distribution	Heterogeneous particle size	Highly homogeneous particle size → longer transport
MicrOmega	Moderately heterog. Comp., possible high OH content	High OH content, phases coexist with ice, Na/Mg ratio in perchlorates	Highly hydrated perchlorates, sulphates	Global/regional composition	Heterogeneous mixture of oxidized surf. And unoxidized subsurf. Layers	comparison to global, regional composition
RLS (Raman)	Moderately heterogeneous comp.	Phases could coexist with ice, high OH content	Highly variable OH content	Mono-mineral dominance	Heterogeneous mixture of oxidized surf. And unoxidized subsurf. Layers)	Comparison to global, regional composition
MOMA	Detrital organics with possible accumulation, poor preservation	Buried organics, good preservation	Few organics expected	Because surface exposure, few organics expected	Possible buried organics	Information on the type of material where organics were bound to

Among the minerals, olivine is expected to be frequent in Martian sediments because it might survive long distance transport due to its hardness. Using the observed ratio of fresh and weathered olivines (identified by MicrOmega and Raman) information on the **weathering potential** (thus w/r ratio, temperature and pH) could be roughly estimated and measured along the drill, where vertical change point to temporal changes of weathering and related past climate.

The high hydration level of perchlorates and sulphates points to saturation conditions in the past, as they might preserve their water content. Bassanite and gypsum are strong indicators of past water ice, but their stability is better in the long term if they are mixed with smectites (dehydration of $MgSO_4 \cdot nH_2O$ systems is slower if smectites are present in the system) and cation exchange also could take place. Sulphates and phyllosilicates can form mostly separately by different processes (Poulet et al. 2005), but occasionally they may be present together and influence each other. The hydration level of minerals should be used together with the textural and sedimentary information to differentiate between past water or ice-related conditions. While textural structures of eutectic freezing might not be observable, upward sulphate and downward chloride migration could also point to evaporation. The existence of much water ice and hydrated minerals together might point to eutectic freezing of bulk brines. Indirect methods, such as the cation abundance could help, for instance by the evaporation of more Mg than Na precipitates as perchlorates, while during the eutectic freezing it is expected that less Mg than Na perchlorates will precipitate (Marion et al. 2010). However because no instrument is present for the direct cation identification, indirect methods should be used to estimate such compositional issues. Regional stratigraphic context from orbital, in-situ panoramic observations, together with the subsurface data from WISDOM, will help to correlate layers with outcrops from a given depth. The co-presence of different mineral phases and sedimentary features could put constraints on estimations of ancient conditions (Table 3).

Based on the above argumentation, substantial improvement is expected for past environment reconstruction, exploiting the joint usage of different observation types and local geological context. It is also worth mentioning that drilling the Martian regolith will be done for the first time, and during the process the rover science team will gain useful experience. More certainly, during the progress of the mission the drilling process will improve significantly. Analytical feedback from the instruments (data from the neutron detector, nearby outcrops for regional context) will also assist in getting the required experience to allow better estimation of the OH content in the subsurface. The knowledge gained during earlier drills will influence the design and planning of the later ones (improving the workflow and the targeting), and despite the EXM is the first rover to carry a high depth drill system, the described synergy will probably reach a high level.

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References

Altheide TC et al. (2010) Mineralogical characterization of acid weathered phyllosilicates with implications for secondary martian deposits. GCA 74:6232–6248

Archer PD et al. (2014) Abundances and implications of volatile-bearing species from evolved gas analysis of the rocknest aeolian deposit, Gale Crater, Mars. JGR 119:237–254
Arevalo R et al. (2012) Advancing the technical readiness of the MOMA miniature linear ion trap mass spectrometer. Int Workshop on Instrum for Planet Miss, 1085
Arvidson RE et al. (2014) Ancient Aqueous Environments at Endeavour Crater, Mars. Science 343:id.1248097
Baglioni P (2014) 2018 ExoMars mission Rover development status. ASTRA Conference, ESTEC
Baglioni P et al. (2013) ExoMars Project 2018 mission - Rover development status. ASTRA Workshop, 3
Balme M et al. (2015) Aaram Dorsum: a Noachian inverted fluvial channel system and candidate ExoMars 2018 rover landing site. 46th LPSC, 1321
Berger G, Ayang-Nzamé L (2014) Acidic Alteration of the JSC-1 Simulant Down to −18 °C: Consequences for the Martian Alteration History. 45th LPSC, 1976
Bibring J-P et al. (2006) Global mineralogical and aqueous Mars history derived from OMEGA/Mars express data. Science 312:400–404
Bish DL (2003) Can hydrous minerals account for the observed mid-latitude water on Mars? 6th Int Conf on Mars, 3066
Bish DL, Scanlan MK (2006) The hydration and dehydration of hydrous mixed-cation sulfates. 37th LPSC, 1011
Bish DL et al. (2002) Properties of potential Martian minerals under simulated surface conditions.33th LPSC, 1895
Bishop, J. L. et al. (2007) Layering of Al- and Fe/Mg-phyllosilicates in Western Mawrth Vallis, Mars, and Implications for Aqueous Processes During the Noachian Period. EOS Trans. Abstract #P13D-1559
Blott SJ, Pye K (2001) GRADISTAT: A grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surf Process Landf 26:1237–1248
Bost N et al. (2013) Missions to Mars: characterisation of Mars analogue rocks for the international space analogue rockstore (ISAR). PSS 82:113–127
Bost N et al. (2015) Testing the ability of the ExoMars 2018 payload to document geological context and potential habitability on Mars. PSS 108:87–97
Brinckerhoff WB (2012) Mars organic molecule analyzer mass spectrometer for 2018 and beyond. Concepts and Approaches for Mars Exploration, 4236
Byrne S et al. (2009) Distribution of mid-latitude ground-ice on Mars from new impact craters. Science 325:1674
Carey JW, Bish DL (1996) Equilibrium in the clinoptilolite-H_2O system. Am Mineral 81:952–962
Carey JW, Bish DL (1997) Calorimetric measurement of the enthalpy of hydration of clinoptilolite. Clay Clay Miner 45:826–833
Carrier BL, Kounaves SP (2014) Effects of Perchlorate on Organic Molecules under Simulated Mars Conditions. AGU Fall Meeting, #P33A-4031
Carter J et al. (2005) Widespread surface weathering on early Mars: A case for a warmer and wetter climate. Icarus 248:373–382
Carter J et al. 2015. Mineralogic context of the circum-Chryse Planitia candidate landing sites for the ExoMars rover mission. 46th LPSC, 1988
Catalano JG (2013) Thermodynamic and mass balance constraints on iron-bearing phyllosilicate formation and alteration pathways on early Mars. JGR 118:2124–2136
Chatzitheodoridis E et al. (2014) A conspicuous clay ovoid in nakhla: evidence for subsurface hydrothermal alteration on Mars with implications for astrobiology. Astrobiology 14:651–693
Chevrier VF (2009) Early Martian surface conditions from thermodynamics of phyllosilicates. Works Modeling Martian Hydrous Env, 4010
Ciarletti V (2009) Performances of the WISDOMGPR designed for the shallow sounding of Mars. 40th LPSC 2367
Clark RN, Hart DC (1981) The salts of Mars. Icarus 45:370–378
Clark BC et al. (2005) Chemistry and mineralogy of outcrops at MeridianiPlanum. EPSL 240:73–94
Cooper CD, Mustard JF (1999) Effects of very fine particle size on reflectance spectra of smectite and palagonitic Soi*l*. Icarus 142:557–570
Cousin A et al. (2015) Compositions of coarse and fine particles in martian soils at gale: A window into the production of soils. Icarus 249:22–42
Dartnell RL et al. (2007a) Martian sub-surface ionising radiation: biosignatures and geology. Biogeosci 4:545–558
Dartnell RL et al. (2007b) Modelling the surface and subsurface Martian radiation environment: Implications for Astrobiology. GRL 34(2):L02207
Dartnell RL et al. (2013) Persistence of Raman biosignatures in the Martian radiation environment. EPSC, 221
De Angelis S et al. (2014) VNIR spectroscopy of Mars analogues with the ExoMars-MaMiss instrument. MSAIS 26:121
Ehlmann BL (2013) Geochemical consequences of widespread Clay Mineral Formation in Mars' ancient crust. Space Sci Rev 174:329–364

Ehlmann BL et al. (2011) Subsurface water and clay mineral formation during the early history of Mars. Nature 479:53–60
Feldman WC et al. (2004) The global distribution of near-surface hydrogen on Mars. JGR 31:E09006
Fialips CI et al. (2005) Hydration-dehydration behaviour and thermodynamics of chabazite. GCA 69:2293–2308
Forray FL et al. (2004) Jarosite stability on Mars. 2ndConf. on Early Mars, 8009
Foucher F, Westall F (2009) Investigating the oldest traces of life by AFM/confocal Raman Spectroscopy: applications for the analysis of martian rocks. AIP Conf Proc 1163:47–58
Foucher F et al. (2011) Effect of grain size distribution on Raman analyses: consequences for ExoMars-C measurements. EPSC-DPS:2011–2426
Foucher F et al. (2013) Effects of powdering rock and mineral samples on optical observations and Raman analyses: consequences for ExoMars measurements. EPSC:2013–2200
Foucher F et al. (2014a) A Blind Test to assess the future ExoMars instruments using samples from the ISAR collection. EPSC, 2014-472-1
Foucher F et al. (2014b) Strategy for the geological exploration of Mars during the ExoMars mission: effect of sample preparation on raman spectroscopy measurements and payload calibration.11th Int GeoRaman Conf, 5003
Foucher F et al. (2015) Revealing the biotic origin of silicified Precambrian carbonaceous microstructures using Raman spectroscopic mapping, a potential method for the detection of microfossils on Mars. J Raman Spectrosc 46:873–879
Friedman GM (1979) Differences in size distributions of populations of particles among sands of various origins. Sedim 26:3–32
Golden DC et al. (1993) Mineralogy of three slightly palagonitized basaltic tephra samples from the summit of Mauna Kea, Hawaii. JGR 98:3401–3411
Gough RV et al. (2011) Laboratorystudies of perchloratephasetransitions. EPSL 312:371–377
Griffiths AD et al. (2006) Context for the ESA ExoMars rover: the panoramic camera (PanCam) instrument. J Astrobio 5:269–275
Grotzinger JP et al. (2014) A habitable fluvio-lacustrine environment at Yellowknife Bay, Gale Crater, Mars. Science 343:1242777
Harvey RP et al. (2006) Cryogenic Evaporite Formation at the Lewis Cliff, Antarctica: A Mars Analog Study. 37th LPSC, 1044
Hasenmueller EA, Bish DL (2005) The hydration and dehydration of hydrous ferric iron sulfates. 34th LPSC, 1164
Herkenoff KE et al. (2004) Evidence from Opportunity's microscopic imager for Water on meridiani planum. Science 306:1727
Hill KS et al. (2011) The Mars-XRD instrument for ExoMars: combined X-ray diffraction and fluorescence measurements. 42th LPSC, 2107
Inman DL (1949) Sorting of sediments in the light of fluid mechanics. J Sediment Petrol 19:51–70
Jänchen J, Brettschneider T (2011) Hydration and dehydration properties of $MgSO_4$, $FeSO_4$ and $Fe_2(SO_4)_3$ close to Martian surface conditions. 42nd LPSC, 1369
Jaumann R et al. (2010) The PanCam instrument on the 2018 ExoMars rover: Scientific objectives. Geophys Res Abs 12:EGU2010-11061-2
Johnson JB et al. (2015) ChemCam passive reflectance spectroscopy of surface materials at the curiosity landing site, Mars. Icarus 249:74–92
Josset J-L et al. (2012) CLUPI, a high-performance imaging system on the ESA-NASA rover of the 2018 ExoMars mission to discover biofabrics on Mars. EGU, 13616
Kahre MA et al. (2008) Investigations of the variability of dust particle sizes in the martian atmosphere using the NASA Ames General Circulation Mode*l*. Icarus 195:576–597
Kereszturi A (2012) Crater wall outcrop analysis for targeting subsurface sampling on Mars. PSS 67:14–27
King TVV, Clark RN (1989) Spectral characteristics of chlorites and Mg-serpentines using high-resolution reflectance spectroscopy. JGR 94:13997–14008
Kok JF, Renno NO (2005) The effect of strong electric fields on lifting of soil particles during saltation. AGU, #P22B-07
Kuzmin RO et al. (2006) Mapping of seasonal bound water content variations on the Martian surface based on the TES data. 37th LPSC, 1846
Leftwich KM et al. (2013) Crystal structure of a new $Na_2Mg(SO_4)_2 \cdot 16H_2O$ hydrate phase measured under Mars-relevant conditions. 44th LPSC, 2795
Leshin LA (2013) Volatile, Isotope, and Organic Analysis of Martian Fines with the Mars Curiosity Rover Science 341:id.1238937
Léveillé RJ (2012) Integrated mineralogical and geochemical studies of authigenic magnesium-phyllosilicates by the Curiosity rover at Gale crater. 43rd LPSC, 2608

Loizeau D. et al. (2006) Phyllosilicates rich terrains in Mawrth Vallis region, Mars, as seen by omega and HRSC/ Mars Express. 37th LPSC, 1658
Loizeau D et al. (2007) Phyllosilicates in the Mawrth Vallis region of Mars. JGR 112(E8):E08S08
Loizeau D et al. (2015) ExoMars 2018: the four final candidate landing sites. EGU, 5555
Lopez-Reyes G et al. (2013) Analysis of the scientific capabilities of the ExoMars Raman Laser Spectrometer instrument. Eur J Mineral 25:721–733
Magnani P et al (2010) The Drill and Sampling System for the ExoMars Rover. i-SAIRASConferece, 044-2769
Mangold N et al. (2007) Mineralogy of the Nili Fossae region with OMEGA/Mars Express data: 2. Aqueous alteration of the crust. JGR 112(E8):E08S04
Marion GM et al. (2010) Modelling aqueous perchlorate chemistries with applications to Mars. Icarus 207:675–685
Martín-Torres H et al. (2015) Transient liquid water and water activity at gale crater on Mars. Nat Geosci 8:357–361
Mazumder MK et al. (2004) Mars dust: characterization of particle size and electrostatic charge distributions. 35th LPSC, 2022
McCarthy C et al. (2007) Solidification and microstructures of binary ice-I/hydrate eutectic aggregates. Am Mineral 92:1550–1560
McLennan SM et al. (2005) Provenance and diagenesis of sedimentary rocks in the vicinity of the opportunity landing site, meridiani planum, Mars. EPSL 240:95–121
Meunier A et al. (2012) Magmatic precipitation as a possible origin of noachian clays on Mars. Nat Geosci 5: 739–743
Ming DW (2014) Volatile and Organic Compositions of Sedimentary Rocks in Yellowknife Bay, Gale Crater, Mars. Science 343:id.1245267
Minitti ME (2013) MAHLI at the rocknest sand shadow: science and science-enabling activities. JGR 118:2338–2360
Mustard J et al. (2008) Hydrated silicate minerals on Mars observed by the Mars reconnaissance orbiter CRISM instrument. Nature 454:305–309
Nachon M et al. (2014) Calcium sulfate veins characterized by ChemCam/curiosity at gale crater, Mars. JGR 119:1991–2016
Newsom HE et al. (2015) Gale crater and impact processes - Curiosity's first 364 sols on Mars. Icarus 249:108–128
Osinski GR, Spray JG (2001) Impact-induced hydrothermal activity within the Haughton impact structure, arctic Canada: generation of a transient, warm, wet oasis. Maps 36:731–745
Pellow-Jarman MV, Hendra JV, Lehnert RJ (1996) The dependence of Raman signal intensity on particle size for crystal powders. Vib Spectrosc 12:257–261
Peterson RC, Wang R (2006) Crystal molds on Mars: melting of a possible new mineral species to create Martian chaotic terrain. Geology 34:957–960
Pilorget C, Bibring J-P (2013) NIR reflectance hyperspectral microscopy for planetary science: application to the MicrOmega instrument. PSS 76:42–52
Poulet F et al. (2005) Phyllosilicates on Mars and implications for early Martian climate. Nature 438:623–627
Rice MS et al. (2013) Reflectance spectra diversity of silica-rich materials: sensitivity to environment and implications for detections on Mars. Icarus 223:499–533
Richardson MI, Wilson RJ (2002) Investigation of the nature and stability of the Martian seasonal water cycle with a general circulation model. JGR 107(E5):5031
Rieck K et al. (2005) Ice/hydrohalite crystallization structures in sub-eutectic freezing experiments in the system $NaCl-H_20$ and possible implications for the properties of frozen brines in Europa: A preliminary report. AGU, #P11B-0110
Robertson K, Bish D (2013) Constraints on the distribution of CaSO4·nH2O phases on Mars and implications for their contribution to the hydrological. Icarus 223:407–417
Robertson KM, Bish DL (2012) Stability of phases in the $CaSO_4{\cdot}nH_2O$ system and implications for their occurrence on Mars. 43rd LPSC, 1547
Rull F et al. (2011) The Raman laser spectrometer (RLS) on the ExoMars 2018 rover mission. 42th LPSC, 2400
Rull F et al. (2013) Raman laser spectrometer (RLS) for ExoMars 2018 rover mission: current status and science operation mode on powdered samples. 44th LPSC, 3110
Schmidt ME et al. (2014) Geochemical diversity in first rocks examined by the curiosity Rover in Gale Crater: evidence for and significance of an alkali and volatile-rich igneous source. JGR 119:64–81
Schulte W et al. (2010) Demonstration of the ExoMars sample preparation and distribution system jointly with an optical instrument head. 38th COSPAR Proc. p. 5
Schulte W. et al. (2012a) The ExoMars Sample Preparation and Distribution System. 39th COSPAR, 1733
Schulte W et al. (2012b) Design and Breadboarding of the Sample Preparation and Distribution System of the ExoMars Mission. i-SAIRAS Conf

Sefton-Nash E et al. (2015) ExoMars 2018 Rover candidate landing sites: Aram Dorsum and the Hypanis Vallis Delta. EPSC:2015–2684
Sephton MA et al. (2014) Perchlorate-induced combustion of organic matter with variable molecular weights: implications for Mars missions. GRL 41:7453–7460
Stack KM (2014) Diagenetic origin of nodules in the sheepbed member, Yellowknife Bay formation, gale crater, Mars. JGR 119:1637–1664
Stoker CR, Bullock MA (1997) Organic degradation under simulated Martian condition. JGR 102(E5):10881–10888
Vago J et al. (2014) ExoMars 2018 Landing Site Selection Process. 40th COSPAR, 1–9-14
Vaniman DT et al. (2004a) Sulfate salts, regolith interactions, and water storage in equatorial Martian regolith. 35th LPSC, 1690
Vaniman DT et al. (2004b) Magnesium sulphate salts and the history of water on Mars. Nature 431:663–665
Vaniman DT et al. (2005) Martian relevance of dehydration and rehydration in the Mg-sulfate system. 34th LPSC, 1486
Vaniman DT et al. (2014) Mineralogy of a Mudstone at Yellowknife Bay, Gale Crater, Mars. Science 343: id.1243480
Vasavada AR et al. (2014) Overview of the Mars Science Laboratory mission: Bradbury landing to Yellowknife Bay and beyond. JGR 119:1134–1161
Wang A (2012) Subsurface hydrous salts and obliquity cycle on Mars. 43rd LPSC, 2172
Weber WH, Hass KC, McBride JR (1993) Raman study of CeO_2: second-order scattering, lattice dynamics, and particle-size effects. Phys Rev B 48:178
Weitz CM et al. (2013) Gypsum, opal, and fluvial channels within a trough of NoctisLabyrinthus, Mars. PSS 87: 130–145
Wentworth CK (1919) A laboratory and field study of cobble abrasion. J Geol 27:507–521
Wentworth CK (1922) A scale of grade class terms for clastic sediments. J Geol 30:377–392
Westall F et al. (2011) Implications of in situ calcification for photosynthesis in a ~ 3.3 Ga-old microbial biofilm from the Barberton greenstone belt, South Africa. EPSL 310:468–479
Westall F et al. (2015) Biosignatures on Mars: what, where, and how? implications for the search for Martian Life. Astrobiology 15:998–1029
Williams R et al. (2013) Martian fluvial conglomerates at Gale Crater. Science 340:1068–1072
Wilson SA, Bish DL (2011) Formation of gypsum and bassanite by cation exchange reactions in the absence of free-liquid H_2O: implications for Mars. JGR 116:E09010
Wilson SA, Bish DL (2012) Stability of Mg-sulfate minerals in the presence of smectites: possible mineralogical controls on H_2O cycling and biomarker preservation on Mars. GCA 96:120–133