Paleo-environment indicators for astrobiology research on Mars

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For the analysis of various astrobiology related potential on Mars, finding from different disciplines should be used in synergy. The analysis of ancient liquid water signatures as channels (Hynek et al. 2010), sedimentary deltas (Pondrelli et al. 2008), standing water bodies (Didibase et al. 2013), and weathering processes based on ancient phyllosilicates (Poulet et al. 2005). However, the reconstruction of ancient conditions is difficult, thus the members of the COST TD1308 action collected and briefly summarized the current knowledge of observable features that could help to reconstruct the ancient conditions on Mars.

Below these indicators are listed, to provide a wider overview than earlier publications that focused on separate indicators; also to identify the missing and weak points; and to provide one more approach for interdisciplinary work to better exploit the analysis of astrobiology potential. The term "indicator" is used for such observable features that hold information on past conditions on Mars, like only some specific aspects (such as temperature, pH, accessible water, etc.) or complex environmental characteristics (like an ancient water erosional-depositional system). Such knowledge supports the better planning of, and data analysis from, future missions to Mars (Barnes et al. 2017).

Table 1. Type of specific indicators

group of indicators	**method of analysis**	**inferred conditions**	**astrobiological relevance**
surface morphology	remote sensing (imaging, topography)	former existence of water or ice	spatial occurrence of potential habitats, climate reconstruction
~~In~~ *in situ* m-µm scale features	*in situ* imaging, excavation	physical depositional conditions, later alterations (H_2O content, transport methods)	searching for favourable conditions (and biomorphic signatures), reconstruction of the sequence of events
mineralogy	remote + *in situ* imaging, Raman, infrared, X-ray data	original chemical conditions and later alterations	temperature, pH conditions, salt content and accessibility of water, water/rock ratio
elements, isotopes	*in situ* and lab. mass spectrometry, orbital neutron spectrometry	evaporation, isotope accumulation, chemistry for mobilization/trapping	processes to support isotopic enrichment, available potential nutrients

Indicators from surface morphology

Morphological indicators of the surface are listed in Table 2. These features were are mostly observable from Mars orbit by remote sensing, however they could also be seen from nearby on the surface. The whole structure should be evaluated for proper interpretation, thus orbital imaging is necessary. The features listed here are mainly analysed in optical range, rarely in infrared or hyperspectral images, and also by laser base data.

Table 2. Indicators of based on surface morphological structures with by name (left) and the conditions they point to (right), with examples. In the second column there are inferred conditions related to climatic characteristics, and the most probable ones are presented among the formation models.

indicator	**inferred conditions**
alluvial fan	surface flow of liquid water (Moore and Howard 2005)
chaos terrains	suggestive of subsurface ice melting (Chapman and Tanaka 2002), or release of bound water from minerals (Max and Clifford 2008)
cryocarstic depressions	former existence of ice and unconsolidated particles (Carr and Schaber 1997)
drumlines	existence and movement of former ice sheets (Kargel and Strom 1992)
eskers	existence of meltwater under former ice sheets (Kress and Head 2015)
faults as outflow channel sources	deep liquid aquifer breakup (Burr et al. 2002)
fluidized ejecta of flow lobe craters	subsurface ice that melted during impact (Mougnis 1981)
fluvial channel	surface flow of liquid water, water source and ice melting (Barnhart et al. 2009), discharge (Irwin et al. 2005), climatic context for surface runoff (Howard et al. 2005)
Gilbert-type delta-like structure	standing water bodies (Dibiase et al. 2013), liquid volume and deposited mass, active duration of rivers (Kleinhans et al. 2010)
gullies	insolation driven melting of formerly deposited ice (Costard et al. 2002)
lake basins	standing water bodies, liquid volume (de Hon 1992)
moraines	glacial ice mass movement, areal distribution of ice accumulation and ablation (Squyres 1978, Head et al. 2010)
polar cap basal melting features	elevated geothermal gradient and/or volcanic heat, melted ice volume (Clifford 1987)
polygonal structures (m scale)	desiccation/ice condensation cycles (Mangold 2005), melting/freezing cycles (Seibert and Kargel 2001)
water ice exhumed in young caters	existence of recently deposited ice below the surface at middle-high latitude terrains

Table 3. Overview of cm-µm scale morphological indicators of the surface. The indicators are listed at the left column, example cases are visible n the middle, while Martian conditions that can be estimated using the given indicator are visible in the rightmost column (occasionally with several models, separated by a semicolon).

indicator	**example(s) if observed**	**indicated conditions/circumstances**
aggregations, concretions	hematite spherules at Sinus Meridiani, H_2O supported aggregation at the Phoenix landing site	supported by iron-oxide, -hydroxide and sulphate cementation; other type is possible by ephemeral humidity with adsorption and cementation; mineral formation according to orbital element changes pointing to moderately elevated temperature and humidity conditions
bedding	planar and irregular lamination, cross and convolute bedding (Grotzinger et al. 2005)	characteristics of the depositional environment; separation of wind/water/ice transport modes; low angle lamination and large-scale cross-bedding might suggest transport across a dry surface (Grotzinger et al. 2004)
cracks in sediments	shrinkage cracks in Erebus crater Olympia outcrop (Grotzingeret al. 2006)	desiccation mainly by H_2O content change; points to earlier H_2O source and later dry conditions
duricrust and cementation	iron-oxide, -hydroxide and sulphates cemented regolith (Kömle et al. 2017)	cementation by sulphates and oxides from trapped atmospheric humidity on the (former) surface; might also form via mobilization of salt ions by adsorbed water layer (Jakosky, Christensen 1986)
fractures and veins	sulphate filled veins (Newsom et al. 2005) in Shoemaker, Grasberg, and Burns formations (Arvidson et al. 2015)	hydrothermal fluid migration; support for the determination of the order of events if superpositional relationships are visible; intergrowth of certain minerals points to eutectic freezing (Rieck et al. 2005); might point to mechanical transport, fluid circulation and desiccation
granular properties	roundness of gravels at Curiosity's landing site (Szabó et al. 2015)	transport mode, relative duration and suffered abrasion estimation; wind strength and atmospheric density (Yingstet al. 2013)
ice/sand wedges	has not been observed but might accompany a range of periglacial features	bulk ice condensation/desiccation; aeolian sand accumulation (Levy et al. 2009)
layer deformations	fallen pyroclastic bomb intrusion at Home Pate (Squyres et al. 2007)	plastic state of deposited material; ice related cryoturbation, water escape features and water content estimation
planation surface in vertical strata	cyclic layer packages at Sinus Meridiani	unconformities in vertical strata might represent subaerial erosion after burial (Wezel, Baioni et al. 2014); intrusion of fluidized clastic material into fractures; production of nodular sulphate dykes and pipe-like fluid conduits; pulses to diapiric rise and exhumation

indicator		inferred conditions
voids left behind by dissolved minerals	psuedomorphic vugs in sulphate rocks in Meridiani Planum (Grotzinger 2004b),	very rough estimation on the previously extant mineral, the plate-shaped voids in Meridiani Planum left behind probably by $MgSO_4*11H_2O$ (Peterson and Wang 2006); hydration and freezing (Marion et al. 2008)
ventifacts, pitted rocks (not primarily vesicular)	various features. like faceted edges, elongated pits, flutes, grooves, etc. at the Pathfinder landing site (Bridges et a. 1999)	produced by wind abrasion scours and ventifacts; ice deposition on rocks under different climate might also exist; might point to different past wind directions (Laity and Bridges 2009)

Indicators from mineralogy

Table 4. Inferred past conditions from mineralogical observations on Mars. The indicated values (temperature, pH, etc.) are rough estimations of averages. Further information can be found in the cited references. (Note: while chlorites and prehnite are two different types of minerals, they are indicated together here as they typically co-occur)

mineral	temperature (°C)	indicated conditions/circumstances
carbonates	from very low up to 680°C (Harvey, McSween 1995)	pH 1.5-7; atmospheric CO_2 plus water are required; if formed under current-like low temperatures it would show ^{13}C enrichment (Socki et al. 2010)
chlorides	low	by evaporation; based on the occurrence they formed separately of phyllosilicates and sulphates, in some case-studies after phyllosilicates and before sulphates (Reusch et al. 2012)
prehnite	200-400°C	hydrothermal; metamorphic conditions (occurs together with chlorite)
sulphates (Ca, Mg)	mainly low	pH ~7 and higher; supported by elevated rock/water ratio; H_2O content is indicative of humidity during formation but certain sulphates could maintain hydrated phase under current conditions; Mg-sulphates have higher hydration state if they were produced by freezing than by evaporation (Marion et a. 2008)
jarosite	<200°C	pH 1.5-2.5 (McKeedby et al. 2017); in acid-sulphate brine
gypsum	colder, less dry, less salty and less acidic than anhydrite	pH ~3 (Marion et al. 2016); might form by acid fog or from basanite by water ice in physical contact
anhydrite, basanite	dehydration >~80°C, but depends on many factors	warmer, dryer, saltier formation conditions than gypsum; located at low latitude sedimentary deposits opposite to higher latitude gypsum (Marion et al. 2016)
haxahydrate	<50°C	pH low, by precipitation from Mg-S-solution (Wang, Freemen 2009)
epsomite	<50°C	pH ~3; by precipitation from Mg-S-solution (Wang, Freemen 2009)

mineral	temperature (°C)	indicated conditions/circumstances
meridianite	<50°C	low pH; formation by precipitation from Mg-S-solution (Wang, Freemen 2009)
kieserite	~95°C	low pH (Al Samir et al. 2012); at <50°C forms only by dehydration (Wang, Freemen 2009); often by dehydration of ferrihydrite (Schwermann 1959)
amorphous sulfate		gains H_2O faster than kieserite at 243 K (Vaniman et al. 2006)
hematite	mainly low T	pH ~8 (McKeby et al. 2017); formation by oxidation of high-T iron minerals; at Terra Meridiani, Aram Chaos and Valles Marineris by precipitation of goethite and dihydroxylation to hematite at or below 300°C (Glotch et al. 2004); above 100°C (Catling, Moore 2003) by hydrothermal activity or buried thermal driven recrystallization
akaganeit (Cl-bearing Fe(III) (hydr)oxide)	using laboratory example test at ~90°C	pH <2; by hydrolysis of Fe(III) in the presence of S and Cl (Pertyazkho et al. 2016); detected by CheMin on Curiosity at Cumberland mudstone
goethite		pH 4-7 (Tosca et a. 2008); dehydrates to hematite under low water activity; could form from magnetite, ferrihydrite or lepidocrocite
phyllosilicates (in general)	relatively low temperature	pH neutral-alkaline, but might survive acidic conditions in general; formation at high W/R ratio; hydrothermal, formation is typical at low-T aqueous (volcanic, impact, subsurface water) environments; stratigraphy of Al rich above FeMg rich ones suggest leaching (Carter et al. 2015), the higher solubility and mobility of Mg compared to Fe and Al suggests that Mg-clay may indicate aqueous conditions (Léveillé 2012); by temperature increase mixed smectite-illite transforms to illite-chlorite
illite	>50°C (but partly 100-200°C)	see “phyllosilactes (in general)”, above
saponite	<100°C	pH 6-9 (at lower values mainly Fe-saponites, at higher mainly Mg-saponites (Tosca et al. 2008)
montmorillonite	low T	neutral to alkaline pH; elevated dissolved Mg concentration (Horowitz 2009)
smectites	0-200°C, but mainly <50°C	pH neutral-weakly alkaline, however based on some tests acidic conditions are not excluded (Peretyazhko et al. 2007); laboratory tests by (Tosca LPSC 2009)

mineral	temperature (°C)	indicated conditions/circumstances
kaoline	100-500°C (but room T formation is not excluded on the Earth (Fripiat Herbillon, 1971)	low pH (more acidic than smectites); high W/R ratio; if occurs together with accompanied amorphous silica and anatase could point to hydrothermal origin; stable at low pH, low K with much SiO_2 content (opposite to mica what is stable at low SiO_2 med. pH, elevated K content); kaoline loses its OH content around 500-600°C
halloysite (more hydrated kaoline)	low-T hydrothermal range, >100°C	pH is moderately elevated, favourable could be both <4.3 and >6.7 (Huang 1974); more hydrated than kaoline, probably never experienced dehydration (as irreversibly dehydrates under low-RH); often occurs together with kaoline and montmorillonite; typical hydrothermal alteration products of alumina-silicates and glasses (Ming et al. 1988)
nontronite	<100°C	pH 8.5-9.5; if it once formed, it has long lifetime relatively to basaltic minerals (Gainey et al. 2012)
zeolite (analcime)	<200°C	high pH (>11) occasionally up to around 13 (Sherameti, Varma 2011, Robinson 1989); low W/R ratio, closed system; alteration of hydrovolcanic basaltic ash and palagonites (Golden et al. 1993), produced zeolites' composition strongly depends on pH and Si/Al ratio

Indicators at elemental and isotopic levels

Certain processes leave behind their signatures in the Elemental or isotopic compositions and ratios have been left behind after certain conditions. In ideal cases interesting units of the samples should be analysed separately, and not as bulk analysis, however the separation of the given part could be difficult on Mars. Not: hydrogen is not listed among the indicators in Table 5, despite it is used to indicate the probable occurrence of H_2O in the shallow subsurface by gamma ray spectrometers.

Table 5. Indicators of elemental and isotopic levels (some of them have already been partially mentioned in Table 4 (like sulphur in the sulphates). The listed examples are from Mars or Martian meteorites in the second column, while the third column shows the formation conditions they imply.

isotopes, elements	observed examples	indicated conditions/circumstances
oxygen isotopes	^{17}O measured in Zagami and Tissint Martian meteorites; ^{18}O in measured in preterrestrial iddingsite of Lafayette (Romanek et al. 1998)	point to distinct isotope reservoirs, but poorly known how to use for temperature estimations in general (Maltsev et al. 2015); the ^{18}O difference between iddingsite, olivine and pyroxene points to low temperature (>100°C) alteration; point to enrichment in secondary silicates and carbonate based in general; the occurrence deviates from Earth based ratio especially above 350°C (Karlsson et al. 1992), implies two isolated oxygen reservoirs; indicate formation of carbonates by low temperature liquids (Clayton and Mayeda, 1988)

isotopes, elements	observed examples	indicated conditions/circumstances
carbon isotopes	observed in the atmosphere of Mars (Webster et al. 2013) and martian meteorites	fluids that exchanged C and O with the atmosphere (Leshin et al. 1996); multiple carbon sources in the surface fines (Leshin et al. 2013)
deuterium	present in all Martian meteorites; its ratio differs for different meteorite groups; measured in phyllosilicates separately too (Mahaffy et al. 2015)	substantially elevated occurrence than on the Earth; in Shergotty meteorite in apatite points to reservoir on the surface and inside the regolith; in GRV 020090 meteorite the H_2O in apatite points to enriched underground water (Hu et al. 2014) on Mars; very early fractionation of near surface reservoirs with atmospheric escape and by 3.9 Ga (Greenwood et al. 2008)
potassium, uranium, thorium	analysed in Martian meteorites, especially in Zagami (Borg et al. 2005), in QUE 94201 (Gaffney et al. 2007); also by some remote sensing based observations from Mars-5 mission (Surkov et al. 1980)	in primary form point to geochemical processes, in secondary form point to leaching and accumulation by aeolian process and aqueous weathering of fine dust (Zolotov et al. 1993); however, complex behaviour regarding the pH and available water is different for K, U, Th; they support the identification of Martian meteorites' origin and formation temperature (Nihara et al. 2012)
chlorine	wide occurrence in topographic depressions at the southern highlands by ponding of runoff water on the surface (Osterloo et al. 2010); also identified inside Martian meteorites (Brigdes et al. 2011)	point to the evaporation of surface water bodies; vertical changes in strata might point to temporal variations in pH and water/rock ratio caused by evaporation from the liquid-saturated sediment; downward increasing concentration at Endurance crater points to the release and migration of Cl from previously precipitated minerals (Squyres et al. 2004, 2006)
phosphorus	identified and analysed on the Martian surface, including in Wishstone by Spirit (Usiu et al. 2008), in Zagami and some other meteorites (McCoy et al 1999)	elevated concentration in the regolith suggests it was soluble element in Martian acidic fluids; in meteorites points to magmatic fractionation events (McCoy et al. 1999); the occurrence of P, Cl and S is often correlated with each other and show elevated occurrence in the regolith in general, probably by leaching and mobilization (Greenwood and Blake 2006)
sulphur	abundant in Mars surface rocks where identified both by remote sensing and *in situ* analysis, as various sulphates also occur in meteorites (Treiman et al. 2005).	vertical changes in strata might point to temporal variations in pH and water/rock ratio caused by evaporation from the liquid-saturated sediment; also could point to intrusive fluid bodies (Wezel and Baioni 2014) and as precipitation produced alteration features (Gooding et al. 1991)

isotopes, elements	observed examples	indicated conditions/circumstances
boron	boron isotopes were analysed in Nakhla meteorite (Spivak-Birndorf et al. 2008); on the Martian surface it was observed *in situ* by Curiosity inside veins (Gasda et al. 2017)	lack of boron isotope enrichment in Nakhla points to high pH driven dissolution (Spivak-Birndorf et al. 2008); occurrence on the Martian surface points to evaporation related migration of subsurface fluids (Gasda et al. 2017) and also to the possible action of thin liquid films (Yen et al. 2005)

Synergy aspects

The joint usage of different indicators for the above listed tables provide the ideal method for paleo-environment reconstruction. Further details could be found in Kereszuri et al. 2016. The summary on the usage of different indicator fir various environment types (rows) are listed in the Table 6. below.

Table 6. Geological "environment types" (different rows) and the specific indicator types (columns) connected to them, which are important for astrobiology related paleo-environment reconstruction.

geological environments and processes	related indicators			
	surface morphology	cm-µm scale layering and grains	mineral composition	elements, isotopes
fluvial activity	channels, depositional fans	moderately-poorly sorted grains with wide size range, cross bedding	various minerals, moderate sorting by type	not characteristics except long term evaporation
lacustrine activity (bulk volume of surface water)	lakebed, bank structure, Gilbert-type deltas	horizontal planar lamination	evaporites, chlorites, carbonates, phyllosilicates	Cl, S, B concentration
subsurface water migration	chaos terrains	ice and sand wedges, layer deformation	differently hydrated minerals, phyllosilicates	leaching increasing the concentration of certain elements
subsurface wet weathering	outcrops of altered minerals	alteration along fractures, grain surfaces, cracks, polygons	phyllosilicate, sulphate production, differently hydrated minerals	C, S, P, B occurrence
bulk ice accumulation	erosion or accumulation (glacier-like) features, lobate ejecta craters	unsorted rectangular blocks	hydrated minerals	

geological environments and processes	related indicators			
	surface morphology	**cm-µm scale layering and grains**	**mineral composition**	**elements, isotopes**
glacier-like ice movement and melting	glacier valleys, moraines, drumlines, eskers, melt pond depressions	bedding types, granular properties, imbrication	hydrated minerals	
thin surface layer wetting	duricrust hardened surface	aggregation, cementation	hydrated minerals, iron-oxides, hydroxides	leaching and accumulation of S, Cl, P, Br, Fe, Al
periglacial-like processes	polygons, cryokastic depressions, desiccation features	sorting, grain orientation, cryoturbation, convolution bedding, ice and sand wedges	occasionally H_2O content	
impact induced hydrothermal activity	spectral signatures mainly around central peaks	fractures and veins	phyllosilicate, zeolite, serpentine, carbonate, chlorite	solvation and accumulation of various mobile elements
volcanic hydrothermal activity	prepared cemented units	filled veins	prehnite, amorphous silica	solvation and accumulation of various mobile elements

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