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A cold and wet Mars

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ABSTRACT

Water on Mars has been explained by invoking controversial and mutually exclusive solutions based on warming the atmosphere with greenhouse gases (the "warm and wet" Mars) or on local thermal energy sources acting in a global freezing climate (the "cold and dry" Mars). Both have critical limitations and none has been definitively accepted as a compelling explanation for the presence of liquid water on Mars. Here is considered the hypothesis that cold, saline and acidic liquid solutions have been stable on the sub-zero surface of Mars for relatively extended periods of time, completing a hydrogeological cycle in a water-enriched but cold planet. Computer simulations have been developed to analyze the evaporation processes of a hypothetical martian fluid with a composition resulting from the acid weathering of basalt. This model is based on orbiter- and lander-observed surface mineralogy of Mars, and is consistent with the sequence and time of deposition of the different mineralogical units. The hydrological cycle would have been active only in periods of dense atmosphere, as having a minimum atmospheric pressure is essential for water to flow, and relatively high temperatures (over ~245 K) are required to trigger evaporation and snowfall; minor episodes of limited liquid water on the surface could have occurred at lower temperatures (over ~225 K). During times with a thin atmosphere and even lesser temperatures (under ~225 K), only transient liquid water can potentially exist on most of the martian surface. Assuming that surface temperatures have always been maintained below 273 K, Mars can be considered a "cold and wet" planet for a substantial part of its geological history.

1. Introduction

Early Mars: warm and wet, or cold and dry? This is one of the major uncertainties in martian science. Geomorphological and sedimentological evidence of liquid water flowing and ponding on the surface of the planet covers much of the martian landscape (Parker et al., 1993; Head et al., 1998; Malin and Edgett, 2000a,b, 2003; Clifford and Parker, 2001; Baker, 2001; Fairén et al., 2003, 2009a; Squyres et al., 2004; Poulet et al., 2005; Bibring et al., 2006; Perron et al., 2007; Mustard et al., 2008), and together with the high D/H of the martian atmosphere pointing to the loss of significant amounts of water to space (Greenwood et al., 2008), collectively indicate that liquid water have been present for long times and in diverse amounts on and/or near the surface in different moments of Mars' history. To explain the presence of liquid water, two different models have been proposed. The first one argues that the early martian climate was substantially different than that at present, capable of sustaining long-term warmer and wetter periods, if only episodically, in an Earth-like hydrological cycle with large lakes or oceans as the evaporative sources (Sagan and Mullen, 1972; Pollack et al., 1987; Baker et al., 1991; Phillips et al., 2001). In the second model, liquid water-related features on Mars have been explained as a consequence of spatially- and temporally-localized thermal energy sources in a cold and dry planet throughout its entire history (Griffith and Shock, 1997; Cabrol et al., 1997; Segura et al., 2002; Gaidos and Marion, 2003; McEwen et al., 2007), in which not even 5 bar of CO_2 would have been enough to rise the temperatures above the freezing point of pure water (Colaprete and Toon, 2003).

The aim of this paper is to suggest an alternative scenario trying to make compatible the widespread geomorphological evidence for long-lasting liquid water on the surface of Mars, with the serious obstacles the climatic models find to simulate planetary conditions in which the mean atmospheric temperatures rise above the freezing point of pure water. To do so, here is considered the hypothesis that aqueous solutions on Mars have been stabilized against freezing by the accumulation of solutes, allowing liquid water to flow in an enduring cold climate.

2. The stability of liquid solutions in freezing environments on Mars

The freezing point depression of aqueous solutions is a function of chemical composition and pressure. Salts are found in the martian soil throughout the entire surface of the planet, and are the primary control on soil geochemistry, indicating that any primeval hydrosphere was probably more salty than that of early or modern

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Earth, and consisted of dilute water–salt brines (Fairén et al., 2009b). The role of solutes as a way to depress the melting point and allow the stability in the liquid state of specific aqueous loaded solutions on the martian surface for temperatures below 273 K, has been considered by several pioneering studies (i.e., Brass, 1980; Clark and Van Hart, 1981; Kuzmin and Zabalueva, 1998; Haberle et al., 2001; Mahaney et al., 2001; Knauth and Burt, 2002; Burt and Knauth, 2003; King et al., 2004; Marion et al., 2008; Altheide et al., 2009; see Table 1). Regarding pressure, 2–3 bars can be assumed as a plausible surface pressure for early Mars (Kasting, 1991; Phillips et al., 2001; Fairén et al., 2004a, 2009b), largely CO_2, necessary to: (a) rise temperatures to values over 245 K so they allow surface solutions to flow and (b) lower the vapor pressure of the liquid solutions with respect to the atmospheric pressure, so they can exist as liquids without evaporating and becoming crusts of hydrated materials.

Fairén et al. (2009b) obtained equilibrium models inducing lineal processes of freezing and evaporation/sublimation of liquid solutions. Simulations were run to analyze the evaporation processes of a hypothetical martian fluid with a composition resulting from the acid weathering of basalt. Interestingly, the model results by Fairén et al. (2009b) were independent of the initial pCO_2 in the atmosphere, and any reasonable atmospheric pressure above the triple point of water for Mars (6.11 mb) resulted in very similar outcomes in terms of liquid water stability. The model explains how a combination of different kinetics of evaporation and freezing affects the minimum reachable temperature of the hypothetical martian solution before its complete freezing, and the sequence of phase formation and destabilization during the temporal evolution of the solution. A general outline of the results presented in Fairén et al. (2009b) is given in Table 2.

The results by Fairén et al. (2009b) indicate that a major fraction of surface liquid solutions with a composition resulting from the weathering of basalts, as reflected in the chemical compositions at Mars landing sites, remains stable at temperatures below 273 K. The higher the initial water mass on Mars and its ionic concentration, the higher the mass of that water that would remain in liquid state at very low ambient temperatures. Higher initial water masses will form more dilute solutions with higher water activities, promoting the precipitation of phyllosilicates; this situation would correspond to the Noachian. Less water will form concentrated brines in which sulfates precipitate, along with huge quantities of ice, a situation characteristic of the Hesperian and the Amazonian.

3. Cycling of liquid water on early Mars at sub-zero temperatures

After the geochemical analysis of Fairén et al. (2009b), a global hydrological cycle can be proposed to explain the long-term presence of open bodies of liquid water on a basically cold early Mars. Depending on input variables, climatic models considering the addition of greenhouse gases to the martian atmosphere offer a wide range of mean surface temperatures. Assuming carbon dioxide alone, for 2 bars of CO_2 and a solar luminosity 75% that of the current value, temperatures are estimated to be between 230 and 300 K (Fig. 1). A more realistic scenario includes additional greenhouse gases, such as small amounts of H_2O–CH_4–NH_3–SO_2, keeping martian mean surface temperatures about 250 K (see Fairén et al., 2009b). For this range of temperatures, liquid solutions may have remained stable in an open acid-sulfate weathering regime during the early history of Mars.

3.1. The onset of the hydrological cycle

In the Earth, the river-forming water comes partly from melted snow and partly from direct runoff of rainwater. On Mars, large-scale valleys and valley networks, ubiquitous on parts of the

Table 1
Very low melting temperatures of usual examples of putative martian solutions.

Substance	K
$H_2SO_4 + H_2O$	199
$Fe_2(SO_4)_3$ (saturated)	201
Up to 3000 ppm salt concentrations (Antarctic Dry Valles)	217
$CaCl_2$ brine, $CaCl_2 + MgCl_2$ and $FeCl_3$	218
$CaCl_2 + NaCl + H_2O$, and $CaCl_2 + KCl + H_2O$	221
$CaCl_2$ eutectic	223
$MgBr_2$ eutectic	230
$MgCl_2$ eutectic, $MgCl_2 + KCl + H_2O$, $MgCl_2 + MgSO_4 + H_2O$, and $MgCl_2 + NaCl + H_2O$	238
$NaClO_4$ eutectic	240
$NaCl_2 + KCl + H_2O$	250
$Na_2SO_4 + NaCl + H_2O$	251
NaCl eutectic	252
$K_2SO_2 + KCl + H_2O$	261
Sulfate salts (maximum)	263
$MgSO_4$ eutectic	269

Table 2
Results of the freezing concentration on the aqueous solutions derived from Pathfinder and opportunity lander data, after Fairén et al. (2009b).

Temperature (K)	Ares Vallis		Meridiani Planum	
	Mass of water (kg)	Mass of ice (kg)	Mass of water (kg)	Mass of ice (kg)
275	1.0	0	1.0	0
273	0.96	0	0.97	0
268	0.90	0	0.89	0
263	0.82	0	0.83	0
258	0.76	0	0.77	0
253	0.32	0.21	0.29	0.19
248	0.17	0.27	0.15	0.26
243	0.11	0.26	0.11	0.25
238	0.08	0.23	0.09	0.23
233	0.07	0.19	0.07	0.19
228	0.06	0.16	0.06	0.16
223	0.05	0.02	0.06	0.02

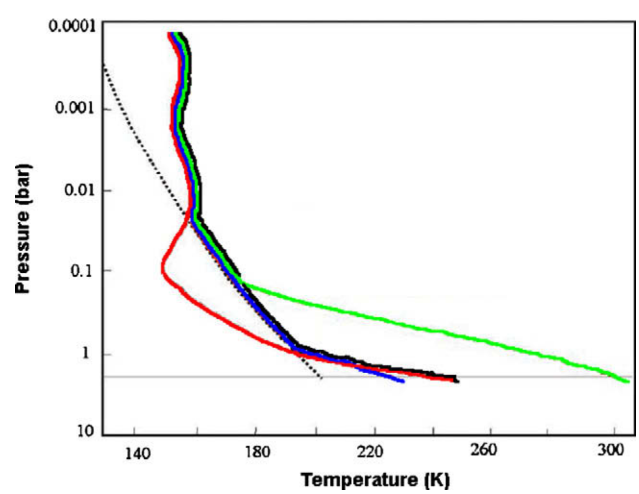

Fig. 1. Temperature profiles on the surface of Mars plotted for 2 bars of CO_2 (horizontal line) and a solar luminosity 75% that of the current value. (Red) Standard Radiative–Convective model by Pollack et al. (1987); (Blue) Radiative–Convective model by Kasting (1991), considering the effect of CO_2 clouds; (Green) Radiative–Convective model considering complete cloud scattering, after Forget and Pierrehumbert (1997); (Black) Temperature profiles considering time average cloud optical depth, in Colaprete and Toon (2003). Dotted line indicates CO_2 saturation. Only considering complete cloud scattering, temperatures on the surface rise above the freezing point of water. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ancient martian terrain, also represent either meltwater from distant snowfields and glaciers, or runoff of local snow precipitation. Here both origins are analyzed separately.

3.1.1. Meltwater

Permanent ice deposits generated widespread massive rock glaciers in the martian highlands. Ice free areas existed because ablation processes in total exceeded all the accumulation processes, as is described in the Antarctic Dry Valles (Wilson, 1979). At the bottom of glaciers the ice contacts crustal rocks, promoting basal melting of ice in the cryolithosphere, in surface ice and in snowpacks. Urquhart and Gulick (2002) demonstrate that with a heat flow of 20 mW/m^2 and a thermal conductivity of 2 W/m K (Clifford, 1993), appropriate for both water ice-cemented regolith and solid basalt with ice filling at less than 10% of the total volume of a fine dust, melting of water ice occurs at less than 3 km depth for surface temperatures $\sim$220 K. The higher the surface temperatures, the shallower the depth at which water ice would melt, therefore preventing the accumulation of water ice in concrete cold spots. This situation would allow the formation of confined crustal aquifers enclosing substantial meltwater, in a similar manner to the confinement of meltwater beneath temperate glaciers on Earth, promoting subterranean aquifers virtually anywhere on the planet.

In addition, the origin and vanishing of localized magmatic intrusions in different locations through time would help melting ice water, by promoting the contact of the widespread ice/snow with the heat sources originated by geothermal heating and/or conductive and advective heat loss from localized magma reservoirs. The heating is driven by magmatic intrusions, which provide sufficient heat flux to cause basal melting of snowpacks and results in meltwater (Fassett and Head, 2006). As there is no evidence for complete planetary coverage by heating events at the same time period, they also offer an explanation for the diverse age and location of the martian valleys. (Early Noachian to Amazonian throughout almost the entire surface of the highlands, see Scott et al., 1995.) Episodes of localized high heat flux in Tharsis–Marineris or Elysium would have resulted in periods of inundations in the martian lowlands (Dohm et al., 2001; Fairén et al., 2003).

Basal drainage of hyperconcentrated meltwater beneath the ice sheets on Mars originated groundwater under rock glaciers, forming cold springs in the same way as in the terrestrial Arctic (Andersen et al., 2002; Grasby et al., 2003) and Antarctic (Lyons et al., 2003; Mikucki et al., 2009) (see Fig. 2). The chemical reequilibration of ice and water with iron- and sulfur-enriched soils produces high ionic level of acidic waters, with elevated concentrations of Fe, SO_4, Br, Na, Cl, and Ca ions. The saltiness of the early martian rivers was next enhanced via two additional sources. First, because the porous nature of the martian regolith, probably caused by its lack of organic matter, allowed the meltwater to flow into the ground for long distances before emerging to the surface. Therefore, the immediate source of the water, in many cases, appears to be sapping of subsurface groundwater, also recharged by precipitation

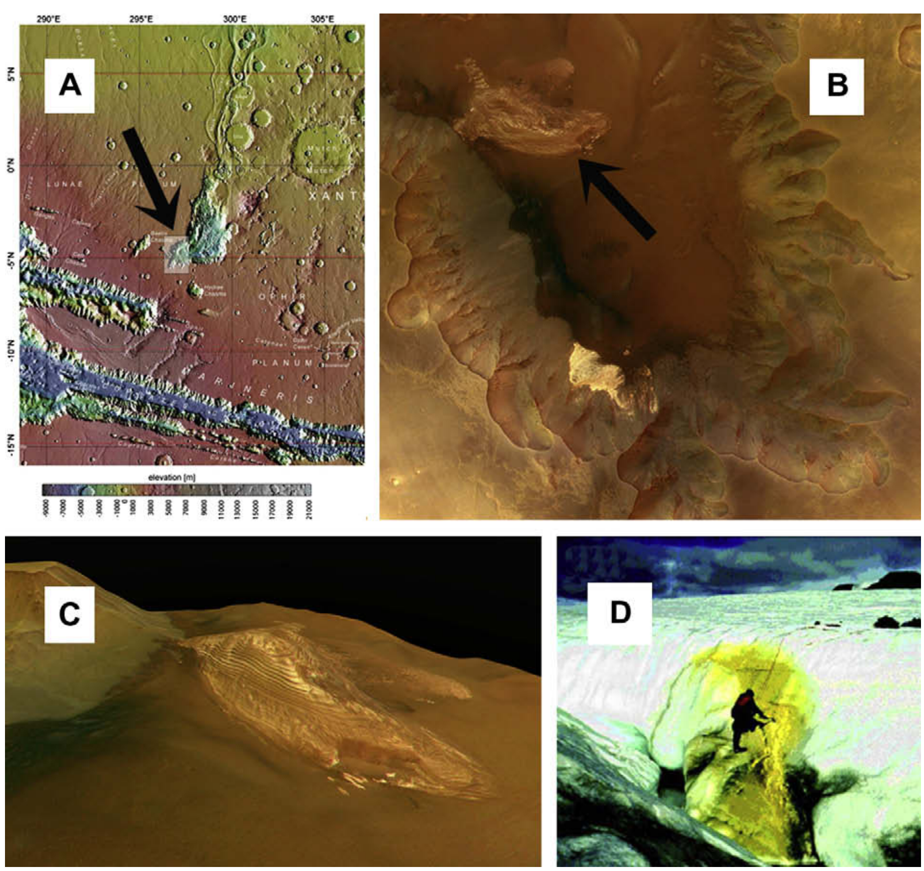

Fig. 2. (A) Location of Juventae Chasma cutting into the plains of Lunae Planum, MOLA elevation data. Arrow indicates the location of a huge sulfate outcrop. (B) Arrow marks the location of a mountain composed of bright and layered material, likely sulfates, outcropping from the Valles of Juventae. The age of the outcrop has been determined in 3.3 ± 0.2 Gyr. Image from HRSC (ESA/DLR/FU Berlin/G. Neukum). (C) Perspective view of the mountain in Juventae Chasma, thought to be composed of sulfates, looking Northeast. This mountain is approximately 2.5 km high, 59 km long and up to 23 km wide, thus in this HRSC image the vertical profile is substantially exaggerated (ESA/DLR/FU Berzlin/G. Neukum). Sulfates are scattered over a wide range of elevations on Mars (Gendrin et al., 2005) and not merely as playa deposits, suggesting spring discharge at different hillslope heights. (D) Dispersed native sulfur at the outlet on the wall of an incised supraglacial melt water channel in the Canadian High Arctic (after Grasby et al. (2003)). A similar process of basal drainage and discharge of subterranean cold, acidic and salty aquifers in periglacial environments could have originated the sulfate mountain in Juventae Chasma.

of snow. As a consequence, the average residence time of melt groundwater was higher in Mars than on Earth, allowing the water to accumulate more salts before coming to the surface. And second, once the water reached the surface, martian paleoweathering would have been noticeably faster due to the lack of vegetation protecting the soils from the energetic erosion of water, finally producing highly saline rivers.

3.1.2. Precipitation

Runoff of local snow precipitation on the Earth does not have enough time to extract salt from the soil by weathering, and there are not enough other volatiles (e.g., sulfate) that are delivered to the atmosphere from volcanism to account for widespread river saltiness by direct atmospheric deposition or rainout. But in early Mars, the atmospheric CO_2 partial pressure was higher by about four orders of magnitude (up to 2–3 bars, as compared to 6×10^{-4} bars), and also sulfur was an important atmospheric constituent. Martian snow/rainwater should therefore have had a pH about 2 log units lower, i.e., 3.7 compared to 5.7 for water containing only dissolved CO_2. This snow/rainwater would undoubtedly leach minerals out of the martian soil more rapidly than it does on modern Earth, where, as weathering is not very efficient, most rivers are fresh. Notorious exceptions of salty terrestrial rivers, like the Tinto river in Spain, are in fact considered very good martian analogs (Amils et al., 2007).

3.2. Cold rivers

Once on the surface, water must have remained in liquid state for time enough to carve out the drainage networks, some of which consist of several tributaries and are several thousands of kilometers long. Valley networks would then develop during millions of years on the martian highlands, conducting acidic water to low-level ponds, where alluvial fans and deltas were occasionally deposited (e.g., Pondrelli et al., 2008; Ehlmann et al., 2008; Kraal et al., 2008a,b). The long-term maintenance of liquid water rivers is well addressed examining the two types of valleys on the martian surface. The formation of mature terrestrial-like dendritic valleys with inner channels (Mangold et al., 2004; Bhattacharya et al., 2005; see Fig. 3A) indeed requires stable liquid water on the surface, sustaining flows over geologically extended periods of time. Their drainage density and degree of ramification are comparable to those in terrestrial valleys thought to be formed by overland flows and seepage (Ansan et al., 2008). The other type is represented by valleys with few small tributaries and tending to start and end up with the same width and shape, likely latest-stage rivers in which the water must have remained in liquid state for a long time once on the surface, to carve out the considerable number of hundreds of kilometer long valleys identified to date (see Fig. 3B).

It is important to note here that a significant number of ancient valleys and rivers may be buried under the martian surface. In the Earth, a complex drainage network consisting in ancient river channels and lakes lays buried under layers of sand in the Sahara desert, and was only revealed by radar imaging (McCauley et al., 1982; Fig. 4). In a dry and windy planet as Mars has been during at least the last several hundreds of millions of years, the burying processes on local geomorphologies will be much more effective, and in fact martian visible outflow channels and valley networks are so dust-covered that few of them show evidence of the presence of hydrated minerals derived from the water that formed the channels themselves. As low-frequency synthetic aperture radar (SAR) has demonstrated its subsurface imaging capabilities on Earth to reveal the dust-covered geomorphology, especially in arid regions, the incorporation of imaging radar systems in Mars missions is indicated to definitively unveil the complete fluvial history of the planet, addressing questions such as where the channels

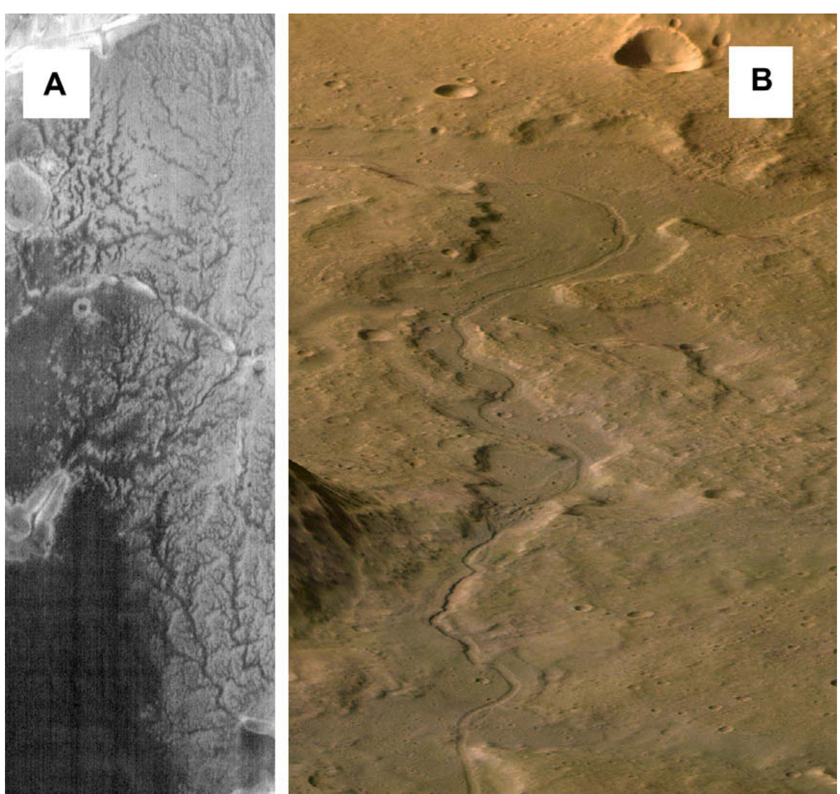

Fig. 3. (A) Portion of THEMIS nighttime infrared image I02119003, showing ancient (Hesperian) dendritic fluvial channels on the mesa west of Echus Chasma. The image is 32 km wide, centered 0.5°S and 279°E (THEMIS Public Data Releases, Arizona State University). (B) Portion of a HRSC image of a modern (Amazonian) valley on Lybia Montes, with no tributaries and constant width and shape. Image centered 2°N and 81°E (ESA/DLR/FU Berlin/G. Neukum).

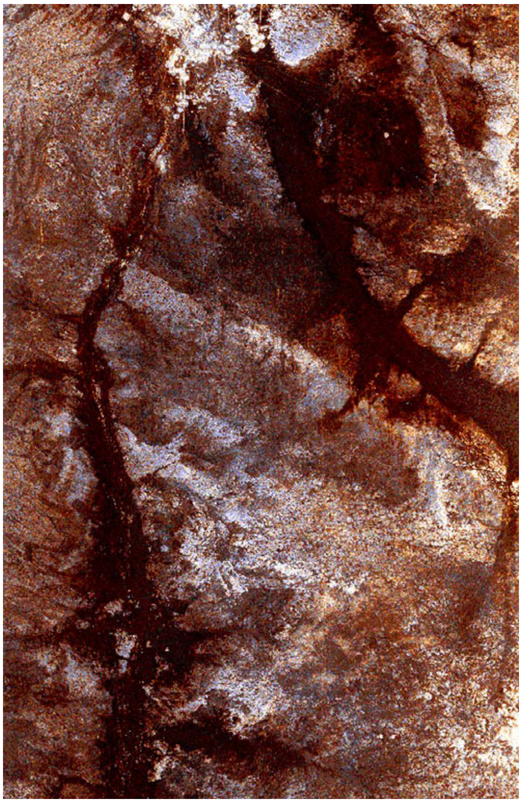

Fig. 4. An ancient river channel buried under layers of sand in the Sahara Desert, southeast Lybia (23.3°N, 22.9°E). The buried river channel was revealed in images taken by the Spaceborne Imaging Radar SIR-C/X-SAR that flew twice on the Space Shuttle Endeavor in 1994. The radar images were processed at JPL and the University of Texas at Dallas. (From http://www.op.dlr.de/ne-hf/SRL-2/p45719_kufra.html.)

originate, where they debouch, and what was the actual extent of the primeval martian fluvial system.

3.3. Lakes, seas, oceans and aqueous mineralogies

Water then filled the martian lowlands and the big impact basins, forming extended and long-lasting oceans and seas. The iron- and sulfur-enriched surface in the lowlands (e.g., Bibring et al., 2006; Boynton et al., 2007; see Fig. 5) likely result from the evaporation of saturated waters after prolonged interactions with crustal rocks and sulfur-rich material. Seas and oceans may have had seasonal floating ice floes, and possibly icebergs (Woodworth-Lynas and Guigné, 2004; Murray et al., 2005), as in the Arctic and Southern Oceans on Earth. Water also ponded inside impact craters forming permanent lakes. Different aqueous sediments record the presence of liquid water on Mars persisting long enough to leave a mineral imprint on the surface (Bibring et al., 2006).

3.4. Closing the cycle

During periods of higher and relatively warmer temperatures, rock glaciers underwent sublimation and wasting, and also ponded water evaporated to the atmosphere. Even on present-day Mars, temperatures exceed the atmospheric frost point everywhere except the poles (Gaidos and Marion, 2003), and so exposed ice will sublimate. Periods of maximum volcanic activity and/or spin axis obliquity and orbit eccentricity enhance these processes. Water accumulated in the atmosphere will precipitate mainly in the form of snowfall, because of the low temperatures: similar to the cycle

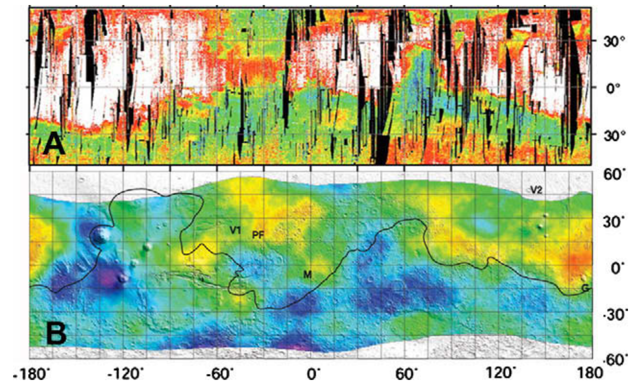

Fig. 5. (A) OMEGA global map of anhydrous nanophase ferric oxides (code color red to white) and mafic materials mainly representing pyroxene content (code color blue to green), after Bibring et al. (2006). (B) GRS map of iron concentrations, after Boynton et al. (2007). Higher concentrations shown in red and yellow, and lower in purple and blue. Ferric oxide phases are present everywhere at the surface, although its abundance varies significantly. Distribution in both maps indicates global dissolution of iron phases into acidic waters across the southern highlands, massive fluvial transfer of soluble ferrous iron into northern plains oceans (in the form of both long-term sustained flow of groundwater and surface valley systems during the Noachian and episodic massive flood discharges by outflow channels during the Hesperian), precipitation of ferrous iron, and photolytic oxidation of ferrous to ferric iron. Alternative hypotheses, such as dust redistribution in the surficial microns (OMEGA resolution), fail to explain the scarcity of ferric oxides all over the highlands. Similar distribution can be found by studying the abundances of potassium and thorium, indicating weathering, evolution of soils, transport and differential deposition of elements related to major water processes (see Dohm et al., 2009). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in the Dry Valles in the Antarctica (McKay, 2004), the hydrological cycle on Mars must have been snow-based. But in the Dry Valles temperatures rise above freezing during some period in the summer, and the cycle can only be maintained because of that critical and essential seasonal thaw, otherwise the entire system would freeze over permanently. On the contrary Mars temperatures may have always been below the freezing point of pure water and the hydrological cycle persisted. For atmospheric pressures of about 1–2 bars, snow accumulates at a rate of 1 m/year at an elevation of 2 km above the water table (Gulick, 2001). Thus, the net accumulation of snow and its metamorphosis to ice formed glaciers and a thick cryolithosphere in the highlands again, closing the cycle. The whole hydrological sequence is schematically represented in Fig. 6.

4. Water and ice through the hydrogeological history of a cold Mars

4.1. The Noachian

The hydrological cycle proposed here would have been active only in periods of dense atmosphere, as having a minimum atmospheric pressure is essential for water to form long-term valley networks, and local relatively high temperatures are required to trigger evaporation and snowfall. Following the model by Fairén et al. (2009b), mean surface temperatures in the order of 245–255 K allowed the flow of 15–35% of the planetary water inventory in the liquid form (see Table 2). Local, temporal and high obliquity excursions with even more elevated temperatures are reasonable assumptions in this scenario. Such atmospheric conditions potentially prevailed during the Noachian, forming hemispheric oceans of water and ice on the northern lowlands (Clifford and Parker, 2001; Fairén et al., 2003; see Table 3 and Fig. 7A), with more ice northbound and a huge northern polar cap. Great lakes also formed

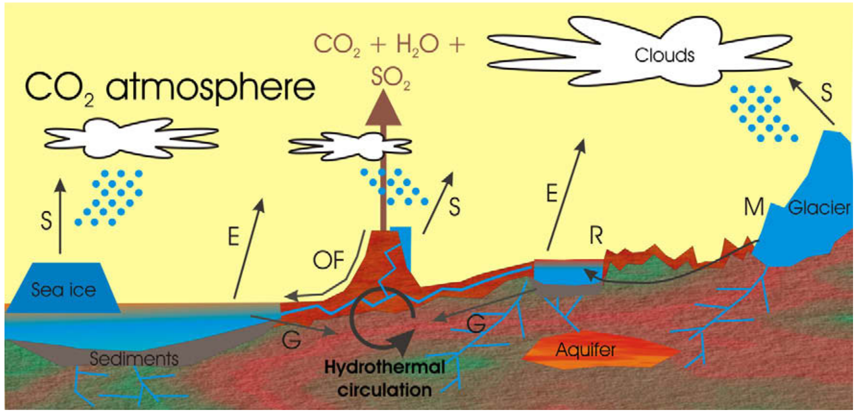

Fig. 6. Schematic representation of land–ocean–atmosphere interactions associated with the presence of a long-term hydrological cycle on Mars in a very cold climate. S: sublimation; E: evaporation; M: meltwater; R: runoff; OF: outburst flooding; G: groundwater flow systems recharge. For the putative martian aqueous solutions modelled here, the cycle is active with an atmospheric pressure of about 2 bar and associated greenhouse effect raising temperatures over 245 K. Similarities to the seasonal water cycle in the terrestrial Antarctic's Dry Valles are evident.

Table 3
Elevation, area, volume, depth (for present-day topography) and length of the putative Noachian and Hesperian oceans on Mars, as shown in Fig. 7.

Epoch	Mean elevation (m)	Basin area (10^7 km^2)	Basin volume (10^7 km^3)	Mean depth (km)	Maximum depth[e] (km)	Global equivalent layer (km)	Length (myr)
Noachian	−1500[a]	5.35	10.54[c]–10.66[d]	1.99	3.75	0.74	0.1–800 (likely ∼800)
Hesperian	−3792[b]	2.43	1.31[c]–1.43[d]	0.54	1.46	0.09	0.1–800 (likely ∼100)

[a] Parker et al. (2000).
[b] Carr and Head (2003).
[c] North Polar Cap not included.
[d] North Polar Cap included.
[e] In the North Polar Basin (minimum topography, −5250 m). From Fairén et al. (2004b).

within impact craters on the southern highlands, such as Argyre or Hellas (Wilson et al., 2007), and also small ponds left polygonally fractured chloride deposits globally widespread over the highlands, mostly in Noachian terrains (Osterloo et al., 2008). Deeply incised valleys interconnected basins in an active hydrological cycle over the intercrater highlands (Howard, 2007) and with the northern plains.

After an active loss of atmosphere (Melosh and Vickery, 1989; Brain and Jakosky, 1998; Carr, 1999; Lundin et al., 2004), surface temperatures dropped below the lower limit calculated in Fairén et al. (2009b) for solutions to flow. In addition, a huge quantity of the water reservoir was lost through thermal and nonthermal escape processes, by chemical weathering of the surface soil (Lammer et al., 2003), and through a progressive crustal assimilation of H_2O (Clifford and Parker, 2001). As a result, the uppermost part of the ocean was completely frozen, resulting in an ice-covered ocean on the northern plains at the end of the Noachian. The ultimate fate of any martian ocean or big lake would probably be complete freezing, as evaporation is a very ineffective process in brines (Sears and Chittenden, 2005) and at very low ambient temperatures: the solutions became more and more concentrated and denser, and a highly saline cryolithosphere formed by deposition of salt minerals in the lowlands due to freezing during the Late Noachian–Early Hesperian. Concentration due to evaporation and freezing explains the large amounts of highly hydrated salts in the dominant layers in basin sequences, and the negligible quantities of anhydrous or less hydrated salts, more likely produced by evaporative concentration at higher temperatures (Kargel, 2004); and also explains the observation that the most soluble salts (halides, Mg-sulfate) coexist with the least soluble salts (Ca-sulfate, jarosite) (Knauth et al., 2005), which is not expected after evaporation in warmer climates.

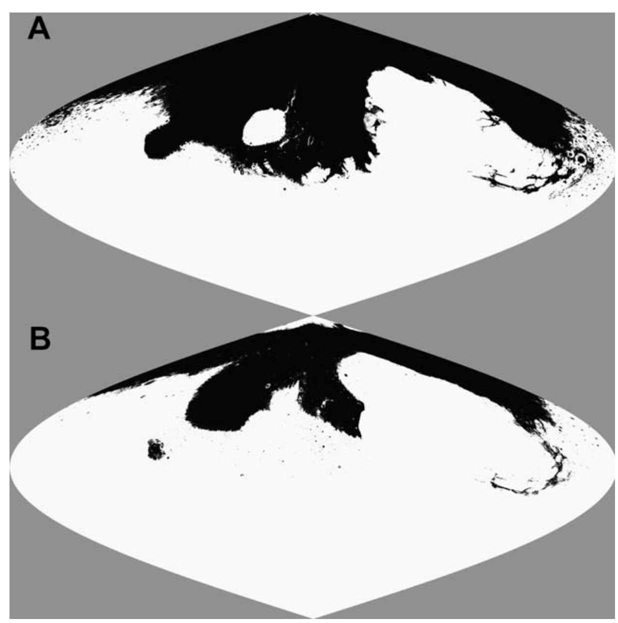

Fig. 7. Mask maps in sinusoidal projection showing the maximum extension of regions on Mars under the sea level (black), during the Noachian (A) and the Hesperian (B). Shorelines extension and localization are after Fairén et al. (2003), and data from Table 3.

4.2. The Hesperian

During the Hesperian, surface temperatures were arguably higher than those today, but it is not likely that they rose to levels comparable to those achieved in the Noachian. After Fairén et al. (2009b), and assuming mean global temperatures between 225 and 245 K, a total of 5–15% of the surface water inventory (massively reduced in comparison to the Noachian) could have been in the liquid form (see Table 2). Small seas could have ponded on the northern lowlands (Fairén et al., 2003; see Table 3 and Fig. 7B). In this scenario, the ionic supersaturation hypothesis qualifies as a compelling explanation for the apparent contradiction between the strong evidence which is provided both for glacier development (Head et al., 2004), and dendritic valley formation (Mangold et al., 2004; Quantin et al., 2004, 2005; Pondrelli et al., 2005) and repeated deposition of layered sediments in lacustrine environments (Glotch and Christensen, 2005; Quantin et al., 2005) in different near-equatorial locations during the Hesperian (Fig. 8). Local climatic and geochemical diversity explain why valley networks and lakes developed in some places and glaciers in others during the same time period: diverse temperature regimes existing in different moments during the 600–800 millions of years that lasted the Hesperian (Hartmann and Neukum, 2001), and at various low latitude areas, would favor local freezing or thaw conditions; and brine composition and salts/water proportions would also experienced large excursions between locations, and throughout hundreds of millions of years.

4.3. The Amazonian

Throughout the Amazonian the climate has been very cold, atmospheric pressures very low, and the planetary budget of water very limited. In these conditions, water vapor partial pressure is the limiting factor for water to flow, and temperatures are close to or below the freezing point for most of the solutions described in Fairén et al. (2009b). Consequently, only transient liquid water can potentially exist on most of the martian surface (Richardson and Mischna, 2005; Heldmann et al., 2005; Cabrol et al., 2006; Fig. 9). Intermittently relatively moist conditions have been reported until geologically very recent times (Fairén et al., 2003, 2009a). In this cold climate, multiple glacial landscapes formed and phases of tropical mountain glaciation occurred even within the past few tens of million years (Kargel and Strom, 1992; Neukum et al., 2004; Shean et al., 2005; Head et al., 2005; Milkovich et al., 2006; Forget et al., 2006). The amount of any post-Hesperian chemical weathering has likely been spatially limited (Christensen et al., 2003; Hoefen et al., 2003; Rogers et al., 2005; Bibring et al., 2006; McEwen et al., 2007; Fairén et al., 2009a), mostly reduced to ephemeral puddles in a hyperarid and cold desert, and atmospheric alteration characterizes Amazonian geochemistry.

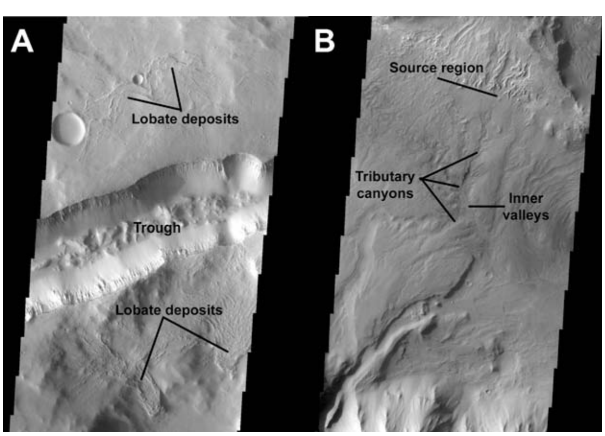

Fig. 8. THEMIS visible-light images of Late Hesperian–Early Amazonian units on equatorial Mars. (A) Portion of THEMIS image V06597003 of ridged deposits and lobate features on the Northern trough rim of the Mangala Valles source region (149.3°W, 18.2°S), interpreted to be formed by accumulations of snow and ice on the graben rim. (B) Portion of THEMIS image V3249001 of a drainage basin showing dense valley networks, tributary canyons and meandering valleys on East Melas Chasma inner plateau (77.5°W, 10°S).

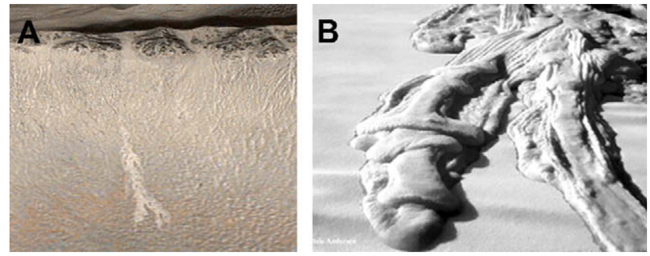

Fig. 9. (A) Portion of MGS MOC2-1619 image of gully deposits in the slope of a crater in the Centauri Montes region, discovered in September 2005 and not observed in previous MOC images of the same crater in August 1999, suggesting contemporaneous water flow on Mars (Malin et al., 2006). The new deposits are light toned and exhibit attributes expected from emplacement aided by a fluid with the properties of liquid water: relatively long, extended, digitate distal and marginal branches, diversion around obstacles, and low relief (Image credit MSSS). (B) Icy brine flowing in low temperature in Axel Heiberg Island, Canadian High Arctic. The brine flows for some minutes and freezes over when the flowing velocity reduces. A complete video can be shown at: http://daleandersen.seti.org/Dale%20Andersen/Home.html. The same phenomena may have created the gully deposits on Mars. (Reproduced with permission of D.T. Andersen.)

5. Astrobiological implications of a cold and wet Mars

From a biological perspective, the presence of liquid water is the only constraint for life development on Mars given the presence of different energy sources (similar to those used on Earth, as reactions involving rock and water at very low temperatures provide geochemical energy free to support metabolism for potential martian microorganisms, see Link et al. (2005)) and alternative radiation protection mechanisms (Amils et al., 2007; Gómez et al., 2007). Terrestrial high acidic and salty waters hold a phylogenetically wide array of microorganisms (Johnson and Hallberg, 2003). Whether favoring an autotrophic or heterotrophic origin of life on Earth, similar conditions of increased salinity (Dundas, 1998; Knauth, 1998; Burt and Knauth, 2003), elevated iron concentration (Holland, 1973), high acidity (Schaefer, 1993; Russell and Hall, 1997; Brocks et al., 2005) and cold environment (Bada and Lazcano, 2002; Vlassov et al., 2004, 2005; Trinks et al., 2005) were likely prevalent.

5.1. Water activity in cold aqueous solutions

To be considered habitable, water on Mars must be available for living beings. Water activity (a_w) is a thermodynamic property of solutions that represent the energy status of the water in a system. a_w is dependent on temperature and salt concentration, and can be used to test the habitability of martian waters. While the a_w of pure water is 1, that of an aqueous solution is always <1. It has been argued (Tosca et al., 2008) that the salinity of surface aqueous solutions on Mars exceeded the levels tolerated by known terrestrial organisms, as the upper a_w they predicted is in the order of 0.70–0.85. These values are relevant only for a little fraction of the terrestrial biota, as halotolerance and halophilism are limited to only a small proportion of Earth's life (Oren, 2008): most terrestrial microorganisms cannot grow at $a_w < 0.9$, comparatively few can tolerate $a_w < 0.85$, survival at $a_w = 0.75$ is limited mainly to extreme eukaryotes and archaea (Oren, 2002, 2008; Grant, 2004), and the numerical limit of habitability is extended to $a_w = 0.61$ by a single fungus shown to grow in high-sugar food (Grant, 2004). Below 0.61 no microbial proliferation has been shown (Harris et al., 1981; Tapia et al., 2007). But the a_w of liquid water in equilibrium with ice at sub-zero temperatures is dependent only on the temperature, as the solute concentration will adjust such that the solution will have the same a_w as ice, if the ice–water equilibrium is maintained (Koop, 2002). Assuming that mean surface temperatures on Mars were in the order of 250 K (Colaprete and Toon, 2003), and that substantial amounts of water remained stable against freezing because of the high ionic concentration (Fairén et al., 2009b), then martian liquid solutions at temperatures over 243 K would have had a water activity higher than 0.90, therefore matching the known limits for terrestrial life (see Table 4 and Fig. 10).

5.2. Molecular adaptations to cold temperatures

A large number of molecular adaptations are clear evidence that many cellular processes contribute to the bacterium's capacity for growth at low temperature, but it is true that our understanding of the molecular structure of cold habitability is still in its initial stage (Scherer and Neuhaus, 2006). Low rates of metabolic activity have been recorded at temperature as low as 245 K in frozen soils (Gilichinsky et al., 2007), both in Arctic and Antarctic permafrost. This is so because within the permafrost, up to 5% of unfrozen water protects cells from biochemical death and mechanical destruction from growing ice crystals, and so the viable cells present are in an overcooled state and in equilibrium with surrounding unfrozen water films (Gilichinsky et al., 2007). Also, the high salt content of the soils and ice in permafrost would lower the freezing point, thus allowing metabolic activity to low temperatures. It is true that the ionic strength would be very high, and this could make it difficult for most species to survive, requiring a great specialization in the microorganisms inhabiting these areas to minimize water loss and osmotic stress, by concentrating intracellular solutes and by adaptations of their enzymes (Boetius and Joye, 2009). But microorganisms are documented on Earth living at as high salt saturation as 35% (Boetius and Joye, 2009, and references therein), the same salt concentration expected for the martian solutions at ~250 K (Table 4) proposed here to have been present during the Noachian. Microorganisms can adapt to lowering temperatures by increasing the "fluidity" of their membranes modifying the structure or the composition of lipids, thereby avoiding the liquid to gel-crystalline membrane transition that would result as the temperature is lowered (Finegold, 1996). Other survival strategies include the synthesis of stress proteins, reduction in cell size, dormancy or sporulation (Russell, 1990), or the use of antifreeze intracellular solutions (Houtkooper and Schulze-Makuch, 2007).

Table 4
Effect of freezing concentration on water activity and salinity in the solutions modeled by Fairén et al. (2009b), analyzing Ares Vallis soil data obtained by the Pathfinder rover.

Temperature (K)	a_w	Salinity (%)
275	0.99	5.2
263	0.98	8.4
253	0.97	31.7
233	0.87	87.9

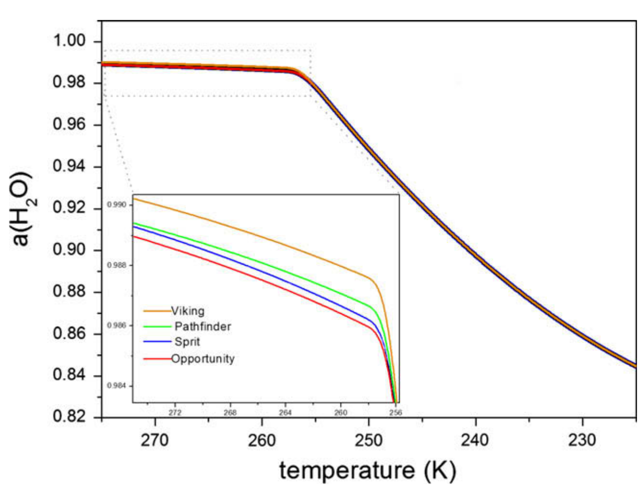

Fig. 10. Water activity for the martian solutions obtained after Mars lander data, as detailed in Table 1 of Fairén et al. (2009b). The calculations were performed using the Phreeqc2.15.0 software, and the temperature dependence of the equilibrium constant was modeled using the Van't Hoff expression. In the version used here, the Phreeqc program implements the Debye–Hückel approach for the calculation of activities as the product of several fundamental constants. The model was run at decreasing temperatures from 275 K to 225 K.

The possibility for life to survive the dryest and coldest periods on Mars (such as at present) is challenging. On Earth, microorganisms have evolved to accommodate to a variety of extreme conditions: desiccation, freezing temperatures, saltiness and acidity. Active communities of psychrophilic bacteria that thrive within liquid inclusions in frozen environments at temperatures as low as 250 K both in Siberia, Greenland and the Arctic (Rivkina et al., 2000; Bakermans et al., 2003; Junge et al., 2004; Tung et al., 2006) and in Antarctica (Priscu et al., 1998; Mahaney et al., 2001; de Angelis et al., 2005; Gilichinsky et al., 2007; Laybourn-Parry, 2009 and references therein) and that derive energy from iron and sulfur compounds in areas covered by glaciers and thick permafrost in or near the Arctic (Grasby et al., 2003; Tung et al., 2006) and the Antarctic (Mikucki et al., 2009), could serve as analogs to search for iron-sulfur based ecosystems living at extremely low temperatures in dilute acidic subterranean brines or within tiny brine pockets in crustal ice on Mars. In fact, experimental data demonstrate that halophilic bacteria remain viable at 193 K in the presence of 25% NaCl (Mancinelli and Landheim, 2002). If similar types of environments have existed (or even exist today) at the surface or subsurface of Mars hosting chemolithoautotrophic microorganisms (Fairén et al., 2005), the results presented here would serve to explain how water has been supplied and maintained liquid in such environments, providing additional arguments to search for evidences of a biosphere of acidophiles–psychrophiles in different moments of the geological history of Mars.

5.3. Methanogens on Mars?

Methanogens are possible candidates to be the source for the methane recently detected in the martian atmosphere (Formisano et al., 2004; Geminale et al., 2008), as the alternative abiogenic sources seem implausible (Ryan et al., 2006). Methanogens are members of the domain Archaea that metabolize H_2 and CO_2 and produce CH_4. At very cold temperatures and anoxic conditions, a subsurface microbial metabolism coupled to sulfate reduction can produce large amounts of CH_4 (Winfrey and Zeikus, 1977). Also, methanogenesis has been described at very high salinity (Joye et al., 2009). As such, a putative martian biosphere could have been formed by communities of halotolerant acidophilic methanogenic psychrofiles, existing contemporarily and/or in the wetter past, creating microniches with very low redox potentials (under −200 mV) and slightly acidic pH values (likely over 5, although methanogenesis has been reported on Earth at pH as low as 4.2, see Florencio et al. (1993)). ATP production would be driven by H_2 as electron donor and CO_2, SO, Fe^{3+}, or NO_3^- as electron acceptors, as it happens on Earth, where methanogenesis is one of the primeval mechanisms for energy scavenging (Wächtershäuser, 1994). If the CH_4 was formed in the past, the model presented here on salty aqueous solutions can account for the current presence of methane in the atmosphere of Mars, as small changes in salinity may be effective drivers for clathrate hydrate dissociation and CH_4 release (Elwood Madden et al., 2007). In addition, if life developed on Mars, it seems reasonable to consider the possibility that it was constituted by chemolithotrophs based on the Fe and S geomicrobiology, living in environments where iron-sulfate precipitation was favored by physical chemistry, to the same extent as the first terrestrial communities lived in carbonate-dominated environments.

5.4. The search for a martian biosphere

The search for extinct, dormant or active life forms on Mars is promising when considering a cold and wet environment: First, viable microorganisms and their metabolic by-products have been identified in the oldest permafrost on Earth (Beacon Valley, Antarctica, 8.1 Ma, see Schaefer et al., 2000; Gilichinsky et al., 2007), suggesting the possibility that ancient martian microbes can be also found in the martian permafrost. Second, microorganisms can be shielded from UV radiation by salt layers (Yopp et al., 1979; Rothschild, 1990), sulfate mineral matrices (Martínez-Frías et al., 2006), iron minerals (Phoenix et al., 2001), and iron in solution (Gómez et al., 2007), indicating that the same solutes that allowed the water to remain in liquid state at sub-zero temperatures in early Mars also contributed to block the harmful radiation. And third, sulfates (Aubrey et al., 2006; Bowden and Parnell, 2007) and iron-bearing minerals (Fernández-Remolar and Knoll, 2008) preserve biological compounds for geologically long periods of time, in the same way as Archean carbonates produced in shallow seas on Earth provide the first clear evidence for microbial life (van Kranendonk, 2006), and therefore sulfate deposits are prime candidate materials to search for biomarkers and extinct and/or extant life forms on Mars.

In the search for evidences of life in martian sulfate minerals, here two different techniques are outlined (Fairén et al., in preparation). First, sulfates on Earth are produced by abiotic processes as well as with the mediation of biological activity (Amils et al., 2007). Both types can be differentiated by means of thermal volatilization coupled with mass spectrometry: different TV-MS fragmentation patterns between biogenic and abiogenic samples would indicate if the synthesis of sulfates has been biologically-mediated or not. Consequently, in the case of a martian in situ study or in a sample return mission, the analysis of the thermal behavior of martian sulfate minerals by TV-MS represents a promising technique to detect evidence of past biological activity on Mars. And second, the analysis of the isotopic fractionation in the martian sulfate deposits can help to determine the presence of life, as is done in the Earth with carbonates: sulfate reducing bacteria fractionate the sulfur atoms producing sulfide which is typically enriched in ^{32}S, and consequently the sulfate that remains in the substrate is more enriched in ^{34}S (Fry et al., 1988; Henneke et al., 1997). Elemental sulfur enriched in ^{34}S versus sulfide will be a definitive biogeochemical marker for the presence of sulfide-oxidizing bacteria in modern or ancient martian environments.

6. Conclusion: the case for a "cold and wet" Mars

Climate models assert that martian surface temperatures have always been maintained below 273 K, and evidences for the flow of liquid water are apparent and abundant throughout the landscape of the planet. Therefore Mars can be considered a "cold and wet" planet for its entire geological history. The hydrogeological model presented here reconciles accumulating evidence for long-lasting liquid water on the surface of Mars in the form of oceans or seas, valleys, channels, gullies, deltas, layered outcrops and aqueous-derived mineralogies, concurrently with widespread glacier formation and existing climatic models which predict serious obstacles to warm martian climate. As such, the model offers a compelling and self-consistent theory to account for a complete martian hydrological cycle. Indeed, all the factors previously suggested to warm the martian atmosphere over the freezing point of pure water, as well as punctuated events releasing water to the surface and groundwater circulation, could be important contributors to firmly assure the presence of substantial quantities of liquid water in different moments on the surface of a really alien, martian Mars.

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