

## Prime candidate sites for astrobiological exploration through the hydrogeological history of Mars

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### Abstract

The hydrogeological evolution of Mars has been proposed to be dominated by the development of the Tharsis Magmatic Complex through superplume activity, with related magmatic-pulse-driven flood inundations that directly influence the shaping of the northern plains, the evolution of the atmosphere and climate, and subsurface and surface water processes. On the other hand, several possible biological models and terrestrial analogues have been suggested for Mars during the last decade, including the description of putative microfossils and the proposal of sedimentary units. Here we revisit these scenarios and present a possible bridge that integrates the geological, paleohydrological, and the putative biological histories of the planet. We primarily focus on the Noachian, a time period that arguably has recorded an inner dynamo, plate tectonics, and an ocean that may have covered one-third of the total surface area of Mars, due to its implications on the possible origin and early evolution of life. This stage is followed by a long-lived cold and dry phase, briefly punctuated by transient magmatic-driven hydrological cycles, dominated by a stagnant-lid/superplume regime, which directly influences the processes of natural selection on the putative early biosphere. Based on this hypothesized evolution of the planet, we suggest three martian locations as prime candidate sites for astrobiological exploration, each one corresponding to an inundation period: Meridiani Planum (Noachian/Early Hesperian), Mangala Valles (Late Hesperian/Early Amazonian), and Orcus Patera (Amazonian).

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### 1. Introduction

The main question to answer in the search for life on Mars is also an ancient problem in Biology: how did life arise and initially evolve? Once initiated, life has been able to colonize every habitat on Earth where biochem-

istry can operate and use almost every thermodynamically favourable energy couple. In an analogous manner, we propose that, if life initially appeared on Mars, its subsequent evolutionary history might have been fundamentally determined by the evolution of the geochemical environment, especially influenced by endogenetic-derived global hydrogeological cycles covering almost all of the entire history of Mars (Fairén et al., 2003). Tharsis is considered here to be the main driver of the proposed global hydrological cycle.

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Although as of this writing there is no definitive evidence for life to have existed on Mars, here we assume this possibility because of its relevance in building a complete and self-coherent model, integrating the many proposed life forms and metabolic pathways into a single evolutionary history, coupled with recently proposed geological and paleohydrological histories of Mars (Baker et al., 1991; Fairén et al., 2003).

Based on this integrating bridge, we unfold three prime candidate sites for further astrobiological exploration, each one corresponding to specific hydrological cycles discussed below that are largely driven by major stages of geological activity recorded for Tharsis (Dohm et al., 2001a; Anderson et al., 2001). This approach may help to motivate further analyses from orbital platforms and in situ geological sampling and return of materials, which might serve to unveil the possible biological history throughout the geological/hydrogeological evolution of Mars.

## 2. Hydrological cycles on Mars

Based on the ideas of episodic greenhouse atmosphere and water stability on the lowlands of Mars (Baker et al., 1991), a conceptual scheme for water evolution and associated geomorphological features on the northern plains has been recently proposed (Fairén et al., 2003). This model highlights Tharsis-triggered flood inundations and their direct impact on shaping the northern plains. Distinct episodes of endogenetic activity that led to the formation of the Tharsis Magmatic Complex are conceived here as a driving mechanism for a massive injection of volcanic CO<sub>2</sub> and CH<sub>4</sub>/NH<sub>3</sub> to the martian atmosphere in relatively short timescales (as it occurs in Earth superplumes, see Jahren, 2002), so dramatically influencing the atmospheric behaviour, as well as making possible the deconfinement of putative biological niches and thus resulting in life's either extinction or radiation.

The inundation hypothesis, however, is not the only hypothesis that offers explanations for martian geomorphological features. Hypotheses to explain the volatile history of Mars which is reflected on its surface include: the variation of martian orbital parameters (Touma and Wisdom, 1993; Laskar and Robutel, 1993), the heat generated by impacts (Segura et al., 2002), and liquid CO<sub>2</sub> as an erosive agent that resulted in a variety of landforms such as the outflow channel systems (Hoffman, 2000). A complete discussion of alternative hypotheses can be found in Fairén et al. (2003).

### 2.1. Noachian to Early Hesperian: The first great ocean

During extremely ancient Mars (see Table 1 for Martian Chronology), a magnetic field was active (from

Table 1  
Absolute age estimates for the surface of Mars

Epoch	Absolute age range (Ga)
Late Amazonian	0.6–0.3 to present
Middle Amazonian	2.1–1.4 to 0.6–0.3
Early Amazonian	3.1–2.9 to 2.1–1.4
Late Hesperian	3.6 to 3.1–2.9
Early Hesperian	3.7–3.6
Late Noachian	3.82–3.7
Middle Noachian	3.95–3.82
Early Noachian	>3.95

Condensed from Fig. 14 of Hartmann and Neukum (2001).

approximately 4.4–4.0 Gyr; e.g., Stevenson, 2001) and plate tectonism may have also been in operation (Sleep, 1994; Fairén et al., 2002; Fairén and Dohm, 2004). Subsequent to or concurrent with the shut down of both the magnetosphere and plate tectonism, the initial stages of major development of the Tharsis magmatic complex (Stages 1–3: stage information is based on Dohm et al., 2001a, and Anderson et al., 2001; and schematically shown in Fig. 1) resulted in the first inundation, an ocean that would have covered the northern plains (approximately 1/3 of the total surface area of Mars; e.g., see Clifford and Parker, 2001). This primitive ocean is best portrayed by a Meridiani–Arabia merged shoreline (revised shoreline by Ruiz et al. (2003) and Fairén et al. (2003) from the Meridiani and Arabia—Contact 1 shorelines of Clifford and Parker (2001), and labelled “Shoreline 1” in Fig. 2).

During this time of incipient TMC development, the CO<sub>2</sub>-charged atmosphere was much thicker than at present. Although thermal escape or impact events triggered atmospheric erosion during the period of heavy bombardment (Jakosky and Phillips, 2001), an average of 0.5–1 bar of CO<sub>2</sub> is estimated for the early martian atmosphere at the end of the heavy bombardment (Carr, 1999). However, the greenhouse effect of gaseous CO<sub>2</sub> and H<sub>2</sub>O would not be sufficient to ensure stable liquid water on the martian surface during the Noachian: not even 1–5 bar of CO<sub>2</sub> were enough to maintain milder temperatures on the surface of Mars (Kasting, 1991), corresponding to globally and orbitally averaged conditions and a 30% reduction in solar luminosity of the early Sun. Kasting (1997) summarized two ideas that could be a solution to the problem of liquid water stability on Mars. One was advanced by Sagan and Chyba (1997), arguing that reduced greenhouse gases such as CH<sub>4</sub> and NH<sub>3</sub> may have contributed to warm early Mars enough to maintain liquid water on its surface. Under the dim light of a young Sun cooler than today's, certain groups of anaerobic bacteria pumped out large amounts of methane on Earth, thereby keeping the early climate warm and inviting (Kasting and Siefert, 2002), and as such, putative

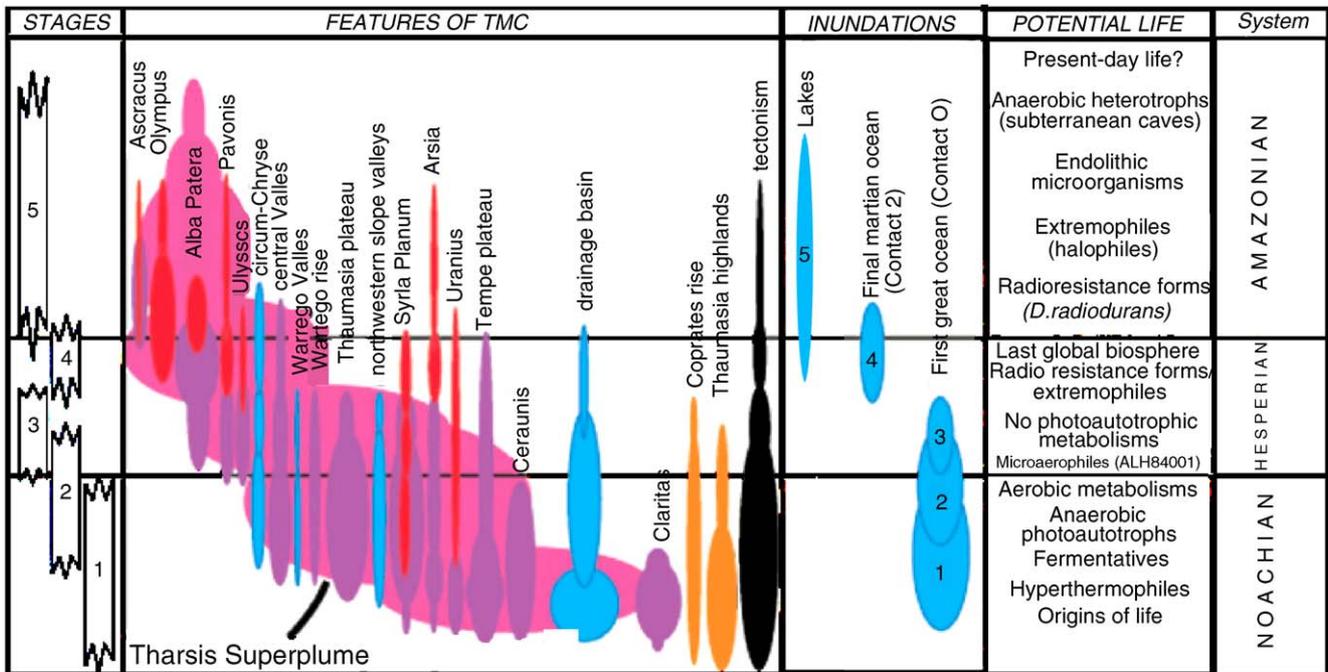


Fig. 1. Chart comparing the evolutionary stages of geologic activity in the Tharsis Magmatic Complex/superplume region with major geologic features and proposed inundations (Stage information corresponds to Stage information of Fig. 2); size of solid areas roughly proportional to degree of exposed deformation and feature extent. Violet—centers of tectonic activity interpreted to be the result of magmatic-driven uplift and local volcanism, dike emplacement, and hydrothermal activity; orange—mountain building; blue—water; red—primarily emplacement of shield-forming and lava-field-forming lavas.

organisms may have done the same for Mars. Tharsis volcanoes are also very good candidates to supply greenhouse gases to the atmosphere. A second suggestion was advanced by Forget and Pierrehumbert (1997), who argued that carbon dioxide ice clouds in the troposphere may have contributed to warming early Mars, as ice particles reflect the outgoing thermal infrared radiation back to the surface. Cloud warming mechanisms are complicated, however, because the amount of surface warming depends on many details such as particle size, cloud height, cloud optical depth, and fractional cloud cover (Kasting, 1997). The question whether and how Noachian Mars could have been kept warm enough for liquid water to be stable on its surface will remain an active research topic for at least the near future.

Landforms evidencing sedimentary processes during a milder and wet early Mars have been recently recognized using MOC imagery and MOLA data (Malin and Edgett, 2003), and further substantiated by images and spectral data through the Mars Exploration Rover (MER) *Opportunity*, which returned field-based evidence for salty and acidic water masses (Squyres et al., 2004). The *Opportunity* landing site occurs near the Meridiani–Arabia shoreline proposed by Fairén et al. (2003), corroborating the hypothesized extensive Noachian ocean.

Without the magnetic field protection in the Late Noachian (Stage 2), the atmospheric erosion rate would have increased, due to energetic solar particles forcing dissociation upon near-surface water molecules, releasing the heavier oxygen into the soil, and allowing the lighter hydrogen to escape into the exosphere (e.g., Jakosky et al., 1994). Surface water stability, however, could have been possible during hundreds of million of years (Lundin, 2001), especially if local remanent magnetic anomalies survived in the crust once the inner dynamo shut off (Jakosky and Phillips, 2001). The ocean would thus have been diminished and ice-covered during the Late Noachian (Parker et al., 1993), and its possible associated geomorphologic features would be mostly erased or largely subdued by subsequent tectonism, wind erosion and major hydrous cycles.

An Early Hesperian pulse of Tharsis activity (Stage 3; Dohm et al., 2001a, c; Anderson et al., 2001) may have triggered more floodwaters to the northern plains adding to the potentially already existing northern plains ocean and/or ice body/ground ice. This third major pulse of Tharsis activity may have contributed enough CO<sub>2</sub> and other volatiles to the atmosphere to induce a short-lived (approximately tens of thousands of years; Baker et al., 1991) climatic perturbation. Another potential contributor to the flood inundation hypothesis during the Early Hesperian is incipient development of the Elysium

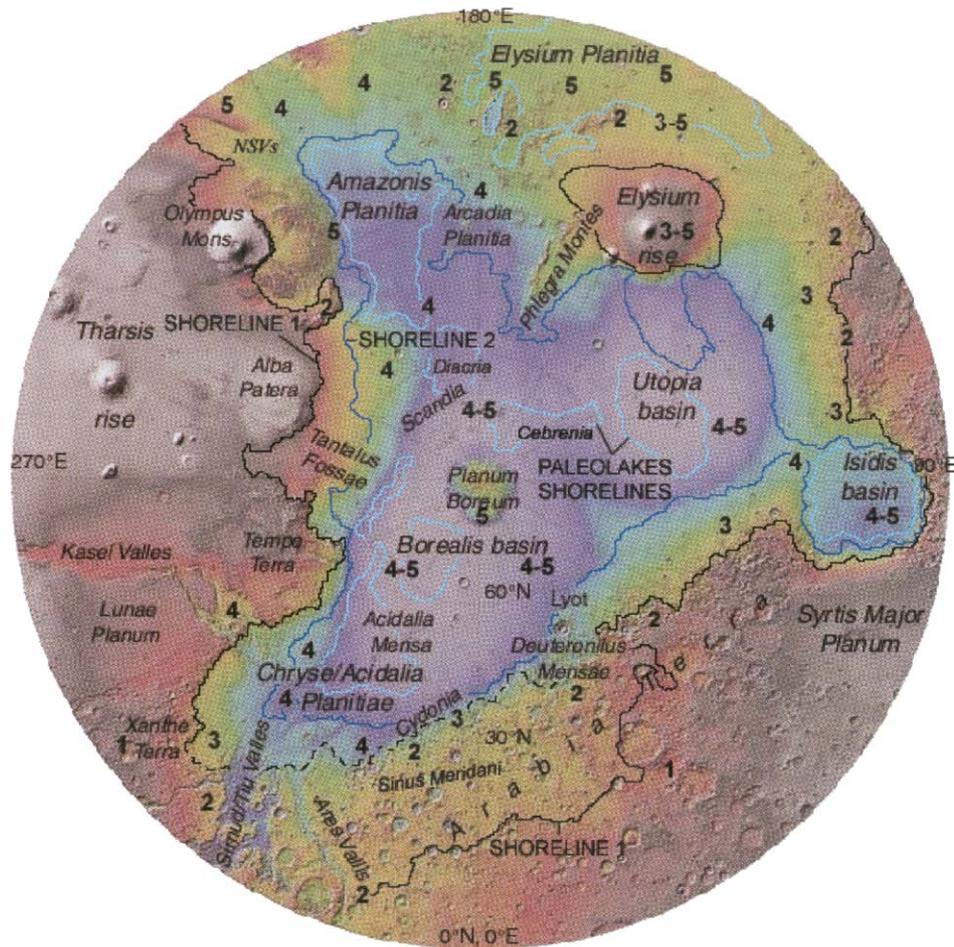


Fig. 2. Topographic shaded relief map of the northern hemisphere of Mars constructed from Mars Orbiter Laser Altimeter (MOLA) data showing major geographic features of the northern hemisphere, including possible oceanic shorelines and paleolakes. Physiographic setting of Meridiani–Arabia extended shoreline (Ruiz et al., 2003; Fairén et al., 2003) based on: (1) western Arabia Terra and northern Meridiani Planum geomorphologically correspond to the martian lowlands instead of to the highlands (Edgett and Parker, 1997); (2) the Arabia region displays lowlands-type crustal thicknesses (Zuber et al., 2000); (3) Meridiani–Arabia extended shoreline is the locus of debouch of almost every Noachian valley channel in Arabia (Carr, 2002); (4) Meridiani Planum encloses the greatest Late Noachian–Early Hesperian martian hematite deposit, superposed on Middle and Late Noachian terrains (Hynek et al., 2002), and likely formed by a process involving chemical precipitation from aqueous fluids (Christensen et al., 2001); and (5) instruments aboard *Mars Odyssey* have recently revealed relatively elevated abundances of hydrated materials, and possibly concentrations of ice beneath the surface of Arabia Terra–Meridiani Planum (Boynton et al., 2002; see Fig. 10). Polar Stereographic projection; scale varies with latitude; modified from Tanaka et al. (2003).

rise (e.g., Tanaka, 1986). If both Tharsis and Elysium were concurrently active during the Early Hesperian, then significant climatic responses would be expected, including growth of ice sheets at the poles (Baker et al., 1991; Head and Pratt, 2001), outflow events of enormous magnitudes to the northern plains (e.g., Nelson and Greeley, 1999; Dohm et al., 2001b), and spring-fed discharge along an unvegetated (unstable) highland–lowland boundary (e.g., Tanaka et al., 2003).

## 2.2. Late Hesperian/Early Amazonian: the last Martian ocean

Between the disappearance of the Noachian–Early Hesperian great ocean and the temporary establishment

of a Late Hesperian minor sea, a cold Late Hesperian intermediate period is proposed to have occurred (Fairén et al., 2003), perhaps related to a transient pause of the Tharsis development (Dohm et al., 2001a). The freezing of the upper most part of the northern plains water body would have protected it from evaporating for a long lapse of time (Wallace and Sagan, 1979), allowing the persistence of a diminished and ice-covered ocean in the Early Hesperian, especially if the water was hypersaline.

Following this period of magmatic quiescence, a major pulse of Late Hesperian/Early Amazonian Tharsis activity (Stage 4) triggered yet more floodwaters to the northeast, incising the existing circum-Chryse outflow channels, and to the north-northwest, carving

Mangala Valles, which ponded in the northern plains to form a sea in the deeper recesses of the lowlands (enclosed by Contact 2 in Parker et al., 1989, 1993, and Deuteronilus shoreline in Clifford and Parker, 2001, and labelled “Shoreline 2” in Fig. 2) inset within Meridiani–Arabia extended shoreline. This new pulse coincides with: (1) the development of the giant shield volcanoes of Tharsis and Elysium (Scott and Tanaka, 1986), which includes the emplacement of extensive sheet lavas such as recorded at Syria Planum; (2) a change from Tharsis magmatic-driven tectonic activity to centralized effusive volcanism and tectonism (Dohm et al., 2001b); (3) significant outflow channel development (e.g., Scott et al., 1995; Head, 2002); and (4) the time proposed for Deuteronilus shoreline formation (Clifford and Parker, 2001). The water, CO<sub>2</sub>, and other volatiles released during this stage of significant Tharsis- and Elysium-related effusive volcanic activity may have produced a transient greenhouse atmosphere.

Once flooding ceased, the resulting ocean water would have either partly percolated back into the subsurface, froze in a relatively short period, and/or, at least, partly sublimated away to form the Vastitas Borealis Formation (VBF) (Kreslavsky and Head, 2002; Carr and Head, 2003). VBF is comprised of extensive and relatively thick (estimated to be more than 100 m in some places) sedimentary deposits that partly blanket the floors of Borealis, Utopia, and possibly Isidis basins (Head et al., 2002; Tanaka et al., 2003). Here, we interpret VBF to be largely comprised of Tharsis-triggered, sediment-laden floodwaters that were routed by the circum-Chryse and the northwest slope valleys (NSVs, a conspicuous system of gigantic northwest-trending valleys which marks the northwest watershed of Tharsis; Dohm et al., 2001a, c) outflow channels to the northern plains. Though, fluvial activity at Elysium rise (Skinner and Tanaka, 2001; Tanaka et al., 2003), spring-fed discharge along the highland-lowland boundary (Tanaka et al., 2003) perhaps concurrent with Stage 4 of Tharsis activity and associated transient climate change, and aeolian deposition (Tanaka, 1986), may have also contributed to the materials of Vastitas Borealis Formation.

### 2.3. Amazonian: Temporary lacustrine environments

Finally, generally cold and dry desert conditions during the Amazonian were punctuated by small outflow releases to form a number of minor transient seas or lakes (which geological contours are labelled “Paleolakes Shorelines” in Fig. 2; see Scott et al., 1995), likely related to late-stage Tharsis magmatism (e.g., Anderson et al., 2001; Dohm et al., 2001a). Late-stage magmatic activity, which is recorded within and nearby the Elysium rise region during the Amazonian (Skinner and Tanaka, 2001), may have also contributed to release

CO<sub>2</sub> and water into the atmosphere. In any case, the warm periods were infrequent and short (10<sup>3</sup>–10<sup>5</sup> years), as recorded in the low cumulative rates of erosion since the end of the Noachian (Baker et al., 1991; Craddock and Maxwell, 1993; Baker, 2001; Carr, 2002). This endogenetic activity, coupled with major changes in orbital parameters, would have enhanced environmental change and influenced the formation of landforms (Baker, 2001) such as gullies and debris aprons (Malin and Edgett, 2000), rock glaciers (Cabrol et al., 2001), water-ice-rich deposits (Head et al., 2003), and aureole deposits of Tharsis Montes volcanoes (e.g., Scott and Tanaka, 1986; Scott et al., 1998).

In addition, the long-term decline in planetary heat flow, loss of CO<sub>2</sub>, and the progressive trapping of H<sub>2</sub>O into clays in the cryosphere (Carr, 2002) would have greatly depleted the original inventory of groundwater. Moreover, the absence of a magnetic field, as well as the comparatively lower martian gravity (compared to Venus, which also lacks a magnetic field but its higher mass allows it to retain a dense atmosphere), prevent a stable thick atmosphere.

Paleolake formation might have not been restricted to the northern lowlands. Impact crater lakes in the highlands appear to have been common during the Amazonian Period (Cabrol and Grin, 1999; Ori et al., 2000).

## 3. An integrating bridge among the putative geological and paleohydrological histories and possible biological evolution of Mars

The long-term hydrological cycle proposed for the Noachian and perhaps into the Early Hesperian allows considerable potential for biochemistry, and even biological processes to occur in the initial oceanic environment. Water stability during later periods (Hesperian to Amazonian) of martian history raises many questions about life’s adaptation and survival during persisting periods of extremely cold and dry conditions, briefly punctuated by moderate-milder epochs. The history of Mars, which is dominated by endogenic-driven paleohydrological activity, is reflected in the prime candidate sites described below.

### 3.1. Noachian to Early Hesperian

During the Early Noachian, the maintenance of the planetary magnetic field (Acuña et al., 1999, 2001) and a thick atmosphere (Fairén et al., 2003) may have contributed to the long-term stability of the planet’s atmosphere and hydrosphere, and for the evolution of a putative biosphere: the magnetic field provided a shield against the lighter particles of the solar wind (Jakosky et al., 1994; Lundin, 2001); and the atmosphere completely

blocked solar wind protons and high-speed interplanetary dust particles, as the atmosphere for a given pressure on Mars is 3 times thicker than that of Earth. The lack of an effective shield against ultraviolet radiation, due to the absence of free atmospheric oxygen and consequently ozone prior to  $\sim 2.5$  Gyr, was not a trouble for life to arise, to evolve, and to expand to the reachable corners of the Earth more than 3.8 Gyr ago (Mojzsis et al., 1996). To the contrary, some dose of ultraviolet radiation may have played a critical role in the origin of life on Earth (i.e., Mulkidjanian et al., 2003). Enough protection against the harmful radiation would have been provided by  $\text{SO}_2$  and scattering species associated with volcanic ashes accumulated in the martian atmosphere during periods of high volcanic activity (Córdoba-Jabonero et al., 2003), the same periods when possible life-bearing oceans/lakes existed on the surface of Mars; although maintaining sufficient levels of  $\text{SO}_2$  in the presence of liquid water has been questioned (Murphy and Bass, 1998).

Furthermore, meteoritic bombardment may have sterilized the martian surface on several occasions, especially during the period of heavy bombardment, as has been postulated to have happened on Earth (i.e., models in Maher and Stevenson, 1988; Zahnle and Sleep, 1997 and references therein; see also Chyba, 1993; Anbar et al., 2001; Nisbet and Sleep, 2001); but the impact events may have been thermally and hydrothermally beneficial rather than deleterious (Ryder, 2003), as life continued, especially below ground. Similar to Earth, it may not have been a problem for life on Mars to arise and evolve in an environment having liquid water on the surface, thick atmosphere, magnetic field, plate tectonism, and geothermal activity. Therefore, the proposed martian global biosphere could have developed recurrently in the Early Noachian ocean until its definitive establishment and wide expansion during the earlier stages (1–3) of Tharsis development.

The Noachian oceans, and possibly also any subsequent liquid water-mass on Mars, were enriched in iron hydroxides and magnesium sulphate salts, as revealed in the sediments at Meridiani Planum through MER *Opportunity* (Squyres et al., 2004). The  $\text{CO}_2$ ,  $\text{SO}_2$ , and water generated from the volcanism and flood outbursts would have produced the acidic conditions to generate extensive sulphate salt emplacement on the martian surface. Aqueous thermodynamic calculations considering a  $\text{CO}_2$ -dominated atmosphere and a steady supply of iron and sulphate to seawater that, respectively, raised concentrations up to 0.8 and 13.5 mM, result in acidic oceanic waters with  $\text{pH} < 6.2$ , thus suggesting paleoenvironmental surface and near-surface conditions at least moderately acidic. This imposed serious requirements for any biosphere to develop, and also precluded carbonate formation by oceanic sedimentation (Fairén et al., 2004).

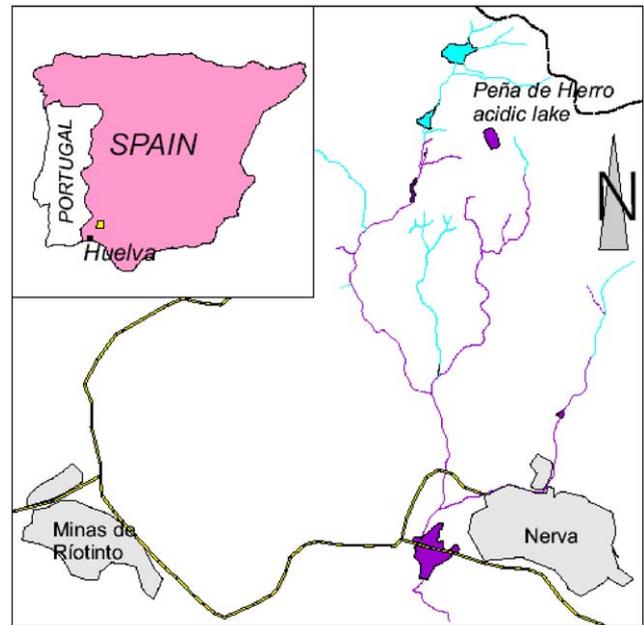


Fig. 3. General setting (small square inside Iberian Peninsula map) and detail map of the Tinto River headwaters, which are composed of different branches with acidic (red) and non-acidic sources.

An environmental model for the possible Noachian biosphere is the Tinto River system (Fernández-Remolar et al., 2002, 2004; see Fig. 3). The headwaters of the Tinto River, which is an extremely acidic environment under the control of iron biogeochemistry, produces ferric iron-enriched sediments dominated by sulphate and oxyhydroxide parageneses, resulting in goethite and hematite. If an aqueous-hydrothermal origin is considered (e.g., Christensen et al., 2001), these features observed in the Tinto basin are reasonable analogs for the Noachian and possibly Early Hesperian rock outcrops investigated by the MER *Opportunity* at the Meridiani site (Fig. 4), especially when considering Meridiani Planum as covered by the potentially long-lasting, great Noachian ocean (Ruiz et al., 2003; Fairén et al., 2003). Moreover, it is possible that some kind of microbial life living in anoxic or extremely low oxygen concentrations could have been involved in the generation of Mars iron oxides, as it occurs in the Tinto system. A complex iron cycle operating in both oxic and anoxic conditions is responsible for the iron mineral paragenesis observed in the Tinto ecosystem, resulting in jarosites, iron oxyhydroxides, goethite and hematite (Malki and Amils pers. comm.; González-Toril et al., 2003; Fernández-Remolar et al., 2004; see Fig. 5). Some organisms could have utilized ferric iron as electron acceptors, as others provided reduced organic carbon compounds to serve as electron donors. In fact, geomicrobiological analyses of the Tinto ecosystem strongly suggest that the extreme acidic properties in the river are a product of the biological activity of

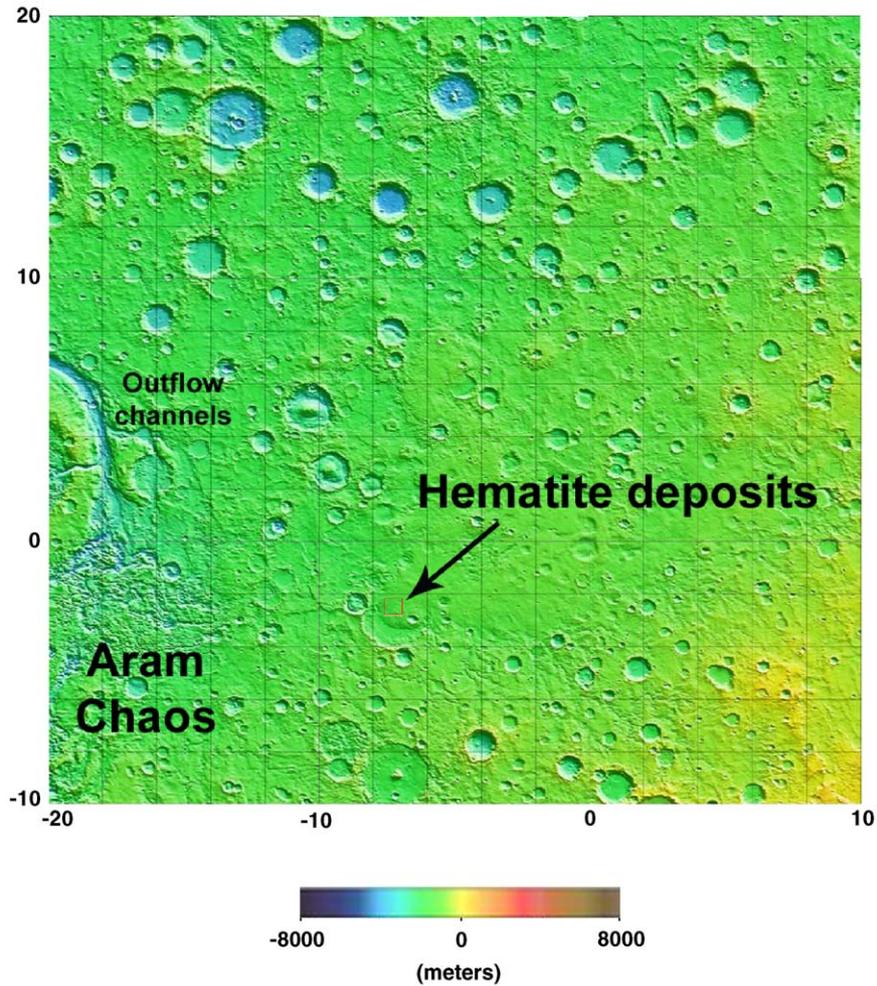


Fig. 4. Coloured MOLA map of Meridiani Planum region southwest Arabia Terra, showing the location of the hematite deposits. Red box locates situation of MOC frame M02-01540, as shown in Fig. 8. (composed from JPL/NASA data.)

chemolithotrophic prokaryotes (González-Toril et al., 2003), mainly iron- and sulphur-oxidizers, using iron both as electron donor and acceptor.

The discovery of such chemolithotrophic ecosystems participating in a radiation-independent carbon cycle allows for the possible existence of some kind of life forms in the less-illuminated primitive *Oceanus Borealis*, perhaps starting on strategies similar to those in the Tinto River (described below); or utilizing  $H_2$ ,  $CO_2$ , and sulphur for organic biosynthesis, harvesting reduced power only from reduced species provided by volcanism, hydrothermal activity, and weathering. Moreover, in the Earth, methane hydrates (clathrates) are mainly produced by chemolithotrophs in the sea floor (Jahren, 2002). If similar processes were promoted in marine sediments of the Noachian acidic ocean (Fairén et al., 2004) by acidophilic and methanogenic microorganisms, huge amounts of  $CH_4$ - $CO_2$  clathrates could have formed in the seafloor. The clathrates may be later destabilized by small decreases in pressure or increases in temperature, thus liberating hundreds of Gt of

methane, which would saturate the deep ocean with the excess migrating up the water column and eventually being released into the atmosphere, significantly contributing to the global greenhouse effect and related warming planetary temperatures.

Nevertheless, time was probably sufficient in the Noachian ocean for the evolution of photoautotrophy, favoured by selective pressure resulting in its efficiency as energy-harvesting system and the ubiquity of solar radiation (e.g., Wynn-Williams et al., 2001), and probably arranged as a secondary use of the radiation-protection systems developed in primitive organisms with radiation independent metabolisms (Gómez and Amils, 2002). But there was never a massive oxygen (nor ozone) accumulation in the martian atmosphere, as can be tested by the weak isotopic oxygen anomaly in the contemporary atmosphere (Jakosky and Phillips, 2001). As such, the photosynthetic biomass, if any, was never as widely distributed and evolved as on Earth. In addition, any atmospheric oxygen was probably trapped almost completely in the oxidation of the iron-enriched

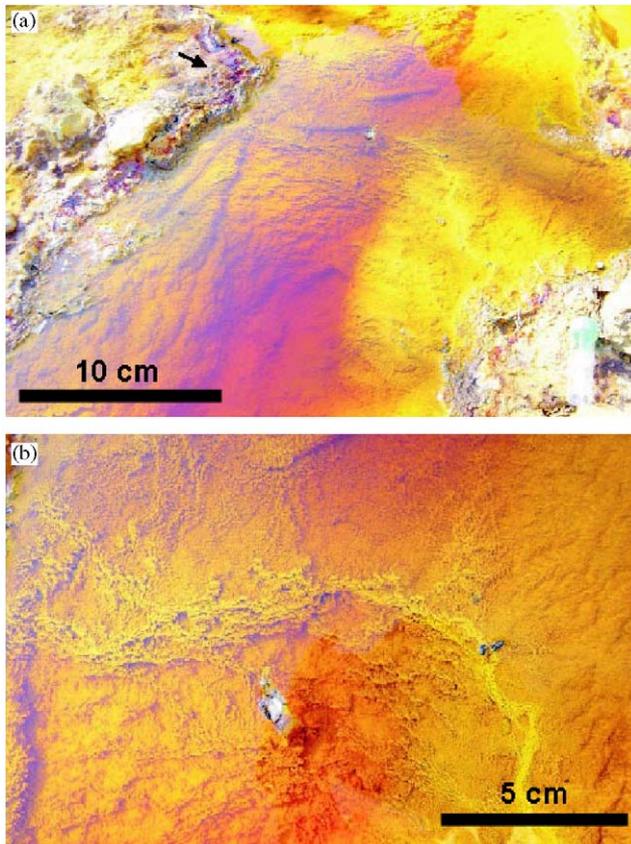


Fig. 5. Sedimentary and biogenic structures resting on a channel of the Tinto River, source area. (a) General view of the I-channel showing laminated iron sediments (black arrow) and iron coatings on filamentous extremophilic microorganisms. (b) Detail of the filamentous coatings.

surface (e.g., wide occurrence of ferric iron-bearing minerals; Zuber, 2001) and/or in the rapid oxidation of the putative atmospheric  $\text{CH}_4$  to  $\text{CO}_2$ , a process which consumes large amounts of free oxygen (Watson et al., 1978; Cicerone and Oremland, 1988), resulting in the current widespread martian anoxia.

The analysis of possible biogenic features (McKay et al., 1996) and magnetite chains (Friedmann et al., 2001; Thomas-Keprta et al., 2001, 2002; Treiman et al., 2002; Barber and Scott, 2002) within carbonates in the interior of the martian meteorite ALH84001 has been recently used to argue for the possible paralleling biogeological evolution of early Earth and Mars, though the conclusions are disputed by a large number of investigators (e.g., Harvey and McSween, 1996; Jull et al., 1998; Scott, 1999; Golden et al., 2003; Buseck et al., 2003, and exhaustively summarized in Treiman, 1999). The magnetization intensities in the carbonates suggests an intensity for the ancient magnetic field on Mars roughly an order of magnitude of that at the surface of Earth today (Weiss et al., 2002), sufficient for magnetotactic bacteria whose putative magnetofossils

have been reported for meteorite ALH84001. This bacterial type documented for Earth are strictly micro-aerophiles and/or anaerobes, living at the oxic/anoxic transition where  $\text{O}_2$  atmospheres are maximum 6–7  $\mu\text{M}$  and with very high  $\text{CO}_2/\text{O}_2$  ratio (Frankel et al., 1978; Bazylinski and Frankel, 2000), not unexpected in the water/sediment interface of the coastal seafloor in the Noachian ocean. Since the meteorite's age is estimated to be  $\sim 4$  Gyr, its putative biological content would be representative of the Early Noachian microfossil record.

The subsequent evolution of both biospheres would be dramatically different for both Earth and Mars due to the very distinct magnetic and climatic histories. Therefore, as the martian dynamo shut off approximately 4 Gyr ago (Acuña et al., 1999, 2001), life may have disappeared from the surface as soon as the intense flux of solar particles erased the atmospheric/hydro-spheric protection (Jakosky et al., 1994). Conversely, living forms may have found some way to reside below the surface, springing to life at the surface during the climatic perturbations, when a thicker atmosphere and water columns would protect the biosphere. Possible magnetotactic bacteria could only have survived for some time in the localized remnant magnetic fields.

### 3.2. Late Hesperian/Early Amazonian

The maintenance of the martian biosphere during the persistent cold/quiescent periods between the developmental stages of Tharsis probably required unique survival strategies. It is possible that the polar regions offer habitable contemporary environments, with temperatures rising over 273 K under some conditions (Jakosky et al., 2003), or with the prevention of total freezing by salinity increases, as it occurs in hypersaline lakes in Antarctica that never freeze completely under average temperatures well below the freezing point of pure water (McKay et al., 1985; Burton, 1988). But, as the atmosphere became thinner and water progressively retreated from the surface during periods of Tharsis inactivity, life forms might preferably have found refuge in subsurface aqueous niches (Boston et al., 2001). In fact, the martian substrate could have maintained large amounts of  $\text{H}_2\text{O}$  between dry periods, including existing in a liquid state in some locations (Barlow et al., 2001), especially in places where elevated geotherms may have persisted such as in the Tharsis and Elysium regions, perhaps as recent as contemporary times (Ferris et al., 2002). If these locations are representative of magmatic/aqueous environments on Earth, then substantial biological activity may occur between 0.5 and 1 km; estimates are that close to 10% of the total surface biosphere lies 0.5 km under Earth's surface (Parkes et al., 2000). Recent investigations have found life in diverse extreme environments, including: (1) bacteria living at depths of 5.3 km in igneous rocks

(Pedersen, 2000), (2) anaerobic hyperthermophilic archaea thriving at depths of 2.3 km in oil wells where average temperatures were around 70 °C (Miroshnichenko et al., 2001), (3) photosynthesizing cyanobacterial communities living in desert soils, which lie inactive deep in the ground for months and only rise to the surface for light exposure after the rare desert rain falls (García-Pichel and Pringault, 2001), (4) bacteria from Arctic permafrost that are metabolically active at –20 °C (Rivkina et al., 2000), and (5) bacteria and fungi occupying the salt-enriched soils of the dry valleys of Antarctica (Mahaney et al., 2001). Given the existence of these microbial-life strategies in Earth's shallow crust, it seems likely that if life gained a foothold during the dry epoch subsequent to the first great and long-lasting Noachian ocean, the probabilities are good that life found a way to survive at depth some time during the Hesperian, perhaps migrating to the surface during the Late Hesperian/Early Amazonian secondary oceanic period.

The subsurface of Mars might include near-surface caves, subsurface fissures, microcracks, intergrain pore spaces, subterranean shallow and deep sealed voids, and aquifers, where microorganisms are protected against extreme temperature fluctuations or desiccation, UV radiation, and cosmic rays (for a comprehensive review of the geomicrobiology of terrestrial caves, see Northup and Lavoie, 2001). The organisms must have been metabolically active rather than in a dormancy state (e.g., spores), because certain dose intensities are lethal for bacteria-like organisms with inactive mechanisms of genetic defect reparation (Pavlov et al., 2000). One exception could be the development of self-protection mechanisms similar to those in terrestrial iron-metabolizing bacteria, in which ferric iron produced by iron metabolism provides high protection against radiation even when the organism is in dormancy state (Gómez et al., 2003). The terrestrial family of Deinococcaceae non-sporeforming bacteria has developed an integrated system for desiccation and radiation resistance, surviving 20 kGy gamma radiation without loss of viability (Battista et al., 1999); equally as cyanobacterium *Chroococcidiopsis*, capable of surviving up to 15 kGy (Billi et al., 2000), whereas doses below 10 Gy are lethal for all other organisms. Radioresistance comes from its ability to efficiently repair the massive DNA damage generated during irradiation in an unknown mechanism perhaps linked to its genome ring-like structure (Levin-Zaidman et al., 2003); but it cannot be an evolutionary adaptation, because there are no natural environments in the Earth that support such a high flux of ionizing radiation (Battista, 1997). In fact, deinococci's radioresistance appears to be a secondary use of the cell's DNA repair capability, which provides them with a selective advantage to some kind of environmental stress, namely extreme desiccation (Mattimore and

Battista, 1996). Furthermore, psychrophilic terrestrial bacteria isolated from snow in the south pole, metabolically active at ambient subzero temperatures (–12 to –17 °C), are closely related to deinococci (Carpenter et al., 2000). Similar evolutionary trends could have formed on early Mars (Late Noachian–Early Hesperian), when putative life forms were exposed to extreme desiccation, cold, and ultraviolet radiative conditions.

A wide range of metabolic types of different biota could have survived the ionizing, dry and cold epochs on the surface, hidden in the subterranean environments (e.g., Boston et al., 2001). These might have been anaerobic, chemo- and lithoautotrophic microorganisms (Vargas et al., 1998), developing reduced and isolated populations that perhaps reached from one watery period to the next. A continual source of energy for their metabolism possibly was the diffusion of H<sub>2</sub> and CO downward into the regolith (Boston et al., 1992; Weiss et al., 2000), readily produced in the atmosphere by the photochemical breakup of H<sub>2</sub>O and CO<sub>2</sub>, respectively.

Some of the life forms migrating to the subsurface, likely evolved to extremophilic metabolism due to the changing environment as Mars dried and cooled in the Early Hesperian. In this sense, it has been proposed that hypothetical martian microorganisms similar to terrestrial halophiles could have survived in subterranean salt deposits (Landis, 2001; for a complete discussion about halophiles and their possible survival in Mars, see Oren, 2002), especially when considering that the salt content of the martian upper crust materials would at least be as great as for land masses on Earth, and can locally be higher (Catling, 1999). If so, techniques of isolation and growth of microorganisms trapped in brine inclusions should be applied to martian samples, as *Bacillus* species have been claimed to be identified in terrestrial 250 million-year-old salt crystal from the Permian Salado Formation (Vreeland et al., 2000).

As the Late Hesperian ocean and the subsequent Late Hesperian to Amazonian paleolakes were likely ephemeral (Fairén et al., 2003), some kind of extremophiles (halophiles or/and others) could have used the transient playas to metabolize and reproduce, but it is unlikely that there was sufficient time for them to evolve to any other non-extremophile life form. However, without knowing the reproduction, mutation, and lateral gene transfer rates (increased by major geological phenomena like those on Mars; Macalady and Banfield, 2003), response to stress (producing self-mutation, see Ilves et al., 2001), and communal relations (e.g., were populations easily isolated from one another?), it is impossible to definitively state whether life was able to make an evolutionary leap during a temporary event of surface liquid water.

The Mangala Valleys region is an exemplifying location where some of these putative biological episodes may be recorded, as diminishing martian

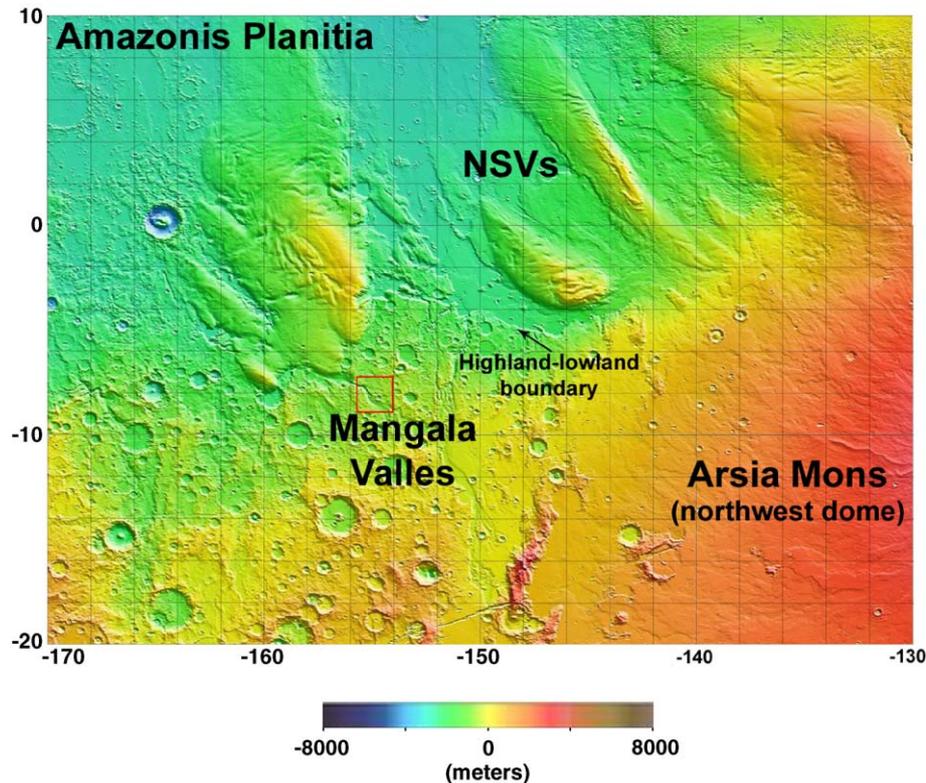


Fig. 6. Coloured MOLA map of Mangala Valles in the NSVs region located southwest Olympus Mons. Red box outlines location of MOC frame M03-03770, as shown in Fig. 10 (composed from JPL/NASA data).

episodic hydrologic events over geologic time are clearly recorded (Craddock and Greeley, 1994; Dohm et al., 2004; see Fig. 6). Magmatic-driven processes, which dominate the geologic record in this region, coupled with significant evidence of past and present-day water/ice above and below the martian surface, indicate that hydrothermal environments certainly existed in the past and may still be active today (Mouginis-Mark, 1990; Wilson and Head, 1997; Dohm et al., 2001a, 2004; Ferris et al., 2002). These sites are of particular astrobiological interest, since they could favour the development and sustenance of life, because if life developed on Mars, its fossil record would presumably be at its greatest concentration and diversity in environments where long-term energy sources and water coexisted. Impact craters in the area may have excavated to the depths where such biologic activity may have occurred (Cockell and Barlow, 2002).

### 3.3. Amazonian

Throughout the Amazonian period, conditions on the martian surface seem to have been hostile to life as we know it, because of the extreme low temperatures, extreme low atmospheric pressures, oxidized soil chemistry, and UV radiation (fluxes capable of damaging DNA three orders of magnitude greater than those on

Earth; see Cockell et al., 2000). However, almost contemporary (Malin and Edgett, 2000; Burr et al., 2002; Ferris et al., 2002) and abundant (Cabrol and Grin, 2001; Baker, 2001) water activity has been suggested on Mars. In fact, some impact crater lakes were formed so recently (Newsom and Thorsos, 2000) that the climatic conditions might have been quite similar to those of today. Thus, if life has survived by any of the proposed models, perhaps some anoxic bacteria-like community could have flourished from the subterranean caves where they have survived during millions of years and migrated to the bottom of surface lakes during nearly contemporary epochs. In this sense, life-supporting, low-temperature brines in Antarctic Dry Valleys provide an excellent terrestrial analogue for such a possibility: as in the Antarctic, depressions may have been water-filled on Mars by temporary thawing of ice resulting in a supply of water to the lakes, preventing them to completely freeze and dry up. So, the recently described surface seepage channels and gullies (e.g., Malin and Edgett, 2000) are not only of enhanced geological significance, but their recent mass flow deposits also provide potential repositories for water and for biomolecules acting as recognizable biomarkers on the surface (Wynn-Williams et al., 2001).

Terrestrial anaerobic methanogens utilize  $H_2$  and  $CO_2$  in metabolism, releasing  $CH_4$  as a by-product. Con-

versely, multiple terrestrial microbial groups living in anoxic cold seep marine sediments oxidize the methane lying buried beneath the seafloor, mainly crystallized as solid phase gas hydrates, to  $\text{CO}_2$ , thus consuming up to 20% of the total methane flux to the atmosphere (Orphan et al., 2002). Similar strategies could account for a large sink of methane in the martian atmosphere, at least throughout the Amazonian age, thus contributing to the prevailing cold climate. Methane hydrates are unstable at the surface, but stable in the subsurface under current ambient martian conditions (Max and Clifford, 2000), and so methane on Mars will reside beneath the cryosphere; overall if both Tharsis and Elysium superplumes are currently inactive, they cannot provide the physical disturbance necessary to liberate methane from methane hydrates. Nevertheless, Earth-based telescopes have detected relatively low concentrations of methane (up to 0.01 ppm) in the martian atmosphere (Mumma et al., 2003; Krasnopolsky et al., 2004), and a comparable methane concentration has also been detected by Mars Express spacecraft (Formisano et al., 2004), implying a current geological and/or biological source, as the residence time of  $\text{CH}_4$  under modern martian atmospheric conditions is less than 500 years. Alternatively, methane could be derived from the destabilization of methane hydrates formed by microbial communities in the Noachian martian seafloor, as argued above. It is possible that during the transition to the colder surface environment, this early life adapted to a subterranean existence where warmer temperatures and the potential presence of groundwater have enabled it to persist to the present day. In this sense, a contemporary deep biosphere of methanogens in the Martian groundwater, isolated well below the ice-rich permafrost, may be maintaining the process of producing the effective greenhouse gas methane, which would be stored in the ground ice as gas hydrate. The destabilization of such hydrates and associated release of methane and carbon dioxide they engaged would have effectively helped to produce episodic atmospheric warming during the Hesperian and the Amazonian. In any case, during the long-term, Hesperian to Amazonian cold and dry prevailing conditions, almost the complete  $\text{CH}_4$  biological cycle may be lying hidden under the surface, in deep subpermafrost aquifers.

Remains of part of the putative ancient martian biosphere might have been preserved to date in subsurface deposits near the primitive shorelines. In that sense, impact craters within impact craters could provide access to deep pre-impact sedimentary units of biological interest (Cockell and Barlow, 2002). The small channels along the flanks of martian volcanoes are indications of water and internal heat operating together in any moment in the past, and areas where hydrothermal systems could have developed (Gulick, 1998;

Gulick and Baker, 1989, 1990; Dohm et al., 2001b), as those reported for the origin of carbonate globules in ALH84001 (Treiman et al., 2002). Terrestrial microbiota such as chemolithotrophic and heterotrophic bacteria, which have a specifically adapted metabolism to inhabit these subsurface environments, provide exciting analogues for such potential extremophile existence in Mars, especially where long-lived, magmatic-driven hydrothermal activity is indicated (Farmer and Des Marais, 1999), as substantial amounts of chemical energy may be available in these systems (Varnes et al., 2003). As such, terrestrial hydrothermal vents driven by the interaction of groundwater and magma support a wide variety of bacteria, including various species of Deinococcaceae (Ferreira et al., 1999).

As Amazonian subsurface liquid water locations are dispersed across large and sterilized distances, the conditions required for microbial growth are discontinuous and generally very distant, thus preventing gene flow. But this is not a problem for life on Earth: terrestrial endemic populations of extremophiles isolated in concrete biogeographic patterns (Whitaker et al., 2003) points to the distribution of a broad array of microbial specialists with interbreeding limitations. Thus, a similar scenario is conceivable for Mars.

A martian location where the search for these Amazonian materials may yield clarifying results is Orcus Patera (Fig. 7), a volcanic caldera or impact crater where ponded bodies of water may have existed during the Amazonian period. Orcus Patera is located in Marte Vallis, a large channel interpreted to be a spillway between Elysium basin northeast into Amazonis basin (for further explanation see Scott et al., 1995); an area where recent tectonic, volcanic, and fluvial activity have been noted, as the average age for fluvial surfaces is  $\leq 200$  myr, with localized water releases within the past 20 myr (Berman and Hartmann, 2002). The floodwaters, which were partly routed into Orcus Patera (see Fig. 7), range from at least the Hesperian to the Amazonian, suggesting the recurrence of the formation of lakes inside the topographic depression even in recent times. Additionally, the floodwaters that formed the sediment layers in Orcus Patera (possibly episodic) probably resulted in the mixing of the Elysium and Amazonis waters, which were derived from distinct source regions of varying temperature, pH, and/or salt concentrations: sources for Elysium basin include the highlands (via Ma'adim and Al-Qahira Valles), the Elysium rise, and subsurface aquifers; whereas for Amazonis basin, sources include the highlands (e.g., Mangala valles: Scott and Tanaka, 1986; Chapman and Tanaka, 1993; Zimbelman et al., 1994; Craddock and Greeley, 1994; Scott et al., 1995) and groundwater discharge as evidenced from Amazonian sapping channels, including Abus Vallis (Dohm et al., 2004). As such, these environments are of great interest in the study of

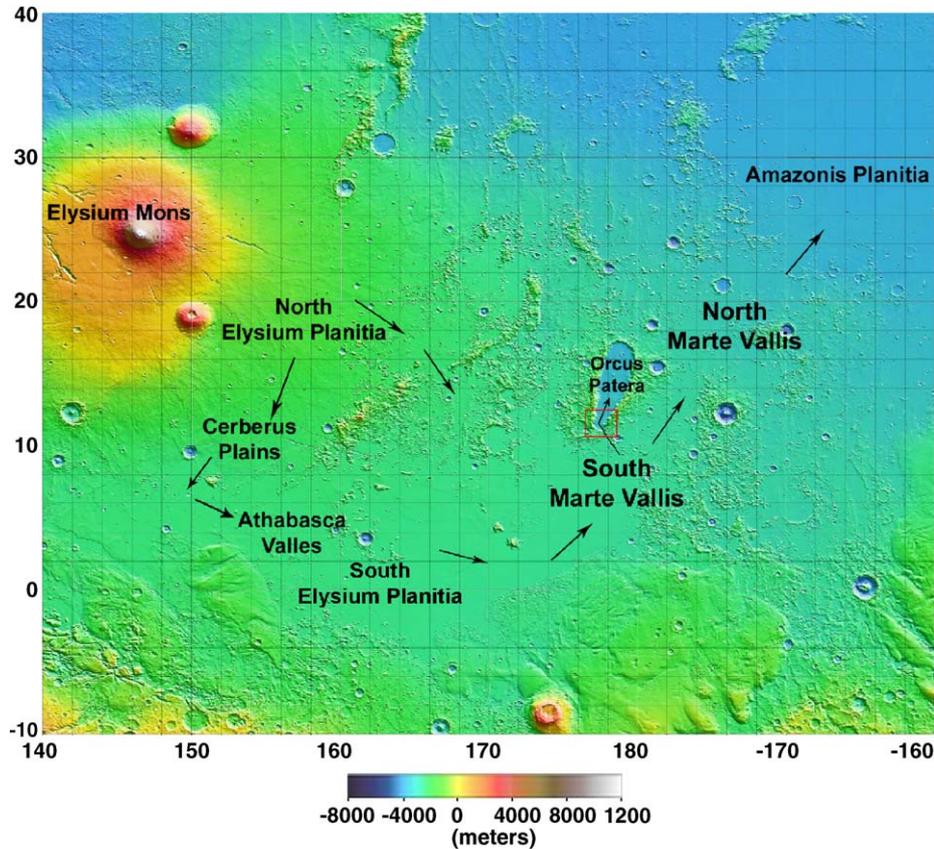


Fig. 7. Coloured MOLA map of Orcus Patera source region located between Elysium and Amazonis planitiae within Marte Vallis. Proposed general water flows (black arrows), after [Berman and Hartmann \(2002\)](#). Note flow directions of Marte Vallis into Orcus Patera, as proposed in [Grin and Cabrol \(1998\)](#). Red box outlines location of MOC M09-03286, as shown in [Fig. 11](#) (composed from JPL/NASA data).

the survival of microbial metabolisms in anoxic aqueous habitats developed recurrently in persistent cold and dry Amazonian conditions. Recovery of isolated DNA in Siberia estimated to be nearly 400,000 years old ([Willerslev et al., 2003](#)), in absence of obvious related fossilized materials, bears on the future investigation of contemporary sedimentary environments such as those that were deposited from the sediment-charged waters ponded in Orcus Patera.

#### 4. Prime candidate sites for future science-driven exploration

A prime candidate site on Mars should lead to an improved understanding of (1) the diversity of rock types that form the crust; (2) the absolute time-stratigraphic information of Mars through sampling, collecting, and returning rock materials of regionally defined geologic map units from known locations; (3) the major periods of the geologic history, which are currently constrained by relative age information; (4) internal and external evolutionary histories; (5) ancient vs. modern aqueous activity; (6) paleoclimate; and (7)

potential for extant and/or fossilized life or biomarkers. Such locations are established through a synthesis of all published information, including stratigraphic, geomorphic, paleotectonic, paleohydrologic, topographic, geophysical, thermal, spectral, and elemental data ([Dohm et al., 2004](#)).

A complete analysis of terrestrial mineral biosignatures, which records evidence of biological activity (with possible relevance in comparative studies on Mars), is provided by [Banfield et al. \(2001\)](#). Searching the substrate of a wide range of sedimentary deposits on Mars is of enhanced interest for the future exploration and sampling, as it is difficult to preserve organic matter or geochemical evidence of biological activity in the present-day surface environment ([McDonald et al., 1998](#); [Benner et al., 2000](#); [Komatsu and Ori, 2000](#)). As per our previously described hydrogeological and biological analyses, here we focus on three prime candidate sites, corresponding, respectively, to Noachian/Early Hesperian, Late Hesperian/Early Amazonian, and Amazonian environments where future science-driven reconnaissance has high probability to yield significant geologic, hydrologic, paleoclimate, geochemical, and possible biological information.

#### 4.1. Noachian to Early Hesperian: Meridiani Planum

A unique region in Meridiani Planum (lat. 5°S–10°N, lon. 12°W–5°E; see Figs. 4 and 8) has been identified to consist of Noachian and possibly Early Hesperian (as shown both in MOC and THEMIS crater countings; see Hartmann et al., 2001 and Lane et al., 2003) layered hematite deposits with a relief of ~600 m and an areal extent of about  $3 \times 10^5 \text{ km}^2$  (Hynek, 2004). This outcrop of hematite, which has been interpreted to consist of basaltic rock materials with ~10–15% crystalline gray hematite (specularite,  $\text{Fe}_2\text{O}_3$ ) deposits, may have been precipitated from the circulation of fluids within the layered materials (Christensen et al., 2001; Hynek et al., 2002; Hynek, 2004). These iron oxides have been compared to terrestrial Archean and Proterozoic aqueous environments hosting Banded Iron Formations (BIFs; see Catling and Moore, 2000; Banfield et al., 2001), especially as IR analyses of terrestrial platy gray hematites support an aqueous origin for these iron oxides in the martian surface (Lane et al., 2002). But the comparison failed subsequent in situ spectral analyses, because TES has not detected silica related to the Meridiani hematite materials, as observed in the mineral associations of terrestrial BIFs.

Nevertheless, groundwater diagenesis can transform precipitates of iron sulfates and oxihydroxides into goethite and hematite, as it occurs in the terrestrial Tinto River that sources from the Iberian Pyritic Belt (among the greatest ferric provinces in the world). Since silica is not precipitated in this modern river system, it is an excellent analogue for astrobiological studies of early (Noachian to Early Hesperian) martian environments (Fernández-Remolar et al., 2004). The creation of the hematite-rich Meridiani area may equally involve precipitation of nano-crystalline iron oxyhydroxides from solutions via a biologically driven system; subsequent burial and heating may have turned these products to coarser hematite (Banfield et al., 2001).

In the Tinto system, the remobilization of iron and subsequent precipitation as goethite preserves biological remains in sometimes remarkable detail. Consideration of Meridiani Planum as covered by the primitive Noachian to Early Hesperian ocean of Mars (Ruiz et al., 2003; Fairén et al., 2003; see Fig. 2), which is consistent with detailed crater counts (Lane et al., 2003) and recent MER analyses (Squyres et al., 2004; Hynek, 2004), provides evidence that the original surface containing the hematite is probably Early to Middle Noachian age (>3.8 Gyr ago); and the stratigraphic analysis of the region (Christensen et al., 2003) indicates that different rock units initially compacted beneath a kilometre or more of overburden (possibly coastal sediments), later were exposed by extensive erosion. Therefore, local rock materials dating from the ancient martian oceanic epoch (further back than those on

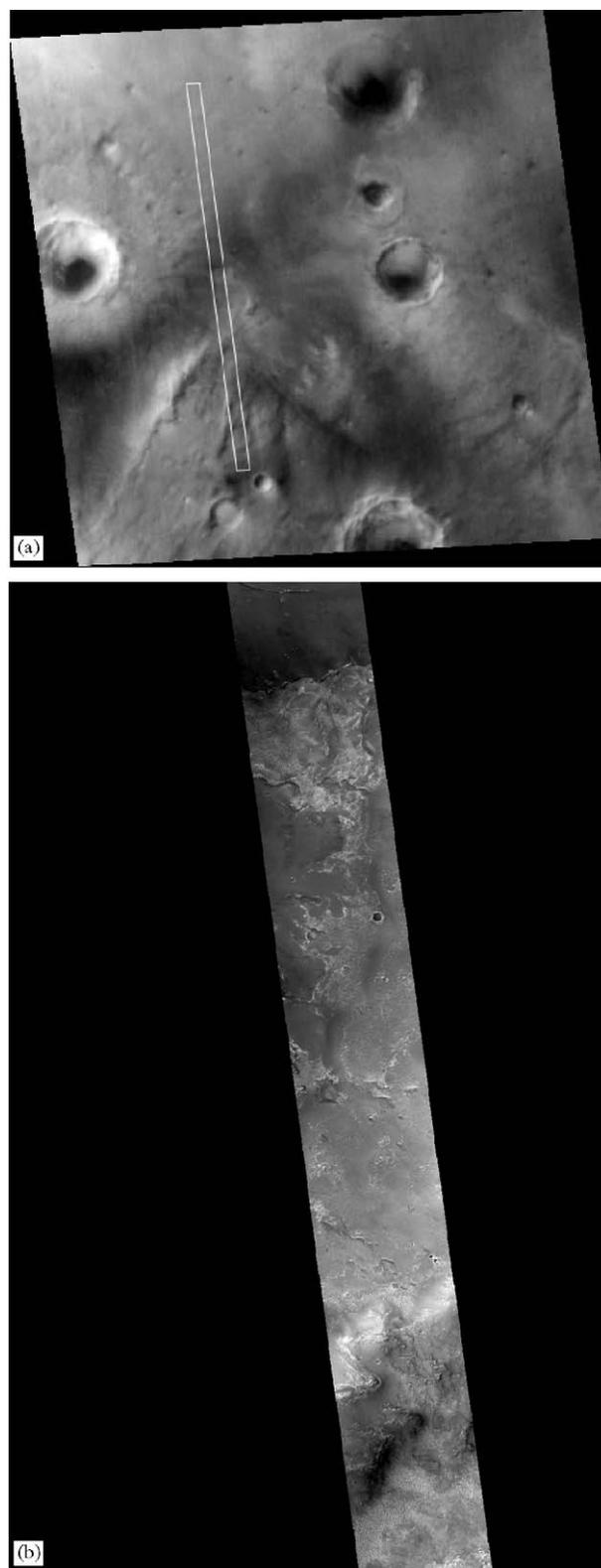


Fig. 8. (a) MOC context frame M02-01540 in Meridiani Planum. (b) Portion of M02-01539 MOC image showing central Meridiani Planum contacts between different materials, including layered hematite deposits. Image centered at long. 6°W, lat. 3°S; width, 2.94 km; height, 86.79 km. See complete image context in Fig. 4 (courtesy of MSSS/JPL/NASA).

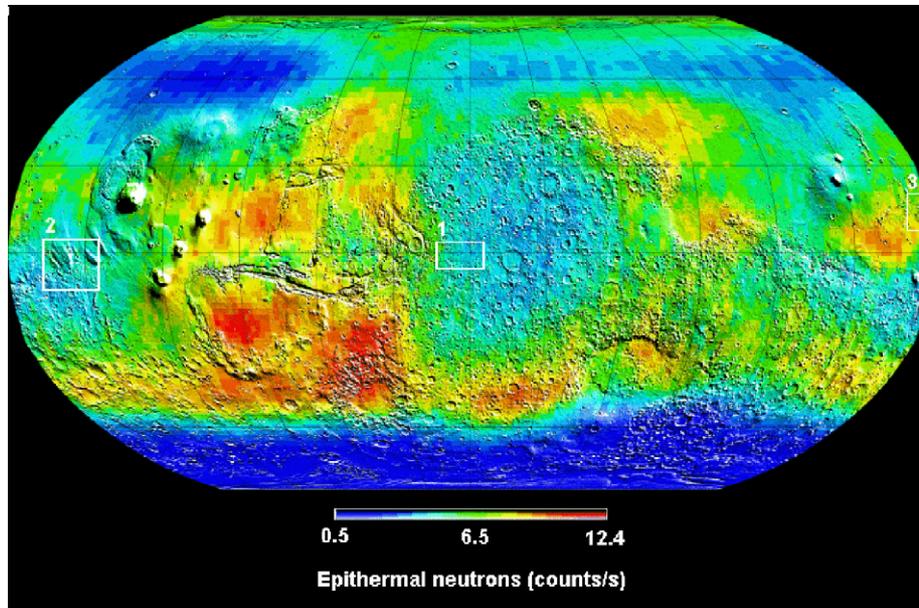


Fig. 9. Epithermal neutron flux, as provided by the Gamma Ray Spectrometer onboard the *Mars Odyssey* spacecraft (after Boynton et al., 2002). Regions with elevated hydrogen abundances may possibly indicate subsurface water, as indicated by low epithermal flux (blue tones). Note that both Meridiani Planum (site 1) and Mangala Valles (site 2) are included in regions with elevated hydrogen abundances, possibly indicating subsurface ice. Orcus Patera (site 3), on the contrary, does not record elevated hydrogen abundances, and thus may not contain water/water-ice at present, though it was a location where surface water flowed and ponded during inundations periods.

Earth) might be accessible. Moreover, this is a province where *Mars Odyssey* orbiter has detected large amounts of hydrogen, most likely in the form of hydrated minerals and possibly groundwater or ice (Boynton et al., 2002; Mitrofanov et al., 2003; Fig. 9). If Meridiani Planum was the seafloor of a shallow Noachian coastal zone, then the layered and smooth hematite deposits of constant thickness resulting in the precipitation from Fe-rich waters may include remarkable clues to unveil the history of the primitive environments of Mars.

#### 4.2. Late Hesperian to Early Amazonian: Mangala Valles

Mangala Valles (lat. 3°S, 12°S; lon. 150°W, 155°W; Figs. 6 and 10) is a sinuous, 880-km long and up to 300-km wide outflow channel system located in the Memnonia region of Mars (Scott and Tanaka, 1986; Chapman and Tanaka, 1993; Zimbelman et al., 1994; Craddock and Greeley, 1994), southwest of the northwestern slope valleys (NSVs) region. Diverse stratigraphic, topographic, tectonic, paleohydrologic, geophysical, and elemental information collectively point to the NSVs region as a prime site for future exploration (Dohm et al., 2004).

Mangala Valles likely was carved by one or more endogenetically driven releases of volatiles sometime during the Late Hesperian into the Early Amazonian, and thus may be representative of a later pulse of Tharsis-driven hydrologic activity. This is reflected both in the stratigraphy (Chapman and Tanaka, 1993) and in

the estimated peak discharge of  $2 \times 10^7 \text{ m}^3/\text{s}$  (Komar, 1979), compared to the estimated peak discharge of the NSVs of  $10^8\text{--}10^{10} \text{ m}^3/\text{s}$  (Dohm et al., 2001a); the source water of the northeast and northwest watersheds of Tharsis, circum-Chryse and NSVs, respectively, is believed to have diminished with time (Dohm et al., 2001a) similar to endogenetic activity of the planet (e.g., Schubert and Spohn, 1990).

Mangala Valles comprises a system of valleys that roughly correspond spatially to gravity lows, interpreted to represent low-density materials that partly infill the valleys and large topographic depressions, where ancient dense materials may have been exposed by flooding/fluvial activity (Dohm et al., 2001c, 2004). They occur within a large topographic depression in the NSVs region (similar to the eastern Chryse Planitia outflow channels; Phillips et al., 2001), which includes several macrostructures (intricate system of basement structures hundreds to thousands of kilometres long as observed from the published paleotectonic maps and MOLA topography). These basement structures have similar trends and spatial associations when compared to both gravity and magnetic anomalies (Dohm et al., 2001c, 2004). The area records structurally controlled releases of putative ground water and other volatiles, and possible recent hydrologic activity noted by the high density of dark slope streaks which occur along many of the walls of the Mangala Valles tributaries (Ferris et al., 2002). The region also comprises potentially long-lived, magma-ground water/ice interactions. Similar to Meridiani Planum, the *Mars Odyssey* orbiter has detected



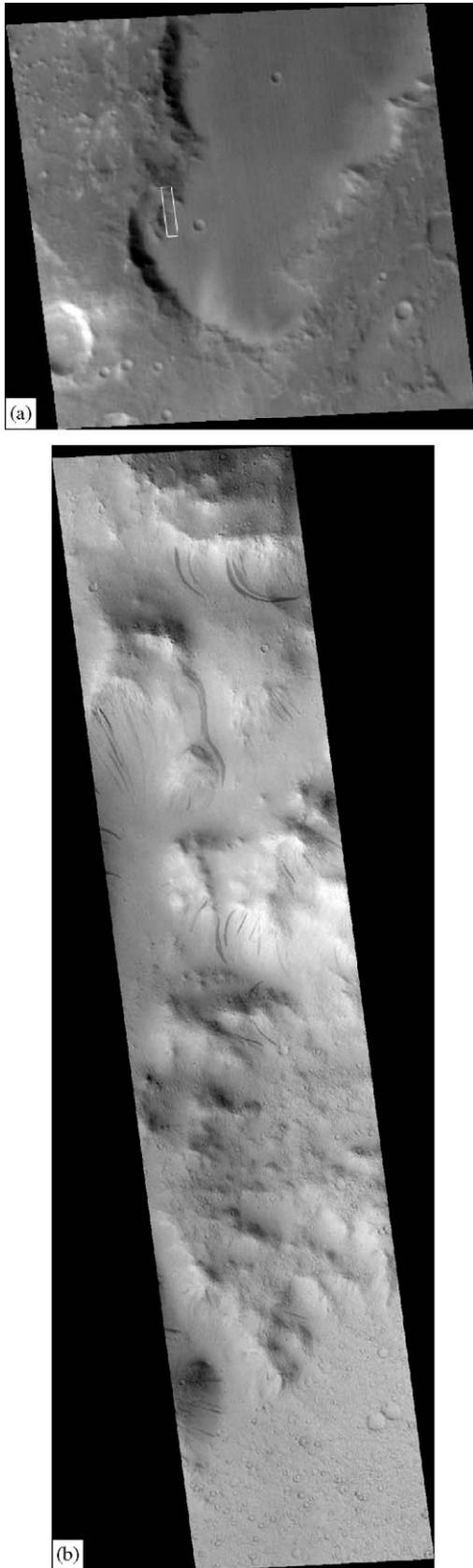
elevated hydrogen abundances (Boynnton et al., 2002; Mitrofanov et al., 2003; Fig. 9). In addition, the Gamma Ray Spectrometer onboard the *Mars Odyssey* spacecraft reveals the NSVs region to be highly elevated in chlorine when compared to the rest of Mars (Boynnton et al., 2004). The elevated chlorine signature could be indicative of its recorded geologic and paleohydrologic histories, including hydrothermal activity, and may mark recent and possibly active magmatic-driven activity. Though, other factors such as atmospheric processes should also be considered as a potential contributor to the elevated signature.

The NSVs region, which includes Mangala Valles, may contain rock materials that could have sourced from different provinces later exposed by flooding (Dohm et al., 2001a,c, 2004), including: (1) the Europe-sized Noachian sedimentary basin in Tharsis, with lavas and interfingering sedimentary deposits, later deformed by Late Noachian–Amazonian magmatic-driven activity such as at the central part of Valles Marineris, where uplift, dike emplacement, tectonism, and volcanism triggered floods sufficient to carve the circum-Chryse outflow channel system; (2) the Noachian Thaumasia highlands mountain range, which may include metamorphic basement complex and possible ancient hydrothermal deposits, such as at Warrego Rise; and (3) Late Hesperian–Early Amazonian basaltic lava flows and possible ash deposits, as well as possibly Noachian silica-enriched volcanoes located to the south of the region and west of the Thaumasia highland mountain range, displaying traits similar to terrestrial field sites where the processes such as fluvial, eolian, and hydrothermal activity are recorded. In addition, this region displays virtually every magnitude and type of fluvial and/or aqueous processes on Mars (Dohm et al., 2001c, 2004).

#### 4.3. Amazonian: *Orcus Patera*

Orcus Patera (lat. 14°N, lon. 181°W; see Figs. 7 and 11) is a large elliptical (360 × 100 km) feature, which could be an impact crater or a volcanic caldera, with the bottom of the topographic depression located 2500 m below the martian datum and the uppermost rim close to 0 m of elevation (Grin and Cabrol, 1998). Orcus Patera borders north Elysium basin at Marte Vallis, a spillway between Elysium and Amazonis basins (Scott et al., 1995). Crater retention ages clearly indicate that Elysium is one of the youngest basins on Mars, with the

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Fig. 10. (a) MOC context frame M03-03770 in the debouching area of Mangala Valles. (b) M03-03769 MOC transect in Mangala Valles, showing streamlined bedforms in the floor of the valley. Image centered at lon. 155°W, lat. 8°S; width, 2.87 km.; height, 27.44 km. See complete image context in Fig. 6 (courtesy of MSSS/JPL/NASA).



volcanic region of Cerberus Plains to the southwest as the youngest regional plains-forming materials on Mars (Berman and Hartmann, 2002), although the geologic and paleohydrologic records of Elysium basin and its surroundings clearly indicate that the basin was a catchment site for water and rock materials since the Noachian (Scott et al., 1995). Hydrothermal activity has also been proposed for the region at least since the Early Amazonian, and possibly persisting to date (Plescia, 2000).

Estimated total water volume presumably enclosed may be of the order of  $42,000 \text{ km}^3$ , with a lake level at  $-1500 \text{ m}$  (Scott and Chapman, 1995). Grin and Cabrol (1998) found a deep, 12-km-wide gap at the southern limit of the crest of Orcus Patera, where water may have flowed from Elysium–Marte Vallis into oblong basin, so providing the combination of volcanism and water activity (hydrovolcanism) even in contemporary epochs. Consistent with this observation, a MOC image shown in Fig. 11 displays bright sediments in the area of the supposed water inflow, interpreted here to mark eventual precipitation by solute concentration through evaporation or freezing in the terminal phases of the last martian global hydrologic episode. So, the layered wall and floor materials in Orcus Patera, which are interpreted to have been deposited by episodically ponded waters, are sites of great interest for future science-driven reconnaissance and sample return.

Water drained northeastward from the Elysium basin to Amazonis Planitia through Marte Vallis, a large channel centred near lat.  $36^\circ \text{N}$ , lon.  $178^\circ$  (see Fig. 7). The fluvial activity postdates earlier volcanic activity, as is observed in the terraces and scour marks chiselled into the lava flow materials (Scott and Chapman, 1991). MOC counts by Burr et al. (2002) are interpreted to indicate ages of 10–100 m yr for the formation of Marte Vallis. Examining the flows in Marte Vallis, Gregg and Sakimoto (2000) and Keszthelyi et al. (2000) separately concluded that the effusion rates were about  $10^3\text{--}10^4 \text{ m}^3/\text{s}$ . Melting of ground ice by geothermal activity derived from the volcanism in the area may be the main source of water, not discounting episodic recharge by precipitation in milder periods and delivery of water from cratered hills north of Cerberus Fossae (Burr et al., 2001, 2002). In any case, the source area may have been the eastern-most end of Cerberus Fossae (Burr et al., 2002). The channel forms of Marte Vallis points to extensive erosion and a significant source: Athabasca

Fig. 11. (a) MOC context frame M09-03286 in southern Orcus Patera, showing the area where water may have flowed into the crater, as the bright sediments possibly indicate. (b) M09-03285 MOC image in the western wall of Orcus Patera, showing terraces and lineations possible indicating an ancient coastal area. Image centered at long.  $183^\circ \text{W}$ , lat.  $12^\circ \text{N}$ ; width, 3.01 km; height, 14.38 km. See complete image context in Fig. 7 (courtesy of MSSS/JPL/NASA.)

and Grjota' Vallis could have provided the water to form the Marte Vallis channels across the Cerberus plains and flowing into Elysium Planitia, implying a fluvial system over 2500 km in total length (Plescia, 2003).

Due to its relatively modern age and the absence of extensive deformation and/or erosion in the area since Early Amazonian, the possible fossil record may be preserved in Orcus Patera, remaining undisturbed in the sedimentary layers of the crater banks and terraces.

## 5. Conclusions

Different-sized bodies of acidic liquid water have been proposed to have occurred episodically in the lowlands of Mars throughout the planet's history, largely related to major stages of development of Tharsis. These water bodies range from large oceans in the Noachian to diminished lakes in the Amazonian. This model also unfolds three prime candidate sites for future astrobiological exploration of Mars, each one corresponding to a major inundation phase of the global hydrological model. Assuming that the search for life is directly linked to the search for water, the possible biological history of Mars must have been largely influenced by the suggested endogenetically driven hydrogeological cycles. In consequence, terrestrial biological and environmental analogues can now be placed in the context with the model proposed here, so contributing to draw a general model for life on Mars. If the search for extant/fossil life or biomarkers on Mars is fully successful, our working hypothesis would suggest that records of microbial activity will be diverse, reflective of the inundation phases and varying aqueous surface and subterranean environments, similar to what is observed on Earth.

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