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Atlantis basin, Sirenum Terrae, Mars: geological setting and astrobiological implications

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Abstract: The accomplishment of detailed geomorphological studies is a prerequisite for the location of regions in which the prevailing conditions in the past, or at present, may allow the development of possible life forms. The Atlantis basin, located in Sirenum Terrae, Southern hemisphere of Mars, is one of these astrobiologically interesting regions, where the existence of geological features such as ancient volcanic edifices, sedimentary deposits of an ancient lake and recent gullies seem to indicate the long-term presence of a thermal source and a water reservoir deep and stable enough to sustain biological processes. Here we describe the most relevant topographic and geomorphologic features in the region, highlighting the possibility for liquid water to have been present in the basin and outskirts in different moments of Mars' history. We also apply this analysis to an initial discussion of the influence of the hydrogeological evolution of the region in the putative development and/or survival of life forms in Atlantis basin.

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The Atlantis basin and Atlantis Lake

The Atlantis basin (Fig. 1), so named in previous works (de Pablo & Druet 2002; de Pablo 2003), is located in the southern hemisphere of Mars, in the Phaethontis quadrangle, Sirenum Terrae region, centred in the geographic coordinates 177° W, 35° S. The basin occupies part of the Cratered unit (CU), a physiographic element in the southern highlands of Mars proposed by Scott & Carr (1978). Following the cartography by Scott & Tanaka (1986), the Atlantis basin is geologically excavated in the CU (Npl_1), probably formed from volcanic materials and impact breccias densely cratered during the Early Noachian. The older Southwest zone is constituted by the Ridge Plains Material unit (Hr), characterized by the presence of abundant compressive tectonic structures (ridges) and volcanic outflows. The interior of the basin is formed by two units: the Smooth unit (Hpl_3), stratigraphically over the formerly described areas, and formed by an interstratification of volcanic materials and eolian deposits during the Early Hesperian; and the Chaotic Materials unit (Hcht), which constitutes the chaotic terrains inside Atlantis and other close basins (i.e. Gorgonum), formed during the Middle and Late Noachian.

The presence of a lake basin in the deeper zone of Atlantis was not described in the seminal cartographies of possible Martian paleolakes (Scott *et al.* 1991, 1995), as they were restricted to the northern lowlands. Parker and Curie (2001) first recognized the possibility of the existence of a former basin in Atlantis, analysing geomorphologic traits similar to those existing in those areas where ancient lakes had existed (Goldspiel & Squyres 1991). The first geological description of the area was performed by a comprehensive study of *Viking* images by de Pablo & Druet (2002), who discussed the possible evolution of the putative former lake. Irwin *et al.* (2002) performed a regional topographic study, concluding that a wide lake basin existed during the Late Noachian. Hence, Atlantis basin, as well as Gorgonum and other close depressed areas, all would have been included in this wide lake named Eridania (Irwin *et al.* 2002), probably the source area of Ma'adim Vallis (Irwin *et al.* 2002, 2004), which outlet in the Gusev Crater, targeted for exploration in 2004 by NASA's MER *Spirit*. Subsequently, de Pablo and co-workers (de Pablo 2003; de Pablo *et al.* 2004; de Pablo & Márquez 2004) carefully studied topographic data and images to precisely describe the geology of Atlantis, providing geomorphologic evidence of an ancient lake development inside the basin, named Atlantis Lake (de Pablo *et al.* 2004).

Topographic analysis

We have analysed in detail Mars Orbiter Laser Altimeter (MOLA) topographic data on board the *Mars Global*

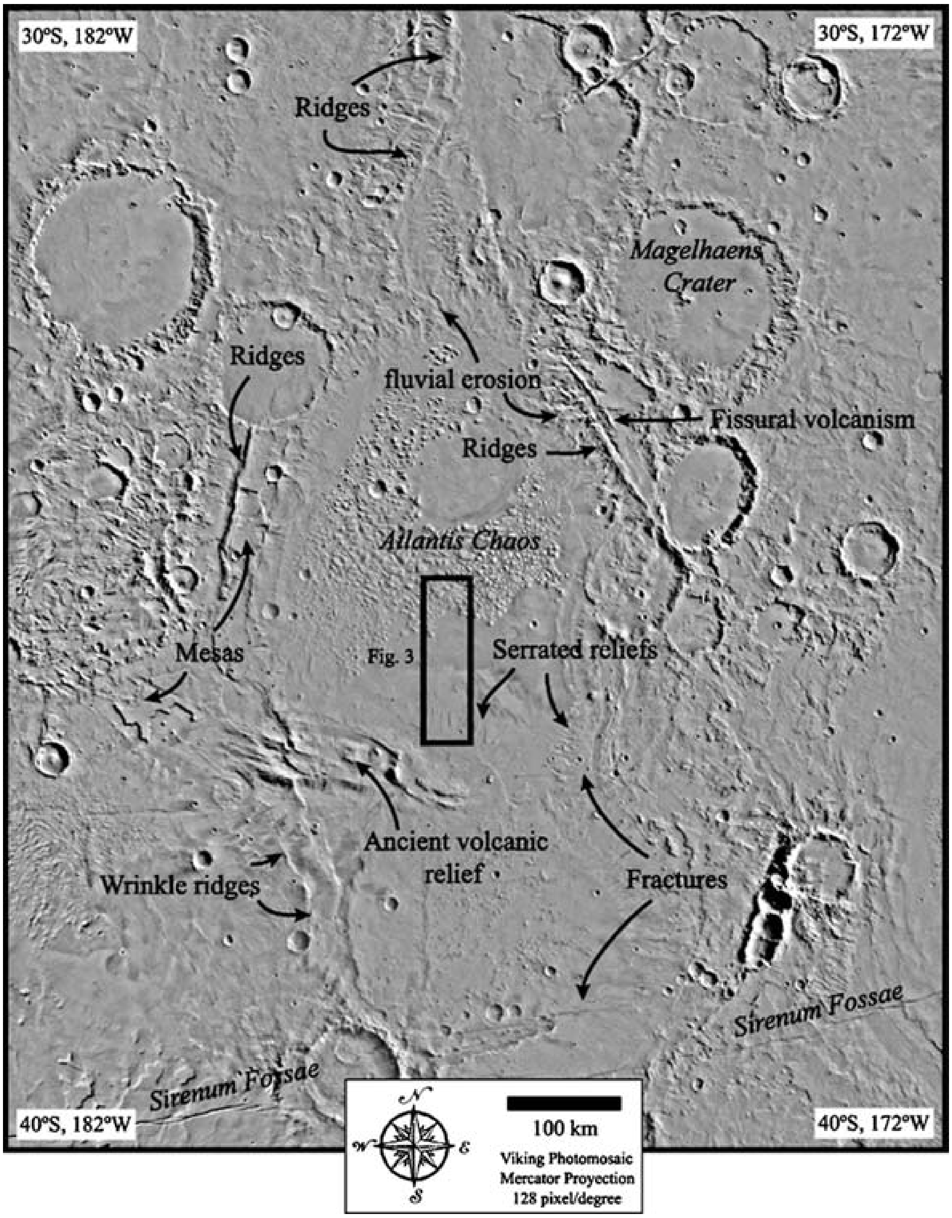

Fig. 1. *Viking* image mosaic of the Atlantis basin region, centered in 35° S, 177° W (35° S, 183° E), highlighting the most interesting geological features (see the text). The box indicates the location of Fig. 3.

Surveyor (MGS) spacecraft to describe Atlantis basin. Atlantis is a rounded depression 400 km in diameter with a depth of up to 880 m (3380 m from the basin floor to the highest elevations in the area, see Fig. 2). Located in a densely cratered region, with impact structures up to 190 km in diameter, the area is characterized by a deep asymmetry, shallower in the South side, resulting from sedimentation of materials carried to the basin from the South (de Pablo & Druet 2002; de Pablo 2003; de Pablo & Fairén 2003). The approximately rounded shape of the basin allows us to propose an impact origin (de Pablo 2003), and its bowl-shaped morphology is consistent with deposition of sediment in a long-term standing water mass, as seems to be usual in the depressions analysed in this area (Irwin *et al.* 2002). The floor of the basin is characterized by a very irregular terrain composed by mesas and disordered blocks, corresponding to the chaotic terrain known as Atlantis Chaos, although many of the valleys have preferential trends W–E and SW–NE (Fig. 2).

Locally, THEMIS images show some lineal structures parallel to the West margin of the Atlantis basin. These structures could be interpreted as possible coastlines formed during the Eridania lake drying period. Due to the low resolution of the digital elevation models, it is not possible to analyse the topography associated with these structures to test the levels of small terraces. However, the topography shows small terraces located at an altitude of 200 m, some meters below the lowest point in the margins of the Atlantis basin (in the Southwest), which is located at an altitude of 230 m.

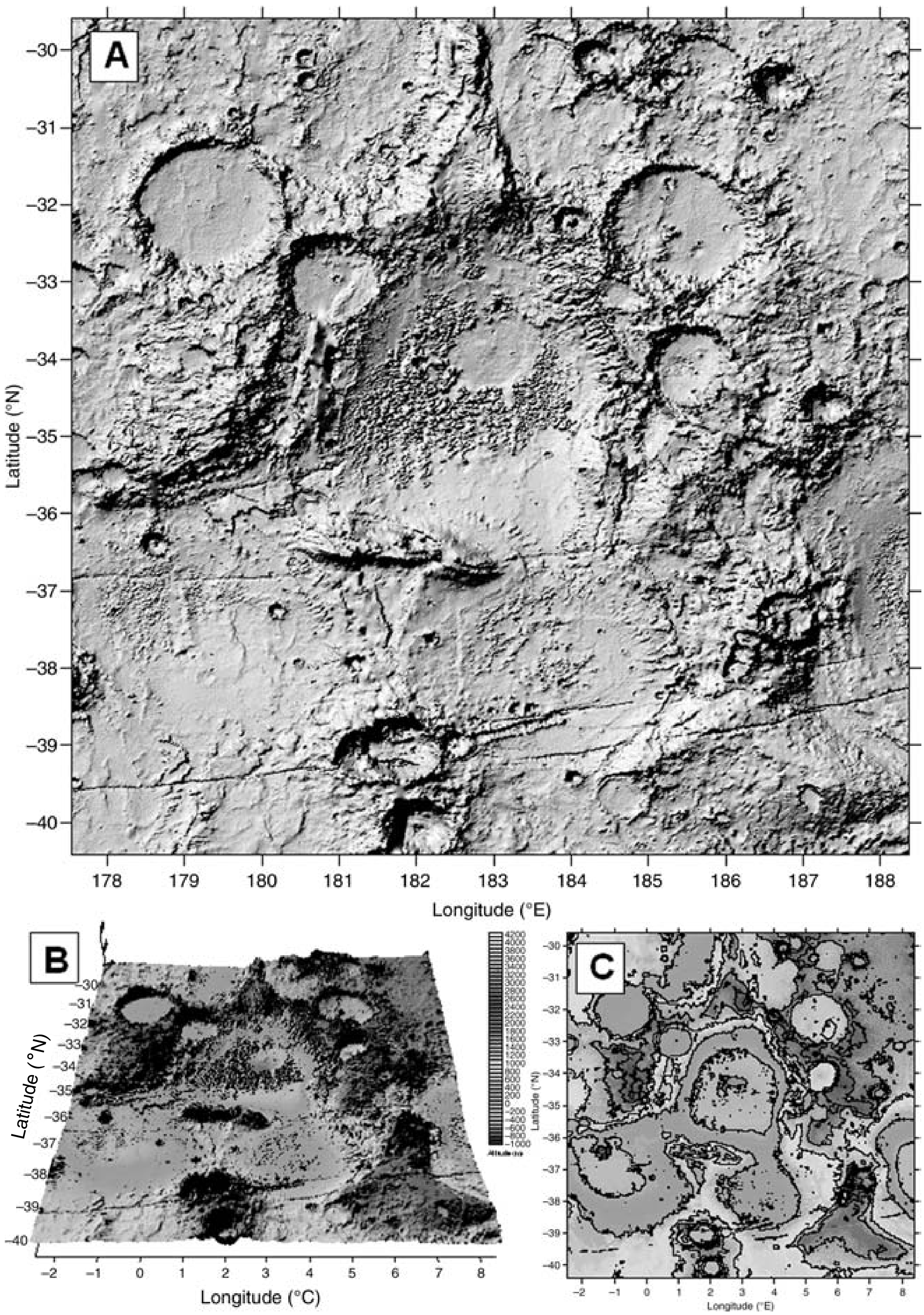

Fig. 2. Shaded relief model of the study area, where the circular appearance of the 400 km width Atlantis basin (A) and its asymmetry and bowl-shaped morphology (B) are shown. Data compiled to elaborate the topographical map of the area (C) have also been used to estimate the maximum filling volume of Atlantis Lake as 121 km^3.

The East, West and North margins are characterized by relief indicating surface runoff to the basin inside, and they are surrounded by the topographically highest and most irregular elevations. Some of the basin inner margins show serrated reliefs, and these are also visible in other basins in the area. The Southwest margin of Atlantis basin is bounded by a relief over 1800 m and with WNW–ESE elongation trending, related to an ancient volcanic edifice (Scott & Tanaka 1986). At both sides of the relief, two depressed areas connect Atlantis with two shallower close basins, both also showing chaotic terrains. The relief is also associated with a longitudinally depressed zone corresponding to the graben system of Sirenum Fossae. In the North margin, lineal reliefs up to 2200 m long are visible, and are related to compressive tectonic structures.

In the shaded relief model (Fig. 2), numerous fractures and lineations are noted, with approximately W–E, NW–SE and SW–NE trending. The topographic model (Fig. 2) also shows the existence of shallow elongated reliefs related to volcanic outflows, wrinkle ridges and mass flows. All of these features are located in relatively sparsely cratered areas, and so are young (Hartmann *et al.* 1981) and related to the ancient water extent of Eridania and Atlantis lakes (Irwin *et al.* 2002; de Pablo *et al.* 2004).

Geologic setting

To test for consistency with the lake hypothesis, we have performed a detailed photogeological mapping of *Viking Orbiter* photomosaics, leading to a general study of the most relevant geological and geomorphologic traits in Atlantis basin (de Pablo & Druet 2002). In addition, MOLA topographic data allow us to go further in the description of the previously analysed features, and so complete the study of the geological history, which is also based on high-resolution THEMIS images of the *Mars Odyssey* spacecraft.

Dikes

Linear structures inside some mesas and blocks constituting the chaotic terrain (Fig. 3) have been described as possible dikes (de Pablo & Márquez 2004). The network of dikes could be related to the formation of the chaotic terrain of Atlantis itself, the proposed origin of which requires a thermal source melting the permafrost (i.e. Komatsu *et al.* 2000; Ogawa *et al.* 2003). If this is so, the mass flows observed in the margins of Atlantis Chaos can be explained as a result of water and debris flow. In the innermost valleys of Atlantis Chaos, numerous mass flow deposits are also described (de Pablo & Márquez 2004), possibly related to thermal reactivations of the dike system. In addition, the existence of sedimentary deposits between the mesas is noted in both the MOC and THEMIS images. The lobular front, hummocky surfaces, distribution confined to the valleys and relation with the dikes of the Atlantis Chaos all support the interpretation of the sedimentary deposits as being originated by mud flows, which is markedly different from the origin of those deposits located at the impact crater inner slopes (de Pablo & Márquez 2004). Older volcanic events that created the ancient volcanoes and lava flows observed in the area can be related to the dikes system. Other small and younger volcanoes, sparsely cratered lava flows and mud-flow deposits around the Atlantis Chaos could indicate a possible thermal reactivation in the dike system.

Mass flows

Mass-flow deposits have also been detected in ancient and elevated slopes in the Northeast margin of Atlantis basin, as well as inside some impact craters. Such deposits undoubtedly indicate the presence of some quantity of water under the surface, reducing the cohesion and resistance of materials and increasing the effort due to water load (see Tarbuck & Lutgens (1999) for a review). In contrast to deposits in Atlantis Chaos (Fig. 3), the Northeast mass-flow deposits are relatively eroded and cratered, and so more aged.

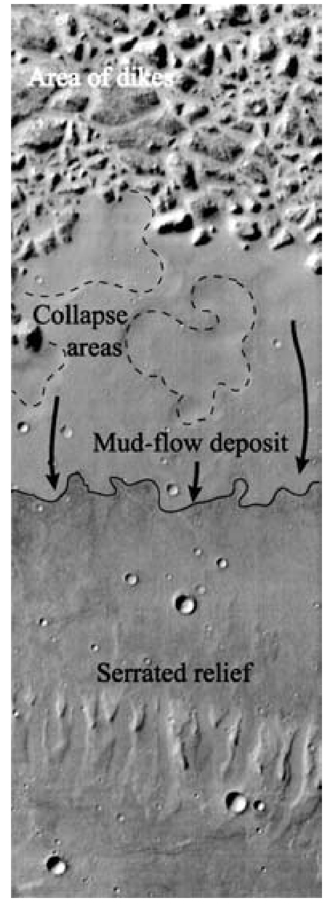

Fig. 3. Serrated reliefs in the margin of Atlantis basin, indicating that the erosion by runoff flows towards the ancient lake. Thermal energy from dikes could have caused the permafrost fusion and mud-flow formation around the chaotic terrain, as observed in the area centered at 35° S, 177° W. Collapse areas could also indicate the existence of groundwater. (I01330002 THEMIS image; 32 km width.)

Collapse zones

A joint of depressions with a depth of up to 60 m and 5–10 km in diameter with rounded edges has been detected under the flow deposits plate in the South margin of Atlantis (Fig. 3). They have been interpreted as subsidence zones due to groundwater flow, and are probably due to thermal activity in dikes at Atlantis Chaos (de Pablo & Márquez 2004; de Pablo *et al.* 2004).

Serrated reliefs

Serrated reliefs seem to indicate runoff water erosion (Fig. 3), probably during the desiccation episode of Eridania and Atlantis lakes (de Pablo & Druet 2002; de Pablo *et al.* 2004). Related to these reliefs, mesas, which were possibly formed by sediments of the former Eridania Lake and eroded during the time of the drop in the water table, are observed.

Fractures

Atlantis basin is crossed by numerous normal fractures forming a graben system with WSW–ENE main trending, part of the fracture system of Sirenum Fossae. Some of these fractures bend in the margins of the topographic relief in the Southwest of Atlantis, potentially indicating a complex tectonic episode with even a directional component, as observed in the fractures crossing the near Gorgonum basin (Martín-González *et al.* 2004). This episode would display a moderately different stress ellipsoid from that originating from the majority of the fractures in Sirenum Fossae, related to the Tharsis dome (e.g. Wise *et al.* 1979; Banerdt *et al.* 1982; Sleep & Phillips 1985; Tanaka & Davies 1988; Mège & Masson 1996a, b; Dohm *et al.* 2001; Wilson & Head 2002). Other fractures with NW–SE and NE–SW directions mark some geomorphologic features, such as little fluvial valleys, mesas or impact crater edges.

Ridges and wrinkle ridges

Compressive structures with N–S general trending and related to the Tharsis rise enclose the basin. In addition, wrinkle ridges/lobate scarps crosscut concentrically over the floor units distributed in the innermost part of the basin, and can be interpreted as a result of sediment compaction under the Eridania Lake water table (Irwin *et al.* 2002).

Gullies

Gullies appear in high-resolution images in the inner sides of some impact craters. Partially eroded dust mantles, associated with flux structures, have also been observed in this region. The dust mantles have been interpreted as ice-cemented dust mantles, flowing in marked slopes (Milliken *et al.* 2003) that could be related to the origin of gullies (Christensen 2003).

Water at the Atlantis basin region

Both topographic and geomorphologic characteristics in Atlantis basin point to the existence of diverse amounts of water (liquid and/or solid) in different moments throughout Martian history. Whether the Atlantis basin contained an intermittent or a persistent lake system is unknown, but all of the observations described here suggest the existence of several lake episodes, and hence we propose the following interpretation for the hydrological evolution of the area. Firstly, a deep area, sparsely cratered and showing abundant fluvial reliefs in the inner margins, suggests the presence of a water table inside the basin, to which the surrounding elevated terrains would have been draining during perhaps a long period of time. At an elevation of 230 m, the maximum extent of the original water sheet was 29 107 km², with a maximum volume of 10 480 km³ (see Table 1 and Fig. 2). This water table would have settled various sedimentary deposits. Later, the gradual desiccation of the primitive great lake caused the separation of each basin, as well as the excavation of some channels in the basin's margins due to a descent in the base level of the channels and to the erosion of some sedimentary deposits potentially formed under Eridania Lake, originating the mesas and serrated reliefs in the inner margins of the basins. As Mars became colder and dryer, Atlantis would have become ice covered, first seasonally and finally perennially. Low crater densities in some lava flows and flow deposits point to recent depositional conditions in Atlantis, although the most recent and accessible watery sediments were likely deposited under ice. The sequence ends with the complete desiccation of the basin.

Table 1. *Water volumes of the Atlantis Lake estimated for different maximum altitudes of the water sheet calculated with MOLA data*

Altitude of the water sheet (m)	Area of the water sheet (km²)	Volume (km³)
230	29 107	10 480
200	27 843	9626
100	23 635	7048
0	19 474	4900
−100	15 494	3150
−200	11 803	1790
−300	7802	797
−400	3371	246
−500	860	54
−600	121	9

Mass flows would have formed in different episodes, when liquid water was more abundant in the subsurface. In contrast, mud flows around some chaotic terrains were formed when the lakes had completely desiccated, and so their formation must be related to great water masses hidden in the subsurface. This is also supported by the lobated ejecta of some craters, and the collapse zones indicating some water flux under Atlantis, perhaps originating in the thermal episodes in Atlantis Chaos.

Finally, floods in the inner walls of some craters point to some water activity in recent times (Malin & Edget 2000, Arfstrom 2002, Cabrol and Grin 2002, Mellon and Phillips 2001). In the same way, frozen dust deposits on the surface suggest the contemporary presence of huge amounts of water in the regolith. The long life of the Atlantis Lake system argues for a well-suited habitat for life forms evolving on the surface of the Martian highlands.

Astrobiological implications

The volcanic and tectonic activities, and the presence of possible dikes in the area, as well as the relation of Atlantis with the former wide Eridania Lake, the gullies and the sedimentary deposits, all highlight the astrobiological interest of Atlantis region. A heat source related to tectonovolcanic activity and flowing and ponded water are both hypothesized to have been present in the basin in different periods of the Martian history, perhaps until recent times (Late Amazonian). All of these conditions could indicate the existence of sites where the environmental setting was once more favourable for life, and their narrow relationship could be used as a key pacemaker for the location of astrobiologically interesting sites. Assuming that the search for life is directly linked to the search for water, the possible biological history of Atlantis must have been largely influenced by such hydrogeological cycles, probably related to the planetary general endogenetically-driven watery epochs (Baker *et al.* 1991; Fairén *et al.* 2003). In addition, the contemporary subsurface of Atlantis might include subsurface fissures, microcracks, intergrain pore spaces, subterranean shallow and deep sealed voids, and aquifers, where microorganisms could be thriving today, protected against extreme temperature fluctuations or desiccation, UV radiation and cosmic rays (Boston *et al.* 2001). So, the sediments in Atlantis basin could preserve information on the long-term hydrological (biological?) evolution over the Southern highlands of Mars, and hence may be considered as an attractive prime candidate site for future drilling, sampling and analysis, searching for extinct (fossilized) and possibly even extant putative Martian life forms.

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