ASTROBIOLOGY
Volume 16, Number 2, 2016
Mary Ann Liebert, Inc.
DOI: 10.1089/ast.2015.1396

The Argyre Region as a Prime Target for *in situ* Astrobiological Exploration of Mars

Alberto G. Fairén,[1,2] James M. Dohm,[3] J. Alexis P. Rodríguez,[4] Esther R. Uceda,[5] Jeffrey Kargel,[6]
Richard Soare,[7] H. James Cleaves,[8,9] Dorothy Oehler,[10] Dirk Schulze-Makuch,[11,12] Elhoucine Essefi,[13]
Maria E. Banks,[4,14] Goro Komatsu,[15] Wolfgang Fink,[16,17] Stuart Robbins,[18] Jianguo Yan,[19]
Hideaki Miyamoto,[3] Shigenori Maruyama,[8] and Victor R. Baker[6]

Abstract

At the time before ∼3.5 Ga that life originated and began to spread on Earth, Mars was a wetter and more geologically dynamic planet than it is today. The Argyre basin, in the southern cratered highlands of Mars, formed from a giant impact at ∼3.93 Ga, which generated an enormous basin approximately 1800 km in diameter. The early post-impact environment of the Argyre basin possibly contained many of the ingredients that are thought to be necessary for life: abundant and long-lived liquid water, biogenic elements, and energy sources, all of which would have supported a regional environment favorable for the origin and the persistence of life. We discuss the astrobiological significance of some landscape features and terrain types in the Argyre region that are promising and accessible sites for astrobiological exploration. These include (i) deposits related to the hydrothermal activity associated with the Argyre impact event, subsequent impacts, and those associated with the migration of heated water along Argyre-induced basement structures; (ii) constructs along the floor of the basin that could mark venting of volatiles, possibly related to the development of mud volcanoes; (iii) features interpreted as ice-cored mounds (open-system pingos), whose origin and development could be the result of deeply seated groundwater upwelling to the surface; (iv) sedimentary deposits related to the formation of glaciers along the basin's margins, such as evidenced by the ridges interpreted to be eskers on the basin floor; (v) sedimentary deposits related to the formation of lakes in both the primary Argyre basin and other smaller impact-derived basins along the margin, including those in the highly degraded rim materials; and (vi) crater-wall gullies, whose morphology points to a structural origin and discharge of (wet) flows. Key Words: Mars—Surface processes and composition of Mars—Liquid water—Geological conditions for the development of life—Planetary habitability and biosignatures. Astrobiology 16, 143–158.

---

[1] Department of Planetology and Habitability, Centro de Astrobiología (CSIC-INTA), Madrid, Spain.
[2] Department of Astronomy, Cornell University, Ithaca, New York, USA.
[3] The University Museum, The University of Tokyo, Tokyo, Japan.
[4] Planetary Science Institute, Tucson, Arizona, USA.
[5] Facultad de Ciencias, Universidad Autónoma de Madrid, Madrid, Spain.
[6] Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona, USA.
[7] Department of Geography, Dawson College, Montreal, Canada.
[8] Earth-Life Science Institute, Tokyo Institute of Technology, Tokyo, Japan.
[9] The Institute for Advanced Study, Princeton, New Jersey, USA.
[10] Jacobs/LZ Technology, JETS Contract, NASA Johnson Space Center, Houston, Texas, USA.
[11] Center of Astronomy and Astrophysics, Technical University Berlin, Berlin, Germany.
[12] School of the Environment, Washington State University, Pullman, Washington, USA.
[13] Higher Institute of Applied Sciences and Technology, University of Gabes, Gabes, Tunisia.
[14] Smithsonian Institution, National Air and Space Museum, Center for Earth and Planetary Studies, Washington, DC, USA.
[15] International Research School of Planetary Sciences, Università d'Annunzio, Pescara, Italy.
[16] College of Engineering, Department of Electrical and Computer Engineering, University of Arizona, Tucson, Arizona, USA.
[17] Division of Physics, Mathematics and Astronomy, California Institute of Technology, Pasadena, California, USA.
[18] Southwest Research Institute, Boulder, Colorado, USA.
[19] RISE Project Office, National Astronomical Observatory of Japan, Oshu, Japan.

1. Introduction

Earth has been an enduringly dynamic and water-influenced planet since early in its geological history. There is evidence of water-deposited rocks in the oldest petrological record of Earth (*e.g.*, Mojzsis *et al.*, 2001) and evidence of continent/ocean structure almost as ancient (*e.g.*, Polat, 2012; Maruyama *et al.*, 2013a; Ge *et al.*, 2014), as well as magmatism involving a water-rich interior—and presumed degassing—at least as early as 4.2 Ga (Iizuka *et al.*, 2006). Earth's biosphere originated and evolved very early in its geological history. There is evidence for Paleoarchean life dating back to ∼3.4 to 3.5 Ga from both organic microfossils and stromatolites (*e.g.*, Schopf *et al.*, 2002, 2007a, 2007b; Knoll, 2004; Allwood *et al.*, 2006; Schopf, 2006; Stüeken *et al.*, 2015), and those microfossils exhibit relatively diverse morphologies and complexity (Oehler *et al.*, 2010; House *et al.*, 2013), suggesting an even earlier origin of life that can be unambiguously identified in the geological record. Consistent with this view is isotopic evidence suggestive of the presence of biological activity dating as far back as 3.8 Ga (Mojzis *et al.*, 1996). Because Paleoarchean life appears to have been relatively diverse, life's origin on Earth is likely to have occurred even earlier than these dates suggest (Eiler, 2007; Abramov and Mojzsis, 2009; Oehler *et al.*, 2010; House *et al.*, 2013; Maruyama *et al.*, 2013b; Patel *et al.*, 2015), possibly even during the Hadean more than 4.0 billion years ago.

At the time when life originated and began to radiate on Earth, Mars was a wetter and more geologically dynamic planet than it is today, with a global hydrological cycle. Mirroring conditions of the Late Hadean or Paleoarchean Earth, early Mars comprised a landmass (the southern cratered highlands acting as a ''supercontinent''); a large ocean, countless crater-hosted lakes, and continental-scale ice sheets (Baker *et al.*, 1991; Kargel and Strom, 1992; Kargel *et al.*, 1995; Cabrol and Grin, 1999; Carr and Head, 2003; Fairén *et al.*, 2003; Head *et al.*, 2005; Di Achille and Hynek, 2010); a relatively thick atmosphere, capable of supporting stable and widespread hydrological activity; and diverse energy sources (such as solar or thermally induced chemical disequilibrium, see Baker *et al.*, 2007; Fairén, 2010, and references therein). Interaction among the landmass, ocean, and atmosphere through hydrological cycling driven by internal (heat flow) and external (the Sun) energy sources is considered key to Mars being habitable during its early evolution (Dohm and Maruyama, 2014).

At the surface, early Mars may have supported an Earth-like erosional regime and relatively warmer and wetter conditions than today (*e.g.*, Baker *et al.*, 2007), perhaps having prevailing modern Earth-like periglacial/glacial conditions, which may have been sufficient for life to originate and evolve (Fairén *et al.*, 2003, 2010; Kargel, 2004). Moreover, subsurface conditions could have been even warmer and wetter, generating local settings that had potentially habitable conditions for far longer periods—perhaps continuously since the Noachian period. Given that early Mars may have hosted habitable conditions approximating those of early Earth, then whatever steps that led to the emergence and early evolution of life on Earth also may have occurred independently on Mars. Alternatively, life could have been transferred from Earth to Mars or vice versa (*e.g.*, Schulze-Makuch *et al.*, 2008; Fairén *et al.*, 2010) when habitable conditions were present on Mars.

The geological and hydrological evolution of the Argyre basin and its margins, located in the southern hemisphere of

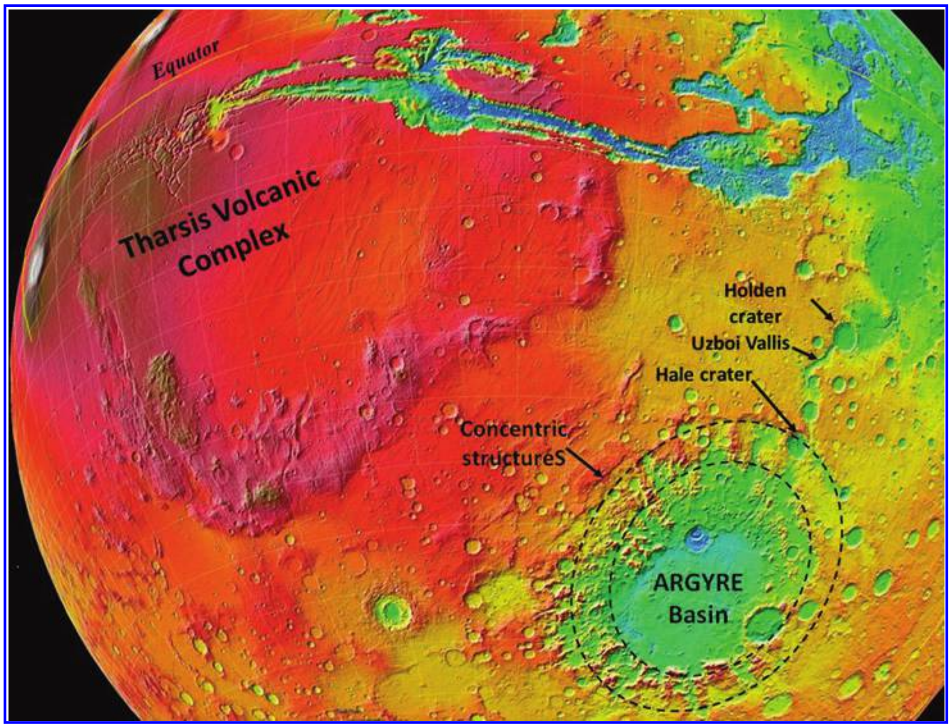

FIG. 1. Location map of Argyre, showing the main features discussed in this article. Base is a Mars Orbiter Laser Altimeter (MOLA) map. (Color graphics available at www.liebertonline.com/ast)

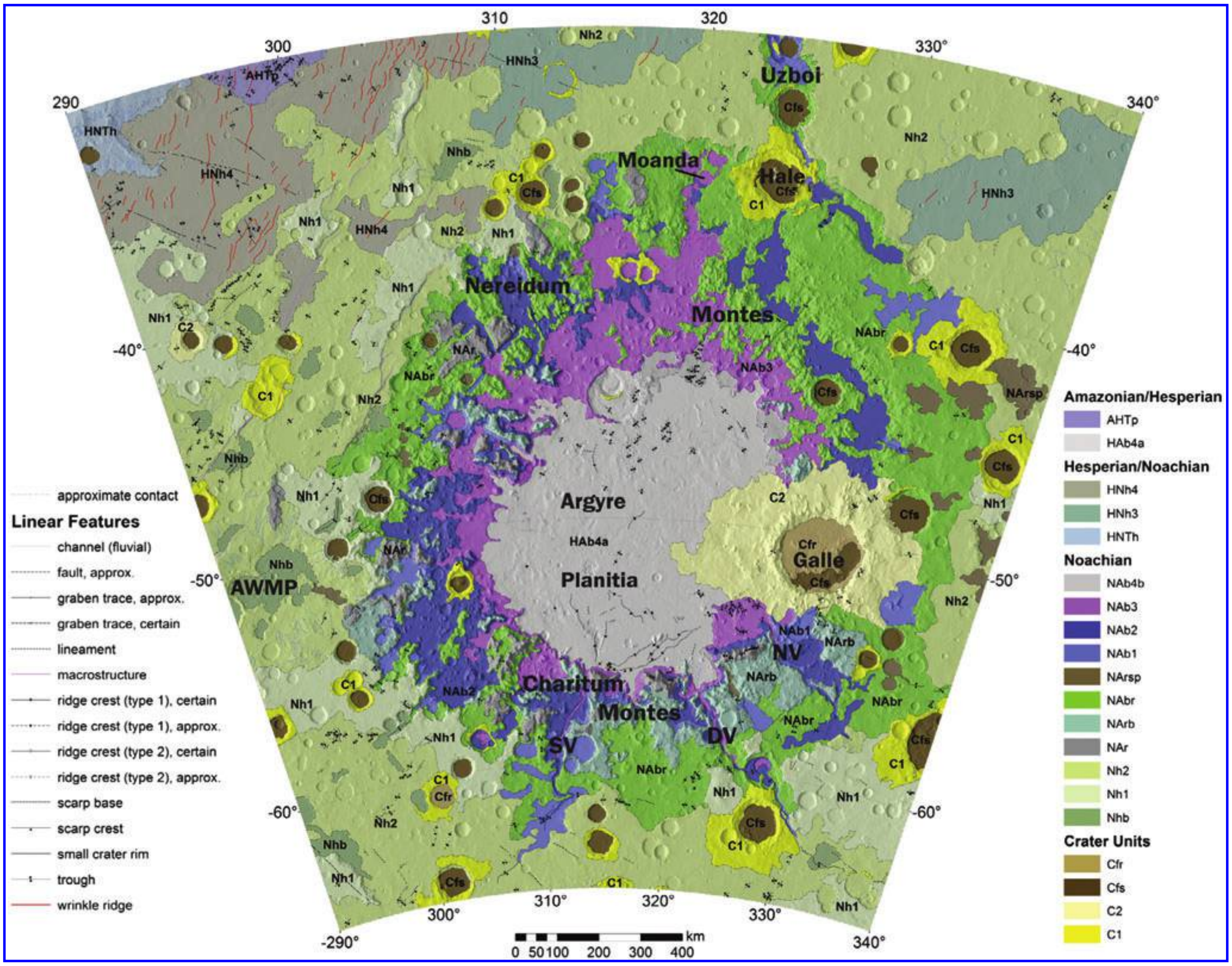

FIG. 2. Geological map of the Argyre and surrounding region of Mars showing stratigraphy and structure. Highlighted are the major valley systems, Uzboi Vallis (Uzboi), Surius Vallis (SV), Dzigai Vallis (DV), Nia Vallis (NV), and the Argyre western-margin-paleolake basin (AWMP). (Color graphics available at www.liebertonline.com/ast)

Mars (Fig. 1), points to a habitable environment where life could have originated (or been transferred to), persisted, and evolved. The early post-impact environment of the Argyre basin possibly contained many of the ingredients we think today are necessary for life: abundant and long-lived liquid water, biogenic elements, and energy sources. Here we suggest that, early in Mars' geological history, the Argyre impact basin and margins supported (and perhaps still support at depth) an environment that is favorable for the origin, development, and maintenance of microbial life.

2. Geological History

The Argyre province (30°S to 65°S, 290°E to 340.0°E; Fig. 2) is a major geological province in the southern cratered highlands of Mars. Geological and hydrological histories have been detailed through a mapping investigation with Viking, Mars Global Surveyor (MGS), Mars Odyssey (ODY), and Mars Reconnaissance Orbiter (MRO) data (Dohm *et al.*, 2015). A synthesis of Argyre's history is provided here, using the formal chronostratigraphic systems (Noachian, Hesperian, and Amazonian) devised by Scott and Carr (1978), as well as the series (upper, middle, and lower divisions of systems) defined by Tanaka (1986).

The Argyre basin formed from a giant impact estimated to have occurred at ~3.93 Ga (Robbins *et al.*, 2013), near the end of the Late Heavy Bombardment (Claeys and Morbidelli, 2011; Fassett and Minton, 2013). The impact left an enormous basin, approximately 1800 km in diameter. The Argyre event occurred at a time when Mars was experiencing major changes in global planetary conditions, including termination of the internal dynamo, the thinning of the atmosphere, and consequential changes in climate (*e.g.*, Fairén *et al.*, 2003; Baker *et al.*, 2007; Fairén, 2010).

The Argyre basin is the best-preserved large multiringed impact structure on Mars. This is more noticeable when Argyre is compared to the larger and more highly degraded ~4.0 Ga Hellas impact basin (Robbins *et al.*, 2013); the distinction is indicative of major planetary-system changes occurring during the estimated 70-million-year time range between the formation of Argyre and Hellas. The giant impact event resulted in the construction of the primary Argyre crater, the uplift of a mountainous rim, and the production of a complex system of tectonic structures. These include small

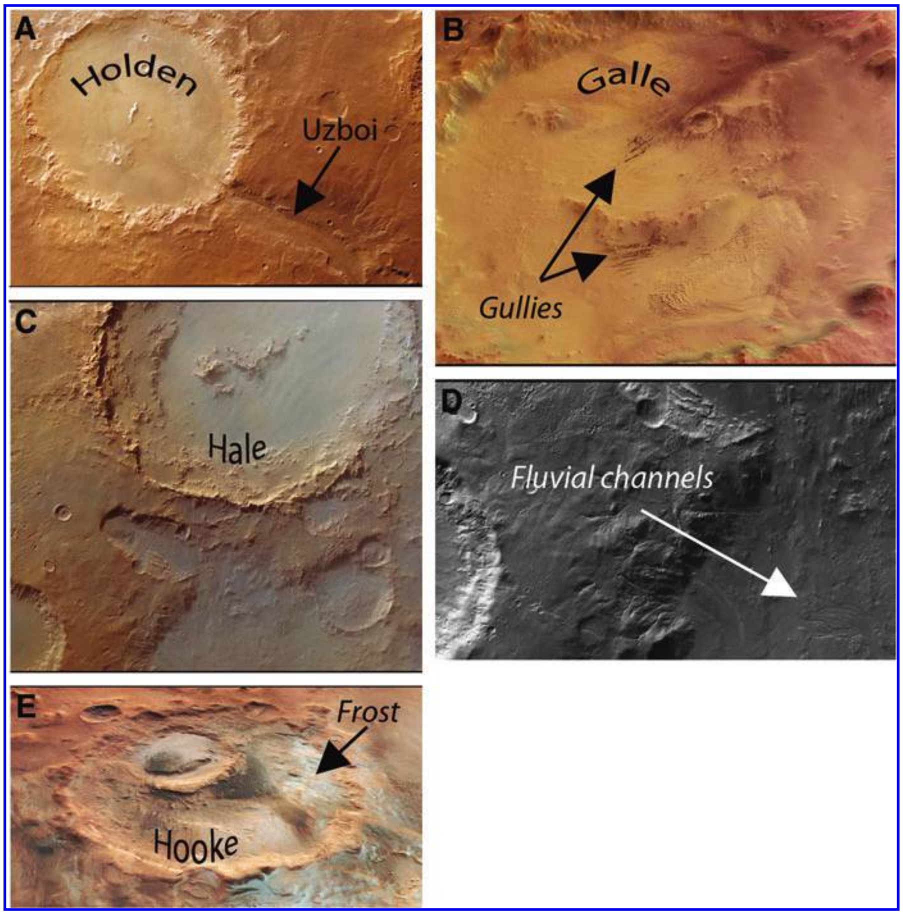

FIG. 3. Examples of big impact craters excavated on the Argyre province. (**A**) The outlet channel of the Uzboi Vallis system debouching into the 140 km wide Holden crater. Holden's rim is cut with gullies, and at the end of some gullies are fan-shaped deposits of material transported by water, and sediments containing clays. (**B**) Close-up view of the 230 km diameter crater Galle, to the east of the Argyre Planitia. A large stack of layered sediments form an outcrop in the southern part of the crater, and several parallel gullies originate at the inner crater walls of the southern rim. (**C**) The 150 km diameter crater Hale, with its terraced walls, central peak, and a part of the inner ring. The wall of Hale crater has a large number of gullies, and its surface shows a network of fluvial channels. (**D**) The network of fluvial channels, which may have been caused by running water, to the west of Hale crater. (**E**) Hooke crater, with a diameter of 138 km, comprises two different impact structures, with a smaller impactor blasting a depression off-center in the floor of a larger, pre-existing crater. The newer crater in the center is filled with a large mound topped by a dark dune field. The mound appears to be composed of layered material, possibly alternating sheets of sand and frost. Dark dunes spread southward from the smaller crater, partially covering the floor of the main crater. Much of the low-lying region to the south, as well as the central mound inside Hooke crater, is covered with a thin, white coating of carbon dioxide frost. Image credits: ESA/DLR/FU Berlin (G. Neukum). (Color graphics available at www.liebertonline.com/ast)

and large (as much as thousands of kilometers in length) extensional and compressional structures, such as structurally controlled fault scarps, broad ridges, valleys, and mountain ranges within several hundred kilometers of the basin margin. With time, erosional and depositional processes have highly resurfaced the Argyre basin and rim materials continuously since the excavation of the impact basin (Fig. 3).

3. The History of Water and Volatiles in the Argyre Region

Topographic, geomorphological, spectroscopic, and isotopic investigations (*e.g.*, Hiesinger and Head, 2002; Kargel, 2004; Banks *et al.*, 2008, 2009; Buczkowski *et al.*, 2010; Jones *et al.*, 2011; El Maarry *et al.*, 2013; Soare *et al.*, 2014a, 2014b; Webster *et al.*, 2015) provide information for reconstructing the hydrological history of Argyre, including long-term water enrichment up to the present day. These investigations provide some evidence for a broad integration of hydrogeological activity within the basin extending to possible headwaters in the highlands south and east of the basin, and to the Uzboi-debouchment area, northeast of the basin, and possibly associated with flooding of the northern plains (*i.e.*, possibly above the Opportunity Landing site) during the Noachian and Early Hesperian (Fairén *et al.*, 2003, 2004); this hydrological system had the Argyre impact-derived lake as the primary contributor of Uzboi Valles (Dohm *et al.*, 2015).

3.1. The geomorphological perspective

Some of Argyre's impact-generated basement structures possibly reach great depths (potentially reaching the lower crust and likely the Moho of Mars) and could have served as conduits for the migration of water, volatiles, and internal heat into the basin from thousands of kilometers away, such as extending well within the Tharsis province and from depths potentially reaching Mars' lower crust and upper mantle (Dohm *et al.*, 2001a, 2001b, 2013). These processes may still be occurring presently (Soare *et al.*, 2014a), though presumably at a slower pace than in the earlier history of the basin. This would contribute to a long-term supply of mineral-enriched water in the subsurface and at the surface of the basin.

Water enrichment could have been augmented by hydrothermal activity associated with the Argyre excavation, with impact-driven, long-term heat energy being supplied potentially for millions of years; for example, Abramov and

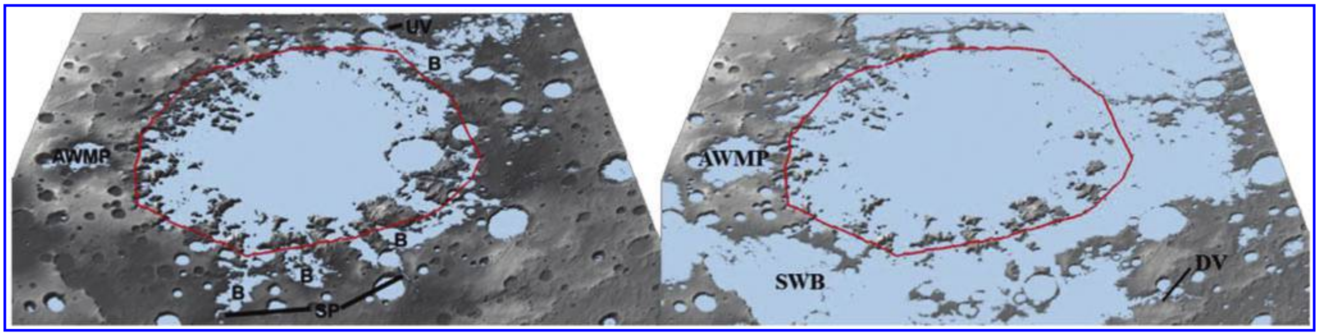

FIG. 4. (**Left**) Schematic paleolake map of the Argyre basin using a maximum topographic elevation of 0 km based on MOLA topography (regions in blue). An estimated extent of the hypothesized Argyre lake based on geomorphological and topographical analyses, as well as detailed geological mapping, is also shown (red line). In addition to the estimated extent, dendritic channel systems (SP), local basins (B) that occur among the crater rim materials, and the Uzboi Vallis system (UV) correspond to the blue-highlighted region. Also shown is a small extent (near base level) of AWMP. The volumes of the hypothesized AWMP and Argyre lakes are estimated to be 1.6×10^4 and 1.9×10^6 km^3, respectively, using MOLA. Ever-changing conditions in the Argyre basin include the possible interplay between lakes, ice sheets, and glaciers through time, as well as waning water bodies. (**Right**) Similar to left, but at 1 km with an estimated volume of 3.1 million km^3, nearing that of the Mediterranean Sea. SWB is the drainage basin located southwest of the Argyre basin; DV is a distinct dendritic valley located southeast of the primary Argyre basin. (Color graphics available at www.liebertonline.com/ast)

Kring (2005) estimated about 10 million years of continuing hydrothermal activity for a Hellas-sized basin, depending on the permeability of the subsurface. Following the same reasoning, Argyre would potentially have had long-lived heat energy, even factoring the smaller size and younger age of Argyre with respect to Hellas. This energy supply, coupled with heat releases from the largest and most enduring volcanic province in the Solar System, the nearby Tharsis superplume (Dohm *et al.*, 2001b, 2007; Baker *et al.*, 2007), could have provided long-term hydrothermal activity near the surface after the impact excavation. To a lesser extent, and in geologically more recent times, the Elysium superplume (*e.g.*, Baker *et al.*, 2007) and the Tharsis/Elysium corridor region (Dohm *et al.*, 2008), as well as changes in obliquity (*e.g.*, Laskar *et al.*, 2004), also could have contributed to the alteration of the interior surfaces of the Argyre basin and associated rim materials.

As a consequence of the water enrichment, the primary Argyre basin contained a large water body that was sufficient in size to have sourced Uzboi Vallis (Dohm *et al.*, 2015). This conclusion is based on several lines of evidence including (i) crater retention ages that are similar among the high-standing Argyre rim materials and intervening valley- and basin-infill materials, and (ii) spatial associations (stratigraphic relations and relative elevations) among the source region of Uzboi Valles, terraces, benches, and a possible spillway that connected a paleolake in Douglass impact crater with the primary Argyre basin, all of which are near the zero-elevation datum (*i.e.*, 0 km as a potential equipotential surface). It is even possible that a more extensive water body could have formed due to the impact, reaching an elevation of 1.0 km or more above the zero-elevation datum. This is suggested by the Geographic Information Systems (GIS) mapping of elongated basins with valley networks along their margins and dendritic valleys. If the water column reached 1.0 km in elevation, then the body of water with a maximum depth reaching ∼4.0 km would have had an estimated volume of $\sim3\times10^6$ km^3, approximating the volume of the Mediterranean Sea, as well as a comparable maximum depth of 5.3 km (Fig. 4).

Following the formation of lakes and associated growth of glaciers, the water bodies would have waned over time, and eventually the lakes would have become frozen, as the planet cooled and impact-generated heat dissipated over time. Evidence has been provided for wet-based alpine and continental-scale glaciation in southern Argyre and the adjoining highlands (Kargel and Strom, 1992; Kargel, 2004; Banks *et al.*, 2008, 2009), with a proposed glacial system extending as far as the south polar region and eastward halfway to Hellas (Baker *et al.*, 1991; Kargel and Strom, 1992; Hiesinger and Head, 2002). Baker *et al.* (1991) considered that a latitude limit of south polar glaciation occurred roughly halfway through the Argyre basin, leaving the southern part glaciated, although El Maarry *et al.* (2013) found evidence for glaciation also occurring farther north. This is also supported by the presence of sinuous ridges in areas surrounding southern Argyre Planitia (Seibert and Kargel, 2001; Banks *et al.*, 2008). The sinuous ridges have been hypothesized by several investigators to be eskers or fluvial sediments deposited in open-walled channels within an ice sheet (*e.g.*, Kargel and Strom, 1992; Seibert and Kargel, 2001; Kargel, 2004; Banks *et al.*, 2008, 2009). Recent mapping suggests that these ridges formed during the Late Hesperian–Early Amazonian (Dohm *et al.*, 2015). The esker development correlates to major Tharsis outgassing, flood erosion of some circum-Chryse outflow channels, and widespread glacial activity (Baker *et al.*, 1991; Kargel *et al.*, 1995; Dohm *et al.*, 2001b, 2007; Rodriguez *et al.*, 2014) recorded in the youngest Argyre plains-forming basin floor deposits of the distinct stratigraphic sequences in the basin (unit HAb4a; Dohm *et al.*, 2015). There has been significant activity since this major stage of Tharsis development, including geologically recent and possibly present-day resurfacing of all the geological units of the Argyre Province (Dohm *et al.*, 2015), which are tied to variable endogenic and exogenic activities at local to global scales on Mars (Kargel, 2004; El Maarry *et al.*, 2013; Rodriguez *et al.*, 2014; Soare *et al.*, 2014a, 2014b).

Periglacial activity has also been identified in and around the Argyre impact basin, including the development of small-scale mounds. These mounds could be open-system pingos (OSPs, see following section), perennially ice-cored mounds fed by hydraulically driven water. These mounds are located downslope of gullies inset within fractures and faults, suggesting structurally controlled groundwater flow and the migration of heat from the interior of Mars (Soare *et al.*, 2014a).

Subsequent modification of the regional landscape seems to reflect the influence of fluvial, alluvial, glacial, periglacial, and eolian processes (Kargel and Strom, 1992; Parker *et al.*, 2000; Hiesinger and Head, 2002; Kargel, 2004; Banks *et al.*, 2008, 2009; Soare *et al.*, 2014a, 2014b; Dohm *et al.*, 2015). Within and around the basin, resurfacing has included physical and chemical erosion, the emplacement of diverse sedimentary deposits, the accumulation and ablation of glacial ice, major etching of the rim materials, and the highly localized flow of gully-associated water. Also, possible fog concentration, including moisture, could have periodically embanked against topographic highs and bottle-necked into valleys and basins in Argyre, providing suitable environmental conditions for fog-dependent ecosystems, similarly to fog-driven ecosystems on Earth (*e.g.*, Hock *et al.*, 2007; Warren-Rhodes *et al.*, 2007; Borthagaray *et al.*, 2010; Azúa-Bustos *et al.*, 2011; Latorre *et al.*, 2011).

3.2. The geochemical perspective

At the time of the impact excavation of Argyre, at 3.93 Ga, water probably was abundant on Mars' surface, according to data obtained by the Curiosity rover. Curiosity's Sample Analysis at Mars (SAM) experiment measured thermally evolved water and hydrogen gas from the ''Cumberland'' rock target in Gale crater (Webster *et al.*, 2015). The samples were Hesperian in age and used to determine the deuterium to hydrogen (D/H) isotope ratio, which can be used to infer the amount of water at the time of formation of Cumberland. The D/H ratio in Cumberland was measured to be about half that of the ratio found in martian atmospheric water vapor today, suggesting that Mars retained much of its surface water at the time when Cumberland formed. Because Argyre was excavated at least 100 million years before the formation of Gale (Gale has an age of 3.8–3.6 Ga, see Greeley and Guest, 1987, and Thomson *et al.*, 2011), water should have been more abundant at the time of Argyre's formation than when Gale formed, because the surface of Mars should have experienced wetter conditions at earlier times (*e.g.*, Fairén *et al.*, 2003; Kargel, 2004). Additional investigations through Curiosity have indicated that Mars had the required climate and atmospheric conditions in terms of pressure and temperature to harbor large crater lakes, streambeds, and deltas long after the excavation of Gale in the early Hesperian period and for tens of millions of years after (Williams *et al.*, 2013; Grotzinger *et al.*, 2014). Considering Argyre's older age of ~3.93 Ga, it is likely that water was even more abundant in the early history of Argyre than of Gale.

Multiple spectroscopic analyses of the basin have helped unveil this history of Argyre's water. More than 100 CRISM (Compact Reconnaissance Imaging Spectrometer for Mars, a visible-infrared spectrometer aboard MRO) targeted observations of the Argyre basin area have been acquired, with the result that (i) phyllosilicates have been identified in locations where aqueous activity has modified the landscape within the basin, and (ii) signatures of olivine in the rim materials of Argyre point to the impact having exposed parts of the upper mantle through the inversion of stratigraphy (Buczkowski *et al.*, 2010). Rock outcrops exposed along the large Argyre impact-derived concentric structures show evidence of high calcium pyroxene materials and phyllosilicates, such as magnesium-rich chlorite and iron-magnesium smectite (Buczkowski *et al.*, 2010). Ancient subglacial drainage of a south polar ice-sheet, together with widespread glaciers on Argyre's rim, would have delivered large volumes of clays to the basin's basal stratigraphy. The reduced permeability of these ancient clay deposits would have promoted the development of regional aquifers within the floor of Argyre. Aqueous activity also is indicated by the phyllosilicates identified in Hale crater ejecta, which are consistent with those observed in western Argyre, CRISM-based signatures of which include chlorite and iron-magnesium smectite along with some prehnite (Buczkowski *et al.*, 2010). Aqueous activity likely included hydrothermalism, related to the Hale impact into the water-enriched Uzboi-Vallis source area (Dohm *et al.*, 2015).

4. The Argyre Region as a Prime Site for Astrobiological Exploration

4.1. Water on Mars and habitability

Early Mars is thought to have been relatively habitable (see previous sections). The Argyre impact event occurred during the Late Heavy Bombardment, when Mars had a much thicker atmosphere than today; CO_2 atmospheric pressures are estimated to have been at about 0.5–1 bar (Carr, 1999) to 1.5 bar (Phillips *et al.*, 2001). Dynamical simulations also suggest that Mars acquired less total bulk of water than Earth, about 0.06–0.27 of Earth's oceans (Lunine *et al.*, 2003); however, this estimate actually represents more water content per planetary volume in Mars than in Earth, which is consistent with the position of Mars in the Solar System retaining more volatiles. Evidence for ancient oceans on the northern plains of Mars comes both from geological and geomorphological analyses (*e.g.*, Fairén *et al.*, 2003, and references therein) and from spectroscopic investigations (*e.g.*, Villanueva *et al.*, 2015, consider a global equivalent layer—GEL—of about 130 m on early Mars).

The above-described amounts of water are also consistent with a deposited volume estimated to be at least 1/10 that of the volume of water on Earth during the Late Heavy Bombardment, shortly following the Argyre impact event, as well as the volume of water mobilized to the surface from subsurface reservoirs of ground ice and water. This estimate includes the Noachian Contact 1-Meridiani shoreline, which would have enclosed a volume of water of more than 10^8 km^3 or roughly 1/6 that of the Pacific Ocean (Fairén *et al.*, 2003; Ormö *et al.*, 2004); a lake body of 3×10^6 km^3 volume in Argyre, approximating that of the Mediterranean Sea; and another lake in Hellas (Moore and Wilhelms, 2007), which is estimated here as roughly equivalent to that of the Argyre lake. This estimate does not account for other possible lakes in the southern highlands, such as those that occupied smaller impact basins (Cabrol and Grin, 1999). A significant amount of water was, therefore, present at the time of the Argyre impact event (also see Di Achille and Hynek, 2010) at, and in, the encompassing region of the target site of the giant impact.

Through time, near-surface liquid water and water-ice dissipated, though it was not totally depleted, as there was subsequent Tharsis-driven, transient hydrological cycling (including enhanced geological and climatic activities, see Dohm *et al.*, 2001b; Fairén *et al.*, 2003; Baker *et al.*, 2007). On present-day Mars, D/H data from meteorites indicate that a GEL of undetected subsurface water/ice that ranges from about 10^2 to 10^3 m (Kurokawa *et al.*, 2014; Usui *et al.*, 2015) should exist. This value far exceeds the sum of the observable present water inventory (~20–30 m GEL) on Mars, as was estimated by Christensen (2006), and the hypothesized deep-aquifer water reservoir that exists today (another 20 m GEL), which was calculated by Villanueva *et al.* (2015) as a conservative minimum volume. The modern phases of aqueous activity would have allowed potential living organisms to become more active and widespread, while during intervening phases, life might have remained in a dormant or at least stationary state (Schulze-Makuch *et al.*, 2005).

4.2. The habitability of Argyre

Argyre's unique geological setting may have contributed to the existence of life and may have significant implications for the search for life on Mars. Conditions compatible with current models for the origin of life were likely present in, or around, Argyre for at least tens of millions of years after the impact. These could have included intermittent and standing bodies of liquid water (*e.g.*, Fairén *et al.*, 2003) with a variety of solutes depressing the melting point of water when conditions on Mars turned colder globally (Fairén *et al.*, 2009); the presence of various mineral surfaces including clays (Cleaves *et al.*, 2012); impact-induced and volcanically induced hydrothermal circulation (Ciba Foundation, 2008); solar radiation; and the input of organic materials from interplanetary dust particles, carbonaceous chondrites, and comets (Flynn, 1996). The long-term persistence of these factors in Argyre also make it an exceptional candidate for the persistence of life on Mars, as well as the preservation of biomarkers in clays or evaporates (Aubrey *et al.*, 2006; Summons *et al.*, 2011). Most of the above-mentioned factors would have been available for long periods of Mars' history, sustaining structurally and thermally stable aquifers.

In particular, water-rich, hydrothermal systems are not only possible sites for the origin of life, but they also provide excellent environmental conditions to preserve mineralized and organic fossils by favoring rapid entombment of cellular structures in precipitating mineral phases. For example, fossil-containing Archean rocks on Earth are often heavily metamorphosed deep-water sediments, hydrothermal deposits, or alternating layers of sediments and igneous rocks. Some of these rocks have preserved fossilized organic remains for at least 2.7 billion years (Rasmussen *et al.*, 2008). Similar fossil remains could exist in sedimentary deposits (*e.g.*, Komatsu and Ori, 2000) within the Argyre basin. The preservation of such fossil remains would have been aided by the pervasive low temperatures, as well as the development of glacial and periglacial conditions both within and around the basin. Evidence for glacial and periglacial activity is widespread throughout the geological history of Mars (*e.g.*, Fairén *et al.*, 2011), and more data from several locations continue to be investigated, including Gale crater (Fairén *et al.*, 2014).

The continued supply of heat and gases in the Argyre basin could have resulted in an entrenched and long-lasting autotrophic microbial biosphere based on subsurface hydrothermal vent systems, possibly generating methane as an end product of their metabolism (*e.g.*, Schulze-Makuch *et al.*, 2005, 2008; Komatsu *et al.*, 2011). Global atmospheric methane of present-day Mars was reported by Formisano *et al.* (2004), Mumma *et al.* (2004), and Krasnopolsky *et al.* (2004), with apparent regional enrichments (Geminale *et al.*, 2008; Mumma *et al.*, 2009). All these methane detections have been challenged (Zahnle *et al.*, 2011). The Mars Science Laboratory (MSL) mission's Curiosity rover has recently identified variable methane concentrations at a maximum of 7 ppb, using SAM (Webster *et al.*, 2015). Reported signatures of methane might be further examined through India's ongoing Mars Orbiter Mission (Mangalyaan) (Lele, 2014) and the upcoming European Space Agency's 2016 ExoMars orbiter (Zurek *et al.*, 2011). Any methane detection could be a result of biogenic or abiotic processes, and additional characterizations would have to be evaluated to determine the likely source of that methane.

Finally, a key factor that supports the habitability of Argyre is the presence of ice at the surface coexisting with aqueous liquids. At lower latitudes, there were aqueous liquids, but the case for coexisting ice is less clear (*e.g.*, Fairén, 2010). This is important because the coexistence of ice with aqueous liquids means that ice was on the liquidus (or down to the eutectic) state, which further means that the water activity (the thermodynamic activity of H_2O; see, *e.g.*, Grant, 2004, Marion and Kargel, 2008) was not as low as might otherwise be the case. Taking terrestrial environments as an example, where there exist highly arid hypersaline environments (*e.g.*, Death Valley), water activities are extremely low, and biodiversity is also extremely low, despite Earth's long-existing biosphere and ample opportunity to evolve and adapt. This argues that life is indeed extremely challenged with water activity declines, due to extremely low relative humidities and extreme evaporation (*e.g.*, Knoll et al., 2005; Marion and Kargel, 2008). Liquid water may still exist, but it is not so suitable for life (Grant, 2004). When ice is present, that buffering factor maintains water thermodynamic activity at higher and less life-adverse levels, preserving lower salinity and potentially truly ''freshwater'' environments. Such large buffering masses of ice make it harder to completely desiccate a body of water, which could therefore contribute to maintaining long-term stable, habitable environments for potential life-forms.

4.3. Astrobiologically relevant landforms in Argyre

Now we highlight some specific landscape features in Argyre that are promising sites for astrobiological exploration. These include the following:

(1) Hydrothermal deposits, including those related to the hydrothermal activity associated with the Argyre impact event, subsequent impacts, and those associated with the migration of heated water along Argyre-induced basement structures. Echaurren and Ocampo (2004) determined impact conditions and predicted possible hydrothermal zones generated after the im-

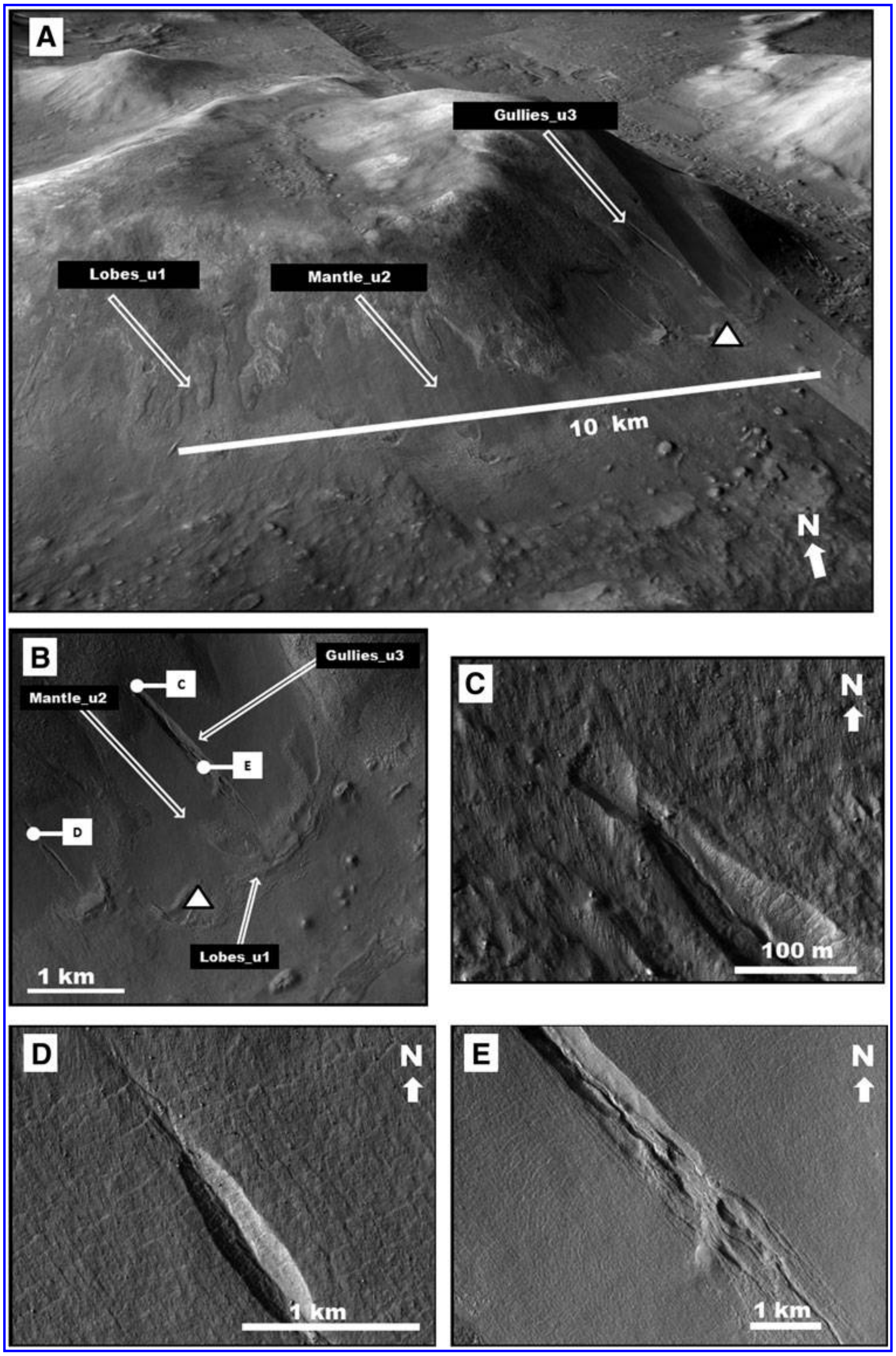

FIG. 5. Examples of gullies, possible grabens and OSPs, faults and fractures. All panels from HiRISE image ESP_020720_1410. (**A**) Overview of the site, showing lobes, mantle deposits, and gullies. (**B**) Locations of insets (C–E) and the downslope position of the putative OSPs relative to the gullies (arrows), and lobes (arcuate ridges) interpreted to be glacial moraines. (**C**) Top of the alcove of the eastern gully, showing an abrupt start of the channel embedded in a grabenlike elongated depression. A possible landslide scar is located at the northern tip of the cavity. (**D**) Top of the alcove of the western gully, with rill-like features running into the grabenlike cavity; the features seem to originate upslope from the nonpolygonized terrain. Note the polygonal network within the cavity and in the surrounding terrain; black arrow points to location with low-centered polygons. (**E**) Midpart of the eastern gully, with multiple terraces (i) and multiple self-blocking digitate deposits (ii), as indicated by black arrows. Note the distinct lineaments, which we interpret to be fractures and faults. Image credits: NASA/JPL/University of Arizona.

pact. The presence of uplifted mantle and lower crustal materials in the basin means that primordial materials composed of P, K, Al, Ca, Fe, and other elements necessary for life to form may have been exposed to the surface and near-surface environments. Internal heat and water, and other volatiles at depth, may have migrated along the impact-induced basement structures. The interaction among primordial crustal materials and hydrothermal activity would be favorable from the metabolic energy perspective (*e.g.*, Schulze-Makuch *et al.*, 2007).

(2) Candidate vent structures along the floor of the Argyre basin. The youngest basin unit, mapped as unit HAb4a (Dohm *et al.*, 2015), comprises landforms interpreted to mark venting related to flooding, the rapid emplacement and burial of flood deposits and associated volatiles, and eventual release to form vent structures. For example, Argyre Mons is a newly identified feature interpreted to have formed from subterranean gas releases (*e.g.*, mud volcanoes), magmatic-driven activity, or an impact event, with gas release being the favored hypothesis (Williams *et al.*, 2014). Numerous and widespread vent structures in the northern plains, interpreted to be mud volcanoes, are likely the result of rapid emplacement of Tharsis-triggered circum-Chryse floodwaters and sediments and associated ocean formation (Skinner and Tanaka, 2007; Skinner and Mazzini, 2009; Oehler and Allen, 2010; Komatsu *et al.*, 2011, 2012) and have been reported to be prime astrobiological targets (Mahaney *et al.*, 2004).

(3) Possible ice-cored mounds, including candidate OSPs (Soare *et al.*, 2014a; see Fig. 5). On the basis of the available photogeology, the OSPs within the Argyre basin are recent features, dating from the Late Amazonian (and possibly still having some activity), and their proposed hydraulic, tectonic, and hydro-tectonic models of formation and functioning involve freeze-thaw cycling. The OSPs within the floor of Argyre basin could bear exceptional astrobiological interest, because the heat gradients produced hydrothermal activity, which in turn resulted in upwelling processes, enhancing the prospect of fossilized and extant life. The upwelling of deep-seated water from aquifers, rich in volatiles and organic material, would act as exhumation pockets into ancient environments; therefore the groundwater or deeply seated water associated with OSP formation could be capable of delivering evidence of past/current microbial activity in the subsurface to the surface or near-surface. In addition, the protecting layers that formed after the wet eolian sedimentation or icy periods would provide a protected environment for existing life or its remains, as mantling by eolian drifts could have reduced the rates of sublimation. In summary, OSPs, as indicated through investigations of analogous terrestrial settings, could be host to past (and maybe present) heat fluxes, ice, liquid water, and nutrients (*e.g.*, Dohm *et al.*, 2004; Hock *et al.*, 2007; Warren-Rhodes *et al.*, 2007).

(4) Sedimentary deposits left behind by glaciers along the basins' margins as evidenced by ridges interpreted to be eskers (*e.g.*, Kargel and Strom, 1992; Kargel, 2004; Banks *et al.*, 2008; Fig. 6). The ridges occur in the Late Hesperian–Early Amazonian basin floor deposits and thus are interpreted to be emplaced during this time period, which is coeval with major Tharsis-driven activity (Dohm *et al.*, 2001b; Fairén *et al.*, 2003). This highlights the far-reaching sedimentological record in the deep Argyre basin developed over time. The eskerlike features could be composed of sediment from environments nearby and distant (*e.g.*, south polar region), laid down during glacial outburst floods debouching under confined ice-covered lakes.

(5) Sedimentary deposits related to the formation of lakes in both the primary Argyre basin and other smaller impact-derived basins along the margin (including those in the highly degraded rim materials). Lakes could have been formed by the glacial flood outbursts mentioned above, and they would be therefore related to major changes in environmental and hydrological conditions associated with major outgassing of Tharsis during the Late Hesperian and Early Amazonian (conditions also related to the formation of the younger northern plains ocean, see Fairén *et al.*, 2003). In addition to floodwaters derived by wet-based glacial activity (Kargel, 2004), the floodwaters could also have originated from a raised hydraulic head, migration of water and other volatiles along Argyre-induced basement structures, and spring-fed (artesian) release. If the water was subterranean-derived, such as related to Tharsis activity (including migration from great distances along basement structures) (Dohm *et al.*, 2015), then the astrobiological potential would be heightened.

(6) Crater-wall gullies (Fig. 3B) occurring upslope of the pingo-like mounds described below (Fig. 5). The morphology of the gully landforms points to ''wet'' flows, and the crater-wall structures in which they are embedded could be indicative of groundwater discharge (Soare *et al.*, 2014a). Against the general backdrop of boundary conditions inconsistent with the flow of liquid water at the surface, gully discharges might be markers of aqueous activity and bearers of nutrients if not fossilized microbes.

5. Strategies for Future Robotic Exploration

The main challenge for the exploration of Argyre is the basin's latitude. Most of Argyre is located between 45° and 55° in the southern hemisphere, and this latitude would present a major energy challenge even for a RTG (radioisotope thermoelectric generator)–powered mission (Anderson, 2005), such as the Curiosity rover. For a solar-powered mission, Argyre's latitude would be troublesome, although not overwhelmingly so, especially if duration is not a large prerequisite; for example, the Phoenix lander successfully operated for 157 martian sols in the northern high latitudes. On the other hand, the low elevation of the Argyre floor is a plus for parachute-aided landings, because lower elevations would provide a longer atmospheric column for the parachutes to open and achieve the desired deceleration of the spacecraft during the entry, descent, and landing (EDL) phase.

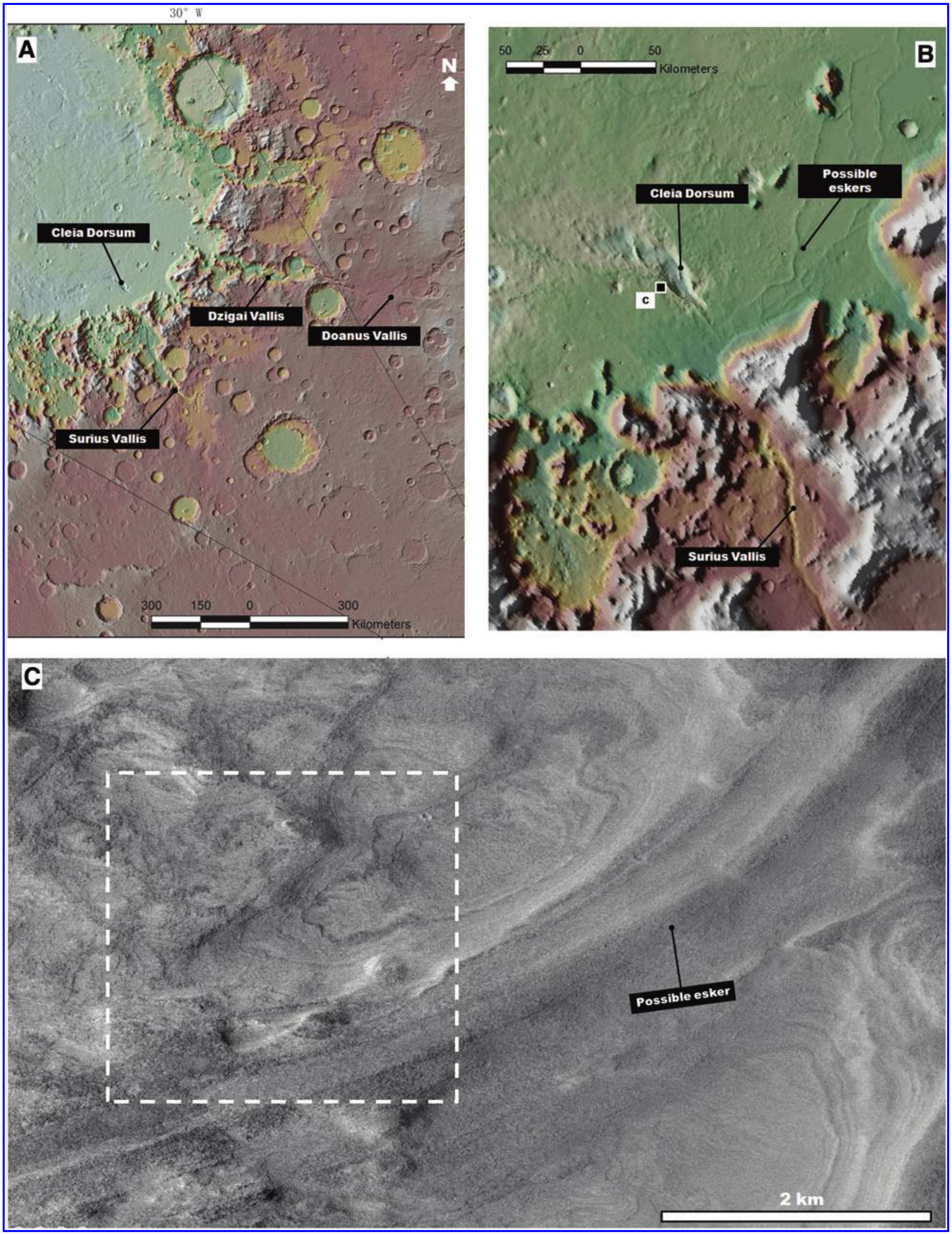

FIG. 6. (**A**) View of Southeastern Argyre basin centered at 62°48'S, 46°56'W. The image shows an integrated fluvial and glacial geological setting that includes deeply dissected upland valleys connected to the upper sedimentary strata that occupy the basin's floor. (**B**) Close-up view centered at 57°4'S, 46°21'W, on the terminal zone of Surius Vallis, where some plains are marked by possible esker ridges. (**C**) The plains shown in (B) include a large depression (Cleia Dorsum) where the regional upper stratigraphy appears exposed, including a region where scarps likely expose glacial and older fluvial deposits (dashed box). These strata appear lightly cratered and thus likely spent a much longer time buried before being exhumed by regional erosional processes, making them an even better exobiological target (CTX view centered at 55°16'S, 45°39'W). (Color graphics available at www.liebertonline.com/ast)

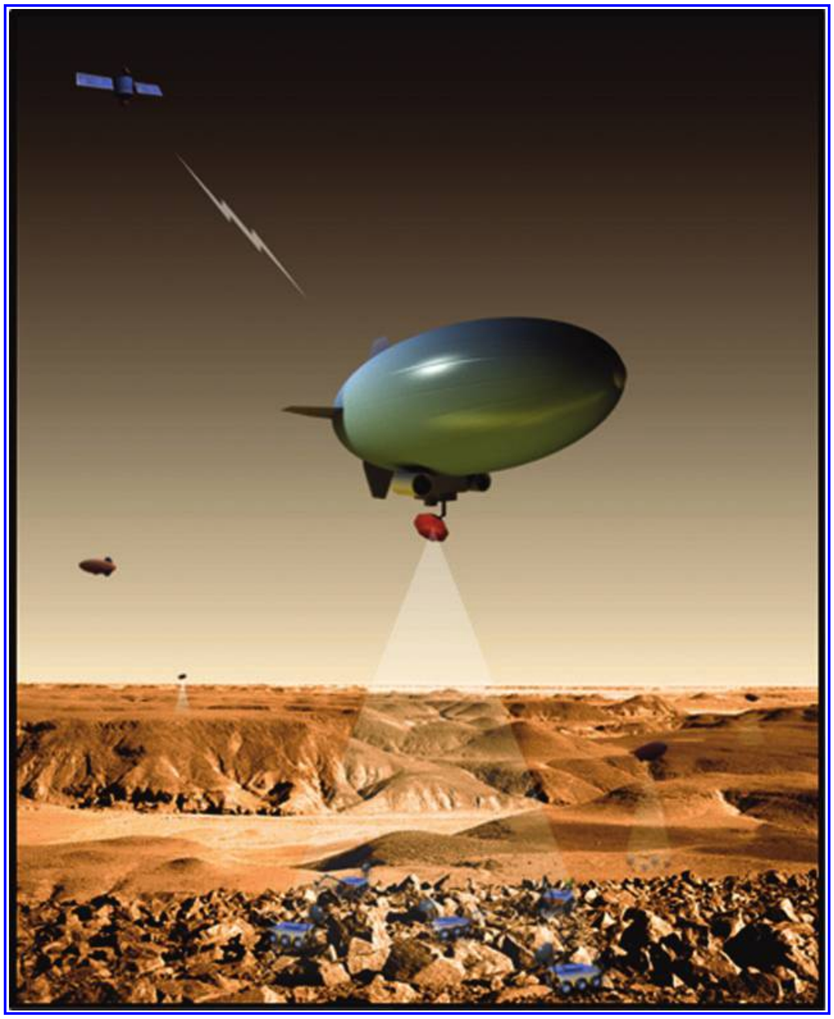

FIG. 7. Tier-scalable reconnaissance: three-tiered utilization on Mars. Tier 1: space-borne orbiter; tier 2: airborne blimps; tier 3: ground-based rovers. (Color graphics available at www.liebertonline.com/ast)

With these engineering constraints in mind, it is important to revisit the merits of Argyre as a promising target for the astrobiological exploration of Mars. If there are compelling scientific reasons to propose the exploration of the potential biological attributes of Argyre, then there are compelling reasons to elevate the discussion of the engineering constraints currently imposed on missions and hence reconsider mission architectures. When these engineering issues are solved, we propose that Argyre could be reached by a *tier-scalable* exploration mission architecture, in which a flotilla of vehicles is used for the regional investigation of several different areas. The large size and diversity of landforms within the Argyre impact basin make it an ideal case for *tier-scalable reconnaissance*, a redundant exploration strategy based on the deployment, operation, and control of vehicles in multiple areas of interest using hierarchical levels of oversight called tiers—each tier controlling the vehicles within the tier beneath it (Fink *et al.*, 2005, 2008; Kean, 2010; Fig. 7). Multi-tiered and autonomous robotic exploration architectures on Mars would comprise an orbiter (or orbiters) in conjunction with aerial platforms (*e.g.*, blimps) along with rovers (Fink *et al.*, 2005, 2008), miniature landing science stations (Schulze-Makuch *et al.*, 2012), sensorwebs (Delin *et al.*, 2005), and autonomous drilling sciencecraft (Ori *et al.*, 2000; Dohm *et al.*, 2011), all of which would help verify the analyses provided in such an investigation through contextual *in situ* evidence.

Particularly appealing for *in situ* investigations is the rich variety of water- and ice-mobilized sedimentary deposits and extant ice deposits, as described above. We propose focusing the astrobiological exploration on the southeastern part of the Argyre basin, near Cleia Dorsum, elevation –2600 m (Fig. 6). In this setting, basal fluvial and overlying glacial deposits seem to be exposed as well-preserved, laterally extensive layers, and topographically the site is low. This is an area of eskerlike ridges, probably glacial river–deposited or debris flow–deposited, containing material derived from the highlands, and situated within reachable distance for a tier-scalable reconnaissance system (60 km max) of lobate debris aprons (icy glacierlike forms), layered rock sequences near the eskerlike ridges (ancient lake deposits), and U-shaped valleys and cirque-like amphitheatres (remnants of wet-based glacial bedrock scour).

Many of these extant environments in Argyre could be suitable for terrestrial extremophiles; therefore it is reasonable to speculate that a Mars-adapted biology would likewise be able to survive in them. The tier-scalable reconnaissance system could confirm whether and where there has been venting of the martian internal heat energy along the impact-induced faults (structural conduits), as well as evidence for groundwater influx with nutrient-enriched rock materials, such as primordial crustal materials enriched in biogenic elements. Such exploration would require careful mission preparation, including proper sterilization of the spacecraft components to ensure compliance with planetary protection policies, as the possible presence of current liquid water or water ice near the surface at these features may categorize them as ''Mars Special Regions,'' that is, places where terrestrial organisms might be able to replicate (Rummel *et al.*, 2014).

6. Conclusions

We propose that the Argyre province should be considered a prime target for the search for past or present life on Mars. This is based on evidence of its long-term water enrichment, heat generation from the Argyre basin–forming impact, basement structures that could have channeled water and heat into the basin from far-reaching geological provinces and from great depths, and potential nutrient-enriched primordial crustal materials that could have been transferred to near-surface and surface environments through impact-induced uplift and inversion. We have highlighted the astrobiological significance of some particular landscape features in Argyre that may be especially promising and accessible sites for the astrobiological exploration of the basin, including hydrothermally altered mineral assemblages, possible mud volcanoes, ice-cored mounds, sedimentary deposits of glacial and lacustrine origin, and crater-wall gullies. Today, the Argyre province also could host extant ice, perhaps near-surface liquid groundwater in places, possible fog concentrations, and potential vents with exhalation of volatiles. Tier-scalable reconnaissance may improve chances for high data return from these complex landscapes, because prime microenvironmental targets may be located in rugged locations, which otherwise would be exceedingly challenging to explore through traditional mission designs.

Acknowledgments

The research leading to these results is a contribution from the Project ''icyMARS,'' funded by the European Research Council, Starting Grant no 307496. J.M.D. was supported by the NASA PG&G Program and JSPS KAKENHI Grant Number 26106002 [Hadean BioScience (Grant-in-Aid for Scientific Research on Innovative Areas)]. J.M.D. and H.M. express their gratitude to the Tokyo Dome Corporation for their support of the TeNQ exhibit and the branch of Space Exploration Education & Discovery, the University Museum, the University of Tokyo. H.J.C. would like to thank the Tokyo Institute of Technology's Earth-Life Science Institute for funding during the preparation of this manuscript. D.Z.O. is grateful to the Astromaterials Research and Exploration Science Division at Johnson Space Center for support. D.S.-M. was supported by European Research Council, Advanced Grant ''Habitability of Martian Environments,'' no 339231. The authors want to thank Chris McKay for a constructive review of this paper.

Author Disclosure Statement

No competing financial interests exist.

References

Abramov, O. and Kring, D.A. (2005) Impact-induced hydrothermal activity on early Mars. *J Geophys Res* 110, doi:10.1029/2005JE002453.

Abramov, O. and Mojzsis, S.J. (2009) Microbial habitability of the Hadean Earth during the Late Heavy Bombardment. *Nature* 459:419–422.

Allwood, A.C., Walter, M.R., Kamber, B.S., Marshall, C.P., and Burch, I.W. (2006) Stromatolite reef from the Early Archaean era of Australia. *Nature* 441:714–718.

Anderson, D.J. (2005) *NASA Radioisotope Power Conversion Technology NRA Overview*, TM-2005-213981, National Aeronautics and Space Administration, Glenn Research Center, Cleveland, OH.

Aubrey, A., Cleaves, A.H.J., Chalmers, J.H., Skelley, A.M., Mathies, R.A., Grunthaner, F.J., Ehrenfreund, P., and Bada, J.L. (2006) Sulfate minerals and organic compounds on Mars. *Geology* 34:357–360.

Azúa-Bustos, A., González-Silva, C., Mancilla, R.A., Salas, L., Gómez-Silva, B., McKay, C.P., and Vicuña, R. (2011) Hypolithic cyanobacteria supported mainly by fog in the coastal range of the Atacama Desert. *Microb Ecol* 61:568–581.

Baker, V.R., Strom, R.G., Gulick, V.C., Kargel, J.S., Komatsu, G., and Kale, V.S. (1991) Ancient oceans, ice sheets and the hydrological cycle on Mars. *Nature* 352:589–594.

Baker, V.R., Maruyama, S., and Dohm, J.M. (2007) Tharsis superplume and the geological evolution of early Mars. In *Superplumes: Beyond Plate Tectonics,* edited by D.A. Yuen, S. Maruyama, S.-I. Karato, and B.F. Windley, Springer, Dordrecht, the Netherlands, pp 507–523.

Banks, M.E., McEwen, A.S., Kargel, J.S., Baker, V.R., Strom, R.G., Mellon, M.T., Pelletier, J.D., Gulick, V.C., Keszthelyi, L., Herkenhoff, K.E., Jaeger, W.L., and the HiRISE Team. (2008) High Resolution Imaging Science Experiment (HiRISE) observations of glacial and periglacial morphologies in the circum-Argyre Planitia highlands. *J Geophys Res* 113, doi:10.1029/2007JE002994.

Banks, M.E., Lang, N.P., McEwen, A.S., Kargel, J.S., Baker, V.R., Strom, R.G., Grant, J.A., Pelletier, J.D., and the HiRISE Team. (2009) An analysis of the sinuous ridges in the southern Argyre Planitia, Mars using HiRISE and CTX images and MOLA data. *J Geophys Res* 114, doi:10.1029/2008JE003244.

Borthagaray, A.I., Fuentes, M.A., and Marquet, P.A. (2010) Vegetation pattern formation in a fog-dependent ecosystem. *J Theor Biol* 265:18–26.

Buczkowski, D.L., Murchie, S., Clark, R., Seelos, K., Seelos, F., Malaret, E., and Hash, C. (2010) Investigation of an Argyre basin ring structure using Mars Reconnaissance Orbiter/Compact Reconnaissance Imaging Spectrometer for Mars. *J Geophys Res* 115, doi:10.1029/2009JE003508.

Cabrol, N.A. and Grin, E.A. (1999) Distribution, classification and ages of martian impact crater lakes. *Icarus* 142:160–172.

Carr, M.H. (1999) Retention of an atmosphere on Early Mars. *J Geophys Res* 104:21897–21909.

Carr, M.H. and Head, J.W., III. (2003) Oceans on Mars: an assessment of the observational evidence and possible fate. *J Geophys Res* 108, doi:10.1029/2002JE001963.

Christensen, P. (2006) Water at the poles and in permafrost regions of Mars. *Elements* 2:151–155.

Ciba Foundation. (2008) *Evolution of Hydrothermal Ecosystems on Earth (and Mars?)*, Ciba Foundation Symposium 202, Wiley, Chichester, UK.

Claeys, P. and Morbidelli, A. (2011). Late Heavy Bombardment. In *Encyclopedia of Astrobiology*, Springer, Berlin, pp 909–912.

Cleaves, H.J., Scott, A.M., Hill, F.C., Leszczynski, J., Sahai, N., and Hazen, R. (2012) Mineral-organic interfacial processes: potential roles in the origins of life. *Chem Soc Rev* 41:5502–5525.

Delin, K.A., Jackson, S.P., Johnson, D.W., Burleigh, S.C., Woodrow, R.R., McAuley, J.M., Dohm, J.M., Ip, F., Ferre, T.P.A, Rucker, D.F., and Baker, V.R. (2005) Environmental studies with the sensor web: principles and practice. *Sensors* 5:103–117.

Di Achille, G. and Hynek, B.M. (2010) Ancient oceans on Mars supported by global distribution of deltas and valleys. *Nat Geosci* 3:459–463.

Dohm, J.M. and Maruyama, S. (2014) Habitable trinity. *Geoscience Frontiers* 6:95–101.

Dohm, J.M., Tanaka, K.L., and Hare, T.M. (2001a) *Geologic Map of the Thaumasia Region of Mars*, U.S. Geological Survey Investigations Series I-2650, USGS Information Services, Denver, CO.

Dohm, J.M., Ferris, J.C., Baker, V.R., Anderson, R.C., Hare, T.M., Strom, R.G., Barlow, N.G., Tanaka, K.L., Klemaszewski, J.E., and Scott, D.H. (2001b) Ancient drainage basin of the Tharsis region, Mars: potential source for outflow channel systems and putative oceans or paleolakes. *J Geophys Res* 106:32943–32958.

Dohm, J.M., Ferris, J.C., Barlow, N.G., Baker, V.R., Mahaney, W.C., Anderson, R.C., and Hare, T.M. (2004) The Northwestern Slope Valleys (NSVs) region, Mars: a prime candidate site for the future exploration of Mars. *Planet Space Sci* 52:189–198.

Dohm, J.M., Maruyama, S., Baker, V.R., and Anderson, R.C. (2007) Traits and evolution of the Tharsis superplume, Mars. In *Superplumes: Beyond Plate Tectonics*, edited by D.A. Yuen, S. Maruyama, S.-I. Karato, and B.F. Windley, Springer, Dordrecht, the Netherlands, pp 523–537.

Dohm, J.M., Anderson, R.C., Barlow, N.G., Miyamoto, H., Davies, A.G., Taylor, G.J., Baker, V.R., Boynton, W.V., Keller, J., Kerry, K., Janes, D., Fairén, A.G., Schulze-Makuch, D., Glamoclija, M., Marinangeli, L., Ori, G.G., Strom, R.G., Williams, J-P., Ferris, J.C., Rodíguez, J.A.P., de Pablo, M.A., and Karunatillake, S. (2008) Recent geological and hydrological activity on Mars: the Tharsis/Elysium corridor. *Planet Space Sci* 56:985–1013.

Dohm, J.M., Miyamoto, H., Ori, G.G., Fairén, A.G., Davila, A.F., Komatsu, G., Mahaney, W.C., Williams, J.-P., Joye, S.B., Di Achille, G., Oehler, D.Z., Marzo, G.A., Schulze-Makuch, D., Acocella, V., Glamoclija, M., Pondrelli, M., Boston, P., Hart, K.M., Anderson, R.C., Baker, V.R., Fink, W., Kelleher, B.P., Furfaro, R., Gross, C., Hare, T.M., Frazer, A.R., Ip, F., Allen, C.C.R., Kim, K.J., Maruyama, S., McGuire, P.C., Netoff, D., Parnell, J., Wendt, L., Wheelock, S.J., Steele, A., Hancock, R.G.V., Havics, R.A., Costa, P., and Krinsley, D. (2011) An inventory of potentially habitable environments on Mars: geological and biological perspectives. In *Analogs for Planetary Exploration*, edited by W.B. Garry and J.E. Bleacher, Geological Society of America Special Paper 483, Geological Society of America, Boulder, CO, pp 317–347.

Dohm, J.M., Miyamoto, H., Maruyama, S., Baker, V.R., Anderson, R.C., Hynek, B.M., Robbins, S.J., Ori, G., Komatsu, G., El Maarry, M.R., Soare, R.J., Mahaney, W.C., Kim, K.J., and Hare, T.M. (2013) Mars evolution. In *Mars: Evolution, Geology, and Exploration*, edited by A.G. Fairén, Nova Science Publishers, New York, pp 1–33.

Dohm, J.M., Hare, T.M., Robbins, S.J., Williams, J.-P., Soare, R.J., El-Maarry, M.R., Conway, S.J., Buczkowski, D.L., Kargel, J.S., Banks, M.E., Fairén, A.G., Schulze-Makuch, D., Komatsu, G., Miyamoto, H., Anderson, R.C., Davila, A.F., Mahaney, W.C., Fink, W., Cleaves, H.J., Yan, J., Hynek, B., and Maruyama, S. (2015) Geological and hydrological histories of the Argyre province, Mars. *Icarus* 253:66–98.

Echaurren, J.C. and Ocampo, A.C. (2004) Calculation and prediction of hydrothermal zones and impact conditions on Argyre Planitia, Mars [abstract 5009]. In *67th Annual Meeting of the Meteoritical Society*, Lunar and Planetary Institute, Houston.

Eiler, J.M. (2007) The oldest fossil or just another rock? *Science* 317:1046–1047.

El Maarry, M.R., Dohm, J.M., Michael, G., Thomas, N., and Maruyama, S. (2013) Morphology and evolution of the ejecta of Hale Crater in Argyre basin, Mars: results from high resolution mapping. *Icarus* 226:905–922.

Fairén, A.G. (2010) A cold and wet Mars. *Icarus* 208:165–175.

Fairén, A.G., Dohm, J.M., Baker, V.R., de Pablo, M.A., Ruiz, J., Ferris, J.C., and Anderson, R.C. (2003) Episodic flood inundations of the northern plains of Mars. *Icarus* 165:53–67.

Fairén, A.G., Fernández-Remolar, D., Dohm, J.M., Baker, V.R., and Amils, R. (2004) Inhibition of carbonate synthesis in acidic oceans on early Mars. *Nature* 431:423–426.

Fairén, A.G., Davila, A.F., Gago-Duport, L., Amils, R., and McKay, C.P. (2009) Stability against freezing of aqueous solutions on early Mars. *Nature* 459:401–404.

Fairén, A.G., Davila, A.F., Lim, D., Bramall, N., Bonaccorsi, R., Zavaleta, J., Uceda, E.R., Stoker, C., Wierzchos, J., Amils, R., Dohm, J.M., Andersen, D., and McKay, C. (2010) Astrobiology through the ages of Mars. *Astrobiology* 10:821–843.

Fairén, A.G., Davila, A.F., Gago-Duport, L., Haqq-Misra, J.D., Gil, C., McKay, C.P., and Kasting, J.F. (2011) Cold glacial oceans would have inhibited phyllosilicate sedimentation on early Mars. *Nat Geosci* 4:667–670.

Fairén, A.G., Stokes, C., Davies, N., Schulze-Makuch, D., Rodríguez, J.A.P., Davila, A.F., Uceda, E.R., Dohm, J.M., Baker, V.R., Clifford, S.M., McKay, C.P., and Squyres, S.W. (2014) A cold hydrological system in Gale Crater, Mars. *Planet Space Sci* 93–94:101–118.

Fassett, C.I. and Minton, D.A. (2013) Impact bombardment of the terrestrial planets and the early history of the Solar System. *Nat Geosci* 6:520–524.

Fink, W., Dohm, J.M., Tarbell, M.A., Hare, T.M., and Baker, V.R. (2005) Next-generation robotic planetary reconnaissance missions: a paradigm shift. *Planet Space Sci* 53:1419–1426.

Fink, W., Tarbell, M.A., and Jobling, F.M. (2008) Tier-scalable reconnaissance—a paradigm shift in autonomous remote planetary exploration of Mars and beyond. In *Planet Mars Research Focus*, edited by L.A. Costas, Nova Science Publishers, New York, pp 17–48.

Flynn, G.J. (1996) The delivery of organic matter from asteroids and comets to the early surface of Mars. In *Worlds in Interaction: Small Bodies and Planets of the Solar System*, edited by H. Rickman and M.J. Valtonen, Springer, Dordrecht, the Netherlands, pp 469–474.

Formisano, V., Atreya, S., Encrenaz, T., Ignatiev, N., and Giuranna, M. (2004) Detection of methane in the atmosphere of Mars. *Science* 306:1758–1761.

Ge, R., Zhu, W., Wilde, S.A., and He, J. (2014) Zircon U–Pb–Lu–Hf–O isotopic evidence for ≥3.5 Ga crustal growth, reworking and differentiation in the northern Tarim Craton. *Precambrian Res* 249:115–128.

Geminale, A., Formisano, V., and Giuranna, M. (2008) Methane in martian atmosphere: average spatial, diurnal, and seasonal behavior. *Planet Space Sci* 56:1194–1203.

Grant, W.D. (2004) Life at low water activity. *Philos Trans R Soc Lond B Biol Sci* 359:1249–1267.

Greeley, R. and Guest, J.E. (1987) *Geologic Map of the Eastern Equatorial Region of Mars*, IMAP I-1802B (1:15,000,000), U.S. Geological Survey, Denver, CO.

Grotzinger, J.P., Sumner, D.Y., Kah, L.C., Stack, K., Gupta, S., Edgar, L., Rubin, D., Lewis, K., Schieber, J., Mangold, N., Milliken, R., Conrad, P.G., Des Marais, D., Farmer, J., Siebach, K., Calef, F., III, Hurowitz, J., McLennan, S.M., Ming, D., Vaniman, D., Crisp, J., Vasavada, A., Edgett, K.S., Malin, M., Blake, D., Gellert, R., Mahaffy, P., Wiens, R.C., Maurice, S., Grant, J.A., Wilson, S., Anderson, R.C., Beegle, L., Arvidson, R., Hallet, B., Sletten, R.S., Rice, M., Bell, J., III, Griffes, J., Ehlmann, B., Anderson, R.B., Bristow, T.F., Dietrich, W.E., Dromart, G., Eigenbrode, J., Fraeman, A., Hardgrove, C., Herkenhoff, K., Jandura, L., Kocurek, G., Lee, S., Leshin, L.A., Leveille, R., Limonadi, D., Maki, J., McCloskey, S., Meyer, M., Minitti, M., Newsom, H., Oehler, D., Okon, A., Palucis, M., Parker, T., Rowland, S., Schmidt, M., Squyres, S., Steele, A., Stolper, E., Summons, R., Treiman, A., Williams, R., and Yingst, A. (2014) A habitable fluvio-lacustrine environment at Yellowknife Bay, Gale Crater, Mars. *Science* 343, doi:10.1126/science.1242777.

Head, J.W., Neukum, G., Jaumann, R., Hiesinger, H., Hauber, E., Carr, M., Masson, P., Foing, B., Hoffmann, H., Kreslavsky, M., Werner, S., Milkovich, S., van Gasselt, S., and the HRSC Co-Investigator Team. (2005) Tropical to mid-latitude snow and ice accumulation, flow and glaciation on Mars. *Nature* 434:346–351.

Hiesinger, H. and Head, J.W. (2002) Topography and morphology of the Argyre basin, Mars: implications for its geologic and hydrologic history. *Planet Space Sci* 50:939–981.

Hock, A.N., Cabrol, N.A., Dohm, J.M., Piatek, J., Warren-Rhodes, K., Weinstein, S., Wettergreen, D.S., Grin, E.A., Moersch, J., Cockell, C.S., Coppin, P., Ernst, L., Fisher, G., Hardgrove, C., Marinangeli, L., Minkley, E., Ori, G.G., Waggoner, A., Wyatt, M., Smith, T., Thompson, D., Wagner, M., Jonak, D., Stubbs, K., Thomas, G., Pudenz, E., and Glasgow, J. (2007) Life in the Atacama: a scoring system for habitability and the robotic exploration for life. *J Geophys Res Biogeosciences* 112, doi:10.1029/2006JG000321.

House, C.H., Oehler, D.Z., Sugitani, K., and Mimura, K. (2013) Carbon isotopic analyses of *ca.* 3.0 Ga microstructures imply planktonic autotrophs inhabited Earth's early oceans. *Geology* 41:651–654.

Iizuka, T., Horie, K., Komiya, T., Maruyama, S., Hirata, T., Hidaka, H., and Windley, B.F. (2006) 4.2 Ga zircon xenocryst in an Acasta gneiss from northwestern Canada: evidence for early continental crust. *Geology* 34:245–248.

Jones, A.P., McEwen, A.S., Tornabene, L.L., Baker, V.R., Melosh, H.J., and Berman, D.C. (2011) A geomorphic analysis of Hale Crater, Mars: the effects of impact into ice-rich crust. *Icarus* 211:259–272.

Kargel, J.S. (2004) *Mars: A Warmer Wetter Planet*, Praxis-Springer, London.

Kargel, J.S. and Strom, R.G. (1992) Ancient glaciation on Mars. *Geology* 20:3–7.

Kargel, J.S., Baker, V.R., Beget, J.E., Lockwood, J., Pewe, T.L., Shaw, J.S., and Strom, R.G. (1995) Evidence of ancient continental glaciation in the martian northern plains. *J Geophys Res* 100:5351–5368.

Kean, S. (2010) Making smarter, savvier robots. *Science* 329: 508–509.

Knoll, A.H. (2004) *Life on a Young Planet: The First Three Billion Years of Evolution on Earth*, Princeton University Press, Princeton, NJ.

Knoll, A.H., Carr, M., Clark, B., Des Marais, D.J., Farmer, J.D., Fischer, W.W., Grotzinger, J.P., McLennan, S.M., Malin, M., Schröder, C., Squyres, S., Tosca, N.J., and Wdowiak, T. (2005) An astrobiological perspective on Meridiani Planum. *Earth Planet Sci Lett* 240:179–189.

Komatsu, G. and Ori, G.G. (2000) Exobiological implications of potential sedimentary deposits on Mars. *Planet Space Sci* 48:1043–1052.

Komatsu, G., Ori, G.G., Cardinale, M., Dohm, J.M., Baker, V.R., Vaz, D.A., Ishimaru, R., Namiki, N., and Matsui, T. (2011) Roles of methane and carbon dioxide in geological processes on Mars. *Planet Space Sci* 59:169–181.

Komatsu, G., Okubo, C.H., Wray, J.J., Gallagher, R., Orosei, R., Cardinale, M., Chan, M.A., and Ormo, J. (2012) Small mounds in Chryse Planitia, Mars: testing a mud volcano hypothesis [abstract 1103]. In *43rd Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.

Krasnopolsky, V.A., Maillard, J.P., and Owen, T.C. (2004) Detection of methane in the martian atmosphere: evidence for life? *Icarus* 172:537–547.

Kurokawa, H., Sato, M., Ushioda, M., Matsuyama, T., Moriwaki, R., Dohm, J.M., and Usui, T. (2014) Evolution of water reservoirs on Mars: constraints from hydrogen isotopes in martian meteorites. *Earth Planet Sci Lett* 394: 179–185.

Laskar, J., Correia, A.C.M., Gastineau, M., Joutel, F., Levard, B., and Robutel, P. (2004) Long term evolution and chaotic diffusion of the insolation quantities of Mars. *Icarus* 170: 343–364.

Latorre, C., González, A.L., Quade, J., Fariña, J.M., Pinto, R., and Marquet, P.A. (2011) Establishment and formation of fog-dependent *Tillandsia landbeckii* dunes in the Atacama Desert: evidence from radiocarbon and stable isotopes. *J Geophys Res Biogeosciences* 116, doi:10.1029/2010JG001521.

Lele, A. (2014) *Mission Mars: India's Quest for the Red Planet*, Springer, New Delhi.

Lunine, J.I., Chambers, J., Morbidelli, A., and Leshin, L.A. (2003) The origin of water on Mars. *Icarus* 165:1–8.

Mahaney, W.C., Milner, M.W., Netoff, D.I., Malloch, D., Dohm, J.M., Baker, V.R., Miyamoto, H., Hare, T.M., and Komatsu, G. (2004) Ancient wet aeolian environments on Earth: clues to presence of fossil/live microorganisms on Mars. *Icarus* 171:39–53.

Marion, G. and Kargel, J.S. (2008) *Cold Aqueous Planetary Geochemistry with FREZCHEM: From Modeling to the Search for Life at the Limits*, Springer, Berlin.

Maruyama, S., Ikoma, M., Genda, H., Hirose, K., Yokoyama, T., and Santosh, M. (2013a) The naked planet Earth: most essential pre-requisite for the origin and evolution of life. *Geoscience Frontiers* 4:141–165.

Maruyama, S., Aono, A., Ebisuzaki, T., and Dohm, J.M. (2013b) Birth place of life on the Hadean Earth: the role of primordial continent [abstract 66-10]. In *125th Anniversary Annual Meeting & Expo*, Geological Society of America, Boulder, CO.

Mojzis, S.J., Arrhenius, G., McKeegan, K.D., Harrison, T.M., Nutman, A.P., and Friend, C.R.L. (1996) Evidence for life on Earth before 3,800 million years ago. *Nature* 384:55–59.

Mojzsis, S.J., Harrison, T.M., and Pidgeon, R.T. (2001) Oxygen-isotope evidence from ancient zircons for liquid water at the Earth's surface 4300 Myr ago. *Nature* 409:178–181.

Moore, J.M. and Wilhelms, D.E. (2007) *Geologic Map of Part of Western Hellas Planitia, Mars*, U.S. Geological Survey Scientific Investigations Map SIM-2953, USGS Information Services, Denver, CO.

Mumma, M.J., Novak, R.E., DiSanti, M.A., Bonev, B.P., and Dello Russo, N. (2004) Detection and mapping of methane and water on Mars. *Bulletin of the American Astronomical Society* 36:1127.

Mumma, M.J., Villanueva, G.L., Novak, R.E., Hewagama, T., Bonev, B.P., DiSanti, M.A., Mandell, A.M., and Smith, M.D. (2009) Strong release of methane on Mars in northern summer 2003. *Science* 323:1041–1045.

Oehler, D.Z. and Allen, C.C. (2010) Evidence for pervasive mud volcanism in Acidalia Planitia, Mars. *Icarus* 208:636–657.

Oehler, D.Z., Robert, F., Walter, M.R., Sugitani, K., Meibom, A., Mostefaoui, S., and Gibson, E.K. (2010) Diversity in the Archean biosphere: new insights from NanoSIMS. *Astrobiology* 10:413–424.

Ori, G.G., Marinangeli, L., and Komatsu, G. (2000) Martian paleolacustrine environments and their geological constraints on drilling operations for exobiological research. *Planet Space Sci* 48:1027–1034.

Ormö, J., Dohm, J.M., Ferris, J.C., Lepinette, A., and Fairén, A.G. (2004) Marine-target craters on Mars? An assessment study. *Meteorit Planet Sci* 39:333–346.

Parker, T.J., Clifford, S.M., and Banerdt, W.B. (2000) Argyre Planitia and the Mars global hydrologic cycle [abstract 2033]. In *31st Lunar and Planetary Science Conference*, Lunar and Planetary Institute, Houston.

Patel, B.H., Percivalle, C., Ritson, D.J., Duffy, C.D., and Sutherland, J.D. (2015) Common origins of RNA, protein and lipid precursors in a cyanosulfidic protometabolism. *Nat Chem* 7:301–307.

Phillips, R.J., Zuber, M.T., Solomon, S.C., Golombek, M.P., Jakosky, B.M., Banerdt, W.B., Smith, D.E., Williams, R.M.E., Hynek, B.M., Aharonson, O., and Hauck, S.A. (2001) Ancient geodynamics and global-scale hydrology on Mars. *Science* 291:2587–2591.

Polat, A. (2012) Growth of Archean continental crust in oceanic island arcs. *Geology* 40:383–384.

Rasmussen, B., Fletcher, I.R., Brocks, J.J., and Kilburn, M.R. (2008) Reassessing the first appearance of eukaryotes and cyanobacteria. *Nature* 455:1101–1104.

Robbins, S.J., Hynek, B.M., Lillis, R.J., and Bottke, W.F. (2013) Large impact crater histories of Mars: the effect of different model crater age techniques. *Icarus* 225:173–184.

Rodriguez, J.A.P., Gulick, V.C., Baker, V.R., Platz, T., Fairén, A.G., Miyamoto, H., Kargel, J.S., Rice, J.W., and Glines, N. (2014) Evidence for Middle Amazonian catastrophic flooding and glaciation on Mars. *Icarus* 242:202–210.

Rummel, J.D., Beaty, D.W., Jones, M.A., Bakermans, C., Barlow, N.G., Boston, P.J., Chevrier, V.F., Clark, B.C., de Vera, J.-P.P., Gough, R.V., Hallsworth, J.E., Head, J.W., Hipkin, V.J., Kieft, T.L., McEwen, A.S., Mellon, M.T., Mikucki, J.A., Nicholson, W.L., Omelon, C.R., Peterson, R., Roden, E.E., Sherwood Lollar, B., Tanaka, K.L., Viola, D., and Wray, J.J. (2014) A new analysis of Mars "Special Regions": findings of the second MEPAG Special Regions Science Analysis Group (SR-SAG2). *Astrobiology* 14:887–968.

Schopf, J.W. (2006) Fossil evidence of Archaean life. *Philos Trans R Soc Lond B Biol Sci* 361:869–885.

Schopf, J.W., Kudryavtsev, A.B., Agresti, D.G., Wdowiak, T.J., and Czaja, A.D. (2002) Laser-Raman imagery of Earth's earliest fossils. *Nature* 416:73–76.

Schopf, J.W., Walter, M.R., and Ruiju, C. (2007a) Earliest evidence of life on Earth. *Precambrian Res* 158:139–140.

Schopf, J.W., Kudryavtsev, A.B., Czaja, A.D., and Tripathi, A.B. (2007b) Evidence of Archean life: stromatolites and microfossils. *Precambrian Res* 158:141–155.

Schulze-Makuch, D., Irwin, L.N., Lipps, J.H., LeMone, D., Dohm, J.M., and Fairén, A.G. (2005) Scenarios for the evolution of life on Mars. *J Geophys Res* 110, doi:10.1029/2005JE002430.

Schulze-Makuch, D., Dohm, J.M., Fan, C., Fairén, A.G., Rodriguez, J.A.P., Baker, V.R., and Fink, W. (2007) Exploration of hydrothermal targets on Mars. *Icarus* 189:308–324.

Schulze-Makuch, D., Fairén, A.G., and Davila, A.F. (2008) The case for life on Mars. *International Journal of Astrobiology* 7:117–141.

Schulze-Makuch, D., Head, J.N., Houtkooper, J.M., Knoblauch, M., Furfaro, R., Fink, W., Fairén, A.G., Vali, H., Kelly Sears, S., Daly, M., Deamer, D., Schmidt, H., Hawkins, A.R., Sun, H.J., Lim, D.S.S., Dohm, J., Irwin, L.N., Davila, A.F., Mendez, A., and Andersen, D. (2012) The Biological Oxidant and Life Detection (BOLD) mission: a proposal for a mission to Mars. *Planet Space Sci* 67:57–69.

Scott, D.H. and Carr, M.H. (1978) *Geologic Map of Mars*, IMap I-1083, U.S. Geological Survey, Denver, CO.

Seibert, N.M. and Kargel, J.S. (2001) Small-scale martian polygonal terrain: implications for liquid surface water. *Geophys Res Lett* 28:899–903.

Skinner, J.A. and Mazzini, A. (2009) Martian mud volcanism: terrestrial analogs and implications for formational scenarios. *Mar Pet Geol* 26:1866–1878.

Skinner, J.A. and Tanaka, K.L. (2007) Evidence for and implications of sedimentary diapirism and mud volcanism in the southern Utopia highland-lowland boundary plain, Mars. *Icarus* 186:41–59.

Soare, R.J., Conway, S.J., Dohm, J.M., and El-Maarry, M.R. (2014a) Possible open-system (hydraulic) pingos in and around the Argyre impact regions of Mars. *Earth Planet Sci Lett* 398:25–36.

Soare, R.J., Conway, S.J., Dohm, J.M., and El-Maarry, M.R. (2014b) Possible ice-wedge polygons and recent landscape modification by "wet" periglacial processes in and around the Argyre impact basin, Mars. *Icarus* 233:214–228.

Stüeken, E.E., Buick, R., Guy, B.M., and Koehler, M.C. (2015) Isotopic evidence for biological nitrogen fixation by molybdenum-nitrogenase from 3.2 Gyr. *Nature* 520:666–669.

Summons, R.E., Amend, J.P., Bish, D., Buick, R., Cody, G.D., Des Marais, D.J., Dromart, G., Eigenbrode, J.L., Knoll, A.H., and Sumner, D.Y. (2011) Preservation of martian organic and environmental records: final report of the Mars Biosignature Working Group. *Astrobiology* 11:157–181.

Tanaka, K.L. (1986) The stratigraphy of Mars. *J Geophys Res: Solid Earth* 91, doi:10.1029/JB091iB13p0E139.

Thomson, B.J., Bridges, N.T., Milliken, R.E., Baldridge, A., Hook, S.J., Crowley, J.K., Marion, G.M., de Souza Filho, C.R., Kargel, J.S., Brown, A.J., and Weitz, C.M. (2011)

Constraints on the origin and evolution of the layered mound in Gale crater, Mars, using Mars Reconnaissance Orbiter data. *Icarus* 214:413–432.

Usui, T., Alexander, C.M.D., Wang, J., Simon, J.I., and Jones, J.H. (2015) Meteoritic evidence for a previously unrecognized hydrogen reservoir on Mars. *Earth Planet Sci Lett* 410:140–151.

Villanueva, G.L., Mumma, M.J., Novak, R.E., Käufl, H.U., Hartogh, P., Encrenaz, T., Tokunaga, A., Khayat, A., and Smith, M.D. (2015) Strong water isotopic anomalies in the martian atmosphere: probing current and ancient reservoirs. *Science* 348:218–221.

Warren-Rhodes, K., Weinstein, S., Dohm, J.M., Piatek, J., Minkley, E., Hock, A., Pane, D., Ernst, L.A., Fisher, G., Emani, S., Waggoner, A.S., Cabrol, N.A., Wettergreen, D.S., Apostolopoulos, D., Coppin, P., Grin, E., Diaz, C., Moersch, J., Ori, G.G., Smith, T., Stubbs, K., Thomas, G., Wagner, M., and Wyatt, M. (2007) Searching for microbial life remotely: satellite-to-rover habitat mapping in the Atacama Desert, Chile. *J Geophys Res* 112, doi:10.1029/2006JG000283.

Webster, C.R., Mahaffy, P.R., Atreya, S.K., Flesch, G.J., Mischna, M.A., Meslin, P.Y., Farley, K.A., Conrad, P.G., Christensen, L.E., Pavlov, A.A., Martín-Torres, J., Zorzano, M.P., McConnochie, T.H., Owen, T., Eigenbrode, J.L., Glavin, D.P., Steele, A., Malespin, C.A., Archer, P.D., Jr., Sutter, B., Coll, P., Freissinet, C., McKay, C.P., Moores, J.E., Schwenzer, S.P., Bridges, J.C., Navarro-Gonzalez, R., Gellert, R., Lemmon, M.T., and the MSL Science Team. (2015) Mars methane detection and variability at Gale Crater. *Science* 347:412–414.

Williams, J.-P., Dohm, J.M., Lopes, R.M., and Buczkowski, D.L. (2014) A large vent structure within Argyre basin, Mars [abstract 2807]. In *45th Lunar and Planetary Science Conference,* Lunar and Planetary Institute, Houston.

Williams, R.M.E., Grotzinger, J.P., Dietrich, W.E., Gupta, S., Sumner, D.Y., Wiens, R.C., Mangold, N., Malin, M.C., Edgett, K.S., Maurice, S., Forni, O., Gasnault, O., Ollila, A., Newsom, H.E., Dromart, G., Palucis, M.C., Yingst, R.A., Anderson, R.B., Herkenhoff, K.E., Le Mouélic, S., Goetz, W., Madsen, M.B., Koefoed, A., Jensen, J.K., Bridges, J.C., Schwenzer, S.P., Lewis, K.W., Stack, K.M., Rubin, D., Kah, L.C., Bell, J.F., III, Farmer, J.D., Sullivan, R., Van Beek, T., Blaney, D.L., Pariser, O., and Deen, R.G. (2013) Martian fluvial conglomerates at Gale crater. *Science* 340:1068–1072.

Zahnle, K., Freedman, R.S., and Catling, D.C. (2011) Is there methane on Mars? *Icarus* 212:493–503.

Zurek, R.W., Chicarro, A., Allen, M.A., Bertaux, J.-L., Clancy, R.T., Daerden, F., Formisano, V., Garvin, J.B., Neukum, G., and Smith, M.D. (2011) Assessment of a 2016 mission concept: the search for trace gases in the atmosphere of Mars. *Planet Space Sci* 59:284–291.

Address correspondence to:
Alberto G. Fairén
Centro de Astrobiología
M-108, km 4
28850 Madrid
Spain

E-mail: agfairen@cab.inta-csic.es

Submitted 6 August 2015
Accepted 11 October 2015

Abbreviations Used

AWMP = Argyre western-margin-paleolake basin
CRISM = Compact Reconnaissance Imaging Spectrometer for Mars
GEL = global equivalent layer
MOLA = Mars Orbiter Laser Altimeter
MRO = Mars Reconnaissance Orbiter
OSPs = open-system pingos
SAM = Sample Analysis at Mars

This article has been cited by:

1. David M. Rubin, A.G. Fairén, J. Martínez-Frías, J. Frydenvang, O. Gasnault, G. Gelfenbaum, W. Goetz, J.P. Grotzinger, S. Le Mouélic, N. Mangold, H. Newsom, D.Z. Oehler, W. Rapin, J. Schieber, R.C. Wiens. 2017. Fluidized-sediment pipes in Gale crater, Mars, and possible Earth analogs. *Geology* **45**:1, 7-10. [CrossRef]