LIQUID WATER ON MARS

M. Usatov[1]
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ABSTRACT

Geomorphological, mineralogical and other evidence of the conditions favoring the existence of water on Mars in liquid phase is reviewed. This includes signatures of past and, possibly, present aqueous environments, such as the northern ocean, lacustrine environments, sedimentary and thermokarst landforms, glacial activity and water erosion features. Reviewed also are hydrous weathering processes, observed on surface remotely and also via analysis of Martian meteorites. Chemistry of Martian water is discussed: the triple point, salts and brines, as well as undercooled liquid interfacial and solid-state greenhouse effect melted waters that may still be present on Mars. Current understanding of the evolution of Martian hydrosphere over geological timescales is presented from early period to the present time, along with the discussion of alternative interpretations and possibilities of dry and wet Mars extremes.

1. INTRODUCTION

The presence of water on Earth, as seen from space, can be implied from the observations of low-albedo features, like seas and oceans, fluvial features on its surface, atmospheric phenomena, polar ice caps, and the snow cover exhibiting seasonal variations, not to mention spectroscopy. It is of a natural consequence that early observations of other planets in the solar system induced comparisons with the world already familiar. Martian snow caps were discovered in 1666 by Giovanni Domenico Cassini, and the early idea of Mars hosting liquid water on its surface can be attributed to William Herschel, who considered dark areas to be oceans (Murdin 2015). Ironically, the early mention of fluvial features on the surface of Mars is also based on the erroneous interpretation of observations of *canali*[2]—a term introduced by Pietro Secchi in 1876. The map, published by Giovanni Schiaparelli some time later, employed it to describe a network of straight dark channels—surface streaks, some extending over the entire hemispheres. Initially, Schiaparelli did not argue explicitly for these channels to comprise evidence in support of the surface water on Mars—the term in Italian language is perfectly suitable for the intention of describing a surface “groove”—although the choice of the term and Schiaparelli’s support of the notion of dark areas representing vast reservoirs of liquid, all point to his belief in aqueous Mars. His later papers revealed the interpretation of these features as a hydrographic system. The ambiguity of the term, translated to English, allowed waterway, even man-made, interpretation of those illusory features, and also sparked suggestions of Mars exhibiting extensive surface vegetation (Hollis 1908). It was not until the fly-by of the Mariner 4 planetary exploration spacecraft in 1965 that these hypotheses were put to rest, with much more data suddenly becoming available for analysis on this subject.

This report will review chemical properties of water and conditions that may be found on Mars in §2. Geomorphological and mineralogical evidence of aqueous environments available in the past and, possibly, present time is presented in §3 which will be correlated with the current understanding of the evolution of Martian hydrosphere at §4. Alternative (dry) interpretations of the evidence are discussed in §5.

2. MARTIAN WATER CHEMISTRY

2.1. *Pure Water*

Measurements from the Viking landers (*VL*) and the Mariner 9 space probe have revealed that the annual condensation and sublimation of CO_2 in Martian polar ice caps results in seasonal pressure cycle that varies with location due to orographic and dynamical effects, i.e. related to the presence of mountains, hills or other terrain that may force upward movement of air and precipitation (Hourdin et al. 1993). Low mean pressure (6.36 mb) and temperature (210 K) confine the average conditions found on Mars to the lower left area of the water phase diagram: water, in average, experiences direct transitions between solid and gas, as shown in figure 1. This may not be a coincidence, as Mars’ atmosphere may be self-limiting: if, due to, e.g. outgassing, it becomes thick enough to support liquid water, the water would react and remove CO_2 by forming carbonate deposits. As CO_2 is an effective greenhouse gas, the average temperature would then eventually drop, and pressure would be reduced back to the equilibrium level (Nolan 2008). Circumstances, however, still exist, fluctuating near the triple point of water, that allow pure H_2O to be found in its liquid phase on Mars. E.g., surface pressure reported at the *VL-2* site ranges from ≈ 7.4 to 10 mbar, and ground temperatures can reach ≈ 280 K, as detected by the Thermal Emission Spectrometer (*TES*) on board of the Mars Global Surveyor (*MGS*) spacecraft. Haberle et al. (2001) demonstrate that the surface pressure exceeds that of the triple point of water (6.1 mbar) for about half the planet, mostly in the northern hemisphere, although exceptions in the South are Argyre and Hellas Planitias. The temperature in the northern regions never exceeds the water freezing point, however, and favorable warmth is generally found to the south of 30 °N.

[1] maxim.usatov@bcsatellite.net

[2] Plural of *canale*—channel, canal, conduit, duct, gully (Collins Italian-English Dictionary). More on controversies about canali is available from Basalla (2005).

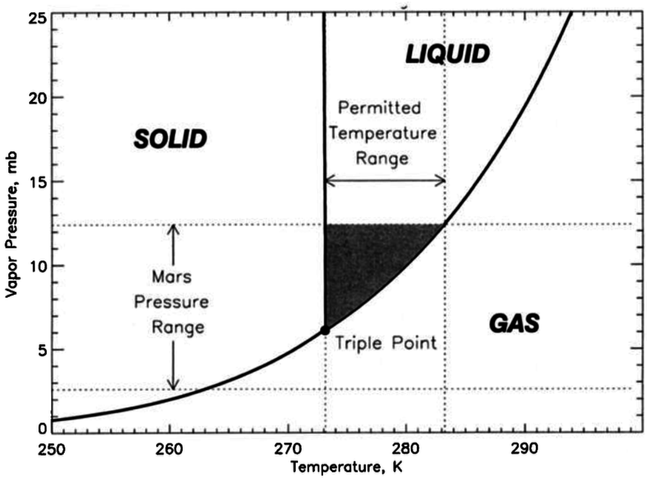

FIG. 1.— Water phase diagram. Shaded area represents temperature and pressure conditions available on the present-day Mars favoring the formation of water in its liquid phase. It is confined by the 273 K vertical—the freezing point of water–and the boiling point. The latter coincides with a condition being stable against boiling, whereby the saturation vapor pressure remains below the external pressure, of atmospheric or any other origin. Figure from Haberle et al. (2001).

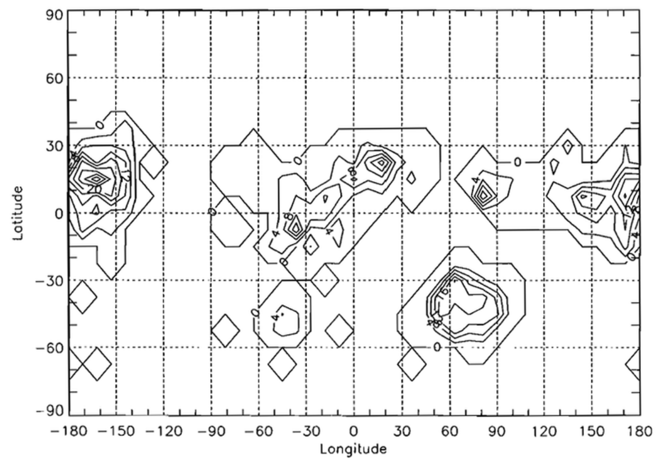

FIG. 2.— Areas on Mars where temperature and surface pressure can be found to be above the triple point of water. Hellas Planitia is centered at 42.4°S 70.5°E, and Argyre Planitia is to the East, centered at 49.7°S 316.0°E. Figure from Haberle et al. (2001).

Figure 1 represents those conditions on Mars, coinciding with the liquid phase confined by water's freezing (273 K) and boiling points. Amazonis Planitia, Western Arabia, southern areas of Isidis and Elysium Planitias in the North, and Hellas and Argyre Planitias in the South, are all capable of hosting water in its liquid phase, representing 29% of the Martian surface area (figure 2).

An important factor in the stability of liquid water on the surface is evaporation. In the case the saturation vapor pressure on the surface exceeds that of the water vapor pressure in the atmosphere, it will evaporate. The primary obstacle of finding a stable lake of pure, liquid water is that the evaporation rate will require a continuous sub-surface supply of water that is not available on Mars (Taylor et al. 2006). Liquid water, however, could still be found in three forms: undercooled liquid interfacial (ULI) water, cryo-brines, and subsurface melted water due to solid-state greenhouse effect (Möhlmann 2010). These forms are reviewed in the subsections below.

2.2. *Undercooled Liquid Interfacial (ULI) Water*

Conditions for liquid water to exist must be present between the adjacent surfaces of Martian ice and minerals, whereby additional pressure due to van der Waals forces lowers the freezing point (Möhlmann 2010). This is also known as the thin-film effect. On Earth, stable ULI water, also referred to as microscopic-scale liquid water, can be found in permafrost, i.e. soil that remains below the normal freezing point of water for a period of at least two years, at temperatures even below –30 °C, and also in polar glaciers (Anderson & Tice 1973; Cuffey et al. 1999). The presence of ULI water also depends on its salinity, discussed in §2.3. Keresztury (2012), using certain assumptions on the amount of insolation and temperature, estimates that ULI water can currently appear on Mars temporarily in the amounts of 10^{-9} to 10^{-6} km^3 every year. E.g., temperature and pressure conditions in Richardson crater, were found to be favorable for the support of ULI water films at the present time (Kereszturi & Rivera-Valentin 2012).

2.3. *Salts and Brines*

The abundance of salts in Martian regolith has been suggested since more than 35 years ago (Brass 1980; Clark & van Hart 1981). The X-ray fluorescence spectrometer (*XRFS*) on board of the Viking lander, the Pathfinder's alpha proton X-ray spectrometer (*APXS*) and Mars Exploration Rover (MER) Opportunity alpha particle X-ray spectrometer have identified high sulfur and chlorine concentrations in the soil (Clark et al. 1982; Foley et al. 2003; Rieder et al. 2004). The eutectic point of salty water solutions (brines) is below that of the pure water, allowing them to be stable in liquid phase, at least temporarily, over vast areas of present-day Mars. Warm sunward slopes provide additional favorable factor to hosting liquids. Salty deposits required for brine formation could have appeared due to the evaporation of salty lakes, and the water component could be supplied from sub-surface reservoirs, e.g. ULI water, or atmospheric vapor (Möhlmann & Thomsen 2011). Hence, brines may exist both on and below the surface if the surface temperature exceeds the eutectic temperature, and the atmospheric humidity exceeds deliquescence[3] relative humidity (DRH), that is, relative humidity at which salt begins to absorb moisture.

2.3.1. *Sulfates*

Volcanic activity is the natural source of sulfate aerosols, H_2S and H_2SO_4, which can be dispersed over long distances and then deposited into the soil, forming ferric sulfato complexes and sulfide minerals (Settle 1979; Burns 1987; Burns & Fisher 1990). Another source of sulfur proposed is the remnant sulfur-rich lithosphere (Clark & Baird 1979). Data from *XRFS* and *APXS* indicate ∼5-9% SO_3 concentration in the soil, and data from *TES* indicate a global distribution of sulfates that

[3] Deliquescence of a substance represents strong affinity for moisture, i.e. tendency to absorb water and form liquid solutions.

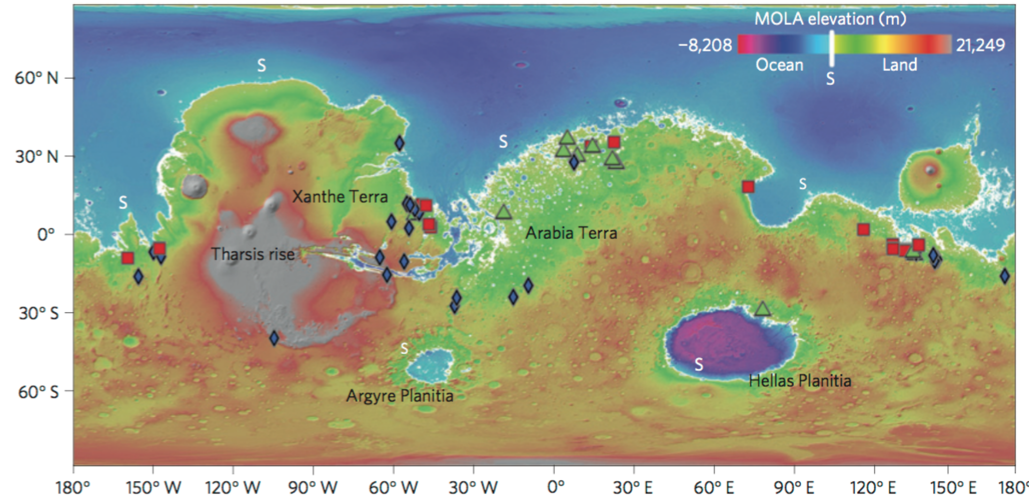

Fig. 3.— Ancient Martian ocean filling lowlands in the northern hemisphere. Red squares represent deltas, green triangles and blue diamonds represent closed basins. Figure from di Achille & Hynek (2010).

were cemented into the soil even far away from the volcanic regions, pointing to an atmospheric related process (Brueckner 2004; Cooper & Mustard 2001). Deposits of sulfate minerals has been confirmed by data from the Compact Reconnaissance Imaging Spectrometer (*CRISM*) on board of the Mars Reconnaissance Orbiter (*MRO*) (Bishop et al. 2007). Sulfates have also been found in Martian group (SNC) meteorites (Gooding et al. 1991; Treiman et al. 1993). Gypsum ($CaSO_4{\cdot}2H_2O$) is one example of a Martian sulfate mineral, and there are many others (Möhlmann & Thomsen 2011).

2.3.2. *Chlorides and Perchlorates*

Data from Thermal Emission Imaging System (*THEMIS*) on board of the Mars Odyssey robotic orbiting spacecraft, as well as that from *MRO* and *MGS*, indicate presence of chloride deposits widespread in the southern highlands (Christensen et al. 2004; Osterloo et al. 2008). On Earth, these compounds precipitate, as Cl-bearing reservoirs of liquids, such as saline lakes and sub-surface brines, evaporate. This implies that similar processes were once active on Mars. As a prominent example of such a lake on Earth with salinity level of 40% could serve the Don Juan Pond in Antarctica that does not freeze at temperatures even as low as 230 K. As is with sulfur, SNC meteorites were found to contain compounds of chlorine (Treiman & Gooding 1992). In the soil samples from Vastitas Borealis, the Wet Chemistry Laboratory (*WCL*) on board of the Phoenix Mars lander has detected perchlorates—very deliquescent salts that combine the ClO_4^- ion (Hecht et al. 2009). Analysis of the WCL data indicates that certain portion of Martian perchlorates are present as $Mg(ClO_4)_2$ or $Ca(ClO_4)_2$, with the most probable salt being magnesium perchlorate hexahydrate, $Mg(ClO_4)_2{\cdot}6H_2O$ (Toner et al. 2014). The eutectic temperature of perchlorate solutions is much below that of pure water, e.g. 206 K for 44.0 wt% magnesium perchlorate, hence, considerably expanding the range of sites on Mars where salty water could be found in liquid phase. For the Phoenix landing site it was derived that perchlorate brines should remain liquid during summers, for a duration of several hours per day (Chevrier et al. 2009). Glavin et al. (2013) have found evidence of perchlorates in the Gale crater, suggesting that perchlorate deposits may be widely distributed on Mars (Nikolakakos & Whiteway 2015).

2.3.3. *Carbonates*

The indication of presence of carbonate-bearing rocks found in the *MRO/CRISM* data provides additional support to that aqueous environment was once available on Mars (Ehlmann et al. 2008). Formation of carbonates is expected within environment that contains water and CO_2 atmosphere, and weathering of mafic rocks, such as basalt, or other solids, e.g. iron (Gooding 1978; Catling 1999). In a process of carbonation, water combines with CO_2 and removes it from the atmosphere, producing carbonate ions that react with ground environment, resulting in carbonate deposits (Tomkinson et al. 2013). An example of a Martian carbonate is $FeCO_3$, siderite. Morris et al. (2010) have identified carbonate minerals in Gusev crater using data from MER Spirit, compositionally found to be similar to the carbonate globules in Martian achondrite, member of the SNC group, ALH 84001.

2.4. *Solid-state Greenhouse Effect Melted Water*

It has been experimentally confirmed that H_2O ice and snow, due to that they are optically thin in the visible spectrum range and opaque in the IR, can produce an effect comparable to the atmospheric greenhouse effect. In this case, the solar radiation is able to reach, heat and melt water under the ice or snow cover (Kaufmann et al. 2006).

3. GEOMORPHOLOGICAL AND MINERALOGICAL EVIDENCE OF AQUEOUS ENVIRONMENTS

3.1. *The Northern Ocean, Argyre and Hellas Seas*

Since the time robotic exploration spacecrafts like Mariner missions and MERs have provided detailed insight into the surface of Mars, a growing number of evidence has been collected in support of the presence of wet environments in the past. The presence of elevated sources of outflow channels and their subsequent erosion by floods enabled early prediction that a global ocean was once present on Mars during the Noachian or, possibly, Hesperian (see §4) periods (Head et al. 1999; Clifford & Parker 2001; Carr & Head 2003). The presence of lakes and marine deltas at the elevation of ~ 2540 m provide strong support to the hypothesis that the primordial ocean was possibly covering up to a third of the surface of Mars about 3.5 Gya, along with the seas in Argyre and Hellas Planitias (di Achille & Hynek 2010). These deltas, along with deltaic deposits of sediments, form naturally at the same (systemic) elevation here on Earth, as water flows into seas and oceans, delineating their shorelines. Martian paleoshorelines were found to follow its crustal dichotomy, tracing lowlands in the northern hemisphere. The surface topography is smooth on the supposed ocean floor, and the shorelines exhibit terrace features consistent with shoreline water activity. The evidence is also reinforced by the distribution of valley networks that is elevationally aligned with the northern ocean. Among the other evidence are ridges and craters that are partially buried in sediment (Kreslavsky & Head 2002; Carr & Head 2010) and crack polygon signatures due to thermal contraction of ice cover (Levy et al. 2009). Finally, the volume of this northern ocean is compatible with the estimates of water inventory available on Mars after formation. Shown in figure 3, one of possible ocean's mean surface level is suggested at ~ 2540 m. Assuming present conditions, the ocean would freeze and sublimate rather quickly—within $\sim 10^4$ yr (Carr & Head 2003), although conditions in the Noachian period should have been substantially warmer, possibly allowing for a longer stability timescale. The presence of such a global ocean, however, still remains controversial (Carr & Head 2010).

3.2. *Outflow Channels and Flooding*

Catastrophic outflow events, i.e. flooding events, occur when a a confined lake or subsurface aquifer breaks out and rapidly releases large amount of water, forming sediment carrying outflow channels, hundreds of km long and up to a km deep (Carr 1979; Carr & Clow 1981). These features can be compared with those created by cataclysmic floods on Earth, e.g. the Channeled Scablands in the Washington state, U.S., due to the drainage of a glacial Pleistocene era Lake Missoula (Marshak 2009). The channels formed by outflow events on Mars are different to, e.g., rilles on the Moon and Venus, in the sense that they are substantially wider and have many features in common with similar terrestrial events (Baker & Milton 1974). The sources of water for these outflow events on Mars could have been high-pressure aquifers buried in the permafrost, formed in the cold and dry conditions at the end of the Noachian period (Clifford 1993; Clifford & Parker 2001). The release of water could have occured due to e.g. tectonics or an impact. An overview of valles and regions containing outflow channels, about two dozen of them identified, is available from Carr (2007). One of the largest outflow channels on Mars, Kasei Valles, ~ 3500 km long, is shown in figure 4.

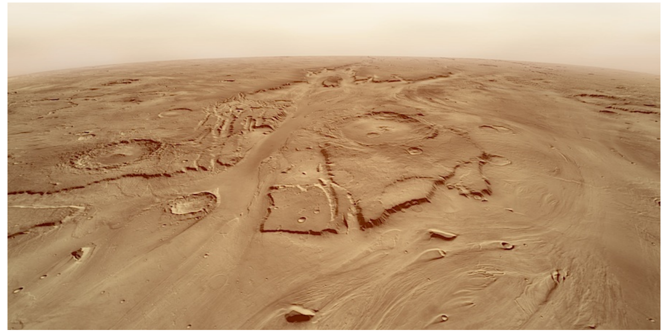

Fig. 4.— An upstream view of the Kasei Vallis outflow channel. Sharonov crater ($d = 100$ km) is seen near the center. Image by NASA/JPL-Caltech/Arizona State University.

3.3. *Lakes and Impact-Induced Hydrothermal Systems*

Recent Curiosity rover data, revealing the presence of sedimentary rocks in the Gale crater, suggests that conditions on Mars once existed to allow the inflow of water sufficient to form a lake, at least intermittently (Grotzinger et al. 2015). Over 210 such paleolakes, some the size of Baikal or Caspian sea, have been identified in impact structures within the data coming from Viking Orbiter (*VO*) and other instruments, having their sediments delivered from valley networks (Cabrol & Grin 1999; Fassett & Head 2008b). The water in crater ice-covered lakes could also be supplied from subsurface aquifers and it could have been stable in the liquid phase due to the heat generated in the impact event (Newsom et al. 1996). Voluminous, km-deep lakes were also suggested, once filling basins of, e.g., eastern areas of the Valles Marineris canyon system, eventually producing spill-over features (Lucchitta 2009; Warner et al. 2013). The stability of such lacustrine environment depends on the water loss via outflows. Assuming Martian lakes had the loss rates comparable to that of subglacial lakes in Antarctica, their lifetimes could have been on order of 10^4–10^5 yr (Cabrol 2003; Kereszturi 2012). Impact-induced hydrothermal systems, such as crater lakes, may have existed on time scales of 10^5 to 10^6 yr for 100–180-km craters. Rocks, uplifted and heated by impact events, may have stored enough thermal energy over a period long enough to support liquid lacustrine environments vila melting permafrost layer underneath (Daubar & Kring 2001). Several terrestrial impact-induced hydrothermal systems are known, one of the largest is the Chicxulub crater (Abramov 2006). As an example of past hydrothermal system showing strong evidence of impact-induced formation on Mars could be the Libya Montes region, connected to the impact event that produced Isidis Basin (Bishop et al. 2013).

3.4. *Sedimentary Landforms: Deltas, Alluvial Fans and Wave-formed Terraces*

Deltas form on Earth, as sediment-carrying river flows enter standing or slower-moving reservoirs of water, such as lakes or seas. Gilbert-type deltas can be characterized as those formed by streams flowing on steep slopes into deep water, with coarse gravels found in foreset beds (inclined part of the delta), and fine sands deposited into bottomset beds, i.e. at the bottom of the body of water where the flow enters (Jones 1965). Gilbert-type deltas have been identified on Mars in crater paleolakes, along with wave-formed terraces formed along crater rims—features normally associated with lacustrine environments, see figure 5 (Ori et al. 2000). The common interpretation is that the water waves are responsible for producing terraces, as is with similar structures found on Earth. Morphologically, wave-formed terraces are distinct from terraces produced by the collapse of crater walls. Structures similar to Gilbert-type deltas have been identified in crater lakes on Earth, suggesting that craters with apparent deltaic deposits on Mars once acted as water sinks. Similar to deltas, alluvial fans are also present on Mars. Those are different from deltas, as fan structures form due to the rapid carriage of coarse sediments into low-relief basins via high-energy fluvial processes, such as flash floods. A good example is the large alluvial fan complex in Holden crater, shown in figure 5, and at least several dozen of other fans have been identified on Mars (Moore & Howard 2005).

3.5. *Valley Networks, Channels and Geothermal Heat-Induced Systems*

Valley networks, perhaps one the most frequent evidence of liquid water once present on Mars, are, in some sense, similar to the outflow channels, although formed via much less energetic processes. These hierarchical networks are reminiscent of fluvial tributaries found on Earth that feed and form streams and rivers—see figure 5. Although resembling hydrological systems on Earth, terrestrial scaling laws fail to describe Martian valley networks well (Penido & Fassett 2012). The common origins of tributaries are ground-water sapping, precipitation and melting processes. Valley networks, formed via such slow discharges of water, are mostly located in the southern highlands of Mars and must be ancient features originating in the warmer Noachian period (Howard et al. 1988). They typically have V or U shaped cross-sections, widths of $\sim$ 1–10 km, and lengths of up to $\sim$ 1000 km (Gulick 2001). Although various formation mechanisms have been proposed, evidence is available that some of the networks, e.g. those on Libya Montes and in Vallis Marineris and Warego Valles areas, were formed via surface runoff due to precipitation (Mangold et al. 2004; Ansan & Mangold 2006; Erkeling et al. 2009). A study of the erosion characteristics in the Libya Montes valley network indicates that while precipitation was the primary fluvial activity during the Noachian period, melting and hydrothermal water release due to volcanic events were responsible for the network development later on (Jaumann et al. 2010). Although ground-water sapping was commonly employed to explain the formation of Martian valley networks early (Kochel & Howard 1985), it was found that other processes can produce similar landforms (Irwin et al. 2014). Simulation show, however, that accelerated weathering of bedrock by seepage must have played major role in the formation of valley networks on Mars in combination with other fluvial processes (Luo & Howard 2008). Clow (1987) has proposed a model for valley network formation via insolation and water snow melting at temperate latitudes.

Magmatic and volcanic heat could have served as the source of thermal energy for melting ice and carving channels on the flanks of Martian volcanoes. Such interaction between magmatic intrusions and cryosphere volatiles is expected on Mars (Wilson & Head 2002). A prominent example is the Ceraunius Tholus volcano, whereby one of its channels runs into a crater, ending with a deltaic deposit—see figure 5 (Yamaguchi et al. 2010; Kereszturi 2012). Hydrated silica deposits have been identified by MER Spirit in the Nili Patera, suggesting aqueous environment on the flanks of the Syrtis Major volcanic complex (Skok et al. 2010). Given the evidence for Martian volcanism as recently as 40–100 Myr, e.g. Arsia Mons caldera, and that it may even be continuing, geothermal heat-induced systems may still have potential to reactivate (Hartmann et al. 1999). Data from Tharsis Montes even points to a < 10 Myr activity time frames (Márquez et al. 2004).

Among the other geothermal heat-induced systems is the south polar deposit (that includes the circumpolar Dorsa Argentea Formation) of Hesperian age that was once covering area about twice that of the current ice cap. Geomorphological features, such as sinuous ridges (eskers), indicates ice melting due to the volcanic activity and subsequent drainage of water into low-lying areas, such as Argyre Basin (Head & Pratt 2001; Plaut et al. 2007; Carr & Head 2010).

3.6. *Gullies*

Gullies, first identified on *MGS* images, are erosional features observed on steep slopes of mid and high-latitude regions, generally ($> 90\%$) found in the southern hemisphere. Morphologically gullies are similar to those in Svalbard on Earth (Malin & Edgett 2000; Reiss et al. 2009). They are ~ 1 km in length and ~ 10 m wide, much smaller than geomorphological features described in the previous chapters, and their existence, at least in the traditional interpretation, suggests presence of sources of liquid water at shallow depths as it seeps, runs off and erodes the surface (Rothery et al. 2011). Gullies can be found on the interior walls and central peaks of craters, as well as the walls of pits and valley networks, e.g., see figure 5. Morphologically, they can be characterized as taking their start from alcoves—surface embayments—and ending at aprons at their bases, linked together via channels. One of the triggers of their formation could be solar insolation (Morgan et al. 2010). Their explanation as the result of dry mass flow is generally problematic—alternative models will be discussed below—hence, gullies are strongly associated with fluvial processes. Although difficult to explain in the present cold climate of Mars, new gullies have been formed as recently as the last decade, indicating that water is still present in liquid phase at shallow depths (Malin et al. 2006). This makes gullies to be of a great importance in searching of habitable environments (Christensen 2003). Although initially interpreted as the result of ground-water seepage, gullies could have been formed by surface melting of ice and snow (Head et al. 2008; Williams et al. 2009). The most recent gully activity can also be explained via melting of snow accumulated in their channels, deposited by winds (Dickson et al. 2007). Among the most prominent example of recent gullies activity is the one in the crater in Terra Sirenum, with apparent differences in appearance in the images of 2001 and 2005 (Malin et al. 2006).

3.7. *Recurring Slope Lineae*

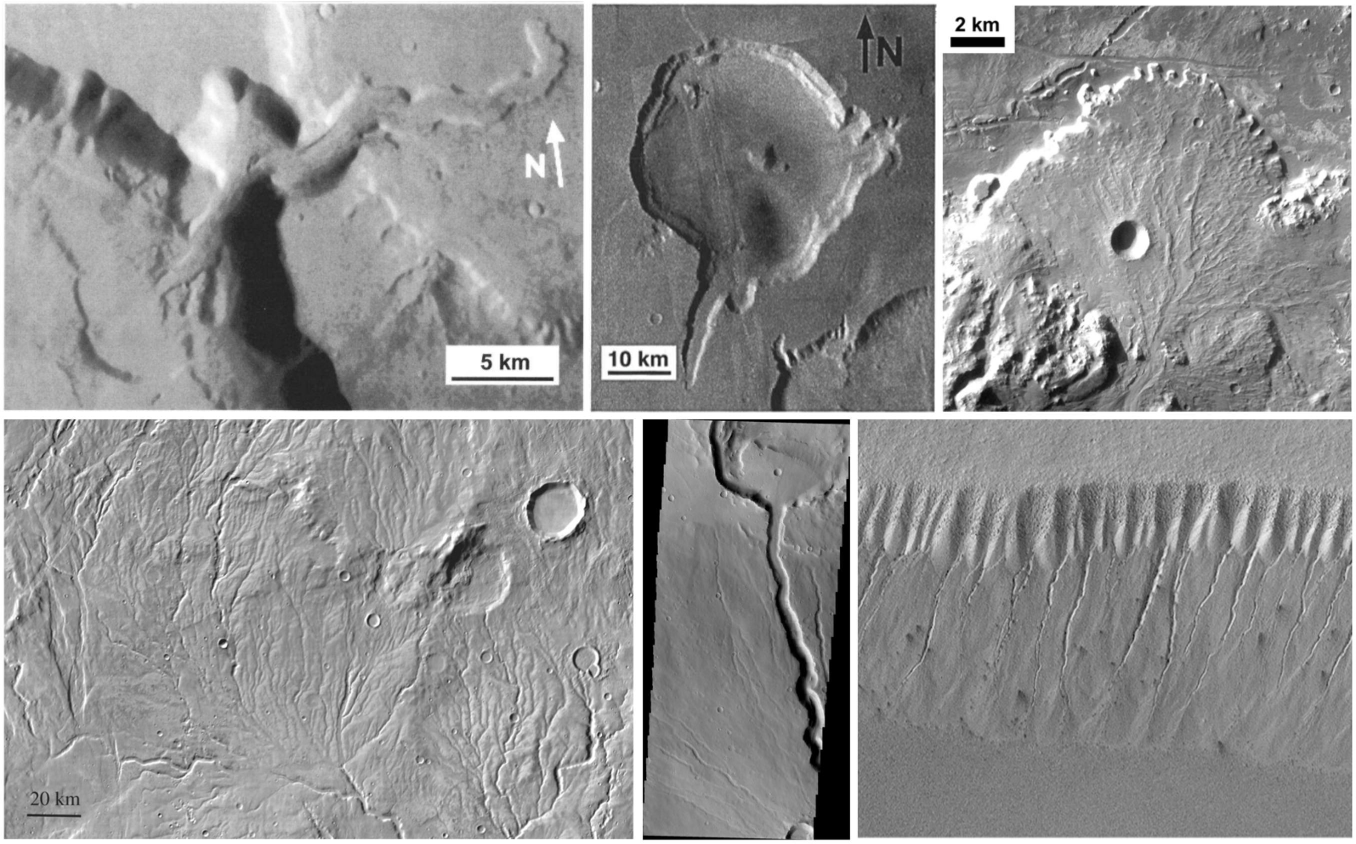

FIG. 5.— Upper Left: Complex Gilbert-type delta on Mars. *VO* image, 34.5 °N, 342 °W. Middle: Wave-formed terraces along crater rims in Ismenius Lacus. *VO* image, 37.5 °N, 347 °W (Ori et al. 2000). Right: Alluvial fan in Holden crater, *THEMIS* Mars Odyssey orbiter image (Christensen et al. 2004). Bottom Left: Valley network in the Warrego Vallis area at 42 °S, 267 °E, image from Carr (2012). Middle: Northwestern flank of the Ceraunius Tholus volcano, showing geothermal heat-induced channel depositing sediment into Rahe Crater, *THEMIS* Mars Odyssey orbiter image (Christensen et al. 2004). Right: Martian gullies that could be produced by liquid ground-water seepage and surface run-off; image no. PIA01034 from *MGS* Mars Orbiter Camera by NASA/JPL.

Recurring slope lineae (RSL), initially dubbed transient slope lineae, are somewhat similar to the gullies. They were first identified in the data from High Resolution Imaging Science Experiment (*HiRISE*) on board of the *MRO* by McEwen et al. (2011a). RSL are oriented downhill, appear in groups only during the summer as dark, narrow ($\lesssim 5$ m) streaks, hundreds of meters in length. They are mostly found on the equator-facing slopes at equatorial and moderate latitudes—see figure 6. RSL disappear during the colder seasons, however recur during multiple Martian years (Ojha et al. 2014). A variety of hypotheses are proposed for their formation. They include dry mass wasting—slope movement that does not necessarily involve liquid water (McEwen et al. 2011b), CO_2 sublimation, and liquid water melting from brines (Hargitai & Kereszturi 2015). They are found to be analogous to fluvial activity features in the Antarctic McMurdo Dry Valleys (Dickson & Head 2012).

3.8. *Wet Debris Avalanches*

Baratoux et al. (2002) have identified a long debris apron (sheet of material) in Reull Vallis that they have interpreted as a debris avalanche (mass wasting) flow, supported by liquid water. This elongated apron was found to be distinct from dry terrestrial avalanches, and more similar to the Mount Shasta avalanche whereby the presence of interstitial[4] water was confirmed.

3.9. *Lobate Debris Aprons and Lineated Valley Fills*

Relatively smooth lobate debris aprons (LDAs), first observed on *VO* data and found at mid-latitudes, surround elevated structures, such as cliffs, massifs, plateaus and mesas. *MRO* shallow radar sounding (*SHARAD*) experiment indicates that their composition, at least of LDAs found in Deuteronilus Mensae, is mainly water ice (Plaut et al. 2009). These features of Amazonian age are interpreted as the result of the downslope material movement (mass wasting), similar to that found in terrestrial glaciers, in dry conditions (Mangold & Allemand 2001; Hargitai & Kereszturi 2015). Lineated valley fills (LVFs), appearing to be related to LDAs, form at the valley floors due to mass wasting. The fact that water-rich LDAs and LVFs are found at mid-latitudes (30–60° on both sides of the equator) implies wet conditions were once present on Mars, followed by a cold period that enforced glaciation.

3.10. *Thermokarst Landforms*

On Earth, thermokarst lakes often form due to the melting of ice, followed by the subsidence of permafrost

[4] Water contained below the surface and between the grains of solid material.

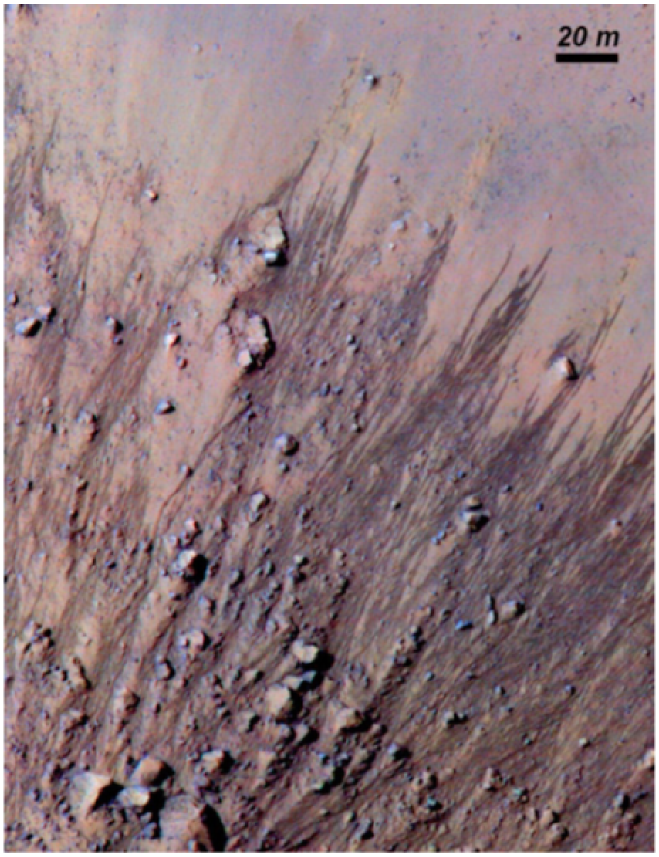

FIG. 6.— Recurring slope lineae (RSL) at Horowitz crater, *HiRISE* image from McEwen et al. (2011a).

as it deflates. Thermokarst lakes can be found, e.g. in Tuktoyaktuk Coastlands in Canada (Hargitai & Kereszturi 2015). Similar scalloped terrain has been identified on Mars—in Utopia Planitia (Costard & Kargel 1995), and Peneus and Amphitrites Paterae (Lefort et al. 2010), indicating thermokarstic (thawing) and, hence, wet processes were running in the past on Mars (Soare et al. 2011).

3.11. *Mineralogical and Meteoritical Evidence, Chemical Weathering*

3.11.1. *Dissolution*

The evidence of the past presence of wet environment can be found in minerals that underwent chemical weathering—aqueous alteration through processes such as dissolution. Olivine, $(Mg, Fe)_2SiO_4$, commonly found in Martian surface basalts, especially in Syrtis Major and equatorial latitudes, as well as Martian meteorites, alters quickly, and can serve as a good indicator (Stopar et al. 2006). Olivine, while dissolving in water, breaks down its structure and releases constituent M-site components—Fe^{2+}, Mg^{2+} cations, and silica. Using microscope imaging data from, e.g. MER Spirit, and data on thermal inertia and conductivity of soil sediments, it is possible to derive average olivine particle size on Mars. Using models of olivine dissolution rates on Earth, and by estimating temperature, pH and abundance of other elements in the past Mars environment, it is possible, thus, to constrain minimum time required for the olivine to dissolve (minimum residence time). Thus far, Stopar et al. (2006) have found that wet environments on Mars have been short-lived and limited, and required cold temperatures in order to explain current mineralogical data. Evidence of silicate dissolution was found in Martian meteorites, e.g. Nakhla meteorite (Lee et al. 2013).

3.11.2. *Hydration and Sedimenting*

There is a variety of minerals, such as clay, that are known to form due to gradual chemical weathering, hydrolysis of rocks by water. Exposed Martian crust from the Noachian period, mostly in impact craters of the southern highlands, was found to be rich in hydrated silicates, mostly clay minerals—phyllosilicates (Bibring et al. 2005; Poulet et al. 2005; Ehlmann & Edwards 2014). These are found to appear as layers, $\sim$ 100 m thick (Murchie et al. 2009). A large sample of data came from the Observatoire pour l'Minéralogie, l'Eau, les Glaces, et l'Activité (*OMEGA*) IR mineralogical mapping spectrometer on board of the Mars Express Orbiter, and also from MRO's *CRISM* and *HiRISE* (Ehlmann et al. 2009). Instead of the formation via surface weathering, as is common on Earth, phyllosilicates at the Martian sites have formed via subsurface circulation of water at high temperatures (Ehlmann et al. 2011). Multiple Martian paleolakes, described in §3.3, exhibit deposits of phyllosilicates and other salts, implying aqueous environments within which these hydrated minerals were formed and delivered. Hydrated carbonate and sulfate deposits were also found on Mars, with detailed review of Martian mineralogy available from Murchie et al. (2009).

3.12. *"Blueberries"*

Spherical hematite (Fe_2O_3) concretions, $<$ 6.2 mm in size, dubbed "blueberries," were found by MER Opportunity in Meridiani Planum (Squyres et al. 2004). They are similar to hematite Moqui "marbles" from Navajo sandstone sites in southern Utah, including their property of making joined doublets and triplets (Chan et al. 2004, 2005). Traditionally, Martian blueberries have been interpreted as formed diagenetically, i.e. after their sedimentation, within the environment of groundwater flows (Chan et al. 2004). A more recent research, however, proposes alternative formation mechanism, that is, due to the ablation of an impacting meteorite (Misra et al. 2014).

3.13. *Meteorites*

Hydrous alteration of the original igneous rock material in meteorites results in the formation of secondary minerals that reveal aqueous environments once present on Mars. Carbonates, iddingsite ($MgO{\cdot}Fe_2O_3{\cdot}3SiO_2{\cdot}4H_2O$), sulfates and phyllosilicates are found to be present in various Martian meteorites. Meteoritical evidence, summarized by Borg & Drake (2005), indicates intermittent water availability on the surface of Mars throughout its geologic history, as well as widespread water abundance during the first 100 Myr—shortly after planet's formation (see §4.1).

4. EVOLUTION OF MARTIAN HYDROSPHERE

The primary geological timescale used for Mars is based on crater counting and intersection relations in *VO* images (Tanaka 1986). It identifies three distinct periods—Noachian (4.1–3.7 Gya), Hesperian (3.7–3.0 Gya) and Amazonian (3.0 Gya to the present time). The boundary between Hesperian and Amazonian periods is largely uncertain. Stratigraphic ages show that Martian volcanic and tectonic activities and the rate of meteorite bombardment have declined over time. Bibring et al. (2006), using data from *OMEGA*, have proposed another, mineralogical timescale, based on the chemical processes that drove mineral alteration during each period. Phyllocian (from planet formation to until ~ 4.0 Gya) is characterized by the formation of phyllosilicates that requires alkaline wet environments (see §3.11.2). Theiikian (~ 4.0–3.5 Gya) is the period of high volcanism, responsible for the release of high amounts of SO_2 into the atmosphere. In reaction with water, sulfur dioxide created acid environment, facilitating the formation of hydrated sulfates (see §2.3.1). Finally, Siderikan—from ~ 3.5 Gya to the present time—is characterized by fading volcanism and water abundance, and also increasing surface oxidization, responsible for the distinctive color of Martian surface we observe today.

4.1. *Early and Noachian Periods*

Given that Mars should have formed without involving giant collisions—otherwise it is difficult to explain its present mass—the water should have been delivered there via accretion of smaller primordial solar system bodies, such as asteroids and comets beyond 2.5 AU (Lunine et al. 2003). Total amount of water made available on Mars should be approximately 6–27% of the present mass of terrestrial oceans (1.5×10^{21} kg). Surface conditions right after the Mars' formation in pre-Noachian are largely uncertain, however numerous impact events could have kept temperatures high enough for global circulation and precipitation (Carr & Head 2010). In fact, Craddock & Howard (2002) argue that rainfall and surface run-off provide the best explanation for a variety of morphological features on Mars. Due to the extensive cratering during Late Heavy Bombardment, among the distinctive features of the period that followed, Noachian, is the formation of impact-induced hydrothermal systems (§3.3), accompanied by valley networks (§3.5) and sedimentary landforms (§3.4) (Burt et al. 2008). Phyllocian falls into this period, during which hydrated silicates have formed—see figure 7. Even if the CO_2 atmosphere was thin, other greenhouse gases—SO_2 and CH_4—may have been responsible for supporting warm climate and widespread wet environments at that time (Carr & Head 2010). Despite extensive fluvial activity associated with lakes in impact basins, producing valley networks, deltas and alluvial fans, large catastrophic outflow events occurred mainly later, in Hesperian.

4.2. *Hesperian Period*

As Noachian period was coming to an end, Martian climate changed to cold and dry, and, thus, weathering by water and the rate of formation of phyllosilicates have declined (Kasting 1991). Warmer environments began to occur only episodically and the cryosphere thickened. Martian fluvial activity during Hesperian is dominated by catastrophic outflow floods and appearance of lakes and seas where the water ran off to. Rapid water discharges in Hesperian could be the result of the development of thick cryosphere during the late Noachian and early Hesperian, which enabled pressure build-up in subsurface aquifers (Carr & Head 2010). These conditions were not present earlier, which explains the lack of prior outflow events. Hesperian floods could have resulted in the appearance of a global ocean, such as the one discussed in §3.1, although this still remains to be one of the most controversial issues in the geology of Mars, primarily due to that warm climate, required for its stability, is assumed to have existed only before, in Noachian. High rate of volcanism during Hesperian is responsible for the resurfacing of about a third of the planet and the release of sulfate aerosols which combined with water and formed hydrated compounds. Valley networks formation has declined during Hesperian, however new networks can still be found appearing on the slopes of volcanoes, some of them, perhaps, due to the melting of snow covers on the summits (Gulick 2001; Fassett & Head 2006, 2008a). Hesperian volcanism has triggered melting of the south polar ice deposit and the formation of Dorsa Argentea (§3.5). Bibring et al. (2006) suggested that volcanism was also responsible for the production of sulfates characteristic for the Hesperian period, as Tharsis finalized its formation.

4.3. *Amazonian Period*

The rates of resurfacing due to cratering, tectonic, volcanic and fluvial activities in the Amazonian period are much lower, if compared to periods it followed. Aeolian processes become one of the main surface weathering mechanisms. Volcanism is confined mainly to Tharsis and Elysium areas, with eruptions occurring only episodically. The most common fluvial feature of the Amazonian period are gullies (§3.6). Due to the prior flooding events, surface and underground ice deposits accumulate globally from middle latitudes to the poles. Changes in obliquity (reaching as much as $60°$ in the past Gyr) and, hence, insolation cycle, facilitate transport of polar ice towards equator (Head et al. 2003, 2008). Melting of these deposits of ice near the surface could be the source of water required for the gully activity seen from the late Amazonian to the present time (Christensen 2003). Young outflow channels and valley networks still appear intermittently throughout Amazonian, albeit at a much lower rate. Among those are outflow channels associated with volcanic activity: in Olympus Mons (Basilevsky et al. 2006) and Cerberus Plains (Berman & Hartmann 2002). Among the examples of Amazonian valley networks is that within the Lyot crater that supported liquid water during high obliquities due to its low elevation and, hence, high surface pressure (Dickson et al. 2009).

4.4. *Solar Wind Erosion of Atmosphere via Sputtering by O^+ Pickup Ions*

The Mars Atmosphere and Volatile Evolution Mission (*MAVEN*), launched in 2013, allowed to get an insight on the causes of the Noachian-Hesperian transition from warm to cold climate (Jakosky et al. 2015; Connerney et al. 2015). There is a direct connection between the magnetic field and the composition of the planet's atmosphere (Brain et al. 2013). As the solar wind sweeps through the interplanetary medium, its interaction with the upper layers of atmosphere are limited and, thus, shielded, by the planet's magnetic field. Given that Mars

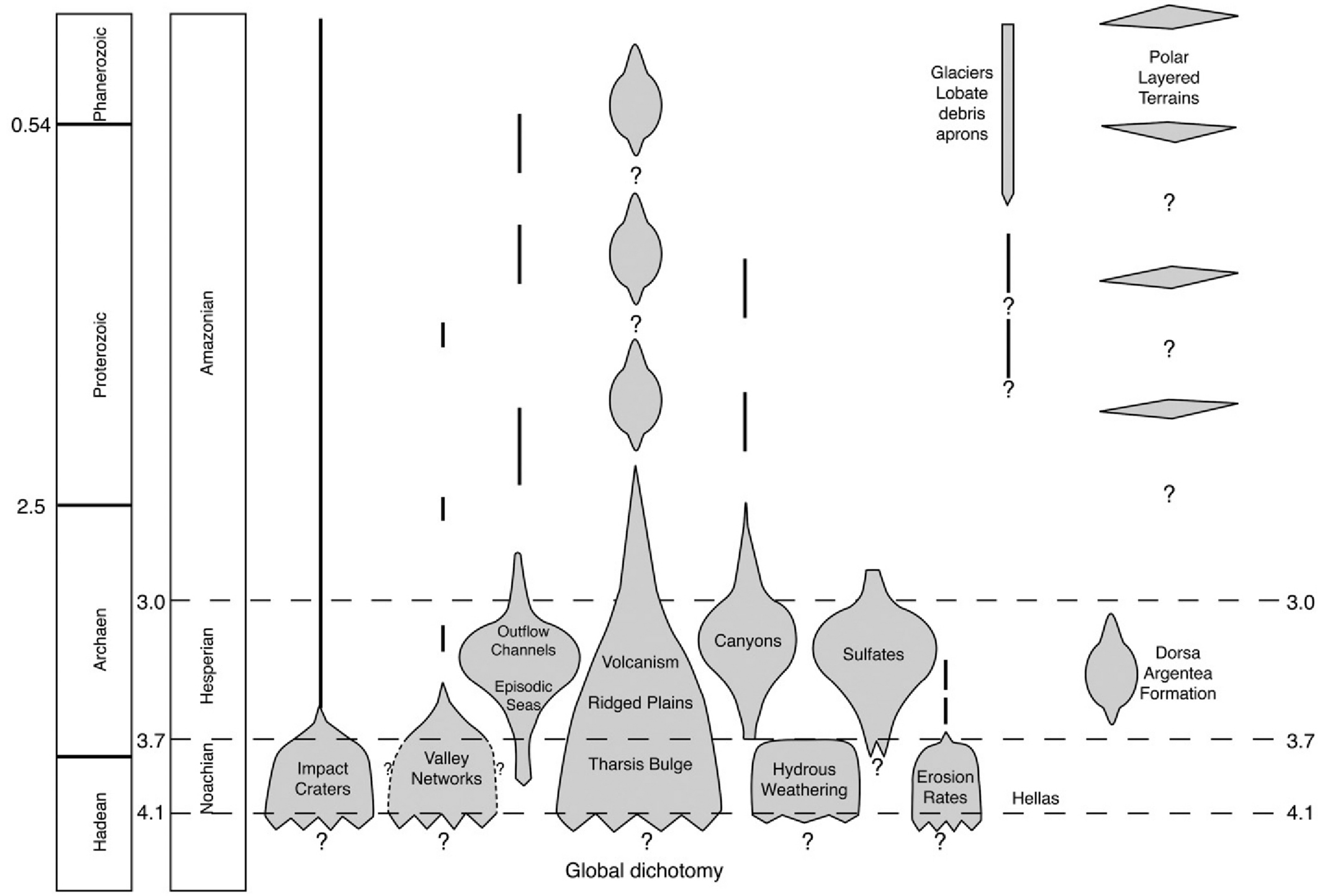

FIG. 7.— Martian geological timescale and related processes, figure from Carr & Head (2010). The line at 4.1 Gya represents the conventional base of the Noachian Period—the formation of the Hellas Basin. Martian history in pre-Noachian (early) period is largely uncertain due to extensive bombardment and tectonic resurfacing.

has lost its magnetism very early, coinciding with the end of the heavy bombardment, a significant fraction of its neutral atmospheric constituents may have been removed via sputtering by ions picked up by the solar wind, such as O^+ (Johnson & Leblanc 2001; Leblanc & Johnson 2001). The fast O^+ ions can collide with and accelerate (sputter) neutral atmospheric constituents which may achieve velocities sufficient enough for atmospheric escape, hence, producing the "neutral wind" of particles (Luhmann & Brace 1991). This may have triggered the loss of greenhouses gases, e.g. CO_2, subsequently resulting in the colder Hesperian climate.

The reasons for the cessation of magnetism on Mars are not fully certain. At the current moment, only crustal magnetic anomalies are observed, mainly in southern highlands (Acuna et al. 1999). At least two constraints on the timeline of the cessation of the dynamo effect on Mars can be identified from magnetic signatures of various landforms (Fassett & Head 2011). Magnetic anomalies are not observed in, e.g., Hellas and other basins, implying they must have formed after the magnetic field was lost. In case of Hellas, this points to an early period in Martian history, i.e. before the base of Noachian at $\sim$ 4.1 Gya. Roberts et al. (2009), using three-dimensional convection models, suggest that a sequence of giant pre-Noachian impact events may have decreased the heat flow at the core-mantle boundary, resulting in the loss of the global magnetism on Mars. Another constraint comes from the dating of Martian meteorites that bear magnetic signatures consistent with that produced by core dynamo. E.g. dating of ALH 84001 results in its age of 4.091 ± 0.030 Gyr (Lapen et al. 2010).

4.5. *D/H Mass Fractionation*

Deuterium is a heavier isotope of hydrogen. As H is more vulnerable to planetary atmospheric escape processes, high D/H ratio implies that significant amounts of H and, hence, water, have been lost to space (Zahnle et al. 1990; Lammer et al. 2008). Martian spectrum reveals the planet has a D/H ratio 6 times that of Earth's, suggesting strong atmospheric water loss in the past (Owen et al. 1988). Kurokawa et al. (2014), using D/H ratios of Martian meteorites, have shown that water loss on Mars was especially rapid during the pre-Noachian early period. Their results, assuming certain volume of water once present in a primordial ocean on Mars, also point to the existence of large undetected subsurface amounts of water and ice.

5. DRY MARS AND ALTERNATIVE INTERPRETATIONS

Alternative interpretations of apparently fluvial Martian features do exist, implying that conditions responsible for their formations may have been dry. Misra et al. (2014) have suggested that hematite spherules ("blueberries," see §3.12) may have formed via ablation of meteorites and that they are substantially different from Navajo sandstone "marbles." Some of the formations suggested, such as the northern ancient ocean, may not have existed at all. E.g., McEwen et al. (2007), using high-resolution data from *MRO* argue that large (~ 2 m) boulders appearing in Vastitas Borealis were erroneously interpreted as fine oceanic sediment. They also point to recent gullies activity that may be explained by dry mass wasting. Pilorget & Forget (2016) proposed that gullies may exhibit such dry mass wasting, lubricated by CO_2 sublimation—a process that has not yet been observed on Earth. The perspective described by Bibring et al. (2006) is that Mars was predominantly a planet with cold and dry surface throughout most of its history. The formation of phyllosilicates could have occurred deep under the surface, although authors allow wet environment due to, e.g., outgassing during the formation of sulfates in the Theiikian period.

Leverington (2011) has suggested that Martian outflow channels and associated terminal basins are of volcanic origin, arguing against their hydrous formation in Hesperian and Amazonian periods. He points that permeability (ability to pass through fluids) values of Martian regolith employed by "wet" hypotheses are unrealistic, as well as the fact that outflow channel heads are often found in highlands, while aquifer outbursts generally should be expected at low elevations. Martian outflows are also found to be different from equivalent landforms on Earth: there are no fluvial deposits along the shores, and terminal basins lack sediment in deltas. There is also little mineralogical evidence of the presence of hydrated minerals in the outflow channel areas. Finally, there is no evidence that water was ever available on Mars in as much volume as that required to incise the channels.

Channels and valley networks are observed to form in dry environments, e.g. over 200 complexes on Venus, revealed by the Magellan robotic space probe (Baker et al. 1992). Morphologically, they found to resemble Martian sapping channels (Komatsu et al. 2001). Among the hypotheses proposed for their formation are incision by silicate lava flows, or even exotic lavas of sulfur and carbonates.

The origin of RSL, discussed in §3.7, is not confirmed with certainty, and proposed interpretations include dry processes, such as mass wasting and CO_2 sublimation. Cryovolcanism has been suggested as one of the triggers for gullies formation, implying that they reflect conditions in the Martian crust instead of being indicative of fluvial activity on the surface (Gaidos 2001).

6. CONCLUSION

Since the beginning of the series of JPL and NASA Mariner missions in the second half of the twentieth century, a wealth of evidence has been collected, favoring presence of wet environments in the Martian past, especially in the Noachian and early Hesperian periods. Martian geomorphologic features dated ~ 4 Gya reveal the appearance of impact-induced hydrothermal systems, valley networks and hydrous weathering of rocks, followed by catastrophic flooding events that incised extensive outflow channels. Many of the features resemble those produced by fluvial activity on Earth. The existence of vast ocean in the northern lowlands of Mars is supported by numerous evidence of geomorphological and mineralogical character.

Alternative, dry interpretations are available for some of the evidence presented thus far, e.g. outflow channels being of volcanic origin, gullies and RSL, created via cryovolcanism and dry mass wasting, and others. It is difficult, however, to allow for a dry Mars extreme primarily due to the following reasons. Many of the microscopic mineralogical features observed, such as the presence of phyllosilicates, require hydrous activity, at least below the surface. If subsurface aquifers are an accepted phenomenon on Mars, the physical property and the presence of salts, combined with numerous past impact events, virtually guarantees the existence of impact-induced hydrothermal systems, in at least some of the Martian landforms, e.g. basins and craters. This may have happened at least intermittently. More over, the widespread volcanic activity that occurred on Mars during the Hesperian period may have also been the trigger for geothermal heat induced hydrothermal systems, if combined with subsurface aquifers. These systems may even re-appear at the present time. It is difficult to reconcile dry Mars extreme with the presence of sedimentary landforms, such as Gilbert-type deltas and alluvial fans, associated with lowland closed landforms. Even if there are no terrestrial analogues for some of the features observed, it should not be excluded that Mars may host unique hydrous processes.

Conditions favoring wet environments might have been created intermittently, by the change of Mars' obliquity, impact events or volcanism during the Noachian period (Carr & Head 2010). The whole set of evidence collected thus far is easier to be reconciled with the concept of Mars being wet at least during the Noachian period. The absence of widespread fluvial activity on the surface during the later periods is supported by our recent findings on the strength of solar wind erosion via O^+ pickup, as well as our current understanding of the time constraints and the reasons for the cessation of Martian dynamo.

Many open questions still remain, and conditions during the early history of Mars are largely uncertain. Liquid water may still be present on the Martian surface today, in the form of brines due to their depressed eutectic point or, perhaps, even in the pure form in areas where geothermal heat may still be available, such as Olympus Mons or the slopes of major volcanoes. This is supported by the fact that Martian volcanoes are found to be dormant, however still may return to activity at the present time, as they have done during the late Amazonian (Neukum et al. 2004). As liquid water is a prerequisite component for the development of all lifeforms here on Earth (Rothschild & Mancinelli 2001), continuing our efforts with exploration missions to Mars is significant from both astrophysical and astrobiological perspectives.

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