The absence of an ocean and the fate of water all over the Martian history

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Key Points:

- The lowlands of Mars likely never hosted an ocean of water
- Liquid water never was available on the surface of Mars
- Water needed for exploration of Mars can be retrieved on nearby asteroids.

Abstract

Existing data returned in > 40 years of planetary missions to Mars provided a good basis to understand that liquid water hardly existed on the surface of the planet during its whole history. The presence of environmental indicators like unaltered jarosite and olivine deposited by the early volcanic activity can be seen as evidence that liquid water was never abundant nor widespread on the surface of Mars since the Noachian. There is a dramatic mismatch with the water equivalent volume of the outflow channels sources with the volume needed to form an ocean. The ubiquitous presence of large volcanoes, with their huge lava fields exactly where liquid water was claimed to be abundant during the Noachian age, makes now very clear that lava and not water was involved in the formation of the outflow channels and the fluvial networks. As a consequence, cheaper robotic exploration might be favoured with respect to the ambitious human exploration program planned for Mars. Unless enough water supplies will be brought to the equatorial regions from the poles through long pipelines, or from nearby asteroids through cargo ships, it will be very difficult to exploit the rich equatorial resources brought up from the mantle by the massive volcanism that characterized the early history of the planet. Digging deeply the equatorial regions searching for water would be too expensive, of uncertain reward, and thus unpractical.

1. Introduction

The observation of anastomosing networks of smaller channels and huge outflow channels has historically fueled speculations that once liquid water may have flowed abundantly on the surface of Mars to feed an ocean in the lowlands (Carr, 1987; Carr & Head, 2015; Carr & Head, 2019). However, it was already clear since the Mariner 4 mission how the low pressure of the atmosphere (Ingersoll, 1970), between 2 and 6 mbar recently confirmed by Curiosity rover measurements (Guzewich et al., 2016), does not allow liquid water to be stable on the surface of Mars (Leighton et al., 1965). Although such an instability is generally acknowledged, there were claims for evidence of water (Buhler et al., 2011;

Hobbs et al., 2016; Martha et al., 2017), despite valid arguments in favour of lava (Greeley et al., 1998; Leone, 2014, 2017; Leverington, 2006, 2011). It was even suggested that the outflow channels of Tharsis would have fed an ocean in the lowlands thought to exist at the frozen state until the Hesperian (Carr & Head, 2019). The evidence shows that the largest outflow channels spread from the volcanoes of Tharsis (Leverington, 2011), where the stratospheric height favours sublimation (Moyer et al., 1996). There is also evidence of lava mantling the lowlands as far as Chryse and Acidalia Planitia (Salvatore et al., 2010), which are the debouching locations of the Tharsis outflow channels. The olivine naturally contained in lava appears unaltered since the Noachian (Ehlmann et al., 2010; McSween et al., 2006a), as it can also be seen from the corresponding units in the geochronological map of Mars (Tanaka et al., 2014). The Noachian has always been regarded as the wet period of Mars (Carr & Head, 2010a) but the presence of unaltered olivine suggests a dry environment. So, it appears that Mars was dry even earlier than the Hesperian when the ocean was postulated. Thus, if water was not present during the Noachian to alter the olivine in the lowlands, it is very likely that this ocean never existed during the Hesperian. Although Mars is an objectively dry world, yet there are authors who claim that liquid water may currently exist to form gullies (Malin & Edgett, 2000) or recurring slope lineae (RSL) (Ojha et al., 2015). These claims were later dismissed and replaced by alternative hypotheses involving granular flows of sand (Dundas et al., 2017). Some authors suggested that water may have existed in the past for long periods of time from the Noachian to the Hesperian (Carr & Head, 2019), or even during the Amazonian (Cabrol et al., 1998), claiming different and favourable climatic conditions, or that conditions for liquid water were transient or time-limited (Wade et al., 2017). However, there are also authors who suggested that water never existed in its liquid state (Lin-Gun Liu, 1988). Several studies assuming a wide range of atmospheric pressures, a faint young Sun, and a denser CO_2 atmosphere, concluded that the climate of early Mars was cold (Forget et al., 2013; Wordsworth et al., 2013; Wordsworth et al., 2015). Several rovers were sent to Mars to verify the hypothesis that the impact craters were once filled of water to form paleolakes (Cabrol et al., 1998, 2009). The findings of Pathfinder at Ares Vallis (Foley et al., 2003; Rieder et al., 1997), Spirit at Gusev (McSween et al., 2006a, 2006b), Opportunity at Sinus Meridiani (Arvidson et al., 2006), and Curiosity at Gale crater (Payré et al., 2017), revealed andesitic and basaltic compositions or presence of specific minerals like tridymite (Morris et al., 2016) more consistent with volcanic (Sautter et al., 2015, 2016) rather than aqueous activity, even if thought to be transported there by putative fluvial processes (Le Deit et al., 2013). Indeed, Gale crater revealed to be just another lava filled crater (Gasparri et al., 2019) like Gusev (Greeley et al., 2005; McSween et al., 2006a) or Palos (Leverington, 2006). The cm-scale of the observed structures in the so-called sedimentary material, including conglomerates (Mangold et al., 2016) or mud-cracks found at Gale (Stein et al., 2018) are too small to justify 154 km of crater filled by water. The chemistry of the sedimentary material is igneous (Stolper et al., 2013; Ollila et al., 2014; Sautter et al., 2014, 2016; Schmidt et al., 2014; Cousin et al., 2017; Payré et al., 2017). As well as already occurred at Gusev, it is likely that evidence previously interpreted as fluvio-lacustrine processes is more consistent with volcanic activity instead (Martínez-Alonso et al., 2005). Conglomerates can also be formed by movement of lava flows and were already classified as “flow breccia” (Fisher, 1960). These findings, coupled to the constraint of the upper limit for the alteration of olivine into serpentine at relatively low temperature (Oze & Sharma, 2007), already raised doubts on the total duration of the stability of liquid water on

the surface of Mars bringing down the estimates to 10,000 years (Grotzinger et al., 2015). Also, the jarosite found at the Opportunity landing site indicates total dry conditions on Mars (to much less than 10,000 years) because it is a mineral that rapidly decomposes in ferric oxyhydroxides in humid climates (Madden et al., 2004) thus favouring the hypothesis of volcanic processes (Hynek et al., 2002) for the formation of the hematite found in Sinus Meridiani. The presence of phyllosilicates (Carter et al., 2015; Ehlmann et al., 2011), claimed as the evidence of liquid water on the surface of Mars (Bibring et al., 2006), showed scarce or no correlation with the lowlands where the ocean was supposed to exist. Furthermore, these phyllosilicates show no correlation with the outflow channels where liquid water was supposed to flow abundantly. So, other mechanisms of formation alternative to surface aqueous processes should be invoked or that aqueous processes must have occurred under the surface of Mars to keep into account the environmental indicators (i.e. unaltered olivine, jarosite). The giant impact event that formed the Martian dichotomy must have removed much of the primordial atmosphere and part of the water that survived after the accretion (Leone et al., 2014). The remaining water was then lost to space (Gillmann et al., 2011; Kurokawa et al., 2014; Krasnopolsky, 2015; Villanueva et al., 2015) through degassing from a still wet mantle (Balta & McSween, 2013; Leone, 2017). Today the amount of water present on the surface and in the atmosphere is nearly negligible. Water is in the order of 1 ppm during winter (Lewis, 1996), with a maximum of ~ 200 ppm (consistent with the maximum amounts of 60-70 precipitable microns) found during the northern summer (Trokhimovskiy et al., 2015) when the CO_2 polar cap retreats and releases its annealed content of water in the atmosphere.
On the basis of the knowledge acquired in > 40 years of missions to the Red Planet this paper will make a scientific case for the fate of past water on Mars explaining why the planet never had an ocean and appears so dry today.

2. Sources and sinks of water

The analysis of all the possible sources and sinks of water since the initial accretion of the planet is important to estimate the potential global and total inventory that Mars may have ever had. Considering both hypotheses of local source (from planetesimals along the orbit) and distal source (from the asteroid belt and comets), Mars had less initial water than the Earth, a global equivalent layer (GEL) of 600-2700 meters (Lunine et al., 2003). Measurements of volatiles in the coma of the comet 67P/Churyumov-Gerasimenko showed how the contribution of cometary water to Earth and Mars was minor than 1% (Marty et al., 2016) also taking into account the possibility of a different impact flux for the two planets (Quintana & Schultz, 2019). The deuterium/hydrogen (D/H) ratio of 5.5 standard mean ocean water (SMOW) estimated for Mars (Owen & Tobias, 1992) was essentially confirmed as order of magnitude by the value of ~ 6 SMOW obtained by in situ observations (Webster et al., 2013). Variations between 6.2 and 7.1 SMOW corresponded to a loss to space of 1200 m of GEL and probably occurred in the first 500 Ma (Krasnopolsky, 2015). The loss of water during the pre-Noachian ranged between 41 and 99 GEL at ~ 6 SMOW, higher than the 10-53 GEL that occurred during the remainder of the whole Martian history; the remaining inventory of water was about 20-30 GEL on the surface and 100-1000 GEL underground (Kurokawa et al., 2014). The latter thought as enough water to carve the outflow channels and the fluvial networks (Lunine et al., 2003).

The polar caps, the atmosphere, and the permafrost of the mid-latitudes were suggested as a possible reservoir for 35 m GEL of water (Christensen, 2006). It was even suggested that a single impact event produced by an impactor of 250 km of diameter may have freed 50 m GEL of water in the atmosphere to fall back down as rain for decades to millennia (Segura et al., 2002). Impactors of this size were recorded for most of the pre-Noachian and Noachian (Carr & Head, 2010b). Thus rain should have been available since the Noachian but this is at odds with the lack of alteration of the olivine seen in the geological units of Noachian age. The lack of specific mineral deposits that require abundant oxygen and weathering, like bauxite, is another sign of the absence of meteoritic waters during the Noachian (West & Clarke, 2010). Assuming 2 wt% of water in magma, which is perfectly reasonable and within estimates made for similar compositions on Earth (Ushioda et al., 2014), and assuming that 120 m GEL degassed only for the build-up of Tharsis with the potential formation of a CO_2 atmosphere estimated at 1.5 bar between the Noachian and the Hesperian (Phillips et al., 2001), there must have been no more water than 155 GEL of total inventory summed to the ≈ 35 GEL currently estimated in the permafrost of the polar regions (Christensen, 2006). These estimates about past water might even be too optimistic because the current low atmospheric pressure may have already been present since the early ages of Mars due to the erosion by primordial impacts (Melosh & Vickery, 1989). This hypothesis includes the giant impact that formed the Martian dichotomy, regardless whether occurred in the northern (i.e. Wilhelms & Squyres, 1984) or in the southern hemisphere (i.e. Leone et al., 2014). Several studies of isotopic hydrogen showed how Mars lost much of its water already in its first 500 Ma (Gillmann et al., 2011; Kurokawa et al., 2014; Krasnopolsky, 2015; Villanueva et al., 2015). Impacts eroded the atmospheres of the terrestrial planets and particularly the giant impacts seriously dehydrate planets (Ahrens et al., 2004). Complete loss of structural water in serpentine may have occurred from accretional impacts already at ~ 3 km s^{-1} (Lange & Ahrens, 1982). The southern polar giant impact (SPGI), for example, was modelled with a giant impactor of 1600 km of radius, 80% of iron in radius, hitting Mars at ~ 5 km s^{-1} between 4 Ma and 15 Ma after CAI (Leone et al., 2014). Such a huge impactor was still barely sufficient to form the Martian dichotomy but its effect was undoubtedly so devastating that it must have reduced further any remaining water after the accretion. Furthermore, the effect of solar wind erosion must be added to the erosion of the impacts. Available estimates account for additional removal from 0.2 to 4 mbar of CO_2 and a few cm of water (Barabash et al., 2007). Combined, impact and sputtering processes may even account from 95 to 99% of the primordial atmosphere (Brain & Jakosky, 1998). The strongest phase of volcanism that Mars had in its first 500 Ma, as consequence of the SPGI, then might have replenished some CO_2 but degassed any remaining water in the mantle as final process (Leone, 2017). This is consistent with the analysis of the shergottites formed by melting of an original wet mantle that degassed over time (Balta & McSween, 2013). Water is lighter than CO_2 to be retained in an environment characterized by low gravity and low atmospheric pressure. All these arguments explain why Mars always had an unfavourable environment for the survival of an ocean of liquid water during its whole history.

3. Arguments claiming past presence of water

Several claims of evidence about past existence of water have been done on the basis of the geomorphologic interpretation of mudcracks, topographic features like shorelines, fluvial networks, gullies, recurring slope lineae (RSL), or the mineralogical interpretation of phyllosilicates, hematite, carbonates, perchlorate salts, and secondary veins of calcium sulphate, or claims of direct radar observations in both equatorial and polar regions. At last, presence of water was found in zircon grains present in Martian meteorites. The majority of these claims attempted to extrapolate at large scale some findings at small scale, which is totally unrealistic, and will be thoroughly reviewed in the following sections.

3.1. Geomorphological arguments

The presence of a past ocean in the lowlands of Mars was suggested on the basis of the interpretation of the Arabia and Deuteronilus gradational unit contacts as potential shorelines (Parker et al., 1989). Subsequent observations of the topographic profiles along the contacts provided little support to the potential surface of a sea level favouring a volcanic origin instead (Carr & Head, 2003). This mismatch between topography and potential shoreline was tentatively explained through a possible true polar wander (TPW) (Perron et al., 2007), or through the emplacement of Tharsis (Citron et al., 2018), or through the emplacement of the Vastitas Borealis Formation (VBF) (Ivanov et al., 2017), the latter two hypotheses being essentially based on volcanic processes. Furthermore, the paucity of coastal landforms (Ghatan & Zimbelman, 2006) suggested that the putative shorelines might also be ascribed to the original emplacement of the Martian dichotomy (Erkeling et al., 2015), or to the possibility that such an ocean would have been completely frozen (Carr & Head, 2019).

The fluvial networks have always been interpreted as formed by flows of water originated mainly by ground sapping rather than surface runoff (i.e. rain) (Baker, 2001). Although it was recognized that some of these fluvial networks required huge amounts of water, if compared to their terrestrial counterparts, there was lack of understanding on how such amounts of water were released from the ground (Baker, 2001). Some authors invoked volcanic heating from rising dykes cutting through a shallow cryosphere (Bargery & Wilson, 2011) or environmental warming due to favourable obliquity (Carr, 2012) in order to melt the ground ice. A possible origin for the ground ice was proposed as “outgassed water entombed as frost, snow, and ice during heavy bombardment” (Brakenridge, 1990). Being located in the ancient cratered regions of Mars, it was suggested that the origin of the valley networks might be quite old, probably since the end of the late heavy bombardment (Brakenridge et al., 1985). Hydrothermal systems produced by impact melting were also invoked to form the fluvial networks, then ice covered the rivers allowing water to stay liquid even in a cold environment. (Brakenridge et al., 1985). Such an hypothesis did not need any significant climatic change from the current status, thus implying that the environment of the surface of Mars was also thought to be cold and with a thin atmosphere like it is today. It was also acknowledged that some fluvial networks and the main outflow channels spreading from the high volcanoes of Tharsis and Elysium can only have a volcanic origin, thus carved by lava, because heated ice would sublime rather than melt at atmospheric pressure well below the triple point of water (Carr, 2012). The volcanoes of the Tharsis and Elysium regions have heights of ≥14 km, corresponding to the stratosphere of Mars, where sublimation or evaporation rather than melting are the dominant conditions (Moyer et al., 1996). Even at the ground height of the Phoenix landing site, ice sublimated in about 4 sols without showing any liquid form of water or significant erosional activity (Smith et al., 2009).

The presence of gullies in several steep slopes of various locations on Mars was claimed as the evidence of recent activity by liquid water, invoking once more an ice barrier to prevent liquid water from sublimation (Malin & Edgett, 2000). Follow-up studies considering a wide range of possible processes, such as insulation (Mellon & Phillips, 2001), geothermal heating (Hartmann, 2001), cryovolcanism (Gaidos, 2001), brine seeps (Knauth & Burt, 2002), eruptions of liquid CO_2 (Musselwhite et al., 2001), and granular flows (Treiman, 2003), concluded that liquid water was not likely involved in the formation of the gullies (Treiman, 2003).

A similar conclusion was reached years later for the RSL as well (Dundas et al., 2017). A phenomenon of water retention by perchlorate salts called “deliquescence” was put forward to explain the seasonal change of low-reflectance features, exactly the RSL, which would be forming on present-day Mars (Ojha et al., 2015). These features were explained later with the same granular flows of sands that explained the gullies (Dundas et al., 2017). The claim of possible current activity of liquid water on seasonal timescale (Ojha et al., 2015) was based on a theoretical effect of salts that were studied at a fixed pressure of 7 mbar (Altheide et al., 2009) and on a range of theoretical conditions of temperature and concentration of salts per volume of water that were never verified yet on the surface of the planet. Furthermore, the RSL in Palikir, Horowitz, Hale, and Coprates Chasma are all located in terrains with very low contents (2 mass percents) of water equivalent hydrogen (WEH) as shown in the Mars Odyssey neutron map (Christensen, 2006).

3.2. Mineralogical arguments

The presence of phyllosilicates and clays was claimed as evidence of aqueous presence on Mars (Bibring et al., 2006). Spectra of submarine terrestrial clays were compared to available CRISM spectra of Martian clays, the results showed that the largest group of clays (smectitic samples with FeO/MgO ratios ≈ 10-30, supposedly between submarine and low-submarine environment) were found on the Noachian highlands of Mars (Michalski et al., 2015) where no ocean was ever reported or possibly be present. Even the presence of smectite is not unambiguously the proof of formation in ponding water (Ehlmann et al., 2013) and might be the result of thermal alteration by lava instead (Che & Glotch, 2014). Another possibility is that phyllosilicates were formed by >400°C-hot hydrothermal fluids under the surface (Ehlmann et al., 2011), where the lithostatic pressure of the rocks still allows the stability of liquid water, and then exposed as outcrops upon erosion or transport by subsequent lava flows. The geochemistry of the clays analysed at Yellowknife Bay shows little evidence for chemical weathering during the transport into the basin (McLennan et al., 2014), so that less support for aqueous processes into Gale crater is available.

Although thermal oxidation of magnetite-rich lavas was included among the alternative hypotheses, the presence of crystalline hematite (α-Fe_2O_3) over an area of 350 by 350-750 km in size located at Sinus Meridiani was preferred as mineralogic evidence for large-scale water interactions (Christensen et al., 2000). Subsequent global mapping revealed detection of crystalline hematite in basaltic sediments at Sinus Meridiani, Aram Chaos, and along Valles Marineris (Christensen et al., 2001). In fact, a subsequent study confirmed that the crystalline hematite in Terra (Sinus) Meridiani may have been formed by thermal oxidation precipitated from circulation of fluids in a 600 m-thick stack of pyroclastic deposits (Hynek et al., 2002). The Opportunity rover discovered that the hematite signature was associated to 1-5 mm small concretions in aeolian deposits dominated by abundant pyroxene-rich basaltic material (Arvidson et al., 2006). These findings revealed nothing that can justify a large-scale or global layer of water so far away from the lowlands where the ocean was postulated.

The search for carbonates started already at the end of the 80's with ground-based observations of the Syrtis Major-Arabia-Hellas regions of Mars (Blaney & McCord, 1989), KAO observations of dust on the surface (Pollack et al., 1990), and the analysis of Mariner 6/7 spectral data (Calvin et al., 1994). Despite a claimed detection of a strong feature at 5.4 micron consistent with hydrous magnesium carbonate (Calvin et al., 1994), the spectroscopic identification of carbonates on the surface of Mars revealed quite uncertain and elusive (Bandfield et al., 2003). The light-toned outcrops at Paso Robles of Gusev crater were sulphates likely formed as volcanic hydrothermal fumarolic condensates (Yen et al., 2008) whilst the 16 to 34 wt% content of carbonate found in the 5 m Comanche outcrop (grain sizes of 0.5 – 1 mm) of the Columbia Hills (Morris et al., 2010) is too small to support the hypothesis of an extensive aqueous process (i.e. paleolake) that would be filling the crater. The finding at the Phoenix landing site is even smaller with a content of $CaCO_3$ of 3-5 wt% in the Wicked Witch sample (Boynton et al., 2009). The various analyses made during the Phoenix mission showed mineral phases (i.e. smectite, montmorillonite) formed at high temperatures (Smith et al., 2009), which only lava flows can explain in the cold environment of Mars. The findings at Nili Fossae showed spectral features of Mg-carbonate scattered over an area of 50 km but with too low spatial resolution to distinguish small quantities and the finding was never confirmed at global scale on Mars (Ehlmann et al., 2008). The scarcity of carbonate on the surface of Mars was tentatively justified by possible volcanic emissions of SO_2, which might have been abundant on Mars as well as on Earth, thus implying an unnecessary presence of worldwide acidic waters (Halevy & Schrag, 2009). The scarce findings of carbonates are not indicative of a past dense atmosphere but rather of a limited availability of water in little and localized hydrothermal environments (Niles et al., 2013).

The presence of perchlorate salts was also considered as the evidence of the activity of water or as a factor favouring the stability of liquid brines on the surface of Mars (Chevrier et al., 2009; Cull et al., 2010; Marion et al., 2010). However, these studies did not even consider the possibility that salts could also be deposited from the vapours emitted during volcanic degassing (Naughton et al., 1974; Glotch et al., 2010) known to occur in the early history of Mars. Nor that formation of perchlorates could even be an ongoing process, produced photochemically on Cl minerals without atmospheric chlorine or aqueous conditions, occurring wherever chloride-bearing mineral phases exist (Carrier & Kounaves, 2015).

At last, water was found in zircon grains present in Martian meteorite NWA7533 aged about 4.43 Ga (Nemchin et al., 2014). However, the isotopic values of $\delta^{18}O$ between 3.5 of the SNC and 7.5 of the zircons contained in NWA7533 and of the decarbonated sample of the meteorite NWA7034 (Agee et al., 2013) likely indicate that it was just mantle water. The higher values of $\delta^{18}O$ (>9) in Jack Hill zircons (JHZ) showed that the Earth's crust coexisted with liquid water whereas values of $\delta^{18}O$ between 5 and 6 indicate zircons crystallized from the mantle (Cavosie et al., 2009).

3.3. Radar observations

Claims of underground ice through SHARAD sounding radar analysis (Karlsson et al., 2015; Orosei et al., 2018), although at the pole might be expected, remained ambiguous at best because the dielectric constant for water used in the experiments (k = 3.15) is not too far from that of dacitic lava (k = 3.80). The dry tephra in the upper layers of Arsia Mons showed k = 2.90 (Ganesh et al 2019). Depending dramatically on the porosity of the geologic layers, the higher the porosity the lower the value of the constant for the same material (Russell & Stasiuk, 1997), the radar sounding remains a method of investigation quite uncertain. Even basaltic lava, if highly degassed and thus very porous, might have a low dielectric constant similar to that of water. Thus, basaltic tephra deposits would be difficult to distinguish from eventual water annealed in the cage of frozen CO_2 forming the polar caps. The mid-latitude regions selected for the experiments of radar sounding were the Mamers Valles (23°E – 39°N and 28°E – 40°N) and Reull Vallis (103°E – 41°S and 105°E – 43°S) (Karlsson et al., 2015), both located in volcanic terrains covered by an eolian blanket of volcanic ashes transported by the wind and characterized by porosity comparable to that of tephra that may vary from a few cm to hundreds of meters of thickness depending on the topography (Leone, 2016). Both regions have much lower WEH than the polar regions (Christensen, 2006).

4. Arguments in favour of lava

The strength of the arguments in favour of lava comes essentially from: a) the weakness of the arguments in favour of water discussed so far; b) the geomorphological observations of the outflow channels spreading directly from the main volcanoes of Mars (Leverington, 2011; Carr, 2012; Hopper & Leverington, 2014; Leone, 2014, 2016, 2017, 2018); and c) the widespread presence of unaltered olivine (Ehlmann et al., 2010). The environmental problems for liquid water on Mars were already well known before the Viking missions (Leighton et al., 1965; Ingersoll, 1970). Even the latest rover missions did not find compelling evidence of liquid water within the craters but just interpretation at large scale of mineralogy of ambiguous origin observed at very small scale. In fact, the mineralogy found in these craters showed scarce sedimentary outcrops, mostly at cm-scale (Mangold et al., 2016), and prevailing basaltic composition (McSween et al., 2006b; Stolper et al., 2013; Ollila et al., 2014; Schmidt et al., 2014; Grotzinger et al., 2015; Sautter et al., 2015, 2016; Cousin et al., 2017), including tridymite at Gale (Morris et al., 2016), thus suggesting infilling of lava rather than water because tridymite is a mineral that forms at temperatures above 850 °C (Morris et al., 2016). Regardless whether autoctonous or alloctonous, tridymite is just one of the many pieces of evidence about volcanic activity. The geochemistry of the crater infill is of volcanic origin, despite the wide and inappropriate use of the term sedimentary that mainly recalls deposition in water in the mind of a geologist. It is now clearly evident that Gale crater was filled by lava coming from Tyrrhenus Mons (Gasparri et al., 2019). Nothing different than something already observed at Gusev (McSween et al., 2006a, 2006b), Palos (Leverington, 2006), or elsewhere on Mars (Leone, 2016). After the initial post-Mariner (Leighton et al., 1965) and post-Viking views (Baird & Clark, 1984), there is now a growing literature that shows compelling evidence of lava as the main fluid carving the outflow channels and the fluvial networks (Leverington & Maxwell, 2004; Leverington, 2004, 2007, 2009, 2011; Hopper & Leverington, 2014; Leone, 2014, 2016, 2017, 2018). Such evidence is also supported by the scarcity of the sources which should have provided the amounts of water necessary to fill the lowlands with enough water to form an ocean.

4.1 Volumetric comparison among outflow channels, fluvial networks, and putative sources of water.

The volume of terrain removed to form Valles Marineris and Kasei Valles was estimated at 12.90×10^6 km^3, a lower estimate that includes the lava filling of the two channels (Leone, 2014). Two or three orders of magnitude of volume of water would be realistically required to carve the outflow channels (Andrews-Hanna & Phillips, 2007; Leone, 2014; Leverington, 2011), something between 90 m GEL and 9000 m GEL. If such a volume of water was concentrated underground on the flanks of the Tharsis volcanoes over the whole area of Noctis Labyrinthus, the column would be ~ 6.24 km deep at an unrealistic value of porosity of 100%, or fractional void space (FVS) of 1. The average FVS of basaltic lava on Earth is 0.25, Mars has essentially a similar basaltic composition, and decreases exponentially with increasing lithostatic pressure (Head & Wilson, 1992)

$$V_v = V_{v0} \exp(-\lambda P) \qquad (1)$$

where V_v is the porosity at depth, the lithostatic pressure is P, V_{v0} is the surface porosity, and λ is a constant equal to 1.18×10^{-8} Pa^{-1} independent of the gravity (Leone & Wilson, 2001). The lithostatic pressure of basaltic lava at depth of 6.24 km on Mars would be ~ 67 MPa and the corresponding FVS would be reduced at 0.11. Less space would thus be available to accommodate water in the putative aquifer. Another study obtained essentially similar results with FVS 0.16 at the surface and 0.04 at 10 km of depth (Hanna & Phillips, 2005). There are also problems of unrealistic permeability, ~ 300 times larger than those associated to the most permeable aquifers on Earth, as already found at Mangala Valles (Ghatan et al., 2005). The proposed mechanism of aquifer recharge from the south polar basal melting (Russell & Head, 2007) is difficult when the outflow channels are located at too high elevations (Carr, 2002; Leverington, 2011). This is particularly evident at Noctis Labyrinthus and Valles Marineris (Leone, 2014). A model of snowpack melting that would recharge the aquifers from above was also suggested (Carr & Head, 2003) but the cold conditions would also prevent water from accessing the subsurface (Clifford, 1993; Russell & Head, 2007). All these problems suggested that water is not a viable fluid to explain the formation of Valles Marineris and of the other outflow channels (Leverington, 2011; Leone, 2014). Volumetric discrepancies were found at Ladon Valles, the channel shows a minimum volume of ~ 4000 km^3 whereas the source can account for only ~ 600 km^3, and at Mamers Valles, the formation of which would have required a column of pure water 7.5 km deep at an unrealistic 100% constant porosity all over the aquifer (Leone, 2016).

5. Discussion

The ubiquitous presence of unaltered olivine and jarosite on Mars, including the low ratio of oxygen isotopes found in Martian zircons, is the best evidence that an ocean of liquid water never existed. These minerals are both environmental and chronological indicators, they show no alteration in dry conditions and the low oxygen isotope ratio indicates mantle water rather than surface water. The contact of water, either liquid or frozen, alters the olivine in 100-10,000 years (Oze & Sharma, 2007). The jarosite is even quicker as it quickly decomposes into ferric oxyhydroxides in presence of humidity (Madden et al., 2004). The presence of phyllosilicates and other mineralogical phases, thought as the evidence of running water on the surface, suggests that an alternative explanation of volcanic origin under the surface of Mars may exist.

The hypothesis of tsunami resurfacing events produced by an impact on Mars during the Hesperian (Rodriguez et al., 2016) was put forward in both the cases of past cold and a warm climates conditions opening the possibility that such events could have happened in a briny and salty ocean surviving for 2.7 millions of years at least (Turbet & Forget, 2019). Such a long duration of a Martian ocean is practically impossible. The scarce or absent alteration into serpentine of the olivine deposited during the Noachian in the lowlands (Ehlmann et al., 2010) and in the highlands (McSween et al., 2006b), as can also be observed from the geo-chronological map of Mars (Tanaka et al., 2014), rules out any possibility that such an ocean ever existed. Depending on warm or cold conditions, the olivine naturally contained in basaltic lava gets altered at the contact with water after 100 or 10,000 years (Oze & Sharma, 2007). Subsequent deposition of fresh lava in the lowlands during the Hesperian (Salvatore et al., 2010) or afterwards does not change the situation. The jarosite just deposited with lava would have quickly formed ferric oxyhydroxides from the humidity that such an ocean would have produced in its interaction with the Martian atmosphere (Madden et al., 2004). At the proposed timescales of millions of years for the existence of the putative ocean in the lowlands of Mars (Rodriguez et al., 2016; Turbet & Forget, 2019) it is clear that traces of alteration would have certainly appeared. As a term of comparison, the olivine deposited in submarine environment on Earth during 1.9-0.5 Ma shows unambiguous traces of alteration (Garcia et al., 2016). So, the Earth and Mars did not have a similar wet past as postulated before (Gulick & Baker, 1989; Paige, 2005; Carr & Head, 2010a, 2010b).

How can be explained such a sharp environmental difference between Mars and the Earth? The Earth was able to retain its water while Mars not, this is an incontrovertible fact that we can still observe today. The low atmospheric pressure of Mars favours degassing from magma already at higher depth compared to the Earth (Bargery & Wilson, 2010). As a consequence, Martian water was likely lost to space and there is evidence that it may have already happened in the first 500 Ma, corresponding to thePre-Noachian – Noachian ages of the Martian history (Gillmann et al., 2011; Kurokawa et al., 2014; Krasnopolsky, 2015; Villanueva et al., 2015). Both olivine and jarosite do not show traces of aqueous alteration at global scale (Madden et al., 2004; Ehlmann et al., 2010) and this is a strong evidence that even a humid climate never existed since the Noachian on Mars. Any degassed water from the strong magmatic activity which started already in the Pre-Noachian never came back to the surface as rain or stationed in the atmosphere as humidity. It is likely that the arid and cold conditions that we see today on Mars might have been already established since then. Regardless of the presence of salts and brines, which are not as widespread as it would be expected from the presence of a global layer of water, it is really hard to imagine any presence of water able to feed the putative Martian ocean only from volcanic sources as shown by the outflow channels spreading from them. It is more a problem of low atmospheric pressure, rather than low surface temperature, which prevents the stability of liquid water on Mars. With these conditions, even ice would sublime as soon as it is brought to the surface. Liquid water would have had no chance of survival, even less of eroding the hard basaltic bedrock on which were carved the outflow channels.

5.1. Implications for the Human Exploration Programme and possible cost-effective solutions

Among the various resources needed for the Human Exploration Programme (HEP) the most important is water, that is also why particular emphasis was put on the search for water in the Mars Sample Return (MSR) programme (Beaty et al., 2019). The estimates of the daily need of drinking water for an astronaut varies from at least 1 or 2 litres (Kerwin & Seddon, 2002) to 3.5 litres (Sanchez & McInnes, 2011) per day. Even with the current recycling systems, water is still consumed for the production of breathing oxygen while hydrogen is dumped to space (Shimada & Fujii, 2012). A study of the water needs per astronaut on the ISS has estimated a daily consumption of 14.2 litres with a specific mass consumption varying from 10 to 20% of the total (Bobe et al., 2007). Water is also important for its use as propellant, better than the carbon monoxide-oxygen combination, and for radiation shielding (Lewis, 1996). The amount of the possible MSR or surface operations and their sustainability with time will depend on the availability of in-situ propellant to send back material to Earth. So where shall we go to find this precious resource on Mars? If the prospections of water under the polar caps with SHARAD will be successful, the polar regions are the obvious choice. Equally obviously, a possible misinterpretation should be taken into account. Even in the successful case of significant finding, transporting water where it is needed by the various operations on the surface would require a long network of pipes all over the planet. Or, at least, connect the poles to a first primary base where to start the initial operations. It could be possible to sample (and launch) directly from the polar regions but the samples would be indicative only of the geologic situation of the place where they are taken without counting the extra propellant needed to move into more favourable orbits to readjust the trip towards the Earth. An expansion towards the equatorial regions seems inevitable in the long run, now the question is how to support this expansion in the meanwhile. Alternative sources of water are needed to support the operations and the ongoing prospections. Sending water directly from Earth has a prohibitive cost, due to its high gravity (Sanchez & McInnes, 2011), so we need to find sources much closer to Mars. Despite the various claims seen so far, the water resources available on Mars seem scarce and unreliable for a long-term and sustainable HEP.

A viable source of water might be available from the asteroids, Mars-crossing (MCs) Amors in particular, with their low delta-V (Lewis, 1996). The MCs Amors contain a significant fraction (50-60%) of water-rich carbonaceous asteroids (Lewis, 2014) and their spectral properties can be studied through available Sloan data (Carry et al., 2016). In order to support the Martian exploration and future settlements, the strategic idea would be using the low delta-V of the MCs asteroids and of the Martian satellites to deliver by cargo ships the water extracted from their surfaces where is needed on Mars. This is a different and more flexible approach than focusing only on the surface of Mars for the search of water. Delta-V maps of many asteroids are already available and improved rocket technologies have made this approach more feasible (Ventura et al., 2005). Furthermore, the advantage in this approach is that the lack of water on the surface of Mars would not be a problem for the support of the initial stages of the HEP and the subsequent necessary prospections. Water supplies can be selectively delivered in any place of the equatorial regions of the planet exploiting the orbits of the Phobos and Deimos satellites or any MCs asteroids. Even shepherding asteroids in Mars' orbit could be possible using the methods proposed for the Earth (Brophy et al., 2012). This requires a continued search and knowledge of the spectral properties of all the possible profitable asteroidal targets and their orbital periods (Elvis, 2014). Running the initial operations from low Earth orbit (LEO) to reach the MCs or the Martian satellites, with both intelligent logistics and use of energy, launching costs would fall down to just one dollar per kilogram (Lewis, 1996) from the previous 10,000 dollars per kilogram (Sanchez & McInnes, 2011). However, exploiting the MCs asteroids is not an unlimited resource, using it well is very important. It takes a long time to replenish a region once it is depleted, something like millions years of natural orbital evolution (Sanchez & McInnes, 2011). Unless we decide to use the available Near Earth Asteroids (NEAs) to jump from asteroid to asteroid towards the water resources of the Asteroid Belt (AB) as a first step to harvest more abundant water resources. The C-type asteroids are mostly located in the outer half of the AB (Chapman et al., 1975). This operation would clearly be aimed at shepherding more water-rich asteroids from the AB to the inner solar system. This strategy could pay off in the long run and would be more cost-effective than just prospecting Mars for years, other profitable mineral resources worth billions of dollars plus water would be available for future Mars operations (Lewis, 1996). Enough resources to support the exploration of Mars and the Moon for long time if a good supply chain will be established.

6. Conclusion

A different picture thus arises with respect to the one that prevailed during the past decades. Mars was not a warm and wet planet but was actually a cold and dry planet. It was dominated by a strong volcanic activity during its early history, shown by the extent of the lava fields forming the largest volcanic provinces of the solar system. Mars was characterized by the loss of any remaining water after that the southern polar giant impact (SPGI) severely dehydrated the planet and triggered its massive volcanism. The SPGI has its advantage with respect to any other impact hypothesis because better explains the distribution of the volcanoes on the planet and the perfect timing of the decline of the magnetic field with the waning of the peak volcanism. This phase of peak volcanism deposited the bulk of the large volcanic edifices and their lava fields containing the olivine that we still see today. It is very unlikely that any ocean may have existed before this event took place, Mars was a planet still very hot due to the decay of the short lived radiogenic elements such as ^{26}Al and ^{60}Fe.

In conclusion, according to the available results in the Martian literature, no ocean could have existed in the lowlands or anywhere else on the surface of Mars. In such a case, no tsunami events could have been existed in any possible climatic scenario because no ocean was ever present to host it on Mars. The fluvial networks and the outflow channels were formed by fluid lava flows that had rheological behaviour similar to water. The warm and wet planet as speculated so far is just a misconception that should not prevent the space agencies from future exploration. The planet is very rich of mineral resources that will become extremely precious when the resources available on Earth will be inevitably depleted. At that point, new techniques of extraction and delivery will make Martian mining economically convenient by using the Mars crossing asteroids and the moons of Mars as close bases. In the meanwhile, it would be good practice to have a map of the available resources on the planet. The scarcity or absence of water should not be seen as an obstacle to any future exploration. Robotic prospections will optimize the initial limited water resources that may come from the poles of Mars (if definitely confirmed) or from the nearby asteroids.

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