Mars: Formation and fate of a frozen Hesperian ocean

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Abstract

Late Hesperian-aged, circum-Tharsis floods interpreted to have formed by catastrophic release of groundwater cut large channels and debouched significant quantities of water into the northern lowlands of Mars. The floods are thought by many to have formed an ocean of significant volume and depth, encircled by contacts that have been interpreted as shorelines. Models of catastrophic groundwater release require a thick and continuous cryosphere with mean annual temperatures well below freezing much like those today. In this environment, the bodies of liquid formed by individual outflow events would have been very short lived, undergoing rapid freezing. We investigate the case where floods repeatedly flowed into the northern lowlands under climatic conditions that resemble those of the present day; the water from each flood froze in a geologically short period of time to form an ice layer. Successive ice layers accumulated to form an ocean-sized body of ice that filled the basin up to the -3650 contour, thereby enclosing a 110 m global equivalent layer (GEL) of water. Subsequent to the filling of the basin the ice slowly sublimated into the atmosphere to be lost to space or to accumulate in various surface and near-surface cold traps, such as the polar layered deposits. Where is this excess water today? The presence of the thick global cryosphere meant that only minor amounts of water were lost from the surface back into the global groundwater system. Approximately 20-30 m GEL of water is estimated to be at or near the surface today and exchanging with the atmosphere on geologic time scales (this includes the polar layered deposits and deposits elsewhere at depths less than approximately 80 m). Below the exchangeable reservoir is a non-exchangeable reservoir of unknown capacity. Present day loss rates to space fall far short of those needed to eliminate the mid-Hesperian ice ocean and those needed to cause the observed doubling of the D/H of the exchangeable reservoir since the mid-Hesperian. The discrepancy implies earlier loss rates must have been higher. Assuming a linear increase in loss rates because of the higher early EUV output of the Sun, we estimate that for a present inventory of 30 m GEL, 42 m GEL remains to be accounted for. Possibilities include greater dependence of losses of EUV than assumed, and enhanced losses during periods of high obliquity. In addition, large volumes of ice may be present near the surface at high latitudes outside the polar layered deposits as indicated by recent discoveries of ice layers in cliffs.

1. Introduction

The possibility that the northern plains of Mars could have once contained ocean-sized bodies of water has long been recognized (e.g. Baker et al., 1991; Lucchitta et al., 1986; Parker et al., 1989, 1993). Large outflow channels, widely interpreted as cut by floods, drain into the plains; the plains have low slopes and roughness (Kreslavsky and Head, 2000) comparable to terrestrial ocean basins; many features on the plains resemble sub-glacial terrestrial landforms and could have formed under a frozen ocean (Kargel et al., 1995); long, continuous breaks in slope surrounding the plains could be shorelines (Parker et al., 1993); widespread fluvial dissection of the highlands may imply an extended water source (see summary in Carr, 2006). More recently, Costard et al. (2017) and Rodriguez et al. (2016) have found geomorphic features that they interpret as evidence of impact-generated tsunamis.

The former presence of oceans has been suggested by two main lines of reasoning. First, high erosion rates and widespread valleys and lakes in the cratered highlands suggest that late Noachian Mars could have had a hydrologic cycle with evaporation from an ocean, precipitation on the ancient highlands to form the valley networks and drainage back into the northern lowlands basin (e.g. Baker et al., 1991; Craddock and Maxwell, 2002). Second, a precipitous drop in rates of erosion and valley network formation at the end of the Noachian has been interpreted to indicate that the climate changed from one that was warm and wet, or warm and arid (Craddock and Howard, 2002; Ramirez and Craddock, 2018), to an extremely cold and dry climate more like the present, and that a thick cryosphere developed during the transition (Clifford, 1993; Carr, 1996). Large outflow channels then formed, interpreted to be the result of massive eruption of groundwater trapped below the cryosphere (Carr, 1979; Andrews-Hanna and Phillips, 2007). The channels drained into the northern plains to form large sea or ocean-scale bodies of water that would then have frozen in the global cold and arid climate (Kreslavsky and Head, 2002a; Turbet et al., 2017). The size and fate of this later Hesperian-aged ice-ocean that formed contemporaneously with the outflow channels, according to this hypothesis, is the main concern of this paper. A possible earlier Noachian-aged ocean is mentioned only peripherally.

Almost everything about the proposed Hesperian ocean is controversial (see summary in Head et al. (2018)) including the cause, the sediments, their age, the climate, the extent, the seasonal variation, the extent of the cryosphere, the deposits on the plains, the extent of the outflow channels, the sources of the water, and the climate. Almost nothing is known about when they formed, accumulated, or froze entirely. Almost nothing is known about the role of impacts in either forming the outflow channels or in creating the cryosphere that eventually froze the volumes of water that eventually flowed into the northern plains.

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number, magnitude and timing of the contributing outflow events, whether the water would have quickly frozen so that any standing body of liquid water would have been short-lived, how compelling the evidence for tsunamis is, and where all the water subsequently went. Climatic considerations are a major source of skepticism that there could have been a long-lived liquid ocean in the Hesperian, one that survived long enough to erode topographically identifiable shorelines along its shore and to have experienced impact generated tsunamis. A long-lived, liquid, high-latitude ocean would require near-equatorial temperatures close to 273 K. Partly because of the less-luminous early Sun, greenhouse warming of a thick CO₂–H₂O atmosphere falls far short of that required to raise the effective surface temperature from the present 215 K to in excess of 273 K (e.g. Kasting, 1991; Haberle et al., 2017). The supplemental effects of other greenhouse gases, such as SO₂, CH₄, NH₃, H₂ and N₂O have also been studied, but for a variety of reasons all, either independently or in combination, fail to give the required long-lived boost in temperature (summarized in Haberle et al., 2017). Temporary warming as a consequence of large impacts has also been examined (Segura et al., 2008; Palumbo and Head, 2017; Turbet et al., 2017) but such effects are more likely in the Noachian, when impact rates were much higher, than in the Hesperian. Complete discussion of all the controversies is beyond the scope of this paper. We acknowledge that large amounts of water flowed into the northern plains during large floods but are skeptical that there was a long-lived liquid ocean. Alternatively, we propose that the water from each successive flood rapidly froze to form a layer of ice (Kreslavsky and Head, 2002a; Turbet et al., 2017) and that multiple floods resulted in accumulation of a long-lived, ocean-sized body of ice, but not an ocean-sized body of liquid water. We assume that the ice slowly sublimated as water was lost to space and as changes in obliquity caused redistribution of the water. The formation and fate of this body of ice is the main concern of this paper.

Parker et al., (1989, 1993) and Clifford and Parker (2001) identified several features encircling the northern basin that they interpreted as shorelines of an ocean. The youngest and most easily identifiable of these proposed shorelines (the Utopia shoreline, or contact 2) is closest to an equipotential surface (Head et al., 1999). In order to explore the validity of the Hesperian ocean hypothesis, we interpret this distinctive contact as marking the edge of a frozen ocean, and we assess the implications of this hypothesis. We re-estimate the volume enclosed by this shoreline in light of recent geologic mapping and THEMIS data. We then try to reconcile this ice volume with the present near surface inventory of water. We re-examine the amounts of water that could have been lost to sinks (such as to space and to groundwater), and the amounts gained from sources other than the interpreted ice-ocean. Again, our concern here is exclusively with the youngest and best preserved of the proposed shorelines (Contact 2 or the Deuteronilus shoreline). We recognize that there could have been additional, older shorelines of Noachian age that imply much larger volumes (Clifford and Parker, 2001), but these are not discussed. We are concerned here exclusively with the volume of the supposed Hesperian ice-ocean and where the water went.

We use the contrast between the present atmospheric D/H (Villanueva et al., 2015) and the D/H in sediments from Gale Crater (Mahaffy et al., 2015) as one constraint on how the near surface inventory of water may have evolved over time. The age of Gale crater is poorly constrained but crater counts on, and superposition relations of, the sediments in the central mound suggest that they are 3.6–3.8 b.y. old and straddle the Noachian–Hesperian boundary (Thomson et al., 2011). In contrast, the outflow channels and the sediments of the northern plains that were deposited by them are upper Hesperian in age (3 to 3.5 b.y. old) (Tanaka et al., 2005). The sediments at Yellowknife bay in Gale Crater unambiguously accumulate in a lake that may have been long-lived (Grotzinger et al., 2014). Our assumption that the waters from the later outflow channels would rapidly freeze may imply, therefore, a change in surface conditions between the early and late Hesperian, and this may not survive further scrutiny.

2. Present inventory of near-surface water

There is abundant evidence of unbound water near the martian surface, particularly at high latitudes. MOLA topography (Smith et al. 1999) and MARSIS and SHARAD data (Plaut et al., 2007; Byrne, 2009) indicate that the layered deposits at the two poles combined contain 17–22 m Global Equivalent Layer (GEL) (Lasue et al., 2013; Carr and Head, 2015). Ground ice has also been detected at latitudes above 60° outside the layered terrains by gamma-ray and neutron spectrometers (Boyon et al., 2002), by ground-penetrating radar (Mouginot et al., 2010), at the Phoenix landing site (Smith et al., 2009), in images of fresh impact craters (Byrne et al., 2009) and in a latitude-dependent mantle derived from mobilization of polar ice during cycles of increased obliquity amplitude (Head et al., 2003) and thought to contain a 7–70 cm thick water global equivalent layer (GEL) today (Kreslavsky and Head 2002b). Ice layers extending from near the surface to depths of 100 m have also been observed in cliffs at latitudes as low as 55° (Dundas et al., 2018). Mouginot et al., (2010) interpret the steep decrease in the 3.5–6 MHz reflectivity observed by MARSIS at latitudes greater than 50° as due to the presence of ground ice, which at these latitudes is stable a few meters below the surface under present conditions (e.g. Mellon and Jakosky, 1993). Mouginot et al., (2010) estimate that the radar is effectively probing to depths of 60–80 m and that at least 10⁶ m³, or 7 m GEL, of ground ice is present outside the polar layered deposits to these depths at latitudes greater than 50°.

Near surface ice may be present at even lower latitudes. SHARAD sounding has detected interfaces interpreted as the bases of extensive ice sheets in Utopia and Arcadia Planitiae that extend as far south as 38° (Bramson et al., 2017). Ice may also be present in the 30°–50° latitude bands in a meters-thick, dust-ice-rich mantle, interpreted to have been deposited during recent obliquity excursions (Head et al., 2003), and in linteated valley fill (Head et al., 2010), concentric crater fill (Levy et al., 2010), pedestal craters (Kadish and Head 2014), debris-covered glaciers (Plaut et al., 2009) and tropical mountain glaciers (Head and Weiss, 2014). Levy et al. (2014a,2014b) estimate that as much as 2.6 m GEL may be present near the surface in these bands. In summary, we estimate that 20–30 m GEL of water is present in the polar layered deposits and at depths shallower than 80 m in the regions surrounding the polar layered deposits extending down to 30° latitude. We recognize that in addition to the 20–30 m GEL of near-surface water, abundant unbound water (possibly hundreds of m GEL) may exist as ice cement and secondary ice within the cryosphere at depths greater than 80 m and as groundwater below the cryosphere (Clifford, 1993).

3. Ocean volume

Parker et al. (1989; 1993) were the first to suggest that various linear features around the northern basin were shorelines of a former ocean. They identified two contacts, an outer contact 1 and an inner contact 2 around the northern plains that they interpreted as shorelines. Subsequent acquisition of MOLA elevation data (Smith et al., 1998) enabled the ocean hypothesis to be tested more rigorously than had previously been possible. Head et al. (1999) used MOLA altimetry data to test whether the Parker et al. shorelines represented equipotential surfaces, and found that Contact 1 (~1680 m) ranged over 11 km and was, therefore, not likely to be a shoreline. Contact 2 (~3760 m) ranged over 4.7 km, but had extensive stretches that had much less variation and could be consistent with an equipotential surface representing a shoreline.

Carr and Head (2002) examined in detail the geologic relations, morphology and elevations of contacts 1 and 2 in light of the MOLA altimetry data and the more precise information on location of the contacts given in Clifford and Parker (2001). They found that some contacts are clearly of volcanic origin and that contact 1, at the
boundary between the southern uplands and the northern plains, has a wide spread of elevations and is unlikely to be a shoreline. In agreement with previous work, however, they concluded that large expanses of contact 2 are close to a constant elevation of around $-3760$ m, and could potentially be consistent with a shoreline. There was, however considerable uncertainty in the exact location of the shorelines and it was not clear how much the spread in elevation was due to the contacts not being ancient shorelines and how much was due to mis-location of the shorelines. The latter problem was particularly acute where the contact was on or close to a steep slope such as along the plains-upland boundary. Carr and Head (2002) concluded that better support for the former presence of water over large parts of the northern plains is provided by the Vastitas Borealis Formation (VBF), an Upper Hesperian thin veneer of material in the central northern lowlands overlying the Lower Hesperian volcanic ridged plains (Tanaka et al., 2005). They found that support for this interpretation came from: (1) the similarity in age between the outflow channels and the VBF, (2) the presence of the VBF at the lower ends of the outflow channels, and (3) identification of numerous features in the outcrop areas of the VBF that are suggestive of basal melting of an ice sheet (Kargel et al., 1995).

Publication of the global geologic map of Mars (Tanaka et al., 2014) and the availability of global THEMIS daytime images (http://mars.asu.edu/data/thm_dir_100m/) enables a new assessment of the exact location of the proposed shorelines and, in conjunction with the MOLA data, their elevation. The availability of the geologic map is particularly useful. Identification of geologic units and the depiction of their distribution are based solely on the observed surface characteristics, having been compiled independently of any model for the northern plains or intent to prove or disprove the presence of shorelines. The THEMIS daytime images have proven particularly useful in providing a new source of data that enables better portrayal of contrasts in the textural and thermal properties of the surface, distinction between units, and sharper definition of their contacts, thereby reducing the dependence solely on topography for recognizing possible shorelines.

We find that one the most compelling cases for a shoreline is provided by the outer boundary of the Vastitas Borealis Formation (VBF) around the southern and western rim of the Utopia basin, as portrayed in the Tanaka et al. (2014) global geologic map (Fig. 1) and in Ivanov et al. (2017). The VBF occurs widely throughout the northern plains. It is characterized by numerous closely spaced low hills, some pitted, and some arrayed in closely spaced curved ridges to form a ‘thumb-print’ texture. Areas of polygonal fractures are common, at different scales and in different locations. Locally in the interior of Utopia, graben-like linear intersecting troughs form complex networks (Heisinger and Head, 2000). A distinctive variety of surface units and textures can be distinguished, assessed stratigraphically and dated using superposed craters (Ivanov et al., 2014, 2015, 2017). Superimposed impact craters commonly have bright halos, thereby giving the unit a mottled appearance (Tanaka et al., 2005). Many of the textures have been attributed to the former presence of a frozen ocean (Kargel et al., 1995; Ivanov et al., 2014, 2015, 2017). The unit is labelled as Late Hesperian on the Tanaka et al., (2014) map but the accompanying correlation chart indicates that the unit may extend down into the Early Hesperian. Kreslavsky and Head (2002a) suggest that the unit is effluent deposited from an ocean (or multiple lakes) that formed contemporaneously with the outflow channels in the Late Hesperian. From the presence of buried ridges and ‘ghost’ craters, they estimated that the unit is approximately $100$ m thick. Around the south and west margins of the Utopia basin the outer boundary of the VBF is easily recognizable in the THEMIS daytime mosaics and readily distinguishable from the surrounding units by contrasts in albedo and surface texture (Fig. 2). The boundary here has little topographic expression. It closely follows the $-3650$ m contour for $2800$ km around the south and west margins of the Utopia basin (Fig. 1). It is difficult to imagine any geologic feature or process, other than a shoreline, that would so closely follow a contour over such large distances, and thus we choose to pursue this interpretation. The precise origin of such a shoreline in southern Utopia is uncertain, however. One possibility is that it marks the furthest reach of the last major flood that entered the northern basin and marks the limit of deposition of effluent from that flood. At the time of the last flood most of the water from the previous floods may have already frozen to form a solidified ice-ocean.

Away from southern Utopia the $-3650$ m contour as a shoreline is not so compelling (Carr and Head 2002) although its characteristics are not inconsistent with this interpretation. To the east of Utopia Planitia the contour crosses Amazonian volcanics that extend from Elysium down into the northern basin, so any Hesperian or older shoreline that might have been formerly present would now be buried. Similarly, the VBF abuts against younger units in northern Arcadia Planitia and north of Alba Patera. It is not clear how far south the VBF, and hence any potential shoreline, extended into Arcadia Planitia because of the presence of these younger deposits. The $-3650$ m contour follows the steep outer boundary of the Olympus Mons aureole deposits. This boundary is almost certainly of volcano-tectonic, not marine origin (Carr and Head, 2002), yet would have been a shoreline if present at the same time as the proposed ocean marked by the $-3650$ m contour. If the outer aureole deposits formed subsequent to the ocean, as is likely (Tanaka et al., 2014), then the deposits would have buried the shoreline of the southern extension of the ocean into Arcadia Planitia. To the west of Utopia Planitia, the contour follows the plains/upland boundary, which is much older than the Hesperian, but which would nevertheless have been a shoreline in the Hesperian if an ocean was present up to the $-3650$ m elevation.

In Chryse Planitia, into which most of the large outflow channels empty, the $-3650$ m contour outlines numerous streamlined islands and other breaks in slope such as the plains-upland boundary (Fig. 3). Ivanov and Head, 2001 used MOLA altimetry data to show that the largest and most prominent outflow channels (Kasei, Maja, Simud, Tiu, Ares and Mawrth) debouch into Chryse Planitia and disappear into the northern lowlands at average elevations that are all within less than $\pm 170$ m of a mean elevation of $-3742$ m, all within $190$ m of the elevation of contact 2, over a lateral distance of over $2500$ km. They proposed that the distinctive change of channel morphology could be consistent with a rapid loss of stream energy encountered at a base level such as a subaerial/submarine boundary. Contact 2 does not follow the VBF boundary specifically, which is to the north further into the basin. The $-3650$ m contour here is an erosional boundary rather than what appears to be a depositional boundary in Utopia Planitia. Possible explanations in the context of this interpretation are that late stage floods removed the VBF in Chryse or that the rapidly moving floods entering Chryse Planitia eroded the ocean floor and did not deposit their sediment load until well below the $-3650$ m contour.

The fate of the water released by the outflow channels and any deposited in an ocean would have depended on the climatic conditions under which it formed. Turbet et al. (2017), using 3-D Global Climate Model simulations, explored the release of water in individual outflow channel events, its fate, and its effect on the climate. They modeled the short and long term climatic impacts of a wide range of outflow channel formation events under cold Mars conditions interpreted to exist in the Late Hesperian, and found that even the most intense (largest, highest flux) of these events cannot trigger long-term greenhouse global warming. In a typical event, the outflow channel water reaches the bottom of the basin in a few days, and freezes over within just a few hundred days. It then sublimates to cold traps at the poles possibly within a few hundred thousand years.

An ocean would clearly have to have accumulated by multiple events as indicated by the number of outflow channels entering the basin. If, as appears likely and as described above, global climate conditions were similar to present conditions and a thick cryosphere was present (required for the overpressurized aquifer origin for the outflow channels), then the body of water that formed after each event would have frozen within a geologically short period of time ($10^3$ to $10^4$
years depending on the size of the event; Kreslavsky and Head, 2002a; Turbet et al., 2017). The ice could potentially stabilize and remain between outflow channel events if a sublimation lag was formed rapidly after each event (Kreslavsky and Head, 2002a, 2002b; Bramson et al., 2017). Mellon and Jakosky (1995) show, for example, that under conditions expected at an obliquity of 30°, ice is stable at all latitudes at depths greater than a 10–20 cm. In this specific scenario, repetitive floods could build an ocean-sized body of ice, layer upon layer as each water outflow event built on the frozen, sublimation lag protected, earlier layers. Once the era of flooding ended the ice would slowly sublimate, possibly over hundreds of thousands to millions of years, with the water being both lost to space and redistributed across the martian surface (Fig. 4). According to this scenario, the −3650 m shoreline never enclosed an ocean-sized body of liquid water; rather, it marked the edge of the last outflow channel flood that flowed across the northern basin, which at the time would be almost completely filled with ice from the previous floods. For the rest of this paper, we will assume this specific scenario, that in the mid-late Hesperian, there was a solidified ice-ocean in the northern plains composed of residual ice layers from the individual outflow channel events. The −3650 m contour, enclosing ~110 m GEL marks the limit of the final flooding event. We will attempt to determine where the 110 m GEL of water went. We saw above that we can account for approximately 20–30 m GEL in currently existing deposits, so that approximately 80–90 m is unaccounted for.

4. Outgassing

In order to know what fraction of the present 30 m near-surface inventory of water has been inherited from the Hesperian we need to

Fig. 1. Section of the Tanaka et al., (2014) geologic map of the northern hemisphere with the −3650 m contour superimposed (sinuous black line). The contour mostly follows the outer boundary of the Vastitas Borealis Formation (VBF). Where the contour is colored red, as northwest of Elysium and in Arcadia Planitia, the boundary is buried by younger units.
Underlying Amazonian units was assumed to have into account protection from cratering by the overlying unit. The sur-
craters upon it. Rim heights as a function of diameter were taken from
was determined from equation 13 and Table III in Ivanov (2001), taking
older unit. The number of craters on the di-
here follows erosional features cut by the large
boundary formed by the last major flood that entered the basin. The prominent
underlying a Hesperian unit was assumed to
The Chryse basin between 300–360° E and 10–50° N. The – 3650 m
countour around the basin traces numerous sharp breaks in slope between the
uplands and the plains and around islands in the flooded areas. The contour
here follows erosional features cut by the large floods entering the basin from
the south and west. The VBF boundary is further to the northeast (MOLA).

know how much has volcanically outgassed since that time. To de-
terminate this we used a procedure somewhat similar to that used by
Greeley (1987) and Greeley and Schneid (1991). The volume of ex-
trusives was derived from the areas of volcanic units, as depicted on the
available geologic maps, coupled with thicknesses derived from the
burial of craters; then an assumption was made about the water content of the lavas. Our procedure was as follows. The areas of different vol-
canic plains units were taken from Table 6 in the brochure accom-
panying the global geologic map of Tanaka et al., (2014). The thickness
was estimated by finding the thickness needed to bury all craters on the
underlying unit within the mapping resolution, which was assumed to
be 10^5 km^3, on the assumption that if there were more craters than the
designated age, then that 10^5 km^2 would have been mapped as the
older unit. The number of craters on the different aged buried surfaces
was determined from equation 13 and Table III in Ivanov (2001), taking
into account protection from cratering by the overlying unit. The sur-
face underlying Amazonian units was assumed to have N_D(3.8) − N_D(3.0)
(3.0) craters upon it, where N_D(3.8) is the number of craters of diameter
(D) that has accumulated on a 3.8 b.y. old surface. Similarly, a surface
underlying a Hesperian unit was assumed to have N_D(4.0) − N_D(3.8)
(3.8) craters upon it. Rim heights as a function of diameter were taken from

5. Infiltration into the ground
Clifford (1987, 1993) suggested that, despite the presence of a near-
global cryosphere during much of Mars’ history, the planet may have
maintained a slow global hydrological cycle as meltwater at the base of
the polar layered deposits infiltrated into the groundwater system to
create a groundwater mound and cause percolation equatorward under
the cryosphere. At low latitudes, the groundwater was episodically re-
turned to the surface as a result of impacts, seepages and eruptions of
groundwater, thereby completing the cycle. The proposed circulation is
driven by the infiltration of meltwater at the poles. Here we examine
the plausibility of melting at the base of the polar deposits in light of
recent estimates of the global heat flow as a function of time.

Present estimates of global heat flow are significantly less than
when the Clifford model was formulated, and these lower heat flow
values make it unlikely that basal melting could occur at the poles
during the Amazonian and Hesperian. A model by
Stevenson et al. (1983), for example, predicted a present heat flow of
30 mW m^2 for present day Mars and approximately 100 mW m^-2 at
the Amazonian-Hesperian boundary 3 b.y. ago. In contrast, from the
geodynamical response of the lithosphere to the presence of the polar
deposits, Phillips et al. (2008) estimate that the present heat flow at the
north pole is in the 8–17 mW m^-2 range. In addition, McGovern et al. (2002) and Ruiz et al. (2011) have inferred lithospheric
thicknesses and heat flows for a number of regions of Mars from
gravity/topography admittance spectra. Estimated heat flow values,
while in excess of 40 mW/m^2 for most Noachian features, are in the
10–40 mW/m^2 range for Amazonian and Hesperian features except for
the large Tharsis volcanoes which have larger local values
(Cassanelli et al., 2015). The lower heat flow estimates have also been
compared and reconciled with geochemical models (Ruiz, 2014). The
upper limit for heat flow (mW m^2) as a function of time given in
Ruiz (2014) was approximated by

H = 14.4 + 5.6t − 1.61t^2 + 0.8t^3
where $t$ is the time before present in billions of years. According to this formulation the heat flow is 14.4 mW/m$^2$ at present and 38 mW/m$^2$ at 3 Ga. For a surface temperature of 150 K, a basal temperature of 273 K and a thermal conductivity of 2 W m$^{-1}$ K$^{-1}$ (Clifford, 1987), the polar deposits would have to be over 6 km thick for basal melting 3 b.y. ago, over 9 km thick 2 b.y. ago and over 12 km thick 1 b.y. ago. The present deposits are approximately 3 km thick. We conclude, therefore, that polar basal melting has been unlikely since the Hesperian ocean was present and loss of water through the poles into the groundwater system can be ignored. Basal melting may, however, have been significant during the Noachian when heat flows and possibly surface temperatures were higher. Following earlier work (Harrison and Grimm, 2004; Russell and Head, 2007), Cassanelli et al. (2015) assessed the possibility that snow and ice accumulation on Tharsis could be sufficient to cause basal melting and recharge of the groundwater system. They found, however, that even the heat flow at Tharsis would be insufficient to cause significant basal melting and recharge, except under the very localized and volumetrically insignificant volcanic edifice heatpipe/drainpipe situation.

Another possibility is that the Hesperian ocean formed under warm climatic conditions before a global cryosphere developed and that some significant fraction of the ocean evaporated, thereby causing precipitation and infiltration into the groundwater system in the surrounding regions. There is, however, little evidence to support such a scenario (Turbet et al., 2017). The outflow channels that are interpreted to have caused the ocean are largely undissected by valley networks as are many plains that clearly pre-date the outflow channels, such as Lunae Planum in the case of Kasei Vallis.

6. Loss of equatorial ice and groundwater to the atmosphere

One of the more puzzling aspects of the evolution of near-surface water is the role of the loss of water from the equatorial cryosphere. Under present climatic conditions, ice present at the near-surface at low latitudes will tend to sublimate and be transferred to the atmosphere, thereby causing depletion of the near-surface ground ice (Fanale et al., 1986; Clifford and Hillel, 1983). The depth of depletion will increase in time at a rate dependent on the properties of the near-surface materials and conditions at the surface, with a particular sensitivity to conditions at different obliquities. This could result in substantial transfer of equatorial ground ice to the polar regions over geologic time. Grimm and Painter (2009), and Grimm (2017) estimate, for example, that approximately 60 m GEL would have been removed from the equatorial regions after the transition to modern cold, dry surface conditions in the early Hesperian, most of the losses having taken place in the first billion years. They assume an abrupt transition at 3 b.y. ago from an earlier climatic regime that allowed retention of equatorial ice to the “modern” regime under which such ice is unstable. The losses are consistent with the scarcity of near-surface ice at latitudes less than 50°–60° as indicated by neutron spectrometer (Feldman et al., 2004) and MARSIS (Mouginot et al., 2010) data. As we saw above, recycling of water through polar basal melting is unlikely, so the ice removed

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Fig. 4. Schematic diagram showing the proposed scenario for formation and elimination of the Hesperian ice ocean. Top: Floods that cut the large outflow channels enter the northern basin and form temporary lakes that rapidly freeze. Successive floods build a sequence of ice layers up to the ~3650 contour which marks the edge of the last large flood. Bottom: After the flooding era the ice slowly sublimes, some being lost to space and some being redistributed to form the polar layered deposits and other near-surface ice deposits.
from the equatorial regions would remain near the surface at high latitudes or be lost to space. The water lost would have had a D/H of the near-surface reservoir at the time of transition, which is assumed to be that of that of the Hesperian aged clays at Gale crater (3x SMOW) (Mahaffy et al., 2015).

If this reasoning is even approximately valid, it would imply that a significant fraction of the present near-surface inventory of water is derived from equatorial ground ice, not directly from a Hesperian ocean and that we would have to account for the fate not only of the 110 m GEL estimated to have been in the ice-ocean, but also the additional approximately 65 m GEL derived from the equatorial cryosphere. However, initiation of loss of groundwater and ground ice from the equatorial regions probably occurred much earlier than the 3 Ga assumed by Grimm (2017). The transition more likely occurred at the end of the Noachian, 3.8 b.y. ago, as indicated by the rapid drop off of the rate of formation of valley networks at that time. Indeed, loss of equatorial groundwater may have been a contributing factor in the subsequent filling of the northern basin both by erosion of ground-water to form the outflow channels and by direct transfer from the equatorial cryosphere to the polar regions through the atmosphere. As a result of these uncertainties we do not include additions from the equatorial cryosphere in our assessment of the fate of the water that formerly filled the northern basin. We assume that the equatorial losses, even if they were substantial, occurred earlier than the final phase of filling the northern basin indicated by the Deuteronilus shoreline.

7. Exchange between near-surface ice and the atmosphere and other reservoirs

The evolution of the D/H of the near-surface water reservoir provides clues concerning the fate of water that formed the ice-ocean. Water in the present atmosphere has a value of 6–7x SMOW (Owen et al., 1988; Aoki et al., 2015; Villanueva et al., 2015). The value for the mid-Hesperian is approximately 2x SMOW (Mahaffy et al., 2015). The main cause of the long-term doubling of the D/H of near-surface water since the mid-Hesperian is losses to space from the upper atmosphere (e.g. Yung et al., 1988). To understand the implications of the D/H measurements, we need to know the size of the water reservoir that is being affected by such losses. We saw above that the bulk of the near-surface inventory of water (17–22 m GEL) is in the polar deposits. Observational evidence and modeling suggest that the polar layered deposits are geologically young and dissipate and re-accumulate on geologically short time scales. Crater counts indicate that the north polar layered deposits (NPLD) are only ∼105 years old (Herkenhoff and Plaut, 2002). The south polar layered deposits (SPLD) are much older, ranging from 106 to 108 years (Herkenhoff and Plaut, 2002; Koutnik et al., 2002), but are still late Amazonian in age. Levrard et al., (2007) modelled the exchange of water between the poles and low latitudes using a 3-dimensional global climate model. Their results indicate that the NPLD completely dissipated during a period of high (> 30°) obliquities 5–10 Ma ago and that they have been re-accumulating during the last 4 Ma as mean obliquity decreased to the present value of 25°. The NPLD are now in an accumulation phase, hence their young age. Superimposed on this long term trend are smaller oscillations. Most recently, geologically, polar water is thought to have been transferred from the poles to lower latitudes where it formed latitude-dependent, ice-rich mantles (Head et al., 2003); the most recent north polar deposits are likely to be derived from the sublimation of the southern part of the latitude dependent mantle. On longer time scales, but still in the late Amazonian, when mean obliquity exceeded 30°, more widespread equatorward transfer of polar ice is interpreted to have resulted in regional ice deposits in the mid-latitudes, including glaciers, lobate debris aprons (LDA), lineated valley fill (LVF) and concentric crater fill (CCF) (Head et al., 2010; Levy et al., 2014a, 2014b; Kadish and Head, 2014; Madeleine et al., 2009; Fastook and Head, 2014). Tropical mountain glaciers are interpreted to have accumulated when the mean obliquity was ∼45° (Head and Marchant, 2003; Fastook et al., 2008). The south polar deposits are more stable than those in the north but still appear to have exchanged with the atmosphere on geologically short time scales (100 Ma). There is little reason to think that the spin-axis/obital factors that govern the transfer of ice in the present epoch are different from those operating at other times during the last 3.5 Ga, although their amplitudes will differ (Laskar et al., 2004). The polar layered deposits are likely to have been dissipating and re-accumulating throughout this period, with their D/H increasing as a consequence of losses from the upper atmosphere. It is less clear how well the 10 m GEL of ice deposits peripheral to the pole have exchanged with the atmosphere, but the presence of mid-latitude ice sheets and tropical mountain glaciers during this period means that at least some of the ice in the upper part of the regolith is being mobilized as cold traps migrate. Laskar et al. (2004) estimate that there is a 90% probability that obliquity reached 47° in the last 20 Ma, which would have led to more widespread loss of polar ice than occurred during the recent episode when obliquities were mostly in the 30°–40° range. In summary, it is likely that on a time scale of ∼100 Ma, all of the 17–22 m GEL polar ice undergoes exchange with the atmosphere as does much of the 10 m GEL near the surface in the circumpolar regions.

Based in part on D/H measurements, Kurokawa et al., (2014; 2016) proposed a three-reservoir model for the distribution of water (the atmosphere, a near-surface reservoir exchangeable with the atmosphere and a deeper ground-ice reservoir). The D/H in the atmosphere and near-surface reservoir co-evolve, differing only as a result of the fractionation factor between ice and vapor. The D/H of the deeper ground ice retained the value it had at the time of transition from a hypothesized warm and wet/ard (Ramirez and Craddock, 2018), vertically integrated hydrologic regime around 3.8–4.0 b.y. ago, to the present horizontally stratified regime with a global cryosphere. Kurokawa et al. (2014, 2016) suggest that there could have been slow exchange between the deep ground ice and the near-surface reservoir as a result of infiltration, hydrothermal activity, impacts and diffusion. The exchangeable reservoir is held constant in the model, with losses to space from the exchangeable reservoir being offset by net additions from the underlying reservoir. From meteorite data (Usui et al., 2012), they assume that the deep ground ice has a D/H of 1–2 x SMOW. With these assumptions they estimate that a few tens of meters GEL of water have been lost to space for D/H fractionation factors of 0.016 to 0.11, and a few tens to hundreds of meters GEL for a fractionation factor of 0.33.

We assume here a similar model, in which a near-surface reservoir that exchanges with the atmosphere overrules a larger ground-ice reservoir that interacts episodically with the overlying exchangeable reservoir. As water is lost from the exchangeable reservoir, its D/H increases and the losses are replaced by incorporating ice from the underlying reservoir, which retains mid-Hesperian D/H of 3x SMOW (Mahaffy et al, 2015). The size of the exchangeable reservoir depends on the time scale of interest. In the present epoch, on a time scale of 103 years, the deeper layers of the NPLD are sealed from the atmosphere and so do not interact with it, but on a time scale of 105 years all the NPLD interact with the atmosphere. On time scales of 106 years, because of excursions to higher obliquities, a larger volume exchanges with the atmosphere. The SPLD are eroded and the areas peripheral to the poles exchange with the atmosphere (Levrard et al., 2007). We are interested here in the long term evolution (3.5 b.y.) and the volume that is exchanging and equilibrating with the atmosphere over long time scales of 105 years. We will assume that all the NPLD, all the SPLD, and the ground-ice peripheral to the poles to a depth of 80 m, a total of 20–30 m GEL, all interact with the atmosphere on times scales of 106 years, and that this volume has been approximately constant for the last 3.5 b.y.

8. Losses to space

If the atmosphere has been episodically exchanging with a reservoir of near-surface ground ice, as just discussed, then the high D/H ratio of
the atmosphere (and by implication the exchangeable ice reservoir) indicates a substantial loss of hydrogen to space. At present day loss rates the equivalent of only 3.6-25 m GEL of water would have been lost over the last 4.2 b.y. (Jakosky et al., 2018). Such a low loss rate is incompatible with the evolution of D/H and the size of exchangeable reservoir as just described. If there had been no loss or gain of water between the near-surface exchangeable reservoir and the deeper surface, then the Hesperian and present inventories would be related by the expression

\[ I_P = I_H (R_{ih}/R_{H})^{(1/3)}f \]

where \( I_H \) and \( I_P \) are the Hesperian and present near-surface inventories, \( R_{ih} \) and \( R_H \) are the Hesperian and present D/H ratios, and \( f \) is the fractionation factor (Kurokawa et al., 2016). Even in the extremely unlikely case of no deuterium lost to space (\( f = 0 \)), a present inventory of 20-30 m and a doubling of the D/H (see above), would imply that at least 20-30 m has been lost.

As noted by almost all who have addressed the issue of losses to space from the upper atmosphere, the loss rates depend on the long term history of the output of the Sun, particularly in the EUV. Comparisons with nearby stars indicate that in the first few hundred million years the Sun’s EUV output declined from 100s to 10 times the present value. Guel (2007) and Guel and Kasting (2011) estimate that by 3.5 b.y. ago the output had declined to 6 times the present value. Their data on the decline can be approximated by the relationship \[ E = 0.0647e^{0.726t} \] where \( E \) is the enhancement over present rate and \( t \) is the time before the present in billions of years. There are uncertainties concerning the dependence of escape rates for oxygen and hydrogen on the intensity of EUV. We assume here a linear dependence. There is also some uncertainty as to whether the solar ages are exactly equivalent to the martian crater ages. The solar ages assume the Sun’s early history is typical of that of nearby stars and derivation of crater ages depend on crater scaling laws and knowledge on the mix of objects in the early Solar System. Such discrepancies could be significant in view of the rapid fall off in the EUV between 3 and 4 billion years ago.

Higher obliquities may also have caused higher hydrogen loss rates in the past. Mellon and Jakosky (1995) suggested that higher obliquities would result in higher column abundances of water in the atmosphere as more water is transferred from pole to pole with the seasons. Their estimated increases are substantial, with an over two orders of magnitude increase from the present day loss rate of 25 m GEL in 4.2 b.y., or half the required loss, even taking into account the higher present day loss rate of hydrogen than the early MAVEN estimates (Jakosky et al., 2018), even taking into account the higher, earlier EUV enhancements.

In order to determine how the mid-Hesperian ice inventory of 110 m GEL with a D/H of 3 x SMOW might have evolved to the present near-surface exchangeable inventory of 20-30 m GEL with a D/H of 5-7x SMOW, a spread sheet was constructed which started with the present situation and stepped back in time in 100 m.y. increments. At each step the losses to space were calculated starting with different nominal values for present day loss rates and scaling with time to account for the past higher EUV as described above under Losses to Space. Additions as a result of outgassing were made as also described above, using 1x SMOW for D/H. The exchangeable volume, nominally 30 m GEL was kept constant by adding from a deeper non-exchangeable reservoir with a D/H of 3x SMOW in order to replace losses from above. The value of 3x SMOW is based on the assumption that the non-exchangeable reservoir has been protected from interaction with the atmosphere since the ice ocean was present. With these constraints the fractionation factor that results in evolution of D/H of the exchangeable reservoir from 3x SMOW at 3.5 b.y. ago to the present value of 5-7 was determined by trial and error. Typical results are shown in Fig. 5.

Assuming a present inventory of 30 m GEL of which 4 m is derived from outgassing, then 84 m GEL must be lost to space to eliminate the 110 m GEL estimated to have been in the Hesperian ocean. Present loss rates of 4-25 m GEL in 4.2 b.y. (Jakosky, 2016) fall well short of the required rates even correcting for the earlier higher EUV fluxes. A present day loss of 25 m GEL in 4.2 b.y. implies a loss of 42 m GEL in 3.5 b.y., or half the required loss, even taking into account the higher EUV fluxes. In addition, doubling of the D/H since the mid Hesperian requires present day loss rate of at least 21 m GEL in 4.2 b.y., that required in the unlikely event of no losses of deuterium since the mid-Hesperian (Fig. 6). In order to lose the 84 m GEL to space estimated to be required to eliminate the 110 m GEL ocean, we estimate that a present day loss rate of 49 m GEL in 4.2 b.y. is required, almost double the measured rate.

One possibility for the shortfall is that the losses to space have been underestimated. This could occur because the measured rates are not

9. Evolution of D/H

For the present and Hesperian inventories of 30 m and 110 m GEL, and D/H values of 6 and 3, equation 1 implies a fractionation factor of 0.46 which is a higher value than most published values (e.g. Krasnapolsky, 2000; Yung et al., 1988). But as we saw above, the near-surface reservoir has not been isolated from the rest of the planet and volcanism has added to the surface inventory. Moreover, the loss of 80 m GEL over the last 3.5 b.y. implies a substantially larger present-day loss rate of hydrogen than the early MAVEN estimates (Jakosky et al., 2018), even taking into account the higher, earlier EUV enhancements.

In order to determine how the mid-Hesperian ice inventory of 110 m GEL with a D/H of 3 x SMOW might have evolved to the present near-surface exchangeable inventory of 20-30 m GEL with a D/H of 5-7x SMOW, a spread sheet was constructed which started with the present situation and stepped back in time in 100 m.y. increments. At each step the losses to space were calculated starting with different nominal values for present day loss rates and scaling with time to account for the past higher EUV as described above under Losses to Space. Additions as a result of outgassing were made as also described above, using 1x SMOW for D/H. The exchangeable volume, nominally 30 m GEL was kept constant by adding from a deeper non-exchangeable reservoir with a D/H of 3x SMOW in order to replace losses from above. The value of 3x SMOW is based on the assumption that the non-exchangeable reservoir has been protected from interaction with the atmosphere since the ice ocean was present. With these constraints the fractionation factor that results in evolution of D/H of the exchangeable reservoir from 3x SMOW at 3.5 b.y. ago to the present value of 5-7 was determined by trial and error. Typical results are shown in Fig. 5.

Assuming a present inventory of 30 m GEL of which 4 m is derived from outgassing, then 84 m GEL must be lost to space to eliminate the 110 m GEL estimated to have been in the Hesperian ocean. Present loss rates of 4-25 m GEL in 4.2 b.y. (Jakosky, 2016) fall well short of the required rates even correcting for the earlier higher EUV fluxes. A present day loss of 25 m GEL in 4.2 b.y. implies a loss of 42 m GEL in 3.5 b.y., or half the required loss, even taking into account the higher EUV fluxes. In addition, doubling of the D/H since the mid Hesperian requires present day loss rate of at least 21 m GEL in 4.2 b.y., that required in the unlikely event of no losses of deuterium since the mid-Hesperian (Fig. 6). In order to lose the 84 m GEL to space estimated to be required to eliminate the 110 m GEL ocean, we estimate that a present day loss rate of 49 m GEL in 4.2 b.y. is required, almost double the measured rate.

One possibility for the shortfall is that the losses to space have been underestimated. This could occur because the measured rates are not

![Fig. 5. Typical result of modeling the evolution of D/H as described in the text. Here the exchangeable inventory is 30 m GEL and the present day loss rate is 30 m GEL in 4 b.y. Curves for two different values of the present polar D/H show how the D/H of the exchangeable reservoir may have evolved over time.](image)
The losses are corrected for earlier EUV enhancements. The colored areas show the measured range of 3.6–25 m GEL (Jakosky et al., 2018). The darker area indicates where losses fall short of those required to explain the doubling of D/H since the mid-Hesperian. The upper curve is for a present loss rate of 49 m GEL in 4.2 b.y., that required to eliminate a 110 m GEL ocean assuming a 30 m GEL present inventory and earlier EUV enhancements.

Figure 6. Estimated losses to space for different values of the present loss rates. The losses are corrected for earlier EUV enhancements. The colored areas show the measured range of 3.6–25 m GEL (Jakosky et al., 2018). The darker area indicates where losses fall short of those required to explain the doubling of D/H since the mid-Hesperian. The upper curve is for a present loss rate of 49 m GEL in 4.2 b.y., that required to eliminate a 110 m GEL ocean assuming a 30 m GEL present inventory and earlier EUV enhancements.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.icarus.2018.08.021.

References


typical of the present epoch, because the effects of the early EUV enhancements were underestimated or because possible higher loss rates during periods of high obliquity were not taken into account. Another possibility is that the present near-surface inventory has been underestimated. Mouginot et al. (2010) acknowledge that their estimate from MARSIS of 7 m GEL outside the polar caps at depths less than 60–80 m is a lower limit. We argued above that significant amounts of water sublimated from the ice-ocean could not have re-entered the ground-water system because of the presence of a thick cryosphere. If true, the missing volume, if not lost to space, must be near the surface. It must also be outside the ~3650 m contour that defines the 110 m volume of the basin and at latitudes greater than 30° because of stability constraints. Since the basin occupies most of the northern hemisphere at latitudes greater than 30°, the missing volume, if still present, is most likely at high southern latitudes. Consistent with this conclusion, seven of the eight cliffs in which layers of ice have been observed are in the 55°–60° S. latitude band (Dundas et al., 2018). The southern latitudes in excess of 30° constitute only one quarter of the planet’s surface area so to accommodate the missing 30–55 m the southern high latitudes would have to typically be underlain by 120–220 m of ice. While this seems an improbably large amount, the ice layers observed by Dundas et al. (2018) are tens of meters to over 100 m thick so that the high southern latitudes could contain a significant fraction of the missing volume.

10. Conclusions

- In the mid to late Hesperian, floodwaters repeatedly flowed into the northern basin under climatic conditions that resemble those of the present day. We assume that each flood froze in a geologically short period of time to form an ice layer that remained there until the next flood. Successive ice layers accumulated to form an ocean-sized body of ice that filled the basin up to the ~3650 m contour thereby enclosing 110 m GEL of water.
- Subsequent to the filling of the basin the ice slowly sublimated into the atmosphere to be lost to space or to accumulate in various near-surface cold traps such as the polar layered deposits.
- Only minor amounts of water were lost from the surface to the global groundwater system because of the thick cryosphere and low heat flow values. The minor amounts lost were in places where anomalously high heat flow values prevailed as in active volcanic edifice regions.
- 20–30 m GEL of water are estimated to be near the surface today and exchanging with the atmosphere on geologic time scales. This includes the polar layered deposits and deposits elsewhere at depths less than approximately 80 m. A non-exchangeable reservoir of unknown capacity underlies the exchangeable reservoir.
- Approximately 5 m of water has been outgassed to the surface since the mid Hesperian.
- Present day loss rates to space fall far short of those needed to eliminate the volume of the mid Hesperian ice ocean and those needed to cause a doubling of the D/H of the exchangeable reservoir since the mid Hesperian. Earlier loss rates must have been higher. Assuming a linear increase in loss rates because of the higher EUV output of the Sun, a 30 m present inventory, and the upper limit on present loss rates from MAVEN, 42 m GEL of water remain to be accounted for. Possibilities include greater dependence of losses of EUV than assumed and enhanced losses during periods of high obliquity. In addition, large volumes of ice may be present near the surface at high southern latitudes as indicated by recent discoveries of ice layers in cliffs.