

**Characterizing the Climate and Hydrologic Cycle of Early Mars:
Assessing the Role of Rainfall, Groundwater, and Transient
Atmospheric Heating**

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INTRODUCTION

Despite the existence of numerous orbital and landed missions and the development of advanced numerical climate models, understanding the nature and evolution of the early martian climate remains an unsolved and compelling scientific problem. Geomorphologic and mineralogic evidence, including the presence of valley networks (Hynek et al., 2010), open- and closed-basin paleolakes (Cabrol and Grin, 1999; Fassett and Head, 2008a; Goudge et al., 2015), aqueous alteration products (Bibring et al., 2006; Carter et al., 2015), and craters with degraded rims that lack visible ejecta deposits (Craddock and Howard, 2002; Jones, 1974), suggest that the long-lived early martian climate may have been “warm and wet”, characterized by above-freezing average surface temperatures and rainfall as the dominant erosive mechanism (Craddock and Howard, 2002; Ramirez and Craddock, 2018; Ramirez, 2017). On the other hand, studies that implement advanced climate models have been incapable of producing continuous and long-lived warm conditions (e.g. spanning the entire Noachian era) when considering reasonable greenhouse gas constraints and the influence of the faint and young Sun (see review in Forget et al., 2013). These modeling studies suggest that the long-lived early martian climate may have more likely been “cold and icy”, characterized by below-freezing average temperatures and surface water trapped as snow and ice in the highlands (Forget et al., 2013; Kasting, 1991; Wordsworth et al., 2013). In this “cold and icy” climate scenario, fluvial and lacustrine activity would have been confined to periods of punctuated and transient heating in which either rainfall and runoff or melting of snow and ice and runoff would have occurred (Fastook and Head, 2015; Head and Marchant,

2014; Wordsworth, 2016). Further, recent work has shown that such potentially necessary “warm and wet” conditions may have only been required to have persisted in the Late Noachian-Early Hesperian (LN-EH, ~ 3.7 Ga), not throughout the Noachian; this scenario is commonly referred to as a climate optimum (Howard, 2007; Howard et al., 2005; Irwin et al., 2005) and is consistent with the hypothesis that the long-lived climate was “cold and icy” with one or more periods of punctuated/transient heating in the LN-EH.

In this thesis, we aim to combine geologic evidence with climate model results to address the question: What was the nature of the early martian climate and hydrologic cycle?

To accomplish this, we introduce nine research chapters that utilize a synergistic approach between geologic observations and climate modeling techniques to address unsolved questions about the early martian climate and hydrologic cycle. Within these nine chapters, we cover three broad topics: (1) testing hypotheses of specific aspects of the proposed long-lived “warm and wet” early martian climate, including the presence, distribution, and erosive capability of rainfall, (2) exploring the characteristics and implications of multiple punctuated and transient heating mechanisms in an otherwise “cold and icy” climate, including volcanism-induced heating from the release of sulfur-based gases into the atmosphere and impact cratering-induced heating, and (3) exploring the role of groundwater release to the surface, within putative paleolakes and oceans, and determining the implications of groundwater release processes for climate and subsurface water inventory. We briefly describe each of these chapters below, highlighting the goals and key findings from each chapter.

In **Chapter One**, titled *Rainfall on Noachian Mars: Nature, timing, and influence on geologic processes and climate history* (Palumbo et al., 2020), we test the hypothesis that rainfall intensity (rate) and atmospheric pressure are inversely related to one another, implying that as atmospheric pressure declined through time, rainfall intensity would have increased until atmospheric pressure was too low to support rainfall (Craddock and Lorenz, 2017). This hypothesis was put forth as a means to explain the observed crater degradation, which suggests that (1) the Early to Middle Noachian was characterized by a relatively low rainfall intensity regime, with rainfall-related erosion dominated by rain splash and negligible runoff, which is proposed to have occurred because of relatively high atmospheric pressures, (2) the LN-EH was characterized by a relatively high rainfall intensity regime, with significant runoff dominating the rainfall-related erosional regime, which is proposed to have occurred because of moderate atmospheric pressures, and (2) the rest of the Hesperian and the Amazonian have been characterized by atmospheric pressures that are too low to support rainfall (Craddock and Lorenz, 2017). We test this hypothesis by implementing mathematical relationships for raindrop velocity, maximum possible raindrop diameter, and rainfall intensity. We show that, in contrast to findings from previous studies, maximum possible raindrop diameter does not depend on atmospheric pressure and, as a result, simple parameterized relationships suggest that rainfall intensity does not depend on atmospheric pressure. Therefore, our results predict that there would not have been a transition from rain splash-dominated erosion to runoff-dominated erosion related solely to decreasing atmospheric pressure; we suggest that future work should test this conclusion with more advanced methods of calculating rainfall intensity.

This finding is not necessarily consistent with the hypothesis of Craddock and Lorenz (2017) that the long-lived Noachian climate was “warm and wet” with continuous rainfall and that rainfall intensity changed as a function of atmospheric pressure declining through time, explaining the observed patterns of crater degradation; our findings do not preclude the possibility that early Mars was predominantly “cold and icy” and that processes other than rain splash and rainfall-related runoff were responsible for the observed crater degradation. Remaining unknown is the mechanism(s) responsible for the observed geomorphic transition in erosion style that is evidenced by crater degradation states (e.g. whether crater degradation, which was previously attributed to rain splash-related erosion, could have been related to post-impact effects, **Chapter Six**, for example), and whether melting of surface snow/ice and runoff during a punctuated heating episode in an otherwise “cold and icy” climate could explain the formation of the LN-EH valley networks and paleolakes in the absence of abundant, widespread, relatively high intensity rainfall.

This chapter, which provides background on the current state of knowledge and sheds light on the unsolved problem of the nature of the early martian climate and hydrologic cycle, provides a framework for the remainder of the thesis. In the subsequent chapters:

- (1) We analyze in detail the hydrologic cycle of a “warm and wet” climate to determine if the predicted distribution of fluvial activity in this climate scenario is well-correlated with the distribution of valley networks and paleolake basins and, further, we compare our findings with the predicted distribution of fluvial activity in a “cold and icy” climate with one or more

periods of punctuated heating in order to determine whether the distributions of valley networks and paleolake basins are more consistent with formation in a long-lived “warm and wet” Noachian climate or with formation in a long-lived “cold and icy” Noachian climate with punctuated heating (**Chapter Two, Chapter Three, and Chapter Four**).

- (2) We test multiple mechanisms for punctuated and transient heating in an otherwise “cold and icy” climate in order to determine if significant rainfall and runoff or melting of snow/ice and runoff is possible and we explore the implications of such fluvial activity (**Chapter Five and Chapter Six**).
- (3) We explore the potential role of groundwater release on early Mars and the implications of such groundwater release for the early martian climate and subsurface water inventory (**Chapter Seven, Chapter Eight, and Chapter Nine**).

In **Chapter Two**, titled *Early Mars climate history: Characterizing a “warm and wet” martian climate with a 3D global climate model and testing geological predictions* (Palumbo and Head, 2018a), we address the question: If the long-lived early climate was “warm and wet”, as researchers have commonly suggested based on geologic observations (e.g. Craddock and Howard, 2002; Ramirez and Craddock, 2018), would rainfall patterns be consistent with the distribution of fluvial and lacustrine features? In an effort to bridge the gap between geologic observations and climate model results, we implement the 3D Laboratoire de Météorologie Dynamique Global Climate Model (LMD GCM) for early Mars and force warm conditions in the model in order to test the geological predictions of a “warm and wet” climate. Specifically, we choose simulate a

canonical “warm and wet” climate, characterized by global MAT above freezing (global MAT ~ 275 K) (e.g. Ramirez and Craddock, 2018), in order to explore the characteristics of the hydrologic cycle and model-predicted fluvial activity and determine whether the valley networks and paleolakes could have formed through rainfall and related processes in this climate scenario. In our simulations, we implement reasonable Noachian spin-axis/orbital parameter values (Laskar et al., 2004), assume present-day topography (e.g. Fassett and Head, 2011; Smith et al., 1999), assume that the Noachian surface water inventory was unlikely to have been more than ~ 34 m GEL (Carr and Head, 2015), and reproduce the desired temperature conditions by introducing gray gas into the model atmosphere, which mimics greenhouse heating without implementing specific gases.

We find that rainfall is limited in abundance and areal distribution, precipitation is dominated by snowfall, and temperatures in the southern highlands are predicted to be < 273 K for the majority of the year. We conclude that, in this simulated climate scenario, (1) LN-EH valley networks and paleolakes could not have formed through rainfall-related erosion, (2) precipitation is dominated by snowfall, not rainfall, (3) crater degradation by rain splash and runoff is not predicted, (4) global clay formation through long-lived rainfall, fluvial activity, and warm temperatures is unlikely, and (5) the presence of a rainfall- and overland flow-fed stable body of water in the northern lowlands (e.g. a vast ocean) is improbable. We suggest that shorter-term transient or punctuated warm temperature phases in an otherwise “cold and icy” background climate, which would permit transient melting of surface snow/ice and runoff, might be a more likely scenario to explain the formation of the valley networks and paleolakes than rainfall in a “warm and wet” climate.

In **Chapter Three**, titled *Global climate model predictions for a change from a long-lived “cold and icy” climate to a punctuated or transient “warm and wet” climate in the Late Noachian-Early Hesperian* (Palumbo and Head, In Revision), we explore further an important implication of earlier work (**Chapter Two**): regardless of whether the early climate scenario was characterized by long-lived “warm and wet” conditions (above-freezing global MAT, ~ 275 K) or long-lived “cold and icy” conditions with periods of punctuated heating, our climate model results suggest that fluvial activity would have been dominated by melting of surface snow and ice and runoff, not rainfall and runoff. In this chapter, we use the 3D LMD GCM for early Mars to assess whether the distribution of valley networks and paleolake basins is more consistent with (1) the model-predicted distribution of snow/ice melting in a long-lived “warm and wet” climate, or (2) the model-predicted snowmelt distribution in a long-lived “cold and icy” climate with one or more periods of punctuated heating. We find that the distributions of valley networks and paleolakes are more consistent with the distribution of model-predicted snow/ice melting for the case of a long-lived “cold and icy” Noachian climate with one or more periods of punctuated heating than for the case of a long-lived “warm and wet” Noachian climate.

In **Chapter Four**, titled *Earth-like temperatures are required for widespread rainfall on early Mars* (Palumbo and Head, Under Review), we explore further the possibility that the martian fluvial and lacustrine features formed through rainfall and runoff, not snowmelt and runoff, and, armed with our conclusions from **Chapter Two**, we address the question: How warm must the early martian climate have been in order for there to have been widespread rainfall in the highlands, the major location of the

valley networks and paleolakes? Specifically, in order for widespread rainfall in the highlands to be possible, the highlands must be above freezing for the majority of the year and there must be minimal-to-no surface cold traps. In this chapter, we use the LMD GCM for early Mars and again introduce gray gas into the model atmosphere in order to explore a range of climates with global MAT >273 K, specifically ~ 273 - 290 K. Our results suggest that: (1) global MAT $>\sim 285$ K, similar to that of present-day Earth (~ 288 K, or 58° F), is required for there to be widespread rainfall in the highlands, and (2) even in these very warm climates, annual widespread snow accumulation and subsequent melting occurs, suggesting that models for Noachian fluvial and lacustrine activity should consider the roles of both rainfall and snowmelt.

In **Chapter Five**, titled *Exploring the influence of volcanism-induced heating on early Mars: Implications for localized and summertime melting*, we use the 3D LMD GCM for early Mars to revisit volcanism-induced heating from the release of sulfur-based gases as a transient heating mechanism on early Mars. Previous studies have explored this transient heating mechanism with 3D GCMs (e.g. Halevy and Head, 2014; Johnson et al., 2009, 2008; Kerber et al., 2015; Mischna et al., 2013; Postawko and Kuhn, 1986; Tian et al., 2010) and have addressed the following question: Assuming that the long-lived background Noachian climate was “cold and icy”, can the presence of globally-distributed sulfur-based gases raise the mean annual temperature (MAT) on early Mars to above 273 K, the melting point of water? These studies have consistently shown that, when considering reasonable concentrations of globally distributed sulfur-based gases, global MAT would remain below freezing. However, in previous work, we have shown that early Mars would have experienced significant seasonal temperature

variation and, even if global MAT was below freezing, summertime temperatures may have exceeded 273 K, permitting melting of surface snow/ice and runoff (Palumbo et al., 2018); Mischna et al. (2013) showed that, for reasonable concentrations of volcanically-released, globally distributed SO₂, summertime temperatures above freezing are possible in some areas. Additionally, the volcanically-released gases do not immediately become globally distributed. The gases are first localized near the volcanic edifice and spread through a latitudinal band (termed *phase one*), and then spread poleward and become globally distributed (termed *phase two*). Therefore, in this work, we explore two additional aspects of volcanism-induced heating from the release of sulfur-based gases that have not previously been considered in detail: (1) the possibility of localized heating and melting immediately following a volcanic eruption when the sulfur-based gases are focused near the volcanic edifice (*phase one*), causing increased localized heating, and (2) the possibility of summertime melting of surface snow and ice after the sulfur-based gases have become globally-distributed (an unexplored aspect of *phase two*).

We find that (1) in *phase one*, significant localized heating can occur near the volcanic edifice, possibly leading to a few days with peak temperatures above freezing, melting of surface snow and ice, and runoff, and (2) in *phase two*, although global MAT is <273 K for reasonable gas concentrations, temperatures above freezing and significant melting of surface snow/ice and runoff can occur during the summer season. Although this mechanism may not produce a sufficient volume of meltwater to explain the formation of all of the valley networks and paleolakes, it is likely to have contributed to LN-EH fluvial activity and thus should no longer be disregarded. Further, our analysis explores only the introduction of SO₂ into the atmosphere, when in reality many other

important greenhouse gases are released during volcanic events, as well, including H₂S, H₂, and N₂ (e.g. Craddock and Greeley, 2009); the magnitude of heating would be increased if all of these gases were included in the simulations. Thus, future work should implement the methods developed and described here to explore the influence of volcanism-induced heating from all volcanically-released gases, not just SO₂.

In **Chapter Six**, titled *Large impact basin-related climatic and surface effects on Mars: Argyre basin as a case study*, we qualitatively and quantitatively explore the climatic and surface effects from the formation of the Argyre basin. The collision of large impactors into the surface of Mars would have brought extreme climate change, specifically including the deposition of a hot spherule layer and abundant, hot rainfall. In previous studies, researchers hypothesized that impact cratering-induced heating and rainfall could have been responsible for formation of the LN-EH-aged valley networks and paleolakes (Segura et al., 2008; Toon et al., 2010). However, the intense characteristics of these impact-related processes (Barnhart et al., 2009; Palumbo and Head, 2018b) as well as the fact that the large basins, which would produce these global effects, all pre-date the timing of valley network and paleolake activity (Fassett and Head, 2011, 2008b), have led more recent studies to conclude that, although post-impact effects are likely to have brought significant climate change and surface aqueous activity, such effects are unlikely to have been related to the formation of the LN-EH-aged valley networks and paleolakes (e.g. Palumbo and Head, 2018b).

In earlier work, we qualitatively explored the effects of basin-scale impact events on early Mars, finding that (1) the deposition of global spherule layers should have a distinct geologic and mineralogic signature, distinguishable at rover scale, and (2) the intense

rainfall and hydrologic cycling may have been responsible for a (potentially large) portion of the observed surface aqueous alteration, degradation of craters, and smoothing of plains, potentially removing these observations from the list of evidence for a long-lived “warm and wet” climate. Thus, despite the fact that basin-scale impact cratering effects were dominant in the Early to Middle Noachian, understanding the implications such effects are intimately related to our understanding of the LN-EH climate.

In this chapter, we apply the results of our earlier study (Palumbo and Head, 2018b) and other earlier studies (Segura et al., 2002, 2012, 2008; Steakley et al., 2019; Toon et al., 2010; Turbet et al., 2020) to explore the effects of the formation of the youngest of the large martian basins, the Argyre basin. The deposited spherule layer and subsequent aqueous alteration from older basins would be buried and eroded, but those associated with the Argyre basin would be preserved at or near the surface.

Our qualitative and quantitative assessment provides an unprecedented framework for identifying and exploring martian units related to the formation of the Argyre basin. We find that: (1) an ~30 meters thick, near-globally-distributed, olivine and glass-rich spherule layer should be preserved on or very near the surface, (2) the induced rainfall would have been characterized by rainfall rates higher than those of rainforests on Earth and would have lasted for decades, which is unprecedented for observed rainfalls on Earth (e.g. Jennings, 1950; Zhang et al., 2013), (3) the intense rainfall would have caused flooding, significant erosion, and smoothing of landforms, and (4) hot rainfall and high temperatures would have caused surface aqueous alteration, including partial alteration of the olivine-rich layer to carbonates as well as alteration of basaltic material to Fe/Mg-

smectites and Al-phyllosilicates (e.g. Bishop et al., 2017), which would present in a leaching profile.

We discuss important implications of these findings, including: (1) distinguishing the role of impact-induced aqueous alteration from that associated with normal climate conditions, (2) predictions of areas where the spherule layer and alteration products may be observed, (3) the transition from a basin-scale impact-dominated regime to a basin-free regime in martian climate evolution (see also our work in Turbet et al., 2020), and (4) guidelines for exploration and recognition of these impact-related units at rover and sample return scale.

In **Chapter Seven**, titled *Oceans on Mars: The possibility of a Noachian groundwater-fed ocean in a sub-freezing martian climate* (Palumbo and Head, 2019), we constrain the climate and subsurface water inventory that are required for the formation of a groundwater-fed Noachian ocean in the northern lowlands. The presence of this ocean has been suggested based on mapped and predicted shorelines (Parker et al., 1993, 1989) and the hypothesis that a much warmer Noachian climate would naturally support an ocean (e.g. Clifford et al., 2010; Clifford, 1993; Clifford and Parker, 2001). Although the evidence for this ocean is debated (Head et al., 2018), the formation and presence of such a large body of water would indubitably have important implications for the early martian climate and hydrologic cycle.

Interestingly, this ocean has been hypothesized to have formed through a mechanism similar to that of a groundwater-fed lake on Earth: if (1) the groundwater system contains a sufficient volume of water such that the groundwater table can intersect the surface, and (2) the local temperature is above freezing, such that there is no

cryosphere to trap the groundwater in the subsurface, then the groundwater will be released onto the surface, forming a groundwater-fed lake or sea. Therefore, understanding the required characteristics for the formation of this ocean can provide critical insight into the Noachian climate and subsurface water inventory. Specifically, we explore the implications of the possible presence of a Noachian ocean by determining (1) how warm the climate must have been in order to support the formation of an ocean in the lowlands, and (2) how large of a Noachian subsurface water inventory would have been required to support the formation of an ocean in the lowlands?

To complete this study, we implement the 3D LMD GCM for early Mars, develop and implement a 1D thermal model, and implement basic subsurface porosity and water saturation calculations. Our key finding is: if the global MAT was $>258\text{ K}$ ($\sim 30\text{ K}$ above the nominal ambient “cold and icy” climate) for a few thousand years and the subsurface contained $>170\text{ m}$ global equivalent layer (GEL) of groundwater, then groundwater would release into the topographically lowest regions of Utopia Planitia, leading to flooding of the northern lowlands and the formation of an ocean. The implications are three-fold: (1) if there was an ocean in the lowlands in the Noachian, we now have estimates for the minimum Noachian subsurface water inventory and climate, (2) if the Noachian climate was colder than the minimum required for the formation of a lowlands ocean or the Noachian subsurface water inventory was not large enough to support the formation of a lowlands ocean, it is unlikely that a Noachian ocean formed through this mechanism, and (3) the possible existence of a Noachian groundwater-fed ocean should not be cited as evidence for a “warm and wet” climate with average surface temperatures above freezing.

In **Chapter Eight**, titled *Oceans on Mars: Exploring mechanisms for recharge of the groundwater system* (Palumbo and Head, Under Review), we expand upon our earlier analysis (**Chapter Seven**) and address the following conundrums: (1) if an ocean formed in the Noachian, the Noachian oceanic water must have been returned to the subsurface in order for there to have been a sufficient volume of water in the subsurface for the Hesperian ocean to have formed, which is evidenced by the presence of outflow channels (Baker et al., 1991), potential shorelines (Parker et al., 1993, 1989), and potential tsunami deposits (Costard et al., 2017; Rodriguez et al., 2016), and (2) if an ocean formed in the Hesperian, most of the Hesperian oceanic water must have been returned to the subsurface because the present-day surface/near-surface water inventory (~34 m GEL) (Carr and Head, 2015) is significantly less than the estimated volume of water contained in the Hesperian ocean (~130 m GEL) (Carr and Head, 2003) and such large volumes of water are unlikely to have been lost to space (e.g. Jakosky, 1993; Jakosky et al., 2017; Lammer et al., 1996).

In this chapter, we review in detail multiple proposed mechanisms for recharge of the groundwater system and assess whether sufficient volumes of water could have been returned to the subsurface through these mechanisms. Previously proposed groundwater system recharge mechanisms include: (1) rapid infiltration into the regolith and groundwater system in the highlands, (2) basal melting beneath the polar caps, (3) basal melting beneath the Tharsis rise and Tharsis volcanoes, and (4) melting of surface and cryosphere ice and infiltration into the subsurface from basal melting due to increased overburden pressure from lava loading. We find that all of the proposed mechanisms are unlikely to have produced sufficient recharge to the groundwater system and suggest that

either (1) if these oceans did exist, they may have formed through processes different than those canonically considered, (2) an additional recharge mechanism exists that has not been previously identified and quantified, or (3) one or both of the oceans did not exist.

In **Chapter Nine**, titled *Groundwater release on early Mars: Utilizing models and proposed evidence for groundwater release to estimate the required climate and subsurface water inventory* (Palumbo and Head, 2020), we extend further our assessment from **Chapter Seven** and **Chapter Eight**. Specifically, the northern lowlands is not the only location on Mars that is predicted to have experienced groundwater release to the surface earlier in planetary history. Other locations that host evidence for past groundwater release include (1) Meridiani Planum, which hosts minerals consistent with groundwater cycling (Andrews-Hanna et al., 2010, 2007), (2) NE Hellas, which has paleolakes in craters and other topographic lows that contain morphologies consistent with groundwater release (Hargitai et al., 2018), (3) Terra Sirenum, which has paleolakes in craters that contain minerals consistent with groundwater release (Wray et al., 2011), and (4) Gale Crater, which exhibits redox stratification that has been attributed to a possible groundwater influence (Hurowitz et al., 2017).

In this work, we implement the same methods as in **Chapter Seven** in order to determine the coldest possible climate and minimum subsurface water inventory required for groundwater release at all of these locations of interest (LOI). We find that: (1) although some of the LOI, including Gale crater and Meridiani Planum, could have experienced groundwater release in globally sub-freezing climates (global MAT <273 K), other LOI require warmer climates, as warm and global MAT ~286 K; (2) in order for

groundwater release to have occurred at all of the LOI, global MAT must have been $>\sim 286$ K and there must have been $>\sim 496$ m GEL water contained in the subsurface and these warm conditions must have persisted for $>\sim 30,000$ years; and (3) if global MAT was never >286 K and/or the subsurface contained <496 m GEL water, the features in some or all of the LOI must be explained via a process other than this mechanism of groundwater release. Thus, although the formation of a groundwater-fed Noachian ocean does not require global MAT above freezing, groundwater release at all of the LOI cumulatively does require global MAT above freezing. These predictions for very warm climates and large subsurface water inventories should be further tested against the geologic record.

Finally, we conclude with a synthesis section, discussing how the results of our work contribute to the current state of understanding of the nature and evolution of the early climate and identifying avenues of future work. The key contribution from each chapter is reiterated below:

- 1) Previous hypotheses for the nature of Noachian rainfall and the evolution of rainfall intensity as atmospheric pressure declined through time are not supported by physical and mathematical relationships. Crater degradation, a key line of evidence for a long-lived “warm and wet” climate persisting throughout the Noachian, may not easily be explained by rainfall regimes that shift with changing atmospheric pressure. Such evidence may no longer be a “smoking gun” for a long-lived “warm and wet” climate.

- 2) Simulations of a “warm and wet” climate (above-freezing global MAT) that do not force a stable ocean in the lowlands are characterized by negligible amounts of rainfall. This implies that the typical view of a “warm and wet” climate is not sufficient to explain the formation of the valley networks and lakes through rainfall and related processes. In this climate scenario, fluvial activity would be dominated by melting of surface snow/ice and runoff, similar to in a “cold and icy” climate with punctuated heating. This is different than an arid climate with persistent or seasonal rainfall that drives fluvial and lacustrine activity (Ramirez and Craddock, 2018) because rainfall is negligible and insufficient to cause any fluvial or lacustrine activity.
- 3) The distribution of valley networks and lakes is more consistent with the model-predicted distribution of snow/ice melting in a long-lived “cold and icy” climate with punctuated heating than the model-predicted distribution of summertime snow/ice melting in a long-lived “warm and wet” climate.
- 4) If the valley networks and lakes did in fact form through rainfall and related erosion, not melting of snow/ice and related erosion, and topography was similar to present-day, the climate must have been characterized by Earth-like temperatures (global MAT $>\sim 285$ K). Additionally, even in these very warm climates, annual snow accumulation and melting in the highlands is predicted; Noachian models for fluvial and lacustrine activity should consider both rainfall and snow/ice melting.
- 5) If the long-lived early climate was “cold and icy”, one or more periods of punctuated or transient heating must have occurred in order to cause melting of

surface snow/ice and runoff and/or rainfall and runoff. One such heating mechanism is volcanism-induced heating from the release of sulfur-based gases in the atmosphere. For the first time, we explored both *phase one* and *phase two* of these heating events with the 3D LMD GCM and found that (1) in *phase one*, significant localized heating can occur near the volcanic edifice, possibly leading to melting of surface snow/ice and runoff, and (2) in *phase two*, although global MAT is <273 K, summertime temperature may be above freezing, permitting summertime melting of surface snow/ice and runoff. Thus, this mechanism may have contributed to the formation of LN-EH valley networks and lakes.

- 6) Although impact cratering-induced heating, deposition of hot spherules, and rainfall are unlikely to be related to the formation of LN-EH valley networks and lakes, such processes could explain smoothing of plains, degradation of craters, and aqueous alteration at the surface. We have qualitatively and quantitatively explored the effects of the youngest of the large basins, the Argyre basin, in an effort to determine which surface features and characteristics could be caused by impact effects, not background climate processes.
- 7) The formation of a groundwater-fed Noachian ocean is possible in a climate with global MAT below freezing and a reasonable subsurface water inventory. Thus, the presence of a Noachian ocean should no longer be used as evidence for a long-lived “warm and wet” climate, characterized by global MAT above freezing.
- 8) Recharge of the groundwater system after both the formation of the Noachian and Hesperian oceans is an unsolved problem, and future work should aim to identify significant recharge mechanisms.

- 9) In order for groundwater release to have occurred at many previously identified locations, including Meridiani Planum, Terra Sirenum, and Gale crater, in addition to the northern lowlands, the global MAT must have been $>\sim 286$ K, similar to present-day temperatures on Earth. Cumulatively, these LOI suggest that the early martian climate was very warm for at least tens of thousands of years. Alternatively, the evidence for groundwater release at these LOI must be otherwise explained.

In summary, our work has taken multiple new approaches to test many aspects of the predicted characteristics of both “cold and icy” and “warm and wet” early martian climates. Together, the findings from our nine research chapters suggest that we should not discount the possibility that the long-lived early climate was “cold and icy” with one or more periods of punctuated heating that increased global MAT to above freezing and persisted for thousands of consecutive years.

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CHAPTER ONE

RAINFALL ON NOACHIAN MARS: NATURE, TIMING, AND INFLUENCE ON GEOLOGIC PROCESSES AND CLIMATE HISTORY

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Abstract

The formation of Noachian-aged geologic features on Mars, including degraded impact craters, valley networks, and lakes, has been interpreted to require a continuously “warm and wet” Noachian climate, with above-freezing surface temperatures and rainfall. More specifically, it has been argued that a change in the nature of rainfall in the Noachian, from a diffusive rain splash-dominated erosion regime to an advective runoff-dominated erosion regime, is the best explanation for the observed temporal differences of erosion style: the degradation of craters has been interpreted to be due to rain splash throughout the Noachian, while the formation of valley networks and lakes has been interpreted to be due to more erosive activity and more abundant fluvial activity at the Noachian/Hesperian transition. However, the presence of a long-lived “warm and wet” climate with rainfall is difficult to reconcile with climate models which instead suggest that the long-lived climate was “cold and icy”, with surface temperatures far below freezing, precipitation limited to snowfall, and most water trapped as ice in the highlands. In such a “cold and icy” climate scenario, fluvial and lacustrine activity would only be possible during transient warm periods, which could produce “warm and wet” conditions for relatively short periods of time. In this work, we review the geomorphic evidence for Noachian rainfall and the various rainfall-related erosional regimes, explore climate model predictions for a “cold and icy” climate and the potential for short-lived “warm and wet” excursions, and attempt to characterize the transition from diffusive to advective erosional rainfall regimes through analysis of atmospheric pressure and rainfall dynamics. We conclude that (1) if rainfall occurred on early Mars, raindrops would have been capable of transferring sufficient energy to initiate sediment transport regardless of

atmospheric pressure, implying that rain splash would have been possible throughout the Noachian, and (2) in contrast to previous findings, maximum raindrop size does not depend on atmospheric pressure and, as a result, simple parameterized relationships suggest that rainfall intensity (rainfall rate) does not depend on atmospheric pressure. Therefore, our results, based on the implementation of a simple parameterized relationship for rainfall intensity, predict that there would not have been a transition from rain splash-dominated erosion to runoff-dominated erosion related solely to decreasing atmospheric pressure in the Noachian. This finding is not consistent with the hypothesis of Craddock and Lorenz (2017) that the long-lived Noachian climate was “warm and wet” with rainfall throughout the Noachian and that rainfall intensity changed as a function of atmospheric pressure declining through time; our findings do not preclude the possibility that early Mars was predominantly “cold and icy”. Remaining unknown is the mechanism(s) for the observed geomorphic transition in erosion style, and whether melting of surface snow/ice and runoff during a punctuated heating episode in an otherwise “cold and icy” climate could explain the formation of the valley networks and lakes in the absence of rainfall. We conclude by outlining future work that introduces more advanced methodology to further explore a possible relationship between rainfall intensity and atmospheric pressure.

Keywords: rainfall; climate; Noachian; erosion

1. Introduction

Observations of martian surface features, including the valley networks (e.g. Fassett & Head, 2008a; Hynek et al., 2010) and open- and closed-basin lakes (e.g. Cabrol & Grin, 1999; Fassett & Head, 2008b; Goudge et al., 2015), indicate that overland fluvial flow and lacustrine activity occurred in the Late Noachian-Early Hesperian era (LN-EH, ~3.7 Ga) (Fassett & Head, 2008a). Evidence suggests that this fluvial and lacustrine activity was most intense in the LN-EH; the majority of valley networks and lakes are on LN-EH-aged terrains (Fassett & Head, 2011). This implies that the nature of the climate and erosive regime in the LN-EH was much different from the nature of the climate both earlier in the Noachian and later in the Hesperian and Amazonian (Howard et al., 2005; Irwin et al., 2005), with the LN-EH interpreted to be characterized by relatively more rainfall and overland flow (e.g. Craddock & Howard, 2002; Ramirez & Craddock, 2018). However, overland flow, a potentially effective form of advective erosion (sediment transport and erosion due to movement via currents of fluid movement), is not the only signature of liquid water activity on the early martian surface: Noachian-aged impact craters commonly have degraded rims, shallow floors, and lack visible ejecta deposits and central peaks, features that cannot easily be explained without the influence of diffusive erosion (Craddock & Howard, 2002) in addition to advective erosion. Interestingly, younger Hesperian or Amazonian-aged craters do not display these characteristics. Researchers have postulated that rain splash, an effective form of diffusive erosion, was important in the Noachian and was predominantly responsible for the observed crater degradation (e.g. Craddock & Howard, 2002); rain splash is a diffusive process through which sediment transport is initiated by the collision of

raindrops with the surface. Many other forms of advective and diffusive erosion exist, such as aeolian erosion, mass wasting, or micrometeorite bombardment. However, rainfall-related mechanisms, including rain splash and overland flow, are interpreted to be the only diffusive and advective erosional mechanisms that are effective enough to leave the observed surficial expression and are not expected to have continued into the Hesperian and Amazonian (Craddock and Howard, 2002). It is important to note that Craddock and Howard (2002) discuss other possible explanations for these characteristics of crater morphology, including solifluction as the dominant diffusional process and surface runoff from snowmelt, but rain splash and rainfall-driven runoff is the “simplest way of explaining” their observations (Craddock and Howard, 2002).

Thus, the paradigm for Noachian erosion follows: diffusive erosion from rain splash is interpreted to have been dominant throughout most of the Noachian, leading to the degradation of crater rims and erosion of ejecta deposits, and advective erosion from rainfall and surface runoff is interpreted to have been dominant at the LN-EH boundary, leading to the formation of the valley networks and lakes (e.g. Craddock and Howard, 2002; Craddock & Lorenz, 2017). In addition to this role of rainfall, some valley networks are sourced from lakes and required lake overspill to form, suggesting the presence of abundant liquid water on the surface in the LN-EH. In this paradigm for martian erosion, at later times throughout most of the Hesperian and Amazonian, temperatures are interpreted to have been too cold to permit rainfall, thereby explaining the absence of degraded craters, valley networks, and lakes on these younger terrains (e.g. Craddock and Howard, 2002).

To explain these erosional regimes and the persistence of rainfall in the Noachian and LN-EH, researchers commonly call upon the hypothesis that the early martian climate was “warm and wet” (e.g. Craddock et al., 1997, 2018; Craddock & Howard, 2002; Craddock & Lorenz, 2017), characterized by global mean annual temperature (MAT) above freezing and rainfall (Ramirez & Craddock, 2018) (Fig. 1); note that this “warm and wet” climate may have been arid to semi-arid in comparison with Earth; however, relatively more rainfall is expected to have occurred in the Noachian (specifically the Late Noachian) than at other times during martian history. The abundance and rates of rainfall are expected to have changed throughout the Noachian, causing the shift from a diffusive rainfall erosional regime (rain splash and infiltration; crater degradation) to an advective rainfall erosional regime (runoff and fluvial erosion; valley networks and lakes) (Craddock & Lorenz, 2017).

In contrast to this evidence for warm temperatures and rainfall, climate modeling studies (e.g. Forget et al., 2013; Kasting, 1991; Wordsworth et al., 2013) have not been able to successfully reproduce long-lived “warm and wet” conditions on early Mars. Due to the influence of the faint young Sun, these recent models of the Noachian climate instead predict that the long-lived background climate was “cold and icy”, characterized by temperatures far below freezing (global mean annual temperature, MAT, ~225 K) and with most surface water trapped as snow and ice in the highlands. In this “cold and icy” climate scenario, fluvial and lacustrine activity would only be possible during periods of punctuated heating, which could have produced short-lived “warm and wet” conditions (e.g. conditions suitable to melting and runoff or rainfall and runoff), for example, in the LN-EH (Fig. 1).

Analysis of the predicted nature and persistence of these two erosional regimes in the Noachian may provide important insight into whether the climate was continuously “cold and icy” (with periods of punctuated heating to permit fluvial activity) or “warm and wet” (with rainfall throughout the Noachian, but varying in rate and intensity as a function of time). In this contribution, we revisit the nature and evolution of the early martian climate through an analysis of rainfall-related processes in an effort to understand the link between the geomorphic observations and the characteristics of the early climate. Specifically, we (1) review the geomorphic evidence for rainfall in the Noachian and the various rainfall-related erosional regimes, (2) explore predictions from some recent climate modeling studies regarding the characteristics of the Noachian climate and the potential for short-lived “warm and wet” excursions, (3) attempt to characterize the transition from a diffusive to an advective erosional regime through mathematical relationships in an effort to link the geology with climate model predictions, and (4) conclude by outlining outstanding questions and potential avenues of future research.

2. Rainfall in the Noachian: Predictions based on geomorphology

Craters of different ages (spanning the Noachian era) are preserved in various stages of degradation, implying that erosive activity was operating nearly continuously throughout the Noachian (Craddock et al., 1997; Craddock & Howard, 2002). Specifically, older Noachian craters have experienced more erosion than younger Noachian craters (e.g. Craddock et al., 1997; Craddock & Howard, 2002; Forsberg-Taylor et al., 2004; Howard, 2007; Jones, 1974) and smaller diameter craters appear to have eroded more quickly than larger diameter craters (Craddock et al., 1997). Rainfall is

likely to have played an important role in the observed erosion, including degradation of crater rims, shallowing of crater floors, and erosion of ejecta deposits (e.g. Craddock and Howard, 2002). Specifically, diffusive activity from rain splash may be required to explain the observed erosion (e.g. Craddock and Howard, 2002). It is important to note that other additional erosive activity may be required to explain the observed erosion in its entirety, including the possible role of some forms of advective erosion, such as backwasting (Forsberg-Taylor et al., 2004). In addition to this, valley networks and lakes imply that a predominantly advective erosional regime, with surface runoff and fluvial activity, was important in the LN-EH (e.g. Howard et al., 2005; Irwin et al., 2005).

This geologic evidence for rainfall and variation of rainfall-related processes, including rain splash and overland flow, that were shaping the surface in the Noachian has led researchers to postulate that there were two different aqueous rainfall-related erosional regimes in the Noachian (e.g. Craddock & Howard, 2002; Craddock & Lorenz, 2017). First, the rainfall-related erosional regime in the Early-to-Mid Noachian is interpreted to have been dominated by diffusive processes, specifically rain splash. In this rain splash-dominated erosional regime, rainfall rates were generally too low to exceed the infiltration capacity of the regolith; most rainfall infiltrated into the subsurface, surface runoff was minimal or negligible, and rainfall-related erosion was mostly diffusive (e.g. Craddock & Howard, 2002). Second, and subsequently, the rainfall-related erosional regime in the LN-EH is interpreted to have been dominated by advective processes, specifically surface runoff and overland flow. In this runoff-dominated regime, rainfall rates were sufficiently high that rainfall exceeded the infiltration capacity of the regolith and runoff occurred (e.g. Craddock et al., 1997; Craddock & Howard, 2002;

Howard, 2007). Rain splash erosion is still expected to have occurred, but the dominant rainfall-related erosive mechanism was surface runoff. This shift in rainfall-related erosional regime through time is interpreted to be consistent with (1) the increasing degree of degradation of Noachian craters as a function of age and (2) the presence of the LN-EH valley networks and lakes (e.g. Craddock et al., 1997; Craddock and Howard, 2002). Prior to the LN-EH, erosion was more effective than in the current Amazonian regime, albeit less effective than in the LN-EH: in the Early-to-Mid-Noachian, rain splash acted to degrade crater rims and effectively remove ejecta deposits, and in the LN-EH, more intense rainfall was responsible for enhanced crater erosion and formation of the observed fluvial and lacustrine features (Craddock & Lorenz, 2017). In summary, “A change in the nature of rainfall during the history of early Mars appears to be the best solution for the observed temporal differences between the style of erosion during the Noachian as represented by modified impact craters (e.g. Craddock and Howard, 2002) followed by more enhanced erosion during the Noachian/Hesperian transition as typified by valley networks (Fassett & Head, 2008a; Howard, 2007; Howard et al., 2005; Irwin et al., 2011; Matsubara et al., 2013)” (Craddock and Lorenz, 2017). Thus, this geomorphic hypothesis provides important predictions regarding the required climatologic characteristics of the Noachian that can be explored further with climate models.

3. Rainfall in the Noachian: Predictions based on climate models

Modeling studies of the early martian climate suggest that the long-lived background climate was more likely to have been “cold and icy” than “warm and wet” (e.g. Forget et al., 2013; Kasting, 1991; Wordsworth et al., 2013). In the Noachian, if

atmospheric pressure exceeded a few tens of millibars, many recent 3-dimensional global climate models (GCMs) predict that the surface and atmosphere would have been thermally linked together, producing an adiabatic cooling effect and causing temperature variations to have been dominantly dependent on altitude, rather than latitude (e.g. Forget et al., 2013). In a “cold and icy” climate scenario, global MAT is predicted to be ~225 K and, because of the adiabatic cooling effect, most surface water is predicted to be trapped in the highlands as snow and ice. Temperatures are far too cold for rainfall to occur and, thus, it is difficult to reconcile these Noachian rainfall-dominated erosional regimes with recent climate models (e.g. Forget et al., 2013; Wordsworth et al., 2013, 2015).

Several studies have focused on how to reconcile the advective rainfall-related LN-EH erosional regime, which is required to explain the valley networks and lakes, with this “cold and icy” climate scenario. Some researchers have suggested that fluvial and lacustrine activity, driven by rainfall and/or snowmelt, could occur during periods of punctuated heating (e.g. Head & Marchant, 2014; Wordsworth, 2016). There may have been specific punctuated heating events in the LN-EH that produced short-lived “warm and wet” conditions in an otherwise “cold and icy” climate regime, potentially explaining the peak in advective erosion (Fig. 1). Some researchers refer to this as a ‘climatic optimum’; for additional discussion of mechanisms that could cause this climatic optimum, see Howard (2007).

Multiple LN-EH punctuated heating mechanisms have been proposed, including impact cratering-induced heating (e.g. Palumbo & Head, 2018b; Segura et al., 2008; Toon et al., 2010), volcanism-induced heating (e.g. Halevy & Head, 2014; Johnson et al., 2008; Kerber et al., 2015; Mischna et al., 2013), spin-axis/orbital variations and

summertime melting (e.g. Kite et al., 2013; Mischna et al., 2013; Palumbo et al., 2018), transient greenhouse-rich atmospheres (e.g. Wordsworth et al., 2017), and the presence of high-altitude clouds (e.g. Forget & Pierrehumbert, 1997; Segura et al., 2008; Urata & Toon, 2013). We identify these as ‘punctuated’ or ‘transient’ heating mechanisms because the associated heating will occur for a finite period of time shorter than the duration of the LN-EH, ranging from days to hundreds of thousands of years (note that other mechanisms have also been proposed which could have led to warm periods of up to ~10 million years in duration, such as climate cycling forced by the carbonate-silicate cycle; Batalha et al., 2016). Studies of the heating potential of each of these punctuated heating mechanisms have shown that the most likely candidates to have been sufficiently active in the LN-EH, and thus to have increased global MAT to >273 K in a long-lived background “cold and icy” climate, are transient greenhouse-rich atmospheres and the presence of high-altitude water clouds. In this section, we review these two punctuated heating mechanisms to determine whether short-lived “warm and wet” conditions could have persisted in a long-lived background “cold and icy” climate and, further, whether abundant rainfall, surface runoff, and advective erosion is expected to have occurred during these transient warm excursions.

Transient greenhouse-rich atmospheres. When considering reasonable source and sink constraints, many greenhouse gases are incapable of producing sufficient greenhouse warming on early Mars (e.g. see review by Forget et al., 2013). However, recent work has shown that, while methane and hydrogen alone are not strong greenhouse gases, collision induced absorption (CIA) effects lead to new and stronger absorptions (e.g. Wordsworth et al., 2017). Ongoing work aims to constrain the magnitude of associated

heating and concentration of these gases required to increase global MAT to >273 K on early Mars (e.g. Ramirez et al., 2014; Turbet et al., 2019; Wordsworth et al., 2017), but preliminary results suggest that it is possible with reasonable concentrations of H_2 or CH_4 (Wordsworth et al., 2017). This punctuated heating mechanism could have occurred in the LN-EH; H_2 and CH_4 could have been introduced to the atmosphere through volcanism (e.g. Ramirez, 2017; Ramirez et al., 2014), or serpentinization (Holm et al., 2015) and/or clathrate breakdown (Kite et al., 2017), respectively.

High-altitude clouds. Given the correct cloud characteristics, including cloud height, clouds can scatter IR radiation back towards the surface, producing a greenhouse effect. Researchers have hypothesized that high-altitude CO_2 clouds (e.g. Forget & Pierrehumbert, 1997) and high-altitude H_2O clouds (e.g. Segura et al., 2008; Urata & Toon, 2013; *for additional modeling studies of the effects of high altitude H_2O clouds, see Madeleine et al., 2012, 2014*) could have significantly heated the early martian surface. However, recent 3D GCM simulations have shown that (1) high-altitude CO_2 ice clouds can only bring sufficient heating if there is $\sim 100\%$ cloud coverage (e.g. Forget & Pierrehumbert, 1997; Mischna et al., 2000), which is unlikely (Forget et al., 2013; Wordsworth et al., 2013), and (2) heating associated with high-altitude H_2O clouds can increase global MAT to above 273 K for centuries or longer (Mischna et al., 2019), but these clouds can only form in very arid conditions (Urata & Toon, 2013; Kite et al., 2019) and require very low precipitation rates (Urata & Toon, 2013).

Characteristics of a transiently-heated climate. In order to determine whether abundant rainfall and surface runoff is expected to have occurred during these periods of

transient or punctuated heating, some researchers have used climate models to explore the characteristics of greenhouse-heated and high-altitude cloud-heated atmospheres.

Palumbo and Head (2018a) used a 3D GCM to simulate a greenhouse-heated atmosphere by using gray gas as a proxy for greenhouse heating. Interestingly, for climates with global MAT ~ 275 K, above the melting point of water and consistent with the canonical view of a “warm and wet” climate, the highest elevation regions, including parts of the Tharsis rise, are below freezing year-round and act as surface cold traps for H₂O. Thus, even in this warm climate, surface water is cold-trapped as ice and, as a result, rainfall is negligible (Palumbo & Head, 2018a). It is important to note, however, that Wordsworth et al. (2015) showed that rainfall is possible in this climate scenario if there is an oceanic water source in the lowlands, but the presence of oceans is uncertain, particularly in the Noachian (e.g. Head et al., 2018), and the model-predicted distribution of rainfall is not well-correlated with the distribution of valley networks.

Urata and Toon (2013) used a 3D GCM and showed that specific conditions are required to produce high-altitude H₂O clouds and associated warm temperatures: (1) ice crystal sizes around 10 μm or larger, which is consistent with thin cirrus clouds on Earth, (2) low conversion rate of clouds to precipitation which is required to increase the lifetime of water in the atmosphere and to permit the formation of thicker clouds (note that this did not naturally occur in their simulations; Urata and Toon (2013) had to force such low precipitation rates), (3) near $\sim 100\%$ cloud coverage to effectively reduce the cloud albedo which, although potentially consistent with thin cirrus clouds on Earth, has been suggested to be unlikely for early Mars (e.g. Forget et al., 2013), and (4) the surface must be inherently dry with limited surface water reservoirs. More recently, Kite et al.

(2019) and Mischna et al. (2019) used a 3D GCM to explore the formation of high-altitude H₂O clouds on early Mars and found that it is only possible in very arid conditions, which is consistent with the earlier findings of Urata and Toon (2013). Even for global MAT ~290 K, the small amount of available water is cold trapped in the highest elevation areas of the Tharsis rise and, as a result, rainfall is negligible (e.g. Kite et al., 2019; Mischna et al., 2019). Note that the warm case from Urata and Toon (2013), their case 17 in table 3, does not find global MAT >273 K, even though the initial starting condition is global MAT ~300 K; instead, they find that “the globally averaged surface temperature is several degrees below the melting temperature of ice, but several areas of the planet, including the Hellas region and the tropics, have annually averaged temperatures near melting”.

It is important to note that, because topography is the dominant control on Noachian climate, the above results are dependent upon the topography that is implemented in the model. These works used present-day topography in their simulations, which is consistent with the major volcanic rises and impact basins having formed by the LN-EH (Fassett & Head, 2011). However, recent studies have suggested that the Tharsis rise may have been largely emplaced after the LN-EH (e.g. Bouley et al., 2018), and thus a better understanding of Noachian topography may improve upon the accuracy of model-predicted characteristics of the early climate.

In summary, these transient “warm and wet” climates do not appear to have been characterized by rainfall. Thus, if the LN-EH valley networks and lakes were formed during a period of transient heating in a long-lived “cold and icy” climate, we conclude that either (1) the transient warm climate was much warmer than those simulated by

Palumbo and Head (2018a) (e.g. global MAT >275 K), removing any surface cold traps and potentially permitting rainfall, (2) a different, currently unidentified, transient heating mechanism exists that causes rainfall, potentially through the introduction of large amounts of water vapor to the atmosphere, or (3) the observed fluvial and lacustrine activity was not caused by rainfall and runoff, but by snow melting and runoff.

Alternatively, the climate models that predict “cold and icy” conditions, albeit being the most up-to-date, complex, and physically self-consistent, do not perfectly capture the atmospheric physics, the long-lived Noachian climate was actually “warm and wet”, not “cold and icy”, and rainfall was continuous throughout the Noachian.

Additionally, it is important to note that rainfall and related processes occurring throughout the Noachian, as required by the proposed diffusive erosion mechanism of rain splash (e.g. Craddock et al., 1997; Craddock & Howard, 2002), are not consistent with a continuous and long-lived “cold and icy” climate with punctuated heating in the LN-EH; all precipitation would be snowfall in a “cold and icy” climate, not rainfall. If the long-lived background climate was “cold and icy”, then this signature of diffusive erosion throughout the Noachian must be explained by other mechanisms. One explanation for this could be one or more episodes of transient/punctuated heating throughout the Noachian that produced some rainfall, but not runoff, causing period(s) of diffusive erosion by rain splash. Alternatively, the observed erosion may have been caused by snowmelt and runoff, not rainfall and runoff (e.g. Fastook & Head, 2015; Palumbo & Head 2018a).

4. Determining whether the nature of the rainfall-related erosional regime depends on atmospheric pressure

How, then, can we explain the erosional regimes that are required to account for the widespread Noachian-aged degraded craters and LN-EH valley networks and lakes? Specifically, what approach can be undertaken in order to reconcile the geologic signature of rainfall with the climate models that apparently cannot reproduce conditions with abundant rainfall? Recent work utilized measurements of fossilized raindrop imprints in conjunction with mathematical relationships in order to estimate the atmospheric pressure on early Earth (Kavanagh & Goldblatt, 2015; Som et al., 2012). Craddock and Lorenz (2017) called upon these methods to provide insight into the evolution of the early martian atmosphere and the process(es) that could have been responsible for the changing nature of rainfall. On the basis of basic equations and relationships, the authors hypothesized that the long-lived Noachian climate was “warm and wet”, with above-freezing temperatures and rainfall, and that the rainfall erosional regime could have shifted from rain splash-dominated to runoff-dominated as a function of decreasing atmospheric pressure through time (Craddock & Lorenz, 2017) as the atmosphere was slowly being lost to space (Fig. 2). Specifically, Craddock and Lorenz (2017) found that (1) rain splash-related erosion may not be possible for atmospheric pressures >4 bar, (2) rainfall intensity sufficient to cause surface runoff cannot exist for atmospheric pressures $<\sim 1.5$ bar, and (3) lighter rain is more probable for higher atmospheric pressures, $\sim 3\text{--}4$ bar, which is more consistent with a rain splash-dominated erosional regime, and heavier rain is more probable for lower atmospheric pressures, ~ 1.5 bar, which is more consistent with a runoff-dominated erosional regime. These

conclusions suggest that multiple rainfall regimes could have existed as atmospheric pressure declined through time, which Craddock and Lorenz (2017) interpreted to be generally consistent with the evidence for both diffusive and advective rainfall-related erosional regimes in the Noachian.

In this section, we revisit these mathematical relationships (following the approach of Som et al., 2012; Craddock and Lorenz, 2017) in order to test the hypothesis that different erosional regimes could have existed under different atmospheric pressure regimes. This test provides insight into the plausibility of the long-lived Noachian climate being “warm and wet” with continuous rainfall, because the changing nature of rainfall throughout the Noachian is predicted to have been controlled by decreasing atmospheric pressure (Craddock and Lorenz, 2017). Although this does not explain the required persistence of warm temperatures that cannot be reproduced by current climate models, it may explain the physical mechanism for the interpreted shift in erosional regime. By improving our understanding of the role that atmospheric evolution has on rainfall intensity and erosional regime, we strive to place tighter constraints on the predicted conditions that climate models must reproduce. To do this, we introduce the mathematical relationships for (1) the energy transfer from raindrops colliding with the martian surface and (2) the maximum raindrop size capable of passing through the martian atmosphere, then discuss the implications of our findings for rainfall intensity and different erosional regimes.

The energy transferred as a raindrop collides with the martian surface can be approximated by assuming that all of the kinetic energy of the falling raindrop is transferred to the surface upon collision, potentially initiating sediment movement. The

kinetic energy, E , is equal to $0.5 m v_t^2$, where m is the mass of the raindrop and v_t is its terminal velocity. Assuming a spherical raindrop (a good approximation for all but the largest raindrops, e.g. Craddock and Lorenz, 2017; Som et al., 2012) of diameter d , the mass is equal to $(\pi/6) d^3 \rho_{\text{water}}$ where ρ_{water} is the density of the raindrop. The terminal velocity of the raindrop is found by equating the weight of the drop, mg , where g is the acceleration due to gravity, to the drag force exerted on the raindrop by the atmosphere, $0.5 \rho_a C_d (\pi/4) d^2 v_t^2$, where ρ_a is the atmospheric density and C_d is a drag coefficient of order unity. Thus, the terminal velocity is given by:

$$v_t = \left(4 d \rho_{\text{water}} g / 3 C_d \rho_a \right)^{1/2},$$

and, hence, the kinetic energy, E , is given by

$$E = \frac{1}{9} \frac{\rho_{\text{water}}^2 g}{C_d \rho_a} \pi d^4.$$

The relationships between raindrop diameter, d , and terminal velocity, v_t , and kinetic energy, E , as a function of changing atmospheric pressure are shown in Fig. 3.

These equations for terminal velocity and kinetic energy provide important insight; however, understanding more about how raindrops form, speeds at which they pass through the atmosphere, and how and why they might break up is required for us to estimate maximum raindrop diameter and begin discussions about rainfall intensity and the erosive ability of the rainfall. Raindrops reaching the surface of a planet have a range of sizes as a result of their formation mechanism. Drops nucleate in clouds by condensation of water vapor onto extremely small nuclei. These nuclei can be dust particles derived from the surface due to the action of the wind or the results of the evaporation or disintegration of small meteoroids in the planetary atmosphere. The drops

grow by ongoing water condensation and by collision-aided size sorting in turbulent eddies in the clouds (Falkovich et al., 2002). Upon saturation, droplets will leave the base of the cloud as precipitation. Droplets leaving the base of the cloud accelerate towards their terminal velocity, v_t , which is potentially reached when the weight of the droplet exactly balances the atmospheric drag force. However, as the drop speed and the drag force acting on it increase, interaction between the stress distribution on the surface of the raindrop and the surface tension at the water-gas interface causes deformational instabilities (e.g. Villiermaux and Bossa, 2009). For relatively large raindrops, this instability is reached before the terminal velocity is attained, and the drop breaks up catastrophically into a spectrum of smaller sizes. If the initial drop was large enough, some of these secondary drops may themselves accelerate and break up before reaching their terminal velocity.

For any raindrop of diameter d that is falling at speed v , this instability occurs when the Weber number, We , equal to $[(\rho_a v^2 d) / \gamma]$, becomes greater than a critical value We_{crit} . We note that Kolev (2005, his chapter 8) discusses the influence of dynamic, viscous and surface tension forces on falling raindrops in great detail, and shows that the instability of falling raindrops also depends on the Ohnesorge number, Oh , equal to $[\mu / (\rho_a \gamma d)]^{1/2}$, where μ is the atmospheric gas viscosity. Oh must be less than ~ 4 to ensure drop instability, but for falling raindrops on both Earth and Mars this requirement is readily met with Oh being on the order of 10^{-2} to 10^{-4} . The value of the critical Weber number is variously taken to be close to 6 (Villiermaux and Bossa, 2009), 8 (Craddock and Lorenz, 2017) or 12 (Kolev, 2005). We follow Craddock and Lorenz (2017) in assuming the value 8, so the critical speed to ensure breakup is $v_b = [(8 \gamma) / (\rho_a d)]^{1/2}$.

Thus, the critical speed depends on the atmospheric density, and hence atmospheric pressure, and on the surface tension, which depends weakly on atmospheric temperature. Over the 0-20° C temperature range of relevance here, surface tension, γ , ranges from 0.0756 N/m to 0.0728 N/m (see https://www.engineeringtoolbox.com/water-surface-tension-d_597.html for a larger range of temperatures). We implement a value of 0.0728 N/m, again following Craddock and Lorenz (2017).

Table 1 shows the result of calculating both the terminal velocity, v_t , and the breakup velocity, v_b , for a range of raindrop diameters and atmospheric conditions on early Mars. Consider the second column, for $d = 1$ mm. In every case the terminal velocity is much less than the breakup velocity, so for all of the atmospheric conditions shown, 1 mm raindrops will reach their terminal velocity without breaking up due to drop instabilities. Now, consider the final column, for $d = 15$ mm. In every case the terminal velocity is greater than the breakup velocity, so all of these large raindrops would have broken up due to drop instabilities before reaching their terminal velocity. The critical result is that for every set of atmospheric conditions, the transition between stability and instability (reaching terminal velocity and not reaching terminal velocity) takes place at the same raindrop diameter, $d_{max} = 10.797$ mm. The speed marking the transition varies with the atmospheric properties but, in contrast to Craddock and Lorenz (2017), we find that the size of the largest stable droplet is independent of atmospheric pressure. This result, that the maximum raindrop diameter, d_{max} , is independent of atmospheric pressure, is consistent with findings from previous numerical and experimental studies of raindrop dynamics (e.g. Villiermaux and Bossa, 2009).

From the maximum raindrop diameter, d_{max} , we can estimate rainfall intensity. Rainfall intensity is useful for estimating regimes where rainfall exceeds infiltration capacity, permitting surface runoff. A parameterized relationship for rainfall intensity and median raindrop size has been developed for rainfalls on Earth (e.g. Marshall and Palmer, 1943) and follows:

$$D_{50} = \alpha I^\beta$$

where D_{50} (mm) is the median drop size, approximated to be half of the maximum drop size (we acknowledge that this is a simplified approach, but implement it because it has been utilized previously; Craddock and Lorenz, 2017), I is rainfall intensity (mm/hr), and α and β are coefficients that have been approximated from empirical measurements of terrestrial rainfalls to range from ~ 0.80 - 1.28 and 1.23 - 2.92 , respectively (e.g. Craddock and Lorenz, 2017 and references therein). Thus, larger median raindrop sizes are correlated with more intense rainfall (Table 2). However, because fragmentation diameter (maximum raindrop diameter) does not depend on atmospheric pressure (Table 1), the range of raindrop diameters within a given rainfall will also be independent of pressure, and the total rainfall intensity due to this range of droplet sizes will also be independent of atmospheric pressure, in contrast to the findings of Craddock and Lorenz (2017).

Thus, our assessment based on this parameterized relationship for rainfall intensity suggests that a change in rainfall intensity as a function of time is not predicted to occur as a result of decreasing atmospheric pressure. Recall that such a change in rainfall intensity is required to explain the shift from a diffusive to advective erosional regime in a long-lived “warm and wet” climate (Craddock and Lorenz, 2017). Our results suggest that either (1) the long-lived climate was “warm and wet” and a mechanism other

than decreasing atmospheric pressure was responsible for the shift in rainfall intensity and erosional regime, or (2) the long-lived climate was “cold and icy,” and the peak in fluvial and lacustrine activity and advective erosion in the LN-EH was due to punctuated heating, ice melting, and surface runoff, not rainfall.

However, it is important to note that this parameterized relationship comes from observations of rainfall of varying intensity and measurements of raindrop counts on Earth (e.g. Marshall & Palmer, 1943; Bennett et al., 1984), has been confirmed for rainfall on Earth when averaged over time and space (Brodie and Rosewell, 2007), and has been confirmed with numerical experiments of terrestrial rainfall (e.g. Villiermaux & Bossa, 2009). Despite the confirmation of the accuracy of this parameterized relationship for describing rainfall on Earth, we must reiterate the potential importance that this relationship was derived under terrestrial conditions based on rainfall on Earth. As such, we should revisit the mathematical equation that was simplified and approximated to arrive at the parameterized relationship ($D_{50} = \alpha I^\beta$) in order to confirm that this relationship can be directly applied to Mars and, more specifically, that the constants α and β do not actually depend on atmospheric pressure. In other words, we look to confirm that rainfall intensity depends only on median raindrop diameter, not atmospheric pressure. To do this, we can revisit the mathematical derivation of rainfall intensity shown in equations 4 and 5 in Villiermaux and Bossa (2009).

Specifically, rainfall intensity is mathematically described as the integral over raindrop diameter of the number of drops of a given size, times the volume of a raindrop of a given size, times the free-fall velocity (the maximum velocity) of a raindrop of a given size passing through the atmosphere (Villiermaux & Bossa, 2009). Their equation 5

shows us that rainfall intensity (noted therein as R , not I) can be expressed in the following way (with variable names updated to match the conventions implemented here):

$$I = n_0 \frac{\pi}{6} \sqrt{\frac{\rho_{water}}{\rho_a}} \sqrt{g} D_{50}^{9/2} \int x^{7/2} p(x) dx$$

Where n_0 is a constant that represents the average spatial density of raindrops per unit volume of space and depends on temperature (Villerraux & Bossa, 2009 and references therein), and the integral is a term approximately equal to the raindrop size distribution of a given rainfall. Of course, the derivation of maximum/median drop diameter and the parameterized relationship for rainfall intensity have already confirmed that rainfall intensity depends on gravity. The new information that is brought to light here is that rainfall intensity also depends on $\sqrt{\frac{\rho_{water}}{\rho_a}}$; rainfall intensity depends on atmospheric pressure. This atmospheric pressure term originates from the velocity term in the original integral in equation 4 from Villerraux and Bossa (2009), because raindrop velocity depends on atmospheric pressure (as we have shown previously, as well). Studies of rainfall intensity on Earth have assumed this value to be constant because the variation in atmospheric pressure on present-day Earth is so small that the term varies negligibly; this term is canonically wrapped in what we refer to as α in the parameterized relationship for rainfall intensity discussed above. However, when considering how atmospheric pressure has changed over billions of years on Mars, we cannot assume that the variation in this term would be negligible. Specifically, if we consider atmospheric pressure ranging from 0.5 to 10 bar (0.903 kg/m³ to 18.062 kg/m³), then $\sqrt{\frac{\rho_{water}}{\rho_a}}$ would range from 33 to 7.5, a

factor of ~ 5 difference. This relationship shows that, if all else remains constant, more intense rainfall would have in fact occurred under lower atmospheric pressure conditions than under higher atmospheric pressure conditions. In order to fully understand whether rainfall intensity could increase substantially enough to cause variations in erosive style, though, would require additional information that is not available at this time.

Specifically, raindrop size distributions and estimates for n_0 on Earth come from observations and measurements, which cannot be made for martian rainfall and have not yet been modeled. However, a quick speculation follows. As atmospheric pressure decreases, interactions between molecules in the atmosphere would also become less common, as a result decreasing the sum of the drop size distribution and the value of n_0 .

Therefore, although the value of $\sqrt{\frac{\rho_{water}}{\rho_a}}$ would increase, the values of n_0 and the integral term should systematically decrease. Whether these factors completely counteract one another, however, is yet to be determined.

We can summarize our discussion about rainfall intensity with two key points:

- (1) By exploring and implementing the parameterized relationship for rainfall intensity that has been proven to be accurate for rainfall on Earth, we find that rainfall intensity does not depend on atmospheric pressure. This is true because maximum raindrop diameter does not depend on atmospheric density and, also for this reason, is in contrast to the finding of Craddock and Lorenz (2017). This finding suggests that decreasing atmospheric pressure on early Mars would not have directly led to increased rainfall intensity.
- (2) We have explored further the physics and math that originally led to this parameterized relationship for rainfall on Earth and find that rainfall intensity

does actually depend on atmospheric pressure, albeit in a different way than assumed by previous studies (e.g. Craddock and Lorenz, 2017). However, the exact nature of the relationship between rainfall intensity and atmospheric pressure cannot be estimated at this time because there are other variables in the equation that are currently unknown.

5. Discussion and Conclusions

The geomorphic evidence for rainfall in the Noachian has been interpreted to mean that there were two distinct erosional regimes on Mars, including a rain splash-dominated diffusive erosional regime in the Early-to-Mid Noachian and a runoff-dominated advective erosional regime in the LN-EH (e.g. Craddock and Lorenz, 2017). However, many recent climate modeling studies have had difficulty reproducing a climate scenario in which abundant rainfall occurs (e.g. Forget et al., 2013; Wordsworth et al., 2013); rainfall does not occur in a “cold and icy” climate, and rainfall is negligible in greenhouse-heated and high altitude-cloud heated transient warm climates. In this research, we set out to test the hypothesis that the two Noachian erosional regimes can be reconciled by a long-lived climate that was “warm and wet” with continuous rainfall and that rainfall intensity changed through time as a function of decreasing atmospheric pressure (as described by Craddock and Lorenz, 2017). This proposed relationship between rainfall intensity and atmospheric pressure specifically suggests that higher atmospheric pressures are consistent with rain splash-dominated erosion and lower atmospheric pressures are consistent with runoff-dominated erosion. We mathematically test the hypothesis by determining whether rainfall intensity depends on atmospheric

pressure. This is critical for our understanding of the evolution of the martian hydrological cycle and for placing tighter constraints on the rainfall characteristics that climate models must reproduce.

Our findings are summarized below.

1. Based on our calculations of the kinetic energy transfer as raindrops collide with the surface, we find that raindrops on Mars are capable of transferring sufficient energy to initiate sediment transport regardless of atmospheric pressure (Fig. 3).
2. Maximum raindrop size, or fragmentation diameter, does not depend on atmospheric pressure. This is in contrast to the findings of Craddock and Lorenz (2017).
3. Parameterized relationships for rainfall intensity have been identified on Earth based on experiments, observations, and mathematical approaches. When we apply this relationship to Mars, we find that rainfall intensity does not vary as a function of atmospheric pressure. We note that the constants in this parameterized relationship come from observations of rainfalls on present-day Earth, and that appropriate assessments of these constants for early Mars is not currently possible. However, these constants do depend on atmospheric pressure in a way that has previously not been considered in assessments of martian rainfall, and, thus, this topic warrants future study.
4. As atmospheric pressure decreased over time during the early history of Mars, our results using parameterized relationships for rainfall intensity predict that there would not have been a transition between rain splash- and runoff-

dominated erosion caused solely by decreasing atmospheric pressure. This finding is inconsistent with the hypothesis that the long-lived Noachian climate was “warm and wet” with continuous rainfall and that the rainfall intensity changed as atmospheric pressure declined. However, future work should aim to better constrain the parameters in the original mathematical equation for rainfall intensity (e.g. Villermaux and Bossa, 2009) in order to better understand the relationship between rainfall intensity and atmospheric pressure, which is more complicated than the simple parameterized relationship suggests.

Many outstanding questions remain, including:

1. If the long-lived Noachian climate was “warm and wet”, what mechanism can explain the apparent shift in rainfall intensity from the Early-to-Mid Noachian to the LN-EH?
2. If the long-lived Noachian climate was “cold and icy”, what mechanism is responsible for producing a period of intense fluvial and lacustrine activity in the LN-EH?
3. Is melting of surface snow/ice and runoff capable of producing sufficient advective erosion to explain the formation of the valley networks and lakes, or is rainfall required?
4. How can continuous diffusive erosion throughout the Noachian be reconciled with a “cold and icy” climate in the absence of rainfall?

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Figures

Figure 1

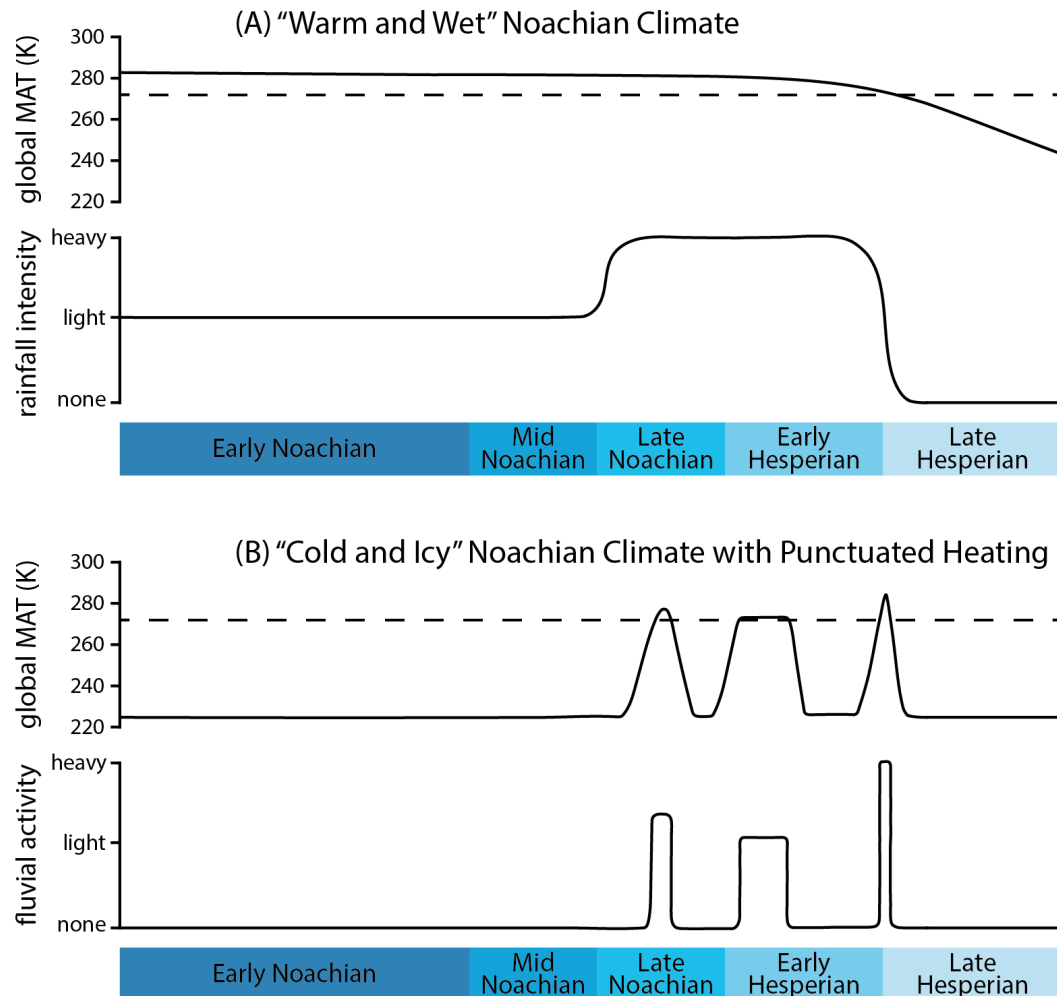


Fig. 1: Schematic diagram of relationship between global MAT, rainfall intensity/fluvial activity, and time for the case of (A) a long-lived “warm and wet” climate, slowly cooling through time as the atmosphere is lost, and (B) a long-lived “cold and icy” climate with periods of punctuated heating in the LN-EH. Horizontal dashed line is at 273 K. The units for rainfall intensity and fluvial activity are ‘none’, ‘light’, ‘heavy’ and are purposefully non-descript as we aim to only place relative estimates in this schematic diagram. For reference, the Early Noachian began ~4.1 Ga when Hellas basin formed, the Late Noachian-Early Hesperian boundary occurs ~3.7 Ga, and the Late Hesperian ended

~3 Ga. Punctuated heating events in a long-lived “cold and icy” climate are illustrated here as spikes in temperature. The magnitude and duration of a punctuated heating event would depend on the mechanism causing the heating; we have illustrated a range of different possibilities and are not referencing one specific heating mechanism. The number of required punctuated heating events is also not well-constrained and may have been only a few or many. Note that more intense (higher temperature) punctuated heating events would have led to more intense melting and fluvial activity.

Figure 2

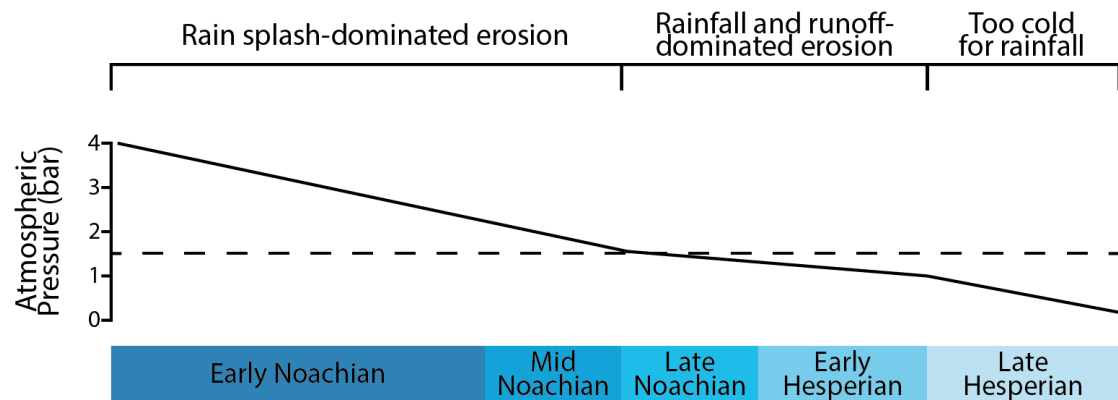


Fig. 2: Schematic diagram of the relationship between time, atmospheric pressure and erosive regime as proposed by Craddock and Lorenz (2017). In the Early-to-Mid Noachian, atmospheric pressure was above 1.5 bar but less than 4 bar, which is consistent with rain splash-dominated erosion (further, a recent study suggests that atmospheric pressure was less than 2 bars by the Middle Noachian, implying that pressures may have never been this high in the Noachian; Warren et al., 2019). In the LN-EH, atmospheric pressure is less than 1.5 bar but high enough to still permit temperatures above 273 K (for the purpose of this illustration, we draw the lower limit for LN-EH atmospheric pressure at ~1 bar), which is consistent with runoff-dominated erosion. Throughout the Late Hesperian and Amazonian, atmospheric pressure is too low for temperatures to be above 273 K and rainfall does not occur.

Figure 3

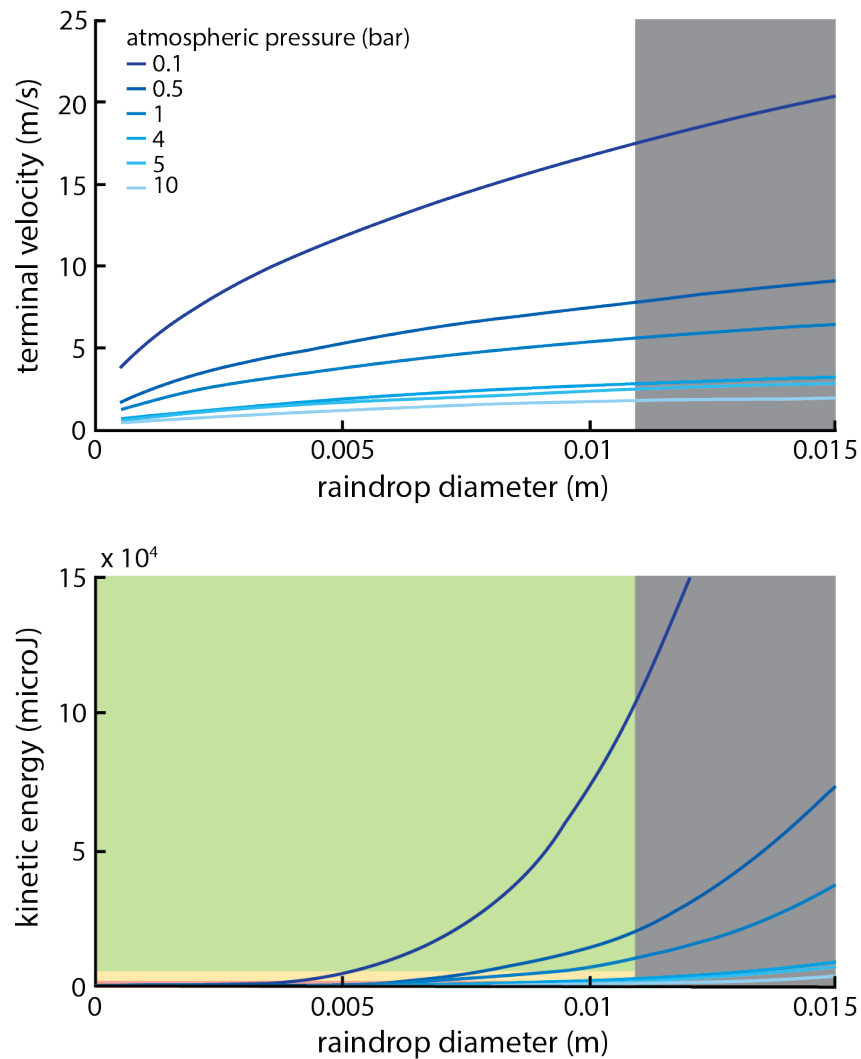


Fig. 3: Results of calculations for mathematical relationships between raindrop diameter and terminal velocity (top) and raindrop diameter and kinetic energy (bottom). Results are shown for atmospheric pressure ranging from 0.1 to 10 bar. In both plots, the region shaded gray represents conditions that are not possible on Mars because the raindrop diameter is larger than the maximum raindrop diameter that can pass through the martian atmosphere and successfully reach the surface, 10.8 mm. In the bottom plot, the region shaded red represents kinetic energy values that are incapable of initiating transport of sedimentary particles (note that the area shaded red is very small), the region shaded

yellow represents kinetic energy values that are incapable of initiating transport of sand-sized particles and larger, but capable of initiating transport of silt, and the region shaded green represents kinetic energy values that are capable of initiating transport of all sedimentary particles, including silt. These plots show that both rain splash-related erosion (sediment transport) could occur for the entire atmospheric pressure range considered here.

Tables

Table 1

atmospheric pressure (bar)	atmospheric density (kg/m ³)	d (mm)	0.5	1	3	5	7	9	10.797	12	15
0.5	0.903	v_t (m/s)	1.66	2.35	4.08	5.26	6.23	7.06	7.73	8.15	9.11
		v_b (m/s)	35.93	25.40	14.67	11.36	9.60	8.47	7.73	7.33	6.56
1	1.806	v_t (m/s)	1.18	1.66	2.88	3.72	4.40	4.99	5.47	5.76	6.44
		v_b (m/s)	25.40	17.96	10.37	8.03	6.79	5.99	5.47	5.19	4.64
4	7.225	v_t (m/s)	0.59	0.83	1.44	1.86	2.20	2.50	2.73	2.88	3.22
		v_b (m/s)	12.70	8.98	5.19	4.02	3.39	2.99	2.73	2.59	2.32
5	9.031	v_t (m/s)	0.53	0.74	1.29	1.66	1.97	2.33	2.44	2.58	2.88
		v_b (m/s)	11.36	8.04	4.64	3.59	3.04	2.68	2.44	2.32	2.07
10	18.062	v_t (m/s)	0.37	0.53	0.91	1.18	1.39	1.58	1.73	1.82	2.04
		v_b (m/s)	8.03	5.68	3.28	2.54	2.15	1.89	1.73	1.64	1.47

Table 1: Variation of the terminal velocity, v_t , and breakup velocity, v_b , for a range of rain drop diameters, d , under Mars atmospheric pressures between 0.5 and 10 bar.

Table 2

Maximum raindrop size (mm)	Median raindrop size (mm)	Rainfall intensity (mm/hr)			
		$\alpha=0.8,$ $\beta=1.23$	$\alpha=1.28,$ $\beta=1.23$	$\alpha=0.8,$ $\beta=2.92$	$\alpha=1.28,$ $\beta=2.92$
10.8	5.4	4.9	3.1	2.2	1.4

Table 2: Results of calculations to estimate rainfall intensity as a function of raindrop size. We characterize rainfall intensity in terms of “light” and “moderate” rain (Craddock & Lorenz, 2017; Kittredge, 1948)*.

* Notes:

(1) Kittredge (1948) focused on terrestrial rainfall rates with respect to erosion in highly vegetated regions, and we acknowledge that a more useful method for characterizing rainfall intensity be with respect to infiltration capacity of the martian regolith instead of highly vegetated regions on Earth for many reasons, including the lack of vegetation on the martian surface.

(2) this approximation of rainfall intensity does not account for intermittency in rainfall events; this method only predicts an average rainfall rate. Nonetheless, we see that both light and moderate rainfall are possible given the range of possible values for α and β .

Note that rainfall intensity does not depend on atmospheric pressure.

(3) “Light rain” is defined as rainfall rates 1-3.4 mm/hr and “moderate rain” is defined as rainfall rates >3.4 mm/hr.

CHAPTER TWO

EARLY MARS CLIMATE HISTORY: CHARACTERIZING A “WARM AND WET” MARTIAN CLIMATE WITH A 3D GLOBAL CLIMATE MODEL AND TESTING GEOLOGICAL PREDICTIONS

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Abstract

Observations of Late Noachian-Early Hesperian (LN-EH)-aged martian surfaces reveal valley networks, lakes, degraded craters, and putative oceanic shorelines, often interpreted to require a persistent “warm and wet” climate, characterized by mean annual temperature (MAT) >273 K and abundant rainfall. We simulate this “warm and wet” climate (global MAT ~ 275 K) with a 3D GCM to determine whether these features could have formed in this climate through rainfall activity. We find that rainfall is limited in abundance and areal distribution, precipitation is dominated by snowfall, and highlands temperatures are <273 K for the majority of the year. We conclude that: 1) LN-EH valley networks and lakes could not have formed through rainfall-related erosion, 2) crater degradation by rainsplash and runoff is not predicted, 3) global clay formation through long-lived rainfall, fluvial activity and warm temperatures is unlikely, and 4) the presence of a rainfall- and overland flow-fed northern ocean is improbable.

Keywords: Mars climate; valley networks; climate model; rainfall; ocean; fluvial activity

1. Introduction

The martian surface contains abundant geological evidence that liquid water was stable at the surface during the Late Noachian-Early Hesperian (LN-EH, ~ 3.7 Ga), including widespread valley networks (VNs) (Fassett and Head, 2008a; Hynek et al., 2010), open- and closed-basin lakes (Cabrol and Grin, 1999; Fassett and Head, 2008b; Goudge et al., 2015), and exposed aqueous alteration products (Bibring et al., 2006; Carter et al., 2015). These features are commonly cited as evidence that the LN-EH was much warmer and wetter than the current hyper-arid and hypothermal Amazonian climate, characterized by mean annual temperature (MAT) ≥ 273 K and rainfall and associated runoff as the dominant erosive mechanism (Craddock and Howard, 2002; Ramirez and Craddock, 2018; Ramirez, 2017). Additional evidence for a “warm and wet” climate includes the preservation state of Noachian-aged craters, which have degraded rims and no visible ejecta deposits (e.g. Jones, 1974), characteristics which have been attributed to rainsplash-related erosion (Craddock and Howard, 2002). The proposition of a “warm and wet” LN-EH climate has further led researchers to conjecture about the possibility of a Noachian ocean in the northern lowlands (Clifford, 1993; Parker et al., 1993), which is considered to be important for driving the vigorous hydrological cycle that would have been required for recycling of water and formation of VNs (Luo et al., 2017).

On the basis of these types of considerations, Craddock and Howard (2002) outlined the evidence for a “warm, wet early climate capable of supporting rainfall and surface runoff” and described this climate as “the most plausible scenario for explaining the entire suite of features in the Martian cratered highlands.” Included in their suite of

features were (1) degraded craters, whose morphology indicated that “modification occurred by creep induced by rainsplash combined with surface runoff and erosion”, and (2) VNs, whose morphology and drainage density are “entirely consistent with [formation through] rainfall and surface runoff”.

More recently, Ramirez and Craddock (2018) outlined the geological and climatological case for a warmer and wetter early Mars. They point out that “ancient terrains preserve landscapes consistent with stream channels, lake basins and possibly even oceans, and thus the presence of liquid water flowing on the Martian surface 4 Ga.” They argue that “a warm and semi-arid climate capable of producing rain is most consistent with the geological and climatological evidence” and that “the geomorphology cannot be explained without the occurrence of above-freezing surface temperatures and rain at least seasonally, if not persistently”.

Despite the widespread evidence for abundant liquid water activity at the surface, recent studies using advanced 3D climate models have been unsuccessful in reproducing the continuous and long-lived “warm and wet” climate conditions interpreted to be necessary for the formation of the fluvial and lacustrine features and observed crater degradation when considering the influence of the faint young Sun (Gough, 1981) and reasonable greenhouse gas concentrations (e.g. Forget et al., 2013; Halevy and Head, 2014; Johnson et al., 2008; Mischna et al., 2013; Postawko and Kuhn, 1986; Wordsworth et al., 2013). Instead, the models predict a “cold and icy” climate, characterized by global MAT ~ 225 K, far below the melting point of water (Forget et al., 2013; Wordsworth et al., 2013). Under atmospheric pressure conditions higher than a few tens of millibar, the atmosphere and surface thermally couple, inducing an adiabatic cooling effect

(Wordsworth et al., 2013); the resulting dominant altitude-dependence of temperature causes water to be distributed as ice in the highlands (Head and Marchant, 2014; Wordsworth et al., 2013).

But what would a Late Noachian Mars with a “warm and wet/arid” climate be like? Previous work by Wordsworth et al. (2015) used a 3D global climate model (GCM) to compare the predicted “cold and icy” climate with the long sought-after “warm and wet” climate; Wordsworth et al. (2015) forced the “warm and wet” climate in the model by implementing either an unrealistically high solar flux or intense artificial greenhouse warming, and by altering topography and albedo to imitate the presence of a lowlands ocean. Specifically, for their “warm and wet” simulations, they were interested in simulating a climate with continuous warm conditions, characterized by global MAT ~ 283 K, similar to the present global MAT on Earth, a long-lived and ice-free ocean in the lowlands with a shoreline at -2.54 km (following Achille and Hynek, 2010), and a vigorous rainfall-dominated hydrological cycle. Wordsworth et al. (2015) found that the distribution of rainfall in this climate scenario is not well-correlated with the VN density distribution. However, this climate scenario and the nature of the associated hydrological cycle are likely to be a function of the global temperatures and the forced presence of a large, stable ocean.

Thus, in order to test the observations, predictions, and interpretations of Craddock and Howard (2002) and Ramirez and Craddock (2018), we have modeled a warm LN-EH climate with “above-freezing surface temperatures” (global MAT, of ~ 275 K, 2 K above the melting point of water); the climate we model here is colder than that considered by Wordsworth et al. (2015), representing the coldest possible “warm and

wet” climate, and the simulations are not initiated with an ocean forced in the lowlands. Wordsworth et al. (2015) had to mimic the characteristics of an ocean because the model did not naturally predict a long-lived, stable ocean; we do not repeat this analysis because we are interested in model-predicted locations of surface ponding and choose not to force the lowlands as a water sink or source. We perform our analysis in order to document the nature of a “warm and wet” climate, to assess the type of precipitation that is predicted to occur, and to assess how its location and amount compare to the distribution of VNs, lakes, degraded craters, and a putative northern ocean. We specifically test the predictions and points outlined in Craddock and Howard (2002) and Ramirez and Craddock (2018) that: (1) rainfall occurs “at least seasonally, if not persistently”; (2) rainfall patterns and locations are coincident with the occurrence and density of VNs, whose morphology and drainage density are “entirely consistent with rainfall and surface runoff”; (3) degraded crater morphometry is due to “modification [that] occurred by creep induced by rainsplash combined with surface runoff and erosion”; and (4) the occurrence of conditions producing “...landscapes consistent with ... possibly even oceans ...”

Our goal is to reconcile the geologic evidence for a “warm and wet” climate with 3D GCM simulations: we assume that a LN-EH climate supporting rainfall and runoff was plausible, based on the overwhelming geologic evidence, and force “above-freezing surface temperature” conditions in the 3D Laboratoire de Météorologie Dynamique (LMD) GCM for early Mars. We first analyze model-predicted temperature and distributions of ice, rainfall, and snowfall. We then compare these results with the distribution of the VNs and lakes to provide useful insight into the possible formation

conditions and driving mechanisms of these fluvial and lacustrine features. We aim to answer the question: Can the predicted rainfall and rainfall-related erosion in a MAT ~ 275 K “warm and wet” climate plausibly explain the formation of features that have previously been identified as evidence for rainfall-related processes (Ramirez and Craddock, 2018)?

2. Methods

We employ the 3D LMD GCM for early Mars (Forget et al., 2013; Wordsworth et al., 2013) to simulate a “warm and wet” climate. We consider a globally-averaged 1 bar CO₂ atmosphere (Jakosky et al., 2017), 25° and 45° obliquity (Laskar et al., 2004), a circular orbit, and 75% of the present solar luminosity (Gough, 1981). Although the atmospheric pressure may have been less than 1 bar CO₂ in the LN-EH, we are interested in producing the warmest possible conditions in our analysis; higher atmospheric pressure provides an increased thermal blanketing effect, and thus higher global MAT. For this reason, we choose the reasonable upper limit for the LN-EH atmospheric CO₂ inventory as determined by recent results from the MAVEN mission (Jakosky et al., 2017). The obliquity values we use represent approximately the reasonable lower limit ($\sim 25^\circ$; -1σ of the mean obliquity over the past 5 Gy) and most probable value ($\sim 45^\circ$) for obliquity variations over the past 5 Gy, as predicted by the statistical analysis of Laskar et al. (2004). We highlight the lower limit, in addition to the most probable value, because lower obliquity focuses maximum incident solar radiation near the equator, where the majority of the VNs and lakes are observed (Hynek et al., 2010); this effect produces warmer conditions in the near-equatorial regions. Periods of higher obliquity are likely to

have existed, but we do not explore that parameter space here because higher obliquity would focus incident solar radiation, and thus temperatures >273 K, toward the poles, where the fluvial/lacustrine features are not observed. Additionally, eccentricity was likely to have been higher than zero, with a predicted statistical average for the past 5 Gy of 0.069 (Laskar et al., 2004). Although theoretically, periods of relatively high eccentricity could lead to increased summer season temperatures, potentially producing summer season conditions more suitable to rainfall in the highlands, analyses of LN-EH peak and seasonal temperature distributions (Palumbo et al., 2018) suggest that changing the eccentricity within the probable LN-EH range would not lead to significant changes in the rainfall, snowfall, or MAT distributions. Thus, assuming a circular orbit is sufficient for our analysis. Finally, assuming that the Sun is a main sequence-like star, Gough (1981) estimated that solar luminosity in the LN-EH would have been approximately 75% the present value, and we adopt this value here.

Previous work has shown that these ambient conditions will naturally produce a “cold and icy” LN-EH climate (Forget et al., 2013; Wordsworth et al., 2013). A plausible combination of greenhouse gases that can produce continuous and long-lived MAT ≥ 273 K has not yet been identified (Forget et al., 2013). Thus, we focus on the lowest temperature end of a “warm and wet” climate (global MAT ~ 275 K, ~ 2 K above the melting point of water) because the least amount of required greenhouse warming is considered to be the most plausible. We note that 273 K is ~ 50 K above the ambient “cold and icy” climate. Because a plausible combination of greenhouse gases that can produce this continuous and long-lived “warm and wet” climate has not yet been identified, we artificially warm the planet by introducing a gray gas into the model

atmosphere. A gray gas uniformly absorbs across the IR spectrum at all wavelengths with a defined absorption coefficient, κ . We choose $\kappa = 7.5 \times 10^{-5} \frac{\text{m}^2}{\text{kg}}$ for the 25° obliquity simulation and $\kappa = 9.5 \times 10^{-5} \frac{\text{m}^2}{\text{kg}}$ for 45° obliquity, which produces the desired climate, with MAT ~ 273 K in the near-equatorial regions where VNs/lakes are abundant and global MAT ~ 275 K.

We run the GCM at a spatial resolution of $64 \times 48 \times 25$ (longitude $\times$ latitude $\times$ altitude) and collect hourly data. These spatial and temporal resolutions are sufficient to capture necessary regional and seasonal variations. We have ensured that the model has reached equilibrium before analyzing the data; the results shown here are not influenced by the initial surface water/ice distribution. Further, simulations shown here include a global water inventory of ~ 5 m GEL, in line with lower limit estimates for the amount of water required to carve the VNs (minimum 3 m GEL; Rosenberg and Head, 2015). We have confirmed that the model has sufficient volumes of water to accurately predict rainfall and snowfall patterns because we have produced similar simulations with 34 m GEL water (likely upper limit for the Noachian; Carr and Head, 2015) and rainfall is concentrated in the same regions. The physics, chemistry, and physical parameterizations for this version of the GCM implemented here is described in detail by Wordsworth et al. (2015) and includes a full water cycle, advanced ice equilibration methodology for accuracy and time efficiency, cloud nucleation dynamics and microphysics, tracers for both CO_2 and H_2O molecules, and MOLA topography. We use present-day topography, assuming that the major impact basins and volcanic rises had formed by the LN-EH (Fassett and Head, 2011).

To better understand the climatic characteristics of a “warm and wet” climate, we analyze the simulated climate on the basis of the factors deemed necessary to explain the formation of the VNs and lakes, temperatures ≥ 273 K and rainfall. We determine regions of the planet that experience temperatures ≥ 273 K and rainfall and how these patterns vary seasonally. Then we perform a spatial correlation between areas with temperatures ≥ 273 K and the distributions of the VNs (from Hynek et al., 2010) and lakes (from Fassett and Head, 2008b, Goudge et al., 2015), and areas with rainfall and the distributions of the VNs/lakes. Specifically, we determine whether the VNs and lakes are within regions characterized by rainfall and temperatures ≥ 273 K, based on the assumption that if liquid water were to run off on the surface and incise a VN, the head (source region) of the channel would have to be at a location where rainfall occurred. We are also interested in whether or not ice is stable anywhere on the planet and if, and where, snowfall occurs, which are important factors for characterizing the global hydrological system and water sinks on the surface. The aim is to determine whether the fluvial and lacustrine features could have formed in a “warm and wet” climate or whether they are inconsistent with this climate scenario. In the latter case, we consider that the formation of these features may have required even warmer and wetter conditions by reflecting on the results of previous work by Wordsworth et al. (2015) which simulated a rainfall-dominated climate with Earth-like MAT (~ 283 K), or that they formed through punctuated ice melting and runoff in a predominantly “cold and icy” climate (Head et al., 2017). We then use our results to address the four main predictions of Craddock and Howard (2002) and Ramirez and Craddock (2018).

3. Results and Discussion

The current Mars atmosphere is so tenuous (~ 7 millibars) that it is not thermally coupled to the surface and surface temperatures vary primarily as a function of latitude, with warmer temperatures focused near the equator and colder temperatures focused near the poles. However, for atmospheric pressures above a few tens of millibars, the atmosphere becomes thermally coupled to the surface and an adiabatic cooling effect becomes the prominent mechanism for heat transport through the atmosphere. Because of the large topographic variations across the surface of Mars and relatively high atmospheric density, the adiabatic cooling effect causes temperature to be dominantly altitude-dependent (Forget et al., 2013; Wordsworth et al., 2015, 2013), instead of dominantly latitude-dependent. Thus, higher altitude surfaces act as cold traps for water, and ice becomes stable at high altitudes year-round. In the typical “cold and icy” scenario, ice is cold-trapped in the southern highlands because of this effect. In the “warm and wet” global MAT ~ 275 K simulations analyzed here (Fig. 1), for the case of 25° obliquity, the highest altitude region, the Tharsis rise, and the south polar region are consistently below 273 K year-round and some water is cold-trapped in these regions as ice (Fig. 1B). In the 45° obliquity simulation, relatively more solar insolation reaches the south polar region and the only part of the planet that is consistently below 273 K is the highest altitude region, the Tharsis rise, and some water is cold-trapped there (Fig. 1B). In addition to this cold-trapping effect, volumes of annually accumulated snow outweigh volumes of melted snow in many areas of the highlands, causing areas in the highlands that are not permanent cold traps to contain some surface snow/ice throughout the entire year (Fig. 1C). At locations where ice is present year-round, the surface is never exposed

to the atmosphere, implying that overland flow and surface erosion at those locations is not possible. On the other hand, at locations where the minimum amount of ice present over the course of one year is zero, any snow/ice that accumulated at that location is melted during periods of relatively warm conditions, such as the summer season. At these locations, the surface is exposed to the atmosphere for at least part of the year, allowing for surface erosion by runoff of meltwater or rainfall. To determine the locations of regions that contain surface snow/ice throughout the entire year, we calculate the minimum volume of surface snow/ice at each latitude/longitude GCM grid cell. The distribution of regions that contain snow/ice throughout the year is shown in Fig. 1C.

3.1 Case 1: 25° obliquity

The global MAT is above the melting point of water (~ 273 K), but the altitude dependence of temperature means that vast portions of the highlands have local MAT < 273 K (Fig. 1A). In Fig. 1A, regions with MAT > 273 K are indicated by the black line, the 273 K contour. With respect to the 273 K contour, regions shaded in warmer colors have MAT > 273 K (reds and oranges) and regions shaded in cooler colors have MAT < 273 K (yellows, greens and blues). Areas with abundant VNs and lakes and MAT ≥ 273 K (Fig. 1A and 2A) include Arabia Terra, near the south-eastern rim of Hellas basin, near the rim of Isidis basin, and regions in close proximity to the dichotomy boundary; in general, however, regions with high VN density are not located in regions with MAT ≥ 273 K (Fig. 1A). In total, $\sim 33\%$ of the VNs mapped by Hynek et al. (2010) and $\sim 54\%$ of the lakes mapped by Goudge et al. (2015) and Fassett and Head (2008) are located within regions with MAT ≥ 273 K. It is important to note, however, that the Hynek et al. (2010)

database includes some mapped fluvial features that are not typical VNs. Specifically, fretted channels in the Arabia Terra region and outflow channels and associated networks in the Hellas basin region are included in these maps. Because the majority of the VNs that are consistent with locations where local MAT ≥ 273 K are within the Arabia Terra and SE Hellas rim regions (Fig. 1A), we note that this correlation may be artificially increased by these non-VN fluvial features.

Seasonal variations increase temperatures to >273 K in the warmest parts of the summer season, producing peak annual temperatures (PAT) >273 K for most of the planet (Fig. 1B). These temperatures are relatively short-lived in the highlands, however, persisting for only the warmest parts of the summer season (Fig. 1D). For a scenario with higher eccentricity and therefore a higher magnitude of seasonal temperature variations, the PAT would be higher, but the duration of temperature ≥ 273 K at any location would be generally similar (Palumbo et al., 2018) within the plausible range of Noachian eccentricity values (Laskar et al., 2004). As a result of the fact that the majority of the year is characterized by temperatures <273 K in the highlands, most precipitation occurs as snowfall instead of rainfall (Fig. 2B, C; snowfall occurs on $\sim 31\%$ of the planet while rainfall occurs on $\sim 0.8\%$ of the planet). The distribution of locations which experience rainfall is very limited, with only a few locations that rainfall occurs; all of the locations in which rainfall occurs are in the highlands (see rainfall distributions in Fig. 2B) due to the adiabatic cooling effect which causes water to be deposited in the highlands, not the lowlands. None of the regions in which rainfall occurs are correlated with areas with MAT ≥ 273 K, implying that even when rainfall does occur, the location where rainfall occurs is likely to return to temperatures <273 K rapidly (Fig. 1D) and the surrounding

regions are likely to be characterized by temperatures <273 K, causing the liquid water to rapidly freeze. In other words, the very small amount of rainfall that does occur in the MAT ~ 275 K model is associated with peak summertime conditions in the highlands. Due to the general atmospheric circulation in the modeled climate and the fact that our simulations do not force the long-lived presence of a standing body of water in the lowlands, precipitation does not occur within the northern lowlands, where temperatures ≥ 273 K are more widespread and persist for longer durations. The lowlands are warmer than the highlands because temperature is dominantly dependent on altitude. However, the adiabatic cooling effect causes water to be deposited as ice in the highlands; the major sink for water is the highlands. Summertime melting will allow the ice to melt and run off down-slope, temporarily ponding in the lowlands, but the adiabatic cooling effect will cause it to be naturally re-deposited as snow in the highlands. We note that a larger global water inventory may permit thicker cold-season ice sheets in the highlands and, in turn, a larger volume of summertime meltwater which could seasonally pond in the lowlands before it is transported back to the highlands in colder seasons. This is in contrast to expected circulation patterns in the presence of a northern hemispheric ocean – the ocean is a major water source and will initiate hydrological cycling in the lowlands, in addition to the hydrological cycling in the highlands, as the water is slowly transported to the highlands, where it will be re-deposited as surface ice (e.g. Kreslavsky and Head, 2002; Turbet et al., 2017). Upon re-deposition of all water from the ocean to the highlands, the precipitation patterns are expected to be similar to the results shown here.

Additionally, locations that experience rainfall are not correlated with the distribution of VNs and lakes (Fig. 2B), mainly because the regions with rainfall cover

such a small surface area (<1% of the planet). Thus, the distribution of VNs and lakes is inconsistent with formation through rainfall-related erosion in this simulated climate that is characterized by globally averaged surface temperatures that are above freezing.

Instead of rainfall, widespread snowfall occurs across most of the highlands (Fig. 2C). In low latitudes and near equatorial regions, the snowfall distribution coincides with the location of many VNs and lakes (Fig. 2C). Specifically, ~33% of the VNs mapped by Hynek et al. (2010) and ~16% of the lakes mapped by Fassett and Head (2008b) and Goudge et al. (2015) are located in regions where snowfall occurs at some point in the year. Generally, snowfall is regionally widespread in the highlands, in the same areas as the lake distribution and regions of both high-density and low-density of VNs (Fig. 2A).

3.2 Case 2: 45° obliquity

The results of the higher obliquity simulation are broadly similar to those of the 25° obliquity simulation (Fig. 1). MAT is ≥ 273 K for the vast majority of the lowlands, but MAT is generally < 273 K in the highlands due to the altitude dependence of temperature and the adiabatic cooling effect (Fig. 1A). In the summertime, peak surface temperatures are ≥ 273 K across most of the planet (Fig. 1B), permitting minor amounts of localized rainfall (Fig. 2B), but precipitation is again dominated by snowfall. Specifically, ~4% of the VNs mapped by Hynek et al. (2010) and ~8% of the lakes mapped by Fassett and Head (2008) and Goudge et al. (2015) are located in regions where rainfall occurs at some point in the year. On the other hand, ~68% of the VNs mapped by Hynek et al. (2010) and ~55% of the lakes mapped by Fassett and Head (2008) and Goudge et al. (2015) are located in regions where snowfall occurs at some point in the year.

The rainfall that does occur is predominantly focused near the south pole and west of Tharsis (Fig. 2B; rainfall occurs on ~7% of the planet and snowfall occurs on ~42% of the planet) because precipitation is most abundant in these two regions and temperatures exceed 273 K in these regions in the summer (Fig. 1B), permitting seasonal rainfall instead of snowfall. Rainfall is observed to the west, but not east, of the Tharsis rise because there is a rain shadow effect induced by the relatively high slopes and increase in elevation associated with Tharsis; warm, moist air approaches the rise in westerly winds and cools as it rises which causes the moisture to condense into rainfall, leaving dry air to advance down the eastern slope of Tharsis. There is more rainfall in the 45° obliquity simulation than the 25° obliquity simulation because temperatures in the 25° obliquity simulation are consistently below 273 K in the south polar region, one of only two locations where rainfall is observed in these simulations. In a manner similar to the 25° obliquity simulation, most of the rainfall does not occur within regions of $\text{MAT} \geq 273 \text{ K}$, implying that the rainwater would rapidly freeze. In the 45° obliquity simulation (Fig. 2C), snowfall is distributed across more of the highlands than the lower obliquity simulation (25°); a larger percentage of the equatorial region experiences snowfall.

Approximately 24% of the VNs mapped by Hynek et al. (2010) and ~43% of the lakes mapped by Goudge et al. (2015) and Fassett and Head (2008) are located within regions with $\text{MAT} \geq 273 \text{ K}$. The VNs and lakes that correspond to regions with $\text{MAT} \geq 273 \text{ K}$ are mostly distributed within Arabia Terra and the SE rim of the Hellas basin and a smaller percentage of the VNs and lakes that correspond to regions with $\text{MAT} \geq 273 \text{ K}$ are distributed along the dichotomy boundary (Fig. 1A). Because a majority of the mapped VNs in the Arabia Terra and Hellas basin regions mapped by Hynek et al. (2010)

are not VNs but are instead fretted channels and outflow channels, almost no LN-EH VNs are distributed in regions with $\text{MAT} \geq 273 \text{ K}$.

3.3 Summary

We have analyzed two artificially simulated “warm and wet” climates, with 25° and 45° obliquity. We have compared the distribution of temperatures $\geq 273 \text{ K}$, rainfall, and snowfall with the observed distribution of VNs and lakes. We now use our results to test the predictions and points outlined in Craddock and Howard (2002) and Ramirez and Craddock (2018).

- 1) *Rainfall occurs “at least seasonally, if not persistently.”* Rainfall did indeed occur in both of our simulations with global $\text{MAT} \sim 275 \text{ K}$, but only seasonally (during peak summer temperatures, Fig. 2B) in very restricted regions, mostly located at southern high latitudes and altitudes and west of the Tharsis rise. We utilized the hourly GCM data to constrain the annual duration of rainfall and percent of the year in which rainfall occurs at each lat/lon GCM grid point. In the 45° obliquity simulation, rainfall occurs on $\sim 7\%$ of the planet and persists for a maximum of $\sim 5\%$ of the year. In most locations, however, rainfall persists for less than ~ 2 days. In the 25° obliquity simulation, rainfall occurs on $\sim 0.8\%$ of the planet and persists for a maximum of $\sim 1.5\%$ of the year.
- 2) *Rainfall patterns and locations are coincident with the occurrence and density of VNs, whose morphology and drainage density are “entirely consistent with rainfall and surface runoff”.* Based on the temperature and precipitation

distributions, the formation of the VNs and lakes appears broadly inconsistent with formation through rainfall-related erosion in the modeled MAT ~ 275 K “warm and wet” climates.

- 3) *Degraded crater morphometry is due to “modification [that] occurred by creep induced by rainsplash combined with surface runoff and erosion”*. The climate simulated in this study is inconsistent with rainfall as the driving mechanism for crater degradation and surface aqueous alteration due to the fact that the dominant form of precipitation is snowfall and rainfall is not widespread or voluminous in the highlands. Future studies should test other mechanisms to explain the degraded crater morphometry that do not require rainsplash-related erosion.
- 4) *“... landscapes consistent with ... possibly even oceans ...”* In our simulations, we found that water in the lowlands would be rapidly transported to the highlands and be re-precipitated as snow. During the summer, some of the surface snow/ice will melt and run off on the surface but will be transported back to the highlands as snow/ice in the colder seasons. In some locations, such as the Tharsis rise (25° and 45° obliquity) and the south polar region (25° obliquity), water is trapped as ice year-round. This description of the global hydrological cycle is not consistent with a stable or long-lived overland flow-fed ocean in the lowlands.

Despite the “warm” 275 K MAT climate, (1) the fluvial and lacustrine features, and the observed crater degradation are unable to be explained through rainfall in this climate scenario, (2) the lack of widespread, persistent rainfall and elevated temperatures,

and the significant areas covered by long-term snow and ice cover, do not favor the formation of widely distributed aqueous alteration products, and (3) a long-lived overland flow-fed ocean in the lowlands is not predicted.

How much higher would MAT need to be to induce more widespread rainfall? Wordsworth et al. (2015) simulated a warmer climate scenario (~ 283 K) with a (forced) stable northern ocean and found that precipitation is dominated by rainfall, instead of snowfall. However, although there is abundant rainfall, the distribution of VNs and lakes is inconsistent with the distribution of rainfall in many regions (Wordsworth et al., 2015). Thus, increasing temperatures even further leads to more areas that experience rainfall, but does not appear to offer a rainfall-related explanation for VN and lake formation. Wordsworth et al. (2015) found that snowfall in a “cold and icy” climate, and associated seasonal or punctuated melting, is better correlated with the VN distribution than rainfall in a “warm and wet” climate. Under these warmer MAT ~ 283 K conditions, rainfall is widespread, and it is important to note that a rainsplash-related explanation for degraded crater rims and aqueous mineral alteration at the surface in the highlands is more plausible than in the MAT ~ 275 K climate that we simulate in this study.

4. Conclusions

Using the 3D LMD GCM for early Mars, we have simulated a “warm and wet” climate, characterized by global MAT ~ 275 K and equatorial MAT ~ 273 K. Rainfall is limited, precipitation is dominated by snowfall, and temperatures in the highlands are < 273 K for the majority of the year. The vast majority of VNs and lakes, as well as degraded craters, occur in areas of snowfall, not rainfall, and the global distribution of

water is dominated by ice in the highlands and near the Tharsis rise, not by an ocean or global liquid water that might form surface clays. The ability to form surface clays in colder conditions, possibly through seasonal snowmelt, requires a better understanding of the temperature, water volume, and duration constraints for in situ clay formation (e.g. Bishop et al., 2017).

The transition from a snowfall-dominated to a rainfall-dominated climate (Wordsworth et al., 2015) occurs at global MAT >275 K and <283 K. Even at MAT 283 K, the distribution of VNs is not well-correlated with predicted rainfall patterns (Wordsworth et al., 2015). Thus, we suggest that shorter-term transient warm temperature phases in an otherwise “cold and icy” background climate (e.g. Head and Marchant, 2014; Wordsworth et al., 2015), permitting transient melting of surface snow/ice and liquid water runoff, might be more likely to explain the formation of the VNs and lakes than rainfall in a “warm and wet” climate. In other words, we suggest that the VNs and lakes, which are commonly cited as the most robust evidence for “warm and wet” Late Noachian conditions, might be better explained by a “cold and icy” climate.

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http://www.planetary.brown.edu/html_pages/data.htm

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Figures

Figure 1

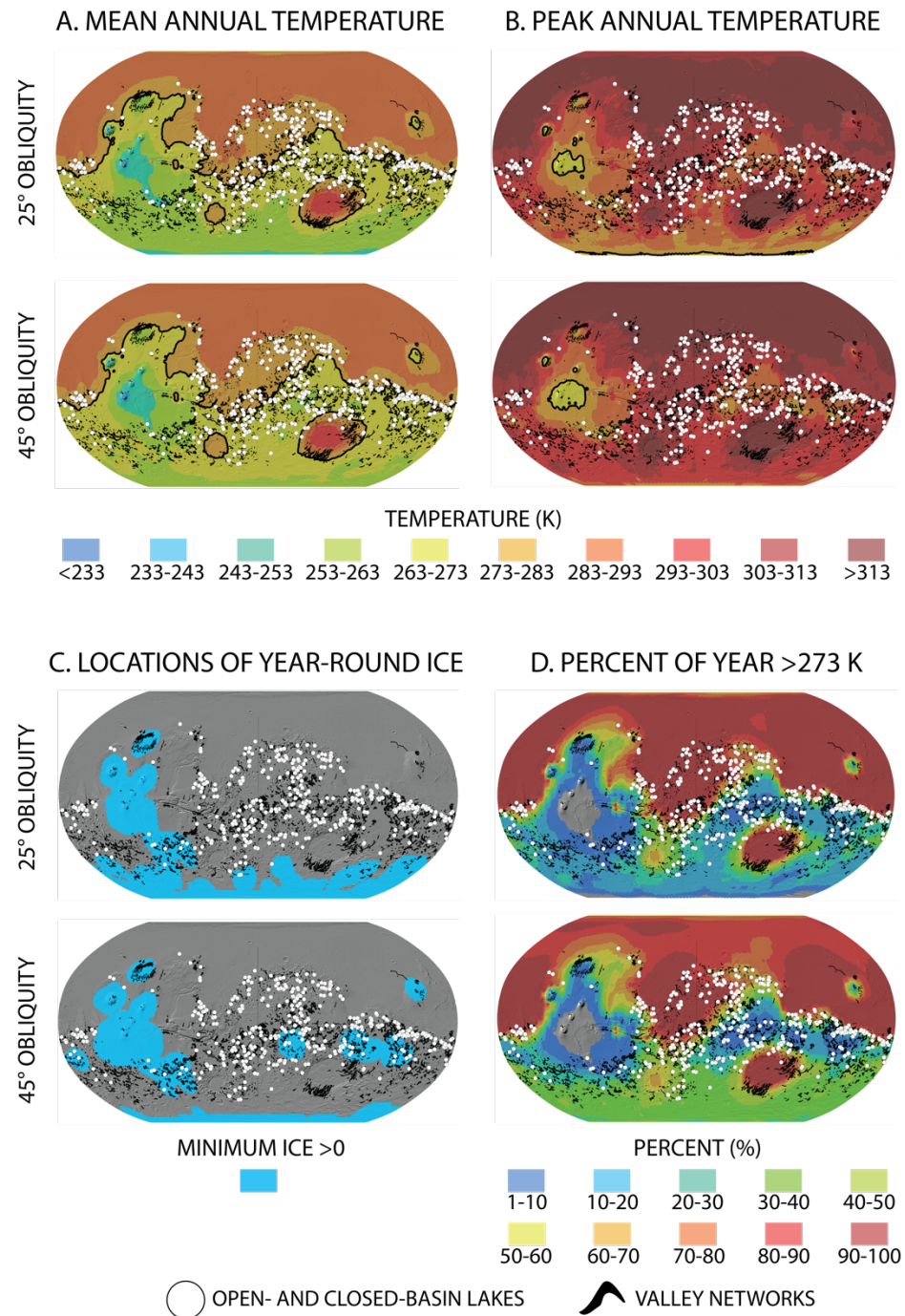


Fig. 1: Results from simulations. (A) MAT and (B) PAT maps. (C) Locations where ice is present year-round. (D) Percent of the year above freezing. This is calculated by

number of data points per year above freezing which is a reasonable approximation because we utilize hourly data. Results are for 25° (top) and 45° (bottom) obliquity. The black line in (A) and (B) is the 273 K isotherm. VNs are black lines (from Hynek et al., 2010) and lakes (from Fassett and Head, 2008b; Goudge et al., 2015) are filled white circles.

Figure 2

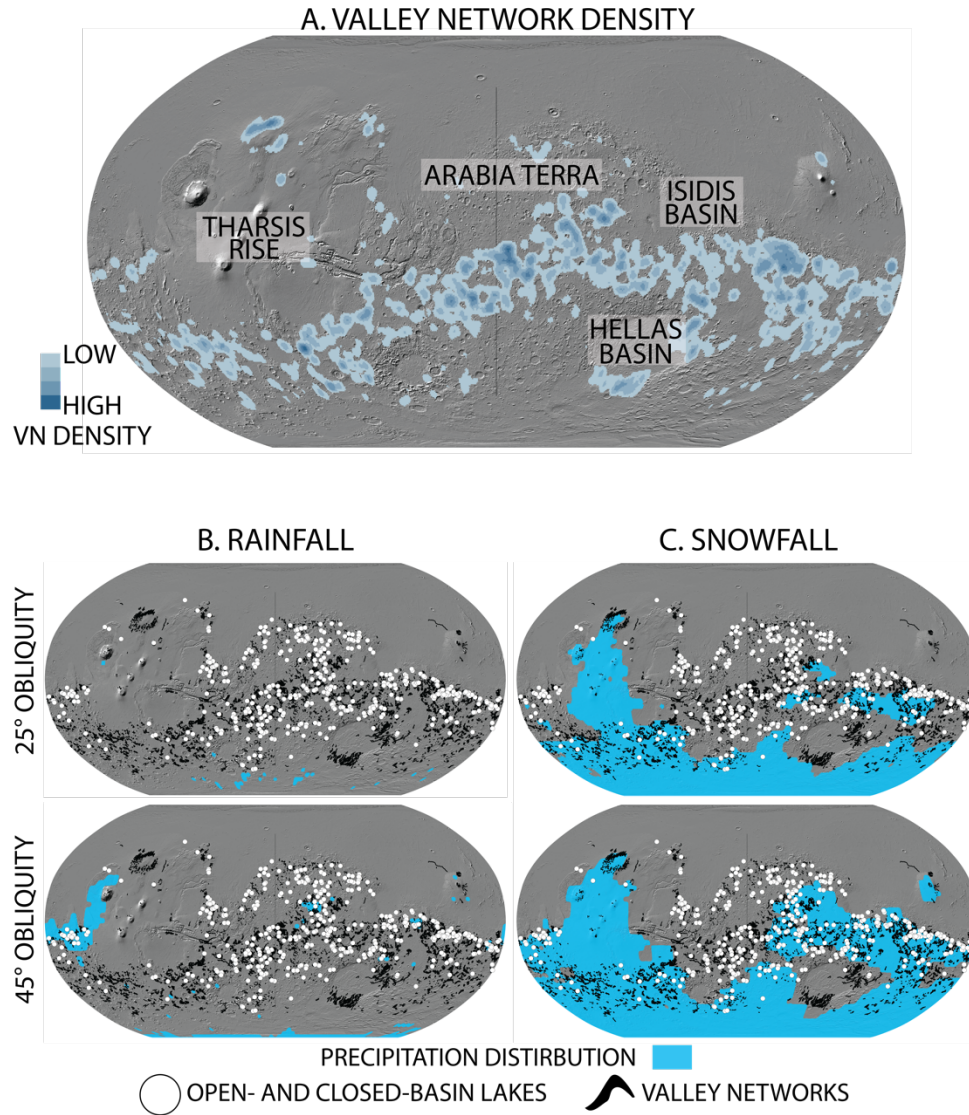


Fig. 2: (A) VN density map, (data from Hynek et al., 2010). Major topographic features that are referred to in the text are labelled. Lighter shades of blue represent lower density; darker shades represent higher density. (B) Distribution of locations where rainfall occurs and (C) distribution of locations where snowfall occurs for both simulations done here, 25° obliquity (top) and 45° obliquity (bottom). In (B) and (C), VNs and lakes are shown as black lines and filled white circles, respectively.

CHAPTER THREE

GLOBAL CLIMATE MODEL PREDICTIONS FOR A CHANGE FROM A LONG-LIVED “COLD AND ICY” CLIMATE TO A PUNCTUATED OR TRANSIENT “WARM AND WET” CLIMATE IN THE LATE NOACHIAN- EARLY HESPERIAN

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Abstract

Two contrasting scenarios for the early martian climate exist: (1) a long-lived “warm and wet” Noachian climate with above-freezing average temperatures and rainfall, as suggested to be required by geologic observations, and (2) a long-lived “cold and icy” Noachian climate with average temperatures far below freezing and all fluvial activity constrained to periods of punctuated heating and melting of surface snow and ice, as predicted by climate model results. Interestingly, recent climate modeling efforts have suggested that, in simulations with a climate with global mean annual temperature (MAT) above freezing (~ 275 K), with topography similar to present-day and that allow the hydrologic cycle to dictate surface water and precipitation distributions, precipitation would have been dominated by snowfall and rainfall would have been negligible. Thus, regardless of which climate scenario persisted on early Mars, fluvial activity may have been dominated by snowmelt and runoff, not rainfall and runoff. In this work, we use the 3D LMD GCM to assess whether the distribution of valley networks and paleolake basins is more consistent with (1) the model-predicted distribution of snow/ice melting in a long-lived “warm and wet” climate (above-freezing global MAT, ~ 275 K), or (2) the model-predicted distribution of snow/ice melting in a long-lived “cold and icy” climate with one or more periods of punctuated heating. We find that the distributions of VNs and paleolake basins are most consistent with the distribution of model-predicted snow/ice melting for the case of a long-lived “cold and icy” climate with one or more periods of punctuated heating. We conclude by outlining further tests of our results and identifying outstanding questions.

Keywords: Mars, surface; Mars, climate; geological processes; atmospheres, evolution

1. Introduction

Geologic evidence suggests that the early martian climate was “warm and wet” with above-freezing surface temperatures and rainfall as the dominant erosive mechanism (e.g. Craddock and Howard, 2002; Ramirez and Craddock, 2018; Ramirez, 2017). This evidence includes valley networks (VNs) (e.g. Fassett and Head, 2008a; Howard et al., 2005; Hynek et al., 2010), open- and closed-basin paleolakes (e.g. Cabrol and Grin, 1999; Fassett and Head, 2008b; Goudge et al., 2015; Irwin et al., 2005), widespread craters that have degraded rims and no visible ejecta deposits (e.g. Jones, 1974), and surface aqueous alteration (e.g. Bibring et al., 2006; Carter et al., 2015). On the basis of this type of evidence, previous work by Craddock and Howard (2002) suggested that a “warm, wet early climate capable of supporting rainfall and surface runoff” is “the most plausible scenario for explaining the entire suite of features in the martian cratered highlands”. More recently, Ramirez and Craddock (2018) argued that “a warm and semi-arid climate capable of producing rain is most consistent with the geological and climatological evidence” and that “the geomorphology cannot be explained without the occurrence of above-freezing surface temperatures and rain at least seasonally, if not persistently”.

In contrast to this evidence, however, climate models for early Mars have been incapable of reproducing these long-lived (spanning the Noachian era) “warm and wet” conditions over a very wide parameter space; the models instead predict that the long-lived early climate may have been “cold and icy”, with average surface temperatures far below freezing (global mean annual temperature ~ 225 K) and surface water trapped as ice in the highlands (Forget et al., 2013; Kasting, 1991; Wordsworth et al., 2013). A potential explanation for the formation of the VNs and paleolakes in a “cold and icy”

climate is significant melting of surface snow and ice and runoff which could have occurred during periods of punctuated or transient heating (e.g. Wordsworth, 2016).

Thus, there are two end-member scenarios for the early martian climate: (1) a long-lived and continuous “warm and wet” Noachian climate, characterized by above-freezing average surface temperatures, rainfall and surface runoff, or (2) a long-lived “cold and icy” Noachian climate, characterized by average surface temperatures far below freezing and one or more periods of punctuated heating, melting of surface snow and ice, and surface runoff.

Acknowledging that these climate scenarios pose very different hypotheses for the characteristics of the hydrologic cycle which should be further tested, recent climate modeling efforts have attempted to estimate the distribution of rainfall in a “warm and wet” climate in order to explore the hypothesis that the valley networks and paleolakes formed through rainfall and runoff in a “warm and wet” climate (Palumbo and Head, 2018; Ramirez et al., 2020; Wordsworth et al., 2015). Collectively, these works have explored a “warm and wet” climate and hydrologic cycle for the conditions of (1) both forcing the presence of a stable, open-water lowlands ocean (Wordsworth et al., 2015) and not forcing the presence of a lowlands ocean, but instead allowing the distribution of surface water to be dictated by the hydrologic cycle (Palumbo and Head, 2018), and (2) present-day topography (Palumbo and Head, 2018; Wordsworth et al., 2015) and flat topography, which is a simplified interpretation of pre-Tharsis topography in the southern hemisphere and a large ocean filling the northern hemisphere (Ramirez et al., 2020). Evidence exists for a lowlands ocean (e.g. Achille and Hynek, 2010; Parker et al., 1993), but these lines of evidence are inconclusive (Head et al., 2018; Rivera-Hernández and

Palucis, 2019). Similarly, evidence supports late growth of Tharsis (e.g. Bouley et al., 2018, 2016), but other evidence supports Tharsis having been largely emplaced by the LN-EH (e.g. Fassett and Head, 2011; Scanlon et al., 2016a). Therefore, exploring both endmembers of these scenarios is critical for our continued understanding of the early climate. Interestingly, these studies find that for a climate with global mean annual temperature (MAT) above freezing:

- (1) If there is a forced open-water ocean in the lowlands and topography was similar to present-day (Wordsworth et al., 2015), then widespread rainfall is expected, but the rainfall distribution is not well-correlated with the VN distribution (see Figure 14 from Wordsworth et al., 2015). This work explored global MAT ~ 285 K, similar to that of present-day Earth.
- (2) If there is not a forced open-water ocean in the lowlands (e.g. surface water and precipitation distributions are dictated by the hydrologic cycle) and topography was similar to present-day (Palumbo and Head, 2018), then (a) despite a reasonable water inventory of ~ 34 m GEL (Carr and Head, 2015), a stable, large body of water does not form in the lowlands, (b) precipitation is dominated by snowfall, not rainfall, (c) the Tharsis rise remains below freezing year-round and much of the surface water is predicted to be cold-trapped on the Tharsis rise, and (d) rainfall is almost non-existent. This work explored global MAT ~ 275 K.
- (3) If there is an ocean in the northern hemisphere and global topography was flat (Ramirez et al., 2020), then (a) widespread rainfall is predicted as long as the ocean is not ice-covered and (b) average rainfall rates in latitudinal bands that

contain VNs could be sufficient to carve the VNs. This work explored a range of global MAT dictated by greenhouse gas concentrations, all near or above 273 K.

These findings show that, similar to the model-predicted “cold and icy” climates, fluvial activity in “warm and wet” climates may be dominated by snowmelt, not rainfall, specifically if topography was similar to present-day. These works and their findings are outlined in more detail in Section II.

These studies (Palumbo and Head, 2018; Wordsworth et al., 2015) and others (e.g. Fastook and Head, 2015; Forget et al., 2013; Wordsworth et al., 2013) have paved the way for future work because they have provided insight into the nature and distribution of fluvial activity for the different proposed climate scenarios of early Mars.

In this work, we use a combination of climate model simulations and analyses of the distributions of VNs and paleolake basins in order to determine whether the formation of these features is more consistent with a long-lived “warm and wet” Noachian climate or a long-lived “cold and icy” Noachian climate with one or more periods of punctuated heating in the Late Noachian-Early Hesperian (LN-EH; ~ 3.7 Ga). Specifically, because previous climate modeling studies have shown that the VNs and paleolake basins may not have formed through rainfall-related processes in either climate scenario, specifically if topography was similar to present-day (e.g. Palumbo and Head, 2018; Wordsworth et al., 2015) and previous estimates for the Noachian surface/near-surface water inventory are accurate (Carr and Head, 2015), we explore whether the distribution of VNs and paleolake basins is more consistent with the distribution of model-predicted melting of snow/ice in a long-lived “warm and wet” Noachian climate or the distribution of model-predicted melting of snow/ice in a long-lived “cold and icy” Noachian climate with one

or more periods of punctuated heating. We first review in more detail the model-predicted characteristics of a long-lived “warm and wet” climate (Section 2), next review the model-predicted characteristics of a long-lived “cold and icy” climate with one or more periods of punctuated heating (Section 3), and then compare the model-predicted distribution of fluvial activity in each climate scenario with the distributions of VNs and paleolake basins in order to determine which climate scenario is more consistent with the formation of these features (Section 5).

2. Model-predicted characteristics of a long-lived “warm and wet” climate

Recent studies have used 3D Global Climate Models (GCMs) and Energy Balance Models (EBMs; resolves climate in latitudinal bins) to simulate a “warm and wet” climate (Palumbo and Head, 2018; Ramirez et al., 2020; Wordsworth et al., 2015). In this section, we review these works, which outline our current state of understanding of a “warm and wet” hydrologic cycle.

Wordsworth et al. (2015) simulated a “warm and wet” climate with global MAT ~ 285 K, similar to present-day Earth, by introducing gray gas into the atmosphere, and forced the presence of an open-water ocean in the northern lowlands, which was treated as an infinite water source in the model. Gray gas mimics the effects of greenhouse warming by absorbing at a constant rate across the infrared spectrum and ‘artificially’ warming the atmosphere; gray gas does not simulate the effects of any one specific gas.

In the higher atmospheric pressure regime that likely persisted in the Noachian (~ 1 bar), the atmosphere and surface become dynamically linked together and temperature becomes dominantly dependent on altitude instead of latitude (‘adiabatic

cooling effect'; Forget et al., 2013; Wordsworth et al., 2013). Thus, the highest elevation regions are predicted to be significantly colder than the lowest elevation regions.

Wordsworth et al. (2015) found that evaporation of water from lowlands ocean and re-precipitation as rain in the highlands was common in their simulations. However, model-predicted rainfall patterns were not well-correlated with the VN distribution (Wordsworth et al., 2015). As a result, Wordsworth et al. (2015) concluded that the VNs and paleolakes are not likely to have formed through rainfall and runoff in the scenario of a “warm and wet” climate with global MAT ~ 285 K, an ocean in the lowlands, and present-day topography.

In a more recent study, Palumbo and Head (2018) simulated a “warm and wet” climate with global MAT ~ 275 K, consistent with the requirement for a “warm and wet” climate of globally-averaged above-freezing surface temperatures (Ramirez and Craddock, 2018). Following Wordsworth et al. (2015), Palumbo and Head (2018) assumed a 1 bar CO₂ atmosphere and simulated the effects of greenhouse warming by introducing gray gas into the model atmosphere. In contrast to Wordsworth et al. (2015), however, Palumbo and Head (2018) did not force the presence of an ocean because the evidence for martian oceans is controversial (e.g. Head et al., 2018 outline the outstanding questions regarding the presence of an ocean; Rivera-Hernández and Palucis, 2019 show that the distribution of deltas in fact do not coincide with a shoreline and should no longer be cited as evidence for an ocean). The simulations by Palumbo and Head (2018) included a surface water inventory of ~ 34 m GEL (Carr and Head, 2015) and an active hydrologic cycle; surface water and precipitation distributions were dictated by the hydrologic cycle. The surface/near-surface Noachian water inventory was

calculated by Carr and Head (2015) by accounting for water sources/sinks through time and back-calculating through the martian epochs. Note that larger estimates for the Noachian surface water inventory exist, up to hundreds of meters GEL (Villanueva et al., 2015), but these estimates cannot be applied to the LN-EH specifically as D/H ratios evolve over the entirety of planetary history. Palumbo and Head (2018) found that, without the forced presence of a persistent ocean in the lowlands and with present-day topography, pluvial activity is predicted to be negligible. Specifically, because of the adiabatic cooling effect and the large elevation variations across the planet, parts of the surface remain below freezing year-round, even for a climate with global MAT ~ 275 K. These areas, which contain the south polar region for relatively low obliquity conditions (see Scanlon et al., 2016a for additional discussion of snow/ice accumulation and melting in the south polar region) and the highest elevation areas of the Tharsis rise, become surface cold traps for water ice. As a result, some surface water is predicted to be deposited in these areas as snow and ice, where it remains permanently stable. Some precipitation occurs in the highlands, but the precipitation is mostly snow because temperatures in most of the highlands are below freezing for more than half of the year. Because rainfall is negligible in this climate scenario ($<1\%$ of the VNs and paleolake basins are located in areas of model-predicted rainfall; see Table 1), Palumbo and Head (2018) concluded that the VNs and paleolakes are not likely to have formed through rainfall in a “warm and wet” climate with global MAT ~ 275 K, with present-day topography, and without forcing the presence of an ocean in the lowlands. They predict that significant fluvial activity is only possible in this scenario through the seasonal melting of snow/ice in the highlands (Palumbo and Head, 2018).

It is important to reiterate that these studies have assumed present-day topography, based on the hypothesis that the large basins and volcanic rises were formed by this time (e.g. Fassett and Head, 2011; Scanlon et al., 2016a; Tanaka et al., 2014). Recent studies, however, have suggested that the Tharsis rise may have been mostly constructed after the LN-EH (e.g. Bouley et al., 2018, 2016). This proposed LN-EH topography would remove the largest surface cold trap in these warm simulations, possibly permitting relatively more hydrologic cycling and pluvial activity. Ongoing work is aiming to quantitatively constrain the role of Tharsis on the hydrologic cycle in a “warm and wet” climate. Specifically, Ramirez et al. (2020) used an EBM to explore a “warm and wet” climate without the presence and influence of Tharsis. As an approximation of pre-Tharsis topography, Ramirez et al. (2020) treated Mars as a flat surface, with the southern hemisphere having constant elevation and the northern hemisphere being filled with an ocean. They introduced H_2 into the model atmosphere to produce above-freezing climates; note that such conditions would be transient, lasting $\sim 10^5$ - 10^7 years, unless there was a continuous supply of these gases into the atmosphere (e.g. Wordsworth et al., 2017). Ramirez et al. (2020) found that, under these conditions, rainfall occurs in latitudinal bands that contain VNs and rainfall rates may be sufficient to incise the VNs. Additionally, on a flat planet, if the ocean freezes over, the surface hydrologic cycle is not expected to continue (Ramirez et al., 2020); note that 3-dimensional simulations with present-day topography show that freezing of an ocean would not terminate the surface hydrologic cycle (e.g. Turbet et al., 2017). Therefore, if there was an open-water ocean in the northern hemisphere and the southern hemisphere was flat, significant rainfall and runoff may occur in regions that contain VNs. Future

work should implement more realistic pre-Tharsis topography (e.g. Citron et al., 2018) and utilize 3D GCMs to better understand how rainfall distributions and rates would vary under these conditions.

In summary, if the climate was characterized by global MAT above freezing (e.g. 275 K) and topography was similar to present-day, seasonal melting of snow and ice in the highlands may be a more likely candidate to explain widespread fluvial activity that is well-correlated with the distribution of VNs and paleolake basins (Wordsworth et al., 2015; Palumbo and Head, 2018).

3. Model-predicted characteristics of a long-lived “cold and icy” climate with punctuated heating

In the “cold and icy” climate scenario, characterized by global MAT ~ 225 K, surface water is cold-trapped as snow and ice in the higher elevation areas, which are much colder than the lower elevation areas (with an ~ 50 K temperature difference between the lowest and highest elevation areas) (Forget et al., 2013; Wordsworth et al., 2013). Although some seasonal melting of snow and ice is possible, meltwater volumes and rates are not volumetrically significant when considering a pure CO₂-H₂O atmosphere, 75% present-day solar luminosity (Gough, 1981), and the statistically most likely values for spin-axis/orbital parameters (25-55° obliquity, $\pm 1\sigma$ mean obliquity for the past 5 billion years; eccentricity 0-0.17, lower and upper limit for statistically probable values for the past 5 billion years with 0.17 having $\sim 20\%$ probability; Laskar et al., 2004) (Palumbo et al., 2018). Furthermore, it is far too cold for rainfall to occur. Thus, if the long-lived background Noachian climate was “cold and icy”, fluvial and

lacustrine activity would have been possible mostly only during periods of transient or punctuated heating (e.g. Fastook and Head, 2015) from, for example, volcanism-induced heating (possibly lasting days to centuries; e.g. Halevy and Head, 2014; Johnson et al., 2008; Kerber et al., 2015; Mischna et al., 2013; Postawko and Kuhn, 1986) or transient reducing greenhouse-rich atmospheres containing H₂ and/or CH₄ (possibly lasting ~10⁵-10⁷ years; e.g. Ramirez et al., 2014; Turbet et al., 2019; Wordsworth et al., 2017). Interestingly, Head and Marchant (2014) showed that the edges of the predicted highlands ice sheet are well-correlated with the distribution of VNs and paleolake basins, implying that fluvial activity from melting of the ice sheet and surface runoff during periods of transient or punctuated heating could occur in regions where the VNs and paleolake basins are abundant (Head and Marchant, 2014; Wordsworth et al., 2015) (Fig. 1). Additionally, Kite et al. (2013) showed that infrequent periods of seasonal snowmelt is consistent with the formation of sedimentary rocks on Mars.

4. Methods

In Sections 2 and 3, we outlined the characteristics of the two end member climate scenarios: (1) a long-lived “warm and wet” climate and (2) a long-lived “cold and icy” climate with one or more periods of punctuated heating. Recent studies find that, in both of these climate scenarios, if topography was similar to present-day, fluvial activity that is well-correlated with the distributions of VNs and paleolake basins would only occur through melting of surface snow and ice deposits, not rainfall. To test the validity of this conclusion, we determine the distribution of meltwater (1) produced through summertime melting of surface snow/ice in the highlands in a long-lived “warm and wet”

Noachian climate (without the forced presence of a long-lived ocean in the northern lowlands, following Palumbo and Head, 2018), and (2) produced through melting of the widespread snow/ice in the highlands during periods of punctuated heating in a long-lived “cold and icy” Noachian climate. We then compare the distribution of VNs and paleolake basins with the areas of model-predicted snowmelt to determine which of the two climate scenarios is more consistent with fluvial and lacustrine activity in areas that contain VNs and paleolakes.

In the following sections, we describe our methodology for climate model simulations (Section 4.1), estimating meltwater distributions in a long-lived “warm and wet” Noachian climate (Section 4.2), estimating meltwater distributions in a long-lived “cold and icy” Noachian climate with punctuated heating (Section 4.3), and estimating the percentage of VNs and paleolake basins that are distributed in areas of model-predicted snow/ice melting (Section 4.4).

4.1 Climate model simulations

We utilize the 3D Laboratoire de Météorologie Dynamique (LMD) GCM for early Mars (e.g. Forget et al., 2013; Wordsworth et al., 2013) to complete this study. We utilize data from the previous studies of a long-lived “warm and wet” Noachian climate by Palumbo and Head (2018) and of a long-lived “cold and icy” Noachian climate by Palumbo et al. (2018).

We utilize a total of four GCM simulations (Fig. 2): (1) a “warm and wet” climate with 25° obliquity, (2) a “warm and wet” climate with 45° obliquity, (3) a “cold and icy” climate with 25° obliquity, and (4) a “cold and icy” climate with 45° obliquity.

The simulations with a “cold and icy” climate (Palumbo et al., 2018) were generated for a globally-averaged 1 bar CO₂ atmosphere (Jakosky et al., 2017), 25° and 45° obliquity (Laskar et al., 2004), a circular orbit, ~34 m GEL surface/near-surface water inventory (Carr and Head, 2015), present-day topography (e.g. Fassett and Head, 2011), and 75% of the present solar luminosity (Gough, 1981). Many previous studies have shown that these early martian conditions would produce a “cold and icy” climate (e.g. Forget et al., 2013; Kerber et al., 2015; Mischna et al., 2013; Wordsworth et al., 2013); global MAT is ~225 K in these simulations.

The simulations with a “warm and wet” climate (Palumbo and Head, 2018) use the same approach and parameter values as the simulations with a “cold and icy” climate but have additional greenhouse warming forced in the model. Greenhouse warming is forced by the introduction of gray gas into the model atmosphere. Palumbo and Head (2018) implemented gray gas coefficients of $\kappa = 7.5 \times 10^{-5} \frac{\text{m}^2}{\text{kg}}$ for simulations with 25° obliquity and $\kappa = 9.5 \times 10^{-5} \frac{\text{m}^2}{\text{kg}}$ for simulations with 45° obliquity in order to produce the necessary greenhouse warming to produce the desired temperature conditions for a “warm and wet” climate: local MAT ~273 K in the near-equatorial regions where VNs and paleolake basins are abundant and above-freezing global MAT, ~275 K (e.g. following the description of a “warm and wet” climate from Ramirez and Craddock, 2018).

For all simulations utilized here, the GCM was run at a spatial sampling of 65 x 49 x 25 (longitude x latitude x altitude; longitudinal resolution of 5.625°, latitudinal resolution of 3.75°, altitudinal resolution best near surface and changes with height) and hourly data was collected. These spatial and temporal resolutions are sufficient to capture

the necessary regional and seasonal variation to complete our study. We ensured that the model reached equilibrium before analyzing the data and confirmed that the model had sufficient volumes of water to accurately predict rainfall, snowfall, and ice accumulation patterns (e.g. the hydrologic cycle is not water limited, requires more than a few cm GEL water; e.g. Bouley et al., 2016). The physics, chemistry, and physical parameterizations for the utilized version of the GCM are described in detail by Wordsworth et al. (2015) and the model includes a full water cycle, advanced ice equilibration methodology for accuracy and time efficiency, cloud nucleation dynamics and microphysics, tracers for CO₂ and H₂O molecules, and Mars Orbiter Laser Altimeter (MOLA) topography (resolution of 0.23 x 0.23 km²) (Smith et al., 1999).

4.2 Estimating meltwater distributions in a long-lived “warm and wet”

Noachian climate

Our methodology for using GCM results to estimate the distribution of model-predicted meltwater in a long-lived “warm and wet” Noachian climate (global MAT ~275 K) is illustrated in Fig. 3a-c. We identify regions where meltwater production occurs within one year (Fig. 3c) as regions in which snow/ice accumulation occurs (Fig. 3a) but snow/ice is only present for part of the year (Fig. 3b). Using GCM data, we estimate the locations where snow/ice has melted by using the yearly minimum ice distribution, which we identify as a contour plot of the lowest snow/ice thickness throughout the year in each GCM grid cell; recall that portions of the highlands are cold traps and contain surface snow and ice year round even in these relatively warm climates. In areas where the yearly minimum amount of snow/ice is zero, but snow/ice accumulation happened at some point

in the year, we deduce that the accumulated snow/ice melted. This method of comparison between where snow/ice accumulation occurs and where the yearly minimum amount of snow/ice is zero provides a reasonable proxy for the distribution of meltwater production for two key reasons: (1) if snow accumulates but is gone by the end of the year (minimum snow/ice thickness of zero), the accumulated snow/ice has melted (a small amount will also have sublimated), and (2) in regions where snow/ice is present year-round, the ground is never exposed and thus surface runoff and regolith substrate erosion is not predicted, so we exclude those areas when identifying areas that could experience fluvial regolith erosion and formation of VNs and paleolakes. It is important to note that this method does not make any predictions about runoff rates, runoff distances, or the volume of meltwater produced.

4.3 Estimating meltwater distributions in a long-lived “cold and icy”

Noachian climate with punctuated heating

Our methodology for using GCM results to estimate the distribution of predicted meltwater in a long-lived “cold and icy” climate with one or more periods of punctuating heating is illustrated in Fig. 4 a-c. To estimate regions in which meltwater would be produced during a climate warming event in an otherwise long-lived “cold and icy” climate, we compare the yearly minimum snow/ice distribution in a simulated “cold and icy” climate (Fig. 4a) with the yearly minimum snow/ice distribution in a simulated “warm and wet” climate (Fig. 4b); the difference between these two snow/ice distribution maps portrays the areas in which snow/ice would be melted during the change from cold to warm conditions during a punctuated heating event (Fig. 4c).

Additionally, after the change to the punctuated warm conditions (for example, a climate with global MAT ~ 275 K, as explored in this study), melting and runoff would continue in areas predicted to experience summertime melting in a “warm and wet” climate for as long as the period of punctuated warm conditions persisted. Thus, the cumulative area that could experience melting of surface snow/ice for the scenario of a long-lived “cold and icy” climate with punctuated heating is actually equal to the sum of (1) the area that would experience melting and runoff during the change from the long-lived “cold and icy” climate to the relatively short-lived warm conditions, and (2) the area that would experience summertime melting during the relatively short-lived warm excursion (which is approximated by the distribution of predicted meltwater in a “warm and wet” climate).

4.4 Estimating the percentage of VNs and paleolake basins that are distributed in areas of model-predicted snow/ice melting

After producing estimates for the model-predicted distribution of meltwater in both climate scenarios, we determine the percentage of VNs and paleolake basins that are located within areas of model-predicted meltwater. Such an assessment provides an estimate of the percentage of VNs and lakes that could have formed through melting of snow/ice and runoff in each climate scenario.

5. Results

In this section, we discuss our findings, which are also shown in Table 1. We discuss the results of our study by (1) analyzing the meltwater distributions in a long-

lived “warm and wet” climate for the conditions of both 25° and 45° obliquity, (2) analyzing the meltwater distributions in a long-lived “cold and icy” climate with punctuated heating and a short-lived warm excursion for the conditions of both 25° and 45° obliquity, and (3) comparing the results to determine which of these scenarios is more consistent with the formation of the VNs and paleolakes.

For the scenario of a continuous and long-lived “warm and wet” Noachian climate (global MAT ~275 K), our simulations predict essentially no rainfall (Palumbo and Head, 2018), however, summertime meltwater is predicted in areas consistent with (1) 27% of the VNs and 14% of the paleolake basins for 25° obliquity and (2) 58% of the VNs and 46% of the paleolake basins for 45° obliquity (Table 1).

For the scenario of a long-lived “cold and icy” Noachian climate with punctuated heating, we discussed two factors in the distribution of predicted meltwater: (1) melting of snow/ice that occurs during the transition from cold to warm conditions, and (2) melting that occurs during the warm excursion. If we consider only the transition from cold to warm conditions, snow/ice melting is predicted in areas consistent with (1) 57% of the VNs and 39% of the paleolake basins for 25° obliquity and (2) 62% of the VNs and 46% of the paleolake basins for 45° obliquity (Table 1). If we also consider the melting that would occur during the warm excursion, which may be a better approximation, snow/ice melting is predicted in areas consistent with (1) 57% of the VNs and 39% of the paleolake basins for 25° obliquity and (2) 72% of the VNs and 61% of the paleolake basins for 45° obliquity.

For the case of 25° obliquity, all areas that are predicted to experience summertime melting of surface snow/ice during the relatively short-lived warm excursion

(e.g. in “warm and wet” conditions) are also areas that are predicted to experience melting of surface snow/ice during the transition from the long-lived “cold and icy” climate to the relatively short-lived warm conditions. Therefore, for the case of 25° obliquity, the percentage of VNs and paleolake basins that are located in areas of predicted meltwater does not change when also accounting for the melting that occurs during the warm excursion. For the case of 45° obliquity, however, some areas that are predicted to experience summertime melting of surface snow/ice during the relatively short-lived warm excursion (e.g. in “warm and wet” conditions) are not areas that are predicted to experience melting of surface snow/ice during the change from the long-lived “cold and icy” climate to the relatively short-lived warm excursion; there is not complete overlap of the predicted meltwater distributions. Therefore, for the case of 45° obliquity, the percentage of VNs and paleolake basins that are located in areas of predicted meltwater increases when accounting for the melting that occurs during the warm excursion.

These results suggest that, while the formation of many of the VNs and paleolakes are left unexplained in the scenario of a long-lived “warm and wet” Noachian climate, the formation of significantly more of the VNs and paleolakes can be explained through snow/ice melting if the long-lived Noachian climate was “cold and icy” with one or more periods of punctuated heating in the LN-EH. Specifically, for both 25° and 45° obliquity, a higher percentage of VNs and paleolake basins are located in areas of model-predicted snow/ice melting for the scenario of a long-lived “cold and icy” climate with one or more periods of punctuated heating than for the scenario of a long-lived “warm and wet” climate. For the case of 25° obliquity, 30% more of the VNs and 25% more of the

paleolake basins are located in areas of model-predicted snow/ice melting for the scenario of a long-lived “cold and icy” Noachian climate with one or more periods of punctuated heating than for the scenario of a long-lived “warm and wet” Noachian climate (Table 1 columns 3 and 7). For the case of 45° obliquity, 14% more of the VNs and 15% more of the paleolake basins are located in areas of model-predicted snow/ice melting for the scenario of a long-lived “cold and icy” Noachian climate with one or more periods of punctuated heating than for the scenario of a long-lived “warm and wet” Noachian climate (Table 1 columns 4 and 8).

Additionally, the scenario of a “cold and icy” climate with punctuated heating leads to model-predicted meltwater production in a higher percentage of areas with VNs and paleolake basins for the condition of 45° obliquity than for the condition of 25° obliquity (Table 1 columns 7 and 8). This is due to (1) the predicted distribution of meltwater due to the difference in obliquity and, as a result, incident solar radiation, (2) the fact that the predicted distribution of meltwater during the period of punctuated warm conditions does not completely overlap with the predicted distribution of meltwater during the transition from the long-lived “cold and icy” climate to the relatively short-lived warm conditions for the case of 45° obliquity, but does completely overlap for the case of 25° obliquity, and (3) the south polar region is a cold trap in the case of 25° obliquity but not 45° obliquity. This finding suggests that a period of relatively high obliquity (45°) may have been required in order for melting to occur in some areas that contain abundant VNs and paleolake basins; such high obliquity conditions are predicted by the statistical analysis from Laskar et al. (2004), which shows that obliquity of 41.8° is the most likely obliquity condition for the Noachian.

In summary, (1) the distribution of VNs and paleolake basins is more consistent with the model-predicted distribution of meltwater for the scenario of a long-lived “cold and icy” Noachian climate with one or more periods of punctuated heating than for the scenario of a long-lived “warm and wet” Noachian climate, and (2) for the scenario of a long-lived “cold and icy” Noachian climate with one or more periods of punctuated heating, the predicted meltwater distributions from higher obliquity simulations (45°) are more consistent with the distributions of VNs and paleolake basins than the predicted meltwater distributions from lower obliquity simulations (25°).

6. Additional implications and considerations

With this new result in mind, there are a few additional considerations of interest, including: (1) estimates of the required duration of the punctuated heating event, (2) estimates of the required number of punctuated heating events to form the VNs and paleolakes, (3) possible causes of punctuated heating in the LN-EH, (4) the distribution and characteristics of VN systems that cannot be explained by melting and runoff in either of the climate scenarios, (5) the distribution and characteristics of paleolakes that cannot be explained by melting and runoff in either of the climate scenarios, and (6) implications of the assumed presence of Tharsis.

(1) Estimates of the required duration of the punctuated heating event, assuming that there was a single punctuated heating event. Fastook and Head (2015) utilized approximate Noachian “cold and icy” surface ice distributions, a numerical ice sheet model, and a Positive Degree Day (PDD) analysis to estimate the volume of meltwater that would be produced during punctuated heating events. They found that if the

punctuated heating event was characterized by conditions of global MAT ~ 273 K and persisted for just one year in a background, long-lived “cold and icy” climate, a sufficient volume of meltwater would be produced to explain filling of all the open-basin paleolakes (~ 0.42 Mkm³; Fassett and Head, 2008b). Thus, we consider that the required duration of a punctuated heating event may be only one year.

If the punctuated heating event did not increase global MAT to 273 K and instead the global MAT was lower (although still warmer than the long-lived “cold and icy” conditions), it is possible that many more years of these punctuated conditions would be required to form sufficient meltwater to form the VNs and paleolakes. For example, Fastook and Head (2015) showed that, for a punctuated heating event that increased global MAT ~ 18 K above ambient “cold and icy” conditions (punctuated global MAT of ~ 243 K), the warm conditions would have had to have persisted for ~ 2000 years in order to produce sufficient volumes of meltwater to fill the open-basin paleolakes. This is because, in these colder climates, smaller amounts of meltwater are produced annually and melting of snow and ice only occurs in the summer season (e.g. Fastook and Head, 2015; Palumbo et al., 2018). This scenario, however, may be less likely when considering the formation of the VNs and paleolakes because the predicted distribution of summertime melting in these colder climates is not consistent with the locations of a large percent of VNs and paleolake basins (see Figure 21 from Palumbo et al., 2018); this is unlike the scenario of a punctuated heating event that increases global MAT to ~ 273 K or higher. Thus, although sufficient volumes of meltwater to fill the open-basin paleolakes are predicted to occur in these slightly colder punctuated heating events, the

meltwater distribution is not as well-correlated with the distributions of VNs and paleolake basins in comparison to warmer punctuated heating events.

(2) Estimates of the required number of punctuated heating events to form the VNs and paleolakes. Considering the previous estimate that a one-year-long punctuated heating event that increased global MAT to 273 K could produce sufficient volumes of meltwater to form the VNs and paleolakes (Fastook and Head, 2015), we suggest that only one punctuated heating event is required to form the VNs and paleolakes. This, of course, does not discount the possibility that more than one punctuated heating event occurred.

(3) Possible causes of punctuated heating in the LN-EH. Many sources of LN-EH punctuated and transient heating have been proposed, including but not limited to (1) the introduction of reducing gases into the atmosphere (e.g. Ramirez et al., 2014; Turbet et al., 2019; Wordsworth et al., 2017), such as methane from clathrate breakdown (e.g. Kite et al., 2017) and/or serpentinization (e.g. Holm et al., 2015), or hydrogen from volcanism (e.g. Ramirez, 2017; Ramirez et al., 2014), (2) volcanism-induced warming from the release of sulfur-based gases into the atmosphere (e.g. Halevy and Head, 2014; Johnson et al., 2008; Kerber et al., 2015; Mischna et al., 2013), and (3) the formation of high-altitude clouds (e.g. Kite et al., 2019; Mischna et al., 2019). Although any heating mechanism that could have caused temperatures to increase above 273 K, even if only seasonally or for a few weeks, could have led to snow/ice melting and runoff, understanding the timing, likelihood, duration and frequency of these transient and punctuated heating events is required in order to provide more detailed insight into the associated distribution, amount and magnitude of melting of snow/ice and surface runoff.

(4) The distribution and characteristics of VN systems that cannot be explained by melting and runoff in either of the climate scenarios. Not all VN systems, as mapped by Hynek et al. (2010), are in areas of model-predicted snow/ice melting, regardless of climate scenario. In some cases, the same areas are inconsistent with the model-predicted distribution of snow/ice melting for all explored climate scenarios, such as Arabia Terra and the eastern rim of Hellas basin (Fig. 3c, 4c). However, many of the features mapped within these regions in the original Hynek et al. (2010) database are not traditional VNs; within these regions, the database includes outflow channels, fretted channels, and other non-VN fluvial features. Thus, the mapped VNs in these regions that appear inconsistent with formation in the climate scenarios explored here may be due to the possibility that the features formed at a different time than the VNs and/or by a different formation mechanism than the VNs. Removing these non-VN features from the database used for this analysis (Hynek et al., 2010) would lead to results that indicate a higher percent of VNs in areas of model-predicted snowmelt for all climate scenarios explored here.

(5) The distribution and characteristics of paleolakes that cannot be explained by melting and runoff in either of the climate scenarios. Similar to the mapped VN systems (Hynek et al., 2010), not all open- and closed-basin paleolakes, as mapped by Fassett and Head (2008b) and Goudge et al. (2015), are in areas of model-predicted snow/ice melting. In some areas, such as Arabia Terra, there are mapped paleolakes that are inconsistent with the model-predicted distribution of snow/ice melting for all explored climate scenarios (Fig. 3c, 4c). It is possible that some of these paleolake basins may have held water at a different time than the rest of the paleolake basins and/or formed through a different process (e.g. one powerful melting event instead of a longer-lived

melting event). Future work should explore the morphologies of these outlying lakes in an effort to determine whether they have differences from the rest of the database that may suggest these paleolake basins did not hold water at the same time or due to the same mechanism as these other basins.

(6) Implications of the assumed presence of Tharsis. In this study, we implemented present-day topography based on the assumption that all major surface features were formed by the LN-EH, including volcanic edifices and impact basins (Fassett and Head, 2011; Tanaka et al., 2014). However, as previously mentioned, whether or not Tharsis was fully-developed by the LN-EH is a topic of ongoing discussion in the literature: for example, approximate ages of terrains and interpretations of the tectonic history in the region suggest that Tharsis may have been growing until much more recently (Bouley et al., 2018, 2016), but the shape and structure of the Dorsa Argentea Formation at the south pole (Scanlon et al., 2016a) and global geologic mapping (Tanaka et al., 2014) suggest that Tharsis was largely emplaced by the LN-EH. Thus, we briefly discuss the implications that the presence of Tharsis may have on the results of our study.

The Tharsis rise is the key cold trap in these simulations because it is at much higher elevation than the rest of the planet; without the presence of Tharsis, there may be a more active hydrologic cycle on the planet and possibly even rainfall in “warm and wet” simulations with global MAT ~ 275 K. Our ongoing work is constraining the role of Tharsis further by (1) performing similar simulations without the presence of Tharsis and characterizing the hydrologic cycle, including the presence of surface ice and distributions of rain and snow, and (2) performing simulations which still include Tharsis

but are much warmer than those done here (global MAT $\gg 273$ K) in an effort to determine just how warm the planet would have had to have been in order for Tharsis to no longer be a cold trap and, in those conditions, determine whether rainfall is possible.

7. Conclusions

We have utilized GCM simulations and analyzed the model-predicted distributions for fluvial activity, including rainfall and snow/ice melting, for the climate scenarios of (1) a long-lived “warm and wet” Noachian climate, and (2) a long-lived “cold and icy” Noachian climate with one or more periods of punctuated heating. Following previous studies, we find that fluvial activity would have been constrained to snow/ice melting and runoff, not rainfall and runoff, regardless of the climate scenario if topography was similar to present-day. We analyzed GCM results and the distribution of VNs and paleolake basins in order to determine whether the distribution of model-predicted snow/ice melting is more consistent with the distribution of the VNs and paleolake basins for the scenario of (1) melting of surface snow/ice during the summer season in a long-lived “warm and wet” Noachian climate or (2) melting of surface snow/ice during a punctuated heating event in an otherwise long-lived “cold and icy” Noachian climate, which produces short-lived “warm and wet” conditions. Our results show that summertime melting in a long-lived “warm and wet” Noachian climate would have only occurred in some regions of the highlands, not in all regions where VNs and paleolake basins are distributed. However, widespread melting of snow/ice in the highlands during a punctuated heating event in an otherwise “cold and icy” Noachian climate could have produced meltwater in most regions where VNs and paleolake basins

are distributed (Table 1). On average, our results show that ~20-30% more of the VNs and paleolake basins are in areas of predicted snow/ice melting for the scenario of a long-lived “cold and icy” Noachian climate with one or more periods of punctuated heating than for the scenario of a long-lived “warm and wet” Noachian climate.

These results are consistent with the hypothesis that (1) the long-lived background Noachian climate could have been “cold and icy”, characterized by widespread snow and ice in the highlands (which may have persisted as cold-based glaciers; e.g. Fastook and Head, 2015) and little-to-no fluvial activity, and (2) one or more periods of punctuated atmospheric and surface heating could have led to relatively short-lived “warm and wet” conditions near the Noachian-Hesperian boundary, characterized by abundant widespread ice melting, runoff, and formation of the VNs and paleolakes.

Topics warranting future study and outstanding questions include:

- (1) A geomorphic assessment of the VN systems and paleolake basins that are not located within areas of predicted melting of snow/ice and runoff. Some questions to answer in such an analysis include: Are these systems and basins outliers with respect to the rest of the VNs and paleolake basins? Are these VN systems relatively under-developed, possibly indicating a ‘one time’ fluvial erosion event? If these VN systems are very similar to the rest of the VNs, did all of the VNs form through a different mechanism, not ice melting and runoff? Similarly, if these paleolake basins are very similar to the rest of the paleolake basins, did all of the paleolake basins form through a different mechanism, not ice melting and runoff?

- (2) A study of terrestrial river systems formed through snow/ice melting and runoff and systems formed through rainfall and runoff in order to determine whether there are morphological differences associated with these different formation mechanisms. Our results suggest that many, if not most, of the VNs may have been formed through snow/ice melting and runoff, not rainfall and runoff, which is also in agreement with predictions from previous studies (e.g. Fastook and Head, 2015; Head and Marchant, 2014; Scanlon et al., 2016b). For example, one might consider an analogue study of the Onyx River and other fluvial features in Antarctica which form solely through snowmelt and runoff (e.g. (Head and Marchant, 2014) and also an analogue study of rivers formed in semi-arid regions on Earth, possibly building on previous studies which focused on branching angles of rivers (Seybold et al., 2018). If morphological differences associated with these formation mechanisms do exist, the question arises: Is the VN morphology more consistent with snow/ice melting and runoff, or is rainfall and runoff required?
- (3) Additional analysis of simulations that do not include the presence of Tharsis. Our models predict that, assuming Tharsis was largely built by the LN-EH (e.g. Fassett and Head, 2011), rainfall would be negligible in climate scenarios with global MAT less than at least 275 K. However, in addition to evidence that Tharsis was largely built by the LN-EH (e.g. Fassett and Head, 2011; Scanlon et al., 2016a; Tanaka et al., 2014), there is contradictory evidence which suggests that Tharsis growth continued throughout the Noachian and into the Hesperian (e.g. Bouley et al., 2018, 2016). In the absence of Tharsis, the largest cold trap

would be removed, possibly permitting more rainfall. Additionally, the rain shadow effect observed by Wordsworth et al. (2015) would no longer exist. Recent work by Ramirez et al. (2020) used an EBM to show that a rainfall-dominated hydrologic cycle could have existed in a “warm and wet” climate if there was an ocean in the northern hemisphere and the VNs formed before Tharsis was emplaced. Future work should build on this important finding, using 3-dimensional GCMs, and implementing a more representative pre-Tharsis topography. Such work should address the question: In “warm and wet” GCM simulations with pre-Tharsis topography, what is the distribution of predicted snow/ice melting, is this distribution consistent with the distributions of VNs and paleolake basins, and is abundant, widespread rainfall in the highlands possible?

- (4) Assessment of the runoff rates associated with snow/ice melting in these climate scenarios. Ramirez et al. (2020) paired calculations of runoff rates with their EBM results, which provided critical insight into the erosive capability of the model-predicted rainfall. Following this approach, future work should pair a snowmelt model with climate model results to answer questions such as: (1) Are there areas that are predicted to experience higher runoff rates than others and are these areas characterized by more intense fluvial erosion, as observed in the geomorphology? and (2) Are runoff rates high enough to produce fluvial erosion in all areas of predicted snow/ice melting, or only some areas, and how does the distribution of model-predicted runoff compare with the distribution of VNs?

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Figures

Figure 1

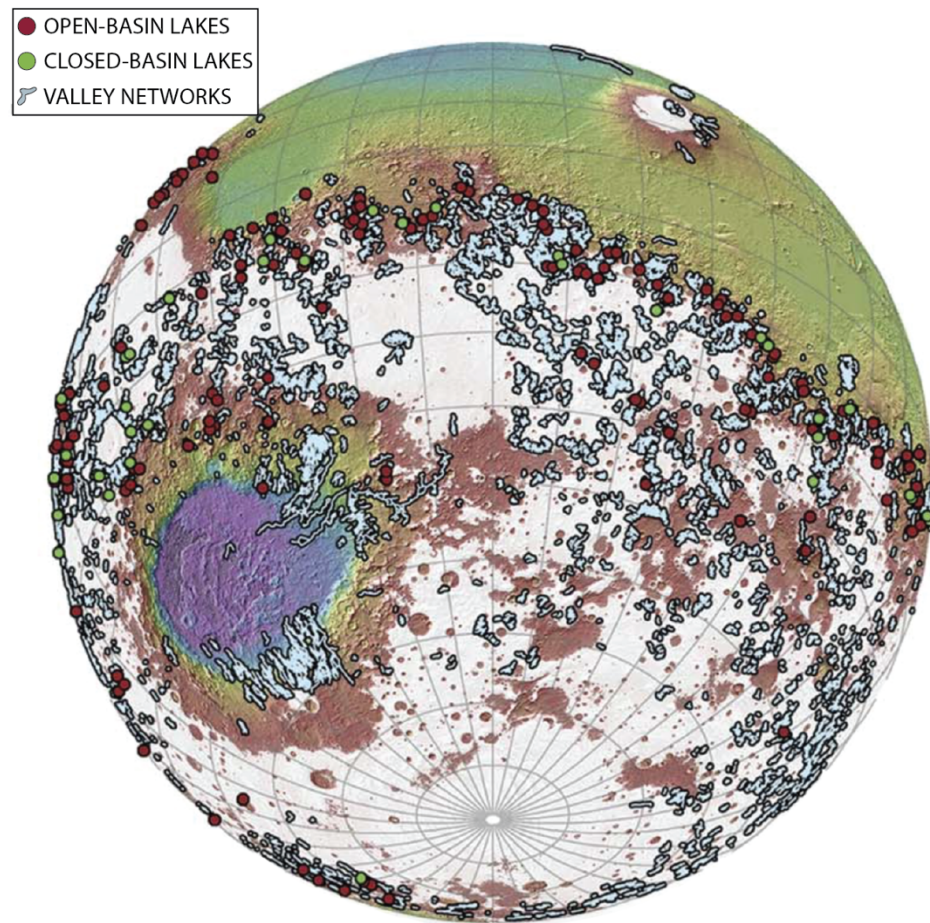


Fig. 1: Map showing spatial correlation between valley networks and lakes and the predicted Noachian ice distribution in a “cold and icy” climate. Approximation of Noachian ice distribution in a “cold and icy” climate as 1 km equilibrium line altitude (ELA) shown as area shaded in white. Open- and closed-basin lakes are shown as red and green circles, respectively, and valley networks are shown as blue lines. Figure from Head and Marchant (2014).

Figure 2

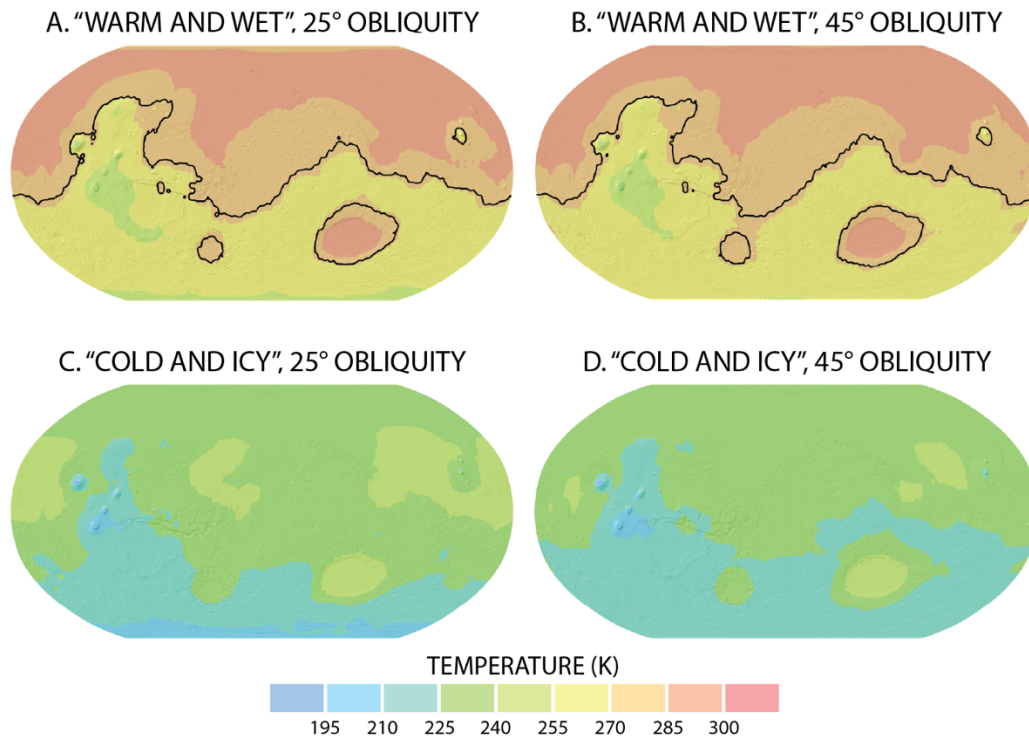


Fig. 2: Model-predicted mean annual temperature (MAT) for all simulations included here: (a) “warm and wet” with 25° obliquity, (b) “warm and wet” with 45° obliquity, (c) “cold and icy” with 25° obliquity, and (d) “cold and icy” with 45° obliquity. Shaded temperature contours follow the color bar at the bottom. The black line is the 273 K contour; note that the simulations of a “cold and icy” climate are characterized by MAT below freezing on the entire planet. Conditions and parameter values for simulations are outlined in the text.

Figure 3

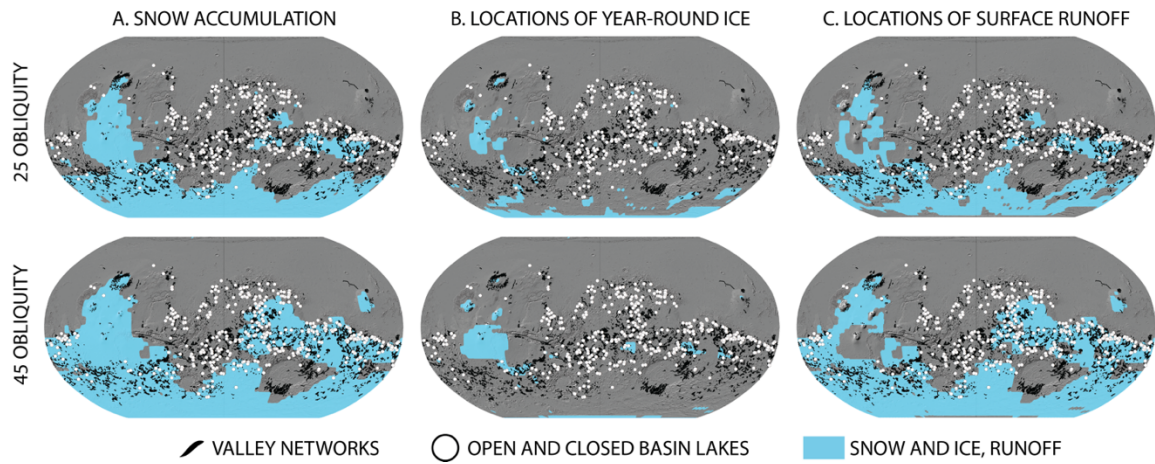


Fig. 3: Model results for the scenario of a long-lived “warm and wet” climate for 25° obliquity (top) and 45° obliquity (bottom). Shaded in blue are (a) all areas where snow accumulates at some point in the year in the “warm and wet” simulations, (b) all areas where surface snow/ice is present year-round in the “warm and wet” simulations, estimated as the minimum amount of ice present in each GCM grid cell over the course of one year, and (c) all areas where surface runoff is predicted based on the approximation that if snow accumulates and the minimum amount of snow/ice is zero, the accumulated snow has melted. In all plots, the valley networks (Hynek et al., 2010) are drawn as black lines and the open- and closed-basin lakes (Fassett and Head, 2008b; Goudge et al., 2015) are drawn as white circles. GCM data for “warm and wet” simulations are derived from Palumbo and Head (2018). Note that these maps do not provide information about the thickness of surface snow/ice deposits, which could range from frost to thick ice sheets, or the volume of meltwater produced.

Figure 4

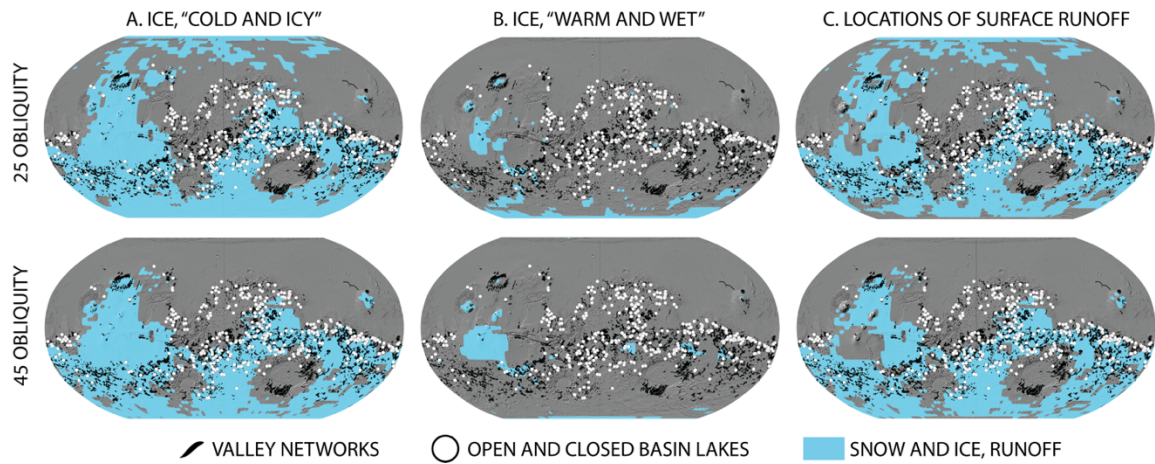


Fig. 4: Model results for the scenario of a long-lived “cold and icy” climate with punctuated heating and a short-lived warm excursion for 25° obliquity (top) and 45° obliquity (bottom). Shaded in blue are (a) all areas where surface snow/ice is present year round in the “cold and icy” simulations, (b) all areas where surface snow/ice is present year round in the “warm and wet” simulations, and (c) all areas where surface runoff is predicted based on the approximation that all areas where snow/ice accumulates in a “cold and icy” climate but not in a “warm and wet” climate would experience ice melting and runoff (and some sublimation) during a period of punctuated heating (to conditions of global MAT ~ 273 K) in a long-lived “cold and icy” climate. In all plots, the valley networks (Hynek et al., 2010) are drawn as black lines and the open- and closed-basin lakes (Fassett and Head, 2008b; Goudge et al., 2015) are drawn as white circles. GCM data for “warm and wet” simulations are derived from Palumbo and Head (2018) and for “cold and icy” simulations from Palumbo et al. (2018). Note that these maps do not provide information about the thickness of surface snow/ice deposits, which could range from frost to thick ice sheets, or the volume of meltwater produced.

Tables

Table 1

	Long-lived “warm and wet” climate				Change from long-lived “cold and icy” climate to short-lived warm climate due to punctuated heating		Change from long-lived “cold and icy” climate to short-lived warm climate due to punctuated heating plus subsequent warm period	
	Rainfall		Snow/ice melting		Snow/ice melting		Snow/ice melting	
Obliquity	25°	45°	25°	45°	25°	45°	25°	45°
Percent of VNs located in areas of predicted melting	<1%	<1%	27%	58%	57%	62%	57%	72%
Percent of lakes located in areas of predicted melting	<1%	<1%	14%	46%	39%	46%	39%	61%

Table 1: Results of assessment determining the percentage of VNs and lakes that are located in areas of model-predicted rainfall or snow/ice melting for all GCM simulations and climate scenarios considered in this work. The first and second columns show the results for the scenario of rainfall in a long-lived “warm and wet” climate for 25° and 45° obliquity, respectively. The third and fourth columns show the results for the scenario of snow/ice melting in a long-lived “warm and wet” climate for 25° and 45° obliquity, respectively. The fifth and sixth columns show the results for the scenario of snow/ice melting in the change from a long-lived “cold and icy” climate to a short-lived warm climate due to punctuated heating for 25° and 45° obliquity, respectively. Finally, the

seventh and eighth columns show the results for the climate scenario of the change from a long-lived “cold and icy” climate to a short-lived warm climate due to punctuated heating plus the subsequent warm period for 25° and 45° obliquity, respectively. The scenario with the highest percent of VNs and lakes that are located in areas of model-predicted fluvial activity (rainfall or snow/ice melting) is the climate scenario of the change from a long-lived “cold and icy” climate to short-lived warm climate due to punctuated heating plus the subsequent warm period and 45° obliquity (last column).

CHAPTER FOUR

EARTH-LIKE TEMPERATURES ARE REQUIRED FOR WIDESPREAD RAINFALL ON EARLY MARS

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Abstract

Martian fluvial and lacustrine features imply abundant rainfall in the southern highlands in the Noachian. However, recent global climate model (GCM) studies, that assume existing topography and do not force the presence of a lowlands ocean, have difficulty producing widespread rainfall in the highlands, even for climates as warm as global mean annual temperature (MAT) ~ 275 K, because (1) the highlands are much colder than the lowlands and remain below freezing for the majority of the year, and (2) of the presence of the Tharsis rise, which acts as a surface cold trap. In this work, we use a 3D GCM and ask: How warm must the early martian climate have been in order for there to have been widespread rainfall in the highlands, the major location of the valley networks and paleolakes? We find that (1) global MAT $> \sim 285$ K, similar to the global MAT on present-day Earth (~ 288 K, or $\sim 58^\circ$ F), is required for there to be widespread rainfall in the highlands, and (2) even in these very warm Noachian climates, annual widespread snow accumulation and subsequent melting occurs, suggesting that models for Noachian fluvial and lacustrine activity should consider both rainfall and snowmelt.

Keywords: climate; early Mars; rainfall; snowfall

1. Introduction and Background

Geologic evidence has been interpreted to mean that the nature of the Late Noachian-Early Hesperian (LN-EH) climate on Mars was likely to have been characterized by above-freezing temperatures and rainfall. Specifically, valley networks (VNs; Hynek et al., 2010) and paleolakes (e.g. Fassett and Head, 2008; Goudge et al., 2015) imply that liquid water flowed on the surface and ponded in topographic lows, and the degradation state of ancient craters has been attributed to rainfall-related erosion (Craddock and Howard, 2002). In order for such a “warm and wet”, rainfall-dominated climate to be reconciled with the distributions of VNs and paleolakes, climate models should predict widespread rainfall in the southern highlands.

However, recent climate models predict that the long-lived background Noachian climate may have been “cold and icy”, not “warm and wet”, characterized by average surface temperatures below freezing and water distributed as snow and ice in the highlands (Forget et al., 2013; Wordsworth et al., 2013). In this scenario, fluvial activity would only occur during periods of punctuated heating and would be dominated by melting of surface snow and ice and runoff (e.g. Wordsworth, 2016). Interestingly, the VNs and lakes are distributed near the edges of the predicted “cold and icy” ice sheet, where runoff and ponding would be expected (Head and Marchant, 2014). However, many researchers have interpreted the geomorphology to be more consistent with rainfall-related erosion (e.g. Craddock and Howard, 2002; Howard et al., 2005; Ramirez and Craddock, 2018), not snow/ice melting-related erosion, and thus investigations into the characteristics of both “warm and wet” and “cold and icy” scenarios are being pursued.

For example, recent work has utilized climate models to explore the hydrologic cycle in a “warm and wet” early martian climate (Palumbo and Head, 2018; Ramirez et al., 2020; Wordsworth et al., 2015). Together, these studies explored a range of parameters, including:

- (1) The presence and absence of an ocean: these studies explored both the forced presence of a lowlands ocean (Wordsworth et al., 2015), and a surface water distribution dictated by the hydrologic cycle and without forced water sources (Palumbo and Head, 2018), both of which are justified because evidence for a Noachian ocean is elusive (e.g. Head et al., 2018).
- (2) The presence and absence of Tharsis: these studies explored both present-day topography (Palumbo and Head, 2018; Wordsworth et al., 2015), which is consistent with the basins and volcanic rises having largely been in place by the LN-EH (e.g. Fassett and Head, 2011; Scanlon et al., 2016), and pre-Tharsis topography (Ramirez et al., 2020), which is consistent with the hypothesis that Tharsis may have been largely emplaced after the LN-EH (e.g. Bouley et al., 2018). Pre-Tharsis topography was implemented by treating Mars as a flat planet: the southern hemisphere was assumed to have been flat and the northern hemisphere was assumed to have been filled with a vast ocean (Ramirez et al., 2020).

Together, the results of these studies show that, unless early Mars was a flat planet and/or had a hemisphere-encompassing ocean, widespread rainfall in the highlands is not predicted for climates with global MAT as high as ~ 275 K, which is consistent with the typical view of temperature in a “warm and wet” climate (e.g. Craddock and Howard, 2002; Ramirez and Craddock, 2018). In such a climate, GCM results show that

fluvial activity would be dominated by snowmelt, not rainfall (Palumbo and Head, 2018). In order for widespread rainfall to occur in the highlands, the highlands must be above freezing for a significant portion of the year and there must be minimal-to-no surface cold traps (Palumbo and Head, 2018).

In this work, we use the 3D LMD GCM for early Mars to address the question: How warm must the early martian climate have been in order for there to have been widespread rainfall in the highlands, the major location of the VNs and paleolakes?

2. Methods

We employ the 3D LMD GCM (Forget et al., 2013; Wordsworth et al., 2013) to explore warm climates, in which the highlands are above freezing for most of the year and surface cold traps are absent or minimal, and determine how warm the climate must have been in order for widespread rainfall to have occurred in the highlands, which is required for rainfall-driven formation of the VNs and paleolakes. We consider a 1 bar CO₂ atmosphere (Jakosky et al., 2017), ~34 m GEL surface/near-surface water inventory (Carr and Head, 2015), 75% present-day solar luminosity (Gough, 1981), and spin-axis/orbital conditions consistent with statistically probable values for the Noachian (Laskar et al., 2004), including (1) 45° obliquity, representative of the most likely value, and (2) a circular orbit, representative of the high statistical probability that the eccentricity was very low and implemented to avoid an unnecessarily large suite of simulations and minimize seasonal perturbations. We assume present-day topography, consistent with the large basins and volcanic rises having been largely in place by the LN-EH (e.g. Fassett and Head, 2011). We allow surface water and precipitation

distributions to be dictated by the hydrologic cycle (Haberle et al., 2017) and do not force any water sources, such as an ocean.

Our simulations include a pure CO₂-H₂O atmosphere, which naturally equilibrates to “cold and icy” conditions with global MAT~225 K (Forget et al., 2013; Wordsworth et al., 2013). To achieve the desired greenhouse warming, we introduce gray gas into the model, a well-established method for when the exact concentrations and species of greenhouse gases are unknown (e.g. Wordsworth et al., 2015). Gray gas absorbs evenly across the infrared spectrum at a defined absorption coefficient and mimics greenhouse warming but is not representative of any specific greenhouse gas. In our simulations, we use gray gas coefficients which correspond to global MAT ~275-290 K; in total we produce a suite of six simulations over this range. Finally, we run the model at a spatial sampling of 65 x 49 x 25 (latitude x longitude x altitude; latitudinal resolution of 3.75°, longitudinal resolution of 5.625°, and altitudinal resolution best near the surface and changing with height) and collect hourly data; these resolutions are sufficient to resolve the temperature and precipitation trends required for this analysis.

In our simulations, we track necessary parameters to characterize the hydrologic cycle and climate: temperature, distribution of surface water ice, and distribution of precipitation (rainfall and snowfall). With this model output, we estimate how warm the climate must have been in order for there to have been widespread rainfall in the southern highlands, where the degraded craters, VNs and paleolakes are distributed.

3. Results

The key findings of our analysis are shown in Fig. 1 which includes GCM-derived mean annual temperature (MAT, Fig. 1A), peak annual temperature (Fig. 1B), and rainfall distribution maps (Fig. 1C).

The climates with widespread rainfall in the highlands (Fig. 1C) are characterized by temperatures above freezing for most of the year in the highlands (e.g. MAT >273 K, implying more than half the year above freezing; Fig. 1A), and peak annual temperature >273 K on most of the planet (Fig. 1B), implying that there are minimal-to-no surface cold traps. Rainfall is relatively more widespread for warmer simulations than for colder simulations (Fig. 1C). Our results show that global MAT >~285 K is required for widespread rainfall in the highlands (Fig. 1C). Thus, we conclude that if LN-EH topography was similar to that of present-day (Fassett and Head, 2011), and the VNs and paleolakes formed through rainfall and related runoff, then the LN-EH climate must have been characterized by global MAT >~285 K, a temperature similar to the present-day global MAT on Earth (~288 K, or ~58° F).

Although the hydrologic cycle in these very warm climates (global MAT >~285 K) is characterized by abundant and widespread rainfall, the highlands also experience widespread snowfall in the colder seasons in all of the climates explored in this study. In most areas, the snow and ice that accumulates in the colder seasons undergoes melting in the warmer seasons. The highest elevation parts of the Tharsis rise and the south polar region retain snow and ice year-round; annually, the accumulated snow and ice does not entirely melt. Therefore, our results show that even for the climate scenarios with abundant rainfall and runoff, snowmelt and runoff will also contribute to fluvial activity during the warmer seasons. We thus recommend that future studies of fluvial activity and

surface erosion in the LN-EH should consider the contributions of both rainfall and runoff and snowmelt and runoff.

4. Conclusions

We implemented the 3D LMD GCM for early Mars to address the question: How warm must the early martian climate have been in order for there to have been widespread rainfall in the highlands, the major location of the VNs and paleolakes? We find that:

- (1) Widespread rainfall in the highlands is possible for global MAT $>\sim 285$ K (Fig. 1C), a temperature much warmer than previously assumed for a “warm and wet” climate and similar to the global MAT of present-day Earth (~ 288 K, or $\sim 58^\circ$ F).
- (2) In all of the climates explored in this study, widespread snowfall and accumulation occurs in the highlands during the colder seasons and melts in the warmer seasons. Thus, even for early martian climate scenarios with rainfall and runoff, snowmelt and runoff is also predicted to contribute to the fluvial and lacustrine activity.
- (3) If the Noachian climate was not warm enough to induce widespread rainfall in the southern highlands, then VNs and paleolakes may have formed predominantly through melting of surface snow/ice and runoff, not rainfall and runoff; Wordsworth et al. (2015) and (Palumbo and Head, 2020) have shown that the distributions of snow/ice accumulation and melting is well-correlated with the distribution of VNs and paleolakes in colder climate scenarios.

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Figures

Figure 1

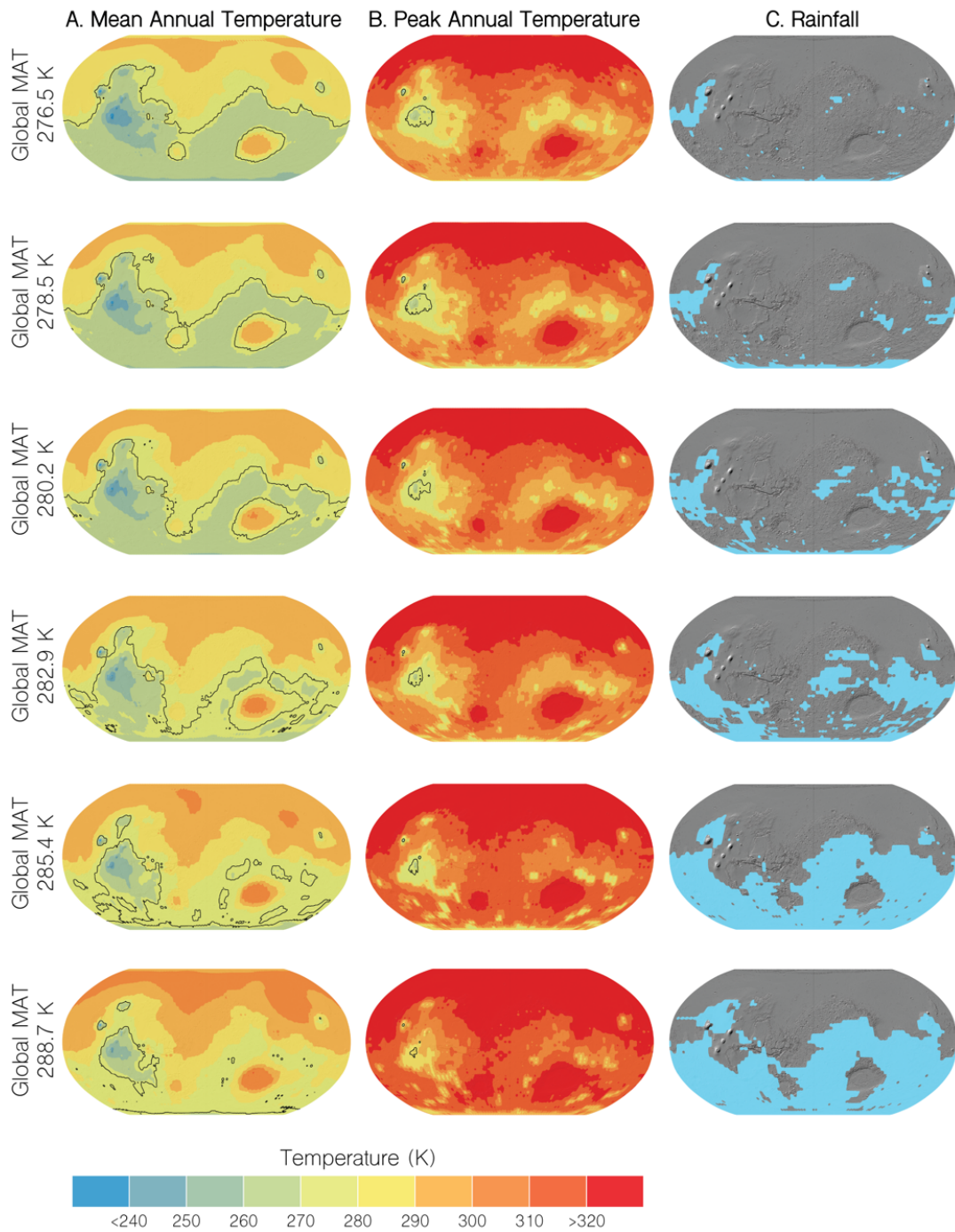


Fig. 1: Results from GCM simulations showing (A) mean annual temperature (MAT), (B) peak annual temperature, and (C) distribution of rainfall shaded in blue. Global MAT

is labelled on the left of each row, the temperature contours in (A) and (B) follow the key at the bottom and the bold black line is the 273 K contour.

CHAPTER FIVE

EXPLORING THE INFLUENCE OF VOLCANISM-INDUCED HEATING ON EARLY MARS: IMPLICATIONS FOR LOCALIZED AND SUMMERTIME MELTING

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Abstract

Geologic features, including widespread valley networks and open- and closed-basin lakes, provide evidence that there was abundant liquid water on the surface of Mars in the Late Noachian-Early Hesperian (LN-EH) era, possibly signifying an ambient “warm and wet” climate. Climate modeling studies, however, suggest that the long-lived early martian climate may have been “cold and icy”, characterized by temperatures far below freezing and surface water trapped as ice in the southern highlands. In this “cold and icy” climate scenario, the persistence of abundant surface liquid water and the formation of the valley networks and paleolakes would have been confined to periods of punctuated heating, ice melting, and runoff. One such punctuated heating mechanism is volcanism-induced heating from the introduction of sulfur-based gases into the atmosphere, but this mechanism has been rejected in the past because (1) sulfur-based gases alone appear to be unable to force global mean annual temperature (MAT) to above 273 K, and (2) the heating is likely to have been short-lived due to the rapid conversion of sulfur-based gases to aerosols, which are atmospheric cooling agents. In this research, we explore this mechanism in more detail in order to determine if significant heating, melting of surface snow and ice, and runoff could occur despite these previously identified caveats.

Specifically, we implement the 3D LMD GCM to explore two key phases of SO₂-related volcanism-induced heating: *phase one*, the period of time in which SO₂ and associated heating are focused near the volcanic edifice and spreading through a latitudinal band, and *phase two*, the period of time in which the SO₂ is spreading poleward and becomes globally distributed. We find that (1) in *phase one*, significant localized heating can occur near the volcanic edifice, potentially leading to a few days with peak temperatures above

freezing, melting of snow and ice, and runoff, and (2) in *phase two*, although global MAT is <273 K for reasonable gas concentrations, temperatures above freezing, melting of snow and ice, and runoff can occur during the summer months. Further, with the conservative assumption that volcanism-induced heating lasts for only one year before conversion of the sulfur-based gases to aerosols and with consideration of reasonable concentrations of SO_2 gas, we find that hundreds of thousands of volcanic events would be required to produce sufficient volumes of meltwater to explain the formation of the valley networks. Future work is needed to assess whether the large amount of LN-EH volcanism could produce the necessary volumes of meltwater.

1. Introduction

Widespread valley networks (VNs) (Fassett and Head, 2008b; Hynek et al., 2010) and open-and closed-basin lakes (Cabrol and Grin, 1999; Fassett and Head, 2008a; Goudge et al., 2015), suggest that there was abundant liquid water on the surface of Mars in the Late Noachian-Early Hesperian (LN-EH). Additionally, widespread aqueous alteration products (Bibring et al., 2006; Carter et al., 2015) and degraded craters (Craddock and Howard, 2002) suggest that these conditions may have persisted throughout the Noachian era, not just in the LN-EH. This evidence for liquid water stability has led to the reasonable deduction that the long-lived early climate (spanning the Noachian era) was “warm and wet”, characterized by ambient continuous and long-lived global mean annual temperature (MAT) >273 K and rainfall as the dominant erosive mechanism (e.g. Craddock and Howard, 2002; Ramirez and Craddock, 2018; Ramirez, 2017). In contrast to this interpretation, climate modeling studies have been incapable of producing a long-lived “warm and wet” climate when considering the faint young Sun and reasonable greenhouse gas concentrations (e.g. Forget et al., 2013; Kasting, 1991; Wordsworth et al., 2013). These models instead predict that the long-lived early climate was “cold and icy”, characterized by global MAT far below freezing (~ 225 K) and water trapped as ice the highlands (Forget et al., 2013; Head and Marchant, 2014; Wordsworth et al., 2013).

In this “cold and icy” climate scenario, surface liquid water and fluvial and lacustrine activity would only occur during periods of punctuated or transient heating, melting of surface snow and ice, and runoff (or rainfall and runoff) (e.g. see review in Wordsworth, 2016). Interestingly, VNs and lakes are distributed near the edge of the model-predicted highlands ice sheet or on steep topographic slopes, where runoff and ponding would be

expected if melting of the ice occurred (e.g. Head and Marchant, 2014). Many punctuated heating mechanisms have been proposed, including impact cratering-induced heating and rainfall (Palumbo and Head, 2018; Segura et al., 2002, 2008; Steakley et al., 2019; Toon et al., 2010; Turbet et al., 2019), seasonal temperature variations and summertime melting (e.g. Kite et al., 2013; Palumbo et al., 2018), transient reducing greenhouse-rich atmospheres (e.g. Ramirez et al., 2014; Turbet et al., 2019; Wordsworth et al., 2017), greenhouse warming from high altitude H₂O and/or CO₂ clouds (e.g. Forget et al., 2013; Forget and Pierrehumbert, 1997; Kite et al., 2019; Urata and Toon, 2013), and volcanism-induced heating from the release of sulfur-based gases into the atmosphere (e.g. Halevy and Head, 2014; Johnson et al., 2009, 2008; Kerber et al., 2015; Mischna et al., 2013; Postawko and Kuhn, 1986; Tian et al., 2010).

In this research, we revisit the mechanism of volcanism-induced heating from the release of sulfur-based gases into the atmosphere and characterize two previously unexplored aspects of this mechanism.

2. Background

Sulfur-based gases are compelling greenhouse agents on early Mars for multiple reasons. First, sulfur-based gases, including SO₂, are strong greenhouse gases in the martian atmosphere because they have fundamental absorptions in the infrared (IR) atmospheric window (Postawko and Kuhn, 1986) (Fig. 1). Additionally, it has been suggested that martian magmas are relatively more enriched in sulfur than terrestrial magmas (e.g. Gaillard and Scaillet, 2009), implying that larger amounts of sulfur-based gases can be introduced into the atmosphere for relatively small eruption volumes. In

other words, for two eruptions of identical volume on Earth and Mars, the martian eruption would release volumetrically more sulfur-based gases into the atmosphere. Finally, at least 30% of the martian surface was covered by basaltic plains from punctuated effusive flood volcanism in the LN-EH (Craddock and Greeley, 2009; Head et al., 2002; Tanaka et al., 2014), implying that volcanism was an active and important geologic process in the LN-EH, and was likely to have been characterized by very high-volume eruptions (e.g. Head et al., 2006). Cumulatively, estimates for the volumes of extrusive volcanic material on Mars suggest that more than half of the extrusive material was emplaced in the Late Noachian and Early Hesperian epochs (Craddock and Greeley, 2009; Greeley and Schneid, 1991). In addition to the evidence for widespread effusive volcanism, explosive volcanism was also likely to have been abundant earlier in martian history due to the relatively low atmospheric pressure and planetary gravity (Kerber et al., 2013; Wilson and Head, 2007). Previous work has identified potential pyroclastic deposits on the surface (e.g. Crown and Greeley, 1993; Greeley and Crown, 1990; Greeley and Spudis, 1981; Kerber et al., 2012; Williams et al., 2008), however the complex wind patterns, which change as a function of atmospheric pressure and obliquity, in combination with the complex dust/tephra lofting and transport processes, makes it difficult to fully map and evaluate the volume and distribution of global pyroclastic deposits on the surface (e.g. Kerber et al., 2013).

We build on the work of many previous researchers who have identified volcanism-induced heating from sulfur-based gases as a compelling punctuated heating mechanism and have implemented climate and radiative transfer models to calculate the heating associated with the injection of volcanically-released sulfur-based gases into the early

martian atmosphere (e.g. Halevy and Head, 2014; Johnson et al., 2009, 2008; Kerber et al., 2015; Mischna et al., 2013; Postawko and Kuhn, 1986; Tian et al., 2010). These previous studies have typically rejected this mechanism as a means to bring significant heating, rainfall and/or melting of surface snow and ice, and runoff because (1) reasonable concentrations of sulfur-based gases cannot cause global MAT to exceed 273 K (e.g. Mischna et al., 2013) and (2) the heating is likely to be short-lived, possibly lasting less than one year (e.g. Kerber et al., 2015; Tian et al., 2010), because the sulfur-based gases would rapidly convert into aerosols, which are atmospheric cooling agents. However, two important factors have not been considered in these previous studies: (1) the possibility of localized heating and melting immediately after an eruption and focused near the volcanic edifice, and (2) the possibility that temperatures could have been above freezing in the summertime, potentially permitting seasonal melting of surface snow and ice, despite the fact that global MAT would have been below freezing (e.g. Palumbo et al., 2018). The latter of these factors is comparable in process to what is observed in the McMurdo Dry Valleys: in the McMurdo Dry Valleys, MAT is ~253 K but temperatures exceed 273 K in the summertime and seasonal summertime ice melting, runoff, stream, and lake activity occur and erode the surface, leaving behind a morphologic signature (Conovitz et al., 1998; Dana et al., 1998; Head and Marchant, 2014). Additionally, Mischna et al. (2013) showed that, for atmospheric SO₂ concentrations of ~100s ppm, summertime temperatures above freezing is possible in certain areas. In this research, we explore the influence of volcanically-released SO₂ from both of these previously unexplored factors.

To best explore these two important factors, we describe the volcanism-induced heating mechanism in two phases (Fig. 2). We identify these phases based on the spreading of a volcanic plume and the changing distribution of the volcanically-released gases as a function of time. *Phase one* is defined as the period of time in which the volcanically-released SO₂ and associated heating are focused near the volcanic edifice and spreading predominantly in a latitudinal band. *Phase two* is defined as the period of time in which the SO₂ is spreading poleward and becomes globally distributed. Specifically, we address the following questions:

- (1) During *phase one*, does significant localized heating occur near the volcanic edifice, permitting above-freezing temperatures and localized melting of snow and ice?
- (2) During *phase two*, are summertime temperatures above freezing, potentially permitting summertime melting of snow and ice, despite the fact that global MAT is below freezing?

3. Methods

To address our two research questions, we implement the 3D Laboratoire de Météorologie Dynamique global climate model (LMD GCM) for early Mars and explore the greenhouse influence of atmospheric SO₂. The model was run at a spatial sampling of 65 x 49 x 25 (longitude x latitude x altitude; longitudinal resolution of 5.625°, latitudinal resolution of 3.75°, altitudinal resolution highest near surface and changes with height) and hourly data were collected. These spatial and temporal resolutions are sufficient to capture the regional and seasonal variation that is necessary to address the questions

posed. Data are collected from model year 15 or later to ensure model equilibration and to avoid unequilibrated ice distributions and potentially spurious warming effects. Our ambient background climate is 1 bar CO₂ (Jakosky et al., 2017), the surface water inventory is ~24 m global equivalent layer (GEL) (Carr and Head, 2015), we implement present-day MOLA topography (Smith et al., 1999; Tanaka et al., 2014), and the spin-axis/orbital parameters we utilize are 25° obliquity (Laskar et al., 2004) and a circular orbit. The atmospheric pressure used in this study has been estimated as an upper limit for the Late Noachian based on recent results from the MAVEN mission (Jakosky et al., 2017). Although atmospheric pressure may have been less than 1 bar, we consider an upper limit here because we are interested in producing the warmest possible simulations; a larger amount of atmospheric CO₂ increases the planetary greenhouse effect and, in turn, increases global temperatures. We utilize a surface water inventory of ~24 m GEL to be consistent with estimates for the surface/near surface water inventory in the LN-EH that are based on calculations of water added to and lost from the surface (Carr and Head, 2015). We implement present-day topography to be consistent with the assumption that the major basins and volcanic rises (e.g. Tharsis) were largely developed by the LN-EH (e.g. Fassett and Head, 2011; Smith et al., 1999). We use 25° obliquity because it has been suggested as a lower limit for obliquity values that are likely to have occurred within the past 5 Gy based on the statistical models of Laskar et al. (2004). Although 41.8° is the statistically most likely obliquity for the Noachian era (Laskar et al., 2004), lower obliquity causes the most incident solar radiation and warmest summertime temperatures towards lower latitudes and, as a result, focuses seasonal meltwater in the near-equatorial regions where VNs and lakes are abundant (e.g. Palumbo et al., 2018); we

have chosen to simulate only 25° obliquity because we are interested in conditions most suitable to the formation of the VNs and paleolakes. Finally, we simulate a circular orbit to maintain a reasonable size for the modeling parameter space, which would increase if we chose to explore different values for eccentricity. However, we acknowledge in the discussion of our findings that summertime temperatures would increase under higher eccentricity conditions and, although statistically probable approximations for LN-EH eccentricity are very low (20% statistical probability that eccentricity was as high as 0.17; Laskar et al., 2004), increased summertime temperatures could permit increased summertime melting (e.g. Palumbo et al., 2018).

The specific methodology for our analyses of *phase one* and *phase two* are outlined below.

3.1 Exploration of Phase One

In our exploration of *phase one*, we are interested in the period of time immediately following an eruption, when the plume is focused near the volcanic edifice and begins spreading through a latitudinal band; in *phase one*, volcanism-induced heating and possible melting would be local instead of global. We simulate the eruption ‘plume’ by introducing 10 ppm SO₂ focused near an LN-EH volcanic edifice; 10 ppm SO₂ is a reasonable upper limit for the amount of SO₂ released from a single volcanic event in the LN-EH (Halevy and Head, 2014). We treat the ‘plume’ as a column of SO₂ above a volcanic edifice. The plume has a lateral SO₂ gradient with most SO₂ concentrated near the center. Our initialized plume contains all atmospheric SO₂ within a 2 GCM grid cell distance from the volcanic edifice in all directions. The plume/column is continuous until

~28 km altitude (following Glaze and Baloga, 2002; Kerber et al., 2013; Wilson and Head, 2007). As the model progresses through time, we track the distribution of SO₂ in the atmosphere and the associated heating of the surface. We do not account for photochemical effects, including OH radical attack, which convert the SO₂ to aerosols; therefore, our predicted temperatures are a maximum.

Using the GCM results for SO₂ distribution, we characterize the duration of *phase one* and the timing of initiation of *phase two*. To characterize the possibility of local heating and melting in *phase one*, we perform temperature time series analysis in which we (1) compare the temperature time series at a volcanic edifice when simulating a 10 ppm SO₂ volcanic eruption with the temperature time series at a volcanic edifice in an SO₂-free atmosphere, and (2) determine the required eruption conditions for localized temperatures above freezing to be possible.

3.2 Exploration of Phase Two

In our exploration of *phase two*, we are interested in globally-distributed atmospheric SO₂ and the possibility of summertime melting. We consider a range of atmospheric SO₂ concentrations, from 0 ppmv to 10000 ppmv, specifically 0, 10, 100, 1000, and 10000 ppmv, following the work of Kerber et al. (2015). We choose a range of values because volcanic eruptions of different magnitude will introduce different amounts of SO₂ into the atmosphere. The largest values considered here are likely to be too high to have been introduced into the atmosphere by a single volcanic event (as noted by Kerber et al., 2015); multiple contemporaneous eruptions would be required to produce such high concentrations of atmospheric SO₂. The LN-EH was a period of increased volcanic

activity, as evidenced by the Hesperian Ridged Plains which led to the resurfacing of ~30% of the martian surface (e.g. Head et al., 2002), and abundant evidence for explosive volcanism (e.g. Crown and Greeley, 1993; Greeley and Crown, 1990; Greeley and Spudis, 1981), implying that it is not unlikely that multiple eruptions overlapped in time. We track surface temperatures, which informs us of the amount of SO₂-related heating of the surface, and the model-predicted distribution of surface ice. Again, we do not account for the conversion of sulfur-based gases to aerosols (we discuss the ways in which we treat this below).

To explore the possibility of summertime melting in *phase two*, we produce both peak annual temperature (PAT) maps and MAT maps. The PAT maps provide an understanding of where temperatures could exceed freezing (>273 K) in the summertime (e.g. as explored for SO₂-rich atmospheres by Mischna et al., 2013), in a manner similar to the McMurdo Dry Valleys on Earth (Conovitz et al., 1998; Dana et al., 1998; Head and Marchant, 2014). The PAT maps show the absolute warmest temperature recorded at each GCM grid cell in a given simulation; our usage of hourly data suggests that this is a reasonable estimate for maximum temperature experienced in the year. Note that these maps do not provide information about how long these peak temperatures persist. Although MAT maps have been utilized to explore the influence of globally-distributed SO₂ in the past (e.g. Kerber et al., 2015), we include them here for completeness and because we are interested in determining the MAT conditions at which summertime melting could occur.

Next, we are interested in understanding where and how much meltwater production occurs in one year. We perform our calculations of meltwater production for the duration

of one year to be consistent with the idea that the sulfur-based gases may have converted completely to aerosols in about one year (e.g. Kerber et al., 2015); we discuss the additional implications of this in our results section. We utilize our GCM output of hourly temperature data and equilibrated ice distribution to perform a positive degree day (PDD) analysis (Fastook and Head, 2015; Palumbo et al., 2018). A PDD analysis uses temperature as a proxy for the thickness of ice melted in one day. A PDD analysis is a method for studying melting of snow/ice on Earth that was first applied to Mars by Fastook and Head (2015); PDD melting rates were adapted for Mars by scaling the necessary factors, including gravity. We utilize our hourly GCM temperature output and implement the following steps to complete the PDD analysis. (1) Calculate the daily PDD number as the average number of degrees above freezing. Repeat this for every day in one model martian year and at each lat/lon GCM grid point. (2) At locations where the PDD number is >0 and the model predicts that ice will be present, multiply the PDD number by the PDD factor for early Mars, 1.08 mm/PDD (Fastook and Head, 2015), to estimate the thickness of ice melted in each model day at each lat/lon GCM grid point. (3) Sum over all the days in the year at each lat/lon GCM grid point, producing a global distribution of thickness of ice melted in one year. (4) Sum over the entire planet to produce an estimate of the volume of meltwater produced in one year. (5) Divide the total volume of meltwater produced in one year by the surface area of Mars to calculate the amount of annual meltwater produced in terms of global equivalent layer (GEL).

Finally, we put our results into geologic context. First, we compare the results of our PDD analysis with the most recent estimate for the total volume of water required to form the VNs, ~ 650 m GEL (Rosenberg et al., 2019) and address the question: Assuming

volcanism-induced heating lasts for only one year, how many eruptions of a given size are required to produce sufficient meltwater to explain the formation of the VNs? Second, we compare the distribution of predicted meltwater with the distribution of VNs and lakes to determine whether the distribution of predicted meltwater is spatially well-correlated with the distribution of the fluvial and lacustrine features.

4. Results

We discuss our findings in terms of *phase one* and *phase two*.

4.1 Phase One

In our analysis of *phase one*, our goal was to determine whether localized heating immediately following an eruption could increase local temperature to >273 K and permit melting, if snow/ice is present. Here, we discuss the case study of an eruption at a volcanic edifice that is located close to the equator in the southern highlands (see distribution of LN-EH volcanic edifices in Fig. 3); we choose a volcanic edifice in the near-equatorial region because temperatures are naturally warmer near the equator than near the poles, even for Noachian atmospheric pressure conditions in which temperature variation is dominantly dependent on altitude, not latitude (e.g. Forget et al., 2013; Wordsworth et al., 2013). Specifically, we explore a 10 ppm SO_2 eruption at Hadriacus Mons (Crown and Greeley, 1993), with the ‘plume’ treated as a column with a lateral concentration gradient and the eruption occurring at southern hemispheric spring equinox. Although multiple martian volcanic edifices are located in near-equatorial regions (e.g. Greeley and Spudis, 1981; Tanaka et al., 2014) (Fig. 3), we chose Hadriacus

Mons as our case study because the volcano was likely to have been active in the LN-EH and shows evidence of localized fluvial activity (e.g. Crown and Greeley, 1993) (Fig. 4). Another volcano that is nearby to Hadriacus Mons is Tyrrhenus Mons. Tyrrhena Patera is likely to have formed around the same time as Hadriaca Patera and is likely to have been characterized by a similar volcanic history (Crown and Greeley, 1993; Greeley and Crown, 1990); both edifices are located on approximate ring crests of the Hellas basin (e.g. Fig. 1 from Greeley and Crown, 1990), have similar crater retention ages, and have fluvial channels on the flanks. While some of the fluvial channels have theater-shaped heads, consistent with groundwater sapping, many also emanate from local topographic highs and are consistent with a surface water source and related overland flow; morphology of the channels suggest a period of surface-sourced runoff followed by a period of groundwater sapping, which may have enlarged the channels (e.g. Crown and Greeley, 1993; Gulick and Baker, 1990). These two edifices are considered case examples of Noachian-Hesperian highlands volcanism (e.g. Greeley and Spudis, 1981). Although the analysis done here is of a volcanic eruption at Hadriaca, not Tyrrhena, the two are so close in proximity that the model-predicted dispersal of SO₂ and associated heating is relevant for both edifices.

In our simulation of a 10 ppm SO₂ eruption at Hadriacus Mons, *phase one* lasts for approximately 45 days following the eruption (Fig. 2). As illustrated in Fig. 2, the plume quickly disperses away from the volcanic edifice (e.g. day 15), has almost spread through the latitudinal band by day 30, and is dispersed across almost half the planet by day 45. During the first 45 days following the volcanic eruption important local climate changes are introduced; the SO₂ greenhouse effect is focused near the eruption site and then

spreads within a latitudinal band, strengthening the local greenhouse effect in comparison to later times (*phase two*) when the SO₂ is more globally-distributed.

To understand quantitatively the localized greenhouse warming, we compare the temperature at the eruption site as a function of time for two different scenarios: following an eruption, and for an SO₂-free atmosphere (Fig. 5). Recall that an SO₂-free atmosphere is the ambient background Noachian “cold and icy” climate; this result comes from our simulations without additional greenhouse warming. Recall that the simulated eruption occurs at southern hemispheric spring equinox. In the first 10 days following an eruption at Hadriacus Mons, the temperature near the eruption site is predicted to be ~15 K warmer than in the SO₂-free case (Fig. 5). Summer temperatures at Hadriacus Mons are ~5-10 K warmer following the eruption than in the ambient climate, but the average daily temperatures do not exceed 273 K (Fig. 5). Although temperatures can increase locally by ~15 K immediately following an eruption, this heating only lasts for ~10 days before rapidly diminishing as the plume disperses through the latitudinal band and then poleward. Thus, some melting is possible if conditions are optimal: the volcanic eruption occurs at the start of local summer and is in an area where the local summertime temperatures in ambient “cold and icy” conditions are within ~15 K of the melting point of water. For higher eccentricity conditions, summertime temperatures would be increased and the number of days above freezing and amount of melting would increase. Although heating in *phase one* is localized and short-lived and only likely to lead to melting and runoff under specific conditions, the cumulative amount of heating and melting from all LN-EH volcanism could produce significant volumes of meltwater locally and potentially contribute to the formation of radial channels observed on the

flanks of Hadriaca (Crown and Greeley, 1993) and Tyrrhena (Greeley and Crown, 1990) volcanic edifices, for example, and potentially also contribute to the formation of VNs and paleolakes located in close proximity to volcanic edifices.

4.2 Phase Two

In our analysis of *phase two*, our goals were to (1) explore seasonal temperature variation, not just global MAT as previous studies have done, (2) estimate the amount of meltwater production in the scenarios where peak summertime temperatures were above freezing, permitting melting and runoff, and (3) compare our results, including distribution and volume of meltwater, with the distribution of VNs and amount of water required to carve the VNs in order to determine whether this process could have contributed to formation of the VNs.

First, we will discuss our findings from our assessment of MAT and PAT maps. MAT and PAT maps for all simulations performed here are shown in Fig. 6a and Fig. 6b, respectively. Recall that PAT maps show the warmest temperature recorded throughout the entire year at each lat/lon GCM grid cell; these maps do not provide any information about the duration of these warm temperatures. In Fig. 6a and Fig. 6b, the shaded contours follow the key at the bottom and the black line is the 273 K contour. With respect to this contour, warmer colors represent temperatures >273 K and cooler colors represent temperatures <273 K. Temperatures are warmer in the lowlands and colder in the highlands in all simulations because the atmospheric pressure is above a few tens of millibar and, thus, there is an adiabatic cooling effect and temperature is dominantly dependent on altitude, not latitude (Forget et al., 2013; Wordsworth et al., 2013). MAT is

<273 K everywhere on the planet for SO₂ concentrations <100 ppmv; this is consistent with previous work that has shown that, for reasonable concentrations of SO₂ from a single volcanic event, MAT is <273 K everywhere (e.g. Mischna et al., 2013). However, our maps show that peak annual temperature (PAT) is >273 K somewhere on the planet for all simulations done here, implying that seasonal temperature variations may permit summertime melting of snow/ice in the southern highlands in areas where surface snow/ice is present. For SO₂ concentrations of 100 ppmv and higher, significant portions of the southern highlands are characterized by PAT >273 K; the highlands are expected to be covered with snow/ice, implying that widespread melting and runoff may occur if one or more volcanic eruptions introduce >100 ppmv of SO₂ into the atmosphere. We constrain this further in our calculations of volume of meltwater produced, which are discussed below.

Next, we discuss the results of our PDD analysis, which are illustrated in Fig. 6c. In the maps in Fig. 6c, the amount of predicted ice melting is shown in blue shaded contours. Our analysis suggests that some melting would be possible in all simulations done here, including the SO₂-free simulation, albeit the amount of meltwater is predicted to be very small for that scenario (in agreement with Palumbo et al., 2018). In the relatively colder (less atmospheric SO₂) simulations, melting is confined to the warmest parts of the southern hemispheric summer season.

To provide an approximation of the number of one-year-long events that would be required to produce sufficient meltwater to form the VNs, we divide the volume of water required to carve the VNs, a minimum of ~650 m GEL (Rosenberg et al., 2019), by the cumulative volume of meltwater produced in one year. This simple approximation is an

important first-order estimate, but it does not account for the locations of meltwater produced or runoff rates. Our findings are included in Fig. 6c and discussed here.

We find that: (1) for an eruption that releases 10 ppmv SO_2 into the atmosphere and, once globally-distributed, the heating lasts for one year before conversion to aerosols, the volume of meltwater produced is $\sim 4.1 \times 10^{-5}$ m GEL (~ 0.0041 cm GEL), implying that 1.6×10^7 events of this size would be necessary to produce the volume of meltwater that is required to form the VNs; (2) for an eruption (or multiple contemporaneous eruptions) that releases 100 ppmv SO_2 into the atmosphere and the global heating persists for one year, the volume of meltwater produced is 2.3×10^{-3} m GEL (0.23 cm GEL), implying that 2.8×10^5 events of this size would be necessary to produce the volume of meltwater that is required to form the VNs; (3) for multiple contemporaneous eruptions that release 1000 ppmv SO_2 into the atmosphere and the global heating persists for one year, the volume of meltwater produced is 1.1×10^{-2} m GEL (1.1 cm GEL), implying that 5.9×10^4 events of this size would be necessary to produce the volume of meltwater that is required to form the VNs; and (4) for multiple contemporaneous eruptions that release 10000 ppmv SO_2 into the atmosphere and the global heating persists for one year, the volume of meltwater produced is 8.7×10^{-2} m GEL (8.7 cm GEL), implying that 7.5×10^3 events of this size would be necessary to produce the volume of meltwater required to form the VNs.

If we consider that atmospheric SO_2 concentrations of 1000 ppmv and 10000 ppmv at any given time is extremely unlikely, which is a reasonable assumption given that a single eruption is likely to have only released ~ 10 ppmv SO_2 into the atmosphere (Halevy and Head, 2014), our results suggest that approximately one million volcanic eruptions

during the several hundred million year period of the LN-EH would be required to produce sufficient meltwater volumes to explain the VNs. Additional research is required to assess the plausibility of these predicted rates, given the abundance of volcanic activity and high volumes implied by individual dike emplacement events in the LN-EH (e.g. Head et al., 2002).

Note again that our analysis assumes a duration of heating of one year. This is done to be consistent with lower-limit estimates on the duration of possible heating before conversion to aerosols, although estimates range from months to centuries (e.g. see review in Kerber et al., 2015). If the duration is longer than one year, for example, persisting for multiple consecutive summers, the amount of meltwater produced following one volcanic eruption would also increase. Therefore, our estimates for volume of meltwater produced can be considered lower limit estimates. Improved estimation of volcanic flux and associated heating duration are required in order to assess this further.

Another factor to consider, in addition to the estimated volume of meltwater produced, is the predicted distribution of meltwater in comparison to the distribution of the VNs. The distribution of meltwater is correlated with temperature variations on the surface; in two locations that both contain surface snow/ice, the location that is characterized by temperatures above freezing for a larger portion of the year will experience relatively more melting. For the relatively colder simulations (less atmospheric SO_2), the distribution of predicted melting is concentrated in small patches near the edges of the predicted ice sheet (Fig. 6c). The VNs and lakes are distributed near the edges of the ice sheet (Head and Marchant, 2014), however their distribution is widespread, not patchy. For the relatively warmer simulations (more atmospheric SO_2),

the distribution of predicted melting is more widespread, covering most of the highlands and more of the areas that contain VNs and lakes (Fig. 6c); note that melting on top of the ice sheet is likely to migrate to the edges of the ice sheet, at which point it will be in contact with the surface and capable of contributing to surface fluvial erosion. Therefore, meltwater production in areas most consistent with VNs and lakes appears most likely for scenarios with higher concentrations of SO₂ (e.g. 100 ppmv and above). Recall that such high SO₂ concentrations might require multiple contemporaneous eruptions. If such high SO₂ concentrations did not persist, it is unlikely that significant volumes of meltwater would have been produced in areas that contain VNs and lakes through the influence of volcanically-released SO₂.

Future work should expand this analysis to include other volcanically-released gases. Although SO₂ is the principal gas constituents in basaltic magmas (in addition to H₂O and CO₂), possibly accounting for ~20 volume percent of the total released gas (e.g. Craddock and Greeley, 2009), other greenhouse gases are also released, albeit in relatively smaller concentrations (see table 2 from Craddock and Greeley, 2009 and references therein). Additional gases worthy of future investigation include H₂S, H₂, and N₂. Specifically, for a given SO₂ concentration, the magnitude of localized heating in *phase one* will increase if there are more volcanically-released greenhouse gases in the plume, in addition to SO₂, and the amount of global heating and ice melting in *phase two* will increase if there are more volcanically-released greenhouse gases in the atmosphere, in addition to SO₂. An eruption that releases 10 ppmv SO₂ as well as other gases, which is a reasonable eruption size for Mars (Halevy and Head, 2014), could very well lead to significantly more heating than we show here. Therefore, future work should implement

the methods developed here to explore the influence of a more ‘realistic’ volcanic event, which contains other greenhouse gases in addition to SO₂.

5. Conclusions

We have developed and implemented methods to explore *phase one*, localized effects, and *phase two*, global effects, following a volcanic eruption on early Mars. In this work, we focus on the greenhouse heating from volcanically-released SO₂. Our key findings are:

- (1) *Phase one*: For a reasonable SO₂ concentration of 10 ppmv, we find that, significant localized heating is possible immediately following the eruption and that temperatures ~15 K above ambient can persist for tens of days near the volcanic edifice. If the eruption occurs at the start of local summer at a near-equatorial location, it is possible that temperatures above freezing could persist and that some localized melting could occur. If an eruption occurred at local summer, increased eccentricity would increase summertime temperatures and, thus, would increase the possibility of localized melting of snow/ice. Although the amount of meltwater production for a given event in *phase one* is likely to be small, the cumulative amount of meltwater production from all LN-EH volcanism could have been significant, possibly leading to formation of radial channels observed on Hadriaca (Crown and Greeley, 1993) and Tyrrhena (Greeley and Crown, 1990) volcanic edifices (Fig. 4) and VNs at and near these and other volcanoes.

- (2) *Phase two*: We explored the global heating from volcanically-released SO₂, focusing on the possibility of summertime melting, for a range of SO₂ concentrations, including 0, 10, 100, 1000, and 10000 ppmv. The higher concentrations explored here (100 ppmv and greater) are likely to be unrealistic for a single event and would thus require multiple contemporaneous events. We find that our simulations with 100 ppmv SO₂ and higher produce meltwater distributions most consistent with the VNs and lakes and that hundreds to thousands of events of this size would be required to produce the necessary volume of meltwater to form the VNs and lakes. Although mean annual temperatures (MAT) are not above freezing, significant summertime melting can occur.
- (3) We have provided evidence that significant localized heating can potentially occur during *phase one* and significant summertime heating and melting can occur during *phase two*. This is an important result in the context of previous studies which have rejected this mechanism as a significant heating and melting mechanism in the LN-EH because MAT does not exceed freezing under the influence of reasonable concentrations of atmospheric SO₂; by investigating the previously unexplored localized and summertime heating (*phase one* and *phase two*), which has not previously been done, we have shown that this mechanism should not be rejected when considering mechanisms of heating and melting in the LN-EH. Indeed, in the McMurdo Dry Valleys, where MAT is ~253 K, peak seasonal and peak daytime temperatures exceed 273 K for a sufficient amount of time in the summer season to produce top-down melting of snow/ice, drainage,

streams and rivers, and lakes (Conovitz et al., 1998; Dana et al., 1998; Head and Marchant, 2014).

- (4) We include SO₂ as the only volcanically-released gas in our simulations; our simulated atmosphere contains only CO₂, H₂O, and the specified amount of SO₂. Actual volcanic eruptions release gases other than SO₂, many of which are also strong greenhouse agents in the martian atmosphere. Our work shows that volcanism-induced heating and melting is likely to have been an important process in the LN-EH and our exploration of *phase one* and *phase two* with SO₂ sets the stage for future studies to incorporate more volcanically-released gases and to assess the distribution of predicted melting in comparison to the distribution of valley networks and paleolakes. Adding additional greenhouse gases into these simulations will increase the temperatures, increase the predicted volumes of meltwater, and, as a result, decrease the number of eruptions that would have been required to produce a sufficient volume of meltwater to form the valley networks. Therefore, future work should implement the methodology introduced here to explore the influence of additional greenhouse gases, as well.

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Figures

Figure 1

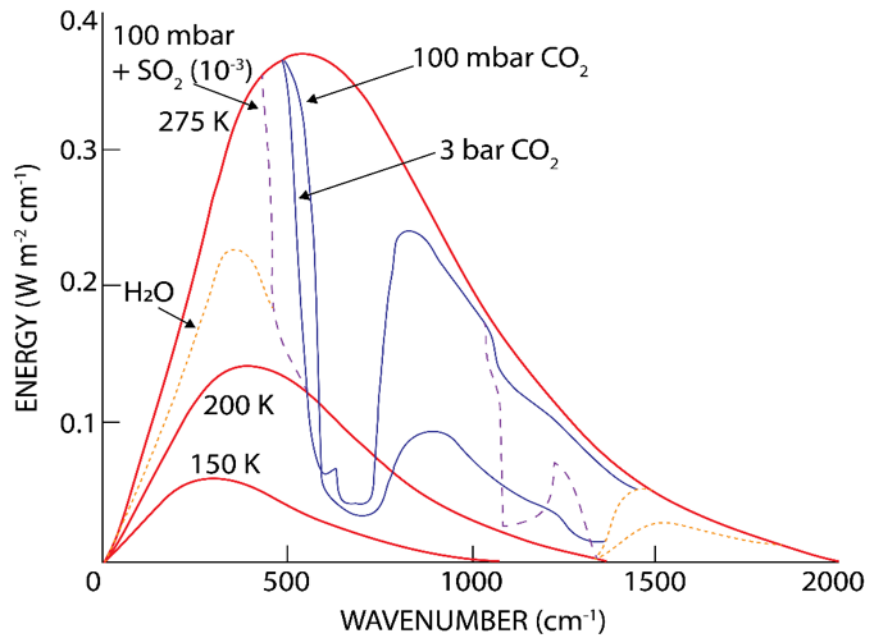


Fig. 1: Blackbody temperature for Mars assuming temperatures of 150 K, 200 K, and 275 K (labelled red lines). For the 275 K line, absorptions from different atmospheric gases are illustrated to show how outgoing flux at the top of the atmosphere changes as a function of atmospheric pressure and composition. A comparison of absorptions from a martian atmosphere of H₂O (orange dashed line) and CO₂ (blue solid line), with absorptions from SO₂ (purple dashed line), shows that that SO₂ absorbs in the martian atmospheric window. Adapted from Postawko and Kuhn (1986).

Figure 2

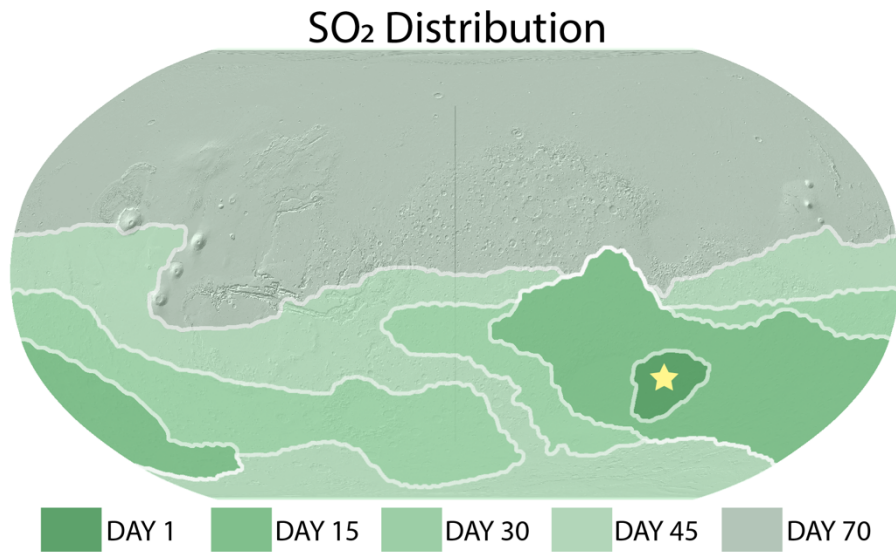


Fig. 2: GCM results for dispersal of a 10 ppm SO₂ plume following an eruption at Hadriacus Mons (31°S 92°E; yellow star). The plume first spreads in a latitudinal band, then spreads poleward, and eventually becomes globally distributed. The SO₂ distribution at different times following the eruption are shown in shades of green, with darkest shades being closest in time to the eruption event; number of days since the eruption event for each shade of green are labelled in the key.

Figure 3

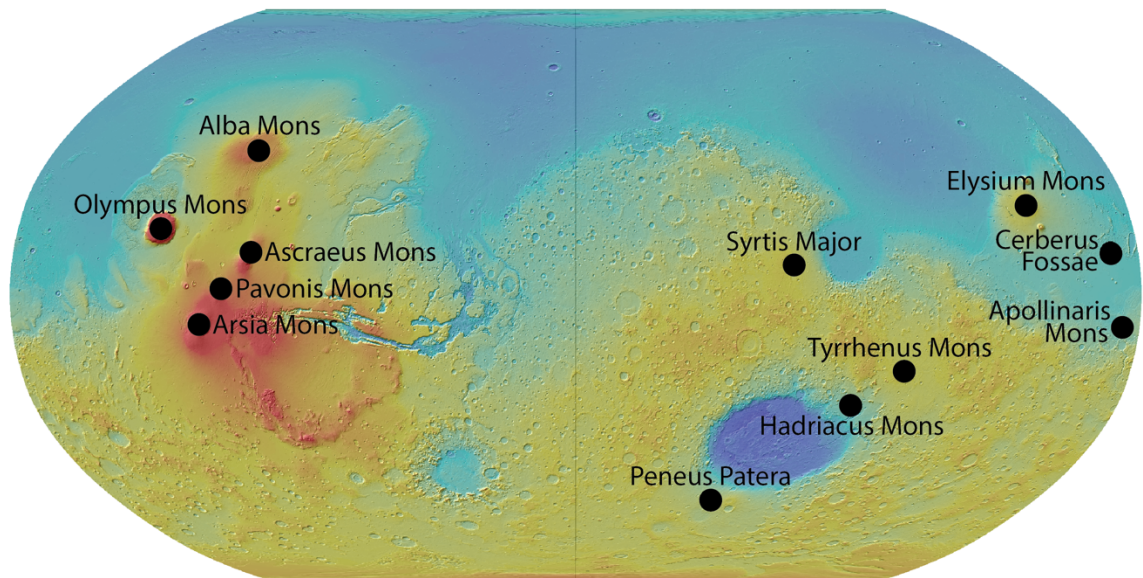


Fig. 3: Locations of major martian volcanoes that were likely to have been active in the LN-EH.

Figure 4

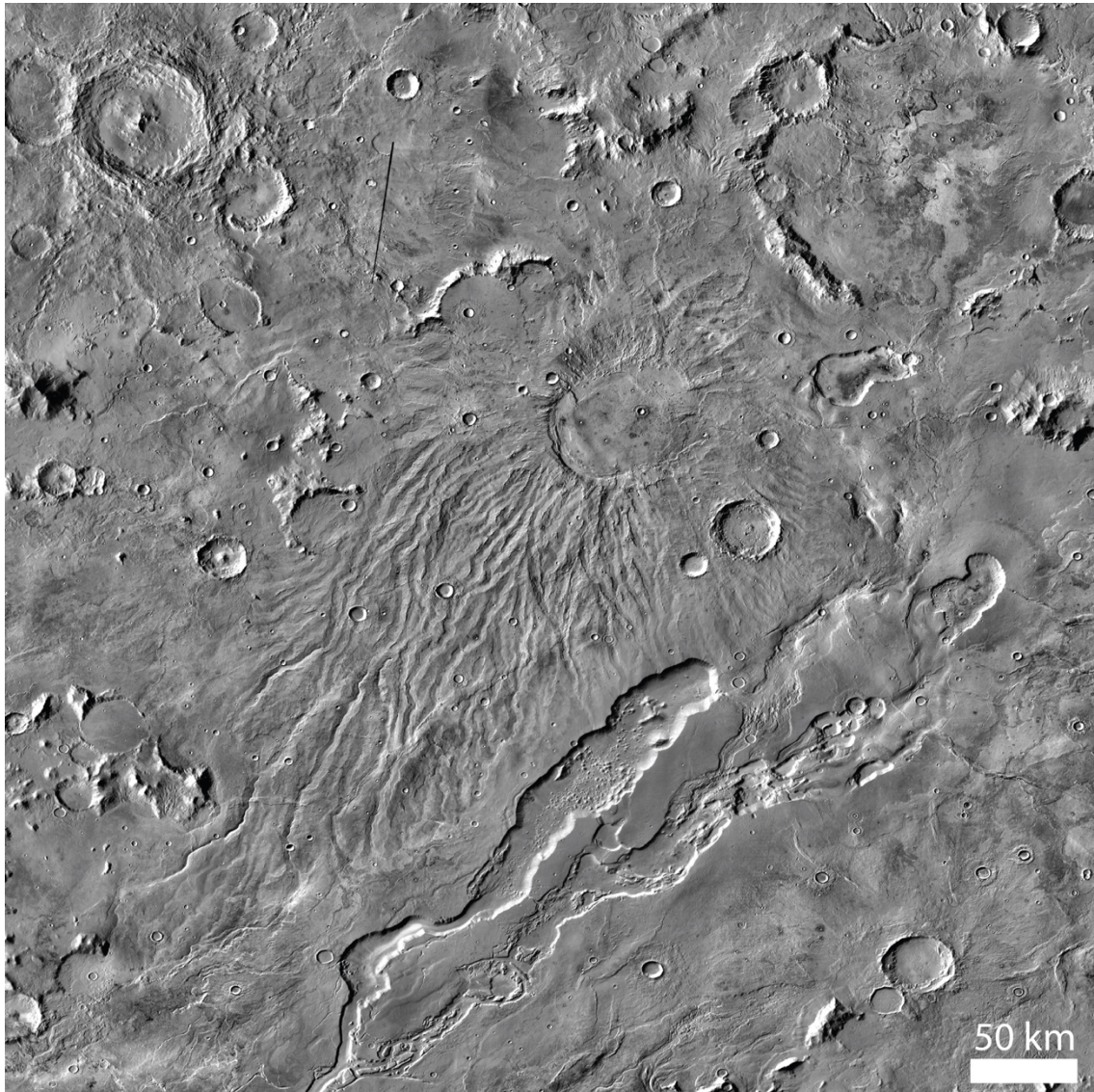


Fig. 4: THEMIS IR daytime image of Hadriacus Mons (centered at 31.29°S 91.86°E), showing evidence of localized fluvial activity through preserved fluvial flank erosion.

The nearby Dao Vallis and Niger Vallis outflow channels are shown in the bottom half of the image. For scale, the central caldera of Hadriacus Mons is 66 km in diameter.

Hadriacus Mons is used for the case study presented in this work.

Figure 5

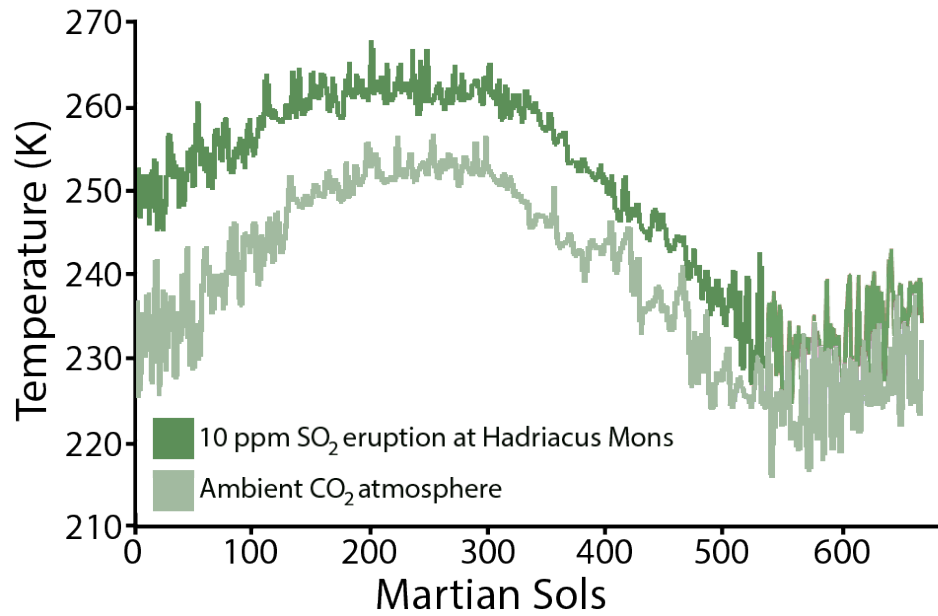


Fig. 5: GCM-predicted time series of average daily temperature at Hadriacus Mons following the simulated 10 ppm SO₂ volcanic eruption (dark green) and in an SO₂-free atmosphere (gray). Initially, the temperature different is ~15 K, but within one year, as the SO₂ spreads globally, the temperature difference decreases to ~5 K.

Figure 6

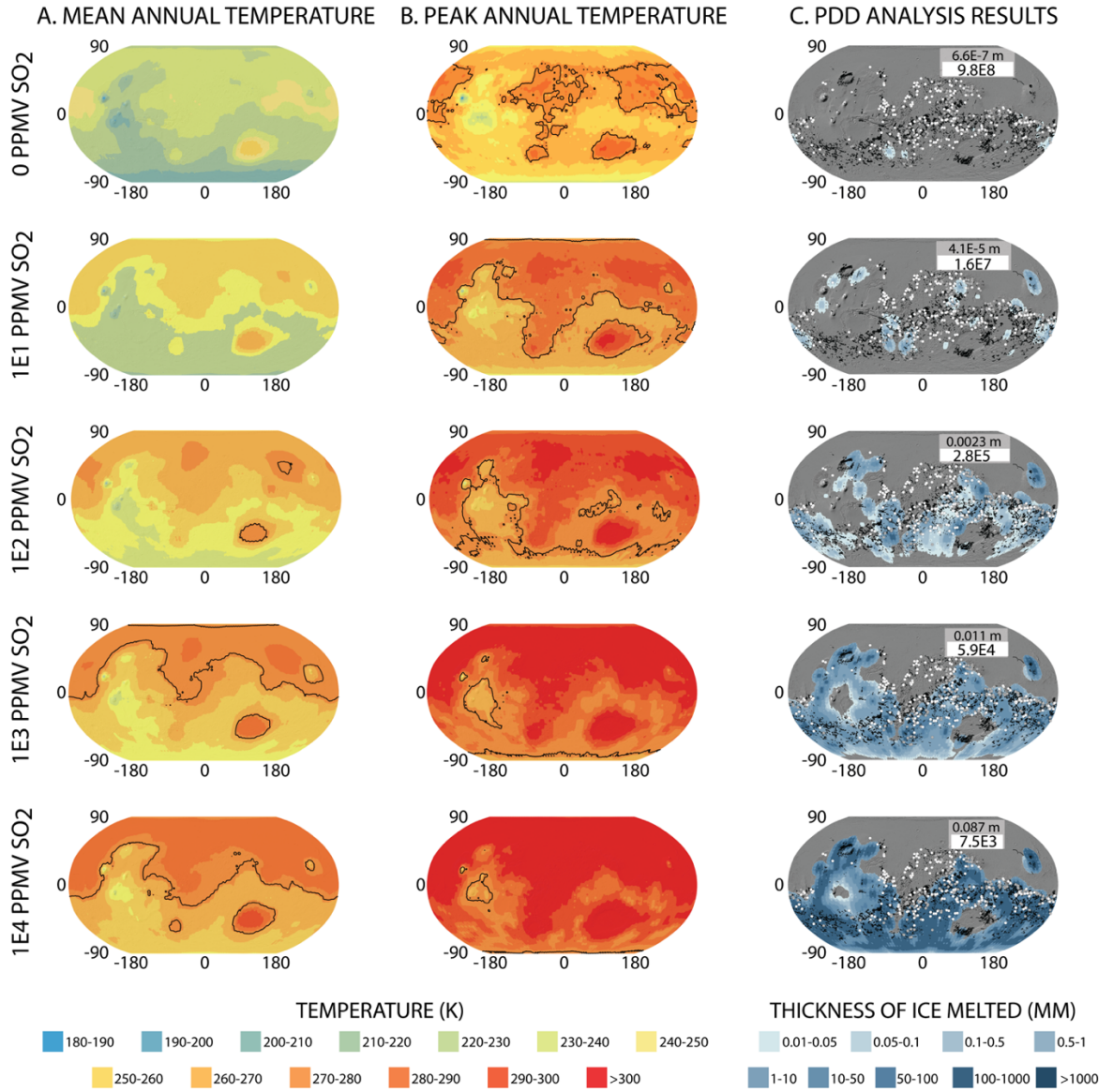


Fig. 6: Results from GCM simulations used in this study. (A) Mean annual temperature (MAT) maps for full range of SO₂ concentrations that we explored. Amount of SO₂ is labelled on the left of each map and ranges from pure SO₂-free atmosphere to 10000 ppmv SO₂. Note that the upper end of SO₂ concentrations are unrealistic for a single volcanic event. Shaded contours show regional variation in MAT and follow the color bar at the bottom. The black line is a 273 K contour. (B) Peak annual temperature (PAT)

maps for full range of SO₂ concentrations that we explored. Contours follow the same key as (A). (C) Results of positive degree day (PDD) analysis for one year shown as thickness of ice melted in mm, following the key at the bottom. The white boxes on the maps include: (top) amount of meltwater produced in one year measured in global equivalent layer (GEL), and (bottom) number of events of this size required to produce sufficient meltwater to form the valley networks, assuming that one event produces only one year of heating. In all plots, valley networks are shown as black lines, open-basin lakes are shown as gray circles, and closed-basin lakes are shown as white circles.

CHAPTER SIX

LARGE IMPACT BASIN-RELATED CLIMATIC AND SURFACE EFFECTS ON MARS: ARGYRE BASIN AS A CASE STUDY

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Abstract

The collision of very large bolides (>100 km diameter) with early Mars resulted in significant, global climatic and surface effects. These effects have been qualitatively and quantitatively explored; however, this type of assessment has not been applied to a specific impact event. Because these drastic, global effects would have occurred following each large basin-scale impact event, a detailed assessment of the youngest of the large basins provides testable insight into the impact-related deposits and alteration products. Here, we expand upon previous work by performing a qualitative and quantitative analysis of the post-impact effects from the formation of the Argyre basin, the youngest of the large martian basins. We find that: (1) an ~30 meters thick, near-globally-distributed, olivine and glass-rich spherule layer should be preserved on or very near the surface, (2) the induced rainfall would have been characterized by rainfall rates higher than rainfall rates in rainforests on Earth and would have lasted for decades, (3) the intense rainfall would have caused flooding, significant erosion, and smoothing of landforms, and (4) hot rainfall and high temperatures would have caused surface aqueous alteration, including partial alteration of the olivine-rich spherule layer to carbonates as well as alteration of basaltic material to Fe/Mg-smectites and further to Al-phyllosilicates, which would be preserved in a leaching profile. We outline criteria to recognize these deposits at global, regional, and local scales to assist in further research and exploration.

1. Introduction

The collision of large bolides with planets with substantial atmospheres, such as Earth and early Mars, results in significant climatic and surface effects (e.g. Abramov and Kring, 2005; Collins et al., 2005; Glass and Simonson, 2012; Johnson and Melosh, 2012; Kring, 2007). For very large impacts, forming basins $>\sim 500$ km in diameter, these post-impact effects would be global and would include (as outlined by Palumbo and Head, 2018): (1) transient high atmospheric and surface temperatures, (2) deposition of material that was vaporized by the impact event and subsequently condensed (speaking specifically of the non-water-vapor component of the vaporized material; e.g. equivalent to terrestrial spherule layers), (3) a transient phase of intense, hot rainfall and (4) surface aqueous alteration, made possible by the hot rainfall and high temperatures. On Mars, the formation of such large basins, including the Hellas, Isidis, and Argyre basins, occurred in the Early to Middle Noachian (Fig. 1) (Fassett and Head, 2011); while younger, smaller basins would have influenced the climate and surface on a local or regional scale, such intense, global effects would have occurred only during the earliest parts of Mars history. Previous studies have qualitatively (Palumbo and Head, 2018) and quantitatively, in both 1-dimension (Segura et al., 2002, 2012, 2008; Toon et al., 2010) and 3-dimensions (Steakley et al., 2019; Turbet et al., 2020), estimated the effects from large basin-scale impact events on early Mars, but lack detailed application to any specific impact event. In this research, we expand upon previous analyses by quantitatively and qualitatively exploring the climatic and surface effects from the formation of the youngest of the large martian basins, the Argyre basin.

In Section 2, we review the previous quantitative studies of post-impact effects and discuss why the Argyre basin is the best candidate for studying these post basin-scale impact effects on early Mars. In Section 3, we describe the geologic setting of the Argyre basin, the context for its origin, and the predicted and observed nature of its associated geologic units and structures. This section provides additional insight into why an assessment of the post-impact effects from the formation of the Argyre basin is fruitful for improving our understanding of the nature and evolution of degradation, erosion, and hydrologic activity on Mars. In Section 4, we discuss each of the four key post-impact effects, providing qualitative and quantitative estimates on what would be expected for the post-impact effects from the Argyre-forming event, and in Section 5 we highlight the important implications from this analysis. Finally, in Section 6, we conclude with our key findings and identify outstanding questions.

2. Background

Segura et al. (2002, 2008) explored the environmental influence of large- (100-250 km diameter bolide; Segura et al., 2002) and moderate-sized (30-100 km diameter bolide; Segura et al., 2008) impact events on early Mars with a 1-dimensional radiative-convective model. Focusing on the influence of large, basin-scale impact events, Segura et al. (2002) (1) characterized the thickness and influence of ‘global blankets of very hot ejecta’ (referring to the equivalent of a terrestrial spherule layer) and suggested that the presence of a thick layer of hot material on the surface may have kept surface temperatures above freezing for decades to millennia and may have caused surface and shallow pore ice to melt, and (2) characterized rates of impact-induced rainfall to be ~ 2

m/yr, which is similar to that of terrestrial tropical rainforests (Malhi and Wright, 2004) and in the range of Earth's greatest observed point rainfalls (Jennings, 1950; Zhang et al., 2013). Further, Segura et al. (2008) suggested that the cumulative rainfall and related erosion from moderate- and large-sized impact events may explain the majority of erosion on early Mars.

Segura et al. (2002) attempted to put their findings of the environmental influence of large, basin-scale impact events into the context of martian geologic history, proposing the scenario of “a cold and dry planet, an almost endless winter broken by episodes of scalding rains followed by flash floods. Only during the brief years or decades after the [basin-scale] impact events would Mars have been temperate”. Further, Segura et al. (2002) and Toon et al. (2010) proposed that the fluvial erosion from large impact events was responsible for the formation of the valley networks.

While several recent studies support the hypothesis that Mars may have been predominantly cold and dry in the Early to Middle Noachian (e.g. Forget et al., 2013; Kasting, 1991; Wordsworth et al., 2013) with basin-scale impacts potentially causing the only periods of hot temperatures and abundant, widespread rainfall (Palumbo and Head, 2018), the hypothesis that impact-induced rainfall is related to the formation of valley networks has been shown to be incorrect on stratigraphic and morphologic grounds (e.g. Barnhart et al., 2009; Palumbo and Head, 2018). Specifically, (1) the predicted rainfall rates are inconsistent with the characteristics of the valley networks (Barnhart et al., 2009), (2) the predicted deluge-like rainfall characteristics suggest that most, if not all, paleolake basins would be open-basin paleolakes, consistent with the lakes having overflowed (Barnhart et al., 2009) and, instead of valley network and paleolake

formation, these intense rainfalls may be more consistent with smoothing of plains and degradation of crater rims (Palumbo and Head, 2018), (3) when revisited in 3-dimensions, predicted precipitation patterns are uncorrelated with the distribution of valley networks (Turbet et al., 2020) and (4) independently, the large basins have been shown to have formed in the Early to Middle Noachian and the valley networks were active in the Late Noachian-Early Hesperian (Fig. 1), implying that the timing of these large basin-scale impact events is not coincident with the timing of peak valley network activity (Fassett and Head, 2011).

While the 1-dimensional radiative-convective models implemented by Segura et al. (2002; 2008) included many important physical aspects for understanding the climate and hydrologic cycle, including greenhouse warming and cloud formation, dissipation, and radiative effects, these processes are better treated in 3-dimensions and, due to the large topographic variations on Mars that control regional climate variations, resolving the climate in 3-dimensions is required for a better understanding of post-impact effects. For these reasons, Turbet et al. (2020) and Steakley et al. (2019) implemented advanced 3-dimensional global climate models (GCMs) and revisited post-impact effects for large- (>100 km diameter bolide) and moderate-sized (30, 50, and 100 km diameter bolides) impact events, respectively.

Turbet et al. (2020) showed that:

- (1) The hot post-impact conditions are short-lived because the radiative budget at the top of the post-impact atmosphere is in strong deficit, implying that energy is quickly lost to space.

(2) Intense rainfall persists until the atmospheric water vapor inventory is depleted; hydrologic cycling is minimal because re-evaporation of water on the surface is minimal. For a 1 bar CO₂ atmosphere, rainfall rates of ~2.6 m/yr are expected; assuming a reasonable Noachian water inventory (e.g. Carr and Head, 2015), the impact-induced rainfall is expected to persist for 10-20 years. These rates are higher than the ~2 m/yr predicted by Segura et al. (2002) and studies of observed rainfalls on Earth show that such continuous, high rate rainfall is unprecedented on Earth for such durations (e.g. Jennings, 1950; Zhang et al., 2013). The predicted duration of 10-20 years is shorter than the predicted duration from Segura et al. (2002), which suggested that these conditions could persist for millenia. This difference in predicted rainfall duration is due to the fact that the 3-dimensional simulations suggest that hydrologic cycling would be minimal in a post-impact climate (Turbet et al., 2020). However, Turbet et al. (2020) did not account for the presence of the hot spherule layer on the surface which could cause re-evaporation of the rain water and induce hydrologic cycling; this is the major source of re-evaporation and hydrologic cycling in the earlier models by Segura et al. (2002). This implies that the estimates for predicted duration of rainfall from Turbet et al. (2020) may be minima.

(3) Despite global, thick cloud cover, surface precipitation patterns in post-impact climates are dictated by circulation patterns in the lower atmosphere. Specifically, the simulations show that rainfall maxima are correlated with the descending branch of the Hadley cell, near the equator, and rainfall minima are correlated with the ascending branch of the Hadley cell, near $\pm 30^\circ$ latitude. Regardless,

cumulative rainfall (amount of rainfall summed over the duration of the impact-induced rainfall) is high everywhere (>20 m). The predicted rainfall distribution is uncorrelated with the distribution of the valley networks, providing further evidence that impact-induced rainfalls from basin-scale impact events are not related to the formation of the valley networks. Further, the rainfall rates and cumulative amounts of rainfall are consistent with deluge-like conditions (e.g. Jennings, 1950; Zhang et al., 2013), characterized by abundant overland flow and more likely to be a factor in smoothing of plains, degradation of crater rims, and surface aqueous alteration than formation of valley network-type features.

Steakley et al. (2019) found results similar to those of Turbet et al. (2020) and further found that, for the relatively smaller impact events explored in their study (30, 50, and 100 km diameter bolides), (1) relatively less rainfall is predicted, and (2) the hot temperatures would persist for relatively shorter durations.

Given reasonable depth-diameter scaling relationships (e.g. Johnson et al., 2016), we can deduce that the three large martian basins, the Hellas, Isidis, and Argyre basins, all formed from the collision of impactors with the surface that were >100 km in diameter. Therefore, the results of Turbet et al. (2020) are more applicable to our assessment of the post-impact effects from basin scale impact events on early Mars than the results of Steakley et al. (2019).

The fact that these drastic, global effects would have occurred following each large basin-scale impact event (Palumbo and Head, 2018; Steakley et al., 2019; Turbet et al., 2020) implies that the effects from the formation of the youngest of the large basins would be best preserved and closest to the present-day surface. Therefore, we perform

our qualitative and quantitative assessment of post-impact effects for the Argyre basin, the youngest of the large martian basins. We utilize the findings of Turbet et al. (2020) as a guide because the conditions simulated are the best representation of Argyre-scale effects.

3. The Origin and Evolution of the Argyre Basin

The Argyre basin (Fig. 2) is a ~900 km diameter basin (Tanaka et al., 2014) located in the southern hemisphere of Mars (50°S, 318°E), southeast of the Tharsis rise and west of the older Hellas basin. In this section, our goal is to utilize the geologic characteristics of the Argyre basin to better understand the amount of post-basin-formation degradation and erosion that may have been related to these post-impact effects. We do this by comparing the morphology of the Argyre basin with the morphology of similarly-aged lunar basins. Because we understand the factors that control the degradation and erosion of lunar basins, a comparison between the preservation states of similarly-aged lunar and martian basins provides insight into the necessary nature and rates of degradation processes on Mars, also.

On the basis of the fact that Argyre is the youngest of the large martian impact basins (e.g. Fassett and Head, 2011), it is logical to compare the characteristics of the Argyre basin to the characteristics of the youngest of the large lunar impact basins, the Orientale basin and the Imbrium basin, which formed on the Moon in the same time period in which Argyre formed on Mars (e.g. Fassett et al., 2012). Such a comparison provides useful insight because both Orientale and Imbrium are basins of similar size to

Argyre but they have not undergone extensive erosion and resurfacing since formation because they exist in the lunar environment.

The ~930 km diameter Orientale basin (Fig. 2) is defined by the Cordillera Mountains, smaller diameter concentric rings of the Outer Rook and Inner Rook Mountains, and the inner depression. Orientale exterior deposits (Morse et al., 2018) consist of a raised rim and a radially-textured ejecta deposit (the Hevelius Formation) out to a radius of ~500 km from the basin rim, which is then surrounded by a field of 2-27 km diameter secondary craters, chains, and clusters. Secondary craters, chains, and clusters have been identified within six basin radii from the basin rim crest (Guo et al., 2018). The Imbrium basin is slightly older and larger than the Orientale basin and is more degraded but retains both a radially-textured ejecta deposit (the Fra Mauro Formation) and identifiable secondary chains and clusters. In summary, the key morphologies associated with the lunar basins are: distinctive raised rim topography due to uplift and ejecta deposition, a radial decrease in topography due to decreasing ejecta thickness, radially textured ejecta deposits, and a field of secondary craters, chains, and clusters.

In order to better understand how modification of the martian Argyre basin and preservation state may have differed from that of the lunar Orientale and Imbrium basins, we must understand the processes that modify and degrade the lunar surface. Lunar modification and degradation processes include impact-induced seismic effects (the more degraded state of the Imbrium basin with respect to the Orientale basin has been attributed in part to the pronounced seismic effects from the subsequent formation of the Orientale basin, which caused shaking and smoothing of topography; Kreslavsky and Head, 2012), degradation from subsequent impact events of all scales (e.g. the general

primary and secondary impact flux and proximity degradation from adjacent events), and post-basin-formation lava flooding and filling (e.g. Whitten and Head, 2013).

How, then, might the modification and degradation of the similarly-aged, youngest martian basin, the Argyre basin, have differed from the lunar Orientale and Imbrium basins? First, basin-scale seismic-induced smoothing effects are not expected to have subsequently modified the Argyre basin, due to the fact that it is the youngest of the large martian basins and these effects are only expected to occur following large basin-scale impact events. Second, if we assume that the impact flux reaching the Moon and top of the atmosphere of Mars has been similar throughout history, then we can suggest that the presence of a dense atmosphere in the Noachian would have served to filter out smaller-sized impactors (e.g. Williams et al., 2014) and, as a result, decrease the rate of degradation from subsequent impacts of all scales. These two factors suggest that the Argyre basin should be relatively less modified and degraded than the Orientale and Imbrium basins, which is in contrast to what is observed. Third, however, the presence of an atmosphere and a water cycle on Mars could have significantly enhanced basin degradation processes due to the effects of eolian, fluvial, glacial, and periglacial processes. Thus, we ask: Could the modification and degradation of the Argyre basin, relative to the Imbrium and Orientale basins, be explained by these erosive properties from typical martian conditions, or must we consider that short-lived, drastic effects, such as the post-impact effects explored in this work, were a dominant control in shaping the Argyre basin and, in turn, the rest of the martian surface?

Geological mapping of the Argyre basin and its ejecta deposit provides insight into the state of preservation of the youngest major martian basin, permitting a direct

assessment of the preservation state of the Argyre basin and a more direct comparison to the lunar Orientale and Imbrium basins, and permitting an assessment of the nature and rates of basin degradation processes on Mars. Thus, we next discuss the geological mapping of the Argyre basin.

As illustrated in the global geologic map of Mars (Fig. 2; Tanaka et al., 2014), the Argyre basin is regionally defined by topographic depressions surrounded by a Middle Noachian unit of highland massifs (mNhm) that has a mean outer diameter of ~1500 km, and is further surrounded out to a diameter of ~3000 km by the highlands unit (mNh) of Middle Noachian age. At the global map scale, the Middle Noachian highland massifs unit (mNhm) consists of tens of kilometers across, high relief massifs which are separated by broad linear valleys and troughs and are interpreted to be crustal blocks that were uplifted by the basin-forming event and then dissected by tectonic and erosional valleys. The Middle Noachian highlands unit (mNh) consists of rolling to uneven topography, with high-relief outcrops that extend hundreds to thousands of kilometers, and is interpreted as ‘undifferentiated impact, volcanic, fluvial, and basin materials... [that have been]... heavily degraded’. Missing from the local geologic signature in comparison to the similar-aged lunar Orientale and Imbrium basins is evidence of the distinctive raised rim topography due to uplift and ejecta deposition, the radial decrease in topography due to decreasing ejecta thickness, radially textured ejecta deposits, and the presence of a field of secondary craters, chains, and clusters (Fig. 2); if these morphologies were present, they would be contained and identifiable within the mNhm and mNh units, and they are not.

Similar to the exterior of the basin, there are discrepancies between the morphologies of the interior of the Argyre basin and the interior of the lunar Orientale and Imbrium basins. Although researchers agree that Argyre is a multiring basin, the identification of specific rings and their diameters has varied widely due to the enhanced state of degradation of the Argyre basin (see summary of this previous work in Hiesinger and Head, 2002). Comparison of the morphology of the interior of the Argyre basin with that of the lunar Orientale basin to identify analogues of the specific and distinctive Orientale Cordillera, Outer Rook Mountain rings and Inner Rook Mountain rings has failed to converge on a consensus of both ring assignments and ring diameters (e.g. Hiesinger and Head, 2002). Indeed, Schultz and Frey (1990) concluded that the Argyre basin does not show clear analogues or identifiable remnants of Orientale-like structure. More recent geological mapping of the Argyre basin region which utilized higher resolution morphologic and topographic data (Viking and post-Viking data) led Dohm et al. (2015) to conclude that “Argyre is the best preserved of the large multi-ringed impact basins on Mars, comparable to the Orientale basin of the Moon when viewed at resolutions less than 1 km/pixel...” but that “the profound differences of the Argyre and Orientale basins due to pervasive post-impact modification of the former by geologic, hydrologic, and aeolian processes, are evident at higher resolution.”. To account for some aspects of this poor preservation and the much more intense degradation of the Argyre basin relative to the Orientale basin, Dohm et al. (2015) entertained the idea that “impact event generated hydrogeologic conditions... such as the melting of surface and subsurface ice, migration of surface and subsurface water from great distances, and impact-induced precipitation” might have been a factor.

Thus, in order to understand whether the differences in degradation of the Argyre basin with respect to the lunar Orientale and Imbrium basins are predominantly due to the post-impact effects that we are exploring in this study (which would not have prevailed on the Moon due to the lack of a thick atmosphere), or due to the background erosional, weathering, and degradation regime that persisted on Mars throughout planetary history, we ask the question: Could these distinctive differences between the state of preservation of Argyre and the similar-aged lunar Orientale and Imbrium basins be accounted for by the martian weathering and degradation regime, which is enhanced relative to the Moon, or is additional weathering and degradation required (which could be due to, for example, post-impact effects)? Golombek et al. (2006) have estimated erosion rates on Mars from a range of local landing site and regional and global perspectives. They conclude that the “long-term erosion rates of ~0.01-10 nm/yr since the Hesperian are consistent with erosion rates calculated in a similar manner for the Viking 1 and Mars Pathfinder landing sites and are 2-5 orders of magnitude lower than the slowest continental denudation rates on Earth. These erosion rates are so low that they preclude liquid water as an active erosional agent and argue for a dry and desiccating climate.” They further find that “erosion rates derived from previous studies of changes in Noachian age crater distributions and shapes and denudation of Terra Meridiani ... are 2-5 orders of magnitude higher (10^3 - 10^4 nm/yr) than those from the Late Hesperian and Amazonian. These Noachian erosion rates are comparable to slow continental denudates rates on Earth that are dominated by liquid water.” Although erosion rates are predicted to be significantly higher in the Noachian than later in history in the Late Hesperian and Amazonian, these rates are similar to (less than) those in the hyper-arid, hypothermal

Stable Upland Zone (Head and Marchant, 2014; Marchant and Head, 2007) of the Antarctic Dry Valleys ($\sim 0.06\text{-}0.3$ m/Ma or 60-300 nm/yr; Brook et al., 1995; Summerfield et al., 1999).

These Noachian erosion rates are so low (possibly hundreds of meters total over the entire post-Argyre history) that if they are applied to the post-Argyre impact basin-related degradation, they are significantly less than the average rates necessary to regionally smooth and subdue the basin-related structures and ejecta deposits. In other words, the Argyre region is significantly more eroded than could have occurred in an erosional regime similar to that of the Antarctic Dry Valleys.

We refer to this discrepancy between the predicted erosion rates and the observed degradation as the ‘apparent degradation deficit’, and ask the question: Could this apparent degradation deficit be explained by processes that occurred simultaneously with, and in the immediate aftermath of, the Argyre basin-forming event (e.g. the processes explored in this study), in addition to the background erosion and degradation integrated over ~ 3.93 Ga since the formation of the Argyre basin? Such an apparent degradation deficit suggests that a more detailed qualitative and quantitative assessment of these post-impact effects is required to better understand (1) the nature and evolution of erosion on Mars and (2) the processes responsible for causing the martian surface to have evolved quite differently than the lunar surface.

4. Assessment

In this section, we discuss the key post-impact effects, including qualitative and quantitative estimates for the post-impact effects from the Argyre-forming event. The

four key post-impact effects are: (1) transient high atmospheric and surface temperatures, (2) deposition of silicate-rich material that was vaporized by the impact event and subsequently condensed (e.g. terrestrial spherule layers), (3) a transient phase of intense, hot rainfall and (4) surface aqueous alteration, made possible by the hot rainfall and high temperatures. The post-impact effects are illustrated in Fig. 3 and discussed below.

4.1 Transient high atmospheric and surface temperatures

The collision of a very large impactor with the surface causes a large energy transfer, with much of the kinetic energy from the impactor motion being utilized to change phase and initiate movement of the substrate and impactor material (e.g. Melosh, 1989); large volumes of substrate and impactor material are ejected from the crater, melted, and vaporized (Fig. 3 A, B). The vaporized component will consist of vaporized water and silicate-rich material (e.g. Segura et al., 2008). The presence of this vapor in the atmosphere and associated formation of global clouds would cause atmospheric and surface temperatures to dramatically increase, possibly to hundreds of Kelvin above ambient conditions (e.g. Segura et al., 2008; Turbet et al., 2020).

4.2 Deposition of silicate-rich material that was vaporized by the impact event and subsequently condensed

The vaporized material has two components: water vapor and silicate-rich vapor (Fig. 3B). As the atmosphere cools from its initial very hot state, it will first reach the condensation temperature for the silicate-rich vapor and then, as temperatures continue to cool, it will reach the condensation temperature for the water vapor (the condensation of

the water vapor is discussed in the next section, Section 4.3). The silicate-rich material will condense and traverse back through the atmosphere, possibly quenching during its travel, and be re-deposited onto the surface (Fig. 3C). For large basin-scale impact events, this deposit is expected to be global (e.g. Glass and Simonson, 2012; Johnson et al., 2016; Melosh, 1989; Turbet et al., 2020). On Earth, these deposits are commonly referred to as spherule layers (e.g. Glass and Simonson, 2012; Johnson et al., 2016; Johnson and Melosh, 2012), are welded solid, and have been identified in association with large basin-scale impact events, such as the Chicxulub impact event (e.g. Kring, 2007; Kring and Durda, 2002).

The identifying key characteristics of the spherule unit are thickness, composition, and texture. Toon et al. (2010) performed mass balance and energy conservation calculations to estimate the volume of material that would have been vaporized and subsequently condensed following impact events of various sizes. Specifically, for an Argyre-sized impact event, Toon et al. (2010) suggested that this deposit would have been ~34 m thick. Palumbo and Head (2018) explored the possible compositions and mineralogical signature of spherule layers on ancient Mars and suggested that the unit would likely be silicate-rich, possibly retaining an olivine signature due to early quenching during traverse through the atmosphere (e.g. Fig. 4). As is true for identifying spherule layers on Earth, the texture of this unit would be easily differentiated from surrounding units at the rover scale due to the presence of the quenched spherules and welded solid nature of this unit (e.g. Fig. 5).

This deposited material is expected to be so hot (~1600 K; Segura et al., 2008) that the thermal blanketing from this unit could cause surface temperatures to stay above

freezing for millenia (Segura et al., 2008); the spherule layer may have a strong control over the duration of post-impact hot temperatures. Additionally, depending on the characteristics of the unit underlying the spherule unit, the thermal interaction between the spherule unit and the underlying unit could lead to partial alteration of the underlying unit (Fig. 4).

4.3 A transient phase of intense, hot rainfall

Following the condensation of the silicate-rich material and the associated deposition of the spherule layer, the atmosphere will cool sufficiently for the water vapor to condense and rain out (Fig. 3 D, E, F).

This phase of intense, hot rainfall is an important factor for our understanding of the early climate and hydrologic cycle. We must briefly describe the current state of knowledge of martian rainfall, including characteristics, continuity, and distribution, in order to put this post-impact rainfall into the appropriate context. Some studies interpret the degradation states of Noachian-aged craters to suggest that rainfall was continuous throughout the Noachian and was characterized by relatively low rainfall rate until the Late Noachian, when rainfall rate increased and rainfall-related runoff became more abundant (Craddock and Lorenz, 2017). Additionally, Noachian-aged alteration products preserved in leaching profiles (e.g. Bishop et al., 2013; Zolotov and Mironenko, 2016) (e.g. Al-phylosilicates overlain on Fe/Mg-smectites overlain on the basaltic substrate) have been cited as evidence for abundant rainfall in the Noachian (e.g. Bibring et al., 2006; Carter et al., 2015). Studies that analyze the implications of this geologic evidence and attempt to constrain the durations and rates of rainfall on early Mars frequently only

consider the ambient, background climate conditions (e.g. Craddock and Howard, 2002; Craddock and Lorenz, 2017) and do not consider events that could dramatically change the physical and chemical landscape on a relatively short timescale, such as basin-scale impact events.

Impact-induced rainfall from these basin-scale impact events is a process that would have dramatically changed the landscape on a relatively short timescale and, because this process was pervasive on early Mars, it must be accounted for when determining the required characteristics of rainfall in the background climate that may be necessary to explain the geologic observations.

Simulations of post-impact effects for basin-scale impact events with 3D GCMs have shown that, when considering a reasonable surface water inventory and bolide composition, rainfall characterized by rates of up to ~ 2.6 m/yr, which is higher than rainfall rates in terrestrial tropical rainforests, could persist continuously for decades (Turbet et al., 2020). Additionally, due to the very high atmospheric temperatures and high atmospheric water vapor concentration, post-impact rainfalls may have been characterized by temperatures near the vaporization point (Turbet et al., 2020). These intense post-impact rainfalls are predicted to have had the characteristics of a hot, long-lived deluge (e.g. Palumbo and Head, 2018), implying that impact-induced rainfall may have contributed to abundant alteration of the surface, including morphologic alteration such as smoothing of plains and degradation of crater rims. Such morphologic alteration may explain the ‘apparent degradation deficit’ that was discussed in Section 3. In addition to morphologic alteration, post-impact rainfall would also contribute to surface aqueous alteration, which we discuss in the next section. Clearly, impact-induced

rainfalls are an important contributor to rainfall-dominated erosion in the Noachian and future studies should consider this process in addition to rainfall that may have occurred in ambient, background climate conditions.

4.4 Surface aqueous alteration, made possible by the hot rainfall and high surface temperatures

The efficiency of surface aqueous alteration is essentially a balance of three factors: (1) interaction with liquid water, (2) temperature, and (3) duration (e.g. Bishop et al., 2017). For example, if a rock is in contact with liquid water for 1,000 years, more aqueous alteration would occur in relatively warmer waters than in relatively colder waters. Similarly, if a rock is in contact with liquid water of a constant temperature, more aqueous alteration would occur if the interaction persisted for relatively longer durations than if the interaction persisted for relatively shorter durations. Post-impact conditions offer all three of these factors, implying that surface aqueous alteration is possible in a post-impact climate. Although post-impact rainfall and warm conditions are not expected to last very long, possibly persisting for decades, the rainfall and atmosphere temperatures would be very high above ambient conditions and, thus, significant aqueous alteration could occur. Future work should explore the extent of aqueous alteration that is possible under post-impact conditions which is required for better characterization of what these post-impact units may look like on the martian surface. For example, should we expect that interactions between the spherule unit and post-impact rainfalls would have left the ~30 m thick spherule unit fully or only partially aqueously altered?

5. Implications

There are four key implications from this assessment, including: (1) distinguishing the role of impact-induced aqueous alteration from that associated with normal climate conditions, (2) predictions of areas where the spherule layer and alteration products may be observed, (3) the transition from a basin-scale impact-dominated regime to a basin-free regime in martian climate evolution, and (4) guidelines for exploration and recognition of these impact-related units at rover and sample return scale. In this section, we discuss each of these implications.

5.1 Distinguishing the role of impact-induced aqueous alteration from that associated with normal climate conditions

Impact-induced aqueous alteration (e.g. Fig. 4) is predicted to have the following characteristics (1) evidence of aqueous alteration having occurred at the surface, including aqueous alteration products in a top-down leaching profile, such as Al-phyllsilicates stratigraphically above Fe/Mg smectites in areas where the basaltic substrate was aqueously altered (as is observed in many locations; see Carter et al., 2015), and (2) partial or full alteration of the olivine-rich spherule layer, possibly to Mg-carbonates (Fig. 4; as observed in NE Syrtis, for example; see Ehlmann and Mustard, 2012) that is located stratigraphically above the (potentially at least partially aqueously altered) basaltic substrate. By identifying locations where these characteristics are observed, we can place first order estimates on areas that may have undergone aqueous alteration in post-impact conditions, as opposed to ambient climate conditions.

5.2 Predictions of areas where the spherule layer and alteration products may be observed

The reason that we chose to focus on the post-impact effects from the formation of the Argyre basin is that the Argyre basin is the youngest of the large martian basins and, as a result, the spherule layer and aqueous alteration products should be best preserved and preserved at or near the surface; although these post-impact effects occurred globally following all of the large basin-scale impact events, the post-impact effects from the formation of the Argyre basin are the most likely to be identified at the surface. Because the post-impact effects from the formation of the Argyre basin were global, the spherule layer and aqueous alteration products that formed from the influence of impact-induced rainfall should be observable on Noachian-aged terrains that have not experienced abundant subsequent morphologic and mineralogic alteration. An olivine-rich signature may be useful to guide identification of possible spherule units (Palumbo and Head, 2018) and subsequent analyses of those areas in order to determine if these are in fact spherule units should include (1) assessment of the thermal inertia of the olivine-rich unit to determine if it is more consistent with a spherule layer, which would be welded solid, or a loose, unconsolidated volcanic ash layer, as has been proposed to be a source of some olivine-rich units on Mars (Kremer et al., 2019), (2) determination of whether aqueous alteration of intact sections of the olivine-rich unit is consistent with surface activity and overland flow, not (for example) subsurface alteration, and (3) a relatively consistent thickness of the unit, as would be expected for a spherule layer. If these criteria are met, we may conclude that an identified olivine-rich unit is in fact formed from post-impact effects and evidence for aqueous alteration in the area, both of

the olivine-rich unit and of the underlying basaltic substrate, may be attributed to impact-induced rainfall, not ambient background climate conditions.

One such area that contains an olivine-rich signature and may satisfy the above criteria includes the olivine-rich unit in NE Syrtis (Fig. 4). This unit may be explored by the NASA Mars 2020 Perseverance rover and in situ observations of this unit can test the hypothesis that this unit may be a spherule unit. Other olivine-rich exposures (Rogers et al., 2009, 2005) are areas of future consideration, as well. Spherule and aqueous alteration units predicted to have formed following basin-scale impact events must be present on Mars, albeit the units from many of the large basins would be buried, and future work should aim to identify surficial exposures of these units in order to put them into the correct context of global mineralogy and climate history.

5.3 The transition from a basin-scale impact-dominated regime to a basin-free regime in martian climate evolution

As originally suggested by Segura et al. (2002), it is possible that Mars in the Early to Middle Noachian was a cold, dry planet that was only characterized by hot temperatures and widespread rainfall following a large basin-scale impact event. As outlined in this work, post-impact effects (e.g. Fig. 3, 4), specifically post-impact rainfall, offer an explanation for smoothing of plains, degradation of crater rims, and surface aqueous alteration. These degraded characteristics of Noachian-aged features and terrains have previously been cited as evidence that the long-lived early climate was “warm and wet” with rainfall throughout the Noachian (e.g. Craddock and Howard, 2002; Craddock and Lorenz, 2017; Ramirez and Craddock, 2018); we suggest that these characteristics

may instead be explained by post-impact effects and may not require “warm and wet” ambient background climate conditions. Further, we propose that impact-induced rainfall could explain the ‘apparent degradation deficit’ that we identify in the Argyre basin region. Future studies should determine the cumulative magnitude of smoothing of plains, degradation of crater rims, and surface aqueous alteration that is possible from basin-scale impact events in order to determine whether the entirety of these features and observations can be explained by post-impact effects in an otherwise cold and dry climate, or if a “warm and wet” climate with rainfall throughout the Noachian is also required.

5.4 Guidelines for exploration and recognition of these impact-related units at rover and sample return scale

While orbital observations can provide important first-order characterization of units on the surface of Mars, including mineralogy, morphology, and thermal inertia, in situ observations at the rover and sample return scale will provide critical information to determine if proposed spherule units are in fact spherule units. For example, in situ observations are required to determine whether the unit morphology looks similar to a spherule unit on the grain scale (e.g. Fig. 5) and laboratory analysis of a returned sample can determine the precise age of the sample, which would determine whether the age of the sampled unit is consistent with the age of the formation of a large martian basin. For these reasons, we look forward to the Mars 2020 mission and the possibilities that a spherule unit may be observed in situ and a sample may ultimately be returned to Earth.

6. Conclusions

We have provided a qualitative and quantitative assessment of the post-impact effects from the formation of the Argyre basin, the youngest of the large martian basins. These effects include (1) transient high atmospheric and surface temperatures, (2) deposition of silicate-rich material that was vaporized by the impact event and subsequently condensed (e.g. terrestrial spherule layers), (3) a transient phase of intense, hot rainfall and (4) surface aqueous alteration, made possible by the hot rainfall and high temperatures. The spherule layer and surface aqueous alteration from the post-impact effects of the Argyre-forming event should be preserved at or very near the martian surface and, as a result, are an interesting topic for future study and exploration.

Post-impact effects from basin-scale impact events, specifically impact-induced rainfall, may be responsible for smoothing of plains, degradation of crater rims, and surface aqueous alteration, and may be a major factor in explaining the ‘apparent degradation deficit’ noted for the Argyre basin interior structure and basin exterior ejecta deposits. We propose that future work should quantify the magnitude of these effects in order to determine whether the majority of the observed smoothing of plains, degradation of crater rims, and surface aqueous alteration products can be explained by post-impact effects in an otherwise cold and dry Noachian climate; it is possible that a long-lived “warm and wet” climate with continuous rainfall in the Noachian is not required to explain these observations.

We have outlined the characteristics of the spherule layer and surface aqueous alteration products and described ways in which these units can be identified at the orbital and rover scale. One area that may contain a spherule layer and impact-related aqueous

alteration is the olivine-rich unit in NE Syrtis (Fig. 4), which will be explored by the Mars 2020 rover. In situ observations and possible sample return will be critical for determining whether these units are in fact related to these post-impact effects or whether they represent other processes and/or ambient climate conditions. Future work should identify additional areas that may contain a spherule layer and impact-related aqueous alteration products.

Finally, these post-impact processes were undeniably acting on early Mars; the presence of multiple large Noachian-aged basins is evidence to this. We must identify the signature of these basin-scale impact effects on the surface of Mars in order to separate impact-related effects from the ambient background climate. Specifically, such an understanding will be critical in determining (1) whether the long-lived Noachian climate must have been “warm and wet” with rainfall throughout the Noachian or (2) whether some of the geologic features that were previously referenced as evidence for a long-lived “warm and wet” Noachian climate, including smoothing of plains, degradation of crater rims, and surface aqueous alteration, can be explained by immediate post-impact effects in an otherwise cold and dry climate.

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Figures

Figure 1

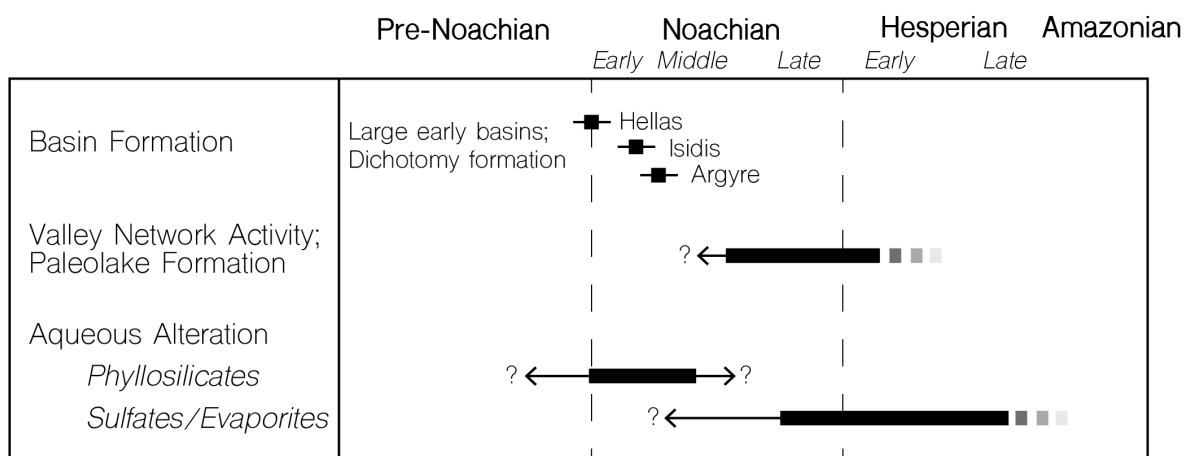


Fig. 1: Relative timing of different processes and events on Mars, including basin formation, valley network activity and lake formation, and aqueous alteration including both phyllosilicate-dominated and sulfate/evaporate-dominated. The three large basins that are preserved at the surface today, the Hellas, Isidis, and Argyre basins formed in the Early to Middle Noachian, with Hellas being the oldest and Argyre being the youngest. Formation of the valley networks and paleolakes occurred mostly in the Late Noachian and Early Hesperian; earlier fluvial activity may have occurred and been subsequently reworked. The two dominant forms of observed aqueous alteration products on Mars are phyllosilicate-dominated and sulfate/evaporate-dominated. Phyllosilicate-dominated aqueous alteration occurred in the Early to Middle Noachian and potentially persisted both earlier in history and later in history. Sulfate/Evaporite-dominated aqueous alteration occurred from the Late Noachian into the Hesperian and Amazonian and potentially persisted earlier in history, as well. The discussions of aqueous alteration in this research are consistent with phyllosilicate-style aqueous alteration, not sulfate/evaporite-style aqueous alteration. Adapted from Fassett and Head (2011).

Figure 2

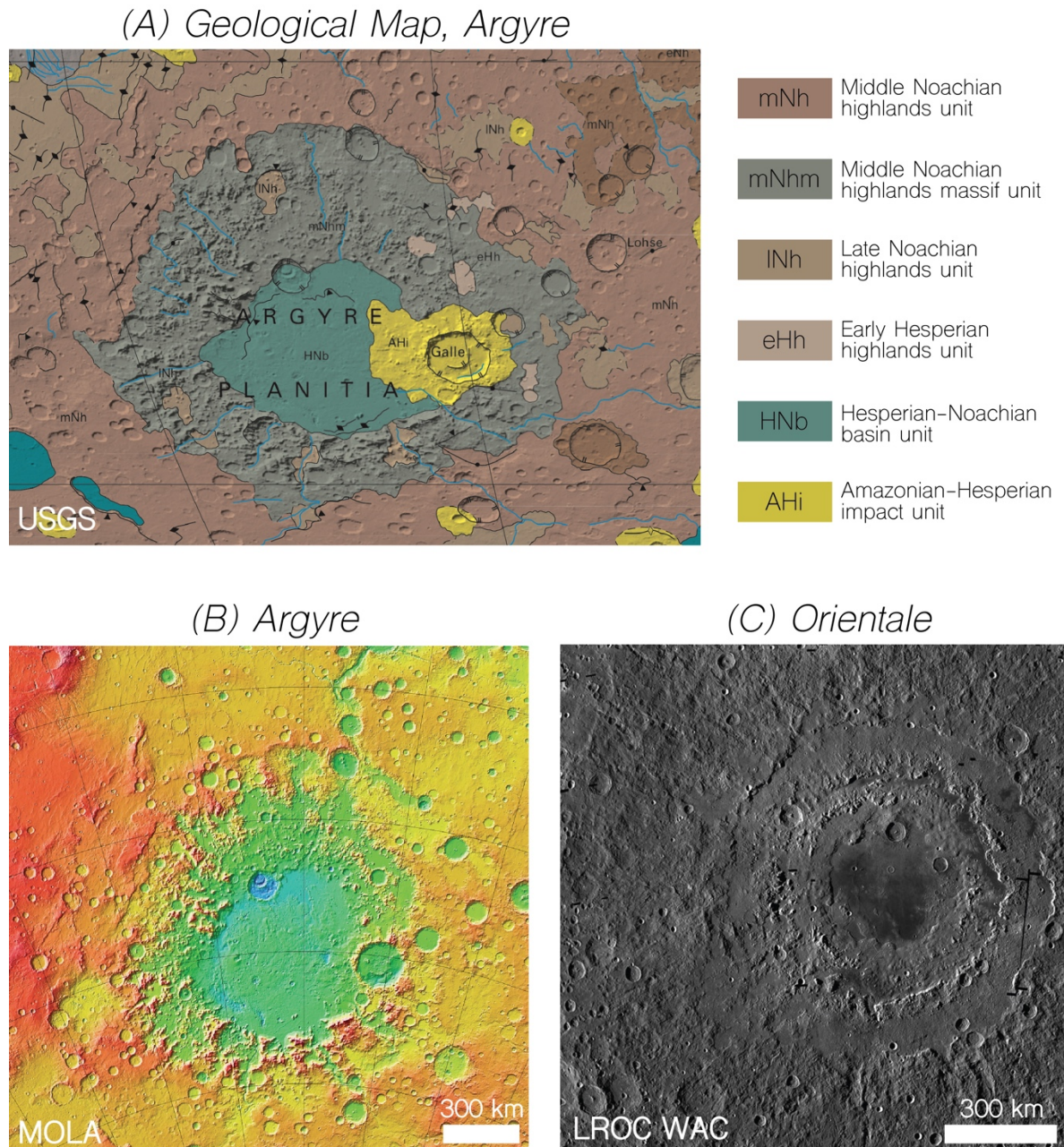


Fig. 2: (A) Portion of the geological map of Mars (Tanaka et al., 2014). Units mNh, mNhm, and HNb are contemporaneous or close in time with the formation of the Argyre basin, the other highlighted units post-date the formation of the basin. (B) Shaded topographic map of Argyre Planitia created using MOLA topography. Warmer colors

represent higher elevations and cooler colors represent lower elevations. As noted in the text, distinctive raised rim topography, radial decrease in topography due to decreasing ejecta thickness, radially textured ejecta deposits, and secondary craters, chains, and clusters are noticeably missing from the Argyre basin and surrounding units. (C) LROC WAC image of the Orientale basin on the Moon. Unlike the Argyre basin, the ejecta deposit, raised rim, and rings are easily identifiable in imagery data.

Figure 3

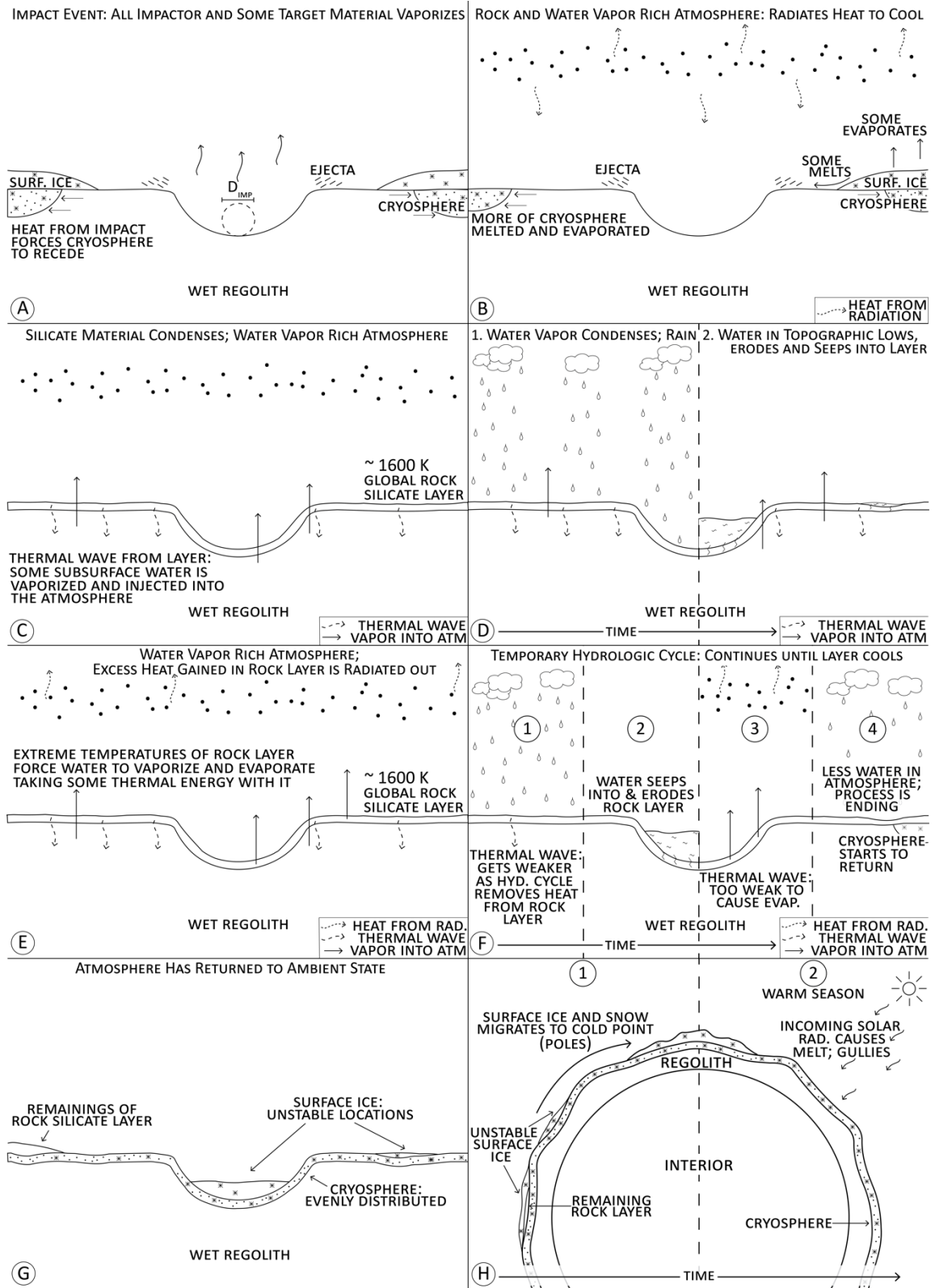


Fig. 3: Illustration of post-impact processes and effects following descriptions by Melosh (1989) for the impact cratering process and Segura et al. (2008) and Toon et al. (2010) for the related atmospheric and surface effects. Note that the ‘global rock silicate layer’ in this figure is what we refer to as the spherule layer. Some aspects, such as the presence and duration of intense hydrologic cycling, are predicted to be different in recent 3-dimensional studies (e.g. Turbet et al., 2020), but the general processes and effects illustrated here still hold. Details of the key post-impact effects are discussed in Section 4. Figure from Palumbo and Head (2018).

Figure 4

Mineralogic predictions for post-impact effects

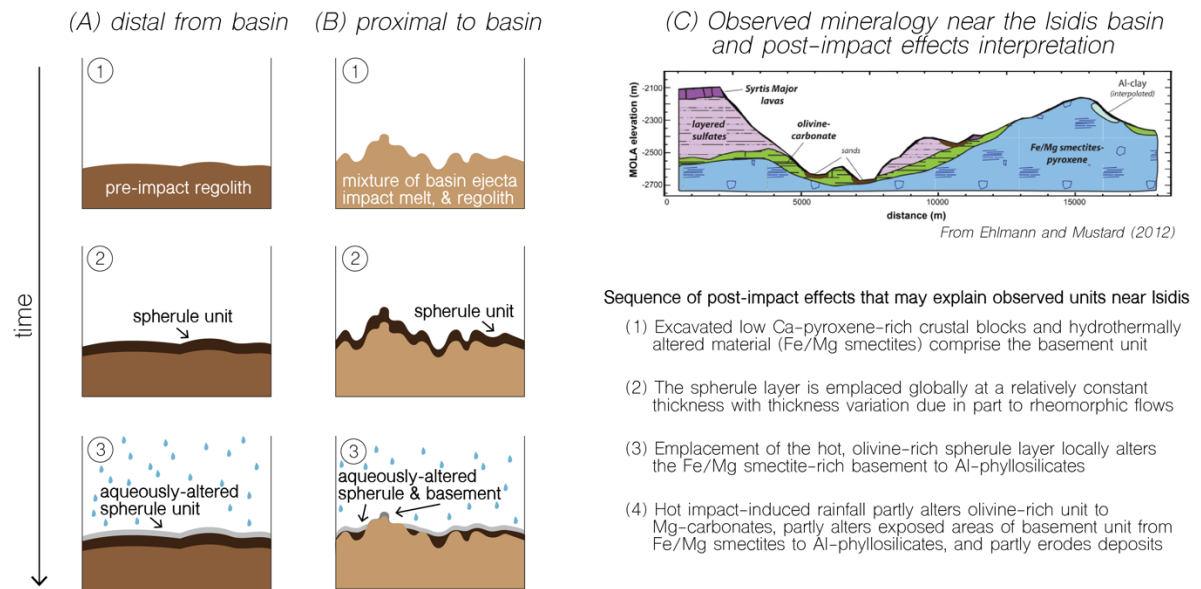


Fig. 4: Illustration of mineralogic predictions for post-impact effects. (A) and (B) show the evolution of an illustrated stratigraphic column through time as post-impact effects occur. (A) represents a stratigraphic column distal from the basin and (B) represents a stratigraphic column proximal to the basin. First, (timestep 2) the hot spherule unit is emplaced globally on top of the basement unit, which is either pre-impact regolith at a location distal to the basin or a mixture of basin ejecta, impact melt, and regolith at a location proximal to the basin. The extreme temperatures of the spherule unit could permit some local alteration of the basement unit at the contact between the basement unit and the spherule unit. The thickness of the spherule unit is expected to be relatively consistent with possible slight variation in thickness due to rheomorphic flow of the hot material; in some locations the underlying basement unit may be exposed (timestep 3). Then, hot, high rate, rainfall will persist for decades, permitting the (at least partial) aqueous alteration of the spherule unit and exposed areas of the underlying basement unit

(timestep 3). The intense rainfall is also likely to contribute to partial erosion of the underlying deposits. (C) shows the observed mineralogy near the Isidis basin (from Ehlmann and Mustard, 2012) and a description of how the sequence of post-impact effects may explain the observed units. Specifically, post-impact effects from a basin-scale impact event, possibly the Argyre-forming event, could be responsible for the formation of the olivine-rich unit (possibly a spherule unit) and the partial aqueous alteration of both the olivine-rich unit to Mg-carbonate and exposed areas of the underlying Fe/Mg-smectite-rich basement unit to Al-phyllsilicates (producing a leaching profile with Al-phyllsilicates overlain on Fe/Mg-smectites) from impact-induced rainfall. Updated from Palumbo and Head (2018).

Figure 5

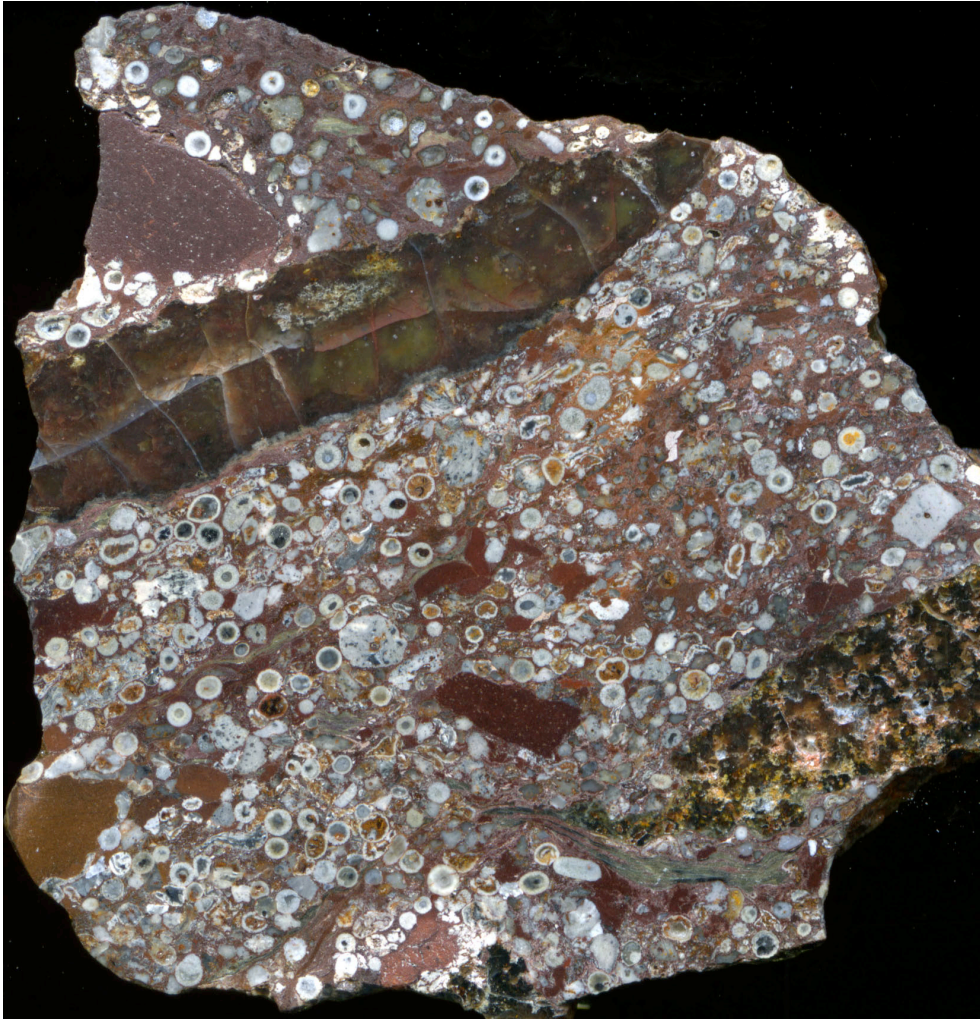


Fig. 5: Image of terrestrial spherule-rich sample. The sample was found in Western Australia and is approximately 2.63 billion years old. Image credit Bruce Simonson.

CHAPTER SEVEN

OCEANS ON MARS: THE POSSIBILITY OF A NOACHIAN GROUNDWATER-FED OCEAN IN A SUB-FREEZING MARTIAN CLIMATE

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Abstract

The Noachian climate of Mars is thought by many to have been “warm and wet”, characterized by a global mean annual temperature (MAT) >273 K and abundant rainfall infiltrating into the groundwater system. In this “warm and wet” scenario, when the groundwater system was in contact with the surface in the northern lowlands, a groundwater-fed ocean could form. In contrast, 1-dimensional climate models and 3-dimensional general circulation models (GCMs) are unable to reproduce long-lived, continuous “warm and wet” conditions due to the influence of the faint young Sun when considering a pure $\text{CO}_2\text{-H}_2\text{O}$ atmosphere; these models instead predict “cold and icy” conditions, characterized by MAT ~ 225 K and water trapped as snow and ice in the southern highlands. Furthermore, a kilometers-thick globally continuous cryosphere is predicted in this “cold and icy” scenario, precluding direct connection of the groundwater system and the surface, and disfavoring a Noachian northern lowlands ocean. However, global MAT values lack information about regional and seasonal temperature variations, which may vary significantly from global MAT. In this work, we explore whether regional or seasonal temperature variations could permit the formation of a Noachian ocean in a climate with global MAT <273 K. We use a combination of a 3D climate model and a 1D thermal model to determine the climatic conditions in which the required criteria for groundwater release could be met: (1) temperatures above 273 K, required for there to be no cryosphere preventing the groundwater from being released onto the surface, and (2) a sufficiently large groundwater reservoir, required for the groundwater table to intersect the surface. Our results suggest that the formation of a groundwater-fed ocean does not require a continuous and long-lived “warm and wet” climate with global

MAT >273 K. If the long-lived Noachian global MAT was >255 K (~30 K above the nominal ambient “cold and icy” climate) and the subsurface contained >63 m GEL groundwater, then groundwater could be released onto the surface and pond on the floor of the Hellas basin; global MAT >258 K and a subsurface water inventory of >170 m GEL are required for release groundwater into the topographically lowest regions of Utopia Planitia. If a subsurface water reservoir of ≥ 770 m GEL existed and local MAT was ≥ 273 K at Utopia, groundwater release could occur at Utopia and lead to flooding of the northern lowlands and formation of an ocean up to the level of Contact 1. Further, in a “cold and icy” MAT 225 K climate, short-term punctuated heating that raised global MAT to >255 K for at least a few thousand years could lead to groundwater release and flooding of the lowest points on Mars. Under the influence of these very cold climates (global MAT ~255-260 K), these bodies of water would remain ice-free for a geologically short period of time, possibly only a few hundred days, and would completely freeze and sublime in only a few thousand years.

Keywords: Mars climate; ocean; groundwater; Hellas basin; Utopia Planitia

1. Introduction and Background

A wide range of evidence has been cited for the presence of at least two oceans in the past history of Mars, including putative shorelines (Carr and Head, 2003; Clifford and Parker, 2001; Head et al., 1999; Parker et al., 1993, 1989), possible tsunami deposits (Costard et al., 2017; Rodriguez et al., 2016), evidence of outflow channel events that released catastrophic amounts of groundwater to the surface (e.g. Baker et al., 1991), the distribution of observed deltas (Achille and Hynek, 2010), the Vestitas Borealis Formation (Carr and Head, 2003), and the possibility of a once warmer and wetter climate, characterized by abundant pluvial activity and ponding of water at the surface (Craddock and Howard, 2002; Ramirez and Craddock, 2018; Ramirez et al., 2014; Ramirez, 2017). Due to age variations in these factors, one ocean is predicted to have existed in the Noachian and the other in the Late Hesperian. Although the evidence for oceans is debated and conclusive evidence is elusive (see review in Head et al., 2018), such a large body of water would have influenced, and been influenced by, the global hydrologic cycle, climate, and thickness and global versus regional extent of the cryosphere. Thus, determining the required conditions for the formation of oceans increases our knowledge of the plausibility of the oceans and, in turn, improves our understanding of the evolution of Mars. Here, we focus on the required conditions for the formation of an ocean in the Noachian. We begin by outlining the thermal and geometric configuration of the crustal substrate including the conditions required for the presence of groundwater and ground ice, the proposed formation mechanism for both the Hesperian and Noachian oceans, and the set of research questions that guides this work.

In the current hyper-arid and hypothermal climate of Mars, characterized by MAT ~ 215 K, a large portion of the upper crustal substrate is characterized by temperatures below the melting point of pure water, 273 K. This zone is defined as permafrost (soil, rock, or sediment that is frozen for more than two consecutive years) and this layer is termed the cryosphere. Water can be held as ice in the pore space of the cryosphere and acts as ice cement. Due to temperature and pressure stability conditions, the natural sink for subsurface water is pore space in the cryosphere. However, upon saturation (complete cementation) of the cryosphere, any remaining subsurface water will persist as liquid groundwater beneath the cryosphere (Clifford, 1993), forming a groundwater system. Groundwater can exist to the depth of overburden-induced pore closure, which has been estimated to lie at ~ 10 km beneath the surface on Mars for reasonable estimates of surface crustal porosity and the decay of porosity with depth (e.g. Clifford, 1993; Clifford and Parker, 2001). If a sufficient volume of groundwater is present, a regionally or globally interconnected groundwater system may result. The formation of both the Hesperian and Noachian oceans requires the presence of a voluminous groundwater system and specific climatic conditions.

The formation mechanism, evolution, and fate of the Hesperian ocean has been studied extensively (e.g. Turbet et al., 2017; Clifford, 1993; Baker et al., 1991). Assuming the conditions of a very cold Hesperian climate, characterized by a globally continuous cryosphere and globally interconnected groundwater system, the ~ 1 -2 km difference in elevation between the northern lowlands and the southern highlands is likely to cause the groundwater system to be out of hydrostatic equilibrium, due to the variation in elevation and overburden pressure across hemispheres (Fig. 1). Thus, if the

opportunity arises for groundwater to be released onto the surface, the water will flood out onto the surface until the system reaches hydrostatic equilibrium (Clifford, 1993). Depending on the amount of water present and location of groundwater release, this could lead to flooding of the northern lowlands. This is the hypothesized formation mechanism for the outflow channel-fed Hesperian ocean: in this scenario, a cold climate combined with groundwater system over-pressurization resulted in cracking of the cryosphere, outflow channel formation and groundwater release onto the surface, and ponding of water in the northern lowlands to form an ocean (e.g. Clifford, 1993) (Fig. 1).

This understanding of the formation mechanism of the Hesperian ocean provides important insight into the potential relationship between the groundwater system and surface in the Noachian. Previous workers have speculated that the opportunity for groundwater release onto the surface was inevitably important in a “warm and wet” Noachian climate, as well as in the Hesperian (Clifford, 1993; Clifford and Parker, 2001), albeit through a different release mechanism. The proposed release mechanism is that of a groundwater-fed body of water and, as a result of this release, a Noachian ocean is predicted to have formed in the northern lowlands (e.g. Clifford and Parker, 2001). On Earth, groundwater-fed bodies of water form where the groundwater table (top of the groundwater system) intersects the surface, exposing water that fills a topographic low to the height of the local water table. This same mechanism has also been proposed to explain the filling of some martian lakes, such as Columbus crater lake (e.g. Wray et al., 2011). Based on our understanding of the formation of groundwater-fed bodies of water on Earth and Mars, we identify two criteria for this mechanism of groundwater release (e.g. Clifford, 1993; Clifford and Parker, 2001): (1) a large groundwater reservoir,

required for the groundwater table to intersect the surface, and (2) mean annual temperature (MAT) >273 K, required for there to be no cryosphere; a cryosphere would prevent the release of groundwater, instead trapping it in the subsurface. With regard to the formation of the Noachian ocean, the first requirement for groundwater release is inferred to be met (e.g. Clifford, 1993; Clifford and Parker, 2001) because formation of the Hesperian ocean required a very large groundwater reservoir (Baker et al., 1991; Clifford and Parker, 2001), implying that such a reservoir existed in the Noachian, as well. The second requirement is commonly inferred to be met because of the hypothesized presence of a long-lived “warm and wet”, global MAT >273 K, Noachian climate (e.g. Craddock and Howard, 2002) (Fig. 2A).

If global MAT was above 273 K (Fig. 2A), the balance between geothermal heating and heat conduction from the surface into the subsurface would not permit a stable globally continuous cryosphere. Under these thermal conditions and assuming a sufficiently large groundwater reservoir, the groundwater system could be in contact with the surface, and groundwater could be released and pond at the surface (e.g. Clifford and Parker, 2001) (Fig. 2A).

Noachian atmospheric constraints provide important insight into where groundwater release and ponding at the surface should occur. When atmospheric pressure was above a few 10s of millibar, as is predicted for the Noachian (e.g. Jakosky et al., 2017), the surface and atmosphere become thermally linked together, which causes temperature to be dominantly dependent on altitude instead of latitude (e.g. Wordsworth et al., 2013). Thus, in the Noachian, temperatures are predicted to be highest in the lowest elevation regions, such as the floor of Hellas Basin and Utopia Planitia. For this reason

and the fact that groundwater naturally ponds in topographically low regions, previous researchers have hypothesized that in a “warm and wet” climate, groundwater would naturally be released onto the surface and pond in the northern lowlands (Clifford, 1993) (Fig. 2A), forming a Noachian ocean. It is important to note that the specific timing of this ocean is not necessarily coincident in time with peak valley network activity. Instead, the Noachian ocean was originally predicted to have formed in the early Noachian, when geothermal heat flux was the highest and atmospheric pressures were likely to have been the highest (e.g. Clifford and Parker, 2001), and as a result, surface temperatures the highest. On the other hand, recent studies have highlighted the potentially important role of this ocean if it were to have formed in the Late Noachian: such a large body of water in the lowlands could have been a driver of the continuous hydrologic cycling that is required to explain the formation of the valley networks (e.g. Achille and Hynek, 2010; Luo et al., 2017) and Late Noachian erosion rates (Golombek et al., 2006), which are high in comparison to erosion rates in the earlier Noachian.

However, the presence of a continuous and long-lived “warm and wet” Noachian climate is a topic of ongoing debate: despite abundant geologic evidence that the Noachian climate was much warmer and wetter than the recent Amazonian climate (e.g. Craddock and Howard, 2002; Hynek et al., 2010; Ramirez and Craddock, 2018; Ramirez, 2017), studies that implement advanced climate models, including for example 1-dimensional climate models (e.g. Kasting 1991; Ramirez et al., 2014) and 3-dimensional global climate models (GCMs) such as the Laboratoire de Météorologie Dynamique (LMD) GCM (e.g. Forget et al., 2013; Wordsworth et al., 2013, 2015) and the Mars Weather Research and Forecasting (WRF) GCM (e.g. Mischna et al., 2013), have been

unsuccessful in producing a continuous and long-lived “warm and wet” climate when considering pure CO₂-H₂O atmospheres. Instead, the models suggest that the continuous and long-lived early climate was more likely to have been “cold and icy”, characterized by global MAT ~225 K. Due to the adiabatic cooling effect and the very cold surface temperatures, surface water is predicted to have been distributed across the highlands as ice (Wordsworth et al., 2013). If this “cold and icy” climate persisted throughout the Noachian and into the Hesperian (e.g. Head and Marchant, 2014), the late Noachian-early Hesperian (LN-EH)-aged fluvial and lacustrine features, including the valley networks (Hynek et al., 2010) and open- and closed-basin lakes (Cabrol and Grin, 1999; Fassett and Head, 2008; Goudge et al., 2015), would have been formed through punctuated heating events and associated ice melting and surface runoff (Head et al., 2017a; Head et al., 2017b; Wordsworth, 2016). Nonetheless, such a continuous and long-lived “cold and icy” climate would have prevented the formation of a Noachian ocean: mean annual surface temperatures everywhere would have been below freezing and, as a result, there would have been a globally continuous cryosphere, which would have impeded groundwater release and the formation of an ocean (Fig. 2B).

Although these endmember “warm and wet” and “cold and icy” climate scenarios and the corresponding estimates of global MAT provide important insight into the globally-averaged climate conditions, it is important to consider the fact that global MAT values lack information about seasonal and regional temperature variations. Seasonal variation is driven by solar insolation changes. Regional variation is driven by the adiabatic cooling effect: lower elevation areas have local MAT that is higher than global MAT and higher elevation areas have local MAT that is lower than global MAT. Specifically, climate

models suggest that the lowest elevation regions, such as the floor of the Hellas basin in the southern hemisphere and Utopia Planitia in the northern lowlands, are characterized by local MAT much higher than the global MAT (e.g. Forget et al., 2013). This suggests that local MAT could be >273 K in the lowest elevation regions even if global MAT is <273 K, and, thus, that the temperature requirement for groundwater release might be met in a climate with global MAT <273 K, colder than the canonical view of a “warm and wet” climate. Previous studies of Noachian ocean formation have only considered global MAT (e.g. Clifford, 1993); the exclusion of regional and seasonal effects has led previous authors to conclude that a continuous and long-lived “warm and wet” climate with global MAT >273 K is required for formation of the Noachian ocean (e.g. Clifford, 1993). Thus, it is important to examine whether a Noachian ocean could have formed in globally-averaged long-lived, subfreezing conditions (global MAT <273 K) (Fig. 2C).

In this contribution, we consider a range of globally-averaged sub-freezing climates, characterized by global MAT <273 K, and explore whether regional and seasonal temperature variations could permit the formation of a Noachian ocean in a climate with global MAT <273 K (Fig. 2C), or alternatively, whether a long-lived “warm and wet” climate is required. Our goal is to determine the coldest possible climate in which an ocean could have existed on the surface of Noachian Mars and consider the requirements for and implications of this ocean. Specifically, we address the following questions:

- (1) What is the coldest possible global MAT at which groundwater release could occur somewhere on Mars?
- (2) In what locations would groundwater release occur?

- (3) If local MAT is slightly below 273 K, are seasonal temperature variations sufficient to remove the cryosphere and permit groundwater release?
- (4) What are the implications of groundwater release at the surface, including the necessary subsurface water inventory and the duration of the liquid water phase at the surface?
- (5) If punctuated heating occurred in an ambient “cold and icy” climate (global MAT ~225 K), how long must these punctuated conditions persist to remove the cryosphere and permit groundwater release?

2. Methods

In this analysis, we use a combination of a 3D GCM and a 1D basic thermal model to explore the possibility of a groundwater-fed Noachian ocean in a globally-averaged sub-freezing climate (global MAT <273 K).

2.1 Global Climate Model (GCM) Simulations

We implement the 3D LMD GCM for early Mars (e.g. Forget et al., 2013; Wordsworth et al., 2013) to explore the characteristics of possible Noachian climates. GCM predicted surface temperatures are utilized in our methods to address all of the questions listed above. The model utilizes a finite-difference approach to solve meteorological, atmospheric, radiative transfer, and physical energy conservation equations. The model traces three species through time and space, CO₂ ice, H₂O ice/liquid, and H₂O vapor; the convective and radiative properties of these species as solids, liquids, and gases are incorporated through the implementation of correlated-k

coefficients. For more detail on the physical processes included in the model and associated parameterizations, we refer the reader to the recent model description given by Wordsworth et al. (2015) and earlier, but also more detailed, descriptions given by Wordsworth et al. (2013) and Forget et al. (2013). We run the model with a spatial resolution of $65 \times 48 \times 25$ (longitude x latitude x altitude) and collect hourly data; these spatial and temporal resolutions are sufficient to capture the regional and seasonal temperature variations necessary for completion of this study. All data are collected after the model has run for 15 model years, which is sufficient to ensure model equilibration and avoid spurious warming effects. Next we provide justification for the parameter values we utilized in our simulations, including obliquity, eccentricity, atmospheric pressure, atmospheric gas concentrations, and topography.

The spin-axis orbital parameters, including obliquity and eccentricity, are not well-constrained for the Noachian. For this reason, we consider two statistically probable obliquity values (Laskar et al., 2004), a low end-member of 25° obliquity, and a higher end-member of 45° obliquity, which is consistent with the most probable value for the past 5 Gy of $\sim 41.8^\circ$ (Laskar et al., 2004). It is important to note that the globally-averaged MAT and regional distribution of MAT differ slightly for the two different obliquity values considered here, 25° and 45° , due to insolation variations that are associated with the axial tilt of the planet. To produce conservative estimates regarding the magnitude of seasonal temperature variations and to avoid an overwhelming suite of simulations, we consider only the condition of a circular orbit.

Although the Noachian atmospheric pressure is not well-constrained, recent studies have tried to improve estimates of Noachian atmospheric pressure based on

geologic observations and estimated atmospheric loss rates. Hu et al. (2015) found that the current atmospheric measurements of $^{13}\text{C}/^{12}\text{C}$, which are used to approximate loss rates by photodissociation and sputtering, and rock and soil carbonate measurements suggest that the early atmospheric pressure was less than 1 bar and that a large, currently unidentified, carbonate reservoir would be required to explain Noachian atmospheric pressures greater than 1 bar (Hu et al., 2015). Another option for reconciling a Noachian atmospheric pressure greater than 1 bar is the possibility that some of the CO_2 could have been subducted into the subsurface if there was ever a short period of plate tectonics (e.g. Connerney et al., 2005). Predictions from the MAVEN mission that approximate CO_2 sputtering loss rates from measurements of $^{38}\text{Ar}/^{36}\text{Ar}$ suggest that 0.5 bar CO_2 or more could have been lost through sputtering (Jakosky et al., 2017). The authors suggest that this amount of predicted CO_2 loss could be significantly higher due to the influence of extreme solar ultraviolet radiation and solar winds earlier in planetary history, possibly reconciling the loss of 1 bar CO_2 or more (Jakosky et al., 2017). Based on the results of these previous studies (Hu et al., 2015; Jakosky et al., 2017), we consider an atmospheric pressure of 1 bar CO_2 in our study. We do not consider atmospheric pressure values that are lower than 1 bar because we are interested in conditions under which local/regional MAT is $\geq 273\text{ K}$; higher atmospheric pressure increases the greenhouse effect, thus increasing the global MAT and the likelihood that local/regional MAT will be $\geq 273\text{ K}$.

Following the calculations by Gough (1981) for the evolution of solar luminosity through time, we assume a solar luminosity of 75% the present day value. This value is an approximation of solar luminosity in the Noachian.

Concentrations, sources, and sinks of greenhouse gases other than CO₂ and H₂O are not well understood or constrained for the Noachian era. For this reason, we consider a range of climate scenarios representing different amounts of greenhouse warming, but do not implement specific greenhouse gases to simulate the different climates. Instead, we introduce a gray gas into the model at varying amounts. A gray gas absorbs evenly across the spectrum at a defined absorption coefficient, κ . It is important to note that gray gas is not physically representative of specific gases in the atmosphere and instead mimics the effects of greenhouse warming. More gray gas implies more greenhouse warming and, as a result, higher surface temperatures. A given value for κ cannot simply be extrapolated to a concentration of specific greenhouse gases. We choose a range of values for κ , which were chosen strategically to span the global MAT range from ~225 K, representing the ambient ~1 bar CO₂ atmosphere with no additional greenhouse warming, to ~273 K, representing a scenario with sufficient greenhouse warming to increase global MAT to the melting point of water; the warmest simulations include the most gray gas warming.

Finally, we assume present day topography in our simulations. There are multiple factors that are likely to have influenced the present day topography since the Noachian, including the deposition of large volumes of volcanic material during a peak phase of flood volcanism in the Hesperian (Head et al., 2002) and possible true polar wander from hypothesized late-stage development of the Tharsis rise (e.g. Citron et al., 2018; Perron et al., 2007). We do not account for these factors in our simulations for the following reasons. (1) Head et al. (2002) analyzed MOLA topography data to constrain the thickness of the Hesperian Ridged (Hr) plains and found that the thickness of this unit is

approximately the same in the Hellas basin and the northern lowlands. Thus, although the floor of the Hellas basin and the northern lowlands would have been $\sim 1\text{-}2$ km lower before the emplacement of the Hr plains, the floor of the Hellas basin would still be the lowest elevation location on Mars, followed by the lowest elevation regions of Utopia Planitia in the northern lowlands. In simulations of the early climate, temperature is dominantly dependent on altitude, implying that temperatures would have been slightly higher in these locations if we were to perform our simulations with pre-Hr emplacement topography. We believe that this effect would be minor; our GCM simulations consistently show that the temperature gradient for MAT within the Hellas basin is ~ 2 K/km elevation, implying that the MAT at the floor of the Hellas basin may have been $\sim 2\text{-}4$ K warmer than our simulations (which use current topography) predict. Similarly, the temperature gradient for MAT within the Utopia Planitia region is ~ 2 K/km, implying that the MAT at the lowest elevation regions in Utopia Planitia may have been $\sim 2\text{-}4$ K warmer than our simulations predict. (2) The rate of development of the Tharsis rise is not well-constrained; some researchers believe that the Tharsis rise was largely emplaced by the Late Noachian (e.g. Scanlon et al., 2016), while others believe that the majority of the Tharsis rise was emplaced later in time, leading to significant true polar wander in the Hesperian or even Amazonian (e.g. Citron et al., 2018; Perron et al., 2007). Thus, the Noachian topography with respect to potential variations from true polar wander is not well constrained, so we cannot account for this effect in our simulations.

2.2 Thermal Model Description and Volume Calculations

The thermal model developed here is implemented to address several of our research questions, specifically for understanding the thermal response of the crust to punctuated and seasonal temperature changes (Questions 3 and 5). The basic thermal model that we have developed for our analysis is an extrapolation of the 1D heat conduction equation, accounting for the influence of solar insolation and geothermal heat flux, following Clifford (1993). The GCM grid cell size is small enough such that surface temperature variations between cells is minimal and therefore we can assume that lateral heat transport on the grid cell-to-cell scale in the subsurface is also minimal, justifying our use of a 1D model. The model is solved numerically by discretizing the differential equation and using a finite difference approach to estimate the thermal reaction of the subsurface to an imposed surface temperature.

Specifically, we implement the following 1D differential equation:

$$\frac{\partial^2 T}{\partial z^2} + \frac{S}{K} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (1)$$

where z is depth (m), α is thermal diffusivity ($\text{m}^2 \text{s}^{-1}$), S is heat generation per unit volume (W m^{-2}), t is time (seconds), T is crustal temperature (K), and K is crustal thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$) (Clifford, 1993). Depth is extrapolated into an array and we calculate pore closure depth as the depth at which porosity is less than 1% (following Clifford, 1993), thermal diffusivity is estimated as 2×10^{-6} (a reasonable estimate for the martian crust; Clifford, 1993), and S is calculated by $\frac{3Q}{R}$ where Q is the geothermal heat flux ($0.045\text{-}0.065 \text{ W m}^{-2}$ for the Noachian; Clifford et al., 2010; McGovern et al., 2004; Solomon et al., 2005; Zuber, 2001) and R is the radius of Mars (m).

Surface crustal temperature is implemented in different ways to address Question 3 and Question 5. (1) When estimating the thermal response of the subsurface to seasonal

temperature variations (Question 3), we assume an initial condition that the temperature profile with depth is representative of that associated with the long-lived, ambient background surface temperature at that location. Then, we run the thermal model for multiple martian years accounting for seasonal surface temperature variation by introducing surface temperature perturbations equivalent to the hourly surface temperature predicted by the GCM and assuming that the time step, dt , is one hour. When the model predicts approximately the same subsurface thermal response for two consecutive years, we assume that the result is representative of the actual annual thermal response. (2) When estimating the thermal reaction of the subsurface to a punctuated heating event (Question 5), we again assume as an initial condition that the temperature profile with depth is representative of that associated with the long-lived, ambient background surface temperature. Then, we introduce an increase in surface temperature equal to the punctuated value and run the model forward through time, assuming that the surface temperature is constant at the punctuated value, and estimate how the depth of the base of the cryosphere changes as the cryosphere equilibrates to the increased top-down thermal wave. When the depth of the 273 K isotherm, or the depth of the base of the cryosphere, is approximately equal to the surface, we conclude that the cryosphere no longer exists.

Finally, we assume that crustal thermal conductivity varies with surface temperature, following Clifford et al. (2010):

$$K = \frac{488.19}{T} + 0.4685 \quad (2)$$

As an initial condition for our 1D thermal model, we consider that temperature increases with depth as a function of the geothermal heat flux (Q):

$$\frac{\partial T}{\partial z} = -\frac{Q}{K} \quad (3)$$

A detailed description of how we utilize the output from our 1D thermal model to address each of these questions is included below.

When estimating the depth of the base of the cryosphere for a given MAT, we use the following relationship (Clifford, 1993):

$$z = K \frac{T_{mp} - T_{mat}}{Q} \quad (4)$$

Where T_{mp} is the melting point of the liquid in the groundwater and cryosphere system, and T_{mat} is the mean annual surface temperature. The melting point of the liquid can range from ~252 K for brines to ~273 K for pure liquid water. In this work, we consider only pure liquid water.

To address Question 4, we estimate the minimum subsurface water inventory that is required for groundwater release to occur. In this work, we define the minimum volume of water that must be in the subsurface for groundwater release to occur as the required volume in order for the groundwater system to intersect the surface at a location where local MAT ≥ 273 K. We thus assume that the pore space must be filled with water at all locations in the subsurface beneath the location where the temperature requirement for groundwater release is satisfied.

To estimate the minimum subsurface water inventory that is required for groundwater release, we must implement reasonable mathematical approximations and parameter values for the characteristics of the martian crust. Porosity has the major control on our predictions of required subsurface water volumes. In our calculations, we assume that porosity is a function of depth:

$$\rho(z) = \rho_{surf} \times e^{z/2.82} \quad (5)$$

Where z is depth beneath the surface measured (km) and ρ_{surf} is the surface crustal porosity, which we estimate as 0.2-0.35, following previous studies (e.g. Clifford et al., 2010; Clifford, 1993; Kleinhans, 2005). Using equation 5, we calculate pore closure depth as a function of surface crustal porosity by calculating the depth at which porosity is less than $\sim 1\%$. If surface crustal porosity is 0.2, then pore closure occurs at ~ 8.5 km beneath the surface and if surface crustal porosity is 0.35, then pore closure occurs at ~ 10 km beneath the surface.

A qualitative summary of our calculations for estimating the minimum subsurface water inventory that is required for groundwater release follows. First, we assume that the cryosphere is fully saturated with water ice cement; this is a pre-requisite requirement for water to be capable of being stable as a liquid in the groundwater system because the primary thermodynamic sink for water in the subsurface is the cryosphere. Second, we assume that groundwater is present everywhere in the subsurface below the location of predicted groundwater release. For example, if we consider groundwater release into a bowl-shaped crater, we assume that the groundwater table is at the floor of the crater and that the substrate beneath the floor of the crater is saturated with water down to the depth of pore closure. Finally, we sum the total volume of water that is trapped as ice in the cryosphere with the total volume of water in the groundwater system to calculate the minimum volume of water required for groundwater release in a given climate scenario. To produce an absolute minimum estimate, we also consider the case of a climate that is warm enough to have no cryosphere region anywhere on the globe and thus, that the required volume of water is only water that exists in the subsurface as groundwater (because there would be no additional water frozen in a cryosphere region).

2.3 Addressing Individual Research Questions

Next, we explain the methods that we will use to address the five questions outlined above, focusing on our methods of implementation of a 3D GCM in conjunction with a basic thermal model.

Question 1: What is the coldest global MAT at which groundwater release could occur somewhere on Mars?

If local MAT is ≥ 273 K in a climate where global MAT is < 273 K, the thickness of the cryosphere is locally zero, implying that the hydrological system is locally vertically integrated (Head and Marchant, 2014), that the groundwater system can be in contact with the surface, and that groundwater release could occur. Recall that if there is sufficient liquid groundwater in the subsurface, the global groundwater system cannot be in hydrostatic equilibrium if all groundwater is trapped in the subsurface (e.g. cannot escape, see Fig. 2B) because (1) there is a large variation in elevation that is associated with the hemispheric dichotomy, and (2) if the groundwater is trapped in the subsurface due to a frozen substrate (e.g. see Fig. 2B), the groundwater table cannot be at a constant elevation. Thus, if local MAT is ≥ 273 K, the groundwater will naturally be released onto the surface until the system reaches hydrostatic equilibrium and the groundwater table is at an approximately constant elevation. This implies that the groundwater table will be above the surface in topographically low regions. It follows that the only reason that groundwater release would not occur where local MAT is ≥ 273 K is if there is insufficient groundwater in the groundwater system to reach the surface at that location (for example, see Weiss and Head, 2017). When addressing Question 1, we assume that

there is sufficient groundwater in the system to permit release onto the surface, and thus we focus mainly on the climatic conditions that are required to permit the release of groundwater onto the surface.

We use GCM temperature output for the range of climate conditions that we simulated by introducing a varying amount of gray gas into the model atmosphere (global MAT ~ 225 K to ~ 273 K) and produce MAT maps with the purpose of highlighting the regional variation in MAT. Due to the altitude dependence of temperature that is characteristic of the relatively high atmospheric pressure in the Noachian, the warmest locations on the planet will be the topographically lowest regions; the floor of Hellas basin, followed by the lowest elevation area within Utopia Planitia. The coldest temperatures occur at the highest elevations of the Tharsis rise (local MAT can be up to ~ 30 K below the global MAT). Due to the large range of global elevations (lowest elevation ~ -8 km, highest elevation ~ 8 km; e.g. Smith et al., 1999), the lowest elevation locations may have local MAT significantly higher than the global MAT, possibly permitting groundwater release in a globally sub-freezing climate. We use the MAT maps to determine the coldest possible global MAT at which some location on the planet is warm enough for the local cryosphere thickness to be zero.

It is important to note that we are assuming an initially charged groundwater system (sufficient groundwater such that the groundwater table intersects the surface) and do not explore specific mechanisms for recharging the groundwater system after the groundwater is released onto the surface. If a plausible recharge mechanism to put sufficient volumes of water back into the subsurface, such that the groundwater table again intersects the surface, does not exist in the globally subfreezing climates that we

consider here, the groundwater release is required to be a one-time event. Further, we conclude that if groundwater release was possible in the Noachian, a groundwater recharge mechanism must exist in order to reconcile the evidence for groundwater release through outflow channel activity in the late Hesperian.

Question 2: In what locations would groundwater release occur?

As global MAT increases, local MAT increases across the planet accordingly. Thus, for each climate scenario considered here, the distribution of locations and percent of the planet with local MAT ≥ 273 K will vary. A larger percentage of the planet will have local MAT ≥ 273 K for a simulation with higher global MAT than a simulation with lower global MAT, implying that groundwater release could occur in more locations under the influence of the hotter climate. To address Question 2, we identify the regions on Mars with local MAT ≥ 273 K for each of the climate scenarios considered here. We explore the implications of our results, focusing on the probable distribution of released and ponded groundwater at the surface. Specifically, we will assess whether groundwater release is likely to occur in the northern lowlands and/or in other topographic lows, such as large impact basins.

Question 3: If local MAT is slightly below 273 K, are seasonal temperature variations sufficient to remove the cryosphere and permit groundwater release?

Climate modeling studies have shown that significant seasonal variation in temperature occurs throughout the year on Mars (Palumbo et al., 2018; Richardson and Mischna, 2005). A consequence of this is that at a given location, although MAT may be far below freezing, the warmest part of the summer may experience temperatures above freezing. If temperatures >273 K persist for long enough in the summer season, it is

possible that the downward-penetrating thermal wave will cause subsurface temperatures to increase sufficiently to remove the cryosphere, allowing the hydrological system to become locally vertically integrated, and groundwater release to occur. To test this hypothesis and address Question 3, we pair hourly climate model data with our 1D thermal model in order to determine which locations are characterized by MAT < 273 K, but spend a sufficient amount of time with temperature > 273 K to cause a cryosphere-base depth of zero at some point during the year. We repeat this for all simulated climate scenarios. The results for this section are illustrated through a global map for each simulated climate that shows regions where local MAT is < 273 K but seasonal temperature variations are sufficient to effectively remove the cryosphere in the summer season and permit groundwater release. We show results for simulations that use a geothermal heat flux value of 0.045 W/m^2 , a reasonable estimate for Noachian geothermal heat flux based on previous studies (Clifford et al., 2010; McGovern et al., 2004; Solomon et al., 2005; Zuber, 2001). A lower geothermal heat flux will lead to a thicker cryosphere than a higher geothermal heat flux, implying that seasonal cryosphere depletion is more likely for higher geothermal heat flux. By highlighting results for simulations with geothermal heat flux of 0.045 W/m^2 , we are presenting a conservative estimate for the influence of seasonal temperature variations.

Question 4: What are the implications of groundwater release at the surface, including the necessary subsurface water inventory and the duration of the liquid water phase at the surface?

Based on our answers for Questions 1-3, we will have a firm understanding of the coldest possible global MAT in which a groundwater-fed body of water could have

formed in the Noachian and the geographical location at which groundwater release could occur and water could pond on the surface. However, there are still multiple unknowns regarding the formation and evolution of this hypothetical groundwater-fed ocean, including (1) the near-surface water inventory that is required for groundwater release to occur at a given location, and (2) the duration of the liquid water phase of the ocean.

To address the first half of Question 4, we estimate the minimum subsurface water inventory, including ice in the cryosphere and liquid water in the groundwater system, that is required for the groundwater table to intersect the surface at the location of predicted groundwater release. It is important to recall that the estimates provided here represent the minimum possible amount of subsurface water such that groundwater could release onto the surface. This means that the groundwater table is exactly at the location where groundwater release is predicted. Because we are focusing on low elevation locations, this assumption implies that the groundwater system is largely not in contact with the cryosphere, allowing for the groundwater system to be mostly equilibrated despite the large variation in elevation between hemispheres. Thus, the estimates produced here would only lead to a very small amount of water being released onto the surface. Of course, any additional water that was originally in the groundwater system would naturally be released onto the surface, if temperature conditions permit, to return the system to hydrostatic equilibrium. As a result, when we consider large bodies of water forming on the surface, we must assume that the entire body of water is in addition to the minimum estimates that we calculate in this work.

To address the second half of Question 4, we speculate on the duration of the liquid water phase based on results from previous work that estimated the duration of the

liquid phase for a Hesperian ocean (Kreslavsky and Head, 2002; Turbet et al., 2017). We define the liquid water phase as the time when the body of water is not completely ice-covered. We also consider how the duration of the liquid water phase would change as a function of different climate scenarios and extrapolate these results to consider whether the presence of the predicted standing body of water would have a large influence on the surface hydrological system.

Question 5: If punctuated heating occurred in an ambient “cold and icy” climate (global MAT ~ 225 K), how long must these conditions persist to remove the cryosphere and permit groundwater release?

Recent climate modeling studies have suggested that the long-lived, background Noachian climate was more likely to have been “cold and icy” than “warm and wet”, characterized by global MAT ~ 225 K, with surface water trapped as ice in the southern highlands (Forget et al., 2013; Wordsworth et al., 2013). In this climatic scenario, the climatic conditions required for groundwater release, which are higher temperatures than the ambient “cold and icy” climate, could have persisted through punctuated heating events (e.g. Head et al., 2017 a,b). To address Question 5, we use our 1D thermal model to estimate how long it would take for the cryosphere to change from its “cold and icy” state and equilibrate at an effective cryosphere depth of zero (e.g. no cryosphere region), permitting vertical hydrological system integration and groundwater release to the surface. We highlight results for simulations that use a geothermal heat flux value of 0.065 W/m^2 and 0.045 W/m^2 ; a lower geothermal heat flux will move the base of the cryosphere deeper into the subsurface, in turn increasing the cryosphere equilibration time. We do this for the local MAT at the locations where groundwater release is

predicted to occur. We assume that the punctuated heating event is global, increasing temperature everywhere; although localized heating is possible (e.g. through volcanism-induced heating), we do not explore this effect here. We also consider the range of punctuated climates; if the punctuated temperature is 300 K at the location of interest, the cryosphere may disappear much more rapidly than if the punctuated temperature is 273 K. The purpose of Question 5 is to determine the necessary length of a punctuated heating event (of varying magnitude of heating) to understand better whether such a punctuated heating event is possible through known heating mechanisms, including volcanism-induced heating (Halevy and Head, 2014; Kerber et al., 2015; Mischna et al., 2013), or a transient reducing greenhouse atmosphere (Wordsworth et al., 2017).

We also note that another mechanism for groundwater release onto the surface in a cold climate with a globally continuous cryosphere is through an impact crater which penetrates through the cryosphere (e.g. see Russell and Head, 2002). Observations of present-day topography inform us that the floor of the Hellas basin is the lowest elevation location on Mars, followed by Utopia Planitia. However, the emplacement of the Hesperian ridged (Hr) plains has led to significant infilling in both of these regions, potentially covering evidence of Noachian-aged craters within the Hellas basin or Utopia Planitia. If an impact crater formed on the floor of the Hellas basin or Utopia Planitia in a climate that is sufficiently cold such that there is a globally continuous cryosphere, the impact event may penetrate through the cryosphere, permitting the release of groundwater onto the surface. Thus, this is a mechanism that would permit groundwater release in climates even colder than those identified in this study. Because the signatures of such craters are likely to be heavily modified or covered by Hr plains and difficult to

recognize, we do not include an in-depth analysis of this mechanism in this work; identification of potential Noachian-aged craters and basins in these regions is currently underway.

3. Results and Discussion

We have utilized a combination of (1) 3D GCM simulations, (2) a basic thermal model, and (3) assumptions about the characteristics of the martian crustal substrate, to determine the plausibility of the formation of a Noachian groundwater-fed ocean in a globally sub-freezing climate; we also addressed the characteristics of any candidate oceans, including location, duration, and required subsurface water volumes. The results of our analysis show that groundwater release and the formation of a groundwater-fed ocean is possible in a globally sub-freezing climate. We discuss our results in the context of the five questions previously identified.

Question 1: What is the coldest global MAT at which groundwater release could occur somewhere on Mars?

Global MAT maps for the range of simulations studied here are shown in Fig. 3 (25° obliquity) and Fig. 4 (45° obliquity). The floor of the Hellas basin has the highest regional MAT on the globe because it is the lowest absolute elevation location on Mars. For both 25° and 45° obliquities, local MAT ≥ 273 K occurs on the floor of the Hellas basin for global MAT ~ 255 K (Figs. 3, 4). Local temperature conditions sufficient for groundwater release occur for global MAT of a minimum of ~ 255 K. Thus, the temperature constraint for groundwater release is met if global MAT was ≥ 255 K; a continuous and long-lived “warm and wet” climate is not required.

Question 2: In what locations would groundwater release occur?

In order for the hydrological system to be vertically integrated and groundwater release to be possible, there must be no cryosphere at that location. Thus, groundwater release onto the surface is possible in any region with local MAT ≥ 273 K, the minimum MAT required for there to be no cryosphere. We find that these conditions are met on the floor of the Hellas basin, the lowest elevation location on Mars, for global MAT ≥ 255 K (Fig. 3, 4). Groundwater effluent is predicted to be released and pond solely within Hellas basin. The second lowest elevation location on Mars is Utopia Planitia in the northern lowlands. Groundwater release in Utopia Planitia could lead to flooding of the northern lowlands and the formation of a northern lowlands ocean. Because temperature is dominantly dependent on altitude in the Noachian atmospheric pressure regime (Forget et al., 2013), Utopia Planitia is also the second warmest location on Mars. In our simulations with 25° obliquity, we find that local MAT can exceed 273 K in Utopia Planitia for a global MAT of at least ~ 258 K (Fig. 3). However, due to the dependence of incident solar radiation on obliquity, the onset of such warm conditions in Utopia Planitia is restricted to a higher global MAT in our 45° obliquity simulations (Fig. 4). Specifically, the local MAT at Utopia Planitia is < 273 K for global MAT ~ 258 K and 45° obliquity. In our simulation with 45° obliquity and global MAT ~ 268 K, the next warmest simulations after the simulation with global MAT ~ 258 K, most of the northern lowlands is characterized by local MAT > 273 K. This implies that the onset of conditions permitting a vertically integrated hydrological system (local MAT ≥ 273 K) in Utopia Planitia lies between a global MAT of ~ 258 K and ~ 268 K for the condition of 45° obliquity.

In summary, groundwater release in the Hellas basin is predicted to occur for global MAT ~ 255 K. A higher global MAT is required for groundwater release to also be possible at Utopia Planitia, which could lead to flooding of the northern lowlands.

Question 3: If local MAT is slightly below 273 K, are seasonal temperature variations sufficient to remove the cryosphere and permit groundwater release?

We have used our basic thermal model to determine whether seasonal temperature excursions in regions with MAT slightly below 273 K are sufficient to melt through the cryosphere, permitting vertical integration and groundwater release. We ran our basic thermal model at hourly resolution and accounted for the surface temperature changes that are predicted by the hourly climate model data. We repeated this process for every model lat/lon grid cell and every GCM simulation in this analysis (25° and 45° obliquity). In general, we find that seasonal temperature variations can increase subsurface temperatures sufficiently such that the cryosphere disappears in the warmest part of the summer season, but only at locations where local MAT is ~ 272 K or higher (Fig. 5) (in agreement with predictions by Ramirez and Craddock, 2018). Thus, we conclude that accounting for the influence of seasonal temperature variations does not decrease the minimum global MAT at which groundwater release could occur because seasonal effects are only an important process for areas with local MAT within ~ 1 K of the melting point of water.

The importance of seasonal effects is demonstrated in Fig. 5B (45° obliquity). When accounting for seasonal temperature effects, we see that groundwater release is possible at Utopia Planitia if global MAT was ~ 258 K; however, local MAT is < 273 K in this climate scenario. This analysis shows that global MAT ≥ 258 K is the condition at

which groundwater release can occur at Utopia Planitia for both 25° obliquity (Fig. 3, local MAT >273 K) and 45° obliquity (Fig. 5B, seasonal temperature effects; compare with Fig. 4).

We have considered a circular orbit in these simulations. Increasing the orbital eccentricity in our simulations would serve to increase the magnitude of the seasonal temperature variations. Although the relatively small statistically probable range of eccentricity for the Noachian period (Laskar et al., 2004) suggests that eccentricity is not likely to have been high enough in the Noachian to sufficiently change the regional MAT distribution (Palumbo et al., 2018), it is important to note that a higher eccentricity value implies higher summer season temperatures. It is possible that the higher summer season temperatures could permit the seasonal increase of temperatures in the crustal substrate to ≥ 273 K for sufficient durations to remove the cryosphere at locations that were too cold when considering the seasonal effects of a circular orbit (e.g. local MAT <272 K). However, because the probable Noachian eccentricity values are relatively low, and the climate is predicted to swing to a colder-than-normal winter following the hotter-than-normal summer, this effect is likely to be negligible, and for this reason we do not treat it in detail here.

Question 4: What are the implications of groundwater release at the surface, including the necessary subsurface water inventory and the duration of the liquid water phase at the surface?

We have concluded that a groundwater-fed body of water, sourced at topographically low regions on Mars such as Hellas basin or Utopia Planitia, could have formed in a globally sub-freezing Noachian climate. Next, we treat the implications of

groundwater release onto the surface, including the necessary near-surface water inventory for this to occur and the potential duration of the liquid water phase of a groundwater-fed body of water.

In our answers to the previous questions, we have only considered the thermal constraint that is required for groundwater release: local MAT ≥ 273 K. However, the thermal constraint is not the only requirement for groundwater release; there must also be sufficient groundwater in the system for release to occur. For example, when considering groundwater release at the bottom of the Hellas basin, the minimum possible depth of the groundwater table (the top of the groundwater system) is equivalent to the lowest topographic location within the Hellas basin (Fig. 6). We are interested in constraining the minimum possible subsurface water inventory that is required to permit groundwater release. This is important because, assuming that there was a Noachian ocean, we can use this ocean formation mechanism as a way to provide insight into the volume of water that is required to have been in the subsurface water inventory in the Noachian.

The required subsurface water inventory, including water as ice in the cryosphere and as liquid groundwater, depends on the global surface climate and geothermal heat flux. This relationship between subsurface water inventory and surface climate can be illustrated through the example of groundwater release at the lowest topographic location within Hellas basin. Consider two cases where the first case is characterized by a warmer surface climate than the second case and, for simplicity, assume that the base of the cryosphere and groundwater table are not in direct contact with one another (e.g. Fig. 6). In the case with a colder surface climate, the cryosphere would be thicker than in the case with a warmer surface climate, and more water can be trapped as ice in the cryosphere.

However, the volume of water that is required to be as liquid groundwater in order to maintain the groundwater table height at the base of the Hellas basin would remain constant in both cases. Thus, the subsurface water inventory that is required for groundwater release to occur at the floor of Hellas basin, including water as ice in the cryosphere and liquid groundwater, would be more in a colder climate than in a warmer climate. Therefore, the minimum possible volume of water that is required for groundwater release would correspond to a climate that is characterized by $\text{MAT} \geq 273 \text{ K}$ across the entire globe; there would be no cryosphere anywhere on the planet in this climate scenario and the subsurface water reservoir would only contain the liquid groundwater component.

The minimum volume of water that is required to permit groundwater release in Hellas basin and Utopia Planitia is shown in Table 1 for all GCM simulations done here, surface porosities of 0.2 and 0.35, porosity decay with depth following eq. (5), and geothermal heat flux of 0.065 W/m^2 . If we consider a very warm climate where there is no cryosphere on the planet and a surface porosity of 0.2, we can estimate the absolute minimum volume of water that is required to permit groundwater release in the Hellas basin, $\sim 62.6 \text{ m GEL}$, and at Utopia Planitia, $\sim 169.7 \text{ m GEL}$. To determine whether the formation of a Noachian ocean is plausible based on these estimates of the minimum required subsurface water inventory, we can compare with other estimates for the subsurface water inventory in the Noachian.

Recent work by Weiss and Head (2017) analyzed different crater morphologies indicative of excavating into and beneath the cryosphere and found that the total subsurface inventory of water trapped as ice in the cryosphere in the Late Hesperian was

~200 m GEL (using a surface porosity of 20% that declines exponentially with depth). More specifically, Weiss and Head (2017) find that, if surface porosity was >17%, more than ~170 m GEL would be in the subsurface water inventory. The authors find that the cryosphere is not fully saturated, implying that there was not an underlying liquid groundwater system that persisted beyond the Hesperian period. Thus, the total subsurface water inventory in the Late Hesperian was estimated to be ~200 m GEL. Assuming that the net input/output from the subsurface were relatively small between the Late Noachian and Late Hesperian, we can infer that 200 m GEL may be a reasonable estimate for the Noachian subsurface water inventory as well. This estimate is more than the ~170 m GEL required for groundwater release at Utopia, implying that a groundwater-fed body of water could have formed in the northern lowlands in the Noachian if surface temperatures were sufficiently high (and surface porosity was above 17%).

Clifford and Parker (2001) estimated that the volume of water that had to be in the subsurface water inventory (cryosphere and groundwater) in order for the outflow channels to have formed is 550-1400 m GEL. The authors suggest that all of this water was trapped in the subsurface before the outflow channels formed and released some of the subsurface water to the surface. Thus, they suggest that this is a reasonable estimate for the subsurface water inventory in the Noachian and that some of this inventory could have been released to the surface in the Noachian if surface temperatures were sufficiently high to remove the cryosphere. This estimate is also more than the ~170 m GEL required for groundwater release at Utopia, implying that a groundwater-fed body of water could have formed in the northern lowlands in the Noachian if surface

temperatures were sufficiently high. It is possible that the discrepancy between the Clifford and Parker (2001) estimate and the Weiss and Head (2017) estimate is due to significant loss of water from the subsurface before the late Hesperian era.

Alternatively, we must consider the possibility that the volume of water in the subsurface water inventory in the Noachian was less than the required amount for groundwater release. If there was $<\sim 62$ m GEL water in the subsurface water inventory, there could not have been groundwater-fed bodies of water in neither Hellas basin nor Utopia Planitia. If there was $>\sim 62$ m GEL but $<\sim 170$ m GEL water in the subsurface water inventory, there could have been a groundwater-fed body of water in Hellas basin, but there could not have been a groundwater-fed body of water in Utopia Planitia.

Further, recall that this volume of water is the absolute minimum required for groundwater release; if only this amount was present, only a very small amount of water would release onto the surface because the system would already be near hydrostatic equilibrium. Thus, to form a large body of water on the surface, additional water must be trapped in the subsurface, forcing the system to be further out of hydrostatic equilibrium and causing more groundwater to be released onto the surface. For example, an absolute minimum of ~ 170 m GEL is required for groundwater release to be possible Utopia Planitia. In order to fill the northern lowlands to Contact 1 (Parker et al., 1989), ~ 600 m GEL of water would have to be on the surface (Carr and Head, 2003). Thus, an additional ~ 600 m GEL of water would have had to have been trapped in the subsurface prior to the period of warmer temperatures, when the groundwater could release onto the surface. In total, filling the northern lowlands to contact 1 would require ~ 770 m GEL of water in the subsurface. This volume, of course, does not account for the additional water that

would have flooded into the Hellas basin, which would increase the total even further. Even these higher approximations of the necessary subsurface water inventory are not inconsistent with previous estimates (e.g. Clifford and Parker, 2001).

However, we also must note that ~600 m GEL of water (Contact 1) is more than 15 times the volume of the present surface/near-surface water inventory (Carr and Head, 2015). Thus, this water must have been removed from the surface since the Noachian. In order to explain the formation of the Hesperian outflow channels, most of this water had to return to the subsurface (e.g. Clifford and Parker, 2001). It is possible that some of this water has been lost to space since the Noachian.

These hypothetical groundwater-fed bodies of water will not be stable on the surface in the long-term in a climate with global MAT ≤ 273 K (e.g. Kreslavsky and Head, 2002; Turbet et al., 2017). This is because of the model-predicted characteristics of the Noachian atmosphere and climate, which it is important to review here. Specifically, when the martian atmospheric pressure is above a few tens of millibars, as is predicted for the Noachian, the atmosphere and surface become thermally linked together and an adiabatic cooling effect (e.g. Forget et al., 2013) ensues, which causes temperature to be dominantly dependent on altitude instead of latitude (e.g. Wordsworth et al., 2013; Forget et al., 2013). Interestingly, the atmospheric pressure on present-day Earth is approximately the same as we use in our simulations of Noachian Mars (~1 bar), but we observe a more dominant latitude-dependence of temperature on Earth, in addition to an altitude-dependence which is most notable across steep altitudinal gradients, such as mountain tops which are much colder than the corresponding summits. One key reason for this contrast is the difference in atmospheric density on Noachian Mars and present-

day Earth; for a given atmospheric pressure, atmospheric density on Mars would be higher due to the relatively lower planetary gravity. As a result of this adiabatic cooling effect on Noachian Mars, paired with the large elevation variations across the surface, water is predicted to have been stable in the highest elevation regions as ice (e.g. Wordsworth et al., 2013). Specifically, the water is predicted to have been cold trapped as ice into regions where temperatures are <273 K year-round. In all simulations done in this analysis, there are regions of the highlands that are permanent cold traps because the highest elevation regions are below freezing year-round. Recent climate modeling studies show that water will migrate to these regions of the highlands where it will be stable as surface ice, even in climates with global MAT as high as 273 K (e.g. Palumbo and Head, 2018; water trapped as ice on Tharsis and near the south pole) when considering reasonable estimates for the surface water inventory (e.g. Carr and Head, 2015). Thus, the lifetime of the ocean can be divided into multiple phases (e.g. Kreslavsky and Head, 2002): (1) completely liquid standing body of water, (2) ice-covered standing body of water, (3) completely frozen body of water, and (4) ablation and migration of ice to the southern highlands where the water will be re-precipitated as snow. Turbet et al. (2017) used the 3D LMD GCM to estimate the duration of the liquid water phase for a Hesperian outflow channel-fed ocean (global MAT ~ 210 K), determining that the ocean would become completely ice-covered within ~ 500 days. Additionally, simulations of the fate of an ocean in the northern lowlands in the cold, Hesperian climate suggest that the presence of a standing body of water in the lowlands does not initiate a vigorous hydrological cycle with abundant rainfall (Turbet et al., 2017).

The duration of the liquid water phase will depend on the temperature of the background climate; the ocean will freeze much more rapidly in a colder climate. For the very cold Hesperian climate simulated by Turbet et al. (2017), the surface and atmospheric temperatures were below the melting point of water everywhere on the planet (global MAT ~ 210 K), leading to almost immediate freezing of the outflow channel-formed ocean. In order for a groundwater-fed Noachian ocean to form through the mechanism explored in this research, the climate must be at least slightly warmer than the very cold Hesperian climate modeled by Turbet et al. (2017). Specifically, although the coldest possible climate scenario in which a groundwater-fed body of water could form in either Hellas basin or Utopia Planitia is characterized by global MAT significantly below the melting point of water (global MAT $>\sim 255$ K) (Figs. 3, 4), these scenarios are characterized by global MAT ~ 40 K higher than the simulations done by Turbet et al. (2017). Turbet et al. (2017) predicts that the duration of the liquid water phase in a climate with global MAT ~ 210 K is ~ 500 days. We would expect that the liquid water phase would persist slightly longer than 500 days in the coldest climate scenarios where groundwater release is possible in the Noachian (global MAT ~ 255 K). The duration of the liquid water phase would be longer in climates with higher global MAT. Consequently, we view 500 days as a reasonable lower limit for the duration of the liquid water phase. Nonetheless, the duration of the liquid water phase for an ocean formed in a climate with global MAT ≤ 273 K is predicted to be geologically short, especially in the coldest climates considered here, on the order of hundreds of days to hundreds of years (e.g. Kreslavsky and Head, 2002).

Following the results of Turbet et al. (2017), we do not expect the standing body of water to have a large influence on the climate and hydrological system, especially for the coldest climates considered. In climates with global MAT ≤ 273 K, the dominant hydrological process associated with the presence of the body of water will be ablation and re-precipitation as snow in the southern highlands (e.g. Turbet et al., 2017; Palumbo et al., 2018). However, we acknowledge that the influence on the hydrological system and precipitation (rainfall and snowfall) patterns associated with a Noachian ocean in a warmer climate (global MAT > 273 K) may be different than in the cold climate simulated by Turbet et al. (2017). We are currently implementing the methods of Turbet et al. (2017) for the predicted volume of a Noachian ocean (e.g. Contact 1; Parker et al., 1989) in order to further constrain the duration of the liquid water phase of the Noachian ocean for the range of climatic scenarios studied here, and for warmer climates (global MAT > 273 K). This effort will also constrain the relationship between the stability, lifetime and fate of these bodies of water and the climate scenario.

Question 5: If punctuated heating occurred in an ambient “cold and icy” climate (global MAT ~ 225 K), how long must these punctuated conditions persist to remove the cryosphere and permit groundwater release?

In the ambient “cold and icy” Noachian climate scenario (global MAT ~ 225 K), the local MAT at the floor of Hellas basin is ~ 255 K and the local MAT at the lowest elevation portion of Utopia Planitia is ~ 245 K. To answer question 5, we explore the possibility of transient or punctuated heating that increases the local MAT to ≥ 273 K at Hellas basin and Utopia Planitia.

First, we consider a punctuated heating event that increases local MAT to 273 K at these locations and then use our 1D thermal model to estimate how long it would take for the cryosphere to equilibrate to the warmer surface temperature, effectively removing the cryosphere and permitting groundwater release onto the surface. Specifically, for the case of Hellas basin we consider a punctuated heating event that yields a global MAT ~ 255 K for the cases of both 25° and 45° obliquity; under this global MAT condition, local MAT is ~ 273 K at the Hellas basin. For the case of Utopia Planitia we consider a punctuated heating event with global MAT ~ 258 K for the case of 25° obliquity and a punctuated heating event with global MAT $> \sim 258$ K for the case of 45° obliquity; in both scenarios the local MAT is ~ 273 K at Utopia Planitia.

If we assume that the crustal substrate beneath Hellas basin has equilibrated to the ambient ~ 225 K global MAT “cold and icy” climate, characterized by local MAT ~ 255 K, and that the Noachian geothermal heat flux was 0.065 W/m^2 , the punctuated heating scenario that increases local MAT to ~ 273 K must persist for ~ 2690 consecutive years for the local upper crustal substrate region to thermally respond and effectively remove the cryosphere there (Fig. 7A). Similarly, if we assume that the crustal substrate beneath Utopia Planitia has equilibrated to the ambient “cold and icy” climate, characterized by local MAT ~ 245 K, and that the Noachian geothermal heat flux was 0.065 W/m^2 , the punctuated heating scenario that increases local MAT to ~ 273 K must persist for ~ 6180 consecutive years for the upper crustal substrate region to thermally respond and effectively remove the cryosphere (Fig. 7B). In other words, the punctuated heating event that increases local MAT to ~ 273 K must heat the climate for several thousand consecutive years to permit groundwater release at Hellas basin or Utopia Planitia (~ 2690

or ~6180 years, respectively). Alternatively, if we repeat the same calculations but assume a lower geothermal heat flux of 0.045 W/m^2 , the necessary durations increase by a factor of about 2 (~5960 years at the Hellas basin, ~15000 years at Utopia Planitia). The duration is longer for simulations that assume a lower value for geothermal heat flux because the base of the cryosphere in the ambient “cold and icy” climate is deeper due to the lower magnitude of the upward-penetrating thermal wave.

Next, we consider the possibility that the punctuated heating event will increase local MAT in the Hellas basin or Utopia Planitia to temperatures above 273 K. The higher MAT at the surface will increase the magnitude of the downward-penetrating thermal wave, causing the cryosphere region to be removed in less time. Again, we assume that the crust beneath the Hellas basin and Utopia Planitia has equilibrated to the ambient “cold and icy” climate before the punctuated heating event occurred. For example, if the local MAT of the punctuated climate is 280 K and we assume that the Noachian geothermal heat flux was 0.065 W/m^2 , it will take ~1180 consecutive years and ~3340 consecutive years for the cryosphere region to be removed in Hellas basin and Utopia Planitia, respectively (Fig. 8 A, C). If we consider a slightly hotter punctuated heating event which increases local MAT to 285 K, it will take ~990 consecutive years and ~2850 consecutive years for the cryosphere to be removed in Hellas basin and Utopia Planitia, respectively (Fig. 8 B, D). Alternatively, if we repeat the same calculations, but assume a lower geothermal heat flux of 0.045 W/m^2 , the necessary durations to remove the cryosphere in Hellas and Utopia, respectively, increase to (1) ~2450 and ~7420 consecutive years for the condition of local MAT 280 K, and (2) ~2077 and ~6247 consecutive years for the conditions of local MAT 285 K. Note that both the downward

penetrating thermal wave from the surface and the geothermal heat flux are important controls on increasing subsurface temperature to >273 K and removing the cryosphere: (1) for a constant geothermal heat flux value, the calculated number of consecutive years that the punctuated heating event must persist in order to remove the cryosphere if the local surface temperature is 280 K is approximately double the calculated number of years if the local surface temperature 273 K; (2) for a constant punctuated surface temperature value, the calculated number of consecutive years that the punctuated heating event must persist in order to remove the cryosphere if the geothermal heat flux is 0.045 W/m^2 is approximately double the calculated number of years if the geothermal heat flux is 0.065 W/m^2 .

In summary, our calculations show that the timescales required to locally remove the cryosphere ($<10,000$ years; $\sim 10^3$ - 10^4 a) are relatively short from a geologic perspective. Thus, we next address the question: Is it possible that a punctuated heating event with global MAT $>\sim 255$ K (local MAT ≥ 273 K at Hellas basin and Utopia Planitia) could have persisted for a maximum of a few thousand years in the Noachian? There are multiple mechanisms that can produce transient or punctuated periods of heating in the Noachian (e.g. Head et al., 2017 a,b), including but not limited to (1) impact cratering-induced heating (e.g. Palumbo and Head, 2017; Segura et al., 2002, 2012, 2008; Toon et al., 2010), (2) a transient reducing greenhouse atmosphere (Wordsworth et al., 2017) with appreciable quantities of gases such as hydrogen or methane (Wordsworth et al., 2017), which could have been introduced to the atmosphere through volcanism (e.g. Ramirez et al., 2014; Ramirez 2017) or serpentinization (e.g. Holm et al., 2015), and (3) volcanism-induced heating from the release of sulfur-based gases into the martian atmosphere, such

as SO₂ and H₂S (e.g. Halevy and Head, 2014; Johnson et al., 2008; Kerber et al., 2015; Mischna et al., 2013; Tian et al., 2010).

In the early- to mid- Noachian, basin scale impact events would have produced very hot surface temperatures (~600 K; Segura et al., 2008) which would have forced a rapid response of subsurface temperatures and caused the cryosphere to disappear rapidly. These conditions could have persisted for tens to hundreds of years (e.g. Segura et al., 2008), with the surface temperature slowly cooling back to ambient conditions over time. Such a duration is likely to be sufficient to remove the cryosphere and permit groundwater release onto the surface. Note that impact cratering-induced heating is not a significant process in the Late Noachian and Early Hesperian, when the valley networks were active, because there are no basin-forming events in this time period (Fassett and Head, 2011); impact cratering-induced heating would be short-lived, minimal, and potentially a localized effect instead of a global effect (e.g. Wordsworth, 2016; Palumbo and Head, 2017; Ramirez and Kasting, 2017; Ramirez, 2017). Thus, although impact cratering-induced heating could have provided the necessary temperature increase to remove the cryosphere and permit groundwater release in the Early- to Middle-Noachian, it would not have provided the necessary temperature increase in the Late Noachian.

Transient reducing atmospheres were likely to contain relatively abundant concentrations of H₂ (Ramirez et al., 2014) and CH₄ (Wordsworth et al., 2017), which are gases that have a strong greenhouse effect when considering the collision induced absorption (CIA) effects of these gases with atmospheric CO₂ (Ramirez et al., 2014; Wordsworth et al., 2017). Researchers have suggested that such atmospheric gases in

concentrations that are reasonable when considering source and sink constraints could lead to significant heating of the surface, possibly increasing the global MAT to ~ 273 K (Ramirez et al., 2014; Wordsworth et al., 2017). The lifetime of these gases in the martian atmosphere is $\sim 10^5$ years (Wordsworth et al., 2017), a duration sufficient for removal of the cryosphere region and groundwater release onto the surface. This estimated lifetime assumes that these gases are not replenishable in the martian atmosphere. It is possible that these gases could have been maintained for longer durations if there was a plausible replenishment mechanism; for example, if the mantle was sufficiently reduced, volcanic events were sufficiently frequent and outgassing rates were sufficiently high to outpace removal of these gases from the atmosphere (e.g. Ramirez et al., 2014). It is important to note that more recent experimental work undertaken to better constrain the CIA and greenhouse effects of these gases in the martian atmosphere (Turbet et al., 2019) has found that the previous approximations from Wordsworth et al. (2017) may overestimate the CIA warming effects by a factor of ~ 1.7 . Thus, sufficient heating of the surface and cryosphere removal may require higher concentrations of H_2 and/or CH_4 than previously considered, and, as evidenced by multiple recent publications on the topic (Wordsworth et al., 2017; Turbet et al., 2019), this is a topic of ongoing research in the field.

Volcanic activity releases large quantities of sulfur-based gases into the atmosphere – sulfur-based gases are strong greenhouse gases in the martian atmosphere because they absorb in the martian CO_2 - H_2O atmospheric window (e.g. Halevy and Head, 2014; Postawko and Kuhn, 1986). However, the sulfur-based gases will rapidly coalesce onto atmospheric water molecules and dust particles, forming aerosols and leading to planetary cooling. As a result, several investigators find that volcanism-

induced heating from sulfur-based gases is expected to be very short-lived, possibly lasting only one summer season (e.g. Kerber et al., 2015; Tian et al., 2010). This duration is not sufficient to remove the cryosphere and permit groundwater release.

In conclusion, multiple transient and punctuated heating mechanisms have been identified that will heat the surface for a sufficient duration to effectively remove the cryosphere, allowing for groundwater release at the surface in a long-lived background “cold and icy” MAT 225 K climate, including impact cratering-induced heating following basin scale impact events and a transient reducing greenhouse atmosphere. Volcanism-induced heating can lead to significant increases in surface temperature, but the duration of these conditions appears to be too short-lived to significantly affect the temperature distribution within the upper crustal substrate region.

4. Conclusions

We have utilized the 3D LMD GCM and developed and utilized a basic thermal model to test the hypothesis that a groundwater-fed ocean could have formed in a long-lived background Noachian climate with global MAT >225 K and <273 K. Specifically, we estimated the coldest possible climate in which a groundwater-fed body of water could have formed, and addressed five specific questions:

- (1) What is the coldest global MAT at which groundwater release could occur somewhere on Mars?
- (2) In what locations would groundwater release occur?
- (3) If local MAT is slightly below 273 K, are seasonal temperature variations sufficient to remove the cryosphere and permit groundwater release?

- (4) What are the implications of groundwater release at the surface, including the necessary subsurface water inventory and the duration of the liquid water phase at the surface?
- (5) If punctuated heating occurred in an ambient “cold and icy” climate (global MAT ~ 225 K), how long must these punctuated conditions persist to remove the cryosphere and permit groundwater release?

Our conclusions based on our findings follow.

- (1) Our simulations show that local MAT > 273 K can exist in specific, low elevation areas for global MAT > 255 K (Figs. 3, 4). Thus, the temperature constraint for groundwater release can be met if global MAT was > 255 K; a long-lived “warm and wet” climate is thus not required not the temperature constraint to be met.
- (2) In the Noachian, atmospheric pressure was likely to have been much higher than the current atmospheric pressure (Jakosky et al., 2017). For atmospheric pressure greater than a few tens of millibars, the atmosphere and surface become thermally linked, producing an adiabatic cooling effect and causing water to be distributed as ice in the southern highlands (e.g. Wordsworth et al., 2013). Because of this effect, the highest local MAT occurs within the lowest elevation regions, Hellas basin and then Utopia Planitia. The temperature constraint for groundwater release is met at Hellas and Utopia for long-lived global MAT > 255 K and > 258 K, respectively (Figs. 3, 4). The release of large volumes of water at Utopia could lead to flooding of the northern lowlands and formation of an ocean.
- (3) Our thermal model results suggest that much warmer summer temperatures are only sufficient to remove the cryosphere temporarily and permit summertime

groundwater release in areas where local MAT is ~ 272 K, very close to the melting point of water.

- (4) We also estimated the volume of groundwater that is required to be in the subsurface in order for the groundwater system to be in contact with the lowest elevation points in the Hellas basin and Utopia Planitia. We calculated this volume for each climate scenario considered here (Table 1); required volumes change as a function of global MAT because colder climates imply a thicker cryosphere, which requires more water to be trapped as ice in the cryosphere before the crustal pore space can be filled with groundwater. We also estimated the absolute minimum volume of water that would be required to be in the subsurface. In this climate scenario, surface temperatures are >273 K everywhere on the planet, implying that there is no cryosphere anywhere on the planet, and that all subsurface water is in the groundwater system. We find that the absolute minimum required volume of subsurface water for groundwater release at Hellas basin is ~ 63 m GEL and at Utopia Planitia is ~ 170 m GEL.
- (5) In a long-lived “cold and icy” MAT 225 K climate, a punctuated heating event would have to occur in order for groundwater release to be possible. We use our 1D thermal model and estimate the maximum duration by assuming that the punctuated climate is characterized by local MAT ~ 273 K at each location. For groundwater release to be possible on the floor of the Hellas basin, we find that the punctuated climate must persist for a maximum of $\sim 2690/\sim 5960$ consecutive years (for geothermal heat flux estimates of 0.065 and 0.045 W/m², respectively). For the Utopia Planitia, the punctuated climate must persist for a maximum of

~6180/~15000 consecutive years for groundwater release to be possible (for geothermal heat flux estimates of 0.065 and 0.045 W/m², respectively). A punctuated heating event of this duration might be explained through either (1) impact cratering-induced heating in the early- to mid-Noachian following basin-scale impact events, which would increase surface temperatures far above the melting point of water for tens to hundreds of years, or (2) a transient reducing greenhouse atmosphere, which could increase global MAT up to ~273 K for up to ~10⁵ years.

- (6) Because Hellas basin is at a lower elevation than Utopia Planitia, and thus characterized by warmer temperatures, the presence of a groundwater-fed ocean in Utopia Planitia also implies the presence of a groundwater-fed body of water in Hellas basin.

In summary, the results of our analysis show that groundwater release and the formation of a groundwater-fed ocean is possible in a globally sub-freezing climate under certain specific conditions. Due to the altitude dependence of temperature, a groundwater-fed body of water could occur in the Hellas basin for global MAT >~255 K. A groundwater-fed body of water could also occur in Utopia Planitia for global MAT >~258 K. Specifically, if (1) stable, long-lived global MAT ever reached >~255 K in the Noachian, (2) the groundwater system contained more than ~63 m GEL of water, and (3) the surface porosity was ≤0.2 and decayed with depth according to equation 5, then groundwater could be released onto the surface at the floor of the Hellas basin and form a body of water that would have been contained within the basin. Further, if (1) stable, long-lived global MAT was ever >~258 K in the Noachian, (2) the groundwater system

contained more than ~ 170 m GEL of water, and (3) the surface porosity was ≤ 0.2 and decayed with depth according to equation 5, then groundwater could be released onto the surface at Utopia Planitia and form a body of water, possibly leading to flooding of the northern lowlands and the formation of an ocean. Further, in a stable long-lived “cold and icy” MAT 225 K climate, a transient heating event that raised global MAT to >255 K for a few thousand years could lead to groundwater release and flooding of the lowest points on Mars. In a globally sub-freezing Noachian climate (MAT <273 K), these bodies of water would freeze, sublime, and re-precipitate as snow in the southern highlands on geologically very short timescales (10^4 - 10^5 years).

Major questions in further assessing the plausibility of this scenario include:

(1) In addition to transient greenhouse-rich atmospheres and impact cratering-induced heating, are there other plausible punctuated or transient heating mechanisms that could raise MAT sufficiently to remove the cryosphere and permit groundwater release in the topographically lowest regions of Mars in the Noachian?

(2) Is there any independent evidence for the presence of the large quantities of excess Noachian groundwater required to produce, first, sufficient hydrostatic head to allow groundwater to flow onto the surface (such as in Weiss and Head, 2017), and secondly, the additional groundwater volume required to fill the northern lowlands to Contact 1?

(3) Are there mechanisms to prevent rapid freezing and sublimation, and prolong the lifetime of a potential Noachian ocean that formed through groundwater release in a climate with global MAT <273 K?

(4) Is there a plausible fate for the huge quantities of surface water predicted by the canonical Noachian ocean extent (Contact 1; ~600 m GEL)?

(5) Formation of a Noachian ocean through this groundwater release mechanism could decrease significantly the Noachian subsurface groundwater inventory. Are there mechanism(s) to recharge and over-pressurize the groundwater aquifer in order to account for the subsequent Late Hesperian outflow channel activity, which has been hypothesized to have formed the Late Hesperian ocean (Clifford, 1993; Clifford and Parker, 2001)?

(6) We find that removal of the cryosphere and groundwater release could occur during periods of transient or punctuated heating in an ambient “cold and icy” MAT ~225 K climate. Could this groundwater release mechanism have occurred in the Late Noachian, implying that the valley networks and lakes may have been active at a time when there was also an ocean in the northern lowlands? What are the implications of this scenario, and could the ocean provide a source for the hydrologic recycling that was likely to have been necessary to form the valley networks (e.g. Luo et al., 2017)?

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Tables

Table 1

Obliquity (°)	Amount of gray gas (kg/m ²)	Global MAT (K)	Surface porosity	Volume in cryosphere (m GEL)	Required subsurface water inventory for release at Hellas basin (m GEL)	Required subsurface water inventory for release at Utopia Planitia (m GEL)
25	7.5x10 ⁻⁵	275.7	0.35	52.9	162.4	349.8
25		275.7	0.2	30.2	92.8	199.9
45		268.4	0.35	95.8	205.4	392.7
45		268.4	0.2	54.8	117.3	224.4
25	5x10 ⁻⁵	263.9	0.35	131.4	240.9	428.2
25		263.9	0.2	75.1	137.7	244.7
45		257.9	0.35	188.1	297.6	-
45		257.9	0.2	107.5	170.1	-
25	4.596x10 ⁻⁵	262.6	0.35	141.7	251.2	438.4
25		262.6	0.2	81.0	143.5	250.5
45		256.0	0.35	209.1	318.6	-
45		256.0	0.2	119.5	182.0	-
25	3.856x10 ⁻⁵	258.7	0.35	180.8	190.3	477.1
25		258.7	0.2	103.3	165.9	103.3
45		252.9	0.35	241.4	350.9	-
45		252.9	0.2	138.0	200.5	-
25	3.235x10 ⁻⁵	255.4	0.35	215.4	324.9	-
25		255.4	0.2	123.1	185.6	-
45		249.6	0.35	276.9	-	-
45		249.6	0.2	158.2	-	-
25	2.5x10 ⁻⁵	250.5	0.35	267.5	-	-
25		250.5	0.2	152.9	-	-
45		245.1	0.35	321.4	-	-
45		245.1	0.2	183.6	-	-
25	0	232.9	0.35	436.2	-	-
25		232.9	0.2	249.2	-	-
45		231.2	0.35	452.4	-	-
45		231.2	0.2	258.5	-	-

Table 1: Minimum volume of water required to permit groundwater release at Hellas basin (fifth column) and Utopia Planitia (sixth column). Obliquity, amount of gray gas warming, global MAT, and surface porosity for each situation is shown in the first four

columns. The fifth column is the amount of water that must be trapped as ice in the cryosphere and the sixth and seven columns are the cumulative amount of water that must be in the cryosphere and groundwater system. To complete these calculations, we assume that porosity changes with depth according to equation 5. If groundwater release is not possible in a given climatic scenario, the total volume of water columns are intentionally left blank. In these calculations we assume a Noachian geothermal heat flux of 0.065 W/m^2 .

Figures

Figure 1

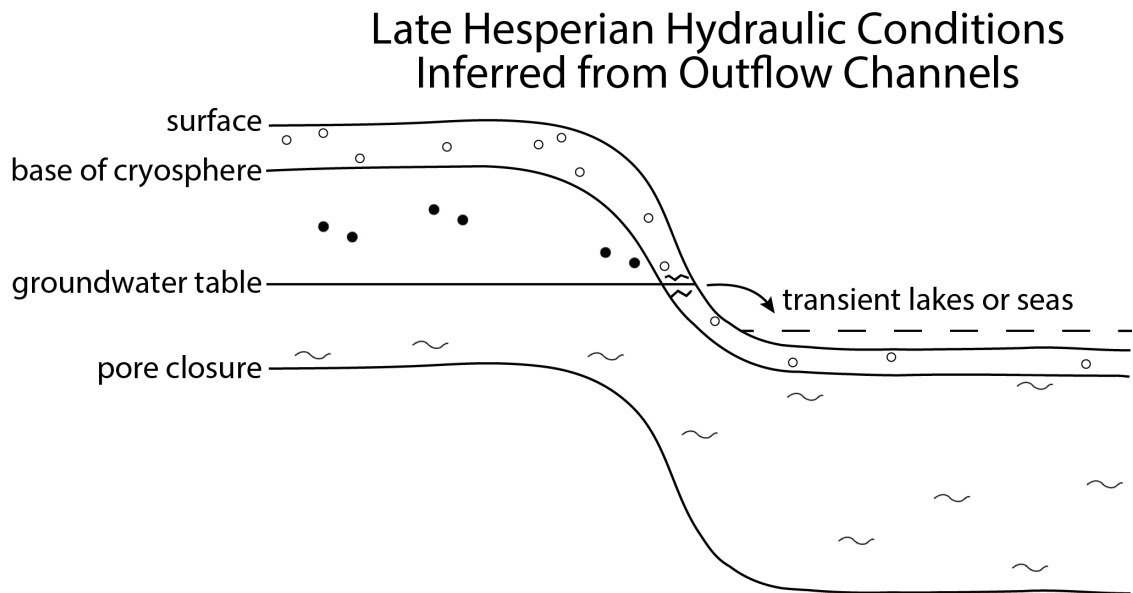


Fig. 1: Illustration of the hydraulic conditions of the groundwater system in the late Hesperian, leading to outflow channel events. Adapted from Clifford and Parker (2001).

Figure 2

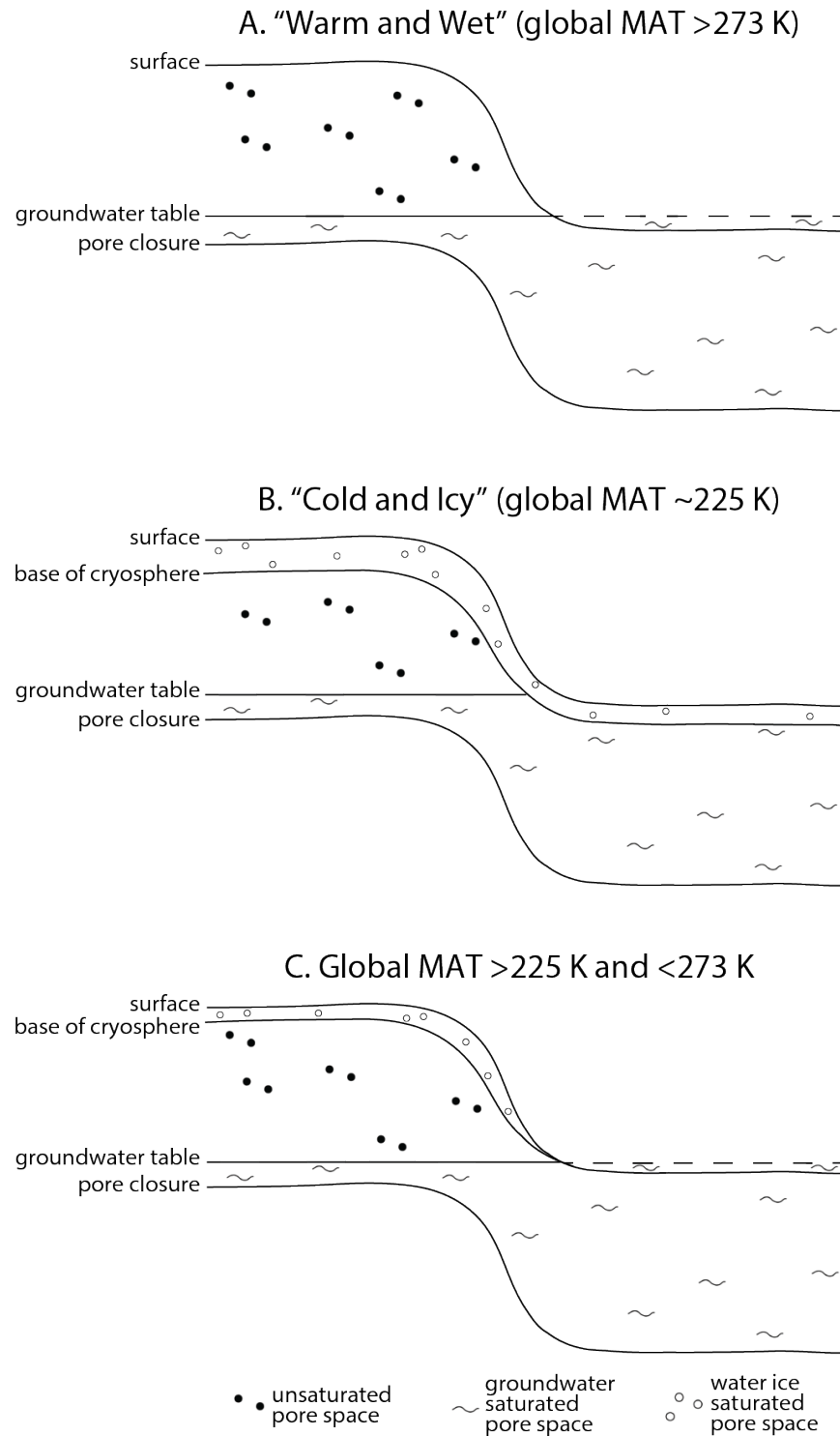


Fig. 2: Illustration of the groundwater system and surface for different climatic scenarios.

In all illustrations, the left side represents the highlands and the right side represents the

lowlands, the filled circles represent unsaturated pore space, the curved lines represent groundwater saturated pore space, and the open circles represent water ice saturated pore space. (A) “Warm and wet” climate, global MAT >273 K: no cryosphere separates the groundwater from the surface. If enough water is present in the subsurface, the water table will intersect the surface and groundwater will release onto the surface. (B) “Cold and icy” climate, global MAT ~ 225 K: global cryosphere prevents groundwater from releasing onto the surface. (C) Global MAT >225 K and <273 K: no cryosphere in the lowest elevation regions (e.g. the northern lowlands), permitting groundwater release to the surface.

Figure 3

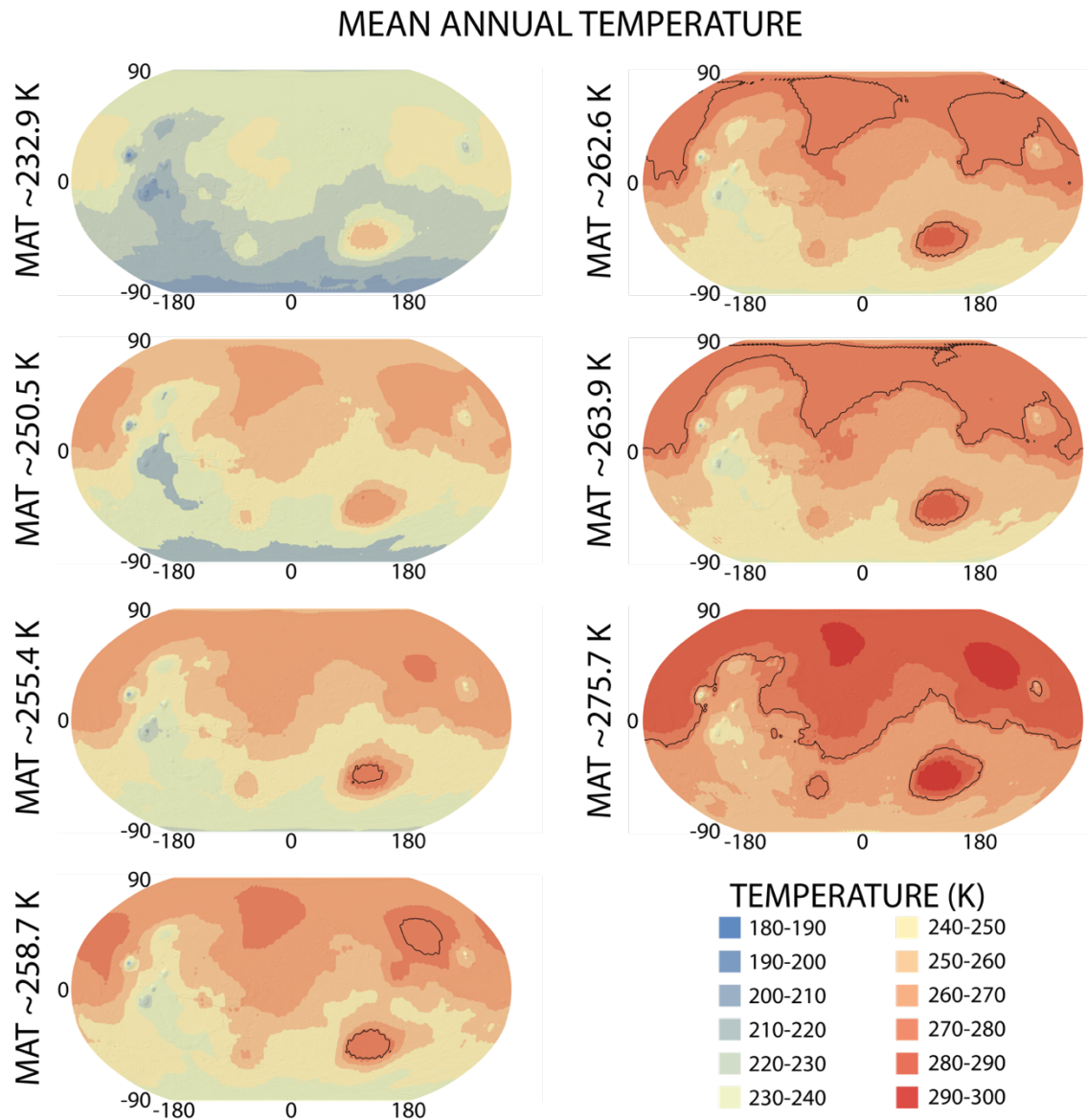


Fig. 3: Results of 25° obliquity GCM simulations: Each map is labeled with the globally averaged mean annual temperature (MAT) and highlights the regional variation in MAT. Regional variation is dominated by elevation changes due to the adiabatic cooling effect and the altitude dependence of temperature; lowest elevations (Hellas basin and northern lowlands) have the highest MAT and highest elevations (Tharsis rise) have the lowest MAT. Warm colors represent hotter temperatures and cool colors represent colder

temperatures (see key). The 273 K contour (black line) separates warmer regions (MAT >273 K; dark reds) from colder regions (MAT <273 K). Note that for climates with global MAT <252 K, regional MAT is <273 K everywhere on the planet.

Figure 4

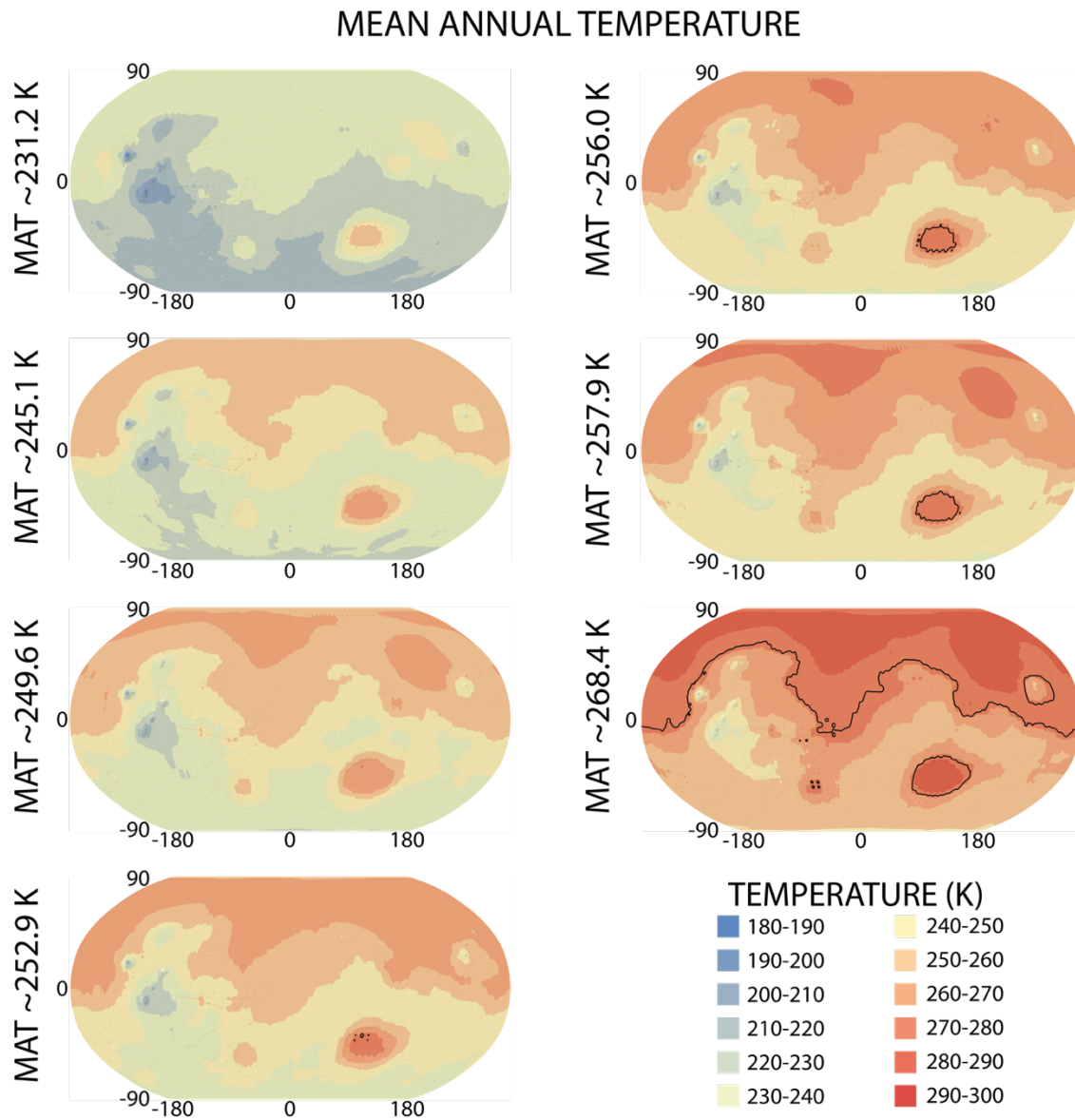
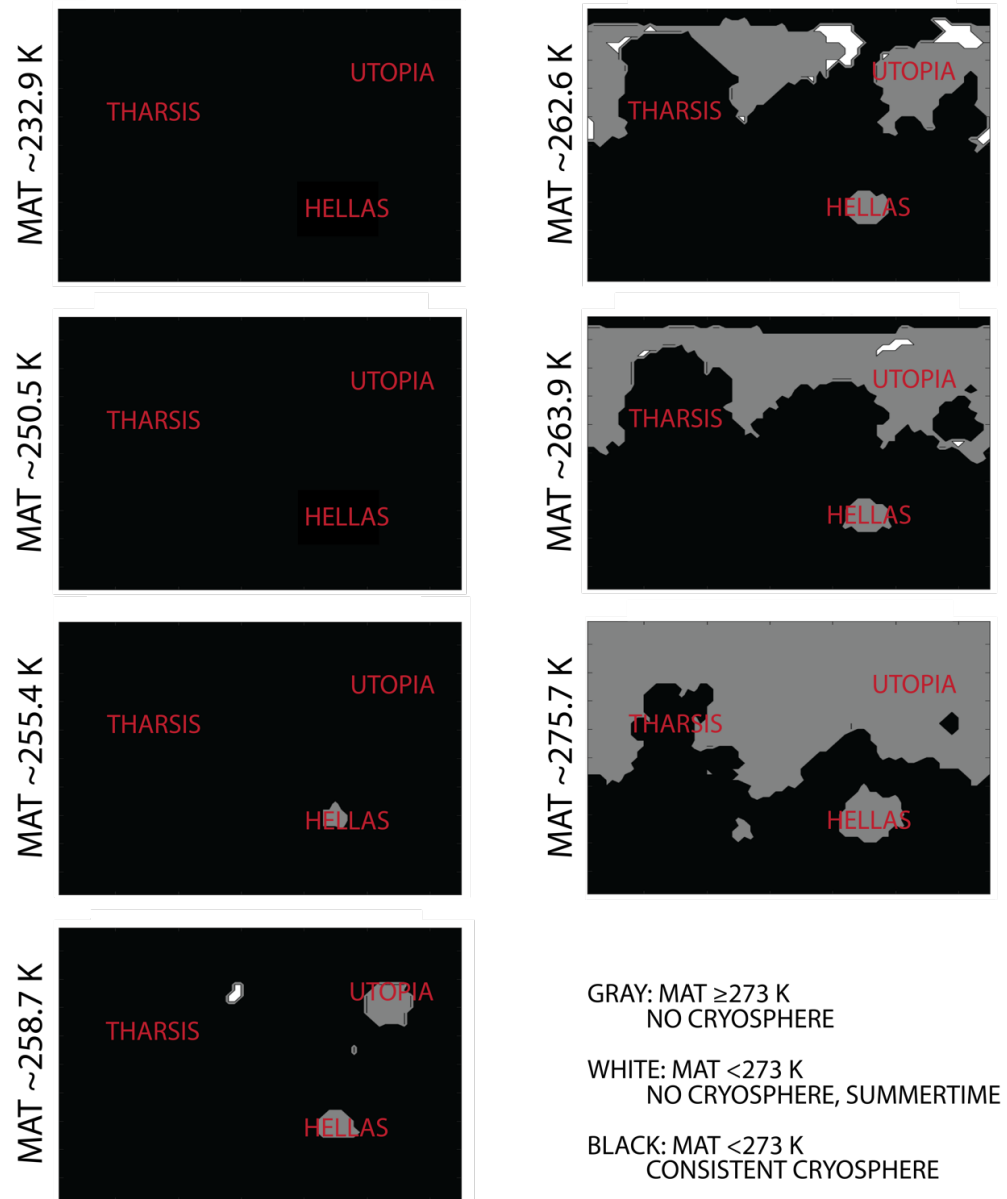


Fig. 4: Results of 45° obliquity simulations: The same amounts of gray gas warming are used for each corresponding map in Figs. 3 and 4. Each map is labeled with global MAT; note that global MAT is slightly different for the 45° obliquity and 25° obliquity simulations for a given amount of gray gas warming due to obliquity-related insolation effects. The color-temperature scheme is the same as in Fig. 3.

Figure 5

(A) 25° OBLIQUITY SIMULATIONS



(B) 45° OBLIQUITY SIMULATIONS

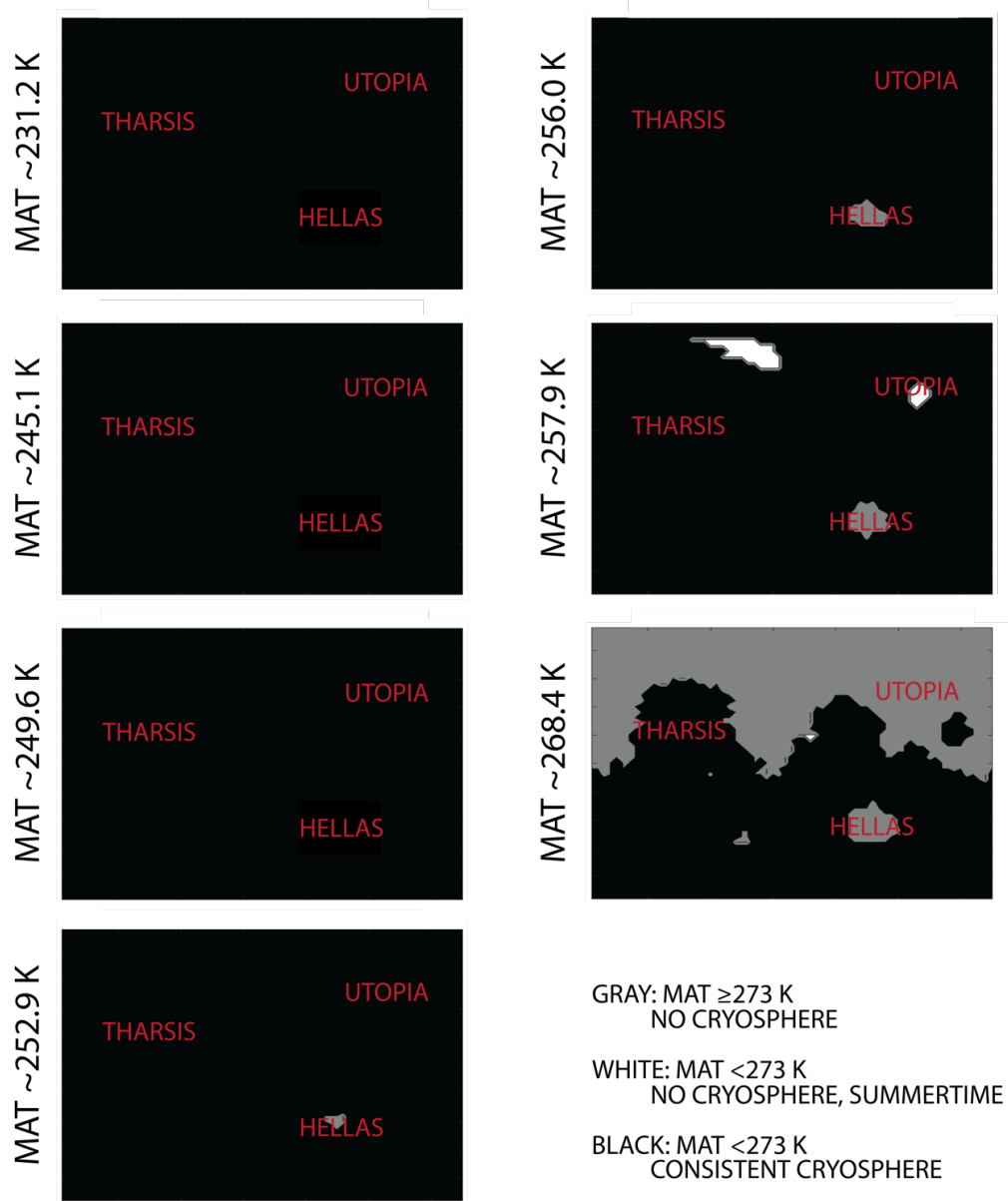


Fig. 5: Effects of global MAT, regional MAT, seasonal temperature variations, and the presence or absence of a cryosphere: Results of thermal model simulations using hourly GCM data to determine if seasonal temperature variations can transiently remove the cryosphere, permitting groundwater release (local MAT < 273 K but the warmest summertime conditions are sufficient in magnitude and duration to remove the cryosphere). Regions shaded gray: MAT ≥ 273 , no cryosphere region throughout the

entire year, groundwater release is always possible. Regions shaded white: local MAT <273 K, seasonal temperature variations cause removal of cryosphere in the warmest part of the summer season; groundwater release is possible in part of the summer season. Regions shaded black: local MAT <273 K, seasonal temperature variations insufficient to remove the cryosphere; continuous cryosphere throughout the entire year. (A) Results for GCM simulations with 25° obliquity. (B) Results for GCM simulations with 45° obliquity. In these calculations we assume a Noachian geothermal heat flux of 0.045 W/m².

Figure 6

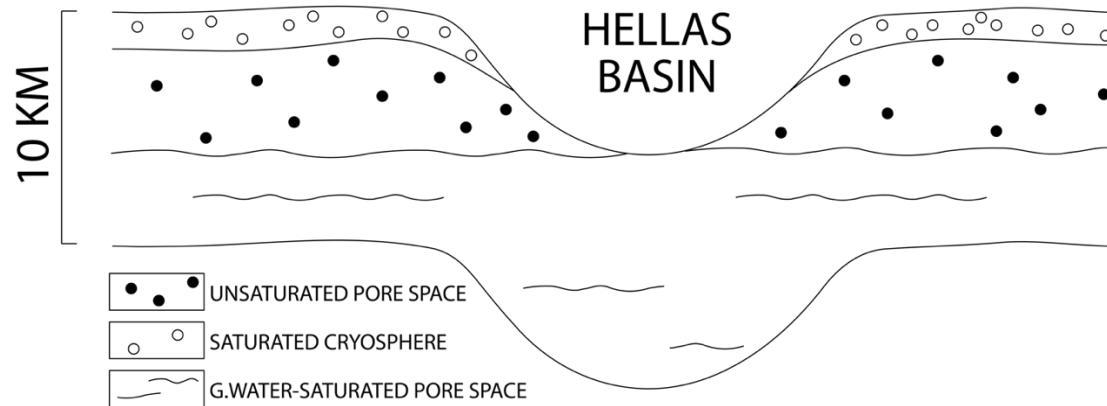


Fig. 6: Conceptual diagram showing groundwater release onto the floor of the Hellas basin. The groundwater table must be in contact with the bottom of the Hellas basin. Between the ice-cemented cryosphere and groundwater system is unsaturated pore space. The groundwater would release at the surface until the system reaches hydrostatic equilibrium. For the scenario where the groundwater table is in contact with the base of Hellas basin, as illustrated here, not much water would be required to release at the surface because the system would already be approximately in hydrostatic equilibrium.

Figure 7

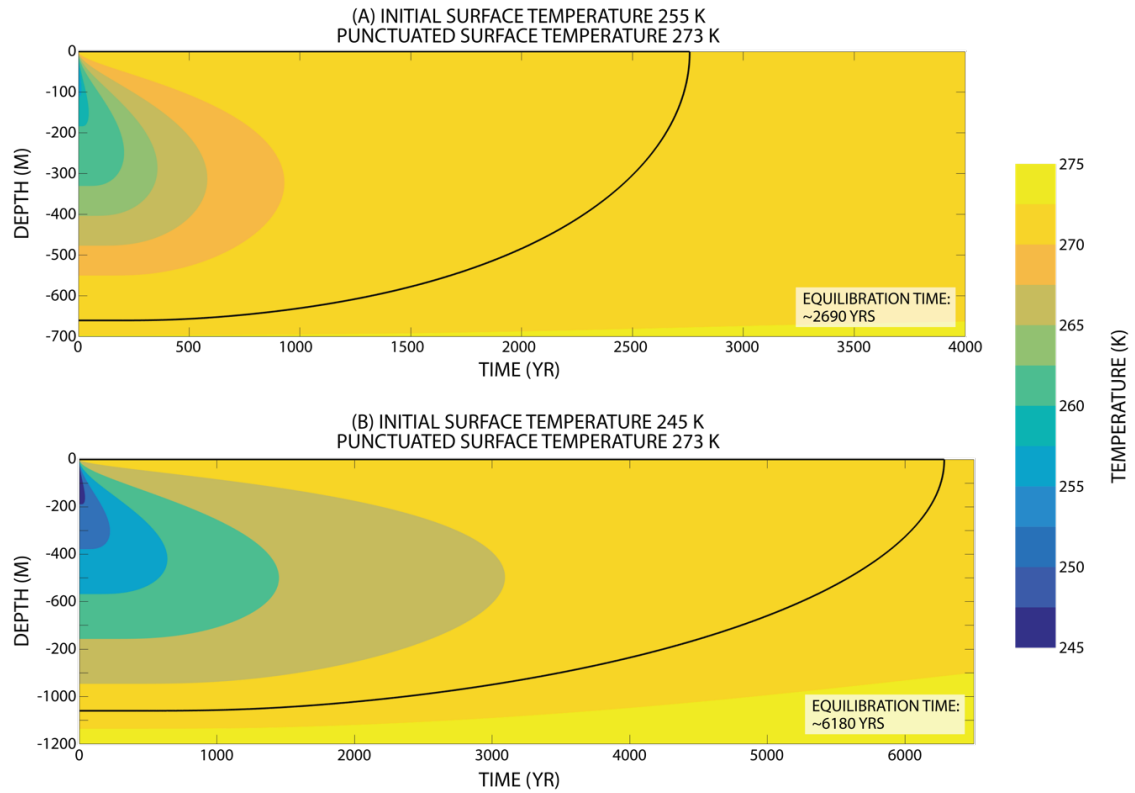


Fig. 7: Time required for the cryosphere to equilibrate to surface temperature perturbations. Local MAT 273 K punctuated climate example: Color-filled contours show temperature variations in the subsurface; black line is the 273 K contour, representing the base of the cryosphere. (A) Simulation with background climate initial surface temperature of 255 K. This simulation represents a punctuated heating event at the Hellas basin, where the local MAT in an ambient “cold and icy” climate is ~255 K (Figs. 3, 4). ~2690 consecutive years are required for the cryosphere disappear on the floor of the Hellas basin, permitting groundwater release. (B) Simulation with background climate initial surface temperature of 245 K, representing a punctuated heating event at Utopia Planitia, where the local MAT in an ambient “cold and icy” climate is ~245 K (Figs. 3, 4). ~6180 consecutive years are required for the cryosphere to

disappear in Utopia Planitia, permitting groundwater release. In these simulations we assume a Noachian geothermal heat flux of 0.065 W/m^2 .

Figure 8

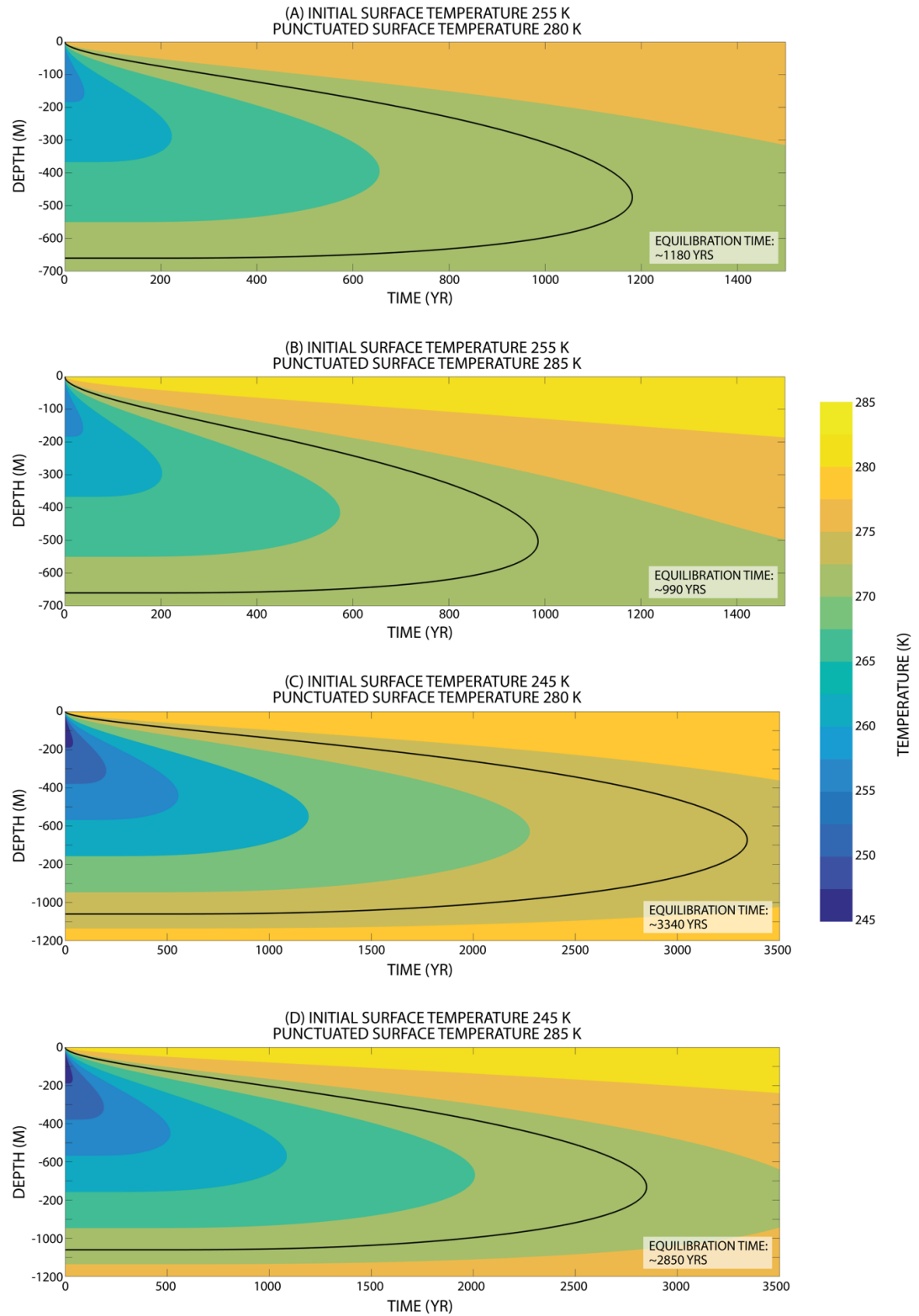


Fig. 8: Time required for the cryosphere to equilibrate to surface temperature perturbations. Here, we explore the scenario where the punctuated climate is characterized by local MAT higher than the simulations that are shown in Fig. 7: local MAT 280 K (A, C) and local MAT 285 K (B, D). Color-filled contours show temperature variations in the subsurface; black line is the 273 K contour, representing the base of the cryosphere. (A, B) Simulation with background climate initial surface temperature of 255 K, representing a punctuated heating event at the Hellas basin, where the local MAT in an ambient “cold and icy” climate is ~ 255 K (Fig. 3, 4). If local MAT is 280 K, ~ 1180 consecutive years are required for the cryosphere to disappear on the floor of the Hellas basin, permitting groundwater release; if local MAT is 285 K, ~ 990 consecutive years are required. (C, D) Simulation with background climate initial surface temperature of 245 K, representing a punctuated heating event at Utopia Planitia, where the local MAT in an ambient “cold and icy” climate is ~ 245 K (Figs. 3, 4). If local MAT is 280 K, ~ 3340 consecutive years are required for the cryosphere to disappear in Utopia Planitia, permitting groundwater release; if local MAT is 285 K, ~ 2850 consecutive years are required. In these simulations we assume a Noachian geothermal heat flux of 0.065 W/m^2 . Note that the duration required for the cryosphere to disappear is shorter than the simulations shown in Fig. 7 because the downward-penetrating thermal wave from the surface is stronger in the simulations with higher punctuated MAT, causing the cryosphere to disappear quicker.

CHAPTER EIGHT

OCEANS ON MARS: EXPLORING MECHANISMS FOR RECHARGE OF THE GROUNDWATER SYSTEM

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Abstract

Geological and empirical evidence suggests the presence of two oceans in the northern lowlands of Mars, including one in the Noachian and one in the Hesperian. The origin and fate of these large bodies of water is important to our understanding of the nature, evolution and state of the martian hydrologic system. Elevation estimates of the putative oceanic shorelines suggest that the two oceans contained hundreds of meters global equivalent layer (GEL) of water, ~650 and ~130 m GEL for the Noachian and Hesperian oceans, respectively. Both oceans are hypothesized to have formed via groundwater-release processes. Such large volumes of groundwater released twice in history underlines the importance of recharging the groundwater system. If significant volumes of water were released from the subsurface in the Noachian, such water must have been returned to the subsurface in order for it to be released again in the Hesperian. Further, if significant volumes of water were released from the subsurface in the Hesperian, such water must also have been returned to the subsurface because the present-day surface water inventory (~34 m GEL) is significantly less than estimates of the volume of the putative Hesperian ocean and it is unlikely that such large volumes of water were lost to space. In this work, we review proposed mechanisms for recharge of the groundwater system following the formation of both the Noachian and Hesperian oceans and then discuss the implications for the possibility of two sequential oceans and the hydrologic system as a whole. We find that all previously proposed mechanisms for recharge of the groundwater system are incapable of providing significant recharge, and suggest that either (1) if these oceans did exist, they may have formed through processes different

than those canonically considered, or (2) an additional recharge mechanism exists that has not been previously identified and quantified.

Keywords: Mars, climate; Mars, surface; Mars, atmosphere; Geological processes

1. Introduction

Multiple lines of evidence suggest that two oceans persisted in the northern lowlands of Mars, including one ocean in the Noachian and one ocean in the Hesperian. This evidence includes putative oceanic shorelines (e.g. Carr and Head, 2003; Clifford and Parker, 2001; Head et al., 1999; Parker et al., 1993, 1989), possible tsunami deposits (Costard et al., 2017; Rodriguez et al., 2016), and outflow channel events that catastrophically released huge amounts of groundwater to the surface (e.g. Baker et al., 1991). Note that evidence for the presence of these two oceans has been questioned on a number of grounds (Head et al., 2018). Both oceans are hypothesized to have formed through groundwater release processes, including a process similar to that of a groundwater-fed lake on Earth for the Noachian ocean (e.g. Clifford, 1993; Clifford and Parker, 2001; Palumbo and Head, 2019) and the catastrophic release of groundwater through cryosphere cracking and outflow channel formation for the Hesperian ocean (e.g. Baker et al., 1991; Clifford and Parker, 2001) (Fig. 1). The possibility of the release of large volumes of groundwater onto the surface multiple times implies that significant recharge of the groundwater system should have occurred, as detailed below.

Clifford (1993) and Clifford and Parker (2001) speculated that an ocean would have formed in the lowlands in the Noachian as a natural consequence of relatively warm Noachian climate conditions (e.g. Craddock and Howard, 2002). Considering a formation mechanism similar to that of a groundwater-fed lake on Earth, Palumbo and Head (2019) showed that the formation of a Noachian ocean in the northern lowlands and a contemporaneous sea in Hellas basin could occur if (1) global mean annual temperature (MAT) was >258 K for at least a few thousand consecutive years, and (2) there was more

than ~170 m global equivalent layer (GEL) of water in the subsurface. Because abundant evidence exists for warm conditions in the Noachian, including valley networks (e.g. Hynek et al., 2010), open- and closed-basin lakes (e.g. Fassett and Head, 2008; Goudge et al., 2015), and hydrous mineralogy (e.g. Bibring et al., 2006), it is possible that global MAT was >255 K for thousands of consecutive years in the Noachian. Additionally, the required subsurface water inventory of at least ~170 m GEL is consistent with an independent estimate of the Noachian subsurface water inventory derived from analyses of crater morphology (Weiss and Head, 2017); Weiss and Head (2017) estimated that the Noachian subsurface water inventory would have been more than 170 m GEL for reasonable porosity estimates. Thus, the climate and subsurface water volume requirements for the formation of a Noachian ocean could have been satisfied under this scenario, implying that an ocean could have formed in the Noachian through a process akin to that of a groundwater-fed lake on Earth.

If a Hesperian ocean formed by catastrophic release of groundwater through a cracked cryosphere (e.g. Baker et al., 1991; Clifford, 1993; Clifford and Parker, 2001), then there must have been a voluminous groundwater system in the Hesperian. Assuming that large volumes of water were removed from the groundwater system in the Noachian to form a Noachian ocean, such a voluminous Hesperian groundwater system requires that the groundwater system was recharged between the period in which a Noachian ocean existed at the surface and the time of the catastrophic release of groundwater that led to the formation of a Hesperian ocean (Fig. 1). Because the required conditions for the formation of a Noachian ocean could have been met (e.g. Palumbo and Head, 2019) and the outflow channels are geologic evidence for the formation of a Hesperian ocean

(Baker et al., 1991), there must be a plausible scenario for groundwater recharge such that the groundwater system contained abundant volumes of water in both the Noachian and Hesperian.

Further, the presence of a Hesperian ocean also requires that much of the oceanic water was returned to the subsurface. This is because (1) it is not possible that the large volumes of water contained in a Hesperian ocean (~130 m GEL based on shoreline estimates; Carr and Head, 2003) could be trapped within the present-day polar caps because the polar caps can only account for ~22 m GEL of water (Carr and Head, 2015) and, (2) it appears to be difficult to reconcile the loss to space of large volumes of water since the Hesperian (e.g. Jakosky, 1993; Jakosky et al., 2017; Lammer et al., 1996). Mars has a present-day surface/near-surface water inventory of ~34 m GEL (Carr and Head, 2015); the loss of approximately 100 m GEL of water to space is difficult to reconcile with various lines of evidence. For example, Lammer et al. (1996) extrapolate and integrate current atmospheric loss rates back in time and find it difficult to reconcile the loss to space of more than 5 m GEL in the past 3.5 billion years. Furthermore, oxygen isotopic measurements from the SNC meteorites suggest that no more than 25% of martian oxygen has been lost over geologic time (Jakosky, 1993); even if we assume that all of the escaped oxygen was within water molecules, such a derived estimate for the Noachian water inventory is significantly less than the ~130 m GEL required to fill the lowlands to the Hesperian shoreline (e.g. Carr and Head, 2003). While the MAVEN mission team is currently working to better estimate the Noachian water inventory by gaining a better understanding of current atmospheric loss rates and extrapolating back through time (e.g. Jakosky et al., 2017), these earlier studies (Jakosky, 1993; Jakosky et

al., 2017; Lammer et al., 1996) certainly suggest that the loss to space of >100 m GEL of water is unlikely. Because such large volumes of water are not consistent with the present-day surface/near-surface water inventory and are not consistent with loss to space, most or all of the oceanic water must have been returned to the subsurface.

In order to further test the Mars oceans hypotheses (e.g. Head et al., 2018), in this work we review possible groundwater system recharge mechanisms and discuss the likelihood that these mechanisms could bring significant recharge to the groundwater system after both the Noachian and Hesperian oceans (Section II), then discuss the implications of our assessment for the evolution of the martian hydrologic system and the presence of multiple oceans (Section III).

2. Discussion of possible recharge mechanisms

Studies of the formation, evolution, and fate of martian oceans have assumed that one or more groundwater system recharge mechanisms exist (e.g. Baker et al., 1991; Clifford, 1993, 1987). In this section, we (1) review the previously proposed groundwater system recharge mechanisms and (2) discuss the plausibility of these mechanisms as mechanisms to provide significant recharge to the groundwater system after the formation of the Noachian and Hesperian oceans. We undertake this analysis in light of the current state of understanding of the Noachian and Hesperian climate and surface/sub-surface water inventories. Previously proposed groundwater system recharge mechanisms include: (1) rapid infiltration into the regolith and groundwater system in the highlands, (2) basal melting beneath the polar caps, (3) basal melting beneath the Tharsis rise and Tharsis volcanoes, and (4) melting of surface and cryosphere ice and infiltration

to the subsurface from basal melting due to increased overburden pressure from lava loading (Fig. 2).

Rapid infiltration into the regolith and groundwater system in the highlands. After the groundwater had been released onto the surface of early Mars, either in the Noachian or in the Hesperian, the water would have become integrated into the surface global hydrologic cycle (e.g. Kreslavsky and Head, 2002; Turbet et al., 2017). The water would have evaporated from the lowlands ocean and reprecipitated in the highlands as either rain or snow, depending on the temperature at the location of precipitation. If average annual surface temperatures were above freezing in the highlands and, as such, the precipitation was rainfall, the rainfall could have infiltrated into the regolith and re-entered the groundwater system. However, if average annual surface temperatures were below freezing in the highlands and, as such, the precipitation was snowfall, the water would not have been able to infiltrate into the regolith and re-enter the groundwater system because the ground would have been frozen solid (e.g. there would have been a cryosphere), preventing the passage of the water through the regolith and into the groundwater system. Thus, in order to understand whether this is a plausible groundwater system recharge mechanism, we now consider the climate scenarios in which the putative oceans may have formed.

First, we consider the climate scenario in which the putative Noachian ocean may have formed and implications for the recharge of the groundwater system after the formation of a Noachian ocean. Early studies considered that the formation of a Noachian ocean would have been a natural consequence of significantly warmer conditions in the Noachian than today, which were expected to have existed because atmospheric pressure

was higher (e.g. Clifford, 1993). A more detailed treatment of the formation of a Noachian ocean, which includes a more recent and detailed implementation of possible Noachian climate conditions, provides insight into just how warm the climate would need to be in order for a Noachian ocean to have formed by groundwater release (Palumbo and Head, 2019). The Noachian ocean formation mechanism can be best described as that of a groundwater-fed lake or sea on Earth (Fig. 1) (e.g. Clifford, 1993; Clifford and Parker, 2001; Palumbo and Head, 2019): in areas where temperatures are above freezing and the groundwater table is sufficiently high such that it intersects the surface, groundwater can be released onto the surface and form a lake or sea. It is important to note, then, that there are two key requirements for the formation of a groundwater-fed lake or sea. First, local temperatures must be above freezing. If temperatures are below freezing, the ground will freeze and trap the groundwater in the subsurface, preventing the formation of a groundwater-fed lake or sea. Second, there must be a sufficient amount of water in the groundwater system such that the groundwater table intersects the surface. If the groundwater table does not intersect the surface, the groundwater cannot be released onto the surface and a groundwater-fed lake or sea will not form.

Palumbo and Head (2019) used a 3D global climate model (GCM) to explore the conditions in which a Noachian ocean could have formed through groundwater release similar to that of a groundwater-fed lake or sea on Earth by determining (1) the coldest possible global mean annual temperature (MAT) in which local MAT somewhere in the lowlands of Mars would have been above freezing, which satisfies the temperature requirement for this groundwater release mechanism, and (2) the necessary subsurface water inventory for the groundwater table to intersect the surface at that location in the

lowlands, which satisfies the groundwater volume requirement for this groundwater release mechanism. Palumbo and Head (2019) found that (1) a subsurface water inventory of at least ~ 170 m GEL is required for groundwater release to have been possible in the northern lowlands in the Noachian, and (2) a Noachian ocean could have formed in the northern lowlands in climates as cold as global MAT ~ 258 K, far below the melting point of water. Groundwater release in the lowlands would have been possible in these very cold climate scenarios because, in the Noachian, when atmospheric pressures were higher than today, the atmosphere and surface would have been thermally coupled and, as a result, temperature variation would have been dominantly dependent on altitude instead of latitude (Forget et al., 2013; Wordsworth et al., 2013). Thus, the highest altitude regions would have been significantly colder than the lowest altitude regions and, although the global MAT may have been well below freezing, local MAT in the lowest elevation parts of the planet may have been above freezing. As a result, models suggest that groundwater release in the lowlands and formation of a Noachian ocean could have been possible even in climates with global MAT well below freezing (Palumbo and Head, 2019).

Although it is of course possible that the ambient Noachian climate was significantly warmer than these conditions of global MAT ~ 258 K (e.g. Craddock and Howard, 2002; Ramirez and Craddock, 2018; Ramirez, 2017), or that the climate was periodically significantly warmer, we cannot discount the possibility that a Noachian ocean formed in a globally-averaged sub-freezing climate. This is especially true because GCMs have difficulty reproducing very warm conditions for early Mars (e.g. Forget et al., 2013; Wordsworth et al., 2013) due to the reduced solar insolation from the faint young Sun

(Gough, 1981), when considering reasonable estimates for spin-axis/orbital conditions (Laskar et al., 2004) and greenhouse gas concentrations (see review in Forget et al., 2013). Further, it is important to note that the model-predicted local MAT in much of the highlands remains below freezing even for simulations with global MAT ~ 273 K (e.g. Palumbo and Head, 2018).

Recall that this recharge mechanism calls on infiltration of surface water through the regolith in the highlands and into the groundwater system, which fundamentally requires that the surface and shallow subsurface in the highlands not be frozen (e.g. no cryosphere). Thus, if a Noachian ocean formed in the lowlands in a climate in which local MAT in the highlands was below freezing, which would be true for a wide range of possible climate scenarios from very cold (global MAT $\ll 273$ K) to relatively warm (global MAT ~ 273 K), recharge of the groundwater system would not be possible by infiltration of the water through the regolith in the highlands because of the presence of a cryosphere. Specifically, for climates in which the local MATs in the highlands would have been below freezing, the evolution of the Noachian oceanic water in the hydrologic system can be described in the following set of steps: (1) the body of water, which may have rapidly frozen, would have evaporated/sublimated and entered the surface hydrologic system, (2) the water would have been precipitated into the highlands as snow, instead of rain, because local MAT in the highlands would have been below freezing, and (3) the snow would have accumulated in the highlands and not infiltrated through the regolith because the surface would have been frozen. Thus, this recharge mechanism is only plausible for very warm climate scenarios (global MAT $\gg 273$ K) in which the highlands would have had local MAT above freezing. Because of these

potentially unlikely climatic conditions (e.g. Forget et al., 2013; Wordsworth et al., 2013), we consider this mechanism to be an unlikely candidate for significant recharge of the groundwater system following formation of a Noachian ocean.

Next, we consider the climate scenario in which the putative Hesperian ocean may have formed and implications for the recharge of the groundwater system after the formation of a Hesperian ocean. The formation of a Hesperian ocean requires cracking of a globally-continuous cryosphere and catastrophic release of groundwater onto the surface (e.g. Andrews-Hanna and Phillips, 2007; Baker et al., 1991; Carr and Head, 2019, 2003; Clifford and Parker, 2001). The presence of a globally-continuous cryosphere requires MAT to be below freezing everywhere on the planet. Thus, the ambient background climate at the time of the cracking of the cryosphere and the formation of a Hesperian ocean was characterized by MAT below freezing everywhere on the planet, implying that the surface and shallow subsurface of the highlands was frozen (e.g. there was a cryosphere) and that infiltration was not possible. However, it has been proposed that the climate could have changed as the ocean formed due to the release of climate-warming gases (e.g. Baker et al., 1991), potentially leading to relatively warmer temperatures in the highlands. In order to understand whether this recharge mechanism could have provided significant recharge to the groundwater system after the formation of a Hesperian ocean, we thus also need to consider the climate conditions during the time that the ocean was on the surface. Specifically, we need to explore whether the climate could have warmed significantly after the formation of a Hesperian ocean, which would be required in order for the groundwater to have been able to have infiltrated through the regolith in the highlands and back into the groundwater system.

Some researchers have proposed that the formation of a Hesperian ocean may have been linked with Hesperian-aged volcanism (Baker et al., 1991), which would have released abundant gases into the martian atmosphere. Although these volcanic gases, including sulfur-based gases, are greenhouse agents and could have led to atmospheric warming, many studies have shown that the amount of warming from these sulfur-based gases is not sufficient to increase global MAT to >273 K when considering reasonable gas concentrations and Hesperian spin-axis/orbital conditions (e.g. Halevy and Head, 2014; Johnson et al., 2008; Kerber et al., 2015; Mischna et al., 2013; Tian et al., 2010), implying that temperatures in the highlands are likely to have been below freezing during the lifetime of the Hesperian ocean. Thus, even if the formation of the Hesperian ocean was linked with volcanic outgassing, temperatures in the highlands would still have been below freezing and infiltration of water into the regolith in the highlands would not have been possible.

In addition, recent studies have implemented various mathematical and modeling approaches to study the formation and evolution of a Hesperian ocean (e.g. Carr and Head, 2019; Kreslavsky and Head, 2002; Turbet et al., 2017). These studies confirmed that the planet must have been very cold at the time of the formation of the Hesperian ocean, if the Hesperian ocean formed through cryospheric cracking and outflow channel activity, and showed further that the climate would have remained cold after ocean formation (Kreslavsky and Head, 2002; Turbet et al., 2017), preventing the return of the water into the subsurface through infiltration of water into the regolith in the highlands.

Because temperatures above freezing in the highlands at the time of a Hesperian ocean seem unlikely and not plausible, we consider this mechanism to be an unlikely

candidate for significant recharge of the groundwater system after formation of a Hesperian ocean.

Of course, very warm periods subsequent to the formation of the Noachian and/or Hesperian ocean, unrelated to the formation/presence of the oceans, may have existed. These warm periods may have been characterized by warmer temperatures in the highlands, which would permit global integration of the subsurface and surface hydrologic systems and recharge of the groundwater system. In this possible scenario of a very warm period subsequent to the formation of the Noachian and/or Hesperian ocean, the oceanic water may have stayed on the surface and been a part of the surface hydrologic cycle for some period of time, then a very warm period persisted in which temperatures in the highlands were above freezing and the water was capable of infiltrating through the regolith and re-entering the groundwater system. Such a period of warm conditions has been suggested based on analyses of the mineral deposits in Meridiani Planum (e.g. Andrews-Hanna et al., 2007), the formation of which may have required very warm conditions, integration of the subsurface and surface hydrologic systems, and rainfall in the equatorial regions and highlands.

Basal melting beneath the polar caps. Basal melting is the process by which (1) the melting point of water decreases under higher pressure conditions, permitting the melting of water at relatively lower temperatures beneath thick glaciers, and (2) the ice melting geotherm at depth becomes shallower, possibly intersecting the cryosphere or surficial ice deposits. Clifford (1987) explored the possibility that basal melting could be possible beneath the polar caps on Mars, as both melting of surface ice and melting of ice in the pore space of the cryosphere. The melted surface and cryosphere ice would infiltrate

downward through the regolith and enter the groundwater system (Clifford, 1980). Using a simple thermal model, Clifford (1987) explored a range of thermal conductivities, assumed local MAT of 157 K at the poles, and considered a geothermal heat flux of 30 mW/m². Clifford (1987) found that polar cap thicknesses ranging from 2-10 km, depending on the parameter values used, would be required for basal melting to occur. Clifford (1980) proposed that, if this polar cap thickness condition was satisfied, basal melting beneath the polar cap(s) could have recharged the groundwater system.

While it is certainly plausible that some water could re-enter the groundwater system through this mechanism if the conditions required for this mechanism were met (e.g. Clifford, 1980), it is necessary to consider, the consequences, that is, the amount of water that could re-enter the groundwater system. We thus assess the following question: Does this mechanism provide an amount of water infiltration sufficient to recharge the groundwater system completely, only partially, or not at all? For the case of a polar cap that is thick enough to permit basal melting, as the thickness of the polar cap decreases (for example, because the base of the polar cap was melted and the meltwater infiltrated into the subsurface), basal melting is no longer possible; after the polar cap decreases to a thickness less than ~2 km, basal melting would cease (Clifford, 1987). Thus, it would only be possible to get a volume of water equivalent to that released from the groundwater system back into the groundwater system if the polar cap was already approximately thick enough to initiate basal melting before the groundwater was released and deposited as snow/ice on top of the pre-existing polar cap. Additionally, after the oceanic water entered the hydrologic system, it must have been deposited as snow/ice at the poles; if it was deposited elsewhere, it would not have been part of basal melting at

the poles and thus could not have contributed to the return of an equivalent volume of water to the groundwater system through this mechanism. With these constraints in mind, we can explore the possible amount of groundwater recharge that could have occurred from this mechanism following the formation of both the Noachian ocean and the Hesperian ocean.

First, we consider recharge of the groundwater system following the formation of a Noachian ocean. As previously described, under the influence of relatively high Noachian atmospheric pressures, surface temperatures were controlled by altitude, not latitude (e.g. Forget et al., 2013; Wordsworth et al., 2013). As a result, snow/ice would have been deposited in the colder, higher altitude regions, the southern highlands (e.g. Wordsworth et al., 2013). Thus, snow/ice is expected to have accumulated at the south polar cap, because snow/ice is expected to have been distributed across the southern highlands. However, snow/ice is not expected to have accumulated at the north pole, because snow/ice is not predicted to have been distributed across the northern lowlands (e.g. Wordsworth et al., 2013). Thus, basal melting at the north polar cap would not have been possible, but basal melting at the south polar cap may have been possible.

If significant volumes of snow/ice accumulated at the south polar cap, basal melting and at least some recharge of the groundwater system could have been possible. However, as previously mentioned, in order for full recharge of the groundwater system to be possible, the initial thickness of the south polar cap, before the formation of the ocean, would have had to have been approximately equal to the limit to initiate basal melting (2-10 km, Clifford, 1987) and all water would have to have been deposited at the pole alone, so that a volume of water equivalent to that released from the groundwater

system could have been returned to the subsurface through this mechanism. Thus, a brief discussion of the current state of understanding of the Noachian water inventory and predicted ice sheet thicknesses and distributions can provide insight into whether basal melting at the south polar cap could have led to significant recharge of the groundwater system.

Carr and Head (2015) estimated that the Noachian surface/near-surface water inventory was ~24 m global equivalent layer (GEL); this estimate does not include the subsurface water inventory (e.g. liquid groundwater and ice trapped in the cryosphere). In a “cold and icy” Noachian climate, most surface/near-surface water would have been trapped as surface snow/ice in the highlands (e.g. Head and Marchant, 2014; Wordsworth et al., 2013). If the water was distributed across approximately half the planet as ice, then the average ice thickness would have been ~48 m. Some variation in ice thickness is probable, given variations in precipitation, accumulation, and melt patterns across the planet. Even if we assume variation in ice thickness of a factor of three or so across the southern highlands, it is difficult to reconcile ice thicknesses sufficient to initiate basal melting in the highlands (e.g. Fastook and Head, 2015). As a result, following the formation of a Noachian ocean, our basic calculations suggest that complete recharge of the groundwater system through this mechanism is unlikely.

It is important to note that there is evidence for basal melting of an ancient south polar ice sheet, the remnants of which form the Dorsa Argentea Formation, in the Noachian/Hesperian (e.g. Fastook et al., 2012; Head and Pratt, 2001; Kress and Head, 2015; Scanlon et al., 2018). This evidence includes eskers and associated valleys (Head and Pratt, 2001; Kress and Head, 2015) and the size and morphology of these features

suggests that the melting was significant in volume and areally widespread (Head and Pratt, 2001). Analyses of the climate, water inventory, and ice dynamics associated with the formation and subsequent basal melting of this south polar ice sheet show that, for reasonable surface water inventories, basal melting would not be possible in a pure CO₂, “cold and icy” climate (global MAT ~225 K), but that basal melting would be possible under slightly warmer conditions (global MAT >225 K but <273 K) (Fastook et al., 2012; Scanlon et al., 2018). Thus, the Dorsa Argentea Formation provides evidence that at least some basal melting did occur during a time when temperatures were warmer than the background “cold and icy” climate, but not necessarily “warm and wet”. Such evidence suggests that basal melting of a south polar ice sheet and recharge of the groundwater system was possible, but water inventory estimates still suggest that the volume of recharge would have been small.

Next, we consider whether some recharge of the groundwater system is possible through this mechanism, although complete recharge through this mechanism does not appear to have been possible. Even if we assume that the thickness of ice could have varied significantly across the southern hemisphere, an average ice thickness in the southern hemisphere of 48 m GEL is difficult to reconcile with the requirement for ice thicknesses of ~2 km in the south polar region to initiate basal melting (Clifford, 1987). The amount of water in the Noachian ocean could have been as much as ~600 m GEL (if one accepts the Arabia shoreline, Parker et al. (1989), and its implied volume, Carr and Head (2003)). If we consider that this volume of water would have eventually been redeposited in the highlands as snow and ice, we can estimate that the snow/ice in the highlands would become ~1200 m thicker, on average, than before the formation of a

Noachian ocean and the addition of this snow/ice to the highlands. Spatial variations in this newly-deposited snow and ice, paired with spatial variations in the pre-existing snow and ice, could have reasonably led to a total possible ice thickness of ~ 2 km and, thus, possible basal melting. However, given reasonable estimates of the pre-ocean surface water inventory and the volume of oceanic water, significant amounts of basal melting would not be expected because the total ice thickness is expected to be only slightly more than 2 km thick (Clifford, 1987). As a result, the entire volume of water that was released from the groundwater system to the surface in order to form a Noachian ocean could not have been returned to the subsurface through this mechanism; a small amount of basal melting at the south polar cap may have occurred, resulting in a decrease in the overburden pressure of the ice, and then basal melting would have no longer been possible. Thus, although a small amount of basal melting and recharge of the groundwater system is possible through this mechanism, we consider this mechanism an unlikely candidate for significant recharge of the groundwater system after formation of a Noachian ocean.

Another important reason as to why south polar basal melting could not have sufficiently recharged the groundwater system after the formation of a Noachian ocean is the elevation of the south polar cap relative to the elevation of the heads of the outflow channels (e.g. Carr, 2002; Russell and Head, 2007). Specifically, as pointed out by Carr (2002), because the outflow channel sources are at a higher elevation than the south polar cap, it would have been impossible for the groundwater system to have been sufficiently recharged through this mechanism such that the groundwater table was raised to the elevation of the outflow channel sources. We conclude that even if the snow and ice

thickness at the south pole was sufficient to induce basal melting (e.g. Fastook et al., 2012; Head and Pratt, 2001; Kress and Head, 2015; Scanlon et al., 2018) this mechanism could not have produced sufficient hydrostatic head to promote the transport of groundwater to the elevations of the outflow channel sources (Carr, 2002; Cassanelli et al., 2015; Russell and Head, 2007).

Next, we consider recharge of the groundwater system following the formation of a Hesperian ocean. Studies of the formation and evolution of a Hesperian ocean have shown that such an ocean, if produced in a cold enough environment to have a globally-continuous cryosphere, would rapidly freeze, sublimate, and be redeposited as snow and ice in the highlands (e.g. Kreslavsky and Head, 2002; Turbet et al., 2017). As previously mentioned, Carr and Head (2015) estimated that the near surface water inventory at this time was ~24 m GEL, which could lead to average ice thicknesses of ~48 m in the highlands. We speculated that variations in ice thickness could have led to some areas in the highlands having ice thicknesses of more than 48 m, but probably significantly less than the 2 km required to initiate basal melting. The Deuteronilus shoreline is at a lower elevation than the Arabia shoreline and, thus, the Hesperian ocean (Deuteronilus shoreline) would have contained less water than the Noachian ocean (Arabia shoreline) (Carr and Head, 2003). Therefore, our conclusion regarding recharge of the groundwater system through this mechanism after formation of a Noachian ocean applies here, as well: a small amount of basal melting and recharge of the groundwater system after the formation of a Hesperian ocean is possible through this mechanism, but this mechanism is an unlikely candidate for significant recharge of the groundwater system after formation of a Hesperian ocean.

Basal melting beneath the Tharsis rise and Tharsis volcanoes. The fact that basal melting at the south polar cap could not have reasonably recharged the groundwater system to the elevation of the outflow channels after the formation of a Noachian ocean and before the formation of a Hesperian ocean (Carr, 2002; Russell and Head, 2007), led researchers to consider other possible areas of basal melting that could have provided sufficient hydrostatic head and recharge of the groundwater system to the elevation of the outflow channels. Specifically, the Tharsis rise is higher in elevation than the heads of the outflow channels, unlike the south polar region, and thus provides the opportunity for easier recharge of the groundwater system to the elevation of the outflow channels if basal melting were to occur on the Tharsis rise. Specifically, Harrison and Grimm (2004) used groundwater models to explore whether groundwater recharge at the Tharsis rise could provide sufficient recharge flux and hydrostatic head to recharge the groundwater system to the elevation of the heads of the outflow channels. They determined that such a recharge mechanism was plausible under certain circumstances (e.g. high obliquity to permit the deposition of thick ice sheets on the Tharsis rise) (Harrison and Grimm, 2004). Thus, if significant ice thicknesses existed on the Tharsis Montes, basal melting and recharge of the groundwater aquifer could have been possible (Russell and Head, 2007) in the time between the formation of a Noachian ocean and the formation of a Hesperian ocean.

The Tharsis Montes are a region of predicted ice accumulation in “cold and icy” climate model simulations (e.g. Wordsworth et al., 2013), suggesting that this mechanism for recharge of the groundwater system could have been significant (Cassanelli et al., 2015) after the formation of both the Noachian ocean and the Hesperian ocean. Cassanelli

et al. (2015) used thermal models to explore the possibility of basal melting at the Tharsis Montes under “cold and icy” Noachian conditions, assuming a range of geothermal heat flux and surface ice thickness values. Here, we highlight their results to describe the plausibility of basal melting at the Tharsis Montes as a mechanism for recharge of the groundwater system. In our discussion of this recharge mechanism, we first consider recharge of the groundwater system following the formation of a Hesperian ocean, because this is what Cassanelli et al. (2015) specifically tested, and then we consider recharge of the groundwater system following the formation of a Noachian ocean.

Cassanelli et al. (2015) found that, following the formation of a Hesperian ocean, for reasonable ice sheet thicknesses and geothermal heat flux values, only a small amount of basal melting and recharge of the groundwater system is possible; widespread basal melting is not expected to occur on the Tharsis rise. Specifically, they found that the geothermal heat flux beneath active volcanoes might be sufficient to cause basal melting and drainage of meltwater into the groundwater system (the heat pipe-drain pipe model), but the size and persistence of these individual thermal anomalies was insufficient to cause significant recharge of the groundwater system. Thus, this mechanism is judged to be an unlikely candidate for significant recharge of the groundwater system after formation of a Hesperian ocean.

Next, we consider recharge of the groundwater system following the formation of a Noachian ocean. This recharge mechanism is especially compelling because it offers a plausible explanation for providing sufficient recharge flux and hydrostatic head to raise the groundwater table to the elevation of the outflow channel sources. Although the work of Cassanelli et al. (2015) focused on the recharge of the groundwater system after

formation of a Hesperian ocean, we can discuss their results in the context of a Noachian ocean because this mechanism is dependent on climate; Cassanelli et al. (2015) considered a “cold and icy” climate, which can be applied to both the time subsequent to the Noachian ocean and subsequent to the Hesperian ocean. Significant variations in climate and ice thickness on the Tharsis Montes is not expected in the Noachian in comparison to the Hesperian because topography (Fassett and Head, 2011) and obliquity (Laskar et al., 2004) may have been similar. Therefore, we suggest that the same conclusion would apply: although some recharge of the groundwater system is possible, this mechanism is an unlikely candidate for significant recharge of the groundwater system following formation of a Noachian ocean.

Melting of surface and cryosphere ice and infiltration to the subsurface from basal melting due to increased overburden pressure from lava loading. Cassanelli and Head (2016) explored the thermal implications of the emplacement of large volumes of lava on the early martian surface. Specifically, they assumed that the climate was “cold and icy”, consistent with predictions from Noachian and Hesperian climate model results (e.g. Forget et al., 2013; Wordsworth et al., 2013), and quantitatively studied (1) the amount of meltwater that would be produced from top-down melting of surface snow and ice, and (2) the possibility of bottom-up melting from the increased overburden pressure due to the thick layer of lava and associated raising of the ice-melting isotherm into the ice-cemented cryosphere and ice, both of which could lead to infiltration of meltwater into the regolith and recharge of the groundwater system. The calculations and parameter space exploration by Cassanelli and Head (2016) led to the following conclusions related to recharge of the groundwater system: (1) raising of the ice-melting isotherm is

inevitable under these conditions, but thick layers of lava are required in order for the melting isotherm to raise through the cryosphere and into the surface ice sheet (~2 km thick or greater), (2) if the isotherm raises into the cryosphere but not the surface ice sheet, melting of ice in the cryosphere pore space will occur and this water will enter the groundwater system, albeit the volume being small (pore ice is typically much less than 20% of the cryosphere volume), (3) considering reasonable lava thicknesses, the thickness of the layers of lava is only likely to be sufficient to cause basal melting of the surface ice sheet in areas where the lava can pond at the surface, such as within craters, and, as a result the volume of meltwater and contribution to the groundwater system is likely to be small. Thus, although Cassanelli and Head (2016) showed that groundwater recharge through this mechanism is possible, especially because abundant volcanism and lava emplacement occurred during the Noachian and Hesperian at Tharsis and elsewhere (e.g. Head et al., 2002), the volumes of water contributed to the groundwater system from this mechanism are likely to have been volumetrically insignificant in comparison to the volumes of the oceans. For this reason, we consider this mechanism an unlikely candidate for significant recharge of the groundwater system after formation of both the Noachian and Hesperian oceans.

3. Implications for evolution of the martian hydrosphere

We explored the proposed mechanisms for recharge of the groundwater system following the release of large volumes of groundwater during the formation of both the proposed Noachian and Hesperian oceans: (1) rapid infiltration into the regolith and groundwater system in the highlands, (2) basal melting beneath the polar caps, (3) basal

melting beneath the Tharsis rise and Tharsis volcanoes, and (4) melting of surface and cryosphere ice and infiltration to the subsurface from basal melting due to increased overburden pressure from lava loading (Fig. 2). We reviewed each of the proposed mechanisms for recharge of the groundwater system, focusing on whether the mechanism could have provided significant groundwater recharge following both the Noachian and Hesperian ocean formation. In this section, we highlight the implications of our assessment for our understanding of the evolution of the martian hydrosphere.

With regard to a Noachian ocean, a recharge mechanism capable of placing most of the Noachian oceanic water back into the subsurface is critical for the following key reason: the outflow channels are commonly cited as evidence for the catastrophic release of large amounts of water from the subsurface in the Hesperian and the groundwater system must have been recharged after the formation of a Noachian ocean in order to explain a sufficient subsurface water inventory to form the outflow channels. However, our assessment of the four key recharge mechanisms suggests that significant recharge of the groundwater system after the formation of a Noachian ocean was unlikely. This finding has important implications for our understanding of the evolution of the martian hydrosphere and the formation and evolution of a Noachian ocean, which we outline below.

- (1) It is possible that the Noachian ocean never formed. A means to significantly recharge the groundwater system after the formation of a Noachian ocean such that the groundwater system is recharged to the elevation of the outflow channel heads is required in order to reconcile the evidence for outflow channel formation through groundwater release. Thus, if such a recharge mechanism does not exist,

one possible conclusion is that the Noachian ocean never formed. Evidence for a Noachian ocean has been questioned (e.g. [Head et al., 2018](#)) and no conclusive geomorphic evidence has been presented. However, Palumbo and Head (2019) found that the two key requirements for the formation of a Noachian ocean through groundwater release could have been met is global MAT Was $> \sim 258$ K for thousands of consecutive years and $> \sim 170$ m GEL of groundwater existed in the subsurface. Such climate conditions might be reconciled with evidence for a warmer Late Noachian climate (e.g. [Craddock and Howard, 2002](#); [Ramirez and Craddock, 2018](#)), including the valley networks (e.g. [Hynek et al., 2010](#)) and open- and closed-basin lakes (e.g. [Cabrol and Grin, 1999](#); [Fassett and Head, 2008](#); [Goudge et al., 2015](#)). However, these geomorphic features could also have formed through multiple short warm pulses, instead of long-lived ambient warm conditions, as is required for the formation of a Noachian ocean. Thus, the presence of these geomorphic features does not directly imply the formation of a Noachian ocean. The required subsurface water volume for formation of a Noachian ocean can be reconciled with another study that found that, independent of an ocean, the subsurface was likely to have contained $> \sim 170$ m GEL in the Late Noachian (Weiss and Head, 2017). Thus, a conclusion that the Noachian ocean never formed would require that (1) global MAT was never $> \sim 258$ K in the Noachian for thousands of consecutive years, and/or (2) the subsurface contained < 170 m GEL of groundwater in the Noachian. If the subsurface water inventory was < 170 m GEL, an additional problem arises: the Hesperian subsurface water inventory had to be > 170 m GEL in order to explain

the elevation of the heads of the outflow channels, and we have shown that adding groundwater to the groundwater system between the Noachian and Hesperian is unlikely. Thus, if the outflow channels formed through cracking of the cryosphere and groundwater release, the only plausible reason for the Noachian ocean to have never formed would be that global MAT was never $> \sim 258$ K for thousands of consecutive years in the Noachian. This conclusion would have additional important implications for the evolution of Mars as a habitable environment and the environment and formation processes of the valley networks and lakes.

- (2) It is possible that the outflow channels did not form through cracking of the cryosphere and groundwater release but instead through overland flow from melting of thick ice sheets due to top-down melting following the emplacement of thick lava loads (Cassanelli et al., 2015). In this scenario, the return of the Noachian oceanic water to the subsurface is not required for the formation of the outflow channels and Hesperian ocean. However, the present surface/near-surface water inventory is much smaller than the volume of the Noachian ocean (34 m GEL and ~ 600 m GEL, respectively), implying that either (1) extremely large volumes of water must have been lost to space or (2) the Noachian ocean was indeed present in the lowlands but the Arabia shoreline is not actually a Noachian oceanic shoreline and the ocean contained a much smaller volume of water. As previously discussed, the loss of such large volumes of water to space is difficult to reconcile with current data, suggesting that the latter option is more likely. However, it is important to note this alternative hypothesis for outflow

channel formation through lava loading and top-down melting also has some qualifications; Cassanelli et al. (2015) found that the predicted meltwater fluxes are likely to have been too low to explain the bankfull flow morphology of the outflow channels inferred by some workers, unless the meltwater ponded prior to catastrophic release.

- (3) It is possible that a very warm phase occurred sometime after the formation of a Noachian ocean, characterized by mean annual temperature above freezing on most of the planet, including the highlands. Under the influence of these very warm conditions, there would be no cryosphere on most of the planet and the hydrologic cycle would become vertically integrated, with possible transport of water between the surface and subsurface, including infiltration of surface water through the regolith and into the groundwater system. If we assume that the ambient conditions were “cold and icy”, then this very warm interval would have to have persisted for thousands to tens of thousands of years in order for the thermal wave to remove the cryosphere and permit vertical integration of the hydrologic cycle (e.g. Palumbo and Head, 2019). This proposed very warm phase might be consistent with, for example, the mineralogical evidence identified by the Opportunity rover at Meridiani Planum (Andrews-Hanna et al., 2010, 2007; Christensen et al., 2004). The evaporites in Meridiani Planum are compelling because they show evidence of ponding of water and later drying out of the area but are not located within a topographic basin; typical lake processes are not expected in this environment. Specifically, Andrews-Hanna et al. (2007) interpreted the mineralogy as being due to multiple cycles of a rising

groundwater table reaching the surface and resultant cycles of wetting and drying. Such integration of the groundwater system and surface requires local $\text{MAT} > 273 \text{ K}$ at Meridiani Planum, which is located in the southern highlands. Thus, the minerals within Meridiani could be consistent with a proposed long-lived very warm phase, characterized by above-freezing temperatures in the highlands. However, the Andrews-Hanna et al. (2007) model required these very warm conditions to persist more for longer than tens of millions of years.

Under what conditions could such a long and very warm phase occur? It is not likely to have been caused by natural spin-axis/orbital variations because no plausible obliquity and eccentricity conditions for the Noachian produce above-freezing local MAT in the highlands (e.g. [Forget et al., 2013](#); [Palumbo et al., 2018](#)). Instead, these conditions may have been caused by a punctuated heating event. One specific example of a punctuated heating event that could plausibly increase MAT to above freezing in the highlands for thousands to tens of thousands of years is the release of hydrogen or methane into the atmosphere ([Ramirez et al., 2014](#); [Turbet et al., 2019](#); [Wordsworth et al., 2017](#)), which could have been introduced through volcanism ([Ramirez, 2017](#); [Ramirez et al., 2014](#)) or serpentinization (e.g. [Holm et al., 2015](#)). It is important to note that these time scales fall short of the time required to satisfy the Andrews-Hanna et al. (2007; 2010) model for the evolution of Meridiani Planum.

- (4) It is possible that an additional groundwater recharge mechanism exists but has not yet been identified and quantified. If (1) the Noachian ocean did in fact exist, (2) the Hesperian outflow channels did in fact form through cryosphere cracking

and groundwater release, and (3) a very warm phase never occurred after the formation of the Noachian ocean (e.g. options 1-3 are not true), some groundwater recharge mechanism must have been acting to return the Noachian oceanic water to the groundwater system before the period of Hesperian outflow channel activity. Because none of the mechanisms described here are likely to have sufficiently recharged the groundwater system, we need to consider that at least one additional groundwater recharge mechanism may have existed. Future work should aim to identify and quantify additional mechanisms for recharge of the groundwater system after formation of a Noachian ocean.

With regard to a Hesperian ocean, a recharge mechanism capable of returning most of the Hesperian oceanic water to the subsurface is critical for the following reason: the average elevation of the Deuteronilus shoreline would require that the Hesperian ocean contained ~130 m GEL of water (Carr and Head, 2003), which is significantly more than the present-day surface water inventory, implying that most or all of that water was either returned to the subsurface or lost to space. Estimates for the amount of water lost to space in recent martian history (e.g. Jakosky et al., 2017) are inconsistent with the loss of >~100 m GEL water to space since the Hesperian. Thus, if ~130 m GEL of water was ponded in the lowlands in the Hesperian, it must have been returned to the subsurface. This finding has important implications for our understanding of the evolution of the martian hydrosphere and the formation and evolution of a Hesperian ocean, which we outline below.

- (1) The outflow channels did not form through cryosphere cracking and groundwater release. As outlined above, it is possible that the outflow channels formed through

melting of surface ice and runoff (Cassanelli et al., 2015), instead of cryosphere cracking and groundwater release. Although this mechanism has some qualifications that have been identified and quantified (Cassanelli et al., 2015) such as meltwater fluxes that are potentially too low to explain the apparently bankfull morphology of the outflow channels, this mechanism offers an alternate means of outflow channel formation that does not rely on large volumes of water being released from the groundwater system. Future work should consider this mechanism, as well as exploring other mechanisms, that may explain the outflow channel morphology without the addition of large volumes of groundwater to the surface/near-surface water inventory.

- (2) An additional recharge mechanism exists that has not yet been identified and quantified: If the outflow channels and Hesperian ocean did in fact form from the catastrophic release of groundwater from the subsurface (e.g. option 1 is not true), and recent estimates are accurate which suggest that the loss to space of ~100 m GEL water or more is not likely (e.g. Jakosky, 1993; Lammer et al., 1996), then an additional groundwater system recharge mechanism must exist. Future work should aim to identify and quantify additional mechanisms for recharge of the groundwater system after formation of a Hesperian ocean.

4. Conclusions

We have explored the various proposed mechanisms for recharge of the martian groundwater system, including rapid infiltration into the regolith in the highlands, basal melting beneath the polar caps, basal melting beneath the Tharsis rise and Tharsis

volcanoes, and melting of surface and cryosphere ice and infiltration to the subsurface from basal melting due to increased overburden pressure from lava loading (Fig. 2). Specifically, we focused on estimating whether any of these mechanisms could sufficiently recharge the groundwater system after the formation of both the Noachian and Hesperian oceans. We found that all of the proposed mechanisms are unlikely to have provided sufficient recharge of the groundwater system and explored the implications of our conclusions. Specifically, if both the Noachian and Hesperian oceans did exist and formed through groundwater release, additional groundwater system recharge mechanism(s) must exist that have yet to be identified and quantified. Alternatively, the Noachian ocean did not exist and/or the Hesperian outflow channels and ocean were formed through a mechanism other than catastrophic groundwater release.

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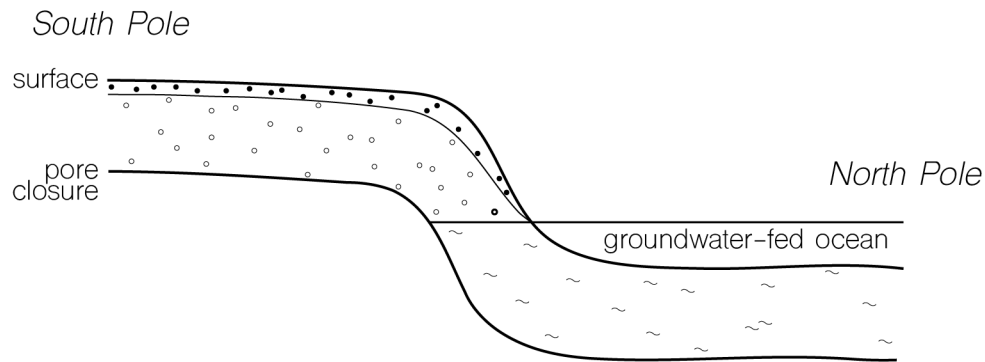
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Figures

Figure 1

(A) NOACHIAN OCEAN



(B) HESPERIAN OCEAN

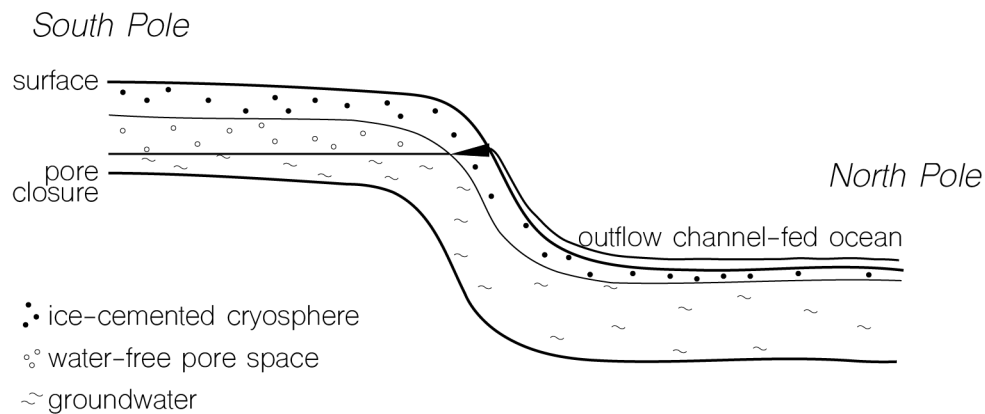
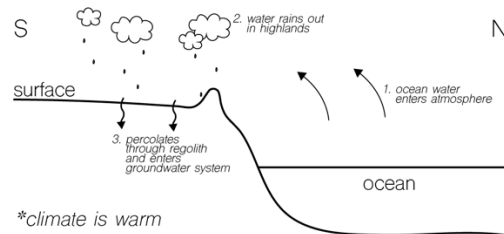


Fig. 1: Schematic diagram for the formation of the martian oceans, highlighting the logic and reasoning for required recharge. In both (A) and (B), Mars is simplified into two dimensions with the southern highlands and south pole on the left and the northern lowlands and north pole on the right. (A) Formation mechanism for the Noachian ocean, similar to that of a groundwater-fed lake or sea on Earth: if average local temperature is above freezing and sufficient volumes of water are in the groundwater system, the water table will intersect the surface in a topographically low area and groundwater will release to the surface, forming a groundwater-fed lake or sea. (B) Formation mechanism for the

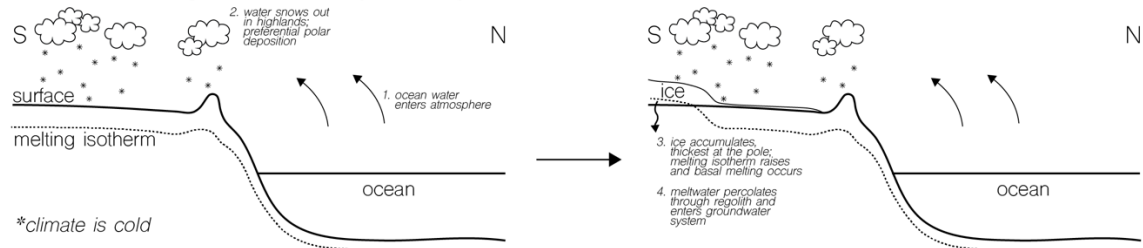
Hesperian ocean. In this scenario, the groundwater system becomes over-pressurized, causing cryospheric cracking and leading to the catastrophic release of very large volumes of groundwater onto the surface. Note that the elevation of the outflow channel sources (e.g. solid black triangle) is indicative of the elevation of the groundwater table in the Hesperian.

Figure 2

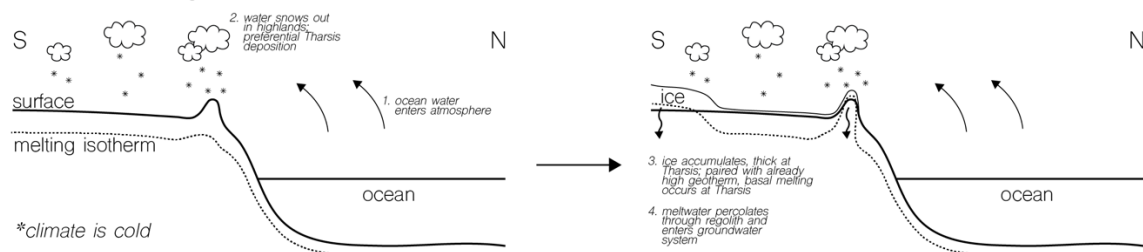
(A) Water percolates through highlands regolith



(B) Basal melting at the south polar cap



(C) Basal melting at the Tharsis rise



(D) Large volumes of lava melt surface and cryospheric ice, meltwater percolates through regolith

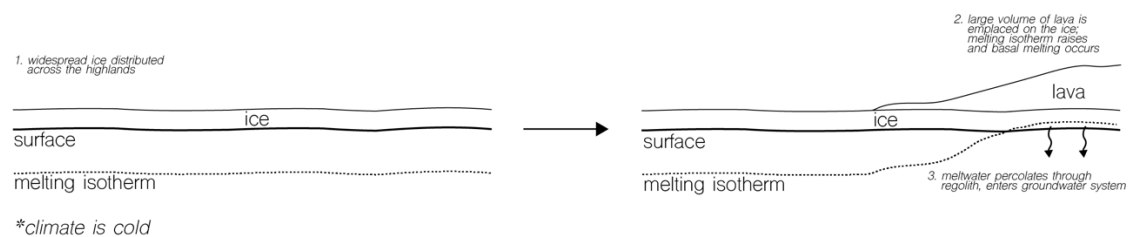


Fig. 2: Illustration of previously proposed groundwater recharge mechanisms. (A) Water percolates through highlands regolith and re-enters the groundwater system. (B) Oceanic water is re-deposited in the south polar region as snow and ice and the increased snow/ice thickness and overburden pressure initiates basal melting. (C) Oceanic water is re-deposited on the Tharsis rise as snow and ice and the increased snow/ice thickness and

overburden pressure initiates basal melting. Note that basal melting in the south polar region may also occur. (D) The climate is “cold and icy”, with large ice sheets across the southern highlands and an ice-cemented cryosphere, and large volumes of lava are emplaced onto the surface, leading to raising of the melting geotherm, melting of cryosphere and surface ice, and percolation of the meltwater through the regolith and into the groundwater system. Illustrations for (A), (B), and (C) are a simplified 2-dimensional Mars with the southern highlands on the left and the northern lowlands on the right. Illustration for (D) is some area of the highlands which would be covered with ice and is located near a volcanic edifice, which introduced large volumes of lava into the area.

CHAPTER NINE

GROUNDWATER RELEASE ON EARLY MARS: UTILIZING MODELS AND PROPOSED EVIDENCE FOR GROUNDWATER RELEASE TO ESTIMATE THE REQUIRED CLIMATE AND SUBSURFACE WATER BUDGET

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Abstract

It has been proposed that groundwater was released onto the early martian surface in several locations, including Meridiani Planum, NE Hellas, Terra Sirenum, the northern lowlands, and Gale crater. We assume that groundwater released in a manner similar to a groundwater-fed lake on Earth, and then use a combination of a global climate model and mathematical relationships to place lower limit estimates on the early climate and subsurface water inventory that are required for groundwater release to occur at all of these locations. We find that the minimum required conditions are global mean annual temperature >284 K and a subsurface water inventory >496 m global equivalent layer. Additionally, thermal models predict that if such warm conditions occurred from punctuated heating in an otherwise “cold and icy” climate, the warm conditions must have persisted for thousands of years in order to remove the cryosphere and permit groundwater release.

Plain Language Summary

Geologic evidence has been interpreted to mean that groundwater was released from the subsurface to the early martian surface at multiple locations. Groundwater release requires both a warm climate and sufficient water in the subsurface. In this work, we estimate the climate and subsurface water inventory that would be required for groundwater to be released at these locations. The plausibility of the predicted climate and subsurface water inventory can act as a test for these groundwater-related interpretations. We find that early Mars would be required to have had average global temperatures similar to present-day Earth and a very large subsurface water inventory.

Key points

- Several locations on Mars have been proposed to have undergone groundwater release to the surface in the Noachian/Hesperian.
- We estimate the climate, subsurface water inventory, and duration of warm conditions required for such groundwater release.
- Requirements for release are global mean annual temperature >284 K for ~ 1000 s of years and >496 m global equivalent layer of groundwater.

1. Introduction

Mineralogic and geomorphic data, both at rover and orbital observation scales, have been interpreted to suggest that several locations on Mars may have experienced groundwater release in the Noachian-Hesperian (e.g. Andrews-Hanna et al., 2010; Clifford, 1993; Hargitai et al., 2018; Hurowitz et al., 2017; Parker et al., 1993; Parker et al., 1989; Wray et al., 2011). These locations of interest (LOI) include Meridiani Planum, NE Hellas, Terra Sirenum, the northern lowlands, and Gale crater. Meridiani Planum hosts minerals interpreted to be consistent with groundwater cycling and a possible playa environment (Andrews-Hanna et al., 2007, 2010). NE Hellas contains paleolakes in craters and other depressions that have morphologies interpreted to be consistent with groundwater release (Hargitai et al., 2018). Terra Sirenum contains paleolake craters, including Columbus crater, that host minerals interpreted to be consistent with groundwater release (Wray et al., 2011). The northern lowlands has been interpreted to have hosted a groundwater-fed ocean in the Noachian, when temperatures were much warmer than present-day (e.g. Clifford & Parker, 2001; Parker et al., 1993; Parker et al., 1989). Finally, the chemistry within Gale crater exhibits redox stratification, which has been attributed to a groundwater influence (Hurowitz et al., 2017).

Groundwater release at these LOI is generally interpreted to have occurred in a process similar to that of a groundwater-fed lake on Earth (Fig. 1). There are two key requirements for groundwater to be released in this manner: (1) local mean annual temperature (MAT) above freezing in order for there to be no cryosphere, which would trap groundwater in the subsurface, and (2) a sufficiently voluminous groundwater system such that the groundwater table intersects the surface. Thus, groundwater release depends on both

climate and subsurface water inventory. In order to test the groundwater release interpretation at the LOI, we use global climate and mathematical models to derive the MAT and subsurface water inventory necessary to satisfy these two requirements. Collectively, if the groundwater hypotheses are correct, the LOI can be used to place lower limit estimates on the early climate of Mars and its subsurface water inventory.

2. Methods

We follow methods of our previous work (Palumbo & Head, 2019), which focused on the requirements for formation of a groundwater-fed Noachian ocean, to answer the following questions:

- (1) What is the coldest climate (global MAT) in which local MAT is >273 K at each of the LOI?
- (2) What is the minimum subsurface water inventory in which the groundwater table intersects the surface at each of the LOI?
- (3) What is the coldest climate and minimum subsurface water inventory required for groundwater release to occur at all LOI?
- (4) If we assume the background climate was “cold and icy” and the climate conditions required for groundwater release persisted during a punctuated heating event, how long must have the heating event persisted in order to remove the cryosphere and permit groundwater release?

For Question 1, we aim to determine the necessary climate to satisfy the temperature requirement for groundwater release at each of the LOI. We implement the 3D Laboratoire de Météorologie Dynamique Global Climate Model (LMD GCM) for early Mars and

explore the following representative Noachian atmospheric pressure and spin-axis/orbital values: 1 bar CO₂ (Jakosky et al., 2017), ~24 m global equivalent layer (GEL) surface/near-surface water inventory (Carr & Head, 2015), 45° obliquity (Laskar et al., 2004), circular orbit (Laskar et al., 2004), and present-day Mars Orbiter Laser Altimeter (MOLA) topography (Smith et al., 1999; Tanaka et al., 2014). We choose 45° obliquity because it is approximately the statistically probable average Noachian obliquity (Laskar et al., 2004). We choose a circular orbit to avoid a large suite of simulations; this mutes seasonal temperature swings that come from increased eccentricity, which is reasonable for this study because we are focusing on MAT and MAT is not influenced by the magnitude of seasonal temperature variations. We implement present-day topography to follow the assumption that the large basins and volcanic rises (e.g. Tharsis) were mostly formed by the Late Noachian-Early Hesperian (Fassett & Head, 2011). The model is run at a spatial sampling of 65x49x25 (longitude x latitude x altitude) and hourly data are collected.

Without additional greenhouse warming, assuming a pure CO₂-H₂O atmosphere, these simulations produce a “cold and icy” climate, characterized by global MAT ~225 K (Forget et al., 2013; Wordsworth et al., 2013). Further, Noachian atmospheric pressure was above a few tens of millibars, which induces an adiabatic cooling effect. This effect causes temperature variation to be dominantly dependent on altitude instead of latitude, and higher elevations to be colder than lower elevations (Forget et al., 2013; Wordsworth et al., 2013); for pressures >~1 bar, the elevation-temperature relationship closely mimics the dry adiabat (Wordsworth, 2016).

In order to identify the coldest climate in which groundwater release could occur, it is necessary to explore a range of climate scenarios. We produce a suite of 9 simulations with

global MAT ranging from ~ 225 K (“cold and icy”) to >273 K (“warm and wet”) (Fig. 2). We do this by artificially warming the atmosphere with gray gas, a relatively common method (e.g. Wordsworth et al., 2015) used to simulate the effects of greenhouse warming without incorporating specific gases.

For each of the LOI, we analyze GCM temperature maps to identify the coldest global MAT at which local MAT is >273 K, which satisfies the temperature requirement for groundwater release. To account for (1) the small scale of some LOI with respect to GCM grid size and (2) our finite number of simulations, we adopt the following approach:

- (1) *Estimate local MAT at small scale LOI.* Some LOI, such as the floor of Gale crater, are in deep, small topographic lows that are below the spatial resolution of our GCM data. In order to provide reasonable estimates of local MAT and avoid the computational expense of higher resolution simulations, we estimate local MAT at these LOI by implementing an empirical elevation-temperature relationship derived from the GCM data. Specifically, recall that the elevation-temperature relationship is approximately linear in the Noachian atmospheric pressure regime (e.g. Wordsworth, 2016). Thus, we plot the data for elevation against local MAT at each GCM grid cell and then implement a moving average-style approach to estimate local MAT at a given location/elevation (Fig. 3A). As a result, we have reasonable estimates for local MAT at LOI that are below the GCM simulation grid size. For example, Fig. 3A shows the elevation-temperature relationship for all GCM grid points for a simulation with no additional warming (“cold and icy” conditions). If we were to estimate local MAT at the floor of Gale based on the GCM data alone, we would suggest that local MAT is ~ 235 K. However, by using our GCM-derived

elevation-temperature relationship, we estimate local MAT to be ~ 242 K, ~ 7 K warmer. This is because the floor of Gale is a small, deep topographic low that is simply too small for our GCM simulations to resolve the local temperature/elevation variation.

(2) *Interpolate across a finite number of simulations.* After completing the previous step for each simulation, we have 9 local MAT data points at each LOI, one per simulation. We are interested in identifying the coldest global MAT at which local MAT is above freezing and it is unlikely that one of our 9 simulations represents precisely those conditions; this would hold true for any finite number of simulations. Thus, for each LOI, we plot these 9 data points for local MAT against global MAT and identify a linear equation for the relationship between global and local MAT (Fig. 3B). Utilizing these equations allows us to make more precise estimates for the coldest global MAT at which local MAT is >273 K.

For Question 2 we aim to determine the minimum subsurface water inventory necessary to satisfy the second requirement for groundwater release, intersection of the groundwater table and surface. Note that we assume the groundwater table intersects the lowest elevation location in each LOI, permitting release of a small amount of groundwater; we do not assume, for example, that a sufficient volume of water is released to fill a paleolake. This assumption is consistent with the possibility that other processes were also contributing water to the LOI; for example, there is evidence of exogenic water contribution to Gale in addition to endogenic contribution (e.g. Palucis et al., 2016).

To address Question 2, we implement equations for subsurface porosity and depth to the base of the cryosphere.

A description of porosity is needed in order to estimate subsurface water volumes. Following Clifford et al. (2010), we assume that porosity decays exponentially with depth:

$$\rho(z) = \rho_{surf} e^{z/\rho_{decay}}$$

where z is depth (km), ρ_{surf} is surface crustal porosity, which we estimate as 0.2-0.35 (Clifford et al., 2010; Clifford, 1993; Kleinhans, 2005), and ρ_{decay} is the porosity decay constant. Clifford (1993) estimated $\rho_{decay}=2.82$ km, based on gravitational scaling of the lunar expression derived by Binder & Lange (1980) and to explain Apollo seismometer data. Recent work (Weiss & Head, 2017) utilized lunar GRAIL data to update this estimate and found a higher value of $\rho_{decay}=4.82$ km. For completeness, and because these approximations are extrapolated from lunar data, not actual estimates for Mars, we perform our calculations with both values. Additionally, we calculate pore closure depth as the depth at which porosity is <1%.

To calculate the minimum subsurface water inventory required for the groundwater table to intersect the surface in a given climate, we sum two components: (1) the amount of water ice in the cryosphere and (2) the amount of liquid water in the groundwater system. We first assume that the subsurface is saturated with water ice to the depth of the base of the cryosphere, D_c ; in order for excess water to be stable as liquid in the groundwater system, the cryosphere must be saturated (e.g. Clifford et al., 2010). We estimate D_c at every GCM grid cell in all simulations with the following relationship:

$$D_c = \kappa \times \left(\frac{273 - T_{avg}}{Q} \right)$$

where κ is crustal thermal conductivity ($\text{Wm}^{-1}\text{K}^{-1}$), T_{avg} is GCM-predicted local MAT (K), and Q is geothermal heat flux ($0.045\text{-}0.065 \text{ Wm}^{-2}$ for the Noachian; Clifford et al.,

2010; McGovern et al., 2004; Solomon et al., 2005; Zuber, 2001). Note that Clifford et al. (2010) defined T_{avg} slightly differently, as local crustal temperature varying with depth due to geothermal heating; they implemented a range of values for T_{avg} from 154-273 K, the calculated minimum and maximum temperatures within the cryosphere. We assume that κ varies with temperature (Clifford et al., 2010):

$$\kappa = \frac{488.19}{T_{avg}} + 0.4685$$

After calculating the volume of water ice in the cryosphere, we calculate the volume of water that is required to exist as liquid in the groundwater system. We assume that the groundwater system is globally-continuous and that groundwater is present everywhere in subsurface pore space below the elevation of predicted groundwater release, down to pore closure depth.

We sum the volume of ice in the cryosphere with the volume of liquid water in the groundwater system to estimate the minimum subsurface water inventory required for the groundwater table to intersect the surface at each of the LOI. This volume is climate-dependent because the presence and thickness of the cryosphere is climate dependent.

For Question 3, we aim to determine the coldest climate and minimum subsurface water inventory in which groundwater release could occur at all LOI; previous steps have allowed us to make these estimates for each individual LOI. For groundwater release to occur at all LOI, the climate and subsurface water volume requirements must be satisfied at all LOI; the warmest required climate and largest required subsurface water inventory are necessary to permit groundwater release at all LOI.

For Question 4, our goal is to determine how long these predicted climate conditions must persist in order to remove the cryosphere and permit groundwater release, assuming

the background climate was “cold and icy”. To do this, we perform thermal model calculations in which we solve the 1D heat conduction equation via a finite difference approach (see description of our thermal model in Palumbo and Head (2019)). We assume that the initial equilibrated temperature at each of the LOI is the model-predicted local MAT in a “cold and icy” climate and then impose a local surface temperature of 273 K and calculate how long that surface temperature is required to persist in order for the subsurface 273 K isotherm to intersect the surface, indicating that the cryosphere has been removed.

3. Results and Discussion

Our key findings are summarized in Table 1 and outlined below.

LOI 1: Meridiani Planum. The average elevation in Meridiani, where minerals interpreted to be consistent with groundwater cycling have been identified (e.g. Andrews-Hanna et al., 2010), is -2949 m. In order for local MAT to be >273 K at Meridiani, global MAT is required to have been >265 K; in colder climates, groundwater release would not have been possible at Meridiani. In order for the groundwater table to intersect the surface, the subsurface is required to have contained $>\sim 273$ m GEL water. Finally, if the ambient climate was “cold and icy” and a punctuated heating event increased global MAT to ~ 265 K, therefore increasing local MAT at Meridiani to ~ 273 K, the punctuated climate must have persisted for $\sim 11,080$ years in order for the cryosphere to have been removed, permitting groundwater release. If local MAT was >273 K, then the required duration of the punctuated climate would decrease.

LOI 2: NE Hellas. The elevation of the interpreted groundwater-related morphologies in the paleolakes in NE Hellas ranges from -6345 to -2011 m (Hargitai et al., 2018).

Because we are interested in determining the coldest climate and minimum subsurface water inventory required for groundwater release at all of these paleolakes, our estimates for minima come from the highest elevation paleolake, which would be characterized by the coldest climate and would require the largest subsurface water inventory for groundwater release to occur. In order for local MAT to be >273 K at all of the paleolakes, global MAT is required to have been >268 K. In order for the groundwater table to intersect the surface at all of the paleolakes, the subsurface is required to have contained $>\sim 319$ m GEL water. Finally, if the ambient climate was “cold and icy” and a punctuated heating event increased global MAT to ~ 268 K, therefore increasing local MAT in NE Hellas to ~ 273 K (or slightly higher for the lower elevation paleolakes), the punctuated heating event must have persisted for $\sim 14,000$ years in order for the cryosphere to have been removed, permitting groundwater release.

LOI 3: Terra Sirenum. The elevation of the paleolakes in Terra Sirenum that contain minerals interpreted to be consistent with groundwater activity ranges from 702-1598 m (Wray et al., 2011). Because all of these paleolakes are at higher elevations than Meridiani and the paleolakes in NE Hellas, they are characterized by relatively colder temperatures in a given climate and would require a relatively larger subsurface water inventory in order for the groundwater table to intersect the surface. As was true for NE Hellas, our estimates for coldest climate and minimum subsurface water inventory required for groundwater release at all of these paleolakes in Terra Sirenum come from the highest elevation paleolake. In order for local MAT to be >273 K at all of the paleolakes, global MAT is required to have been $>>273$ K, specifically >284 K. In order for the groundwater table to intersect the surface at all of the paleolakes, the subsurface is required to have contained

>~496 m GEL water. Finally, if the ambient climate was “cold and icy” and a punctuated heating event increased global MAT to ~284 K, therefore increasing local MAT in Terra Sirenum to ~273 K (or slightly higher for the lower elevation paleolakes), the punctuated heating event must have persisted for ~30,000 years in order for the cryosphere to have been removed, permitting groundwater release.

LOI 4: Northern Lowlands. In previous work, we implemented similar methods to those described here in order to determine the coldest climate and minimum subsurface water inventory in which groundwater release and flooding of the lowlands could have occurred (Palumbo & Head, 2019). We found that global MAT is required to have been >268 K (for 45° obliquity, considered here; >258 K for 25° obliquity) and the subsurface is required to have contained >~158 m GEL water (for 45° obliquity, considered here; ~170 m GEL for 25° obliquity) (Palumbo & Head, 2019). Further, if the ambient climate was “cold and icy” and punctuated heating was responsible for increasing temperatures and permitting groundwater release in the lowlands, the punctuated heating event must have persisted for at least ~6,200 years (Palumbo & Head, 2019).

LOI 5: Gale Crater. The present-day lowest elevation in Gale, which is interpreted to have had a groundwater influence (Hurowitz et al., 2017), is ~-4540 m; this is lower elevation than Meridiani and most of the paleolakes in Terra Sirenum and NE Hellas, implying that Gale would have had relatively warmer temperatures in a given climate and that a relatively smaller subsurface water inventory would be required for the groundwater table to intersect the surface. In order for local MAT to be >273 K at the floor of Gale, global MAT is required to have been >261 K. In order for the groundwater table to intersect the surface at the crater floor, the subsurface is required to have contained >~187 m GEL

water. Finally, if the ambient climate was “cold and icy” and a punctuated heating event increased global MAT to ~ 261 K, therefore increasing local MAT on the floor of Gale to ~ 273 K, the punctuated heating event must have persisted for $\sim 8,300$ years in order for the cryosphere to have been removed, permitting groundwater release.

Requirements for groundwater release at all LOI. In order for groundwater release to have occurred at all LOI, and assuming that significant recharge of the groundwater system did not occur between groundwater release events at different LOI, the temperature and subsurface water inventory requirements must have been satisfied at all LOI. Thus, the global MAT must have been $>\sim 284$ K and the subsurface must have contained $>\sim 496$ m GEL water.

4. Conclusions

In order to test the interpretation that groundwater release occurred at various locations in the Noachian-Hesperian, we determined the coldest climate and minimum subsurface water inventory in which groundwater release could have occurred at each of the LOI. We find that:

- (1) Although some LOI, including Gale crater and Meridiani Planum, could have experienced groundwater release in globally sub-freezing climates (global MAT < 273 K, as low as ~ 260 K), other LOI require climates as warm as global MAT ~ 284 K.
- (2) In order for groundwater release to have occurred at all LOI, global MAT is required to have been $>\sim 284$ K, the subsurface water inventory is required to have been $>\sim 496$ m GEL, and, if the ambient climate was “cold and icy” and these warm

conditions persisted due to punctuated heating, the punctuated heating event is required to have persisted for ~30,000 years.

(3) A global MAT of ~284 K is significantly higher than climate models can reconcile, given reasonable greenhouse gas constraints and the faint young Sun (see review in Forget et al., 2013). Recent studies have shown that hydrogen and methane can be significant greenhouse agents on Mars when accounting for collision induced absorption (Ramirez et al., 2014; Turbet et al., 2019; Wordsworth et al., 2017); although ongoing work is constraining the magnitude of heating from these effects, the required gas concentrations to increase global MAT to ~284 K may be unrealistically high. A subsurface water inventory of ~496 m GEL may be difficult to reconcile with independent estimates, which suggest that ~170 m GEL is likely to be more plausible (Weiss & Head, 2017). Other interpretations suggest that the subsurface water inventory may have been much larger, possibility consistent with ~496 m GEL (e.g. Costard et al., 2017; Rodriguez et al., 2016). Finally, a heating duration of ~30,000 years in the Noachian-Hesperian is plausible if we consider the hydrogen-methane mechanism because these gases would have an atmospheric lifetime of $\sim 10^5$ - 10^7 years (Wordsworth et al., 2017).

(4) If global MAT was never >284 K and/or the subsurface contained <496 m GEL water, the features in some or all of the LOI must be explained via a process other than this groundwater release mechanism. Alternative options include: (a) groundwater release via an impact puncturing through the cryosphere, which could permit local groundwater release even if local MAT was <273 K, (b) a perched aquifer beneath one or more of these (higher elevation) regions, which would

decrease the required subsurface water inventory, (c) these features were formed by processes other than groundwater release (e.g. above-ground water source).

Our results provide a framework of (1) global and regional climate, (2) subsurface water inventories, and (3) durations of episodic warming events that can all be used to revisit, modify, or expand the interpreted Noachian-Hesperian groundwater release LOI. To test further the hypotheses of groundwater release at the LOI, future work should seek to reconcile whether these estimates for climate and subsurface water inventory are consistent with geologic relationships and history.

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http://planetary.brown.edu/html_pages/data.htm

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Tables

Table 1

Location	Minimum global MAT (K)	Required minimum subsurface water inventory (m GEL)	Absolute minimum subsurface water inventory (m GEL)	Required duration of punctuated conditions (yr)
Meridiani Planum	265	340 / 651	273 / 577	11,080
NE Hellas	268	367 / 702	319 / 643	13,800
Terra Sirenum	284	503 / 879	496 / 870	29,650
Northern Lowlands	268	212 / 468	158 / 409	6,180
Gale Crater	261	275 / 547	187 / 451	8,330

Table 1: Key findings: coldest possible climate (column 2) and required subsurface water volumes (columns 3, 4) for groundwater release to occur, and results of thermal models (column 5). For water inventory calculations, the first number uses $\rho_{decay}=2.82$ (Clifford, 1993) and the second uses $\rho_{decay}=4.82$ (Weiss & Head, 2017). Surface porosity is 0.2, geothermal heat flux is 65 mWm^{-2} . Required minimum subsurface water inventories are calculated for the identified minimum global MAT. Absolute minimum subsurface water inventories are calculated for a climate sufficiently warm such that there is no cryosphere. Note: (1) our earlier analysis of groundwater release in the lowlands (Palumbo and Head, 2019) showed that groundwater release could have occurred for colder global MAT, $\sim 258 \text{ K}$, if obliquity was lower (25°) and (2) these earlier calculations only implemented $\rho_{decay}=2.82$.

Figures

Figure 1

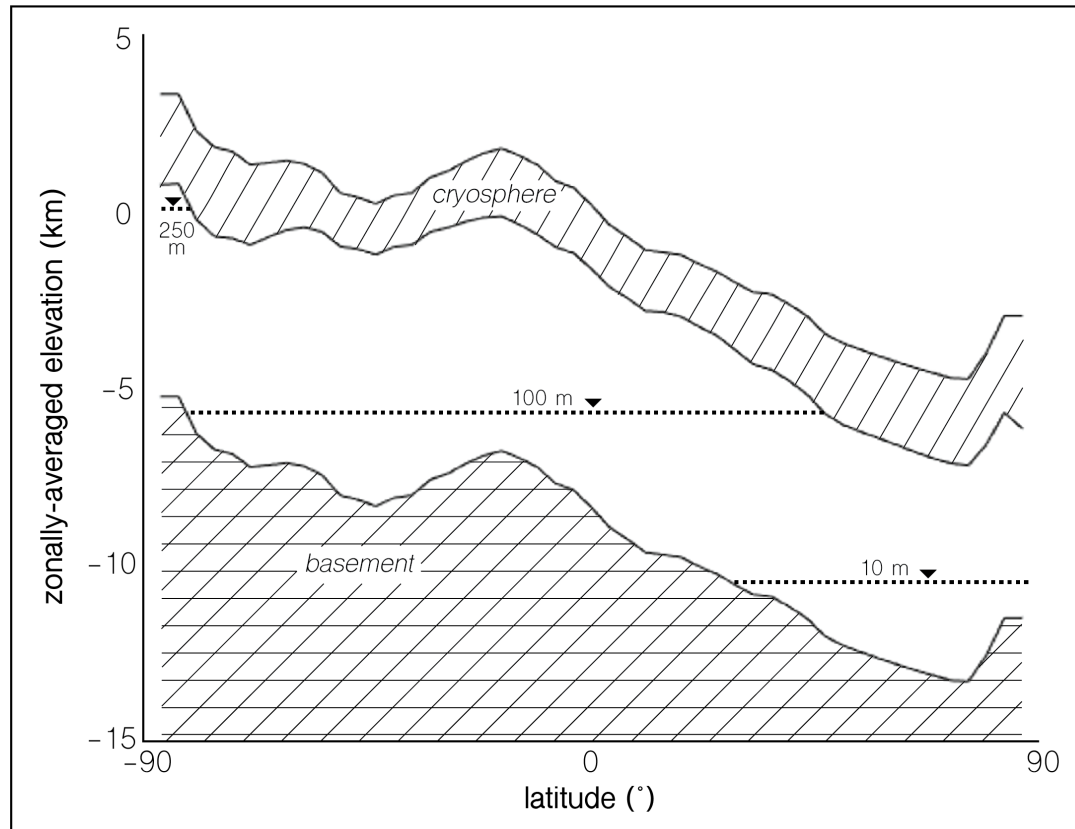


Fig. 1: Schematic for groundwater/cryosphere system with examples of volumes of liquid groundwater (in GEL) (updated from Clifford, 1993) for surface porosity 0.2, geothermal heat flux 65 mWm^{-2} , and a “cold and icy” climate. For larger water volumes, it is clear that, if the cryosphere was not present (climate was warmer), the groundwater table could intersect the surface, permitting groundwater release.

Figure 2

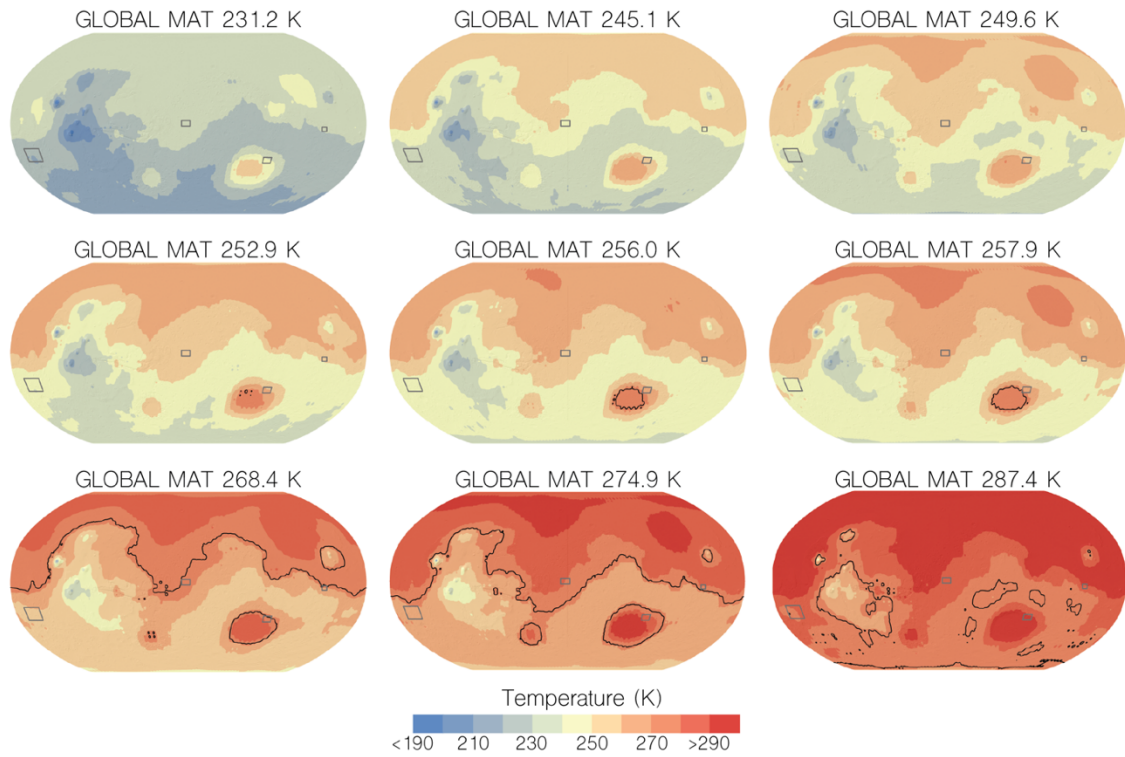


Fig. 2: MAT maps produced from GCM simulations. Global MAT is labelled and colored contours show regional MAT variation. The black line is the 273 K contour. LOI are shown as gray boxes, except the lowlands.

Figure 3.

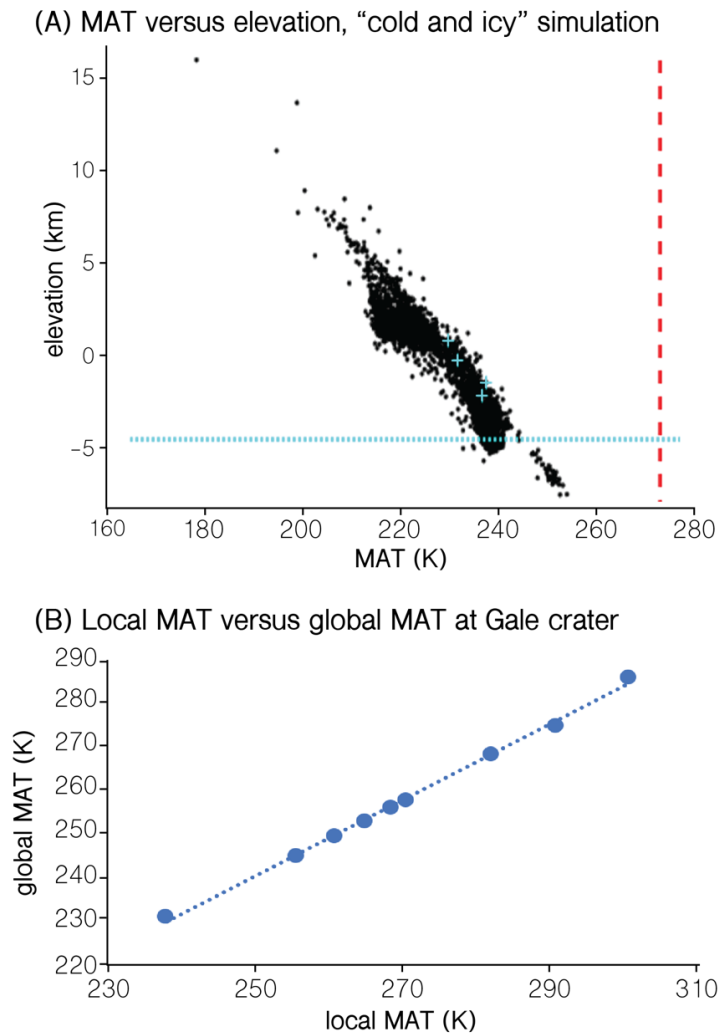


Fig. 3: (A) Methodology to estimate local MAT at small LOI, using Gale and a “cold and icy” climate as an example. Elevation versus MAT for each GCM grid cell is plotted. These data are combined with a moving average approach to estimate temperature at small-scale LOIs. Red line is 273 K, cyan line is the elevation of the crater floor, -4540 m, and cyan crosshairs mark the four GCM data points closest in location to the lowest elevation location in Gale. As shown, the GCM data points near Gale are not a precise estimate for the crater floor. (B) Plot of local versus global MAT (data from GCM in blue dots, linear fit in blue line).

CHAPTER TEN

CHARACTERIZING THE CLIMATE AND HYDROLOGIC CYCLE OF EARLY MARS: ASSESSING THE ROLE OF RAINFALL, GROUNDWATER, AND TRANSIENT ATMOSPHERIC HEATING

A SYNTHESIS

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1. Introduction

The nature and evolution of the early martian climate remains a compelling and unsolved scientific problem. Geomorphologic and mineralogic evidence, including valley networks (Hynek et al., 2010), open- and closed-basin lakes (Fassett and Head, 2008; Goudge et al., 2015), aqueous alteration products (Bibring et al., 2006; Carter et al., 2015), and groundwater release to form lakes (e.g. Wray et al., 2011) or seas (Clifford and Parker, 2001), suggest that the long-lived early climate (spanning the Noachian era) may have been “warm and wet”, characterized by above-freezing average surface temperatures and rainfall as the dominant erosive mechanism (Craddock and Howard, 2002; Ramirez and Craddock, 2018; Ramirez, 2017). In contrast, climate modeling studies suggest that the long-lived early climate may have more likely been “cold and icy” (Forget et al., 2013; Kasting, 1991; Wordsworth et al., 2013), characterized by below-freezing average surface temperatures, water trapped as snow and ice in the highlands, and fluvial activity confined to periods of punctuated heating which would cause melting of snow/ice and runoff.

In this thesis, we aim to bridge the gap between these two end-member climate scenarios and utilize both geologic observations and 3-dimensional global climate models (GCMs) to determine the nature of the early martian climate. To do this, we tested and explored three broad aspects of the early martian climate and hydrologic cycle: (1) the role of rainfall, including the presence and erosive capability (Chapters One, Two, Three, and Four), (2) the characteristics and implications of multiple punctuated/transient heating mechanisms, specifically when considering an otherwise “cold and icy” climate (Chapters Five and Six), and (3) the climate and subsurface water inventory requirements

for groundwater release to occur (Chapters Seven, Eight, and Nine). This final chapter summarizes the key findings from each of the preceding chapters and outlines outstanding questions and avenues for future work.

2. Chapter One. Rainfall on Noachian Mars: Nature, timing, and influence on geologic processes and climate history

Previous work has suggested that the observed patterns of Noachian crater degradation can be explained by a relationship between rainfall intensity (rate) and atmospheric pressure and fundamentally requires a long-lived “warm and wet” climate (Craddock and Lorenz, 2017). Specifically, the observed martian crater degradation has been proposed to be consistent with relatively low rainfall intensity in the Early to Middle Noachian (rain splash-dominated rainfall-related erosional regime), relatively high rainfall intensity in the Late Noachian-Early Hesperian (runoff-dominated rainfall-related erosional regime; consistent with the formation of valley networks and paleolakes), and no rainfall in the rest of the Hesperian and Amazonian (Craddock and Howard, 2002). If rainfall intensity and atmospheric pressure were inversely related to one another, the required rainfall intensity trend could be explained by atmospheric pressure declining through time: (1) in the Early to Middle Noachian atmospheric pressures were highest and, thus, rainfall intensity was relatively low, (2) the atmosphere was slowly being lost through time and, as a result, in the Late Noachian-Early Hesperian, atmospheric pressure was relatively lower than in the Early to Middle Noachian and, thus, rainfall intensity was relatively higher than in the Early to Middle Noachian, and (3) in the rest of the Hesperian and in the Amazonian, atmospheric pressure was too low to support rainfall. In

this chapter (Palumbo et al., 2020), we introduced physical and mathematical relationships to test these hypotheses.

We implemented a parameterized relationship for rainfall intensity to be consistent with previous work by Craddock and Lorenz (2017); this parameterized relationship was developed based on empirical and laboratory data of rainfall on Earth. Our assessment with this parameterized relationship and other relevant equations shows that rainfall intensity is not inversely related to atmospheric pressure, in contrast to previous findings (Craddock and Lorenz, 2017), implying that there would not have been a transition from rain splash-dominated erosion to runoff-dominated erosion solely related to decreasing atmospheric pressure. In addition to showing that continuous Noachian rainfall of changing intensity may not have persisted and thus may not be responsible for the observed crater degradation, these findings do not preclude the possibility that the long-lived climate was “cold and icy” and crater degradation was caused by a process separate from the characteristics of the long-lived Noachian climate.

A few key avenues for future work exist. First, we discuss that a useful avenue for future work is further investigation into the equations from which the parameterized relationship for rainfall intensity was derived. We show that the physical (not parameterized) equation for rainfall intensity may actually be consistent with a relationship between rainfall intensity and atmospheric pressure, albeit in a different way than was previously suggested by Craddock and Lorenz (2017). Second, future work should explore other mechanisms that may have been responsible for the observed crater degradation if the observed crater degradation cannot be simply explained by decreasing atmospheric pressure and, as a result, a shift from a rain splash-dominated rainfall-related

erosional regime in the Early to Middle Noachian to a runoff-dominated rainfall-related erosional regime in the Late Noachian and Early Hesperian. Finally, understanding and characterizing the factors that control rainfall intensity is important for first order characterizations of hydrologic cycles on planets other than Mars, as well, both within our Solar System and beyond.

In Chapters Two, Three, and Four, we explore the possibility and characteristics of rainfall on early Mars further with a 3-dimensional global climate model (GCM), specifically focusing on the possibility of abundant, widespread rainfall as the mechanism for the formation of the valley networks and paleolakes in the Late Noachian-Early Hesperian.

3. Chapter Two. Early Mars climate history: Characterizing a “warm and wet” martian climate with a 3D global climate model and testing geological predictions

Based on the abundant geologic evidence, researchers have put forth qualitative descriptions of the proposed long-lived “warm and wet” Noachian climate, including above-freezing average surface temperatures and seasonal or persistent rainfall (Craddock and Howard, 2002; Ramirez and Craddock, 2018). In this chapter (Palumbo and Head, 2018a), we implemented the 3D Laboratoire de Météorologie Dynamique (LMD) GCM for early Mars (Forget et al., 2013; Wordsworth et al., 2013) and forced the conditions of above-freezing average surface temperatures (global MAT ~275 K). We assumed present-day topography (e.g. Fassett and Head, 2011; Smith et al., 1999) and did not force the presence of an ocean in the lowlands but instead allowed the surface water

distribution to be controlled by the hydrologic cycling of a (maximum of) ~34 m GEL surface water inventory (Carr and Head, 2015) (these two assumptions are not always made in similar studies, for example see Ramirez et al., 2020; Wordsworth et al., 2015). Our goal was to characterize the hydrologic cycle under these canonical “warm and wet” temperature conditions and determine if the distribution rainfall in this climate scenario is consistent with the distribution of valley networks and paleolake basins.

We found that, in this climate scenario, rainfall is negligible, precipitation (and fluvial activity) is dominated by snowfall, and temperatures are below freezing in the highlands for the majority of the year. Further, (1) the valley networks and paleolakes could not have formed through rainfall and related erosion in this climate scenario and, if the valley networks and paleolakes did form in this climate scenario, they would have had to have formed through snowmelt and runoff, (2) crater degradation by rain splash and runoff is not consistent with this climate scenario, (3) global surface aqueous alteration and clay formation through long-lived rainfall, fluvial activity, and warm temperatures is not plausible in this climate scenario, and (4) the presence of a rainfall- and overland flow-fed stable body of water in the northern lowlands is improbable.

Based on our findings, we identified multiple avenues for future work, including: (1) determining whether the model-predicted distribution of snowmelt-driven fluvial activity in a long-lived “cold and icy” Noachian climate with periods of punctuated heating or the model-predicted distribution of snowmelt-driven fluvial activity in a long-lived “warm and wet” Noachian climate is more consistent with the distribution of valley networks and paleolake basins; (2) determining how warm the climate would have had to have been in order for widespread rainfall to have occurred, again assuming present-day

topography; (3) understanding the role of Tharsis on the hydrologic cycle and, specifically, determining whether a climate with global average temperatures just above freezing (~ 275 K, as explored in this chapter) with pre-Tharsis topography could be rainfall-dominated because the major cold trap would be removed; and (4) determining if the morphologic characteristics of the valley networks could in fact be explained through snowmelt and runoff, or if rainfall-driven erosion is required. We addressed the first two of these avenues for future work in Chapter Three and Chapter Four.

4. Chapter Three. Global climate model predictions for a change from a long-lived “cold and icy” climate to a punctuated or transient “warm and wet” climate in the Late Noachian-Early Hesperian

One key finding from Chapter Two is that, in a climate with global MAT ~ 275 K, present-day topography, and ~ 34 m GEL surface water inventory, fluvial activity would have been dominated by melting of snow/ice and runoff, not rainfall and runoff, similar in nature to fluvial activity in a long-lived “cold and icy” climate. Therefore, in this chapter (Palumbo and Head, In Revision), we utilized the 3D LMD GCM for early Mars and analyzed the distribution of valley networks and paleolake basins in order to address the question: Is the distribution of valley networks and paleolake basins more consistent with the model-predicted distribution of melting of snow/ice in a long-lived “warm and wet” climate (global MAT ~ 273 K) or the model-predicted distribution of melting of snow/ice in a long-lived “cold and icy” climate with one or more periods of punctuated heating?

We found that the distributions of valley networks and paleolake basins are most consistent with the distribution of model-predicted snow/ice melting for the case of a long-lived “cold and icy” climate with one or more periods of punctuated heating. On average, our results show that ~20-30% more of the valley networks and paleolake basins are in areas of predicted snow/ice melting for the scenario of a long-lived “cold and icy” climate with punctuated heating than for the scenario of a long-lived “warm and wet” climate. These findings are consistent with the hypotheses that (1) the long-lived background Noachian climate was “cold and icy” characterized by widespread snow and ice in the highlands (which may have persisted as cold-based glaciers; Fastook and Head, 2015) and little-to-no-fluvial activity, and (2) one or more periods of punctuated atmospheric and surface heating could have led to abundant and widespread melting of snow and ice, runoff, and formation of the valley networks and paleolakes.

5. Chapter Four. Earth-like temperatures are required for widespread rainfall on early Mars

Another key finding from Chapter Two is that, in a climate with global MAT ~275 K, consistent with the canonically assumed temperature condition for a “warm and wet” climate of “above freezing” (e.g. Ramirez and Craddock, 2018), rainfall is negligible and precipitation is dominated by snowfall. This is because, due to relatively high Noachian atmospheric pressure conditions and the associated adiabatic cooling effect, the southern highlands would have been much colder than the northern lowlands (Forget et al., 2013; Wordsworth et al., 2013) and, as a result, even in climates with global MAT ~275 K, above freezing, the highlands would have been below freezing for the majority of the

year, causing precipitation to be snowfall-dominated instead of rainfall-dominated. In this chapter (Palumbo and Head, Under Review), we implemented the 3D LMD GCM for early Mars in order to address the question: How warm must the early martian climate have been in order for there to have been widespread rainfall in the highlands, the major location of the valley networks and paleolake basins? Similar to the previous chapters, we implemented representative Noachian spin-axis/orbital conditions (Laskar et al., 2004), present-day topography (e.g. Fassett and Head, 2011; Smith et al., 1999), and assumed a surface water inventory of ~34 m GEL (Carr and Head, 2015) and allowed surface water distributions to be controlled by the hydrologic cycle.

We found that: (1) in order for widespread rainfall in the highlands to be possible, global MAT must have been $>\sim 285$ K, similar to the global MAT on present-day Earth (~ 288 K, or 58°F), and (2) even in climates with widespread rainfall, annual widespread snow accumulation and melting is predicted, suggesting that models for Late Noachian-Early Hesperian fluvial and lacustrine activity should consider the contributions from both rainfall and snowmelt.

Cumulatively, Chapters One, Two, Three, and Four provided new insight into the nature of the early martian hydrologic cycle. These contributions refined our understanding of (1) the plausibility and erosive capability of martian rainfall, (2) the hydrologic cycle in a typical “warm and wet” Late Noachian-Early Hesperian climate, and (3) the drivers of fluvial and lacustrine activity on early Mars.

In these first chapters, we focused largely on the characteristics of a “warm and wet” early martian climate. However, climate models have suggested that the early climate

may have been “cold and icy”, with average temperatures far below freezing and fluvial and lacustrine activity occurring only during periods of punctuated/transient heating. Many mechanisms for punctuated and transient heating on early Mars have been proposed, including volcanism-induced heating (e.g. Halevy and Head, 2014; Johnson et al., 2008; Kerber et al., 2015; Mischna et al., 2013; Postawko and Kuhn, 1986), impact cratering-induced heating (e.g. (Palumbo and Head, 2018b; Segura et al., 2002, 2008; Steakley et al., 2019; Toon et al., 2010; Turbet et al., 2020), seasonal and diurnal temperature variations and summertime melting (e.g. Palumbo et al., 2018), high altitude H₂O and/or CO₂ clouds (e.g. Forget et al., 2013; Mischna et al., 2019; Urata and Toon, 2013), and transient reducing greenhouse-rich (e.g. containing H₂, CH₄) atmospheres (e.g. Ramirez et al., 2014; Turbet et al., 2019; Wordsworth et al., 2017). In the next chapters, Chapter Five and Chapter Six, we explored two specific mechanisms for punctuated/transient heating on an otherwise “cold and icy” early Mars: volcanism-induced heating and impact cratering-induced heating.

6. Chapter Five. Exploring the influence of volcanism-induced heating on early Mars: Implications for localized and summertime melting

In this chapter, we implemented the 3D LMD GCM for early Mars to revisit the role of volcanism-induced heating from the release of sulfur-based gases in an otherwise “cold and icy” climate. Previous studies have consistently shown that, for reasonable concentrations of sulfur-based gases, global MAT would remain below freezing (e.g. Halevy and Head, 2014; Kerber et al., 2015; Mischna et al., 2013). In this work, we focus on previously unexplored aspects of volcanism-induced heating, including (1) the

possibility of localized heating and melting immediately following an eruption when the gases are focused near the edifice (*phase one*), and (2) the possibility of summertime melting of snow and ice after the sulfur-based gases have become globally distributed, despite global MAT <273 K (a relatively unexplored aspect of *phase two*). We focused on the influence of atmospheric SO₂ and performed simulations for an eruption at Hadriacus Mons, a near-equatorial volcanic edifice that is likely to have been active in the LN-EH and contains fluvial features on the flanks (e.g. Crown and Greeley, 1993). We find that volcanism-induced heating may have caused melting of snow/ice, both (1) local to the edifice and (2) globally in the summer season. Thus, this punctuated heating mechanism should not be disregarded and may have contributed to fluvial activity in the Late Noachian-Early Hesperian and formation of the valley networks and paleolakes.

Future work includes (1) performing simulations with other volcanically-released gases, such as H₂S, H₂, and N₂ (in this work we focused only on SO₂), (2) performing simulations for eruptions at other volcanic edifices that were also likely to have been active in the Late Noachian-Early Hesperian, (3) improving estimates for the duration of possible heating from sulfur-based gases before the conversion to aerosols (in our calculations, we assumed that heating would persist for one year), which will in turn improve estimates for the amount of heating and melting of snow/ice for given eruption conditions, and (4) estimating runoff rates for both the predicted localized melting and global summertime melting and determine whether these runoff rates could have plausibly carved the valley networks.

7. Chapter Six. Large impact basin-related climatic and surface effects on Mars: Argyre basin as a case study

Previous work has shown that, although impact cratering-induced heating, deposition of a hot spherule layer, and induced rainfall from basin-scale impact events is unlikely to be related to the formation of valley networks for multiple reasons, including the fact that the large basin-scale impact events occurred before the period of valley network activity (e.g. Fassett and Head, 2011) and the very high predicted impact-induced rainfall and runoff rates (e.g. Barnhart et al., 2009; Palumbo and Head, 2018b), these post-impact effects were likely to have left behind a signature on the Noachian surface (e.g. Palumbo and Head, 2018b; Steakley et al., 2019; Turbet et al., 2020). In this chapter, our goal was to determine the characteristics of this signature by performing qualitative and quantitative analyses of the post-impact effects from the formation of the Argyre basin, the youngest of the large martian basins. We find that (1) an ~30 m thick, near-globally-distributed, olivine and glass-rich spherule layer should be preserved at or very near the surface, (2) the impact-induced rainfall would have been characterized by rates higher than that of terrestrial tropical rainforests and persisted continuously for decades, which is unprecedented for terrestrial rainfalls (Jennings, 1950; Zhang et al., 2013), (3) the hot, impact-induced rainfall would have caused smoothing of plains, degradation of crater rims, and surface aqueous alteration. This work provides critical insight into the transition from a basin-scale impact-dominated regime to a basin-free regime in martian climate evolution and offers explanations for various geologic and mineralogic observations that are difficult to otherwise explain in the absence of a long-lived “warm and wet” Noachian climate.

We outline multiple avenues for future work, including: (1) additional analyses, potentially including in situ data from the Mars 2020 Perseverance Rover, to determine whether specific olivine-rich units are spherule layers, as opposed to having a different source, and (2) determining where on the planet the impact-related alteration products may be observed and, as a result, whether a significant amount of the observed alteration could have been formed under post-impact conditions.

In the first six chapters, we explored the mechanisms controlling runoff-driven surface fluvial activity on early Mars and the characteristics of such fluvial activity. However, there is also abundant evidence that some of the surface liquid water activity was sourced by groundwater, not runoff from rainfall or melting of snow/ice. Groundwater release may have been an important aspect of the early martian hydrologic cycle, including the formation of groundwater-fed paleolakes and seas. Further, groundwater-release is only possible under specific climate and subsurface water inventory conditions; evidence for groundwater release can provide insight into the early climate. In Chapters Seven, Eight, and Nine, we explore the requirements and implications of groundwater release on early Mars.

8. Chapter Seven. Oceans on Mars: The possibility of a Noachian groundwater-fed ocean in a sub-freezing martian climate

Researchers have proposed that a Noachian groundwater-fed ocean may have formed in the northern lowlands (e.g. Clifford and Parker, 2001). Although the evidence for martian oceans is elusive (Head et al., 2018), the formation and persistence of such a

large body of water in the lowlands would have undoubtedly influenced the climate and hydrologic cycle. Further, the formation of a groundwater-fed lake or sea requires specific local climatic and subsurface water inventory conditions. Therefore, in this chapter (Palumbo and Head, 2019), we use a combination of the 3D LMD GCM for early Mars, a 1D thermal model that we developed for this work, and basic equations for subsurface water volumes in order to determine the coldest possible climate and minimum subsurface water inventory in which a groundwater-fed Noachian ocean could have formed in the northern lowlands.

We find that: (1) a groundwater-fed Noachian lowlands ocean could have formed in a climate with global MAT >258 K, ~ 15 K below the freezing point of water, and a reasonable subsurface water inventory of >170 m global equivalent layer (GEL), and (2) if we assume present-day topography and a globally-connected groundwater system, in order for a groundwater-fed ocean to have formed in the lowlands, a groundwater-fed sea would have also been present in the Hellas basin. Because a groundwater-fed ocean could have formed in the lowlands in a climate with global MAT below freezing, we suggest that a Noachian lowlands ocean should not be cited as evidence for long-lived “warm and wet” conditions (global MAT >273 K).

Based on these findings, avenues for future work include: (1) exploring mechanisms for recharge of the groundwater system after the formation of a groundwater-fed ocean, because the water is not still present on the surface today (Carr and Head, 2015) and it is unlikely that such a large volume of water (~ 650 m GEL; Carr and Head, 2003) was lost to space (e.g. Jakosky, 1993; Lammer et al., 1996), (2) applying our methods to other locations on Mars that have been identified as locations of previous groundwater release,

and (3) exploring other mechanisms for groundwater release, such as an impact event puncturing through the cryosphere and releasing groundwater to the surface. We addressed the first two of these avenues of future work in Chapter Eight and Chapter Nine, respectively.

9. Chapter Eight. Oceans on Mars: Exploring mechanisms for recharge of the groundwater system

In this chapter (Palumbo and Head, Under Review), we reviewed and assessed four proposed mechanisms for recharge of the groundwater system and assessed whether significant volumes of water could have been returned to the subsurface through these mechanisms. The proposed mechanisms for recharge of the groundwater system are (1) rapid infiltration into the regolith and groundwater system in the highlands, (2) basal melting beneath the polar caps, (3) basal melting beneath the Tharsis rise and Tharsis volcanoes, and (4) melting of surface and cryosphere ice and infiltration to the subsurface from basal melting due to increased overburden pressure from lava loading.

This assessment is of critical importance because, if large volumes of groundwater were released to the surface earlier in planetary history (as required for the formation of both the proposed Noachian and Hesperian oceans; Baker et al., 1991; Clifford et al., 2010; Clifford and Parker, 2001), most of this water must have been returned to the subsurface because it is not present at the surface today (Carr and Head, 2015) and it is unlikely that such large volumes of water (hundreds of meters GEL; Carr and Head, 2003) were lost to space (e.g. Jakosky, 1993; Lammer et al., 1996).

We found that all of the proposed mechanisms are unlikely to have been capable of returning significant volumes of water to the groundwater system and suggest that either (1) if the oceans did exist, they did not form from groundwater release processes, (2) an additional recharge mechanism exists that has not been identified and quantified, or (3) one or both of the proposed martian oceans did not exist.

10. Chapter Nine. Groundwater release on early Mars: Utilizing models and proposed evidence for groundwater release to estimate the required climate and subsurface water inventory

The northern lowlands is not the only location on the surface of Mars that has been proposed as having experienced groundwater release in the Noachian/Hesperian. In this chapter (Palumbo and Head, 2020), we implemented similar methods to Chapter Seven and explored the required climate and subsurface water inventory for groundwater release to have occurred at these other locations, including Meridiani Planum, paleolakes in NE Hellas, paleolakes in Terra Sirenum, and Gale crater.

We found that, in order for groundwater release to have occurred at all of these locations in the Noachian/Hesperian, the global MAT must have been >286 K for at least 30,000 consecutive years and the subsurface must have contained >496 m GEL water; although a groundwater-fed ocean in the northern lowlands could have formed in a climate with global MAT <273 K, groundwater release at these other locations does require above-freezing global MAT. Future work should seek to reconcile whether these estimates for climate and subsurface water inventory are consistent with geologic relationships and history.

11. Summary

Canonically, previous studies of the early martian climate have relied on either the predictions from geologic observations or predictions from climate models. In this thesis, we implemented a variety of techniques, including qualitative and quantitative geologic assessments and 3D climate modeling, to bridge the gap and address the following question: What was the nature of the early martian climate and hydrologic cycle?

With nine unique thesis chapters, we explored three broad aspects of the early martian climate and hydrologic cycle: (1) the role of rainfall, including the presence and erosive capability (Chapters One, Two, Three, and Four), (2) the characteristics and implications of multiple punctuated/transient heating mechanisms, specifically when considering an otherwise “cold and icy” climate (Chapters Five and Six), and (3) the climate and subsurface water inventory requirements for groundwater release to have occurred (Chapters Seven, Eight, and Nine).

In our exploration of the role of rainfall, including the presence and erosive capability, we found that:

(1) atmospheric pressure and rainfall intensity are independent, implying that the previously proposed explanation for crater degradation does not hold true and the mechanism(s) responsible for the change of intensity of fluvial activity and the nature of the hydrologic cycle in a “warm and wet” climate warrant future study;

(2) in simulations of a climate with global MAT ~ 275 K, above freezing, precipitation and fluvial activity were dominated by snowfall and snow accumulation/melting and rainfall is negligible, implying that if the valley networks and

lakes formed in this climate scenario, they would have formed through snowmelt and runoff, not rainfall and runoff;

(3) the model-predicted distribution of snowmelt in a long-lived “cold and icy” Noachian climate with punctuated heating is better correlated with the distributions of valley networks and lakes than the model-predicted distribution of snowmelt in a long-lived “warm and wet” Noachian climate with global MAT ~ 275 K; this implies that the valley networks and lakes may be more consistent with formation in a long-lived “cold and icy” climate with one or more periods of punctuated heating; and

(4) in order for temperatures in the highlands to be sufficiently warm such that widespread rainfall occurs, global MAT must have been >285 K and, even for these relatively warm conditions, seasonal snow accumulation and melting would still occur and, thus, depictions of fluvial activity on a warm early Mars should include both rainfall and runoff and snowmelt and runoff.

In our exploration of the characteristics and implications of multiple punctuated/transient heating mechanisms in an otherwise “cold and icy” climate, we found that:

(1) volcanism-induced heating in the Late Noachian-Early Hesperian could have led to melting of snow and ice and runoff both local to the volcanic edifice during phase one and in the highlands in the summer season during phase two; and

(2) impact cratering-induced heating and related effects would not have been prominent in the Late Noachian-Early Hesperian because global-scale effects would have only occurred in relation to large basin-scale impact events and the large basins formed in the Early to Middle Noachian; the global effects following the formation of the large

basins (e.g. abundant, hot rainfall), however, would have contributed to smoothing of plains, crater degradation, and aqueous alteration in the Early to Middle Noachian, implying that these geological observations may not have required a long-lived “warm and wet” Noachian climate.

In our exploration of groundwater release, specifically the climate and subsurface water inventory requirements for groundwater release to have occurred, we found that:

(1) a groundwater-fed Noachian ocean could have formed in climates with global MAT far below freezing and, as a result, a groundwater-fed Noachian ocean should not be considered evidence for long-lived “warm and wet” conditions;

(2) the evolution of large oceans must be a topic of future research because there is currently no plausible way to return such large volumes of water to the subsurface and, further, the large volumes of oceanic water are not on the surface today and are unlikely to have been lost to space; and

(3) in order for groundwater release to have occurred at all previously identified locations, global MAT must have been >286 K for thousands of consecutive years and the subsurface must have contained at least 500 m GEL of groundwater.

All of the chapters converge to one key point: We should not discount the possibility that the long-lived Noachian climate was “cold and icy” with one or more periods of punctuated heating that increased global MAT to above freezing and persisted for thousands of consecutive years.

I urge future work to continue to combine geologic observations with climate models in order to better understand the nature of the early martian climate and hydrologic cycle.

It is only through collaborative, synergistic analyses that we will address the compelling scientific problems of the future.

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