EARLY MARTIAN CLIMATE AND SUBSURFACE WATER INVENTORY: EVIDENCE FROM MODELS AND LOCATIONS OF GROUNDWATER RELEASE.

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Introduction: Mineralogic and geomorphic data, both on rover and orbital scale, have been used to identify locations of interest (LOI) on Mars that may have experienced groundwater (GW) release earlier in martian history [1-6]. The LOI include: (1) Meridiani Planum, which hosts minerals consistent with GW cycling [1], (2) NE Hellas, which has paleolakes with morphologies consistent with GW release [2], (3) Terra Sirenum, which has paleolakes with minerals consistent with GW release [3], (4) the northern lowlands, which may have hosted a GW-fed ocean in the Noachian [4,5], and (5) Gale crater, which exhibits redox stratification that has been attributed to a possible GW influence [6].

GW release at the LOI may have occurred in a process similar to that of a GW-fed lake on Earth. There are two key requirements for GW to be released in this manner: (1) local mean annual temperature (MAT) must be above freezing in order for there to be no cryosphere, which would trap GW in the subsurface, and (2) a sufficiently voluminous GW system is required such that the GW table intersects the surface. If we assume that these two requirements were satisfied at all LOI, we can place lower limit estimates on the early climate and subsurface water inventory.

Methods: Following previous work [7], we use global climate model (GCM) simulations to estimate the required climate and a simple mathematical approach to estimate the required subsurface water volume for GW release at each of the LOI. Specifically, we perform calculations for Meridiani, 11 paleolakes in Terra Sirenum [3], 10 paleolakes in NE Hellas [2], the floor of Gale crater, and the northern lowlands. Then, by assuming that all LOI did in fact experience GW release, we provide lower limit estimates on the early climate and subsurface water inventory.

GCM simulations. We use the 3D LMD GCM for early Mars and implement representative Noachian atmospheric pressure [8] and spin-axis/orbital [9,10] values. Without additional greenhouse warming, these simulations produce a "cold and icy" climate (global MAT ~225 K) [e.g. 11,12]. Further, for Noachian pressures (~1 bar), temperature is dominantly dependent on altitude, not latitude [11,12].

In order to identify the coldest climate in which GW release could occur, we must explore a range of climate scenarios. Thus, we produce a suite of 8 simulations with global MAT ranging from ~225 K ("cold and icy") to >273 K ("warm and wet") (**Fig 1**). We do this by artificially warming the atmosphere with gray gas, which simulates 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, such that the temperature requirement for GW release is met. To account for the small scale of some LOI with respect to the GCM grid cell size and our finite number of simulations, we do the following:

(1) *Estimate local MAT at small scale LOI.* Some LOI are in deep, small topographic lows that are below the spatial resolution of our GCM data. In order to provide reasonable estimates on local MAT while saving 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.

(2) *Interpolate across a finite number of simulations.* After completing the previous step for our GCM simulations, we have 8 local MAT datapoints at each LOI. We plot these datapoints against global MAT and derive linear equations for the relationship between global and local MAT; these equations allow us to make more precise estimates on the coldest global MAT at which local MAT is >273 K.

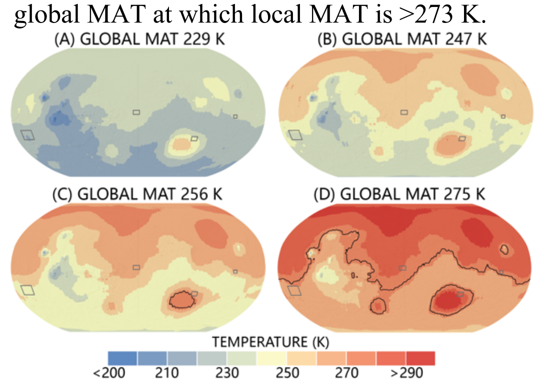

Fig 1. Subset of GCM simulations used, spanning the range of global MAT explored here, from ~225 K to >273 K. Gray boxes highlight all LOI except the lowlands and the black line is a 273 K contour. Higher elevations are colder than lower elevations. Obliquity is 45°.

Subsurface water volume calculations. We need a description of subsurface porosity in order to estimate water volumes held in the subsurface. Following previous studies, we assume that porosity decays exponentially with depth [e.g. 13].

We use the following steps to calculate the minimum subsurface water inventory that is required for the GW table to intersect the surface. First, we assume 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 GW system, the cryosphere must first be saturated [e.g. 5]. We estimate D_c at every GCM grid cell in all simulations with the following relationship:

$$D_c = \kappa \times (273 - T_{avg} / Q)$$

where κ is thermal conductivity [13], T_{avg} is local MAT, and Q is geothermal heat flux [14].

Second, we assume that the GW system is globally-continuous and that GW is present everywhere in the subsurface pore space below the elevation of predicted GW release down to pore closure.

Finally, we sum the volume of water ice in the cryosphere with the volume of water in the GW system to estimate the minimum subsurface water inventory required for the groundwater table to intersect the surface at each of the LOI. Note that this volume is climate-dependent because the presence and thickness of the cryosphere is climate dependent.

Results: Our key findings are summarized in **Table 1** and outlined below for each LOI.

Location of Interest	Minimum global MAT (K)	Subsurface water inventory (GEL)	Minimum subsurface water inventory (GEL)
Meridiani Planum	266	327	273
NE Hellas	270	340	313
Terra Sirenum	286	512	496
Northern Lowlands	268	224	170
Gale Crater	260	242	187
Required for all LOI	*286*	*512*	*496*

Table 1. For each LOI: minimum global MAT for local MAT >273 K, subsurface water inventory for GW table to intersect surface for the identified climate, and minimum possible subsurface water inventory (assumes warm enough climate for no cryosphere anywhere). For Terra Sirenum and NE Hellas, where we look at multiple lakes, we highlight the highest elevation lake because it is coldest and requires the largest subsurface water inventory. Parameter values: 45° obliquity, surface porosity 0.2 [13], geothermal heat flux 65 mW m^{-2} [14].

LOI 1: Meridiani Planum. In order for local MAT to be >273 K at Meridiani, global MAT must have been >266 K (**Fig 1**); in climates colder than this, GW release would not have been possible at this LOI. In order for the GW table to intersect the surface at Meridiani (average elevation -2949 m), the subsurface must have contained at least ~273 m GEL of water (**Table 1**).

LOI 2: NE Hellas. The elevation of GW-related morphologies in the identified lakes ranges from -6345 to -2011 m [2]. In order for local MAT to be >273 K at all of the lakes, global MAT must have been >270 K (**Fig 1**). In order for the GW table to intersect the surface at all of the lakes, the subsurface must have contained at least ~318 m GEL of water (**Table 1**).

LOI 3: Terra Sirenum. The elevation of the lakes that contain minerals consistent with GW activity in the identified paleolakes ranges from 702 to 1598 m [3]. Because all of these lakes are at higher elevations than Meridiani and the lakes in NE Hellas, they are characterized by relatively colder temperatures in a given climate. In order for local MAT to be >273 K at all of the lakes, global MAT must have been >> 273 K, specifically >286 K. In order for the GW table to intersect the surface at all of the lakes, the subsurface must have contained at least ~496 m GEL of water (**Table 1**).

LOI 4: Northern Lowlands. Previous work [7] implemented the same methods as those described here to determine the coldest climate and minimum subsurface water inventory in which GW release and flooding of the lowlands could have occurred and found that global MAT must have been >255 K and the subsurface must have contained at least ~170 m GEL of water [7].

LOI 5: Gale Crater. Gale is located in the southern highlands and the present-day lowest elevation area of the crater floor is ~-4540 m; this is lower elevation than Meridiani and most of the lakes in Terra Sirenum and NE Hellas, implying that Gale would have had relatively warmer temperatures for a given climate. In order for local MAT to be >273 K at Gale, global MAT must have been >260 K (**Fig 1**). In order for the GW table to intersect the surface at Gale, the subsurface must have contained at least ~187 m GEL of water (**Table 1**).

Conclusions: We determined the coldest climate and minimum subsurface water inventory in which GW release could have been possible at each of the LOI in the Noachian/Hesperian. We find that:

(1) Although some LOI, including Gale and Meridiani, could have experienced GW release in globally sub-freezing climates (global MAT <273 K), other LOI require warmer climates, as warm as global MAT ~286 K.

(2) In order for GW release to have occurred at all of the LOI, global MAT must have been at least 286 K and there must have been at least 496 m GEL water contained in the subsurface (**Fig 1, Table 1**). Future work will determine whether these estimates can be reconciled with the geologic history.

(3) If global MAT was never >286 K and/or the subsurface contained <496 m GEL water, the features in some or all LOI must be explained via a process other than this mechanism GW release.

Future work will use the methods of Palumbo and Head [7] to determine the required duration of these warm conditions (global MAT ~286 K) if they occurred due to a punctuated heating event in a "cold and icy" background climate.

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