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Key Points:

- Hydrological modeling and observational constraints at Gale crater are used to reconstruct the past climate of post-Noachian Mars
- Late-stage lake levels in Gale crater require semiarid climates
- Subsurface flow may contribute up to half of the water flux into lakes at the dichotomy boundary

Supporting Information:

- Supporting Information S1

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Reconstructing the past climate at Gale crater, Mars, from hydrological modeling of late-stage lakes

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Abstract The sedimentary deposits in Gale crater may preserve one of the best records of the early Martian climate during the Late Noachian and Early Hesperian. Surface and orbital observations support the presence of two periods of lake stability in Gale crater—prior to the formation of the sedimentary mound during the Late Noachian and after the formation and erosion of the mound to its present state in the Early Hesperian. Here we use hydrological models and late-stage lake levels at Gale, to reconstruct the climate of Mars after mound formation and erosion to its present state. Using Earth analog climates, we show that the late-stage lakes require wetter interludes characterized by semiarid climates after the transition to arid conditions in the Hesperian. These climates are much wetter than is thought to characterize much of the Hesperian and are more similar to estimates of the Late Noachian climate.

1. Introduction

The broad distribution of dendritic valley networks [Craddock *et al.*, 1997; Craddock and Howard, 2002; Hynek and Phillips, 2003; Irwin *et al.*, 2005b; Howard *et al.*, 2005; Hynek *et al.*, 2010] and abundant clay bearing units exposed in Noachian-aged terrain [e.g., Pollack *et al.*, 1987; Bibring *et al.*, 2006; Mustard *et al.*, 2008; Murchie *et al.*, 2009; Ehlmann *et al.*, 2011; Carter *et al.*, 2013] led to the idea that early Mars was warmer and wetter and likely experienced a hydrologic cycle that included precipitation-induced runoff and stable surface water. Morphological studies [Howard, 2007; Barnhart *et al.*, 2009] and discharge estimates [Hoke *et al.*, 2011] of Martian channels supported semiarid to arid climate conditions during the Late Noachian, although other studies argued that the morphology and immaturity of the fluvial systems are more consistent with arid to hyperarid environments on Earth [Stepinski and Stepinski, 2005; Irwin *et al.*, 2011]. An investigation of the surface hydrology using open-basin lakes and valley networks in the southern highlands [Matsubara *et al.*, 2011, 2013] suggested a climate similar to the Pleistocene Great Basin region when conditions were wetter and colder during the Last Glacial Maximum. Hydrated clay minerals [Mustard *et al.*, 2008], fan deposits, and fluvial channels discharging into impact basins indicate that water existed on the surface as crater lakes [Forsythe and Blackwelder, 1998; Cabrol and Grin, 1999; Fassett and Head, 2008; Goudge *et al.*, 2012, 2015] over time-scales necessary to deposit and aqueously alter rocks in a lacustrine environment.

This early wet period was followed by a transition in the Late Noachian and Early Hesperian to sulfate deposition [Bibring *et al.*, 2006] and potentially subsurface-dominated hydrology [Andrews-Hanna *et al.*, 2007, 2010]. These sulfate-rich sedimentary deposits appear to have been more widespread in the past [Zabrusky *et al.*, 2012], having undergone extensive erosion requiring a period defined by a deeper water table and a cessation of hydrological activity [Andrews-Hanna and Lewis, 2011]. This progression from clay alteration and lake and valley network formation to sulfate deposition and finally to erosion of those deposits indicates an increasingly arid climate beginning in the Late Noachian to Early Hesperian. However, evidence for fluvial activity into the Hesperian and possibly as late as the Amazonian [e.g., Irwin *et al.*, 2005a; Mangold *et al.*, 2008; Hynek *et al.*, 2010; Goudge *et al.*, 2016] indicates that wetter climate conditions than those of the present day may have existed later than previously thought during short-lived episodes.

Gale crater, first identified as containing a potential closed-basin lake by Forsythe and Blackwelder [1998], is a Late Noachian to Early Hesperian crater located on the dichotomy boundary and is currently the location of the Mars Science Laboratory (MSL) on the Curiosity rover. In addition to the extensive aeolian erosion, geomorphic observations of Gale crater noted layered deposits in a central crater mound (Aeolis Mons) that had been fluvially eroded, fan deposits on the crater floor, and fluvial dissection of the crater rim [Cabrol

and Grin, 1999; Irwin *et al.*, 2005b; Anderson and Bell, 2010; Le Deit *et al.*, 2013; Grotzinger *et al.*, 2015; Palucis *et al.*, 2014, 2016]. Spectral analyses of the Gale crater mound deposit noted the presence of clays at the base of the deposit, mixed with sulfates at higher levels, together making up the lower ~250 m of the mound [Milliken *et al.*, 2010; Thomson *et al.*, 2011]. Recent observations by MSL revealed further evidence for a past wet environment in Gale [e.g., Palucis *et al.*, 2014; Grotzinger *et al.*, 2014; Stack *et al.*, 2014; Siebach *et al.*, 2014]. Mudstone layers forming the basal unit of Aeolis Mons on the crater floor, deltaic deposits extending from the crater rim, and millimeter-scale varves provide evidence for stable lakes in Gale crater and lake sediments forming the basal unit of Aeolis Mons early during the evolution of Gale crater [Grotzinger *et al.*, 2014, 2015; Ehlmann and Buz, 2015; Hurowitz *et al.*, 2017].

In the lower mound, there is evidence for a change in the aqueous environment, from a more neutral lacustrine environment under wetter climates indicated by clay deposits to a more acidic environment under drier conditions indicated by sulfate-bearing aeolian deposits [Milliken *et al.*, 2010; Thomson *et al.*, 2011]. The sulfate deposits are in turn overlain by aeolian deposits with no evidence for aqueous alteration, likely representing ash or dust [Milliken *et al.*, 2010]. The mound deposits were likely more laterally extensive during their deposition, possibly forming a continuous crater-filling deposit [Siebach and Grotzinger, 2014; Grotzinger *et al.*, 2015; Watkins *et al.*, 2017]. This deposit then must have been eroded into its current mound shape. Alternatively, it has been argued that the mound could have formed in its current configuration through aeolian processes [Kite *et al.*, 2013].

Evidence for later stage hydrology, after mound formation and erosion, has been identified from fan deposits on the Gale crater floor [Le Deit *et al.*, 2013; Palucis *et al.*, 2016]. Palucis *et al.* [2016] identified three distinct lake stands based on several Gilbert-style deltaic deposits, similar to those found in lakes on Earth, and other immature fans breaking at roughly the same elevation within Gale crater. Based on the observed elevations of deltas and fans, these lake stands were estimated to fluctuate between –3280 m elevation (followed by a desiccation period), –3980 m, and –3780 m. These lakes were likely active during the Hesperian, though an Amazonian age cannot be ruled out [Palucis *et al.*, 2016]. The large extent of these fan deposits suggests that these lakes persisted for 10,000 to 100,000 years depending on assumed discharge rates in the surrounding catchments and a rock to water ratio of 0.0001 [Palucis *et al.*, 2016].

Although the existence of persistent liquid water ponded within Gale crater both before and after the formation of Aeolis Mons is clearly demonstrated by the orbital and MSL observations, the aridity of the past climate cannot be constrained from the observations alone. Lake levels are a product of the complicated interplay of the surface and subsurface components of the hydrological cycle, which in turn are driven by the climate and the topography of a basin and its watershed. Here we focus on the climate during the wet interludes responsible for the late-stage lakes. We use hydrological models of Gale crater lake to constrain a range of post-Aeolis Mons climates compatible with the lake stands inferred by Palucis *et al.* [2016] and open- and closed-basin lakes outside of Gale crater [Cabrol and Grin, 1999; Fassett and Head, 2008; Goudge *et al.*, 2012, 2015]. The models assume an average annual temperature above the freezing point of water, a surface hydrology similar to semiarid and arid terrestrial regions, the presence of a porous and permeable aquifer to enable subsurface hydrology, and a range of climates based on scaled terrestrial climates. We examine a range of climates representing different humidity regimes (hyperarid, arid, semiarid, and subhumid based on the United Nations Environment Programme [1997] aridity classification), as well as a range of assumptions in the hydrological model, in order to constrain the conditions on Mars around Gale crater required to reproduce the observed postmound lake levels.

2. Methodology

To constrain the climate and hydrogeology at the Gale crater lake, we used a hydrological model [Horvath *et al.*, 2016], representing surface runoff in localized catchments, subsurface flow in deep aquifers, and lakes. The lake stands of the modeled Gale crater lakes were then compared to the observed lake stands. The modeled domain around Gale crater was nested in a larger regional model using a constant-flow boundary condition in the subsurface model in order to capture any effects of longer-distance flow into and out of the model domain (see supporting information).

In order to investigate a range of post-Aeolis Mons climates, the hydrological model was forced at the surface using evaporation potential (E_p , the evaporation rate from a standing body of water) and precipitation (P)

rates from Earth-based observations of analog climates provided by the North American Land Data Assimilation Systems Phase 2 (NLDAS-2) [Xia *et al.*, 2012a, 2012b]. Earth climates were chosen to provide realistic daily and seasonal variations in precipitation and evaporation potential, analogous to a past Mars climate. Although multiple data sets were tested, we focus on a semiarid, Great Plains climate from central Kansas and an arid, desert climate from the Gila River catchment to the southwest of Phoenix, AZ (Figure S1 in the supporting information). Model results are most sensitive to the mean annual ratio of E_p to P , referred to as the aridity index (ϕ), with less sensitivity to the annual precipitation. The Kansas and Arizona climates have aridity indices of 3.6 and 9 and are seasonally representative of semiarid to arid climates, respectively. The semiarid and arid climate data sets were scaled to investigate a range of aridity indices and annual precipitation rates to allow for an investigation of a wide range of climate parameters while maintaining a consistent seasonal profile for each aridity range. We transition between the scaled Kansas and scaled Arizona climate at an aridity index of 5, although this transition has little effect on the results. For this study, we investigated an aridity index range between 1.5 and 33, representing an aridity range that encompasses subhumid (1.5 to 2), semiarid (2 to 5), arid (5 to 20), and hyperarid (above 20) climates, while maintaining a constant annual precipitation of 160 mm/yr. At aridity indices above 20, this annual precipitation rate is unrealistically high for such hyperarid climates on Earth. For the sake of consistency, we maintain this constant annual precipitation rate to investigate the lake behavior for different aquifer permeability values and aridity indices. Other annual precipitation rates were also investigated over this aridity index range for annual precipitation rates of 26, 50, 100, 320, 600, and 800 mm/yr, encompassing hyperarid desert climates similar to the Arabian and Namib Deserts (<100 mm/yr), and semiarid steppe climates, similar to central Kansas (300 to 800 mm/yr). Although higher and lower annual precipitation rates were investigated for select aridity indices, annual precipitation only had a minor influence on the aridity index inferred for the late-stage lakes at Gale. We emphasize that our model does not explicitly take temperature into account, depending only on the rates of evaporation and precipitation. The model does require mean annual temperatures above freezing in order to allow for a vertically integrated hydrological cycle in which infiltration is not impeded by a continuous permafrost layer.

Surface boundary conditions to the groundwater and surface runoff models were determined from the climate data using an empirical method from terrestrial hydrology known as the Budyko relationship [Budyko, 1974]. The Budyko relationship determines the fraction of precipitation falling on the surface that evaporates into the atmosphere rather than contributing to runoff and aquifer recharge. Budyko-type estimates of evaporation from watersheds approximate the microscale processes at the surface-atmosphere interface using empirical discharge data from terrestrial basins. This method derives a functional relationship for the actual evaporation within a given basin dependent on the evaporation potential, the aridity index, and a shape parameter (ω) [Zhang *et al.*, 2004]. In terrestrial hydrology, the shape parameter is derived for specific catchments of interest based on measured runoff and climate fluxes and is based on the hydrologic and atmospheric properties of individual catchments (see supporting information). We considered shape parameters between 1.3 and 2. Water that does not evaporate back into the atmosphere is partitioned into either deep aquifer recharge or surface runoff to lakes. For the purpose of this study, an equal partitioning to recharge and runoff was used (see supporting information).

While multiple processes may control runoff and channelized flow, the large time steps associated with numerical subsurface modeling in comparison with the timescales for dynamic surface runoff necessitate the use of a simple analytic approximation to represent runoff [e.g., Cunge, 1969; Overton, 1970; Dooge, 1973]. For this study, a linear reservoir approximation was used to determine surface runoff based on the assumption that the storage in a catchment is linearly related to the runoff in the catchment. Water that recharges the aquifer will flow in the subsurface, which was modeled using a finite difference approximation to the groundwater flow equation, dependent on the permeability distribution, aquifer depth, and intrinsic properties of water. Lake formation was allowed to occur where the water table intersected the surface. Ponded surface water was then run through a lake diffusion scheme in order to bring each lake surface to an approximately constant hydraulic head.

For the subsurface model, we assumed a laterally homogenous aquifer in which the permeability varies with depth based on the megaregolith aquifer model of Hanna and Phillips [2005] (herein referred to as the nominal aquifer model). This model assumed a brecciated megaregolith overlying a fractured basement. The Gravity Recovery And Interior Laboratory (GRAIL) data from the Moon found that the highly impacted

Figure 1. (a) Mars Orbiter Laser Altimeter topography of the Gale crater region showing the inferred post-Aeolis Mons lake stands in Gale (colored outlines) [Palucis *et al.*, 2016] and identified open- and closed-basin lakes outside of Gale (“O” and “C,” respectively) [Cabrol and Grin, 1999; Fassett and Head, 2008; Goudge *et al.*, 2015]. Lakes (shown in black) and hydraulic head maps (contour) overlain on Gale crater topography for different aridity indices of (b) 1.5, (c) 3.5, and (d) 9. All models shown are compared to the highest observed lake stand (shown as the white outline) and use an annual precipitation 160 mm/yr, a $k = 3 \times 10^{-13} \text{ m}^2$ and a shape parameter of 1.6.

lunar surface maintains high porosity to great depth [Wieczorek *et al.*, 2013; Besserer *et al.*, 2014; Soderblom *et al.*, 2015], which may support a higher permeability for the heavily impacted southern highlands on Mars. For the purpose of this work, we investigate a range of vertically averaged permeabilities from the surface to 10 km between $3 \times 10^{-14} \text{ m}^2$ and $3 \times 10^{-11} \text{ m}^2$, an order of magnitude lower and 2 orders of magnitude higher than the nominal aquifer model ($3 \times 10^{-13} \text{ m}^2$). Each aquifer permeability model follows the same decrease with depth as the nominal aquifer model, with a 100 times decrease in the vertically averaged permeability from the surface to a depth of 5 km. Flow within the aquifer is controlled by the average permeability between the water table (which varies in space and time) and the base of the aquifer. Aquifer porosity is assumed to follow a simple exponential decrease with depth, with a porosity at the surface of 0.2 [Clifford and Parker, 2001; Bahr *et al.*, 2001]. Full details of the surface and subsurface hydrological model are given in Horvath *et al.* [2016].

3. Lake Stand Dependence on Climate and Permeability

The predicted surface elevation of a lake in Gale crater is primarily dependent on the aridity index (E_p/P ; Figure 1). For the nominal permeability model, subhumid conditions at an aridity index below 2 predict lake levels that exceed the highest observed lake stand (Figures 1b and 2a), while arid conditions at an aridity index above 6 predict lake levels that fall short of the lowest observed lake stand in Gale crater (Figures 1d and 2a). Depending on the amount of water assumed to participate in the surface and subsurface hydrology (as determined by the shape parameter, ω), an aridity index range between 3 and 4, in the semiarid regime, matches the highest lake stand at -3280 m elevation for the nominal permeability model at an annual

Figure 2. The dependence of the Gale crater lake elevation on the aridity index is shown for (a) several shape parameters at an annual precipitation of 160 mm/yr and an aquifer permeability of $3 \times 10^{-13} \text{ m}^2$, (b) different annual precipitation values for a shape parameter of 1.6 and a permeability of $3 \times 10^{-13} \text{ m}^2$, and (c) different aquifer permeabilities at an annual precipitation of 160 mm/yr and a shape parameter of 1.6. The horizontal dashed lines are the lake stands inferred by Palucis *et al.* [2016] and correspond to the colored contours in Figure 1, while the vertical lines delineate climate zones.

precipitation of 160 mm/yr (Figures 1c and 2a). The subsurface flow contribution to these lakes is between 39% and 47% of the total influx depending on the assumed shape parameter. An aridity index range between 4 and 6, at the transition between a semiarid to arid climate, fits the lowest inferred lake stand at -3980 m elevation. An aridity index range between 3.5 and 5 fits the middle lake stand at -3780 m elevation, proposed as the final major lake stand in Gale. At the assumed annual precipitation of 160 mm/yr, this range of aridity indices (3–6) is comparable to water-limited semiarid desert regions on Earth, similar to high-altitude regions of the Great Basin in the western United States and the eastern slope of the Andes mountain range in Patagonia.

The nominal permeability model predicts lake formation in the majority of large southern highland craters in the proximity of Gale crater as well as ponding in topographic lows in the northern lowlands. Many of these southern highland craters exhibit evidence for open- and closed-basin lakes (Figure 1a) [Cabrol and Grin, 1999; Fassett and Head, 2008] including Sharp crater to the west of Gale, found to have fan deposits and a similar mineralogy as Gale crater [Ehlmann and Buz, 2015]. The modest permeability in these models causes a steep hydraulic head gradient and a near-surface water table, forcing water to the surface in local topographic lows. Although evidence for widespread lakes is not observed at this location in the northern lowlands, fluvial systems are observed at the dichotomy boundary [Kite *et al.*, 2015] that may have channeled away much of the fluid that forms the modeled northern lowland lakes. Present-day topography includes partially eroded Aeolis Mensa deposits and young impact craters in which lakes are predicted to form, and thus, much of the ponding in the northern lowlands predicted by the models may not have actually occurred.

Although the aridity index has the strongest influence on the Gale lake elevation, the annual precipitation also influences the distribution of lakes inside and outside of Gale. Decreasing the annual precipitation for a given aridity index (and thus decreasing the evaporation potential proportionally) results in a proportional decrease in aquifer recharge. A lower aquifer recharge rate and lower evaporation rate over the Gale crater lake will result in a deeper aquifer and thus fewer lakes outside of Gale, in turn resulting in a larger Gale crater lake for decreased annual precipitation at a given aridity index. In other words, at lower precipitation rates Gale captures more of the regional groundwater flow and the Gale lakes are stable at higher aridity indices. At the lowest annual precipitation shown here (50 mm/yr), an aridity index in the arid climate regime (6) matches the lowest lake stand in Gale, although a semiarid climate (4) is still required to match the highest lake stand, even at this low precipitation (Figure 2b). In contrast, a higher annual precipitation predicts a shift toward lower aridity indices. For annual precipitation rates $<600 \text{ mm/yr}$, a semiarid climate range is still required. However, we find that the absolute precipitation rate has a much weaker influence on the outcome of the models than the aridity index. For the full range of precipitation rates considered, the observed range of lake stands can be met with aridity indices ranging from 2.5 to 6, similar to the results from the range of shape parameters considered.

Figure 3. Lakes (shown in black) and hydraulic head maps (contour) overlain on Gale crater topography for different combinations of aridity indices and permeabilities that predict lake levels matching the highest lake stand in Gale crater. Panels show (a) $\phi = 4$ and nominal aquifer model, (b) $\phi = 5$ and 10 times permeability, and (c) $\phi = 9$ and 100 times permeability. All models shown use an annual precipitation of 160 mm/yr and a shape parameter of 1.6 and match the highest observed lake stand (shown in the white outline).

with the earlier Gale lake stands. Given their proximity to Gale, it seems probable that lake-stage lakes may have existed in those basin as well. Furthermore, it is difficult for the high permeability models to match the open-basin lakes at any time independent of the constraints on the Gale lake. At the highest permeability investigated here, a climate much wetter than the semiarid conditions inferred are required to match the open-basin lakes, contrary to climate estimates during the Noachian. In contrast, low-permeability models match the Gale lake for wetter climates but predict a shallower water table and more lakes outside of

The aquifer permeability also influences the predicted Gale crater lake elevation and the distribution of lakes outside of Gale (Figure 3). As permeability is increased, subsurface flow becomes a prominent source to the Gale crater lake, allowing a given lake stand to be achieved for more arid climates. However, relative to the nominal permeability model, this also has the effect of reducing the lake area outside of Gale crater, similar to the effects of lowering the annual precipitation. The high permeability and lack of lakes outside of Gale crater in these models enhances subsurface flow to Gale by tapping an extensive recharge zone, driving long-distance subsurface flow and resulting in a stable Gale crater lake for drier climates. As a result, for an aquifer model with higher permeability than the nominal model, more arid climates fit the range of observed lake stands in Gale crater. An aridity index of 5, at the transition between semiarid and arid climates, fits the highest Gale lake stand for a permeability 10 times the nominal model (Figure 2c). Likewise, a permeability 100 times the nominal model matches the highest lake stand at an aridity index of 9, well into the arid climate range (Figure 2c). However, these high permeabilities fail to meet the constraint imposed by geological evidence for lakes within a number of craters outside of Gale (compare Figures 3b and 3c and Figure 1a). There is geologic evidence that the lakes outside of Gale may have been present prior to the late-stage Gale lakes [Irwin *et al.*, 2005b; Fassett and Head, 2008] and thus been contemporaneous

Gale. Although it is difficult to argue against the presence of numerous small lakes as predicted by these models, there is no geological evidence supporting their existence. While permeability has a larger impact on the climates required to support the Gale crater lake relative to the annual precipitation and the shape parameter, both the highest and lowest permeability models are difficult to reconcile with evidence for lakes outside of Gale.

4. Discussion

This work provides constraints on the post-Noachian climate at Gale crater using a hydrologic model and indicators of paleolake levels. These climatic inferences cannot be made based on the lake levels alone, since lake levels are controlled by the complicated interplay of the surface and subsurface hydrology, and by the effects of the unique topography surrounding this crater situated on the dichotomy boundary.

Results favor a semiarid climate for the post-Aeolis Mons lakes, possibly reaching arid climates for the lower lake stands depending on the assumed annual precipitation, shape parameter, and permeability. The nominal aquifer model coupled with an annual precipitation between 50 and 600 mm/yr matches the full range of Gale crater lake stands and predicts lakes in southern highland craters that roughly match the observed open-basin lakes [Cabrol and Grin, 1999; Fassett and Head, 2008] at aridity indices between 2.5 and 6, corresponding to climates ranging from the Eurasian steppe or western Kansas, to the Great Basin desert in the United States or eastern slope of the Andes mountain range in Patagonia. These models also show that subsurface flow is an important component of inflow to the Gale crater lake, accounting for ~39% to 47% of the total influx at the highest lake stand for the nominal permeability models.

Inferred climates in the semiarid to arid range at this time in the post-Noachian are consistent with previous estimates of the climate on Mars during the Noachian based on geomorphology and the properties of the fluvial systems [Howard, 2007; Hoke et al., 2011; Matsubara et al., 2011, 2013]. Combined with the existing interpretations of the evolution of Gale crater, these results indicate drastic climate change over the lifetime of the hydrological system at Gale. Wet conditions were required to form the Murray formation mudstones at the base of Aeolis Mons [Grotzinger et al., 2015]. A transition to sustained arid conditions is then required to explain the evaporitic sulfate cementation of aeolian sediments found at higher elevations in the mound [Milliken et al., 2010; Thomson et al., 2011], similar to the sulfate deposits found by the Mars Exploration Rover Opportunity at Meridiani Planum [Grotzinger et al., 2005; McLennan et al., 2005; Squyres and Knoll, 2005; Arvidson et al., 2006, 2014] and elsewhere on Mars [Bibring et al., 2006; Glotch and Rogers, 2007; Murchie et al., 2009; Zabusky et al., 2012]. Subsequently, a further increase in the aridity and a drop in the water table deep beneath the surface are required to explain the erosion of the crater fill to the present-day mound shape [Andrews-Hanna et al., 2010; Zabusky et al., 2012]. Finally, the results of this work indicate a return to semiarid conditions at some point during the Hesperian or later in order to produce the late-stage Gale crater lakes. Thus, although evidence supports increasingly arid conditions on Mars during the transition from the Noachian through Hesperian, the climate was clearly variable on shorter timescales with returns to Noachian-like conditions for sufficiently long periods of time to produce the observed deltas and associated late-stage lakes [Palucis et al., 2016].

Although much remains to be done to work out the details of Mars' climate evolution, and debate continues between warm-wet [e.g., Craddock and Howard, 2002; Hynek and Phillips, 2003; Hynek et al., 2010; Ramirez et al., 2014] and cold-icy scenarios [e.g., Carr and Head, 2003; Fastook et al., 2012; Wordsworth et al., 2015], our work shows that these late lake stands in Gale crater are consistent with semiarid climates with active hydrological cycles that require mean annual temperatures above freezing. With continued observations of the extent and elevation of lake bed deposits from MSL as it climbs Aeolis Mons, we can further constrain the past Martian climate and hydrogeology.

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