THE INFLUENCE OF CLIMATE AND PERMEABILITY ON THE FORMATION AND GEOLOGIC STABILITY OF THE GALE CRATER LAKE. D. G. Horvath[1] and J. C. Andrews-Hanna[2,1], [1]Department of Geophysics and Center for Space Resources, Colorado School of Mines, Golden, CO, dhorvath@mines.edu. [2]Southwest Research Institute, Boulder, CO.

Introduction: While evidence exists for a warmer and wetter ancient Mars [1], the timing and sustainability of this past climate is still debated. Evidence for persistent late stage hydrology in Gale Crater over geologically long time periods (10^4-10^7 yrs [2]) raises questions regarding the nature of hydrology and climate on Mars. Mudstone layers on the crater floor provide evidence for a past lake with in Gale Crater [2] and fan deposits suggest younger surface hydrology [3]. The Gale Crater lake has implications regarding the past climate and the timing and nature of hydrological activity. This study explores the climatic and hydrological conditions needed to form a Gale Crater lake and the implications that this may have for the past climate of Mars.

Model: Remote sensing observations [4], ground-based observations [2], and hydrological modeling [5] have all identified evidence for extensive hydrological activity at Gale Crater. Previous hydrological modeling [5] identified preferential sites of groundwater upwelling and potential sedimentary deposits on Mars, using a global groundwater model to understand the formation of the Gale Crater mound (Mt. Sharp). These hydrological models identified Gale Crater as a region of preferential subsurface upwelling owing to its unique location on the dichotomy boundary. Here we focus on the regional subsurface and surface hydrology required to form the lake within the crater, using precipitation and evaporation potential rates from several Earth-based climates.

In this study, we used a hydrological model over Gale Crater that combines a finite-difference approximation of the groundwater flow equation to simulate subsurface hydrology with an analytical surface runoff model. The model was forced using evaporation potential and precipitation rates from Earth-based observations provided by the North American Land Data Assimilation Systems (NLDAS). The total annual aquifer recharge and surface runoff were determined from the precipitation and evaporation rates using an Earth-based empirical relationship [6], which uses the ratio of evaporation potential to precipitation to determine the amount of precipitation that will take part in the hydrological system.

Here we focus on a semi-arid Great Plains climate from central Kansas, although models were run for both an arid climate from Arizona and a marine climate from Seattle. With the semi-arid climate outputs, we then scaled the precipitation and evaporation potential rates to match the average annual totals for a range of other North American climates under controlled conditions.

In addition to climate, we also considered the subsurface properties, mainly focusing on the effects of aquifer permeability. These models considered a horizontally uniform aquifer permeability ranging from 10^{-9} cm^2, comparable to a consolidated bedrock aquifer, to 10^{-6} cm^2, comparable to a fractured aquifer, allowing permeability to exponentially decrease with depth due to the closure of pore space.

Results: While a dry Arizona climate predicts no stable lake formation in Gale Crater, a semi-arid Kansas climate and an intermediate permeability aquifer predicts two stable lakes to form within Gale Crater in the lowest elevation reaches in the northwestern and northeastern sections of the crater floor (Fig. 1a). The total lake area within Gale Crater is ~800 km^2 with the lake surface reaching up to 500 m above the crater floor. The total annual flux of subsurface and surface water required to stabilize these lakes is 1.8×10^9 m^3/yr and 0.5×10^9 m^3/yr respectively. While only 2% of the total annual precipitation reaches the hydrological system as either aquifer recharge or runoff based on the Earth-based empirical relationship [6], lake formation still occurs in Gale Crater, driven primarily by long distance subsurface flow from distal recharge to the aquifer.

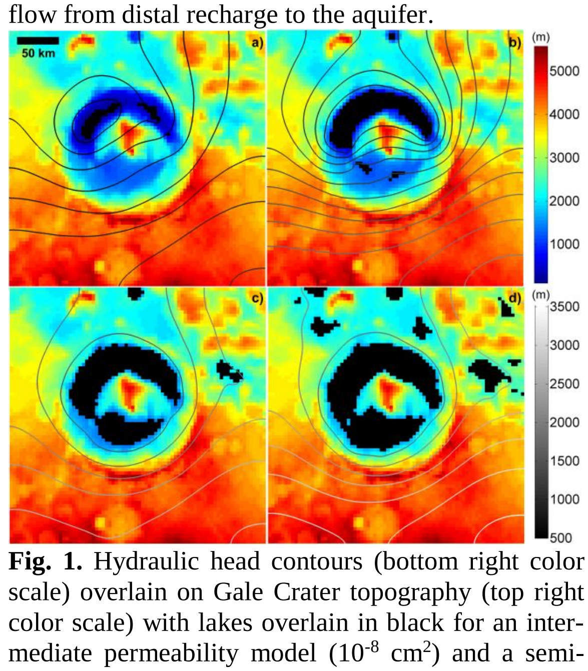

Fig. 1. Hydraulic head contours (bottom right color scale) overlain on Gale Crater topography (top right color scale) with lakes overlain in black for an intermediate permeability model (10^{-8} cm^2) and a semi-arid climate (a), a semi-arid climate allowing 2.4× (b), 5.5× (c), and 9× (d) more recharge and runoff.

A wetter climate (scaling the evaporation potential by 0.75 resulting in 2.4× more recharge and runoff) predicts a single large lake in northern Gale with smaller lake formation occurring in the southern half of the crater (Fig. 1b). A large continuous lake covers the entirety of the exposed crater floor for the wettest climates (scaling the precipitation by 1.3 and 1.7 and the evaporation potential by 0.8 and 0.92, resulting in 5.5× and 9× more recharge and runoff; Fig. 1c,d). These lakes range from 3700 km^2 to 9700 km^2 in area, reaching up to 1600 m above the crater floor. Saturation also occurs at low elevations and craters in the northern lowlands forming lakes beyond Gale Crater.

Aquifer permeability also influences the distribution of lakes within Gale Crater. For a semi-arid climate at high permeability (10^{-6} cm^2), a single large lake ~900 km^2 in area covers the northwestern floor of Gale Crater (Fig. 2a) while at lower permeability (10^{-9} cm^2) several smaller lakes form in the northern region of Gale crater ranging from 100 km^2 to 300 km^2 (Fig. 2b). Lower permeability decreases the influence of subsurface flow on lake stability with a total annual subsurface flow volume to all Gale Crater lakes of 1.2×10^9 m^3/yr, while the total annual volume of surface runoff was 0.8×10^9 m^3/yr. In comparison, the annual subsurface flow and runoff volumes for the high permeability model were 2.4×10^9 m^3/yr and 0.3×10^9 m^3/yr, respectively. Although permeability has an important effect on the distribution of lakes in semi-arid climates, it has only a modest effect on the total lake area. Thus, the lake area inferred from the sedimentary deposits is a strong indicator of the paleoclimate.

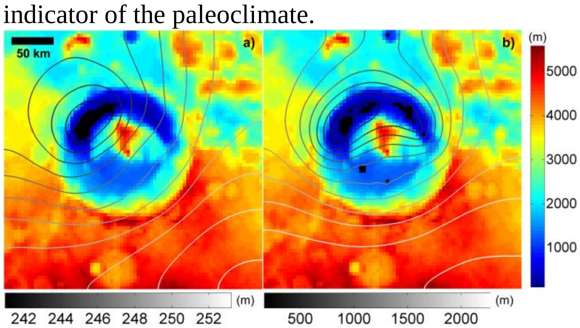

Fig. 2. Hydraulic head contours overlain on Gale Crater topography with lakes overlain in black for a high permeability (10^{-6} cm^2; a) and a low permeability (10^{-9} cm^2; b) aquifer under a semi-arid climate.

Permeability also influences the stability of lakes during dry climatic periods. Starting with a wet model (Fig. 1b) and transitioning to a dry Arizona climate, we test the influence of permeability on the stability of lakes. For a high permeability aquifer (10^{-6} cm^2), lake area rapidly decreases to negligible surface liquid ~5 Kyr after the dry climatic conditions begin (Fig. 3). High rates of subsurface flow in the high permeability models results in rapid removal of aquifer water to the lakes, where the water evaporates. In contrast, an intermediate permeability (10^{-8} cm^2) has a slower subsurface response to the removal of liquid from lakes, while allowing enough subsurface flow to stabilize lakes for up to ~10 Kyr. The lowest permeability case does not supply liquid to the lake rapidly enough to offset evaporation after the change to arid conditions, resulting in rapid lake loss (Fig. 3).

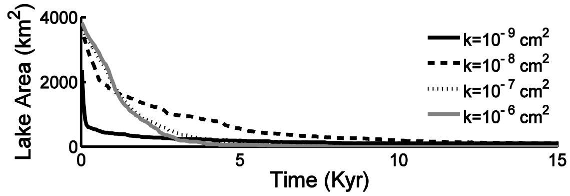

Fig. 3. Lake area over time for different permeability aquifers starting with the results for a scaled semi-arid climate (2.4× more recharge and runoff) and transitioning the model to an arid climate.

Conclusions: For a semi-arid climate, with only 2% of the total annual precipitation recharging the aquifer or running off over the surface, the formation of a single large lake (~900 km^2) for high permeability (10^{-6} cm^2) or several medium sized lakes (between 300 km^2 and 600 km^2) for intermediate permeability (10^{-8} cm^2) are predicted in Gale Crater. Permeability is also shown to affect the stability of lakes as Mars progresses to a drier climate with an intermediate permeability aquifer stabilizing lakes over longer periods of time.

Wetter climates predict a single lake covering the northern part of Gale Crater, while the wettest climates predict a lake covering the entire crater floor outside the central mound. In contrast, the driest case, using an Arizona climate, predicts no lake formation within Gale Crater. If the lake deposits discovered by MSL form the basal unit of the Mount Sharp deposit, this indicates that the lake at one time covered nearly the entire crater floor. These results suggest that the climate at the time was substantially wetter than that present in Kansas today. If instead the lake deposits are isolated and do not extend under Mount Sharp, a present day Kansas climate may explain isolated lakes in the northern crater floor.

References: [1] Hynek, B. M. et al. (2003) *Geology*, 31, 757-760. [2] Grotzinger, J. P. et al. (2015) *Science*, 350, 6257. [3] Palucis, M. C. et al. (2013) *JGR*, 119, 705-728. [4] Thompson, B. J. et al. (2011) *Icarus*, 214, 413-432. [5] Andrews-Hanna, J. C. et al. (2012) *3rd Conf. Early Mars*, 1680, id.7038. [6] Budyko, M. I. (1974) *Climate and life*, Academic Press., New York, 508.