FLUID FLOW IN THE MARTIAN SUBSURFACE DURING THE EARLY AMAZONIAN PERIOD CONSTRAINED VIA NUMERICAL SIMULATIONS: IMPLICATIONS FOR HABITABILITY.

E.V. Christou[1], L.J. Hallis[1], L. Daly[1,2], A.E. Pickersgill[1], T. Keller[1], C.L. Hayward[3], and M.R. Lee[1]. [1]School of Geographical & Earth Sciences, University of Glasgow, Glasgow, UK; [2]Space Science and Technology Centre, School of Earth and Planetary Sciences, Curtin University, Perth, Australia. [3]School of Geosciences, Grant Institute, University of Edinburgh, Edinburgh, UK; E-mail: e.christou.1@research.gla.ac.uk;

Introduction: Meteorites from Mars are a powerful source of knowledge that may decipher many of the geological mysteries of the red planet. We know that Mars once hosted abundant surface fluids and impact-induced hydrothermal activity [1-3]. However, it is yet unclear whether water-rock interactions on the planet's surface and subsurface ever resulted in the emergence of microbial life, and there is still weak consensus on whether our planetary neighbor was even habitable at some point in its geological history. Our research aims to determine whether fluid flow and water-rock reactions on Mars during the Amazonian period have been sufficient to produce a bioenergetic yield.

Methodology: In this work, we used the Hydrotherm (HT) 3 code of the USGS [4] to simulate the aqueous fluxes in two putative early Martian volcanic environments, constrained by the assumed host rock thermodynamic conditions of the shergottite (e.g., Northwest Africa (NWA) 8159) and nakhlite (Lafayette, NWA 817 and Nakhla) meteorite samples. In particular, the thermodynamics of the environments of origin of these Martian rocks were determined after obtaining Scanning Electron Microscopy - Energy Dispersive X-ray Spectroscopy (EDS) maps, Electron Probe Microanalysis, Transmission Electron Microscopy – EDS and Atom Probe Tomography datasets from the primary minerals and aqueous alteration products observed in our samples [5-10].

Starting from the boundary conditions of our simulations, the input parameters were defined via Fortran programming and the interface of the HT Interactive software. A putative 2D Martian geological setting of a 200 km horizontal distance and a maximum depth of 10 km from the Martian surface was designed for each scenario. The gravity value was decreased by 62% in our simulations to be consistent with Mars' field strength; furthermore, the porosity, permeability and decay constant of the Martian crust were adjusted according to the methodology followed by [11]. HT simulations have also the capability to suggest the depth within the Martian crust at which these volcanic rocks were emplaced and affected by hydrous flows.

For all sets of simulations, the top boundary of the simulative grid was programmed to represent the icy ground – Martian atmosphere boundary during the early-mid Amazonian ($T_{ground} = 0$ °C). The thickness of the ice deposits is assumed no greater than 2 m and the average thickness of the regolith is 50 m. The physical properties of the rocks beneath the regolith represent those of permeable ($k = 10^{-17}$ m^2) basalts. Deeper lithologies comprise lower permeability ($k = 10^{-18}$ m^2) basalts and gabbros ($k = 10^{-21}$ m^2, at a depth ≥ 6 km). All physical properties of the rocks were programmed according to the reported petrophysical properties of fractured lithologies in impact-induced and volcanic settings by [11-12]. Precipitation and runoff rates on the surface (top boundary) were adjusted to 0.5 mm/day and < 0.1 mm/day as reported for early Martian environments, respectively [13]. The basal heat flux was adjusted to a 10 km depth and programmed with a value of 17.5 mW/m^2 for low temperature hydrothermal scenarios ($T_{max} < 175$ °C). The basal heat flux (at a depth of 10 km) for moderate (175 °C $\leq T \leq 250$ °C) and higher (250 °C $\leq T \leq 360$ °C) temperature volcanic sources was assigned to values of 25 mW/m^2 and 40 mW/m^2, accordingly. Thus, this parameterization should account for a variety of heat flow estimates during the early-mid Amazonian period for both (shergottite and nakhlite) host rock environments (based on estimates by [14] for the Noachian period). Subsequently, six sets of simulations were performed in this work.

Results: *Modelling on the Shergottites*. Our simulations show that fluid flows in the modelled basaltic environment consistent with the shergottites' source region lasted from between 11 months to 160 years (yr) (Fig.1 - A2). The maximum lifetime of fluid flow in the shergottite source region is only attained by considering a plutonic heat source with 250 °C $\leq T_{max} \leq 360$ °C. Such a heat source has never been reported to have affected the shergottites; and so, this result should be considered as an overestimate of the lifetime of fluid flow for this setting. Hence, our computations rule out heating due to a plutonic source and suggest fluid flows with a $T_{max} \leq 250$ °C, and a maximum flux duration of 50 yr (A1) within the shergottite. Such aqueous flows should have occurred at depths ≤ 1 km, with Water Mass Flux (WMF) $\geq 9.0\text{e-}7$ g/s·cm^2 (Fig.1-A1; red envelopes at the upper boundary corners).

Modelling on the Nakhlites. We know that impact-cratering processes have affected the nakhlites' environment of origin [10, 15]. Thus, scenarios of impact-induced flows were additionally explored in our computations. The simulations revealed that low to mid temperature fluxes (175 ℃ ≤ T_{max} ≤ 250 ℃) may have kept the near surface hydrothermal cells (depth ≤ 2 km) active for more than 35 Kyr, with appreciable WMF ≥ 7.0e-7 g/s·cm^2 (Fig.1 – B1, B2). Conclusively, our results show that nakhlites hosted flows for a longer period than the shergottites; which is consistent with geochemical observations on the nakhlites [10, 16-17].

Implications for Habitability. The simulations presented in this work imply that since aqueous flows in the shergottites' host environment lasted for a short amount of time (months to 50 years), then it is highly unlikely for such a geochemical system to yield an appreciable bioenergetic potential, based on previous biogeochemical pathway reaction models by [18]; such models indicate that terrestrial basaltic rocks produce nanomolal to micromolal quantities of aqueous hydrogen and nutrients in the course of 100 Kyr. Thus, the bioenergetic potential of Martian shergottites could be considered negligible, according to our models. However, the impact-induced thermodynamics that affected the nakhlites could have provided appreciable flows into their host rock system and could have thus preserved the water-rock reactions for a longer time (up to 40-50 Kyr). Subsequently, fluid-(nakhlite) rock reactions may have released enough nutrients in the Martian subsurface realm for potential microbial communities to harvest for their metabolic pathways.

Acknowledgments: E.V. Christou and L.J. Hallis thank the Leverhulme Trust for the Research Project Grant 2018-298. Special thanks also to the developers of the HYDROTHERM 3 Code ([4]) and the USGS. A.E. Pickersgill is supported by the Leverhulme Trust Research Project Grant number RPG-2018-061.

References: [1] Ehlmann B.L. et al. (2011) *Nature*, 479, 53-60. [2] Wray J.J. (2013) *I.J. of Astrobiology*, 12, 25-38. [3] Osinski G.R. et al. (2012) *Icarus*, 224 (2), 347–363. [4] Kipp K.L. et al. (2008) *USGS*, Version 1, 6–A25. [5] Christou E.V. et al. (2020) *51st LPSC Abstract* #1100. [6] Hallis L.J. et al. (2012) *GCA*, 97: 105–119. [7] Hallis L.J. and Taylor G.J. (2011) *MAPS*, 46: 1787– 1803. [8] Lee M.R. et al. (2015) *GCA*, 154, 49-65. [9] Lee M.R. et al (2018) *MAPS* 53, 2395–2412. [10] Daly L. et al. (2019) *Science Adv*. 5 (9): eaaw5549. [11] Abramov O. and Kring D.A. (2005) *JGR*, 110, E12S09. [12] Lamur et al. (2017) *Scientific Reports*, 7 (6173). [13] Ramirez R.M. et al. (2020) *J.G.R. Planets*, 125 e2019JE006160. [14] Ojha L. et al. (2020) *Science Adv*. 6 (49), eabb1669. [15] Fritz J. et al. (2005) *MAPS*, 40 (9/10) 1393–1411. [16] Changela H. and Bridges J.C. (2011) *MAPS* 45, 1847-1867. [17] Udry A. et al. (2020) *JGR: Planets*, 125, e2020JE006523. [18] Bach W. (2016) Frontiers in Microbiology, 7:107.

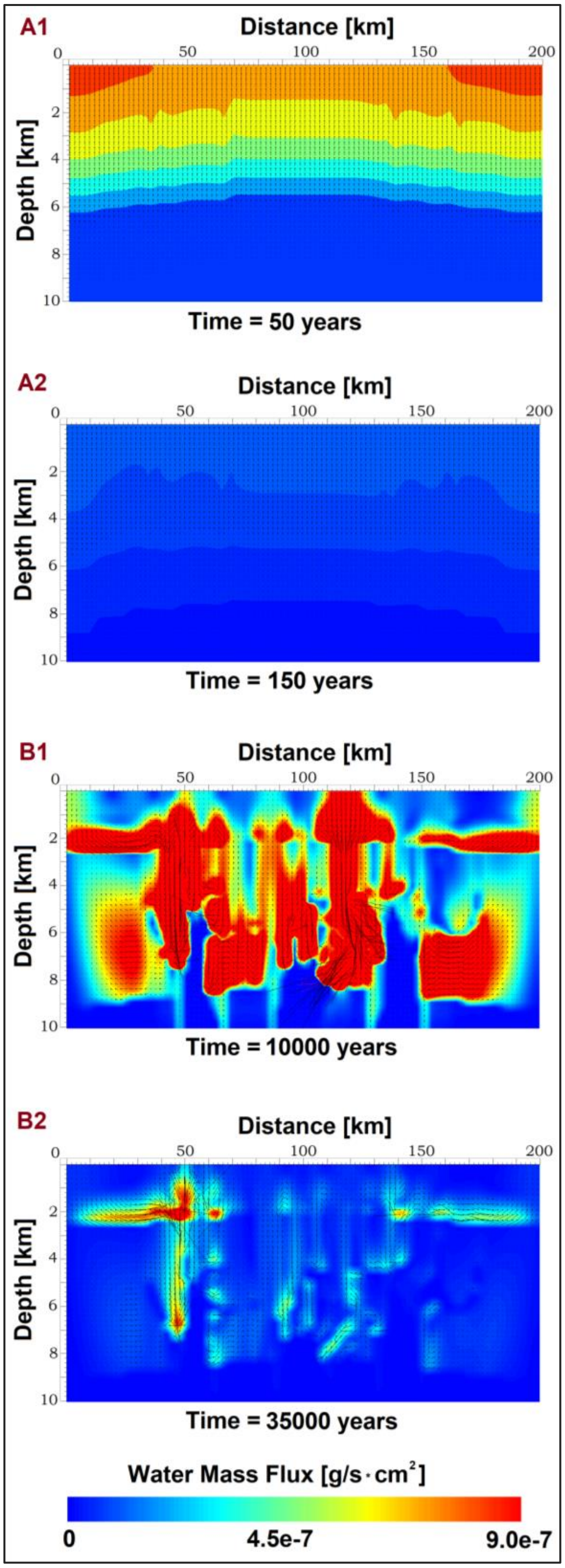

Figure 1. *Water flow in two putative Martian volcanic settings; A1 and A2 illustrate the water flux evolution in the shergottites' environment of origin, where* T_{max} ≤ *250℃. B1 and B2 show the aqueous flow evolution in the host rock of nakhlites, where 175℃ ≤* T_{max} ≤ *250℃.*