MARS' SUBSURFACE ENVIRONMENT: WHERE TO SEARCH FOR GROUNDWATER? A.-C. Plesa[1], V. Stamenković[2], D. Breuer[1], E. Hauber[1], J.D. Tarnas[3], J.F. Mustard[3], M. Mischna[2] and the TH2OR and VALKYRIE Teams. [1]DLR Institute of Planetary Research, Berlin, Germany (ana.plesa@dlr.de), [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA, [3] Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, USA.

Introduction: The surface of Mars has been shaped by liquid water during its planetary evolution. Geomorphological analysis, spectroscopic investigations to generate mineralogical surface maps and rover measurements show evidence for outflow channels, valley networks, deltas [1], sedimentary deposits [2], hydrated minerals [3], cementation [4] and mineral veins containing, e.g., manganese oxides that require water [5]. Such features amongst many others suggest that liquid water was present at the surface and in the subsurface of Mars throughout the Noachian and in transient episodes during the Hesperian and Amazonian [6, 7], which has important implications for the habitability of the planet.

Today, liquid water is generally thermodynamically no longer stable at the surface due to the low temperature and pressure conditions. However, liquid groundwater may still exist in the martian subsurface [8, 9]. Evidence for such a global groundwater system on early Mars has been reported in a recent study [10]. Part of the surface and subsurface water has been lost to space, but part of it may be locked today in the subsurface as ice and liquid groundwater. If the post-Noachian crustal H_2O inventory was ~100s meters GEL or more, [11] concluded that modest loss since then would suggest that groundwater likely exists globally on Mars today. This is further supported by the measured deuterium-to-hydrogen ratio (D/H), which indicates that the total water loss since the Hesperian has only been about 60 m (interquartile range 30-120: [11]). In addition, heat flux estimates for modern Mars [12] allow for subsurface conditions that are favorable for liquid groundwater.

In this work we discuss the presence and distribution of potential liquid groundwater on Mars based on the thermal state of the subsurface as predicted by thermal evolution models of Mars.

Methods: We calculate the depth at which the conditions are favorable for liquid water assuming that a cryosphere exists globally on Mars today. To this end, we use fully dynamical 3D thermal evolution models [13, 14] and 3D parametrized models [15, 16]. While the former calculate the temperature distribution during the entire evolution self-consistently, taking into account the effect of mantle plumes, such models are computationally expensive, and large parameter ranges are difficult to cover. The 3D parametrized models, though requiring additional parametrizations to be able to account for thermal anomalies in the mantle, are computationally fast and can cover a large range of parameters. Both type of models calculate the subsurface temperature over the entire thermal history of Mars. In addition, both models are coupled to a 3D crustal model that is compatible with today's gravity and topography data [14, 17].

Some of the most important parameters that affect the depth of liquid water are the spatial variations of crustal thickness and crustal thermal conductivity, since the crust has a lower thermal conductivity compared to that of the mantle and can shift the groundwater table locally closer to the surface (Fig. 1). The amount, but in particular the distribution of heat sources and the presence of mantle plumes, can introduce additional perturbations to the depth of groundwater. The surface temperature distribution and the presence of salts and clathrate hydrates considerably affect the depth and locations where subsurface liquid water may be stable. In particular hydrated magnesium (Mg) and calcium (Ca) perchlorate salts, whose presence has been suggested at various locations on Mars [18, 19], may significantly reduce the melting point of water ice. In addition to thick regolith layers, clathrate hydrates, if present in the subsurface, would provide an insulating effect reducing the crustal thermal conductivity at least locally [e.g., 20].

In our simulations, we use various 3D crustal thickness models compatible with gravity and topography data [11]. We vary the crustal thermal conductivity and the amount of heat sources located in the crust. In addition, we test the effects of salts and quantify the effect of mantle plumes for the location of groundwater table.

Results: The effects of the crustal thermal conductivity and of salts on the depth of subsurface liquid water are shown in Fig. 1. All cases in Fig. 1 use the same crustal thickness model and crustal enrichment in radioactive heat sources. The model in Fig. 1a assumes an average crustal conductivity of 3 W/mK, while the model in Fig. 1b has a lower conductivity of only 2 W/mK (see panel 1e for the spatially averaged conductivity profiles that, due to crustal thickness variations, show average values between mantle and crust in the topmost 110 km). Fig. 1d shows the effect of the crustal thermal conductivity on the subsurface temperature profile. For the lower conductivity case the subsurface temperature is warmer, and the groundwater table shifts, on average, 2.5 km closer to the surface. The model shown in Fig. 1c is similar to the one in Fig. 1a but assumes the presence of salts. Instead of using the melting temperature of pure water ice, as was done for the models in Fig.

1a and b, we lower the melting temperature to 199 K over the entire depth, by assuming that $Ca(ClO_4)_2$ is present in eutectic concentration (Fig. 1f).

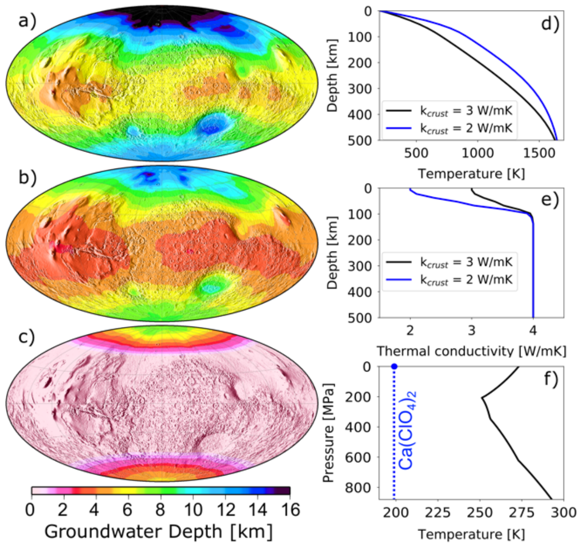

Figure 1: *Thermal evolution models to determine the groundwater depth: a-c) groundwater depth at present day. Case a) uses a crustal thermal conductivity of 3 W/mK and assumes the melting temperature of pure water ice, case b) uses a thermal conductivity of 2 W/mK and the melting temperature of pure water ice, and case c) uses the same crustal conductivity as case a) but assumes that $Ca(ClO_4)_2$ is present in eutectic concentration, and, hence, the melting temperature of ice is reduced to 199 K [21] over the entire depth; d) average temperature profiles in the uppermost 500 km for case a) and case b); e) the corresponding thermal conductivity profiles. The depression of the melting temperature of pure water ice by $Ca(CO_4)_2$ is illustrated in panel f) (see text for details).*

Although this assumption is extreme, it places constraints on the minimum depth at which liquid water may be present in the martian subsurface today, since kinetic factors such as the flow of groundwater due to gravity may increase the depth of the water table, depending on the total amount of liquid water, porosity and permeability.

In Fig. 1a and b, the depth of the groundwater shows the combined effect of crustal thickness distribution and surface temperature variations. Mantle plumes have only a small effect on the cryosphere/liquid water table interface and may introduce perturbations only if the groundwater is located, on average, at about 5 km depth or deeper. The effect of the crustal thickness is mainly evident in basins, along the dichotomy, and in volcanic provinces, whereas surface temperatures give general water table depth trends with latitude. In Fig. 1c the effect of the crustal thickness is minimal, as the groundwater table is located very close to the surface (between 0 – 1 km for latitudes between -57° and 57°). The depth variations of the groundwater table are mainly caused by the surface temperature distribution. Nevertheless in all cases (Fig. 1a – c), the water table is shallower in equatorial regions compared to polar regions, and it is deeper at the martian north pole (latitude > 70°) than at the south pole (latitude < -70°) due to a combination of differences in crustal thickness and surface temperature.

Implications for future missions: Our results suggest that the Martian subsurface has had, and still has, the potential to enable deep environments with stable liquid groundwater. Combined with the analysis of geomorphological features at the martian surface and maps of subsurface water ice [22], such models could provide valuable estimates of the depth of liquid groundwater on past and present-day Mars.

Due to attenuation, MARSIS and SHARAD measurements generally have great difficulty detecting groundwater beneath a depth of a few hundred meters, particularly on an aquifer horizontal scale of less than a few tens of km and away from the polar caps. Since initial estimates of the groundwater table are generally beyond a depth of 1 km [8, this study], martian groundwater is difficult to detect with current missions. However, the technology to probe the martian subsurface at depths of 10s of meters to kilometers is getting ready [9]: TH_2OR (Transmissive H_2O Reconnaissance), a low-mass and low-power transient electromagnetic sounder capable of detecting the presence of liquid water to depths of kilometers is currently being developed at JPL [23]. Moreover, mission concepts such as VALKYRIE (Volatiles And Life: KeY Reconnaissance & In-situ Exploration) [24], which would add to the liquid water sounder a drill capable of accessing depths of 10s-100s of meters or more and a (bio)geochemical analysis package on the surface, would provide the measurements necessary to characterize the modern-day subsurface habitability of Mars.

References: [1] Fassett C. & Head J., 2008, *Icarus,* 198(1); [2] McLennan S. et al., 2019, *Annu. Rev. Earth Planet. Sci.*, 47; [3] Ehlmann B. & Edwards C., 2016, *Annu. Rev. Earth Planet. Sci.*, 42; [4] McLennan S. et al., 2005, *EPSl*, 240(1); [5] Lanza N. et al., 2016, *GRL*, 43; [6] Carr M. & Head J., 2010, *EPSL*, 294(3-4); [7] Grotzinger J. & Milliken R., 2012, *Sedim. Geol. Mars*, 102; [8] Clifford et al., 2010, *JGR*, 115(E7); [9] Stamenković V. et al., 2019, *Nat. Astron.,* 3(2); [10] Salese F. et al., 2019, *JGR*, 124(2); [11] Grimm R. et al., 2017, *JGR*, 122(1); [12] Plesa A.-C. et al., 2018, *GRL*, 45(22); [13] Hüttig C. et al., 2013, *PEPI*, 220; [14] Plesa A.-C. et al., 2016, *JGR*, 121(12); [15] Breuer D. & Spohn T., 2006, *PSS*, 54(2); [16] Thiriet M. et al., 2018, *PEPI*, 286; [17] Wieczorek M. & Zuber M., 2004, *JGR*, 109(E8); [18] Kounaves S. et al., 2014, Icarus, 232; [19] Leshin L. et al., 2013, Science, 341; [20] Kargel J. et al. 2007, *Geology*, 35(11); [21] Marion G. et al., 2010, *Icarus*, 207(2); [22] Piqueux S. et al., 2019, *GRL*, 46.; [23] Burgin M. et al., 2019, AGU Fall Meeting, P44B-02; [24] Mischna M. et al., 2019, AGU Fall Meeting, P41C-3466.

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