# A STORY OF WATER, ICE, AND FIRE ON MARS: CONDITIONS FOR GENERATING LIQUID WATER UNDER THE SOUTH POLAR LAYERED DEPOSITS

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**Introduction:** Identification of liquid water on Mars is profoundly important for a variety of geological, astrobiological, and exploratory reasons. Recently, a deposit of liquid water has been proposed at the base of the south polar layered deposits (SPLD) [1]. This identification was made using the MARSIS instrument aboard ESA's Mars Express spacecraft. Analysis of radar returns revealed an anomalously bright locality, which was inferred to be sourced from material with dielectric permittivity >15. This material was interpreted to be liquid water at the SPLD base. Water could be generated at this location if the overlying 1.5-km-thick ice provided enough insulation to achieve melting at the base, and the authors argued that salts were required to facilitate this process by lowering the melting point of basal ice [1].

Here, we show that no quantity of salt is sufficient to melt ice at the base of the SPLD under typical Martian conditions. First, we calculate temperature-depth profiles through the SPLD using thermal models that consider important factors such as temperature-dependent thermal properties, dust content, orbital parameters, and geothermal heat flux. Second, we compare basal temperatures to the melting points of various $H_2O$-perchlorate mixtures, and show that a substantially enhanced geothermal heat flux is necessary to melt ice at the SPLD. Third, we use finite element method (FEM) models of heat diffusion to show that subsurface magmatism could plausibly create the required thermal environment for melting of ice. We conclude that liquid water at the south pole of Mars would require magmatic activity to exist, no matter the salt content [2].

**Temperature-depth profiles:** We use Fourier's law of thermal conduction to calculate vertical temperature-depth profiles through the 1.5 km of SPLD ice at the location of the putative liquid water. Our approach is similar to methodology used by previous studies that quantified the conditions under which basal melting could be achieved at the polar deposits [3–5].

We calculate an annual-average surface temperature of 162 K using a 1D thermal conduction model [6]. The SPLD is assumed to be an ice-dust mixture, and we allow for volumetric dust contents ranging between 0–20%. Thermal conductivity of SPLD material is dependent upon both temperature and composition. Geothermal heat flux is considered a free parameter. Example results of temperature-depth profiles for a few parameters are shown in Figure 1.

**Basal melting:** The goal of our thermal simulations is to quantify what salt content and geothermal heat flux are necessary to achieve melting of ice at the base of the SPLD. We thus record the temperature at the bottom of our temperature-depth profiles, and determine if it exceeds the melting point of various chemical mixtures.

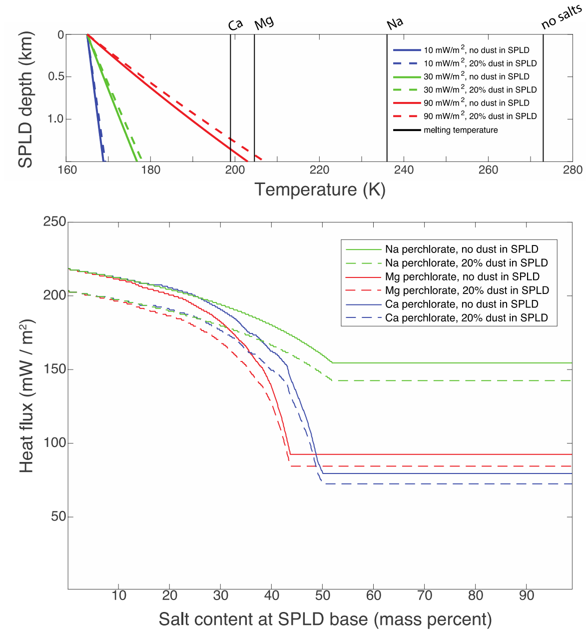


**Figure 1.** *Top*: Simulated temperature-depth profiles in the SPLD at the location where basal liquid water has been proposed. Vertical lines are where at least partial melting of $H_2O$ will occur for cases of pure ice and ice mixed with Ca, Mg, or Na perchlorate. *Bottom*: Minimum geothermal heat fluxes required to fully melt SPLD basal ice as a function of salt content at the base and dust content in the ice.

The compositions we consider are $H_2O$-perchlorate mixtures. Mg, Ca, and Na perchlorates were detected on Mars by the Phoenix Lander [7], and so those are the salts we consider here. The temperature at which any water is generated is given by laboratory experiments and theoretical calculations [8, 9]. The minimum temperatures to reach the melting point are 236 K for Na, 205 K for Mg, and 199 K for Ca. For the case of all the $H_2O$ being liquid, these temperatures correspond to salt concentrations at or above the eutectic points, >52%, >44%, or >50%, of the Na, Mg, or Ca perchlorate by mass in the solution, respectively.

We find that a heat flux of at least 72 $mW/m^2$ is needed to generate liquid water, under ideal conditions

(20% dust in the SPLD, Ca perchlorate at the base). This result assumes a high perchlorate content of >50% by mass if it were to cause complete melting of $H_2O$ at the base. Perchlorates may act as nucleation particles for ice in the atmosphere [10], and then become concentrated at the SPLD via migration of thin films of liquid water [11] or repeated episodes of sublimation when the units currently at the bottom of the SPLD were near the surface [12]. If instead no perchlorates are present, a heat flux of at least 204 mW/m$^2$ is required for basal melting. See Figure 1.

**Magmatism on Mars:** The minimum geothermal heat flux of 72 mW/m$^2$ is too high to be attained under typical Martian conditions. A commonly used value for the average Martian heat flux is 30 mW/m$^2$ [13], and geophysical analysis of loading of the north polar deposits suggests that even that value is too high [14]. A global average of 19 mW/m$^2$ has been proposed, with regional variations across the planet ranging from 14–25 mW/m$^2$ [15]. NASA's InSight mission will elucidate this number [16], but it is highly unlikely to discover a value so high that would allow basal melting at the SPLD today. If liquid water is present at the SPLD base, special local conditions must be invoked.

A plausible set of processes that could substantially elevate local heat fluxes consists of magmatic processes. Studies have identified volcanic features with ages in the late Amazonian [e.g., 17, 18]. Thus, while volcanic eruptions have not been observed in real-time on Mars, it is likely the planet retains some degree of igneous activity, which could generate a local enhancement in geothermal heat flux. Other factors that can lead to increased geothermal heat flux [e.g., 19] are either not applicable to Mars (plate tectonics), would not elevate the heat flux enough (concentration of radioactive elements), or are already considered in the average heat flux calculations (crustal thickness).

We use 2D FEM models of heat diffusion to quantify the heat flux that would be present above a cooling magma chamber on Mars. We assume a circular chamber geometry of diameter *D* buried at a depth *H* beneath the SPLD. The magma is assumed to be instantaneously emplaced at a temperature of 1300 K. The magma chamber cools, and heat diffuses through the crust. We record the heat flux directly above the magma chamber at the interface between the bottom of the SPLD and the top of the rocky crust. See Figure 2. Our methodology is similar to that employed by previous work for a different location on Mars [20].

We find that a heat flux of >72 mW/m$^2$ is achieved for a magma chamber with *D* = 5 km and *H* = 8 km 300,000 years after its emplacement. Solutions are non-unique; for example, a magma chamber with *D* = 6 km and *H* = 9 km also causes the required heat flux. Thus, melting of basal SPLD ice could occur under these conditions, for an ideal salt content. If no perchlorates are present, instead the required heat flux of >204 mW/m$^2$ could be attained with a magma chamber where *H* = 6 km and *D* = 6 km.

**Conclusions:** There is no concentration of salt that allows for melting of ice at the base of the SPLD under typical, present-day Martian conditions. If the interpretation of radar data that there exists liquid at a locality at the base of the SPLD is correct, special geological conditions that greatly elevate geothermal heat flux are required. We find that these special conditions could be plausibly attained if subsurface magmatism has occurred within the past 1 Myr underneath the SPLD. Thus, the presence of liquid water under ice deposits on Mars today may be inherently linked to volcanic activity.

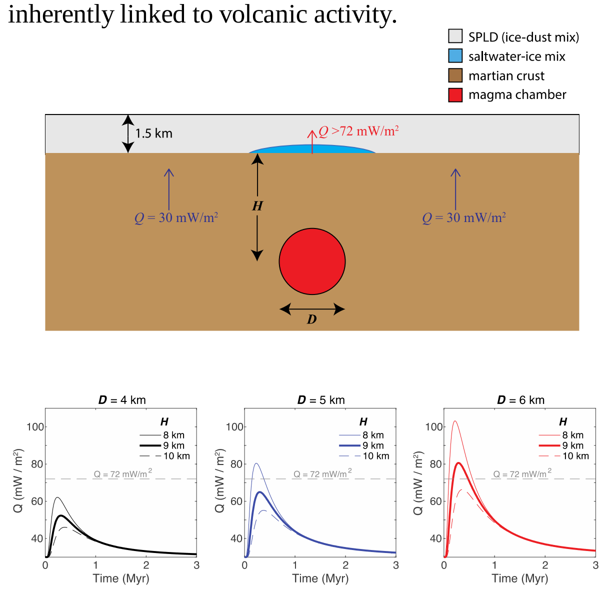


**Figure 2.** *Top:* Schematic of the case we consider: a magma chamber of diameter *D* is bured at a depth *H* below the SPLD where liquid water is proposed to exist. *Bottom*: FEM results showing the heat flux at the SPLD-crust interface directly above the magma chamber as a function of *D* and *H*.

**References:** [1] Orosei et al. (2018), *Science* 361. [2] Sori and Bramson (2019), *GRL.*, in revision. [3] Clifford (1987), *JGR.* 92. [4] Wieczorek (2008), *Icarus* 196. [5] Fisher et al. (2010), *JGR* 115. [6] Bramson et al. (2017), *JGR Planets* 122. [7] Hecht et al. (2009), *Science* 325. [8] Pestova et al. (2005), *Rus. J. Applied Chem.* 78. [9] Chevrier et al. (2009), *GRL* 36. [10] Santiago-Materest et al. (2018), *Icarus* 202. [11] Cull et al. (2010), *Geophys. Res. Lett.* 37. [12] Head and Marchant (2014), *Antarctic Science* 26. [13] Fanale (1976), *Icarus* 28. [14] Phillips et al. (2008), *Science* 320. [15] Parro et al. (2017), *Nature Sci. Reports* 7. [16] Spohn et al. (2014), *LPSC* 45th, 1916. [17] Jaeger et al. (2010), *Icarus* 205. [18] Horvath and Andrews-Hanna (2018), *LPSC* 49th, 2435. [19] Rezvanbehbahani et al. (2017), *GRL* 44. [20] Fassett and Head (2006), *Planet. Space Sci.* 54.