**THE OCCURRENCE AND DEPTH OF SUBPERMAFROST GROUNDWATER ON PRESENT-DAY MARS: IMPLICATIONS OF REVISED ESTIMATES OF CRUSTAL HEAT FLOW, THERMAL CONDUCTIVITY, AND FREEZING POINT DEPRESSION.** S. M. Clifford[1,2], E. Heggy[2], J. Boisson[2], P. McGovern[1] and M. D. Max[3]. MARSIS Team. [1]Lunar and Planetary Institute, 3600 Bay Area Blvd, Houston, TX 77058, clifford@lpi.usra.edu; [2]Institut de Physique du Globe de Paris, 4 avenue de Neptune, 94107 St Maur des Fosses Cedex, France, [3]MDS Research, 1601 3rd Street South, St. Petersburg, FL 33701-5552.

**Introduction:** Based on a conservative estimate of the volume of water required to erode the outflow channels, and the likely extent of their subsurface source regions, Carr [1] estimates that Mars may possess a planetary inventory of water equivalent to a global ocean 0.5–1 km deep, if uniformly distributed over the planet's surface. Because the peak in outflow channel activity appears to have occurred ~2-3 Gya [2], it significantly post-dates the period when the most efficient mechanisms of planetary water loss (impact erosion and hydrodynamic escape) were thought to be active (>4 Gya). For this reason, it is expected that the vast bulk of this water still survives on Mars, stored in the subsurface as ground ice and, possibly, as subpermafrost groundwater [3].

The fraction of the Martian inventory of water that is held in these two volatile reservoirs, depends on the relative size of the planetary inventory of $H_2O$ vs. the pore volume of the cryosphere (that region of the crust where the temperature is below freezing). If the planetary inventory of water exceeds what can be stored as ice within the pore volume of the cryosphere, then the excess will exist as a groundwater, saturating the lowermost porous regions of the crust. Based on the observed range of mean annual surface temperatures (~154 K - 218 K) and previous best estimates of mean global heat flow (~30 mW $m^{-2}$), crustal thermal conductivity (~2 W $m^{-1}$ $K^{-1}$), and freezing-point depression (~252 K, for NaCl-saturated groundwater), Clifford [4] estimated that the nominal depth of the cryosphere varied from ~2.5 km at the equator to ~6.5 km at the poles – noting the likelihood of significant (±50%) local variations in this depth, due to the potential range of these thermal properties and the natural heteorgenity of the crust.

Here we revisit these calculations, examining the potential consequences and implications of our evolving understanding of crustal heat flow, thermal conductivity and groundwater freezing-point depression as deduced from recent Mars' surface, orbital, and Earth-based investigations. We conclude that the present day cryosphere may be up to twice as deep as previously believed, raising questions about the continued survival of subpermafrost groundwater. If subpermafrost groundwater does continue to persist on Mars, its shalowest occurrence will most likely be found at sites combining low-latitude and low-elevation.

**Heat flow:** Early estimates of the present-day mean Martian crustal heat flow varied between 15 – 45 mW $m^{-2}$ [4], with a nominal value of ~30 mW $m^{-2}$ based on the assumption that Mars possesses a chondritic composition [6]. However, more recent estimates, based on rheologic estimates of lithospheric thickness [7 – 9] suggest a significantly lower range of values (~8 – 25 mW $m^{-2}$). While these regional estimates are specific to Tharsis and the polar northern plains, they suggest that the 'mean' global heat flux of Mars may have been overestimated by a factor of two -- which, if true, would double the expected thickness of frozen gound.

**Thermal conductivity:** Based on an average of many hundreds of laboratory measurements of the thermal conductivity of frozen soil and basalt, Clifford [4] concluded that the spatially variable thermal conductivity of the Martian cryosphere likely fell within the range of 1 – 3 W $m^{-1}$ $K^{-1}$, with a probable mean value of ~2 W $m^{-1}$ $K^{-1}$. However, most of the laboratory measurements, on which this estimate was based, were made at temperatures between 253 – 273 K. This is important because the thermal conductivity most geologic materials is temperature-dependent, exhibiting a behavior similar to that of water ice – which varies from ~2.25 W $m^{-1}$ $K^{-1}$ at 273 K, to ~4.62 W $m^{-1}$ $K^{-1}$ at 154 K. This suggests a column-averaged (although latitudinally variable) Martian cryosphere value closer to ~3 W $m^{-1}$ $K^{-1}$ (Appendix A, [5]).

One important caveat to this 50% higher estimate of crustal thermal conductivity is the possibility that methane hydrate (rather than water ice) is the principal volatile constituent of the cryosphere. This possibility is suggested by the likely subsurface origin of the methane recently detected in the Martian atmosphere [10 – 12]. Various studies suggest that large quantities of methane may have been produced -- either biotically or abiotically -- within the subsurface, where it may have become trapped, under conditions of low temperature and high pressure**,** within the cubic crystalline lattice of water ice, forming gas hydrate [1- - 15]. In its pure state, the thermal conductivity of gas hydrate is ~0.5 W m-1 K-1 [14]. Therefore, depending on its abundance and distribution within the cryosphere, the presence of gas hydrate may partially offset some of the increase in thermal conductivity expected from the recognition of the temperature dependent behavior exhibited by most geologic materials.

**Freezing point depression:** The freezing point of Martian groundwater can be significantly depressed by the presence of dissolved salts (e.g., [16-19]). The evolution of Martian groundwater into a highly mineralized brine is an expected consequence of three processes: (1) the weathering that occurs when groundwater is in direct contact with crustal rocks, (2) the influx of salts and other minerals leached from the unsaturated region between the water table and base of the cryosphere by low-temperature hydrothermal convection [4, 5], and (3) the concentration of dissolved minerals by the steady depletion of groundwater in response to the progressive growth of the cryosphere over geologic time.

As a result, at those locations where the cryosphere is in direct contact with groundwater, the presence of dissolved salts may significantly reduce the thickness of frozen ground. Early studies suggested that NaCl and possibly other Cl-rich brines (with freezing points of ~210-252 K at their eutectic), were the most likely candidates to be found in the Martian crust [18]. However, the continued acquisition of Mars compositional data, obtained from both the surface and orbit, indicates that sulfur, especially in the form of Mg-, Ca- and Fe-sulfates, is abundant on the planet. Indeed, at Meridiani, chemical anlyses indicate that the local groundwater had initial S/Cl ratios of 6 – 30 [20]. The sulfate-rich brines which are produced under these conditions depress the freezing point by only ~5 K [18]. Compositional variations within the evaporite deposits at Meridiani indicate that, either by progressive freezing or evaporation, the local brines became more concentrated, resulting in the precipitation of sulfate minerals and the evolution of more Cl-enriched brines with lower freezing points.

Subpermafrost groundwater on Mars is likely to have undergone a similar evolution, with the precipitation of sulfates and carbonates, and concentration of more Cl-rich brines, as more of its initial groundwater inventory was cold-trapped into the thickening cryosphere.

**Conclusions and Implications:** Based on these revised estimates of heat flow, thermal conductivity, and freezing-point depression, we believe that the zonally-averaged thickness of the cryosphere on Mars is likely to exceed 5 km at the equator and 13 km at the poles. However, natural variations in crustal heat flow and thermal conductivity may result in significant local departures from these predicted values – especially where the base of the cryosphere and subpermafrost groundwater are in direct contact.

As discussed in Clifford [4] and Clifford and Parker [5], the distribution of ground ice is expected to follow the thermal structure of the crust, while the distribution of groundwater, under the influence of gravity, will drain and saturate the lowermost porous regions present at depth. For this reason, the vertical distance separating these subsurface reservoirs may vary considerably, such that the intervening unsaturated zone is maximized in regions of high elevation and minimized (or absent) at lower elevations (see Figure 1 of [5]).

Although the outflow channels provide persuasive evidence that Mars once possessed a sizable inventory of subpermafrost groundwater, it is possible that today such a reservoir no longer survives – a potential consequence of the cold-trapping of a once-large inventory into the pore volume of the thickening cryosphere, as the planet's internal heat flow declined with time [5].

Calculations by Clifford and Parker [5, Fig. 11] indicate that -- depending on the assumed porosity profile of the crust, the effective freezing-point of the surviving brines, and the rate of decline in mean crustal heat flow -- an initial planetary inventory of 500 m of $H_2O$ could have been fully cold-trapped into the thickening cryosphere by the end of the Hesparian (~ 2 Gya), while – given an initial inventory of 1-km of $H_2O$ – the equivalent of up to several hundred meters of subpermafrost groundwater might survive to the present day.

Thus, the present state of deep subsurface water on Mars is bracketed by two extremes: one in which a small planetary inventory, combined with the progressive cooling of the crust, has eliminated any persistent reservoir of groundwater, and another in which the planetary inventory is sufficiently large that a sizable reservoir of liquid may still survive at depth over much of the planet.

As argued by Clifford and Parker [5], the locations that are likely to minimize the depth to groundwater and provide the best opportunity for its detection and access are those that combine low latitude (minimizing the thickness of frozen ground) and low elevation (minimizing the depth to a water table in hydrostatic equilibrium). The locations that appear to offer the best combination of these criteria are the interior of Valles Marineris, southern Amazonis Planitia, Isidis Planitia, a region to the southeast of Elyisum, and the northern interior of Hellas (see Table VI in [5]). The results of the analysis of MARSIS radar soundings obtained over these areas will be discussed.

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