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The Response of Martian Ground Ice to Burial by a Volatile-Poor Mantle: Potential Implications for the Volatile Evolution of the Medusae Fossae Formation

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The Medusae Fossae Formation (MFF) consists of a number of distinct, friable, highly eroded, near-equatorial deposits, extending from Elysium to Amazonis Planitia, that are up to 3 km thick and cover a total area of ~$2x10^6$ km^2. Proposed origins of the MFF have included everything from paleopolar deposits, whose presence reflects a prior location of the planet's spin axis [1], to dry, high porosity volcanic ash [2-3]. Radar sounding investigations of the deposits indicate that they have a dielectric constant of ~2.9, consistent with either high porosity lithic materials or a large volumetric content of water ice [3].

Here we consider the thermal and volatile response of an ice-rich crust to burial by an initially dry porous mantle of sediment or volcanic ash. Given reasonable values of surface temperature (~200 - 220 K), effective pore size (1-10 μm), mantle porosity (20-50%), thermal conductivity (0.05 - 2 W m^{-1} K^{-1}), and global heat flow (15–30 mW m^{-2}), we find that the thermal reequilibration of the crust, following deposition, will cause a migration of the local crustal cold-trap (lowest mean annual temperature) from an initial position several meters below the original surface to a final position, at an approximately equal depth, a few meters below the surface of the mantle. This upward displacement of the local cold-trap then results in the thermal redistribution of the underlying ground ice at a rate sufficient to saturate the available pore space in an initially dry 100 m-thick mantle within ~10^7 – $l0^8$ years (and a 1 km-thick mantle, in a time span just several times longer) .

This vertical redistribution of ground ice occurs by three different processes that involve all three phases of water. These include: thermal vapor diffusion (where vapor migrates from the warmer depths to the colder near-surface crust), thermal liquid transport (in response to the temperature-induced gradient in soil water potential that can occur in the interfacial films between rock and ice), and regelation (the movement of ice through soil pores via pressure induced melting and refreezing) [4-5]. Of these processes, thermal vapor diffusion is generally the most efficient – its magnitude being directly proportional to the gradient in saturated vapor pressure associated with the local geothermal gradient.

The potential effect of a depositional mantle on the thermal and volatile evolution of the near-surface crust is illustrated in Figure 1, where the consequences of the instantaneous burial of an initially ice-rich crust by a 100 m-thick volatile-poor mantle is considered. Because deposition is assumed to have occurred rapidly under ambient Martian conditions, the initial temperature profile of the mantle is taken to be isothermal. Given the previously noted estimates of thermal conductivity and geothermal heat flux, it takes ~10^3 years for the top 300 m of the crust to thermally reequilibrate. For a mean annual surface temperature of 210 K (corresponding to a latitude of ~30°), the timescale for the redistribution of ground ice is ~10^7 – $l0^8$ years.

The results summarized in Table 1 demonstrate the importance of both the local temperature and geothermal gradient to volatile transport. Although gradients of ~0.015 K m^{-1} are thought to be representative of the crust today, models of the thermal history of Mars suggest that, ~4 Ga ago, crustal gradients may have been as much as ~3x – 5x greater [4-5] -- implying a similar increase in the efficiency of thermal vapor transport. At a smaller scale, thermal gradients as large as ~10^2 K m^{-1} might occur in association with active geothermal regions -- such as volcanoes, igneous intrusions, and impacts -- or on a transient basis within the diurnally- and seasonally-active near-surface regolith.

The results of this analysis indicate that even a small change in crustal temperature can exert a strong influence on the transport, stability, and ultimate distribution of subsurface H_20. In particular, it demonstrates that through the process of thermal vapor diffusion, an initially volatile-poor depositional mantle, overlying an ice-rich crust, may (on a geologically short time scale) become quickly charged with ice -- a fact that is likely to have important implications for reconciling the geologic evidence for extensive resurfacing on Mars with the widespread geomorphic evidence for the occurrence of ice within the near-surface crust. It also suggests that, even if the MFF deposits were initially dry, they may have become charged with ice in a geologically short span of time.

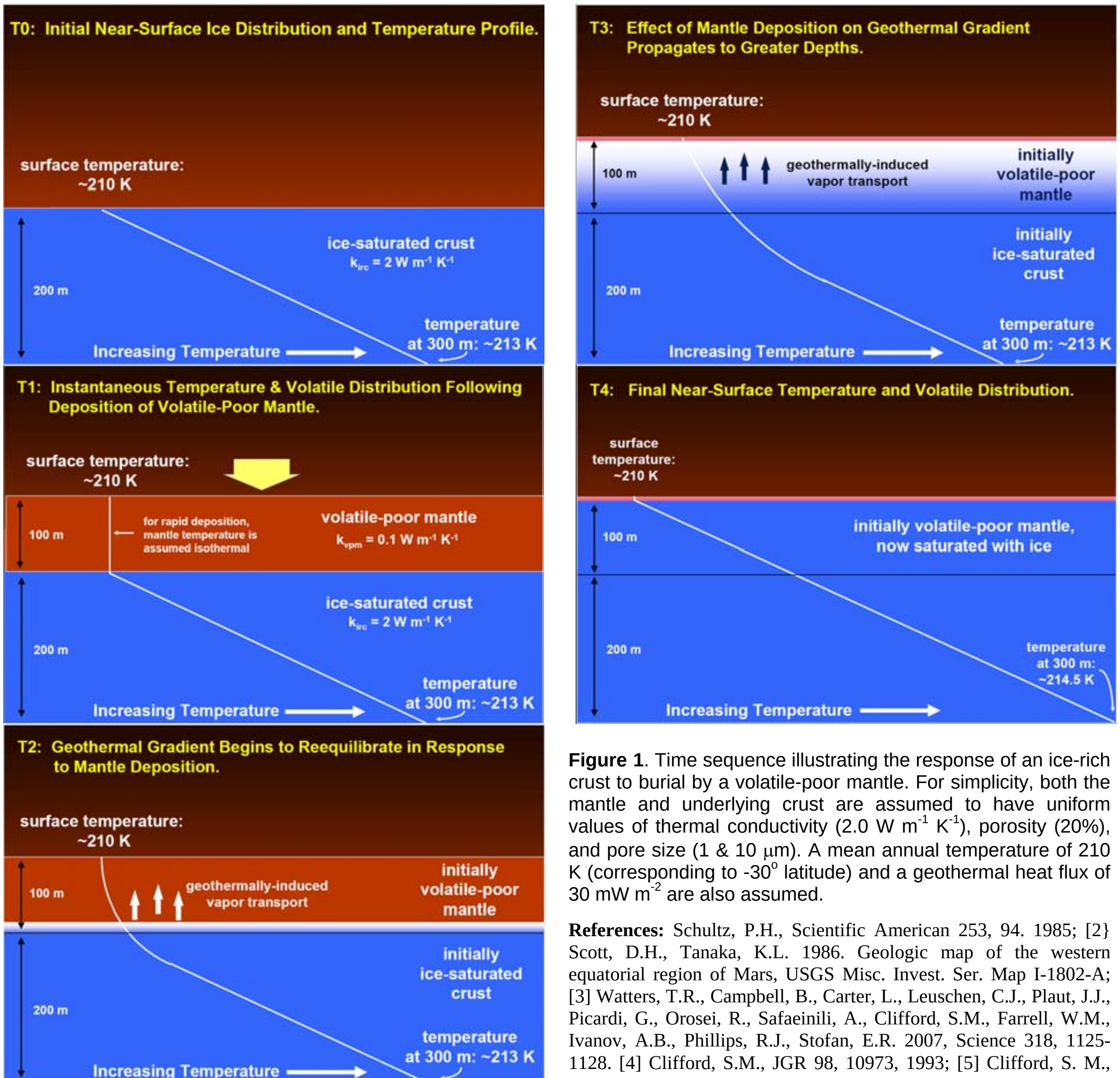

Figure 1. Time sequence illustrating the response of an ice-rich crust to burial by a volatile-poor mantle. For simplicity, both the mantle and underlying crust are assumed to have uniform values of thermal conductivity (2.0 W m^{-1} K^{-1}), porosity (20%), and pore size (1 & 10 μm). A mean annual temperature of 210 K (corresponding to -30^{o} latitude) and a geothermal heat flux of 30 mW m^{-2} are also assumed.

References: Schultz, P.H., Scientific American 253, 94. 1985; [2} Scott, D.H., Tanaka, K.L. 1986. Geologic map of the western equatorial region of Mars, USGS Misc. Invest. Ser. Map I-1802-A; [3] Watters, T.R., Campbell, B., Carter, L., Leuschen, C.J., Plaut, J.J., Picardi, G., Orosei, R., Safaeinili, A., Clifford, S.M., Farrell, W.M., Ivanov, A.B., Phillips, R.J., Stofan, E.R. 2007, Science 318, 1125-1128. [4] Clifford, S.M., JGR 98, 10973, 1993; [5] Clifford, S. M., LPSC XXVI, 262, 1995.

Table 1. Time required to saturate a 100 m-thick depositional mantle with water ice (yrs).

1 μm pore size

	Geothermal Gradient (K m^{-1})					
Temp. (K)	0.015	0.03	0.075	0.15	1	100
273	2.4E+05	1.2E+05	4.9E+04	2.4E+04	3.7E+03	3.7E+01
220	3.0E+07	1.5E+07	5.9E+06	3.0E+06	4.4E+05	4.4E+03
210	1.0E+08	5.0E+07	2.0E+07	1.0E+07	1.5E+06	1.5E+04
200	3.9E+08	2.0E+08	7.8E+07	3.9E+07	5.9E+06	5.9E+04
190	1.8E+09	8.8E+08	3.5E+08	1.8E+08	2.6E+07	2.6E+05
180	9.5E+09	4.7E+09	1.9E+09	9.5E+08	1.4E+08	1.4E+06
170	6.3E+10	3.1E+10	1.3E+10	6.3E+09	9.4E+08	9.4E+06
160	5.3E+11	2.6E+11	1.1E+11	5.3E+10	7.9E+09	7.9E+07

10 μm pore size

	Geothermal Gradient (K m^{-1})					
Temp. (K)	0.015	0.03	0.075	0.15	1	100
273	7.1E+04	3.6E+04	1.4E+04	7.1E+03	1.1E+03	1.1E+01
220	6.9E+06	3.4E+06	1.4E+06	6.9E+05	1.0E+05	1.0E+03
210	2.4E+07	1.2E+07	4.8E+06	2.4E+06	3.6E+05	3.6E+03
200	9.5E+07	4.7E+07	1.9E+07	9.5E+06	1.4E+06	1.4E+04
190	4.4E+08	2.2E+08	8.8E+07	4.4E+07	6.6E+06	6.6E+04
180	2.4E+09	1.2E+09	4.8E+08	2.4E+08	3.6E+07	3.6E+05
170	1.6E+10	8.2E+09	3.3E+09	1.6E+09	2.5E+08	2.5E+06
160	1.4E+11	7.2E+10	2.9E+10	1.4E+10	2.2E+09	2.2E+07

*Assumed porosity of 20%