Implications of Martian Excess Ground Ice Stability

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30 Second Summary

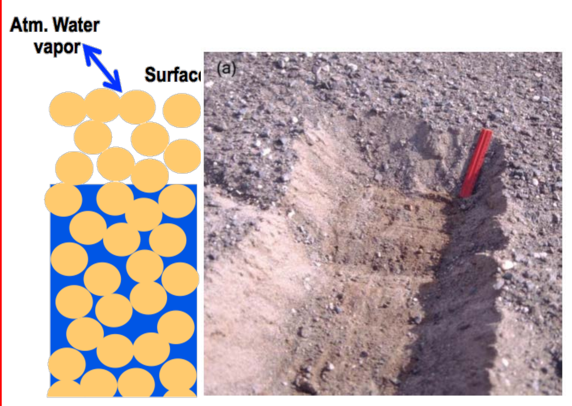
- There is extensive evidence for 10s of meters of excess ice deposits in the mid-latitudes of Mars, which are known to be 10s of Myr old.
- We use a standard thermal conduction model to test the effect of regolith thickness, latitude and atmospheric water vapor on ice retreat.
- We find that all cases predict the excess ice should have been removed.
- Future model improvements are planned to test conditions that lead to decameters of ice being stable between 38°-50° N.

1. Evidence for Excess Ice in the Mid-Latitudes

Many lines of evidence point to the existence of relatively pure, excess ice (higher water ice abundances than can fit into the pore spaces of the regolith) in the northern mid-latitudes of Mars:

- thermokarstically expanded craters
- scalloped depressions
- SHAllow RADar (SHARAD) sounding, terraced craters and dissected mesas in Arcadia Planitia and Utopia Planitia
- ice-exposing impacts
- water-equivalent hydrogen content from Gamma Ray Spectrometer

Pore filling ice vs Excess ice



Pore-filling ice
Right image: Beacon Valley, Antarctica (Mellon et al. 2004)

Excess ice on Earth

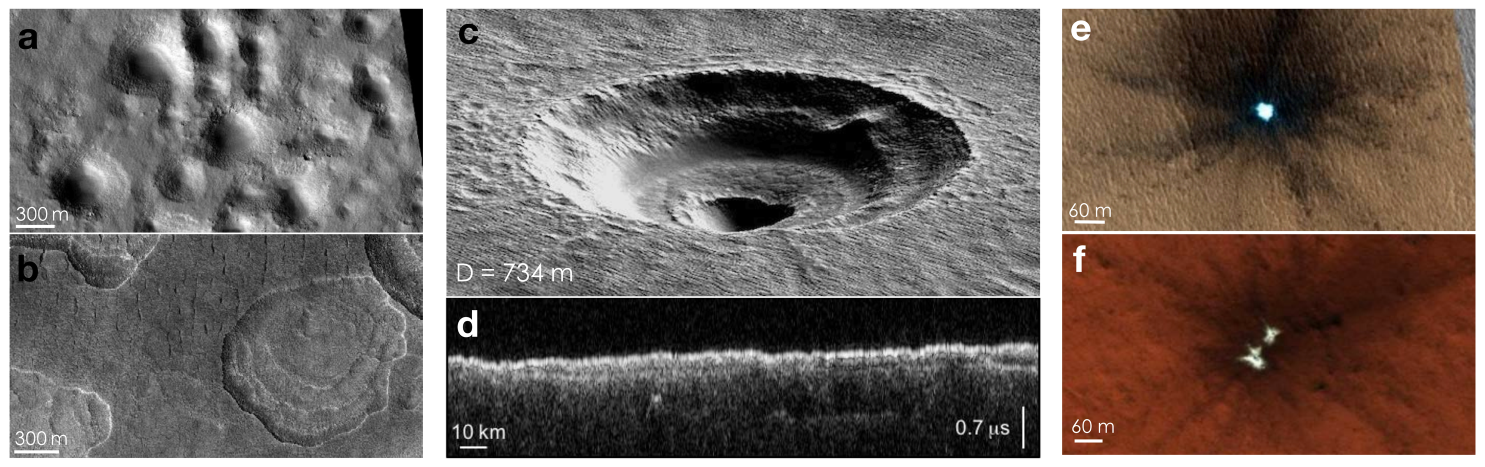
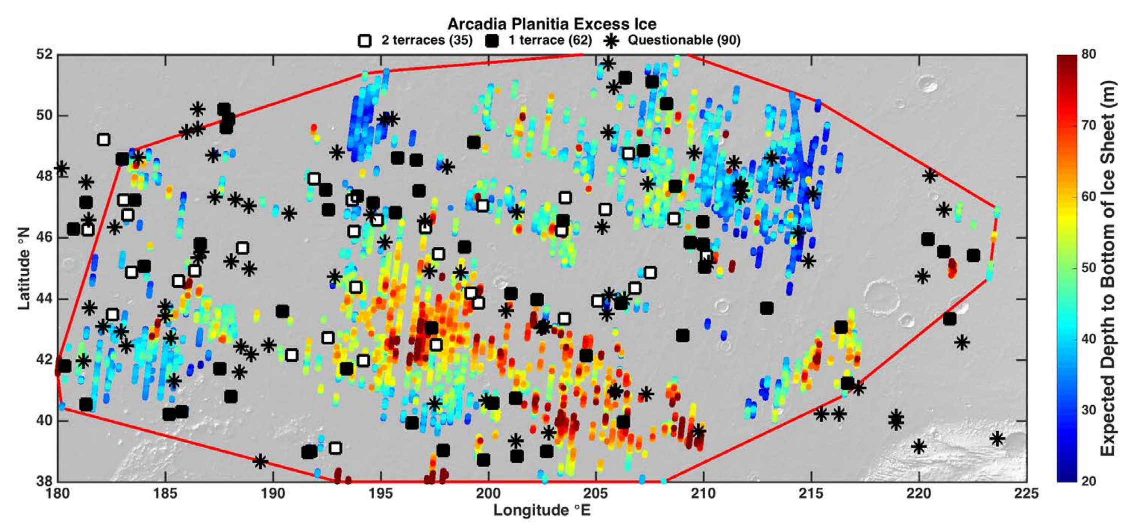


Fig 1. (a) expanded craters, HiRISE image ESP_028411_2330; (b) scallops, HiRISE image PSP_001938_2265; (c) terraced crater- deeper terrace at 43 meters depth is interpreted to be at the ice-rock interface, 3D view created from HiRISE Digital Terrain Model DTEEC_018522_2270_019010_2270_A0; (d) SHARAD track 949601000 shows a subsurface radar reflector at the bottom of the Arcadia ice layer; (e and f) ice exposing impacts, HiRISE images ESP_025840_2240 and ESP_032340_1060



The Arcadia Planitia ice was found to cover an area of up to 1,200,000 km^2 over the latitude range of 38°N-50°N (Bramson et al. 2015), while the Utopia Planitia ice covers 400,000 km^2 between 40°-50°N (Stuurman et al. 2015, in review). Each of these deposits is up to ~100 m thick and holds ice volumes on the order of 10s of thousands of km^3.

Fig 2. Plot adapted from Bramson et al. 2015 showing SHARAD delay times converted to expected depths (colored dots), locations of terraced craters due to impacts through the ice layer (black and white dots), and expected area covered by the ice sheet (red outline).

2. Motivation

- There is a disparity between thick deposits of excess ice and the conventional picture of mid-latitude ice as young, pore-filling ground ice that reacts quickly to climatic conditions through atmospheric exchange.
- The age of this ice was unexpectedly found to be at least 10s of Myr (Viola et al. 2015). In this time, Mars has had many excursions through low obliquities (when equatorial ground ice gets transported to the poles) that should have caused any mid-latitude ice (excess or pore-filling) to sublimate away.
- Replenishment of this ice in subsequent epochs can only create pore-filling ice.
- Understanding the conditions that have led to the excess ice's continued survival to the present day is important for understanding a) the stability of ice in the Amazonian (3 Ga to present), b) the subsurface structure in the mid-latitudes and c) the orbital forcing of the Martian climate.

3. Thermal Modeling of Excess Ice

- We modeled subsurface temperatures following equations 1 and 2.
- We investigate the stability of excess ice covered by a layer of dry regolith (which damps temperature oscillations) for different regolith thicknesses, climatic histories and latitudes.
- From the temperatures at the ice table, we used the Clausius-Clapeyron equation and the ideal gas law to calculate the annual average vapor densities at each orbital solution (obliquity, eccentricity, and longitude of perihelion) from Laskar et al. 2004.
- When $\rho_{vapor} > \rho_{atmos}$, the ice sublimates, causing a retreat of the excess ice (eq. 3).
- We tested two atmospheric water vapor conditions: a) constant and b) obliquity-dependent (eq. 4).
- We plan to add the effect of re-accumulation of pore-filling ice (which could choke off vapor diffusion) to our model and explore further atmospheric water densities vs. time.

$$\text{(eq. 1)}\quad \varepsilon\sigma T_{surf}^4 = S_o\cos(i)\,(1-A) + L_{CO2}\frac{dm_{CO2}}{dt} + k\frac{\partial T}{\partial z} + IR_{\downarrow} + vis$$

$$\text{(eq. 2)}\quad \rho c\frac{\partial T}{dt} = \frac{\partial}{dz}\left(k\frac{\partial T}{dz}\right)$$

$$\text{(eq. 3)}\quad \Delta\text{ice} = \frac{D\,(\rho_{vapor} - \rho_{atmos})\,\Delta t}{(\text{regolith thickness})\ \rho\text{ice}}$$

$$\text{(eq 4.)}\quad \ln P = \begin{cases} a_1 + b_1(\theta - 28°) & \text{for } 10° < \theta < 28° \\ a_1 + b_1(\theta - 28°) + c_1(\theta - 28°)^2 & \text{for } 28° < \theta < 50° \end{cases}$$

$$\text{where } a_1 = -1.27\ \ b_1 = 0.139\ \ c_1 = -0.00389$$

From Schorghofer and Forget 2012

Parameters		Value
L_{CO2}	latent heat of CO_2 frost on the surface	590 kJ kg^{-1}
ε	emissivity of the surface	1 for regolith, 0.9 for CO_2 frost
σ	Stefan-Boltzmann constant	5.67x10^{-8} Wm^{-2}K^{-4}
S_o	solar flux at Mars	1367 W/m^2 / Mars' solar distance^2
i	incidence angle of sunlight	varies with latitude, slope, time
A	surface albedo	.25 for regolith, .65 for CO_2 frost
IR↓	downwelling infrared from the atmosphere	4% of noon-time flux
vis	scattered visible light	2% of solar flux
m_{CO2}	mass of a CO_2 surface layer	calculated when T_{surf} < frost point
t	time	runs over multiple Martian years
z	depth	between 0 and 6 diurnal skin depths
T	temperature	calculated at each time step
k	thermal conductivity	set initially for each layer
ρ	density of the layer	set initially for each layer
c	heat capacity of the layer	set initially for each layer
D	diffusivity of dry regolith layer	3x10^{-4} m^2 s^{-1} (Dundas et al. 2015)
ρ_{atmos}	annual average near-surface atmospheric vapor density	assumed constant at 3.4x10^{19} m^{-3} (Mellon et al. 2009) -or- varying with obliquity (Schorghofer and Forget 2012)
θ	obliquity	from Laskar et al. 2004 solutions
I	thermal inertia	$I = \sqrt{k\rho c}$ J m^{-2} K^{-1} s$^{-1/2}$

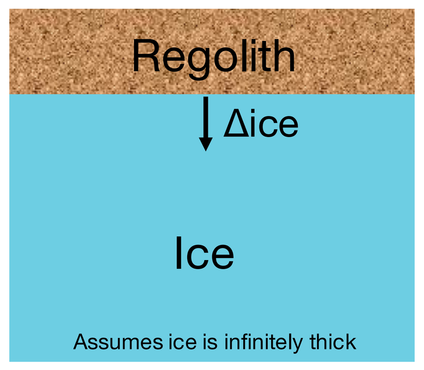


Fig. 3: Schematic of layer setup

Layer Properties

Regolith Properties

I = 250 J m^{-2} K^{-1} s$^{-1/2}$
ρ = 837 kg m^{-3}
c = 1626.18 J kg^{-1} K^{-1}
k = 0.0459 W m^{-1} K^{-1}
Thicknesses tested:
0.5 m, 1m, and 2m

Ice Properties

I = 2100 J m^{-2} K^{-1} s$^{-1/2}$
ρ = 925 kg m^{-3}
c = 1615 J kg^{-1} K^{-1}
k = 2.952 W m^{-1} K^{-1}

4. Preliminary Results

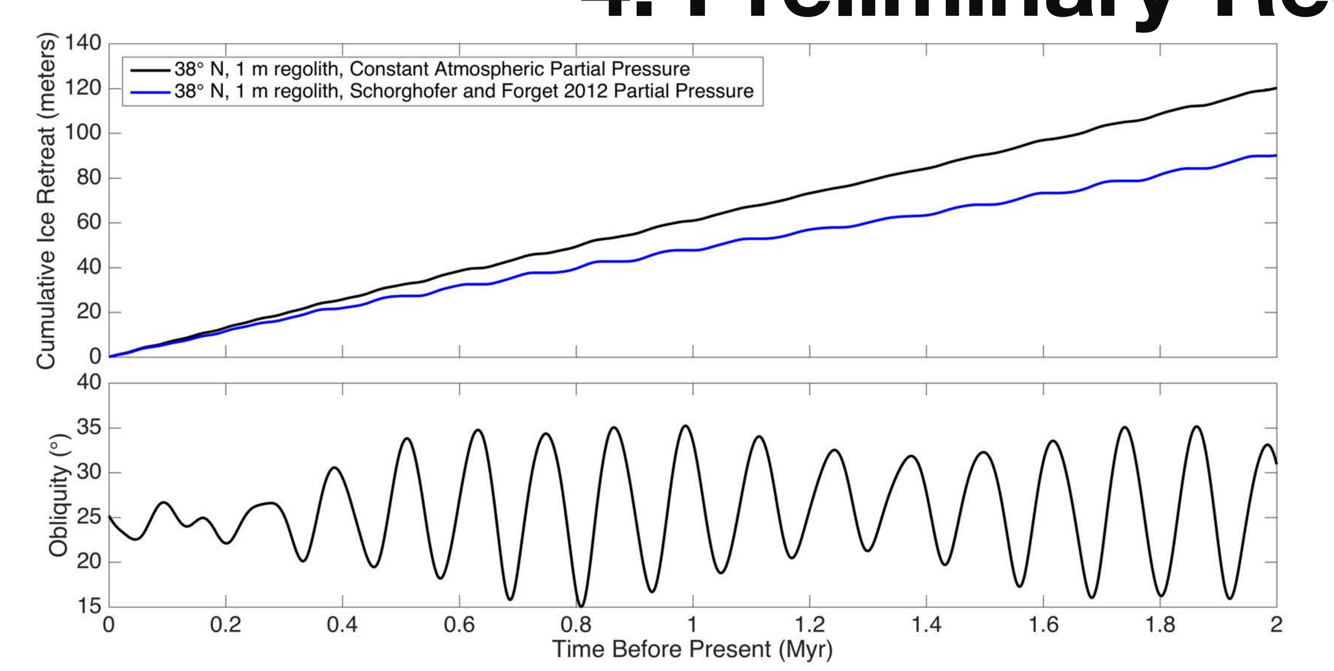


Fig. 4: Effect of atmospheric water vapor contents on ice retreat over 2 Myr for a) constant partial pressure (black) and b) an approximate obliquity dependence (blue) converted to densities with ideal gas law and annual average surface temperature.

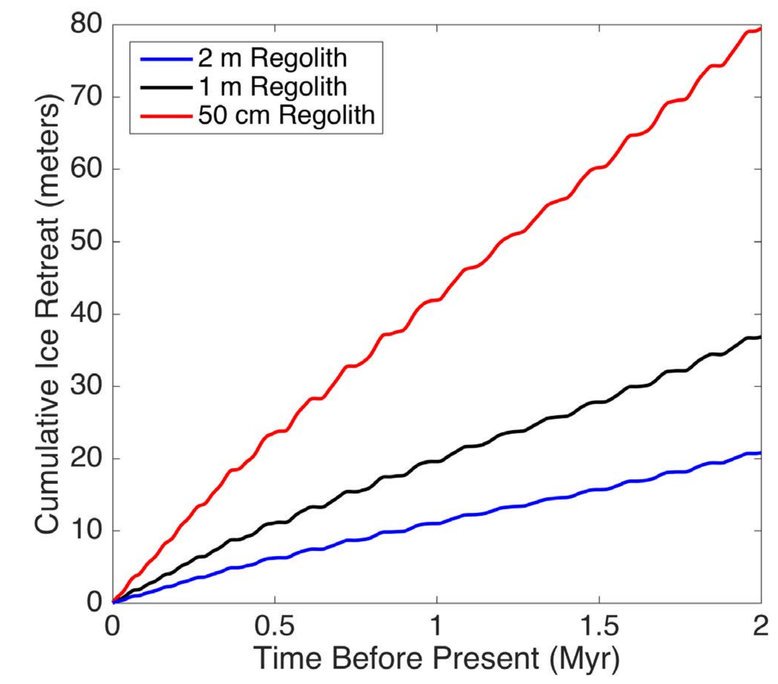


Fig. 5: Effect of regolith thickness on ice retreat at 45° N and constant ρ_{atmos}

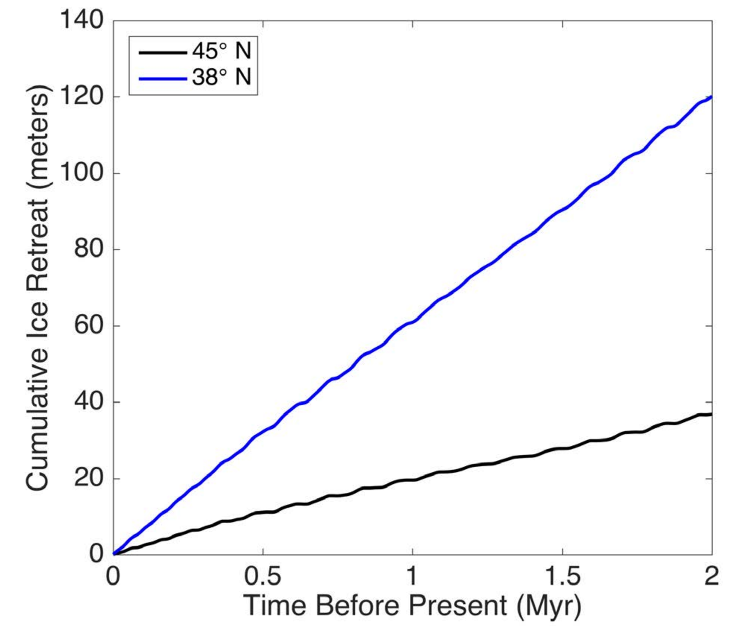


Fig. 6: Effect of latitude on ice retreat for 1 m of regolith cover and constant ρ_{atmos}

Conclusion: Decameters of excess ice will not survive under these conditions over 10s of Myr.
Possible resolutions:

- Regolith thicknesses are an order of magnitude larger (this is not supported by dielectric constants measured by Bramson et al. 2015 or Stuurman et al. 2016, submitted)
- Vapor diffusivities are an order of magnitude lower (unlikely based on lab experiments by Hudson et al. 2007)
- Atmospheric water vapor content has varied in the last 10s of Myr, suppressing sublimation rates.

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