Subsurface Ice at Mars:

A review of ice and water in the equatorial regions.

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Outline

- States of Water.
- Why Ground Ice? Theory and Observations.
- Potential for Equatorial Ice.
- Hydration and Hydrous minerals.

States of Water on Mars

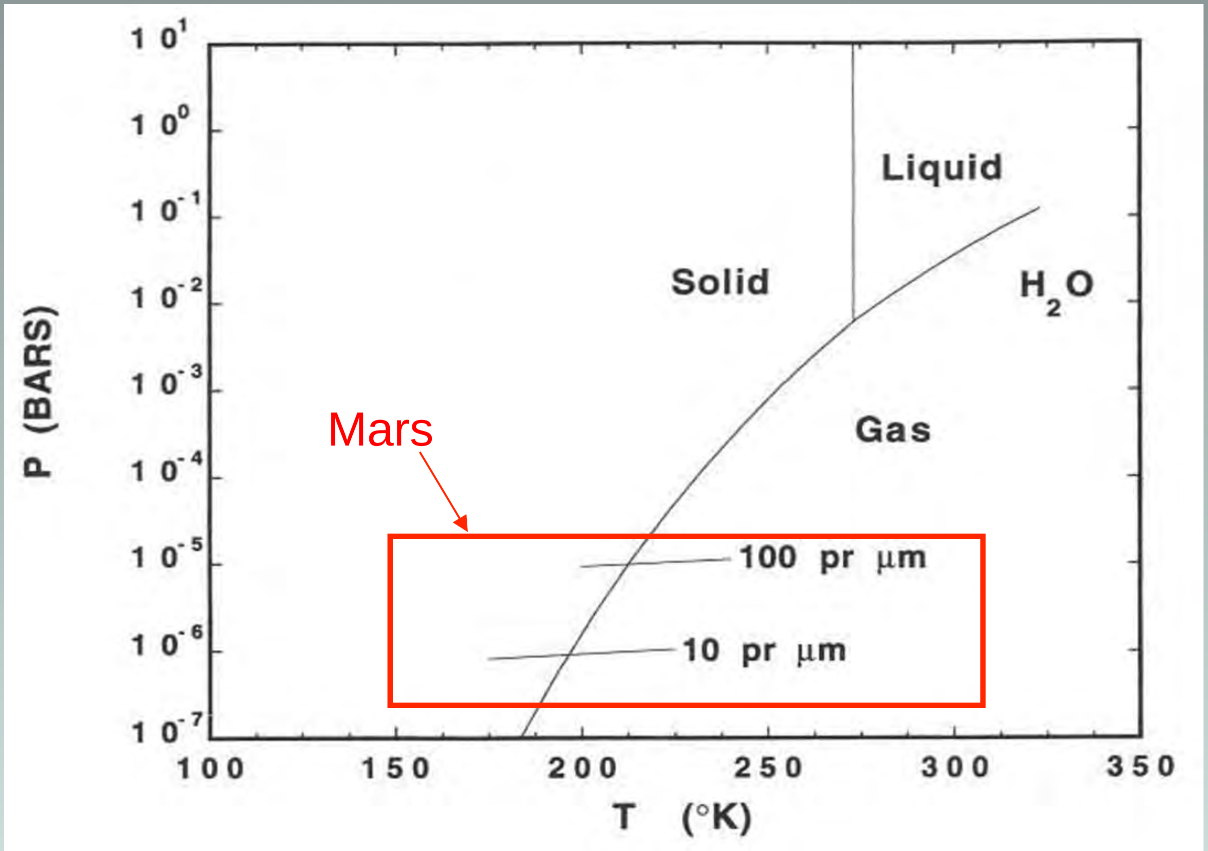
- Vapor → Atmosphere and soil pores. Varies seasonally.
- <u>Ice</u> → Polar caps, surface frost, ground subsurface (ground ice).
- Liquid → Gullies, other speculations...brines, ponds, subsurface aquifers, etc.
- <u>Adsorbed</u> → Omnipresent on mineral surfaces -- variable amounts.
- <u>Mineral Hydration</u> → Water included within mineral crystal structure

Why Ground Ice?

- Mars is cold and dry:
  - Global & annual mean soil temperature ~205K
    - Regionally: ~160K polar regions, ~230K equator
    - Seasonally: ~145K (CO_2 frost), ~310K noon/equator
  - Atmosphere contains an average 0.03% water
    - ~10 precipitable microns (pr um)
    - Seasonally and regionally: few ↔ ~100 pr um
    - 10,000x less water than Earth's atmosphere.
- Cold and Dry Balance regionally and seasonally.

Why Ground Ice?

H_2O Vapor Pressure
(Absolute Humidity)

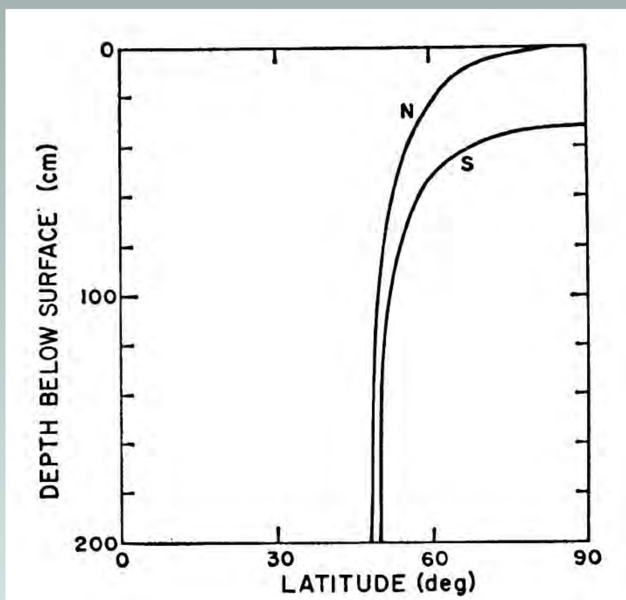


[from Carr, 1996]

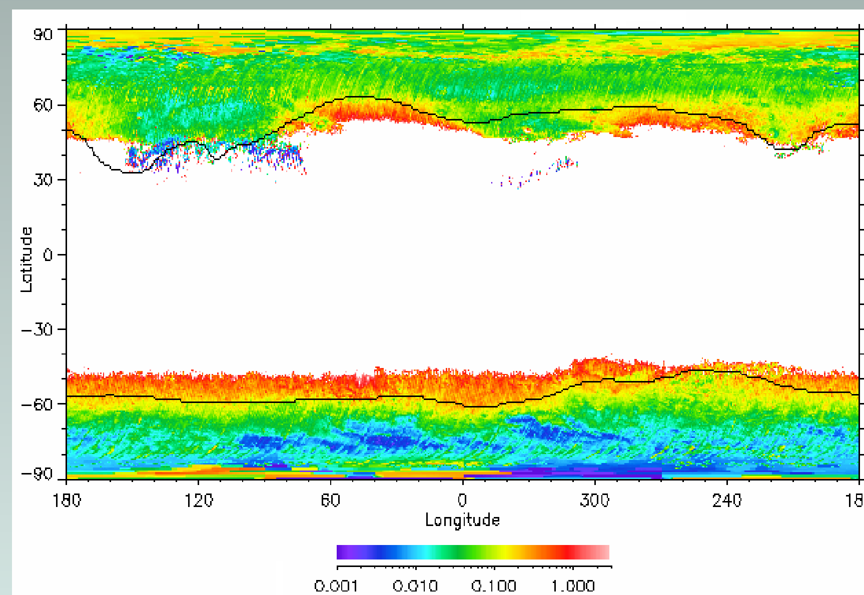
Overall, Mars is too dry for liquid water to persist and too cold for vapor to condense as a liquid.

Why Ground Ice?

- This is not a new idea…
  - Numerous theoretical studies over the past 4½ decades.
  - Examined many aspect of ground ice: stability, distribution, dynamics, and the effects of climate change.



Leighton and Murray 1966



e.g., Mellon et al 1993; 2004; 2006

Why Ground Ice?

- Ground ice is stable where soil temperatures are cold for relative to the atmospheric frost point.

- More precisely:

$$\overline{N_{ICE}(z)} = \overline{N_{ATM}}$$

The annual mean absolute humidity, $\overline{N}$

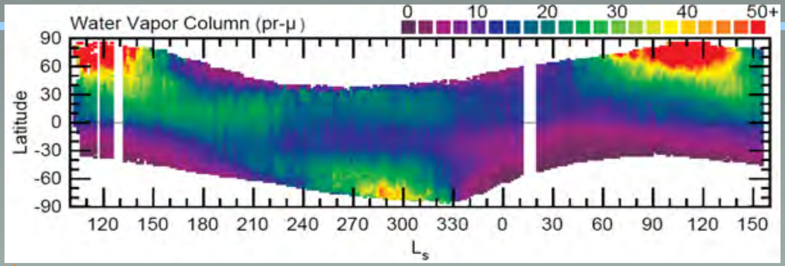
with respect to ice at depth = the atmosphere

<u>Consider annual mean values because diffusion of water vapor through soil is slower than a year.</u>

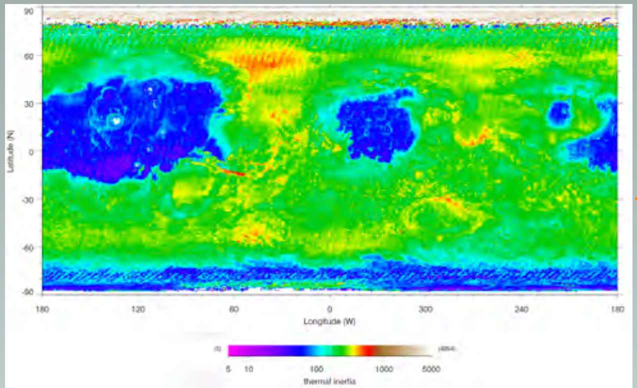
Ground Ice Stability – Key Factors

Ground Temperature: Thermal inertia, Albedo, Elevation.

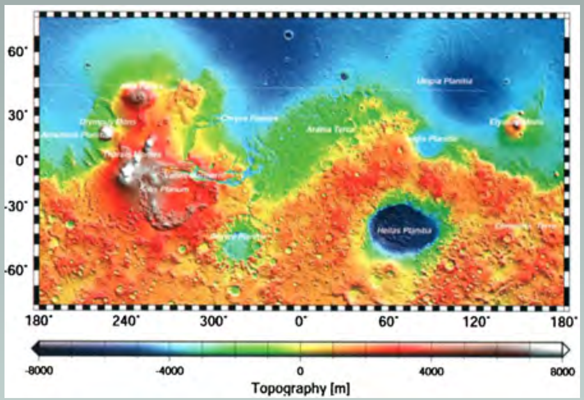
Humidity: Season (polar cap), Elevation & scale height, Surface frost (drying effect).



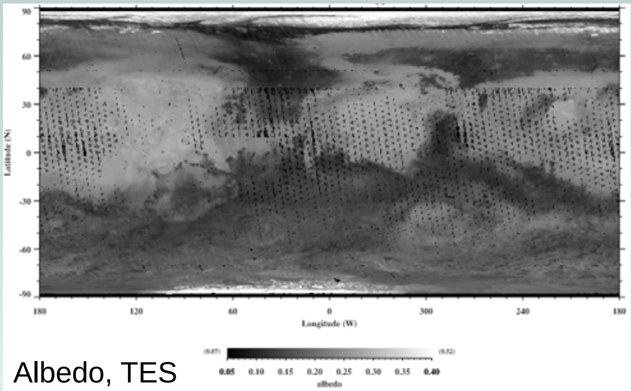
(e.g., M Smith et al., 2001)



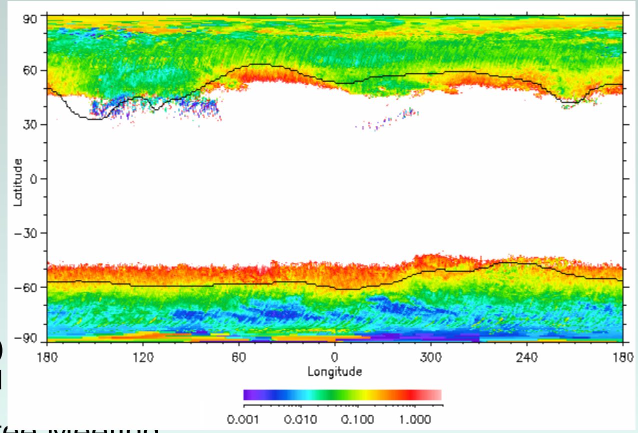
Thermal Inertia (from Mellon et al 2000)



Elevation (D Smith et al., 2000)

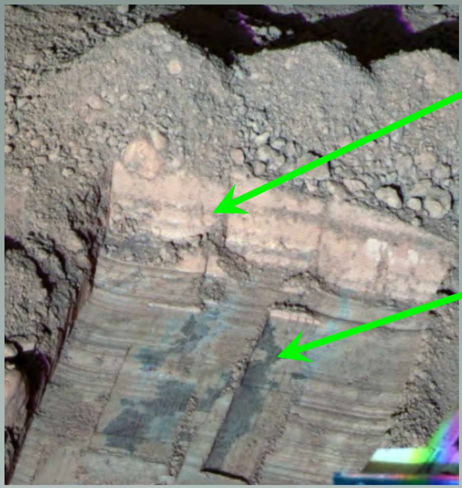


Albedo, TES



Ice Table Depth [m]
(Mellon et al., 2006)
assumes 20 pr um scaled

Consensus on Theory Ground Ice Stability



Mars: Phoenix Site

Dry, loose soil

Ice table

Ice-rich soil beneath

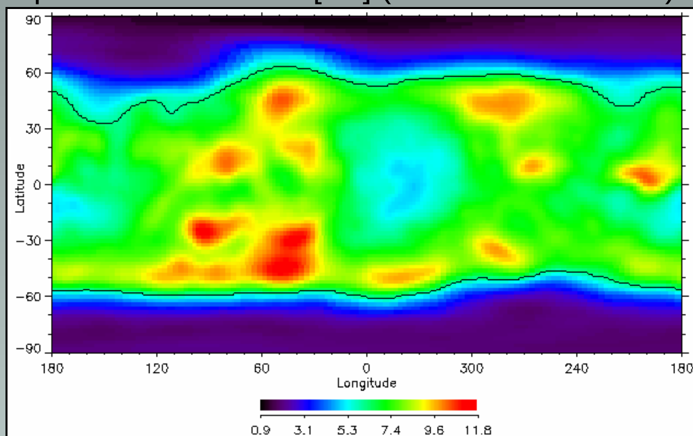
Antarctic Example (Beacon Valley)

- General Results:
  - Regolith and atmosphere will exchange water.
  - Ground ice should condense (or remain stable if from another source), **poleward of about 45º Latitude**.
  - Equatorial ground ice should <u>sublimate</u> away over time.
  - Dry soil should overlie icy soil. The boundary should be sharp. Represents **diffusive equilibrium.**

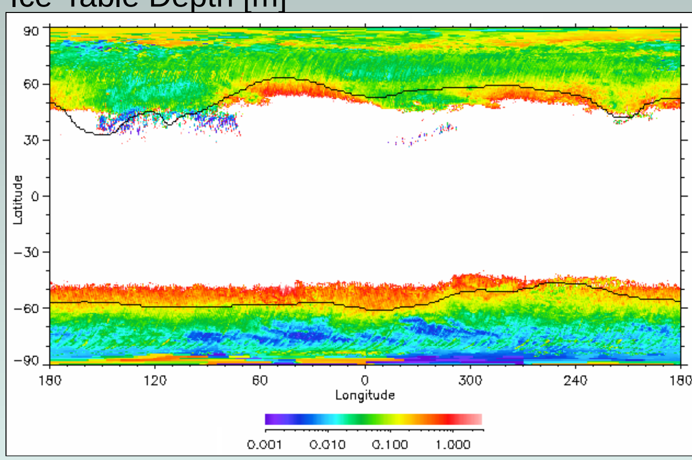
Ground Ice – Observations

Gamma Ray & Leakage Neutron Spectroscopy

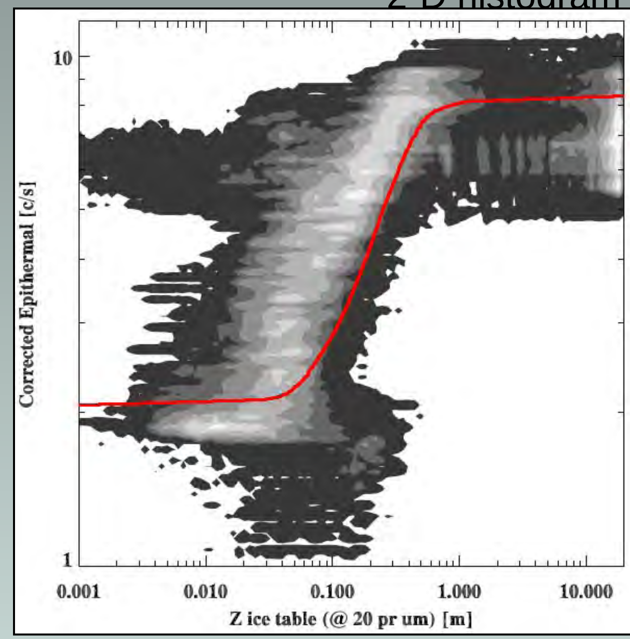
Epithermal Neutrons [c/s] (Feldman et al 2004)



Ice-Table Depth [m]



2-D histogram



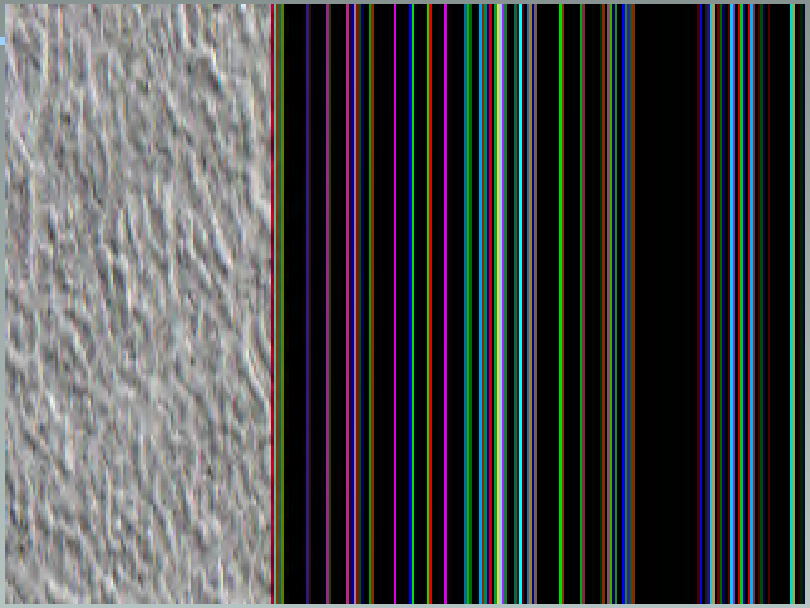
- Geographic and depth distributions agree well with Neutrons.
- Compared with neutron transport theory {red line: 35% wt water ice}.
- 2x shift in depth, due to surface rocks.
- **Observed ice is in diffusive equilibrium.**

(from Mellon et al 2004; 2006)

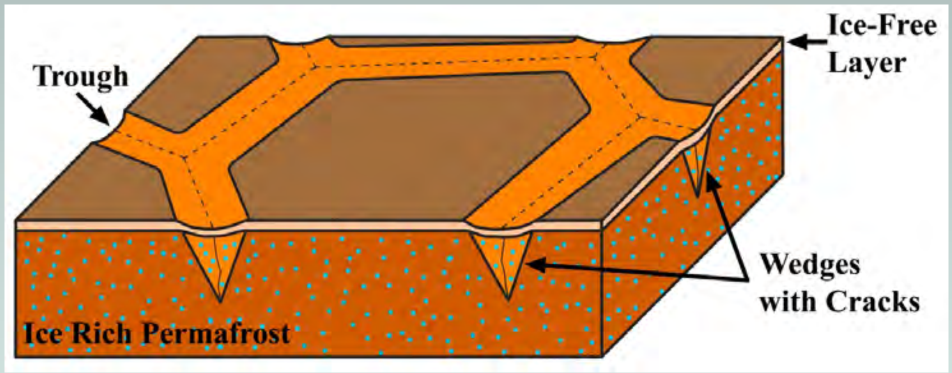
Ground Ice – Observations

Polygonal Patterned ground

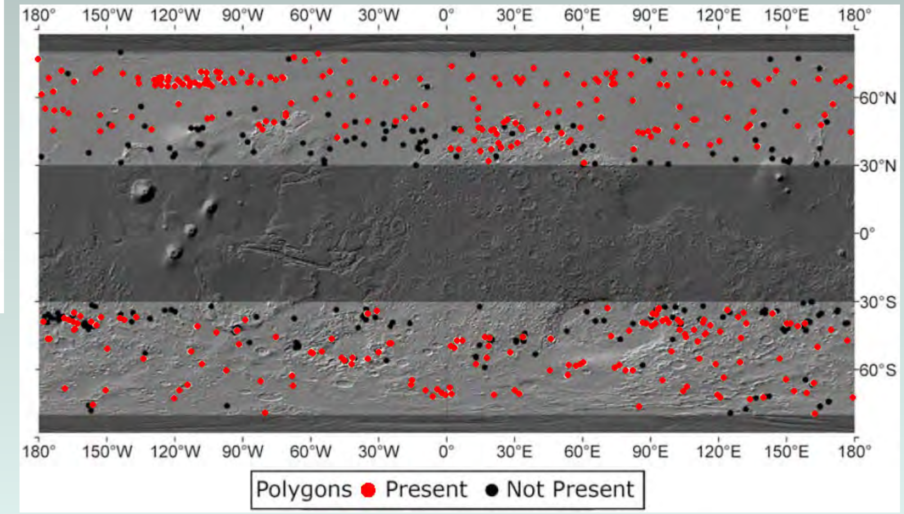
- Polygons on Mars are ubiquitous!
- 100% coverage of terrains at high latitudes.
- Thermal cracking of ice-rich permafrost.
- Locations consistent with ice stability.



HiRISE: 100 m



(Mellon et al. 2010)



(Levy et al. 2009)

Ground Ice – Observations

Phoenix: 12 trench systems within a 2 m^2 workspace.

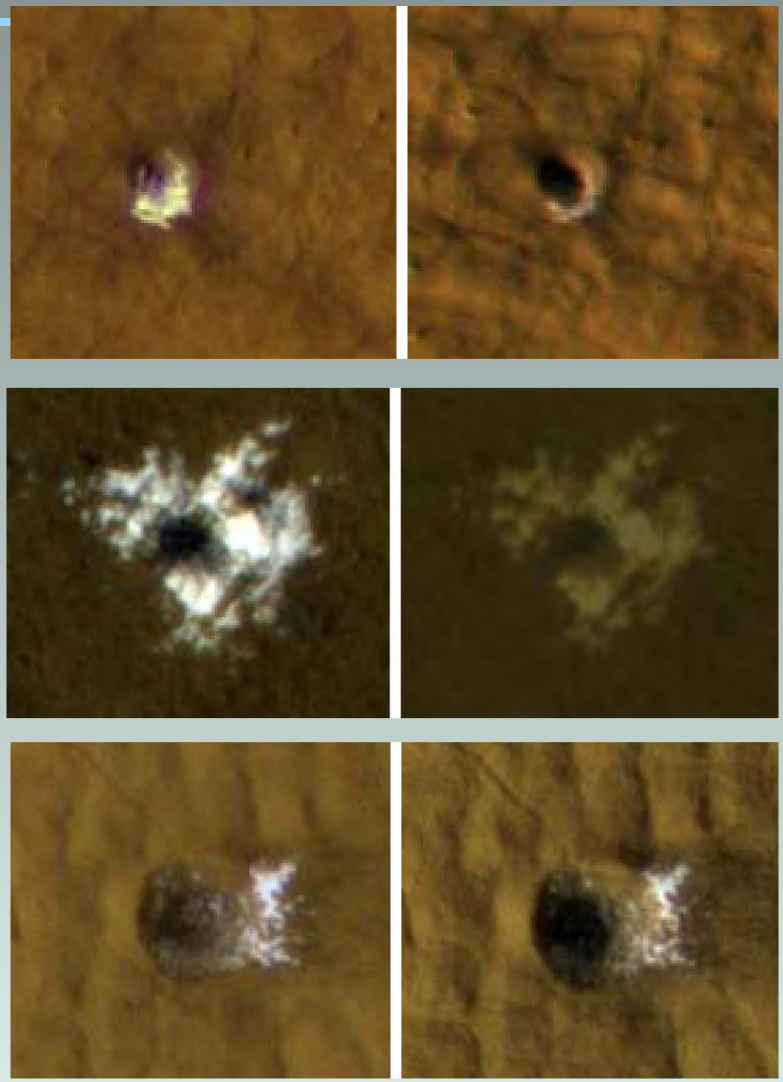
- **Icy soil**
  - Fills pore volume of existing soil
  - 90% of the excavated ice is this type
- **Light-toned ice**
  - 99% pure ice
  - Origin not understood
  - 10% of the excavated ice is this type
- <u>Ice-table depths consistent with diffusive equilibrium with the current climate.</u>
- Soil properties and local slopes play a role.

(From Mellon et al., 2009)

Ground Ice – Observations

Recent Icy Impacts

- CTX and HiRISE observed fresh small craters.
- Most of the fresh high- and mid-latitude craters show exposed icy surfaces in varying degrees.
- Darkening over time indicates sublimation of water ice.
- Ice may be exposed subsurface ice or post impact condensate.
- Not observed in equatorial regions.
- Locations consistent with ice stability.



(Byrne et al., 2009)

Observations – What We Know.

- **Theory and observations are in good agreement.**
  - Geographically: ground ice is observed in regions where it was predicted
  - Depth: Observed ice table depth is consistent with ice stability models.
  - Gives us confidence in the theory.

- We believe the **ground ice is currently in equilibrium with atmosphere** and current climate (or close to current climate).
  - The depth and location is controlled by diffusive equilibrium.

- High concentrations of ice are sometimes observed - not understood.

  …*But this does not effect depth and geography equilibrium.*

Potential for Equatorial Ground Ice

- Key Question:
  - **What is the potential for the occurrence of ground ice in the equatorial regions of Mars?**

- Equatorial ground ice is generally not stable.
- Widespread equatorial is ice not consistent with observations.

- Local ground ice deposits require special circumstances:
    - Special thermophysical properties.
    - Relic ice from ancient climate (Gyrs).
    - Impervious layer, “cap rock”.
    - Very recent large climate change (few-100 kyrs).
    - Poleward slopes.
    - Special shadow conditions.

Potential for Equatorial Ground Ice

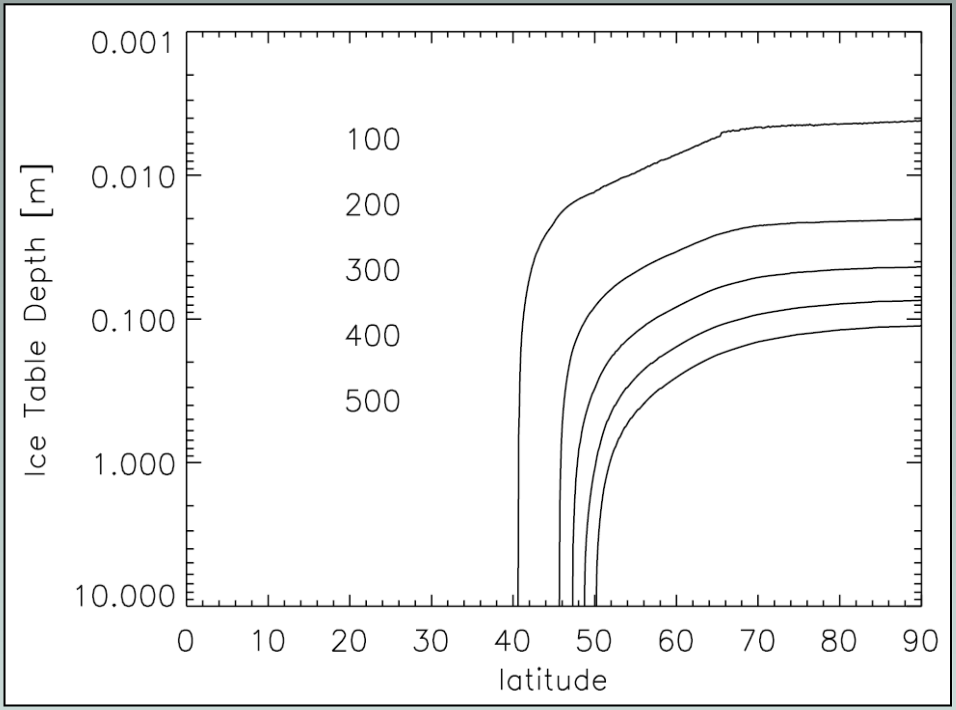
Thermophysical Properties.

Thermal Inertia and **Albedo** are key parameters controlling soil temperatures and ground ice stability.

- Responsible for regional ground ice depth and distribution.
- Thermal inertia is the larger factor: most of Mars between about 50 and 400 (MKS).

Difficult to make ground ice stable much equatorward of ± 35° lat.

(see theoretical ice depth map)



Potential for Equatorial Ground Ice

Relic ice: What is the lifetime of equatorial ice.

There've been a number of studies examining the lifetime of unstable ground ice at the equator. **Assume an initial ancient ice-rich soil and let is sublimate.**

(Smoluchowski, 1968; Clifford and Hillel, 1983; Fanale et al., 1986; Mellon et al., 1997)

Example from Fanale et al (1986): They suggests desiccation to depths of 100+ m in current climate .

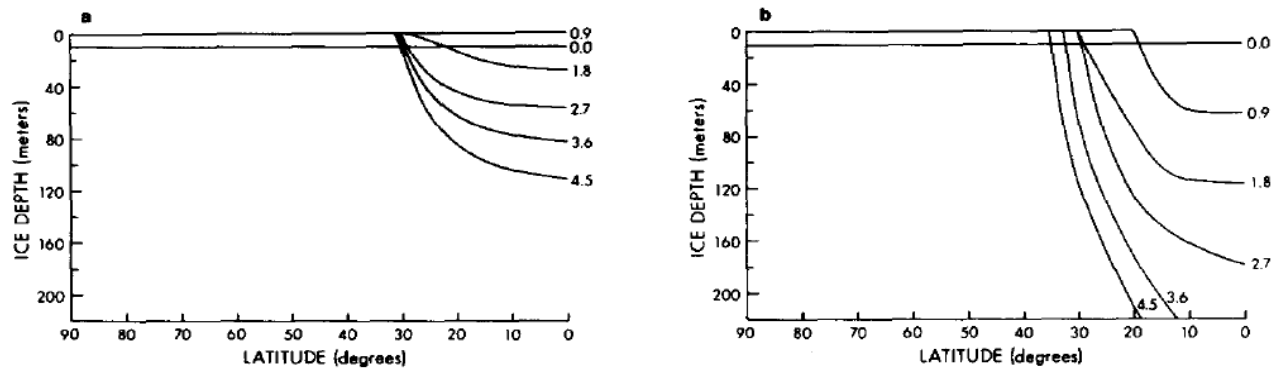


FIG. 5. Ice layer depth vs latitude for indicated times from the beginning of Mars' geologic history for the case where obliquity and eccentricity cycles are in phase and for (a) 1-μm pore radius and (b) 10-μm pore radius.

(Fanale et al., 1986)

Left to sublimate, unstable ice in the equatorial regolith will be lost. The regolith will become desiccated to substantial depth.

Potential for Equatorial Ground Ice

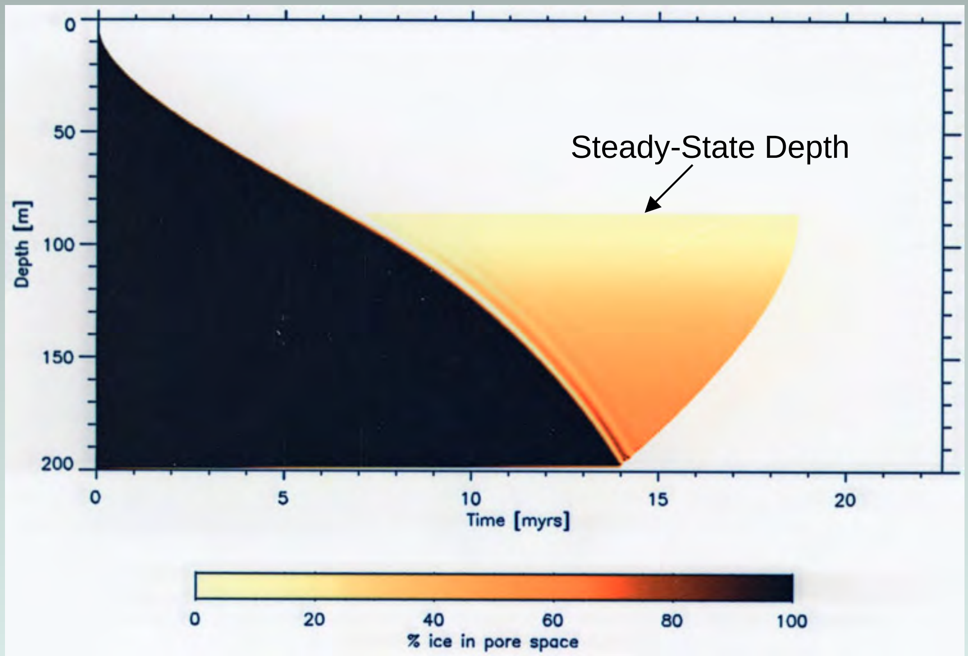
- Another scenario (from Mellon et al., 1997).

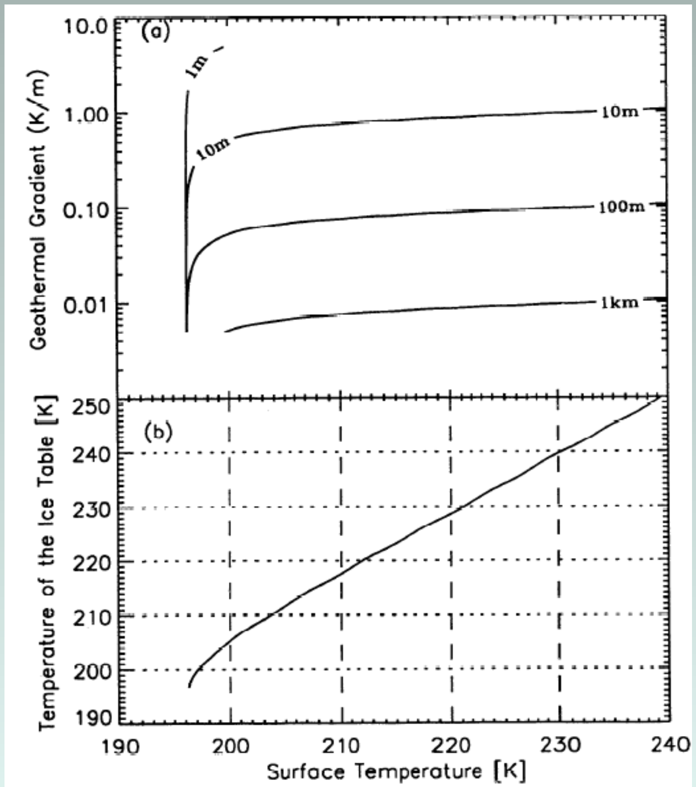
  Model sublimation loss with recharge of an initial ice-rich soil deposit.

  A steady-state depth is reached where: loss = recharge.

  However, all the ice is eventually lost, as with other studies.

  Would need deep source of water to maintain to present day.

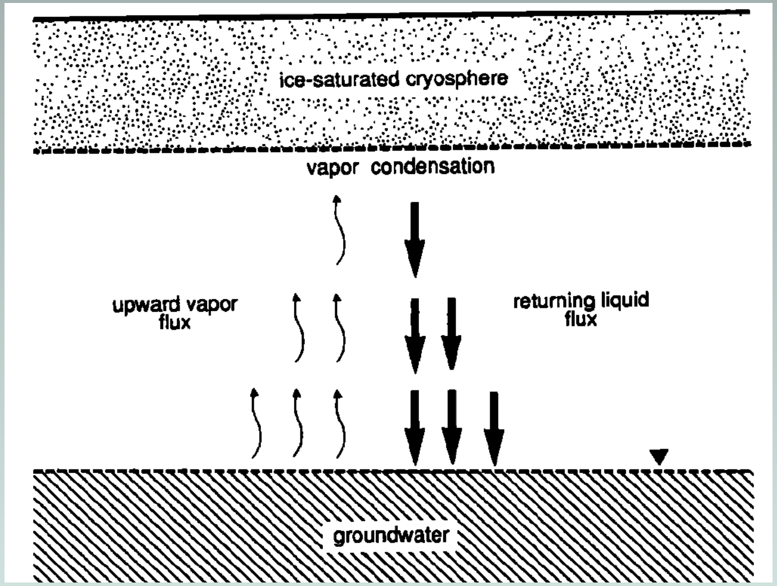




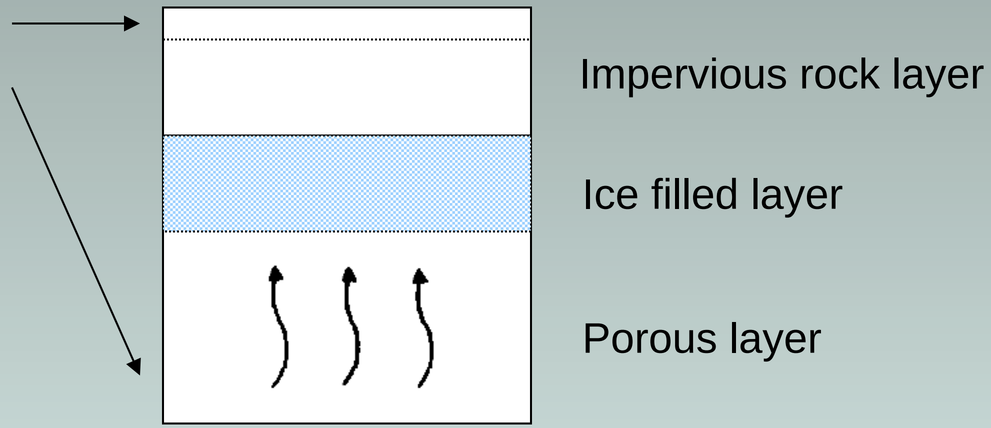
Potential for Equatorial Ground Ice

Ice trapped beneath impervious layer.

Geothermal gradient drives water up, such that ground water and associated water vapor circulate to the underside of the permafrost (Clifford 1991)



(Clifford 1991).

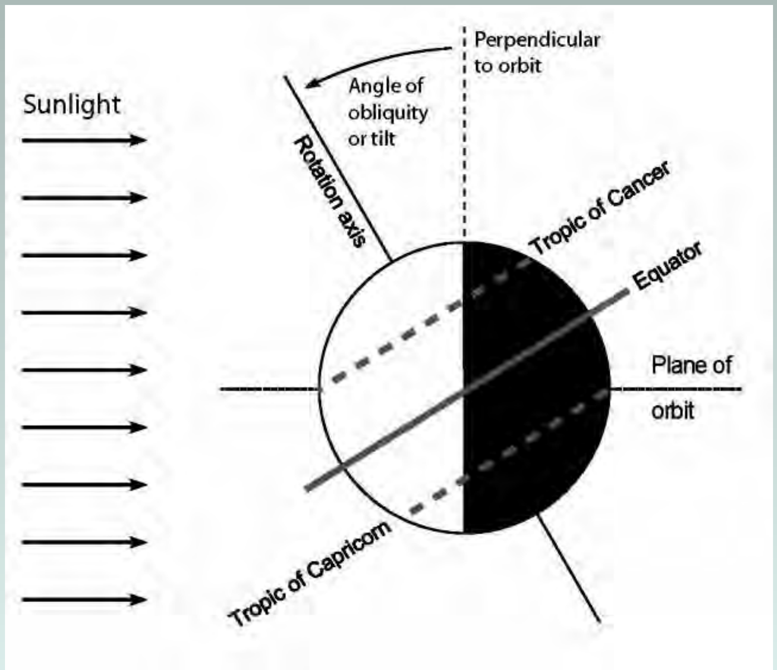


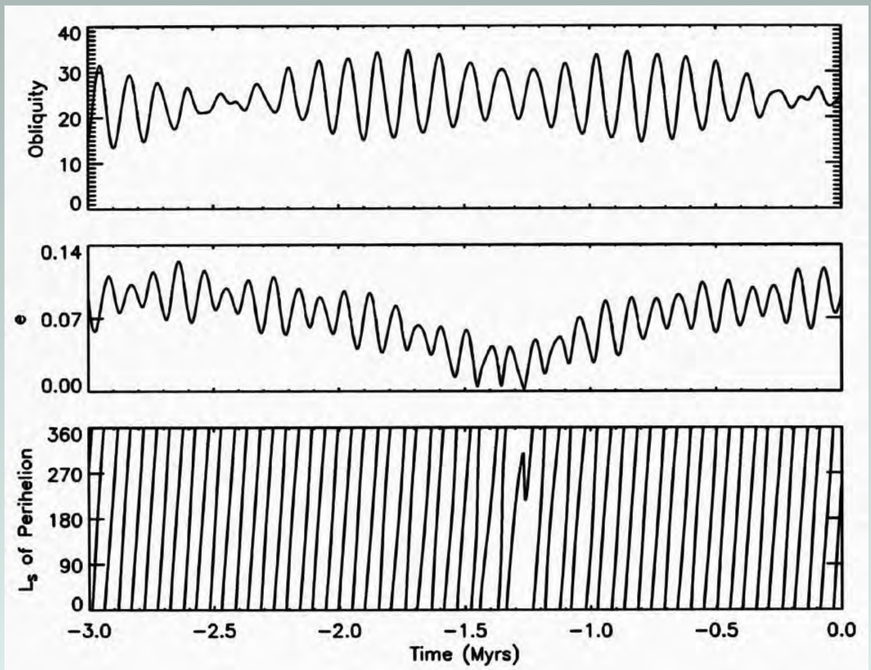
Possible … requires a deeper source of water (e.g., ground water).

Potential for Equatorial Ground Ice

Recent Climate change (1): Orbital and climate cycles.

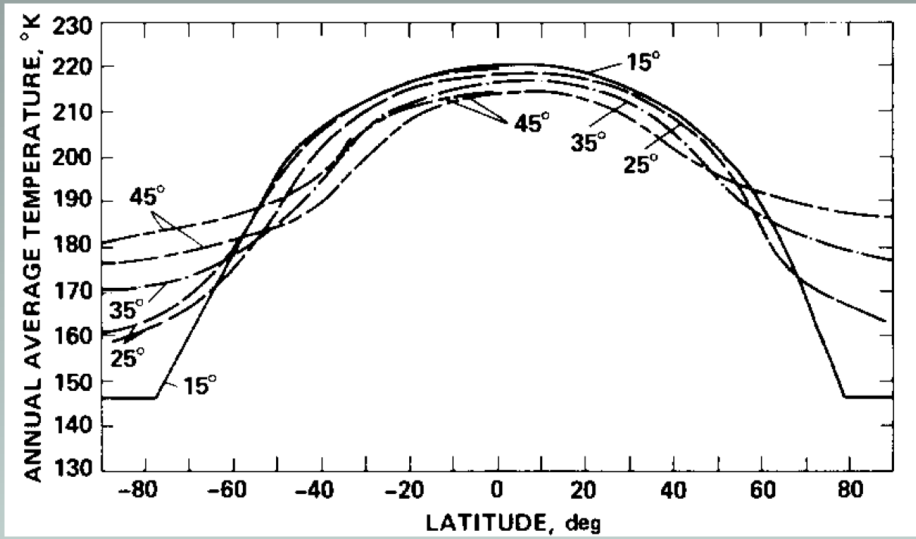
- Orbit cycles drive climate cycles on 10^5-10^6 year time scales.
- Obliquity is the biggest driver. Controlling:
  - polar sublimation and atmospheric water (absolute humidity),
  - ground temperatures.





Potential for Equatorial Ground Ice

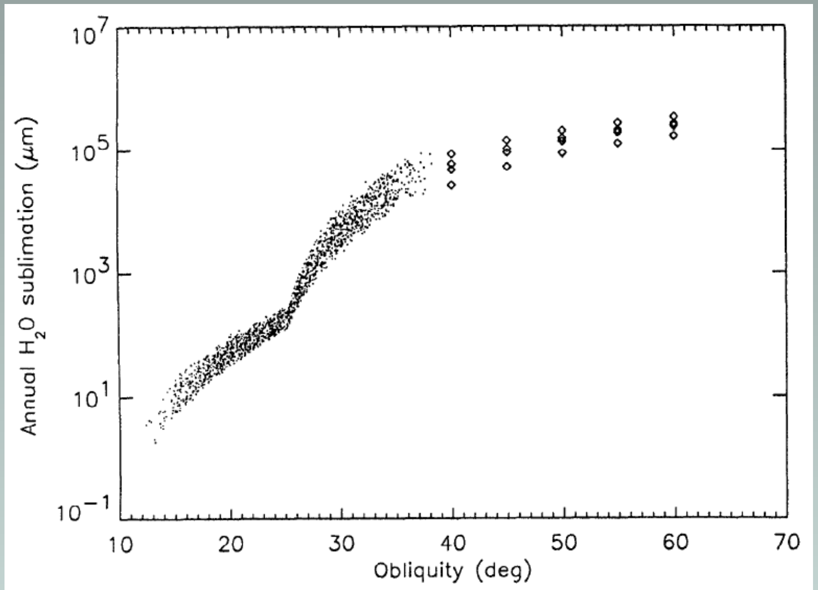
Climate change (2): Atmospheric water and ground temperatures.



(Toon et al., 1980)

Obliquities 15, 25, 35, & 45

Higher obliquity results in warmer poles and cooler equator.



(Jakosky et al., 1995)

Warmer poles sublimate more ice and increase the atmospheric humidity.

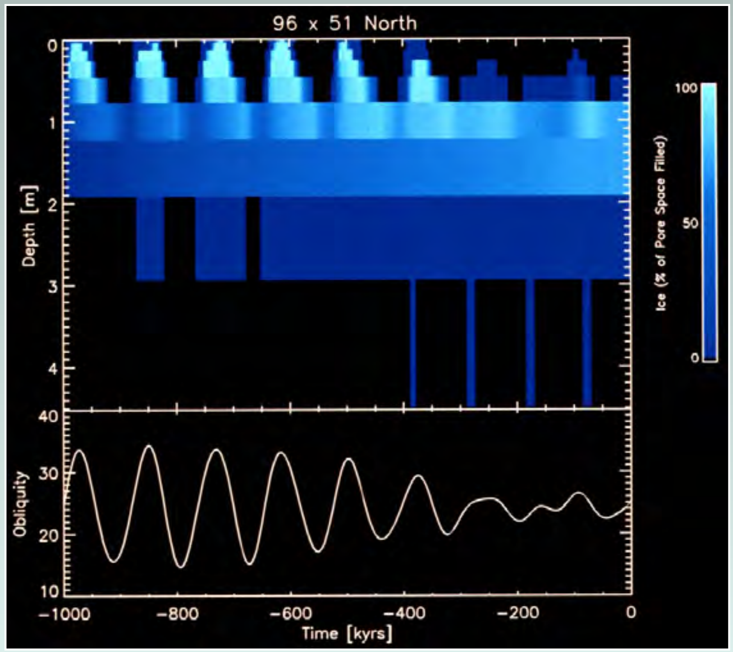
Controls atmospheric humidity.

Potential for Equatorial Ground Ice

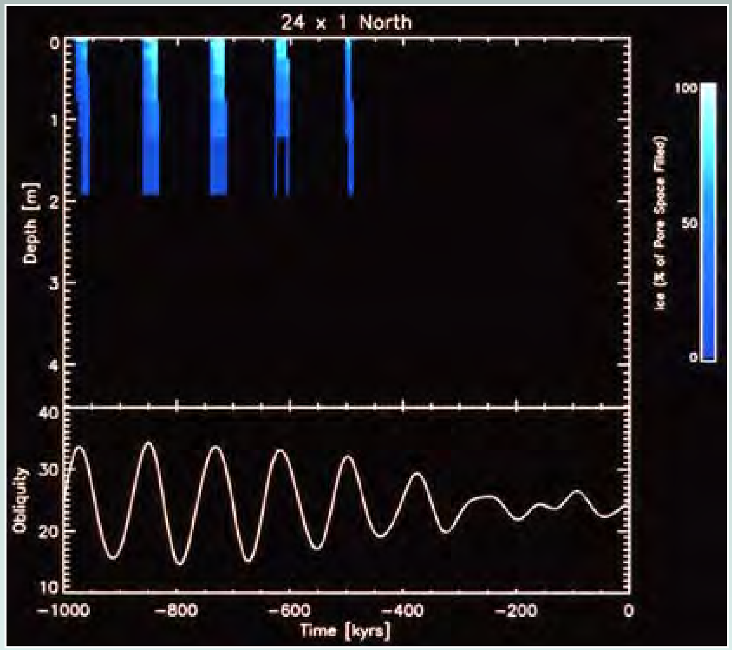
Climate change (3): Resulting ground ice cycles (modeled)…

- At high obliquity …Ground ice becomes stable globally.
- Water vapor diffusion into regolith is fast enough to populate the soil with ice.
- However, accumulated ice sublimates back at lower obliquity about as fast as it condenses at high obliquity.
- Equatorial ice should not persist today except, where most recently stable.

Mid Latitudes



Equator



(From Mellon and Jakosky 1995)

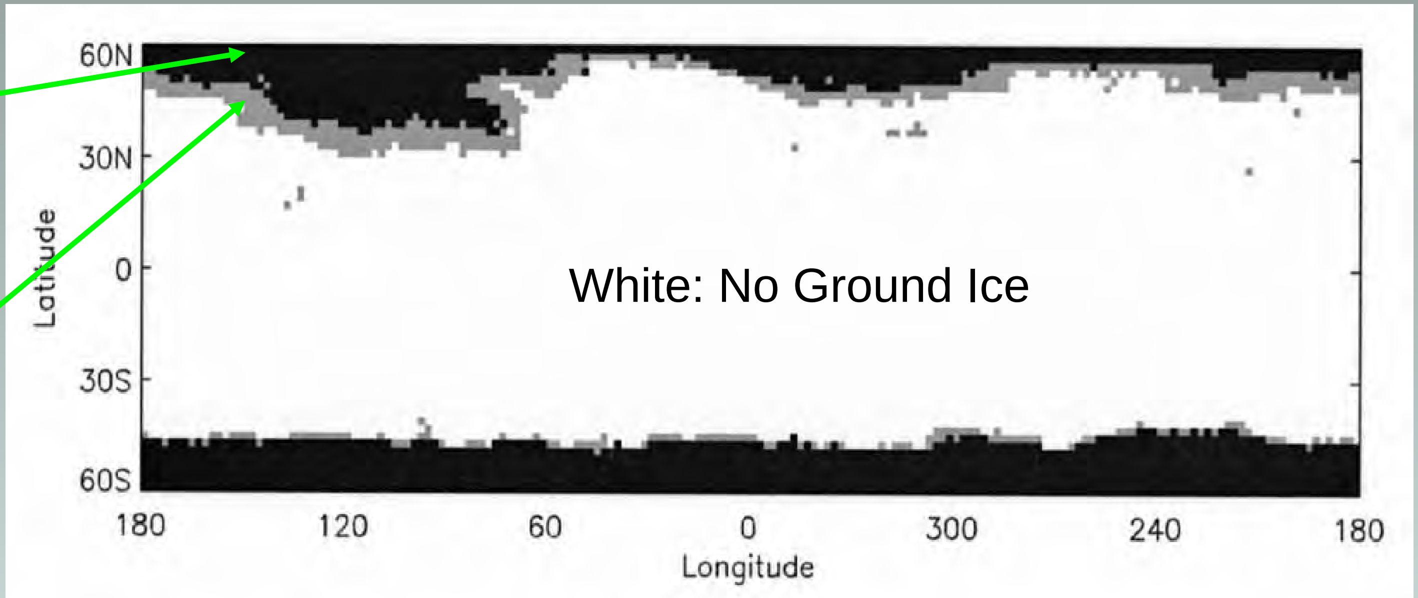
Potential for Equatorial Ground Ice

Climate change (4): Persisting unstable ice

… Equatorial ice should not persist today, except where most recently stable.

Black: Stable Ground Ice

Grey: Unstable Ground Ice



(From Mellon and Jakosky 1995)

In the mapped grey areas, ground ice would have recently accumulated, and is currently sublimating and receding.

Potential for Equatorial Ground Ice

Slopes: Poleward tilt reduces insolation and cools ground surface – under right conditions may result in ice stability.

(Conversely, equatorward tilt will warm ground and results in ice instability.)

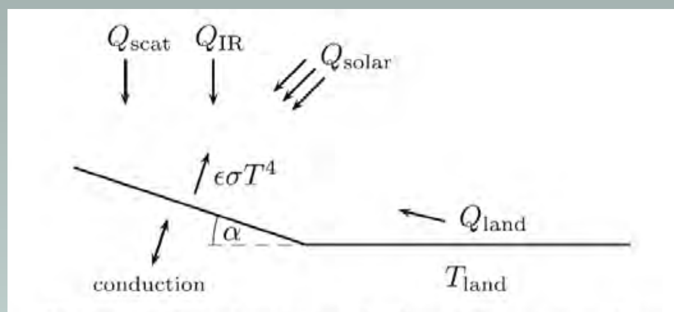
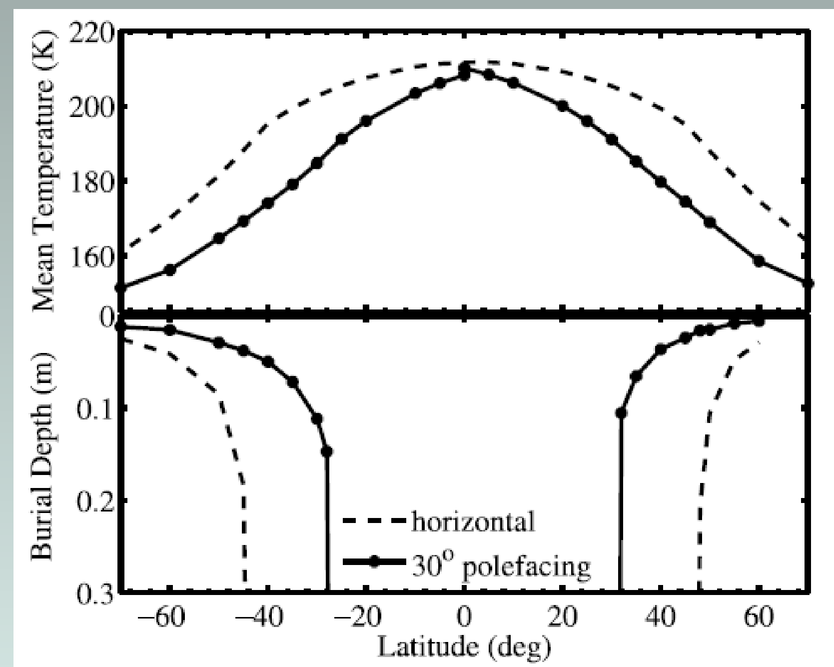


Figure 1. Contributions to the heat balance on a slope with surface temperature T.



(Aharonson and Schorghofer, 2006)
Assuming: A=0.3, I=150 MKS, Tfrost=200K

Example:

- 30º poleward slope
- low thermal inertia / high albedo
- Ice stability shifted…
  - from 45-50º latitude
  - to 30-35º latitude

Potential for Equatorial Ground Ice

Slopes, ground ice, and CO2 frost.

- It's know that shallow ground ice thermally effects the CO2 frost cycle (Haberle et al., 2008), and slopes effect ground ice (Aharonson and Schorghofer, 2006).

- Vincendon et al., (2010) put these together with observed CO2 cycle vs latitude:

1 - The timing of mid-latitude CO2 cycle is best explained by shallow ice.

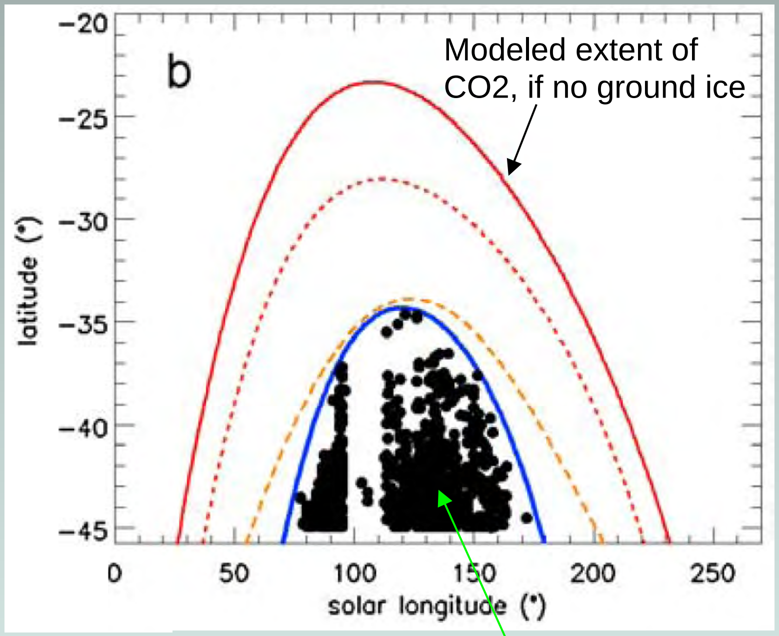
2 - The absence of CO2 frost at lower latitude on poleward slopes is explained by shallow ice.

3 - Inferred stable ice on 30° poleward slope at 25° lat.

Caveat: Assumed CO2 properties maximally favor ground ice at lowest latitude.

albedo	emissivity	
0.65	**1.0**	**assumed -** not realistic combo
0.65	0.8	fine frost (Warren et al 1990)
0.40	0.97	slab ice (Warren et al 1990)

Qualitatively correction will drive stable ice boundary poleward. How much is a research project.



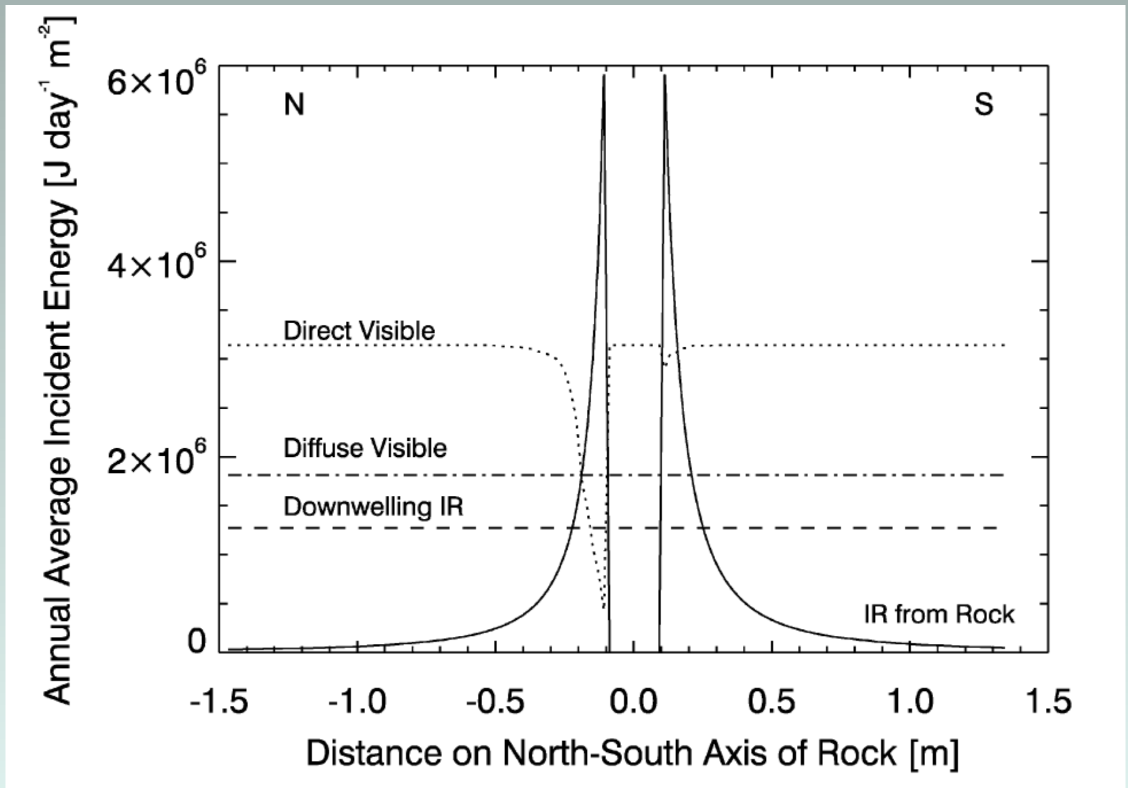
(Vincendon et al., 2010)

Potential for Equatorial Ground Ice

Shadows

Small scale shadows (e.g., near rocks and boulders) have only a **small effect** of local ground temperatures which are dominated by re-radiated energy (Sizemore and Mellon 2009).

Large scale shadows would result from large slopes.



Potential for Equatorial Ground Ice

Summary of special circumstances.

- Thermophysical properties.
  - Can cause 10 or so degrees of latitude differences but at mid-latitudes.
- Relic ice from ancient climate
  - Unlike to survive (unless under impervious trap).
- Impervious trap (cap rock).
  - Special geometries and water sources required. (infinite scenarios)
  - Possible but unlikely to be wide spread.
- Very recent large climate change (few kyrs).
  - Condensation over 10's of kyrs would only need 10's of kyrs to sublimate
  - Most recent climate shifts small, but may have left some ice behind.
- Slopes
  - Has most potential for stable ice in equatorial regions.
- Special shadow conditions.
  - Unlikely. Dominated by re-radiated energy.

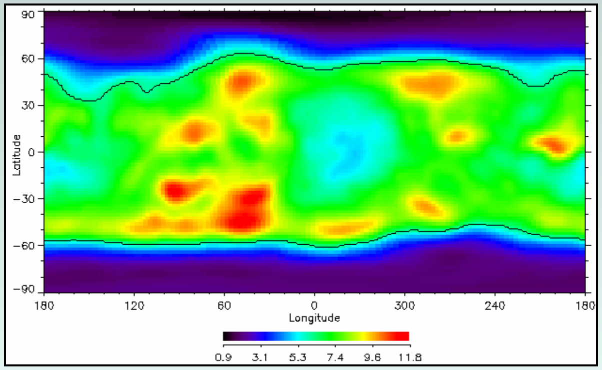
Hydration and Adsorption

Two main types of mineral hydration.

- Physically adsorbed water – mobile surface layer
  - Depends on environment (H2O vapor pressure, temperature) and the substrate (mainly surface area, slightly mineralogy).
- Chemically bound - integrated into the mineral structure
  - Types of hydrated salts -- e.g., sulfates
  - Hydrated and silicates -- e.g., Phyllosilicates, zeolites

At this point most/all of the above have been observed on Mars.

Hydrogen observed by GRS is typically attributed to this water, but debate is still open.



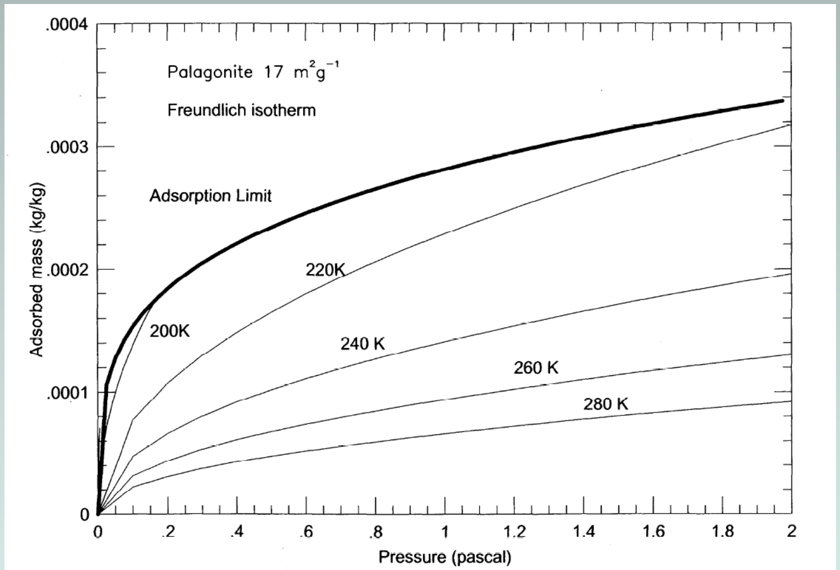
Epithermal Neutrons [c/s]
(Feldman et al 2004)

Adsorbed Water

- Adsorbed water is ubiquitous on Earth and is expected on Mars.
  - Equilibrium between surface substrate and water vapor.
  - Requires a surface and water vapor to collide with and stick to the surface.
  - Observed by Phoenix via electrical properties probe (Zent et al., 2010).
  - Under Mars conditions, adsorbed water is ~ a monolayer or less thick.

- Total water depends on the soil grain surface area.
  - Granular particles: few – 10's m^2/g
  - Clay minerals: up to 1000's m^2/g

- Thermodynamic change drives water between vapor and adsorbed phases.
- Equilibration is rather fast.
- Diffusion in soil is slow.

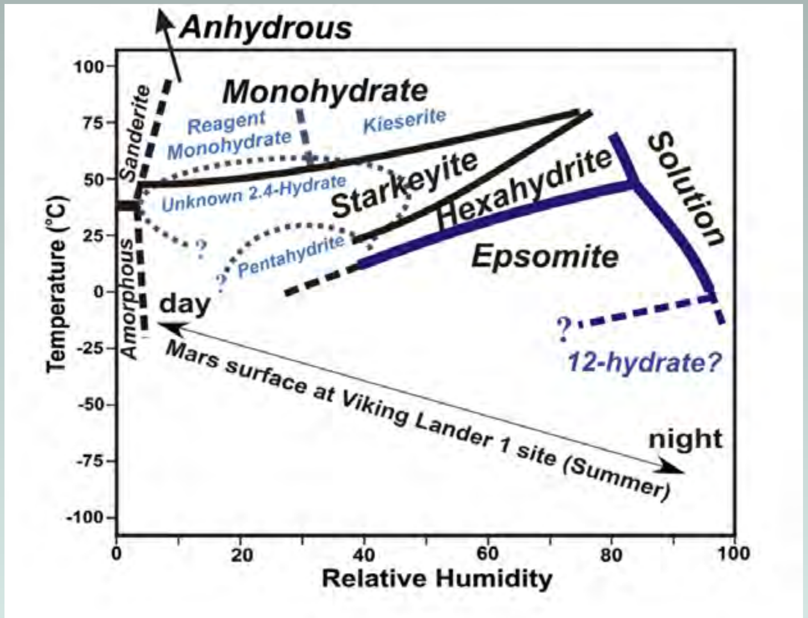


Example from Zent and Quinn, (1997)

Hydration and Adsorption

- Sulfates are observed to be common on Mars.
- Mono- and poly-hydrate (e.g., Kieserite, Hexahydrite, Epsomite)

- Changes in stability conditions results in water exchange with vapor phase.
- Crystal structure changes and causes fracturing changes in density.



Form Chipera and Vanimen (2007)

Phyllosilicates and Zeolites

Phyllosilicates are sheet silicates of Al and Fe/Mg.

- Contain chemically both bound water (hydroxyl) and water adsorbed within interlayer regions (also binding sheets)
  - Clays
    - Kaolinite - $Al_2Si_2O_5(OH)_4$
    - Montmorillonite - $(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$
  - Micas
    - Muscovite – $KAl_2(AlSi_3O_{10})(OH)_2$
    - Biotite - $K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$

Zeolites are porous silicates that can hold substantial water.

- Heating is know to drive off water vapor.

Changes in environmental conditions for both may drive off some physically bound water (e.g,. adsorbed), but high temperatures may be needed to drive off chemically bound water.