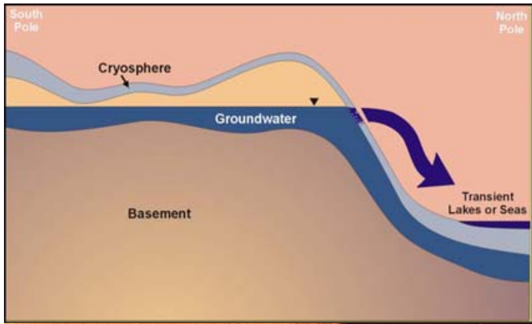

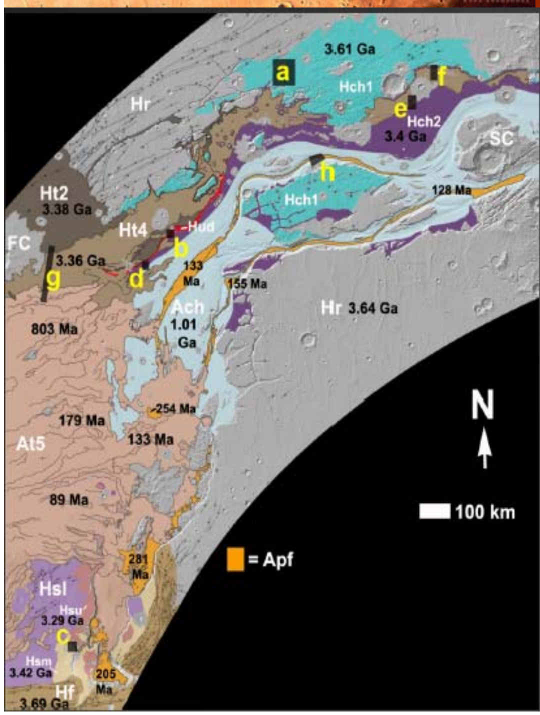

Evidence for the Long-Term Persistence of Habitable Conditions in the Deep-Subsurface of Mars.

S. M. Clifford[1], J. Lasue[2] and M. D. Max[3]

[1]Lunar and Planetary Institute, Houston, TX
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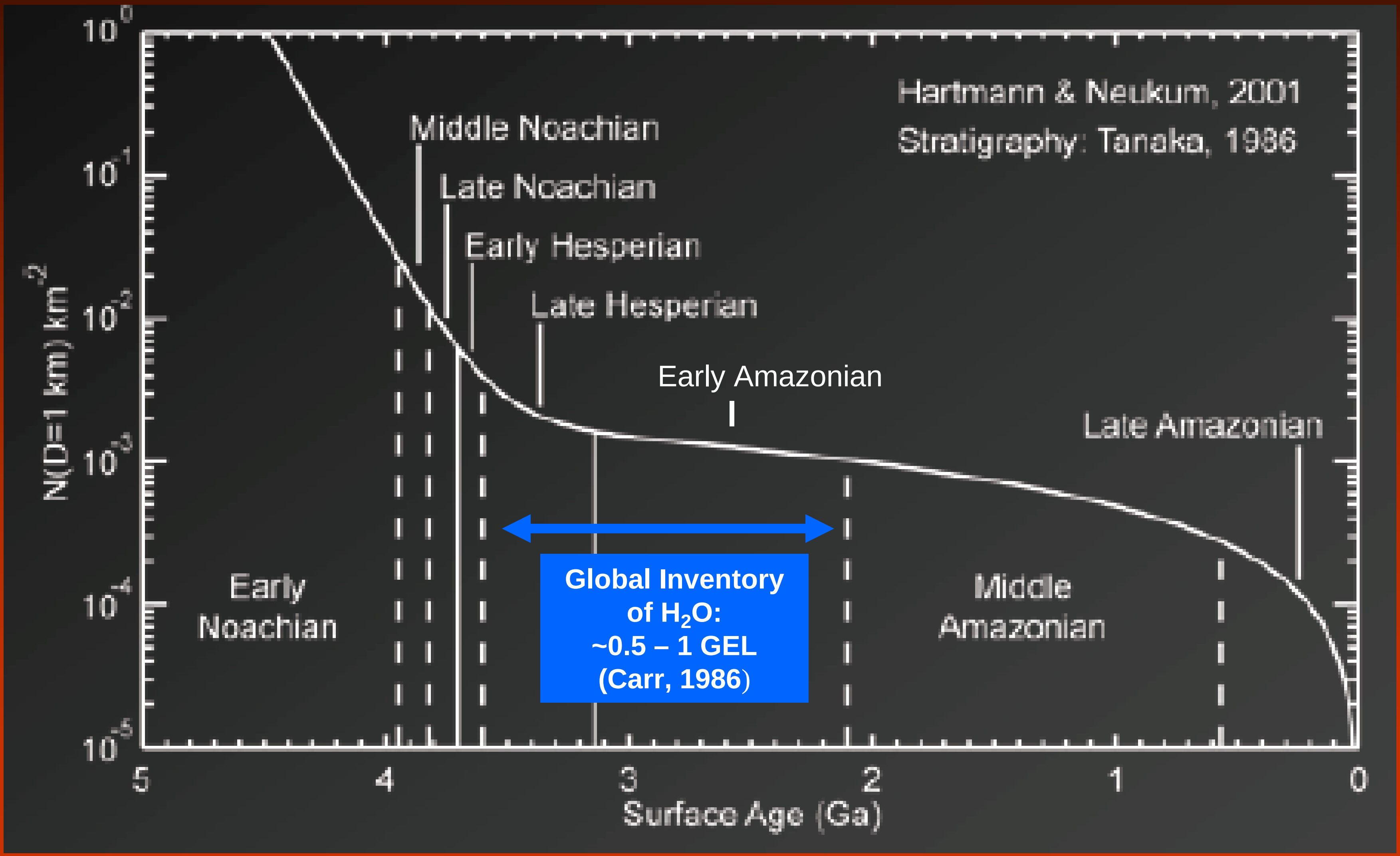
[3]Hydrate Energy International, Kenner, LA

Estimated
Late Hesperian-Early Amazonian Planetary Inventory of H_2O

- Based on the volume of water necessary to erode the outflow channels, Carr (1986, 1996) estimated a Martian inventory of H_2O equivalent to global ocean ~0.5 – 1 km deep.
- Of this amount, only ~5% is present in visible reservoirs (the atmosphere and polar caps), with the remaining ~95% believed to reside as ground ice, groundwater and hydrated minerals, in the subsurface.

Late Hesperian-Early Amazonian Inventory of H_2O: ~0.5 – 1 km GEL (Carr, 1986, 1996)



Neukum et al. (2009)

Maximum H_2O Loss Due to Exospheric Escape Over the Past 3.5 Ga: ~15 m GEL

(Valeille et al., 2010)

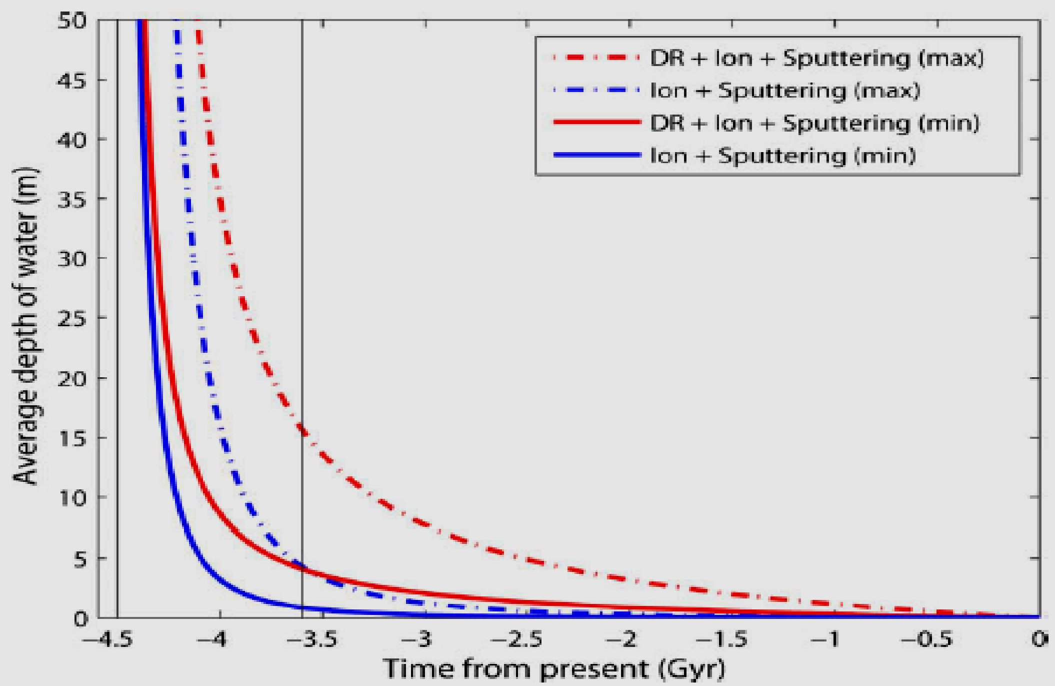
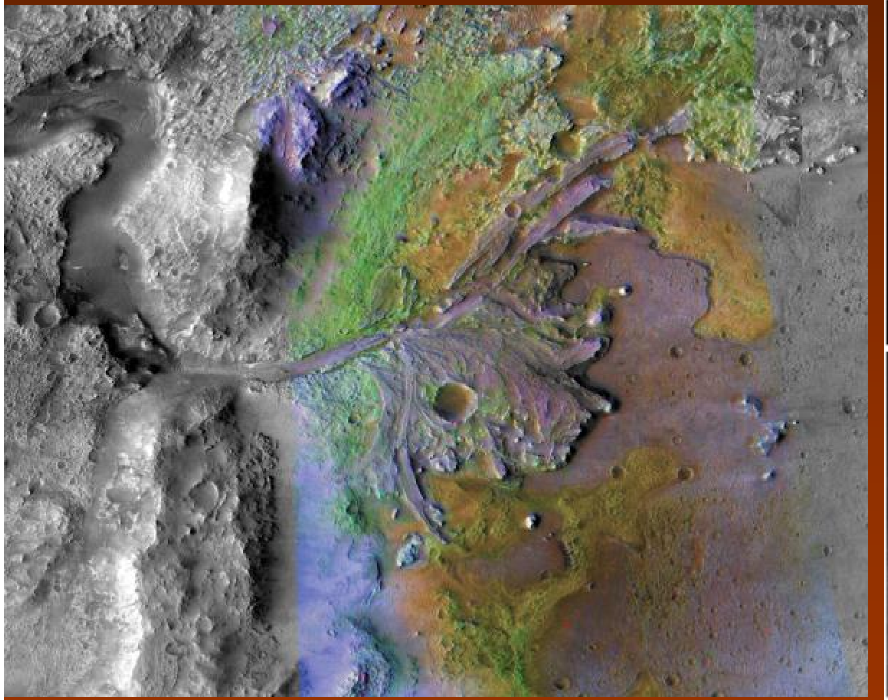


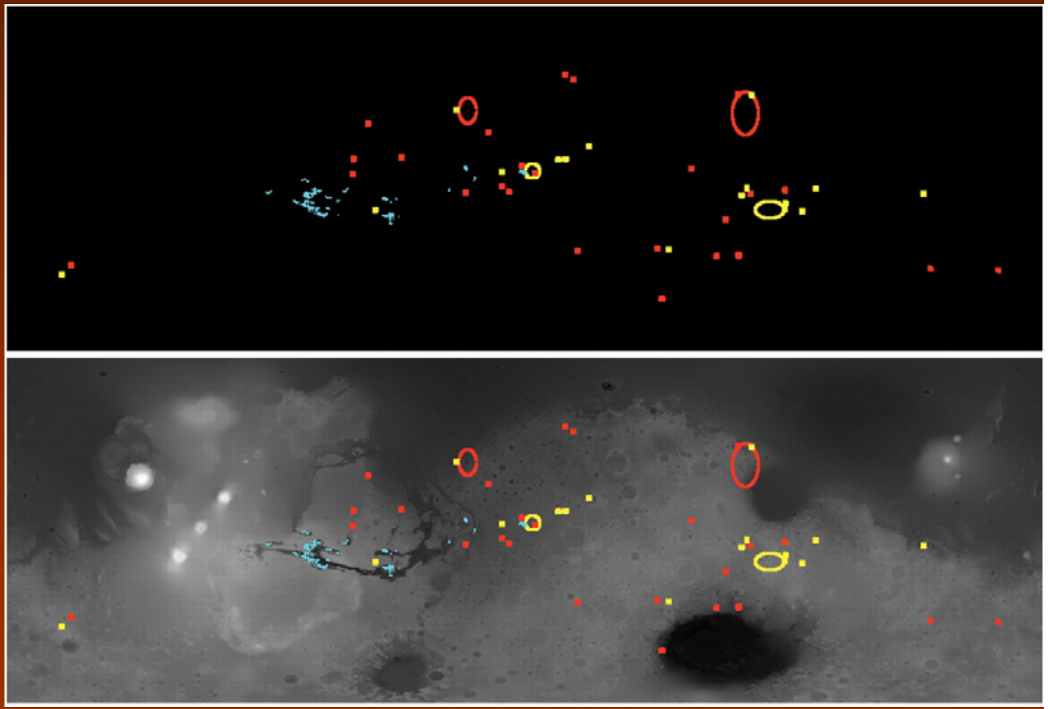
Fig. 8. Cumulative water loss due to sputtering, ion loss (blue lines) and DR (red lines) for solar minimum (solid lines) and maximum (dashed-dotted lines) conditions. Sputtering before −3.6 Gyr ago is not shown as the presence of a magnetosphere at that time would have protected the planet from its effect. In the first 0.1 Gyr, the atmospheric composition is believed to be far different from the present CO_2 dominated one.

Phyllosilicates and Other Hydrated Minerals: A Mineralogical Sink for H_2O

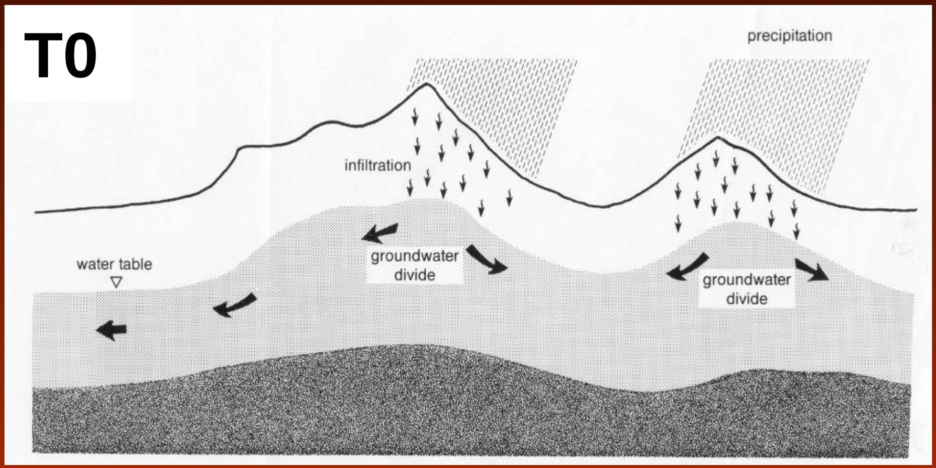
CRISM: Phyllosilicates (green) in delta deposits in Jezero Crater (NASA, 2008)

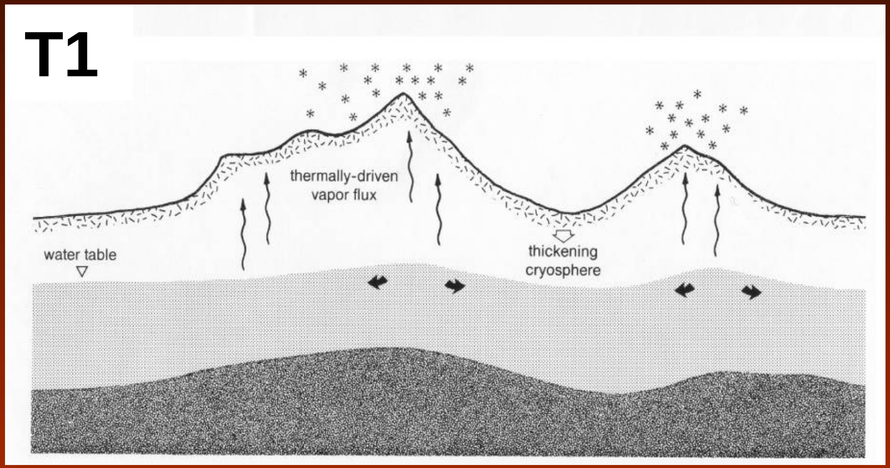


OMEGA Global Map: Red: phyllosilicates; blue: sulfates; yellow: other hydrated minerals (Bebring et al., 2006).



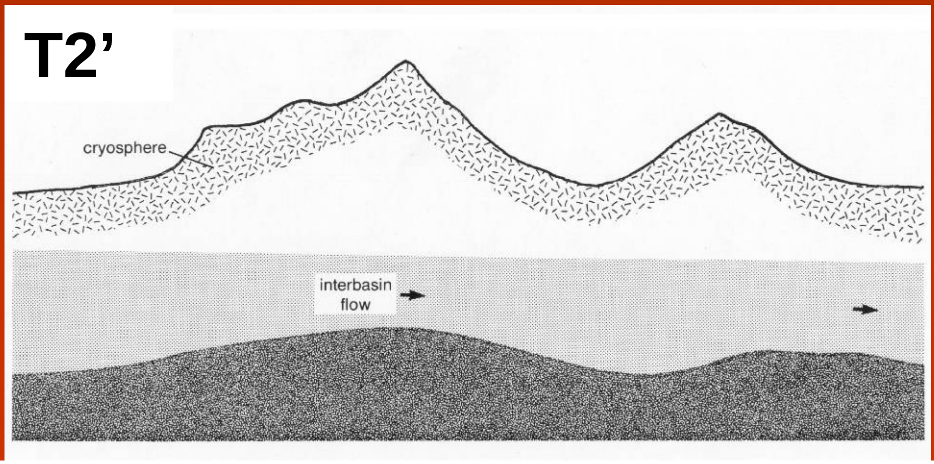
Evolution of the Martian Hydrosphere in Response to the Decline in Global Heat Flow

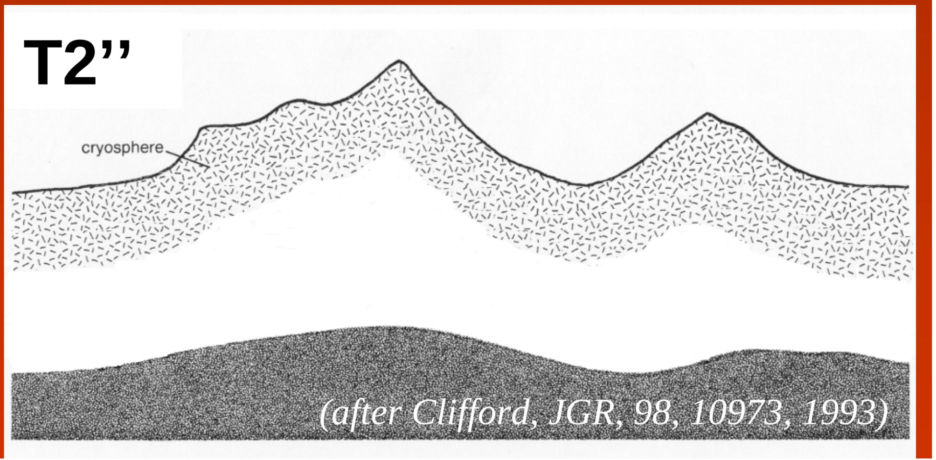




Planetary inventory of H_2O > pore volume of cryosphere:
A reservoir of groundwater should still persist at depth.

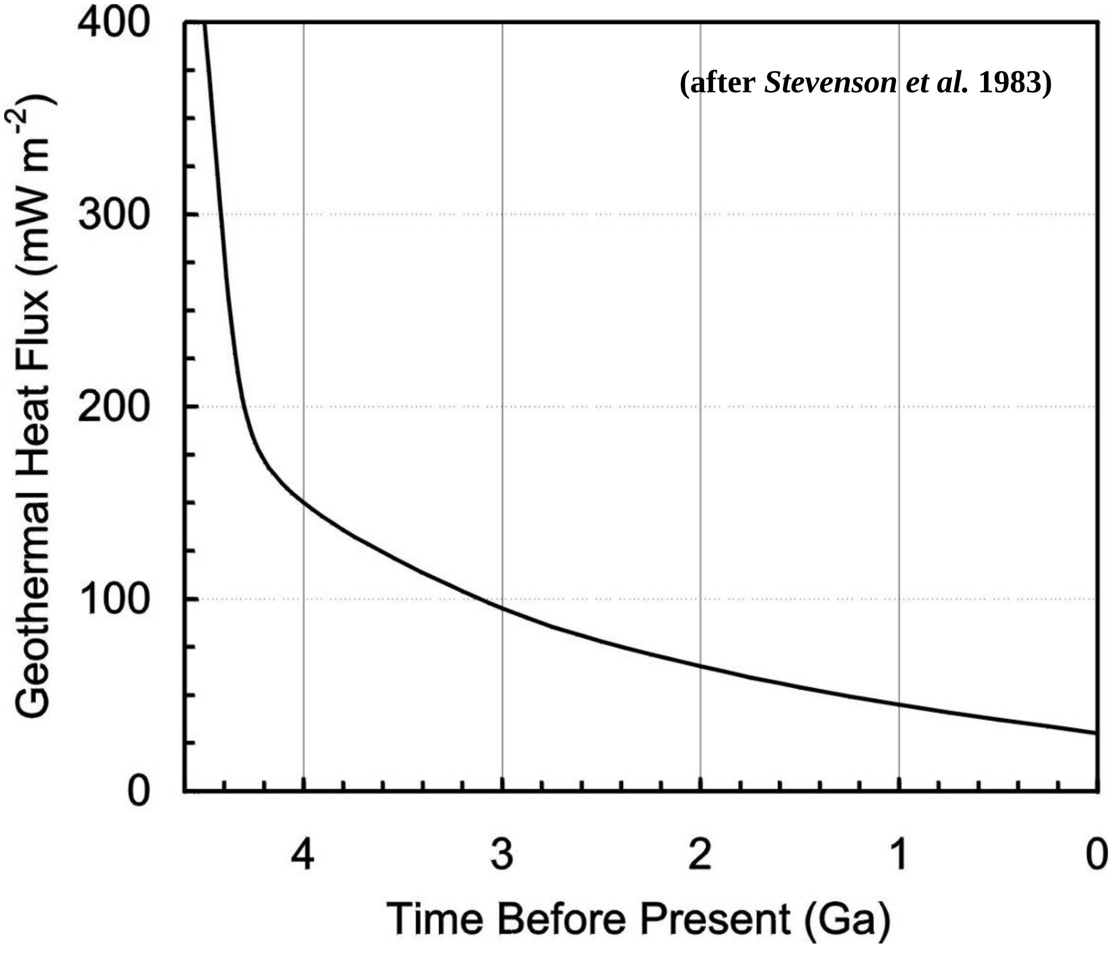
Planetary inventory of H_2O < pore volume of cryosphere:
Inventory entirely cold-trapped, groundwater no longer survives.



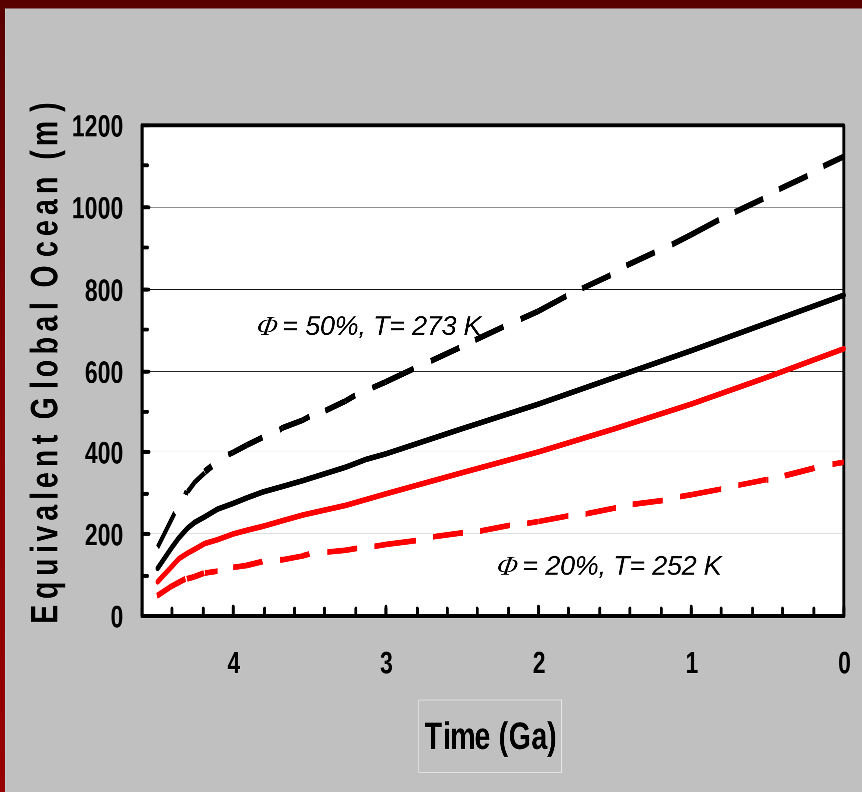


(after Clifford, JGR, 98, 10973, 1993)

Decline in Martian Geothermal Heat Flow vs. Time:



Volume of H_2O Assimilated by Cryosphere vs. Time*

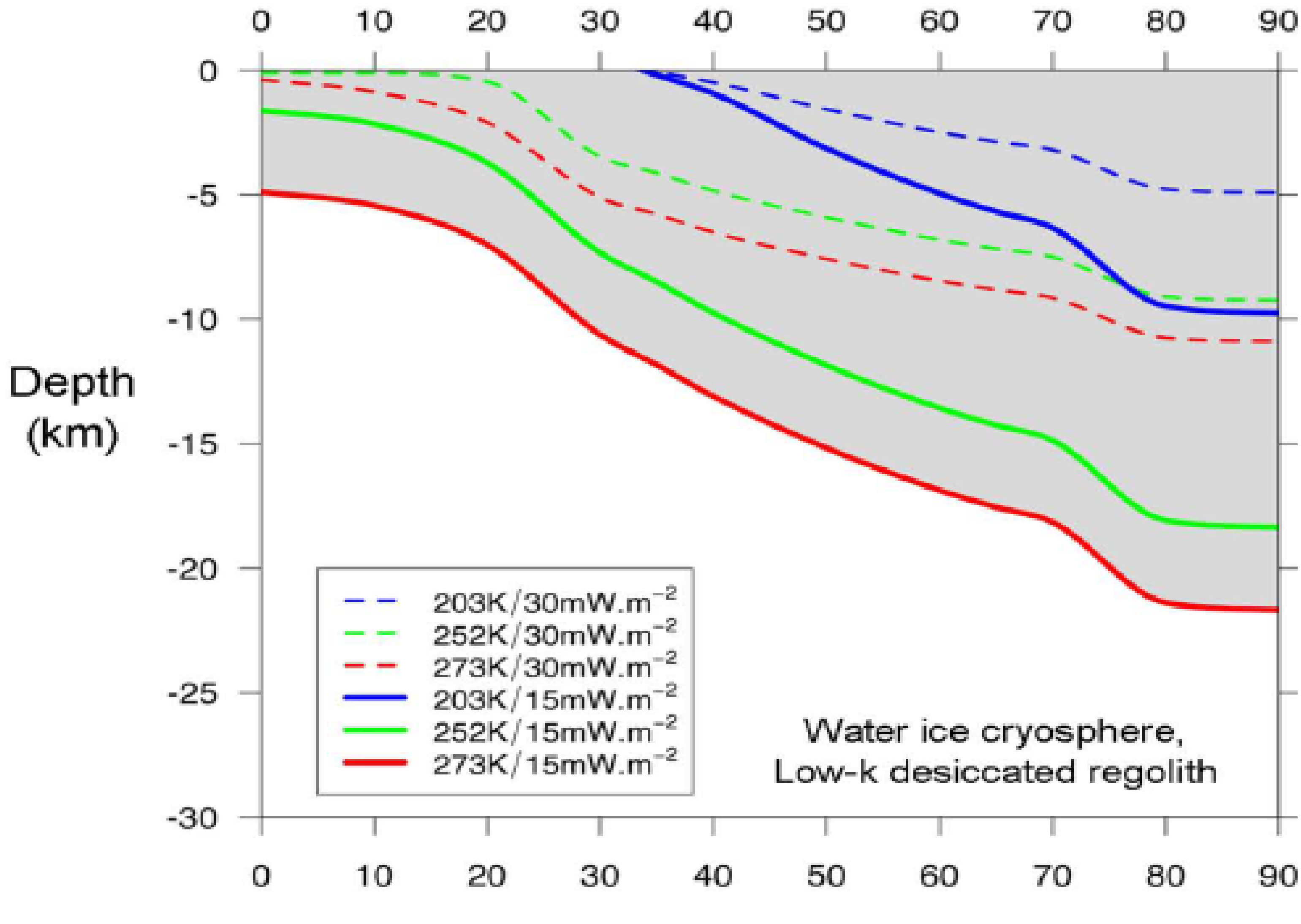


Φ= 35%,
ΦT= 252 -273 K

Time (Ga)	H_2O (m)
4.5	~100
4.3	180
4.0	240
3.0	350
2.0	460
1.0	580
0	720

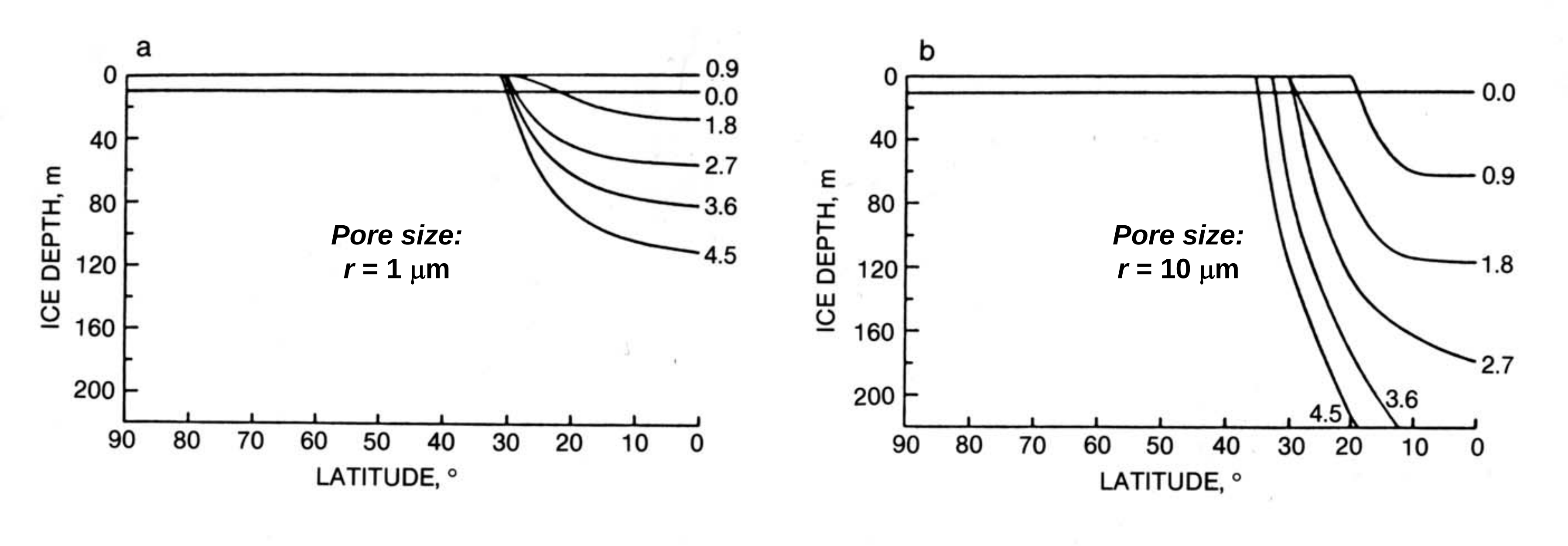
**Clifford and Parker* (2001)

Estimated Thickness of Present Day Cryosphere*

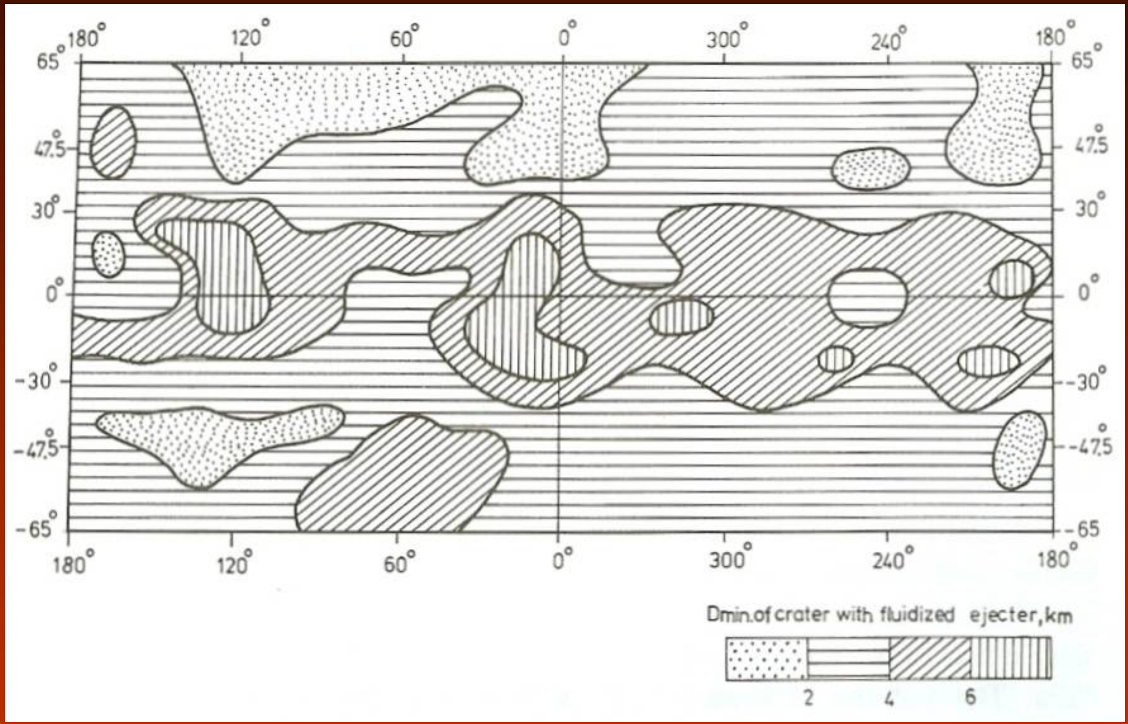


**(Clifford et al., Icarus 115, E07001, 2010)*

Instability of Ground Ice at Low-Latitudes (Fanale et al., 1986):

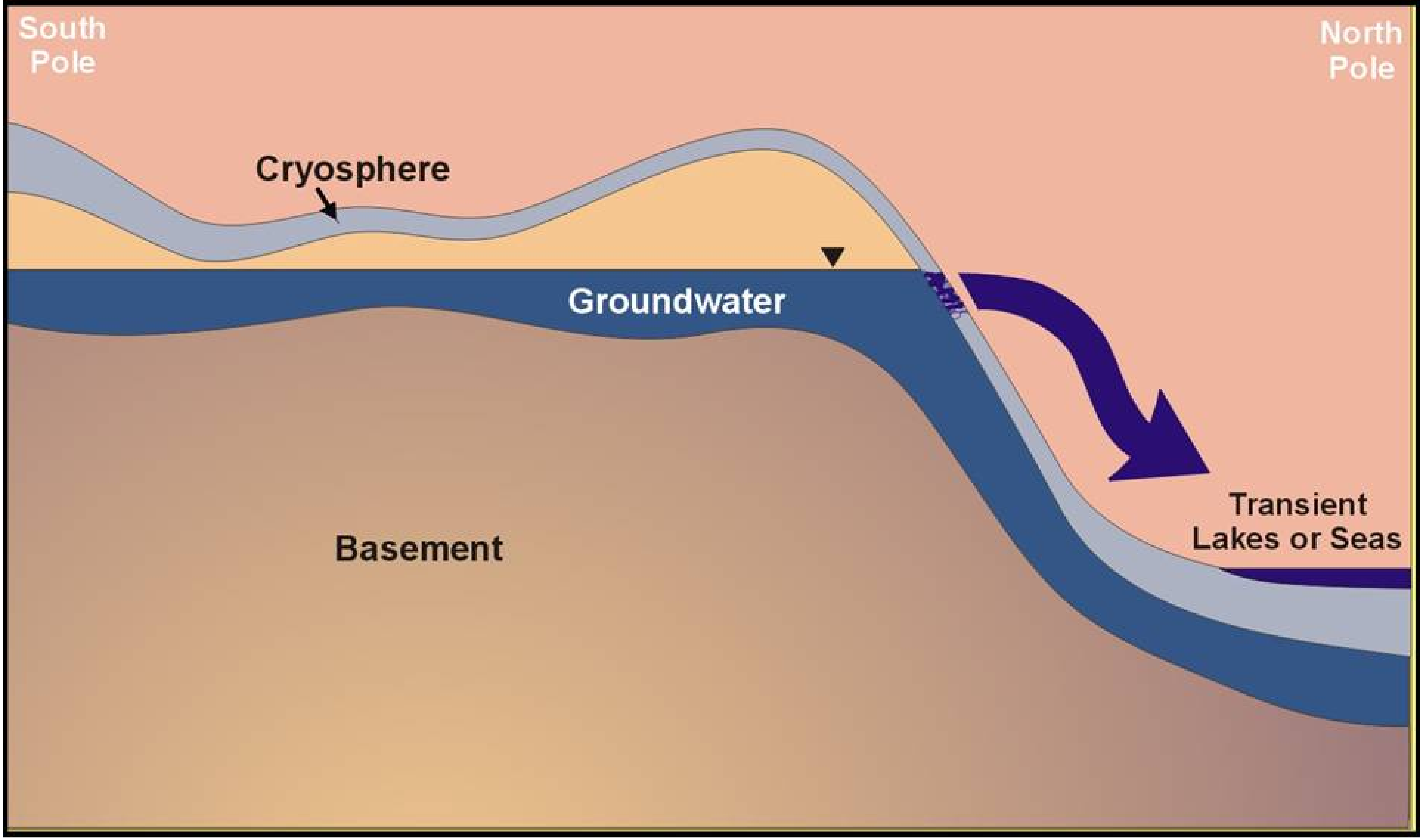


Occurrence of Rampart Craters:



- Rampart craters are present in even the youngest equatorial terrains, suggesting that, if they were formed by an impact into a volatile-rich target, the volatiles are still present (Kuzmin, 1983; Costard, 1989; Squyres et al., 1992; Barlow, 1994).

Inferred hydraulic conditions by Late Hesperian, implied by elevation of outflow channel source regions:



Mid- to Late Amazonian (~0.2 - 1 Ga)* Fluvial Activity in Mangala Valles

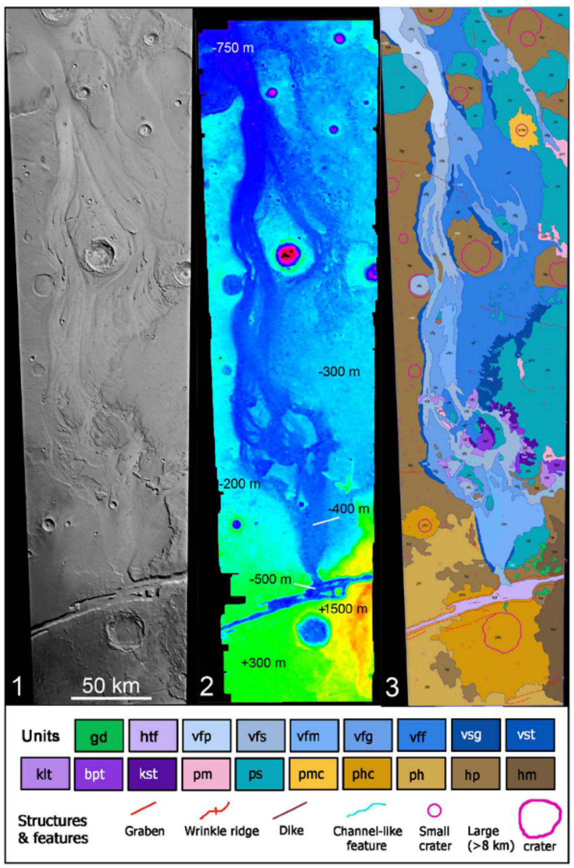


Fig. 2. Study area: (1) HRSC image H0286; (2) Color-coded DTM; (3) Geomorphic map. Legend for the morphologic units: gd—glacial deposits; htf—head trough floor; vfp—valley floor pitted, vfs—valley floor smooth; vfm—valley floor mottled; vfg—valley floor grooved; vff—valley floor fluted; vsg—valley slope grooved; vst—valley slope terraced; klt—large knob terrain; bpt—polygonal block terrain; kst—small knob terrain; pm—plains with mesas; ps—smooth plains; pmc—post-Mangala (large) crater; phc—post-hummocky-plains (large) craters; ph—hummocky plains; hp—highland plateau; hm—highland mountains.

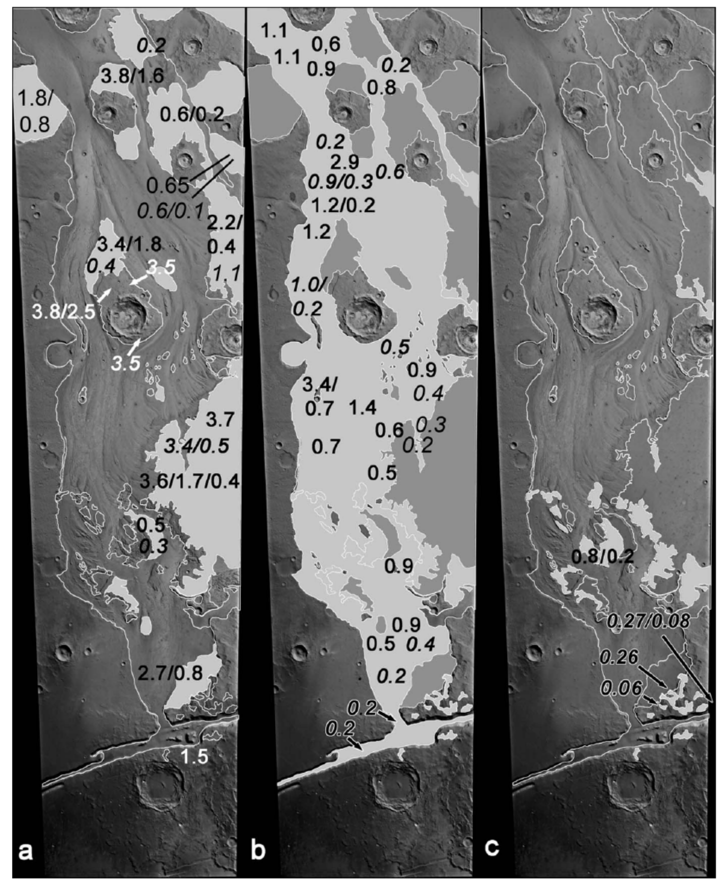
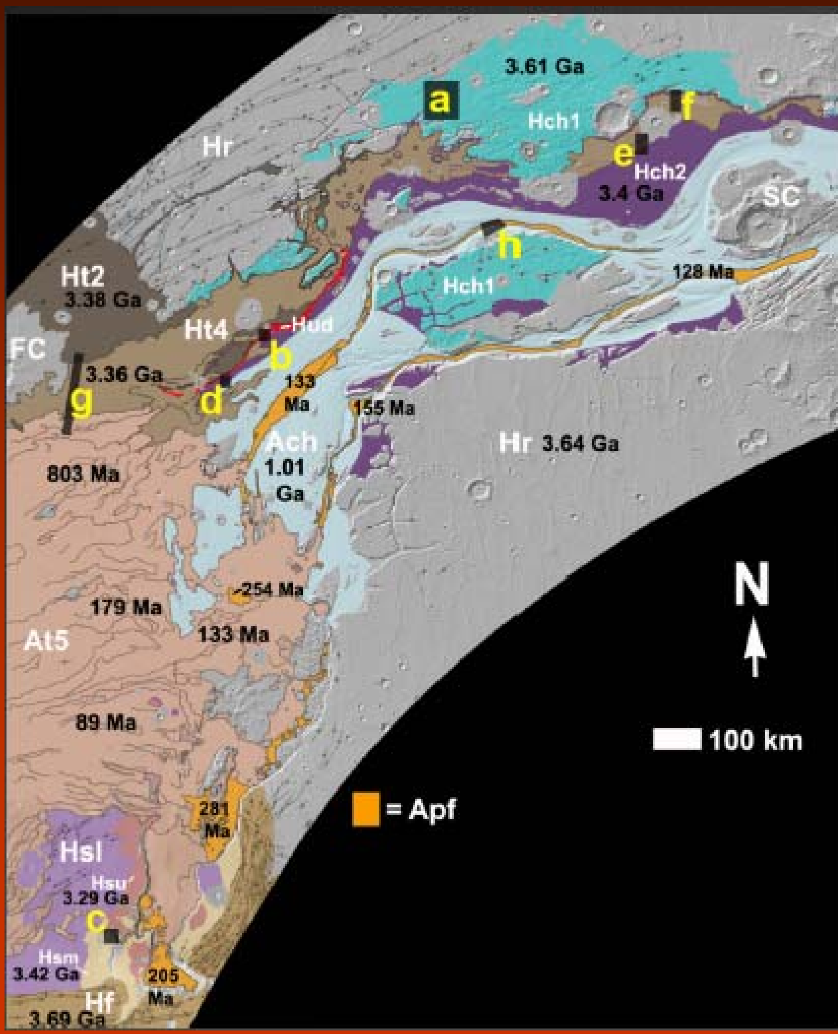


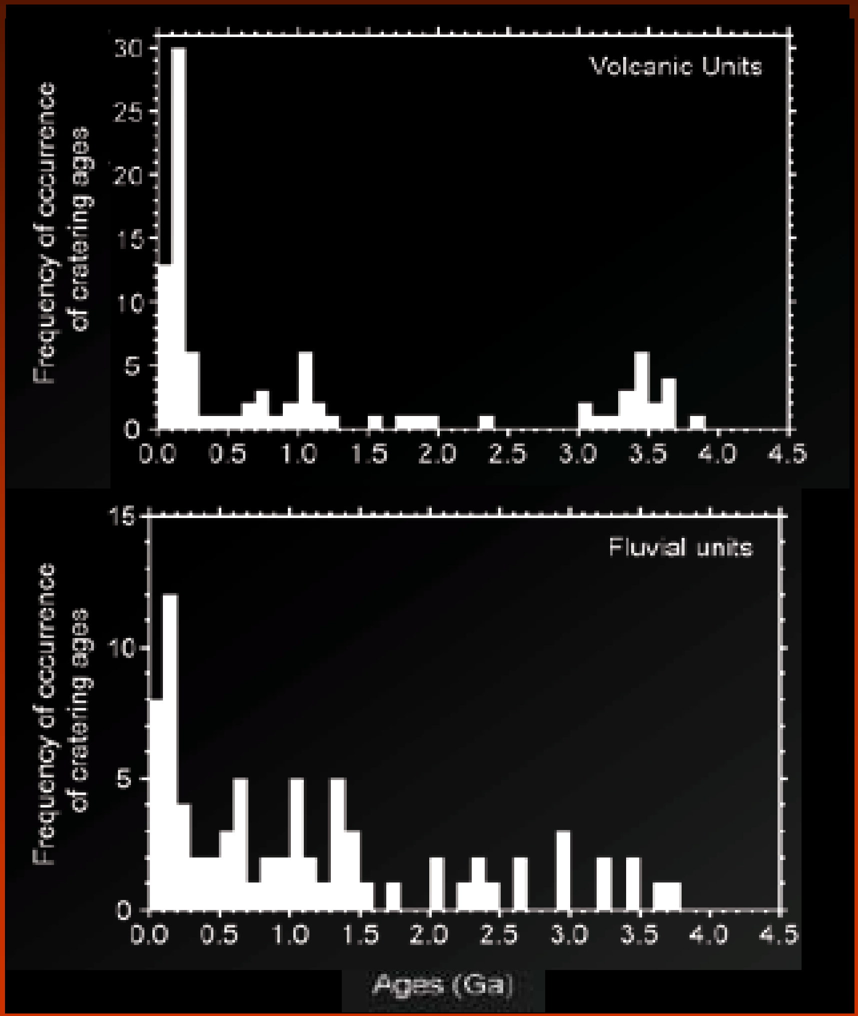
Fig. 30. Results of age estimates for different unit assemblages: (a) highland units (white numbers) and smooth plains (black numbers), (b) units of the deeply incised part of the valley, and (c) units representing degradation of the valley elements and glacial deposits. Counts on HRSC image are shown by a regular font, counts on MOC and THEMIS images, by italics. Positions of numbers on the figure correspond approximately to locations where crater counts have been done.

**(Basilevsky et al., 2009)*

Mid- to Late Amazonian (~70 Ma - 1 Ga)* Fluvial Activity in Kasei Valles and Echus Chasma

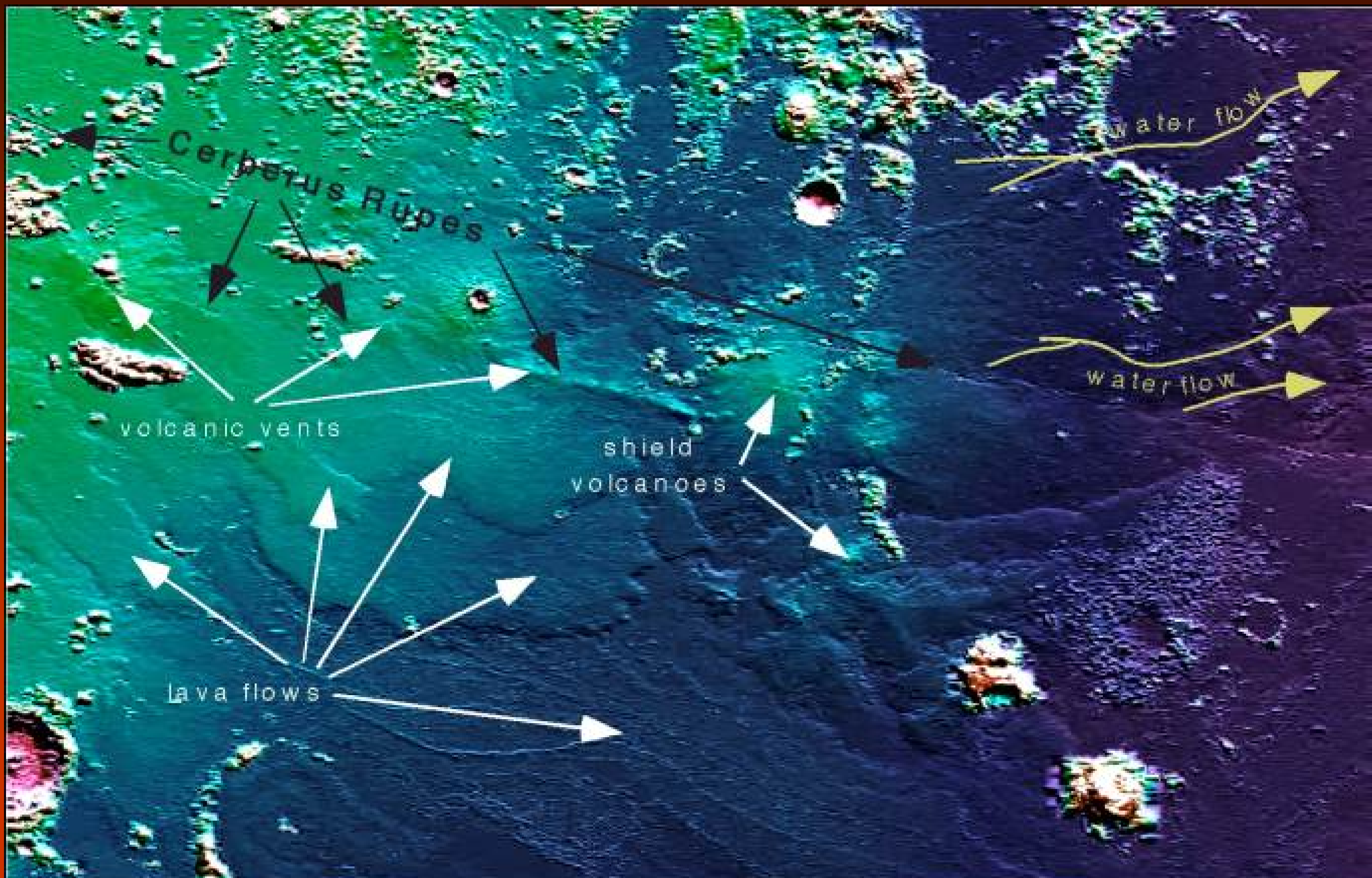


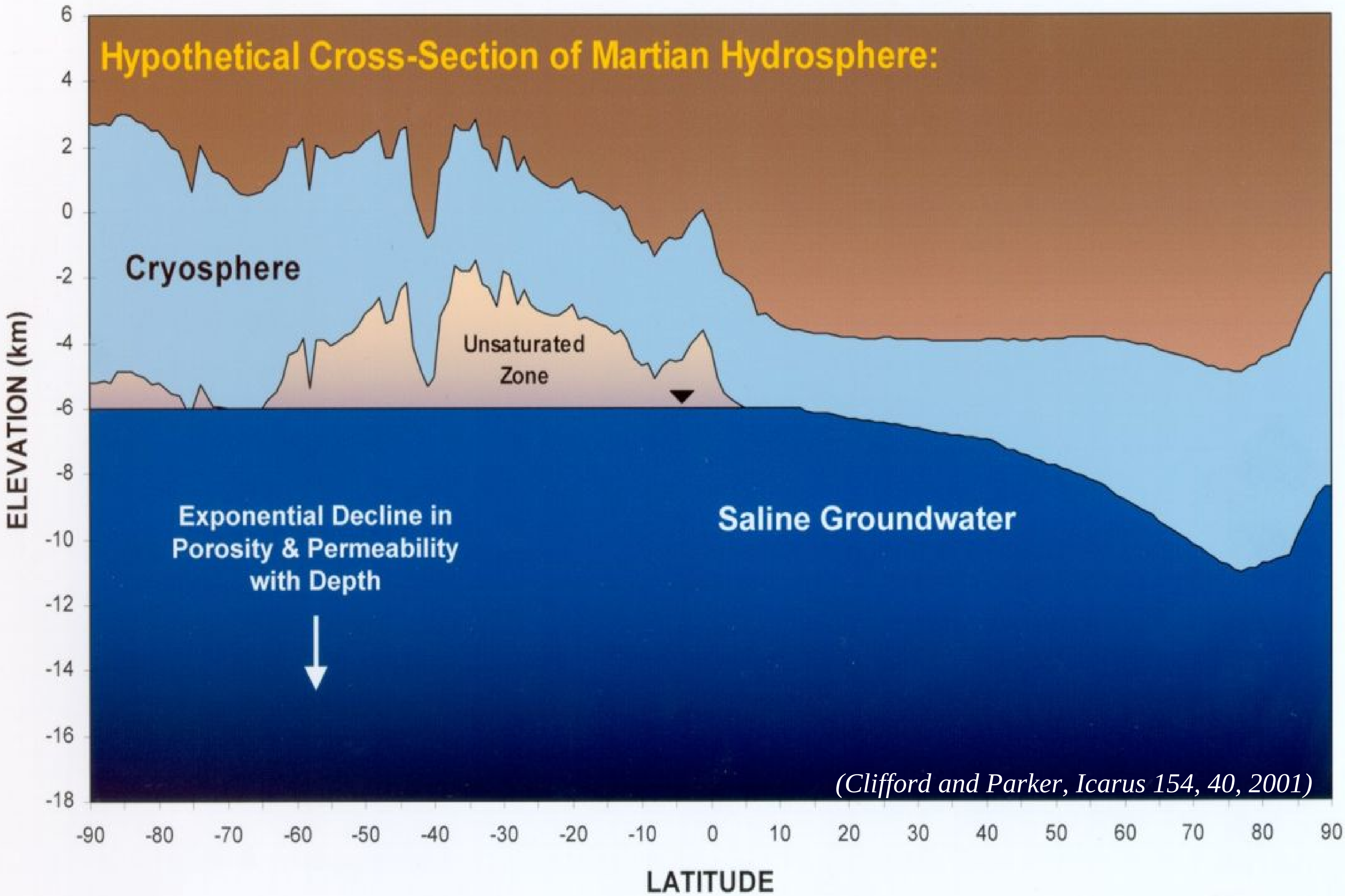
*(Chapman et al., 2009)



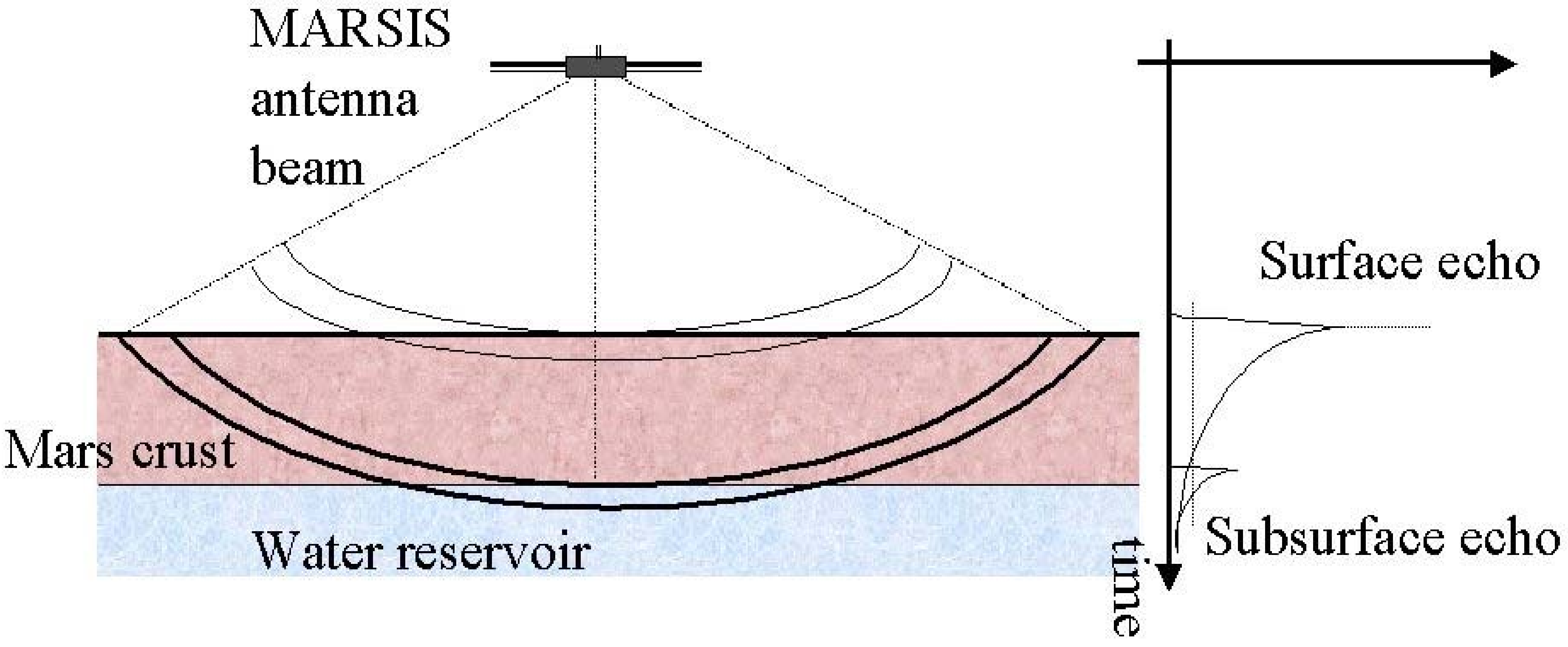
*(Neukum et al., 2009)

Athabasca V., Marte V. and the Cerberus Plains: Youngest (~2 – 70 Ma)* of the Late Amazonian Outflow Channels



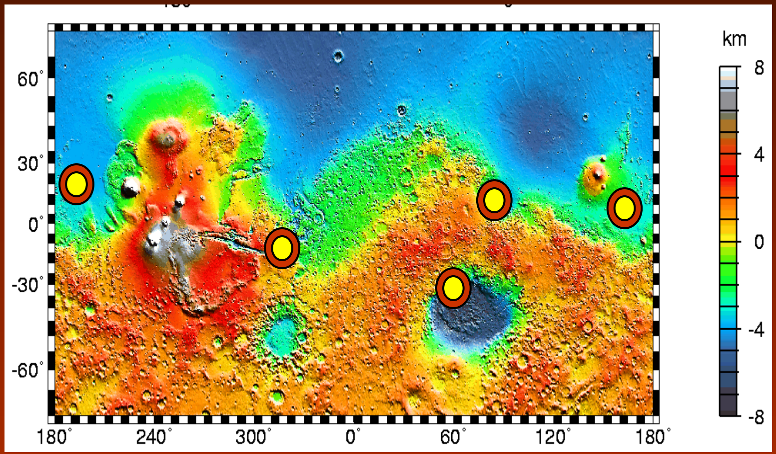

Hypothetical Cross-Section of Martian Hydrosphere:
Cryosphere
Unsaturated Zone
Saline Groundwater
Exponential Decline in Porosity & Permeability with Depth
ELEVATION (km)
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
LATITUDE
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
90
(Clifford and Parker, Icarus 154, 40, 2001)

Detection of Surface and Subsurface Interfaces by an Orbital Sounding Radar



Optimal Locations for the Geophysical Detection of Subpermafrost Groundwater*

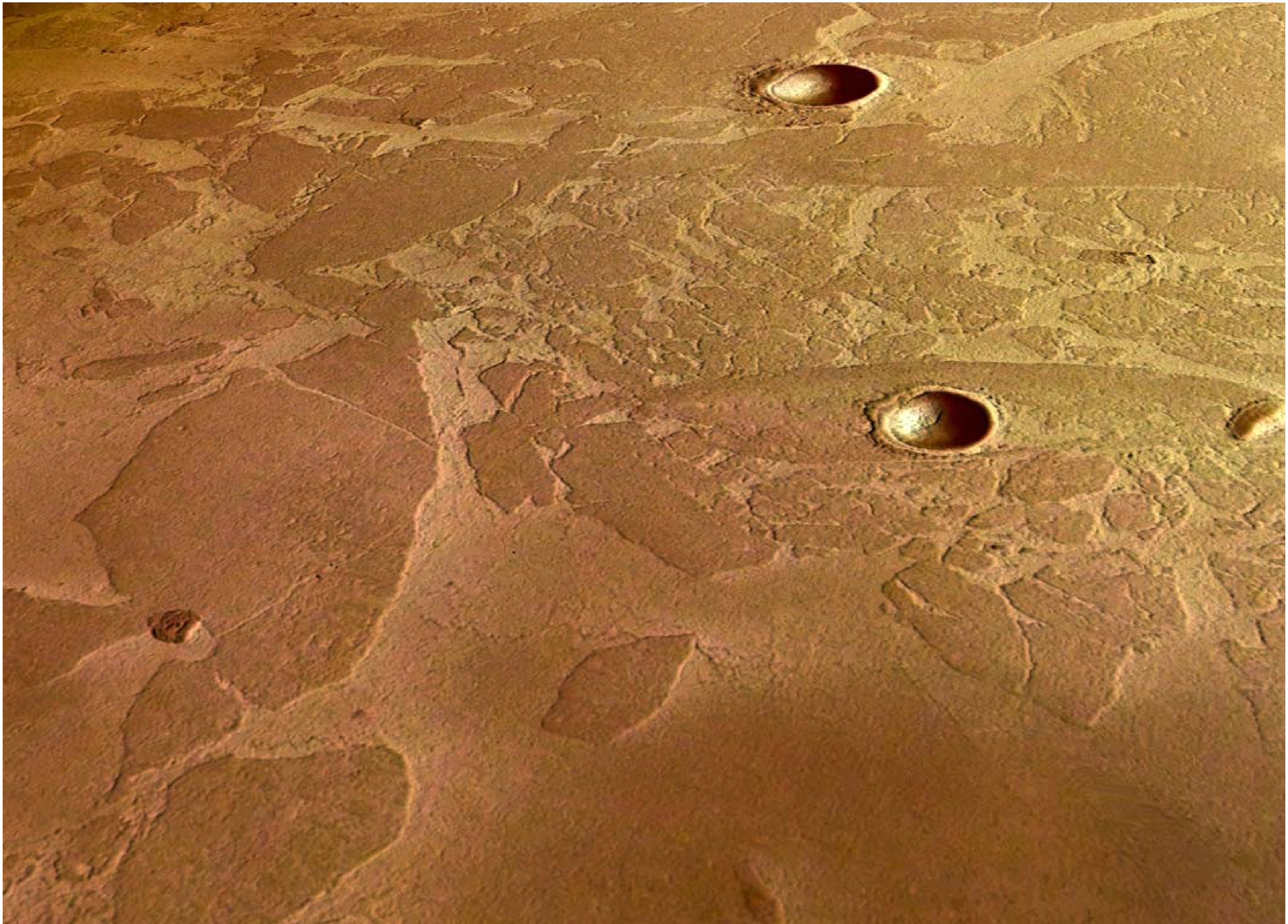
- The best locations for the potential detection of groundwater are those that combine low latitude (mini-mizing the thickness of frozen ground) and low elevation (minimizing the depth to a water table in hydrostatic equilibrium).
- In practice, local variations in crustal heat flow and thermophysical properties may cause significant deviations from this general expectation.



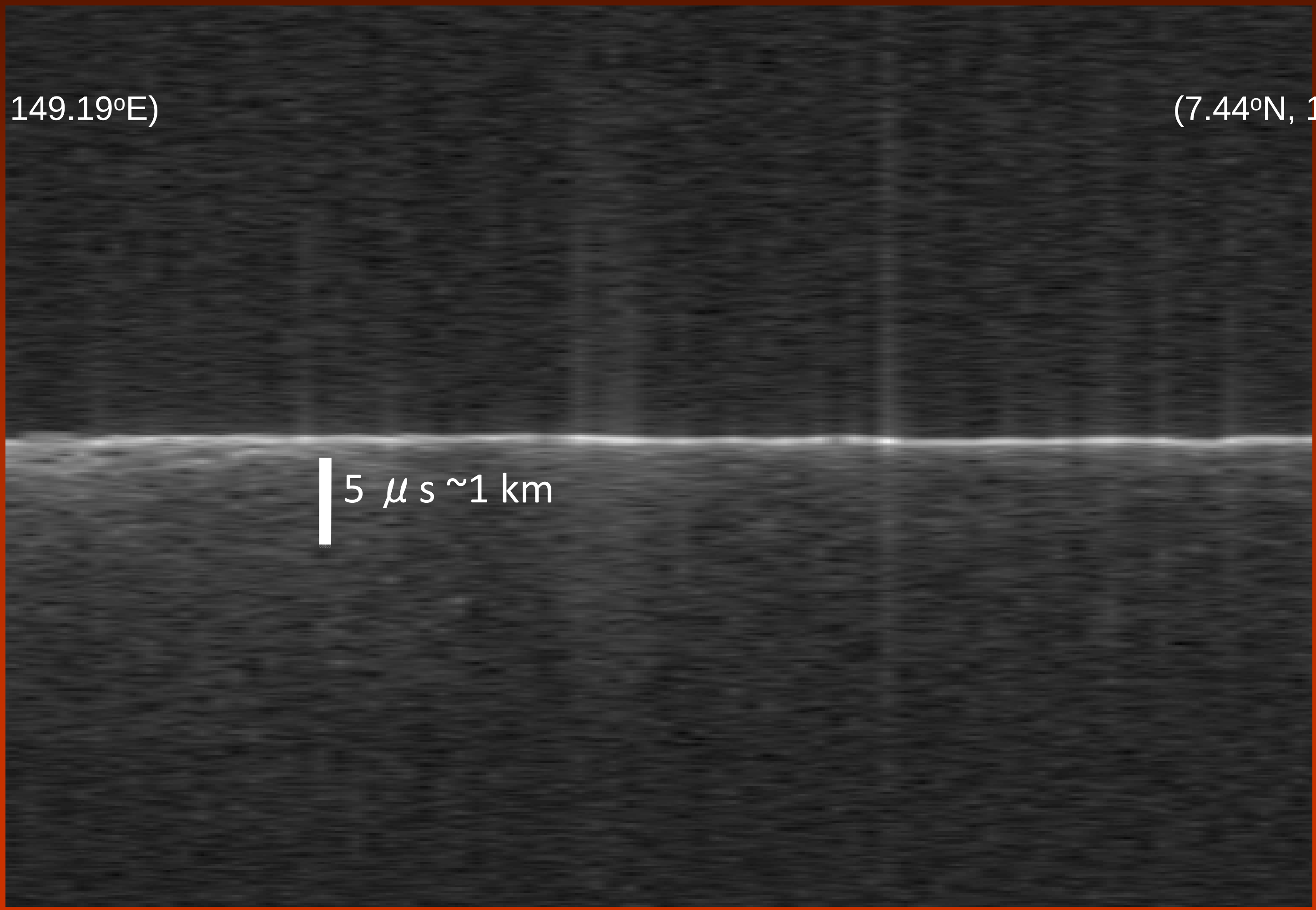
Location	Latitude range	Longitude range	Elevation[b] (km)
Interior of Valles Marineris	Varies between ~5–10°S	~30–80°W	< −4 km
Southern Amazonis Planitia	~5°S–20°N	~150–170°W	< −3 km
Southeast of Elysium	~0–10°N	~180–200°W	< −3 km
Isidis Planitia	~5–20°N	~265–280°W	< −2 km
Northern interior of Hellas	30–40°S	~280–305°W	< −6 km

[a] All latitude and longitude ranges represent approximate maximum extensions.
[b] Smith *et al.* (1999).

**From Clifford and Parker, Icarus 154, 40, 2001.*



MARSIS 5-MHz Radargram of Athabasca (MEX Orbit 4082)



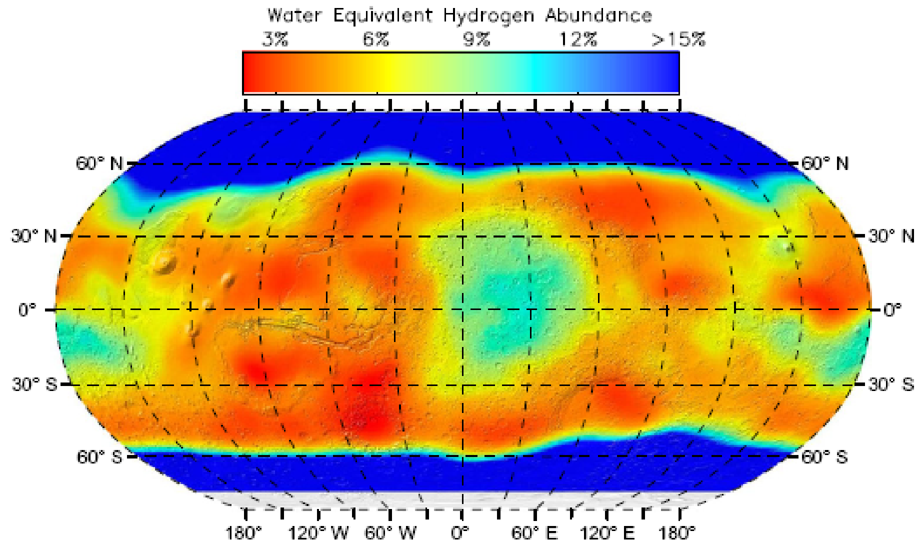
Possible Explanations for the Lack of Detection of Deep Groundwater Table by MARSIS

- Groundwater may no longer survive on Mars, having either been cold-trapped into the thickening cryosphere or lost by other processes (e.g., chemical weathering).
- Groundwater is present but the cryosphere is deeper than previously believed, placing it beyond the maximum sounding depth of MARSIS.
- Gradients of thin films of unfrozen water in the cryosphere, or within the vadose zone above a subpermafrost groundwater table, have reduced the dielectric contrast necessary to produce a reflection.
- The dielectric loss and scattering properties of subsurface may be greater than previously believed, resulting in lower than expected MARSIS sounding performance.

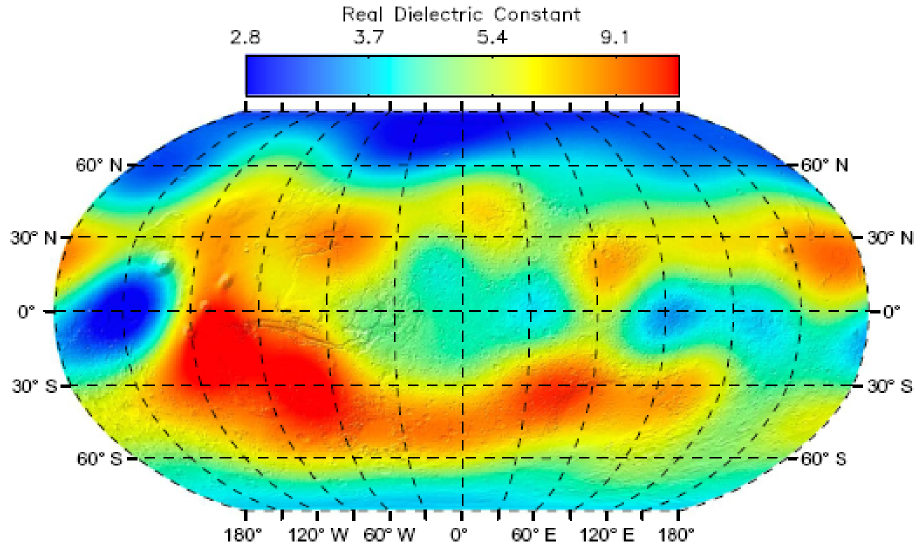
Derived Dielectric Map of Mars

Based on MARSIS Reflectivity Measurements (*Mouginot et al., Icarus 210, 612, 2010*)

GRS Water Equivalent Hydrogen Map (Boynton et al., 2009)

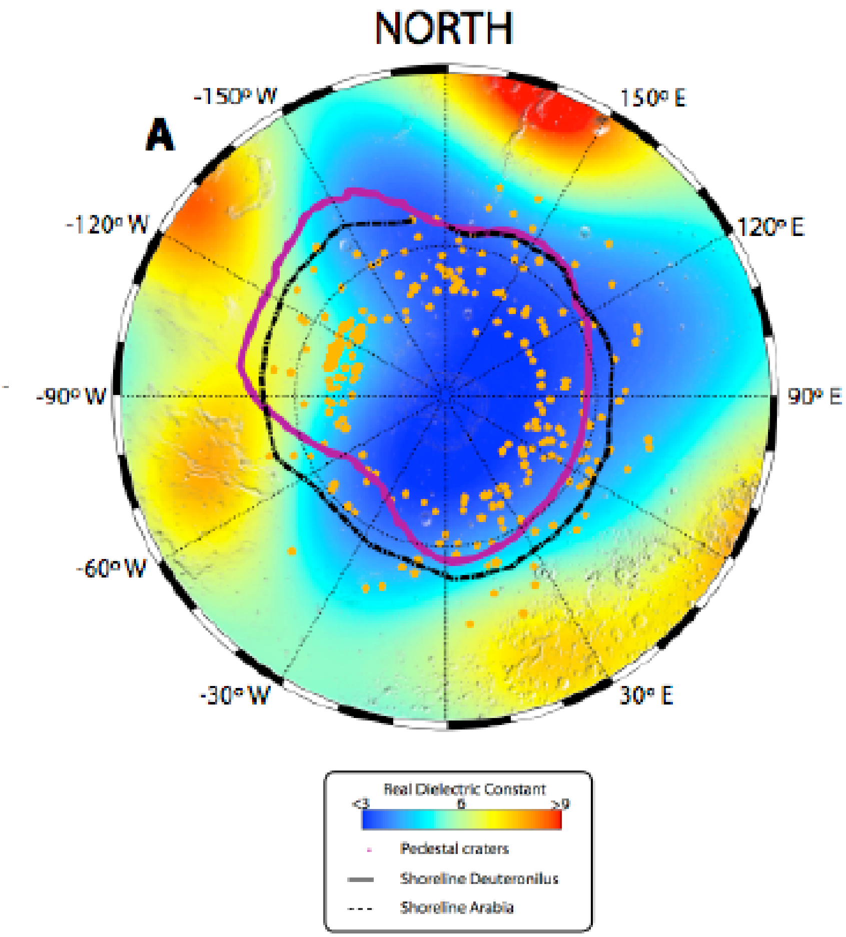


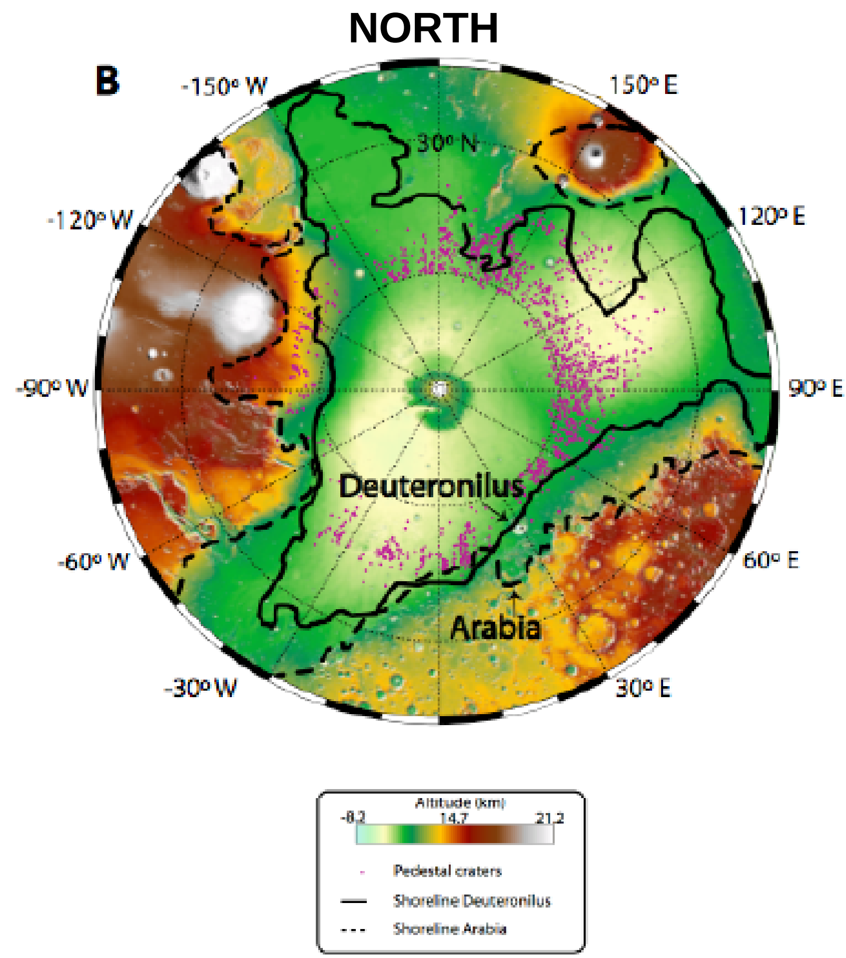
MARSIS Dielectric Values Mapped in Spherical Harmonics



Low Dielectric Properties of N. Plains (Mouginot et al., 2011):

High Porosity Sediments/Volcanics? Or Massive Ground Ice?





Most Capable Techniques for the Detection of Subpermafrost Groundwater*:

1. *Lander-based low-frequency GPR,* operating over the MARSIS frequency range with a much improved dynamic range (~140 dB vs. ~40 dB).
2. *Large-loop Transient Electromagnetics (TEM)* which can determine the resistive structure of the crust to depths as great as several 10s of km.
3. *Seismic investigations*, where the seismic attenuation characteristics of the crust can provide evidence of the presence or absence of subpermafrost groundwater.

*Best employed as part of a geophysical network.

Conclusions:

- The geologic evidence suggests that, during the **LH-EA,** Mars possessed a global inventory of water equivalent to a global ocean ~0.5 – 1 km deep, stored primarily in the subsurface.

- As the global heat flow declined, the Martian inventory of ground water was progressively depleted by cold-trapping into the thickening cryosphere.

- MARSIS has yet to provide any evidence of deep reflectors (>200 m), potentially indicative of the presence of groundwater, in lithic environments – a likely consequence of the greater than expected electromagnetic attenuation characteristics of the crust.

Conclusions (cont.):

- However, the persistence of a large reservoir of subpermafrost groundwater throughout Martian geologic history is supported by the occurrence (and discharge) of outflow channels through the Late Amazonian.

- Re: habitability, If early Martian life successfully adapted to a subterranean existence, the long-term survival of subperma-frost groundwater represents a potentially habitable environment that may endure to the present day.