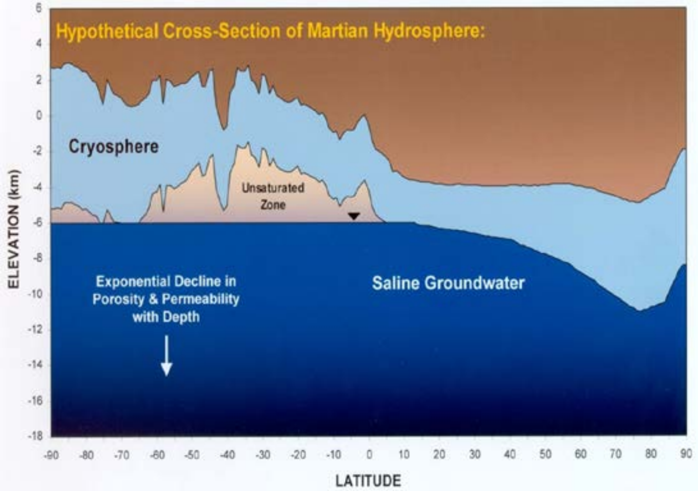
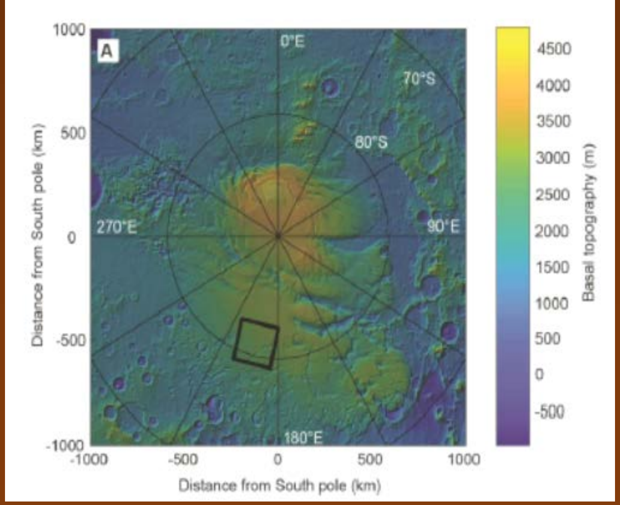
Martian Aquifers and Planetary Protection Considerations

Stephen Clifford

Planetary Science Institute

May 17, 2021





Outline

Occurrence of Liquid Water/Brines:

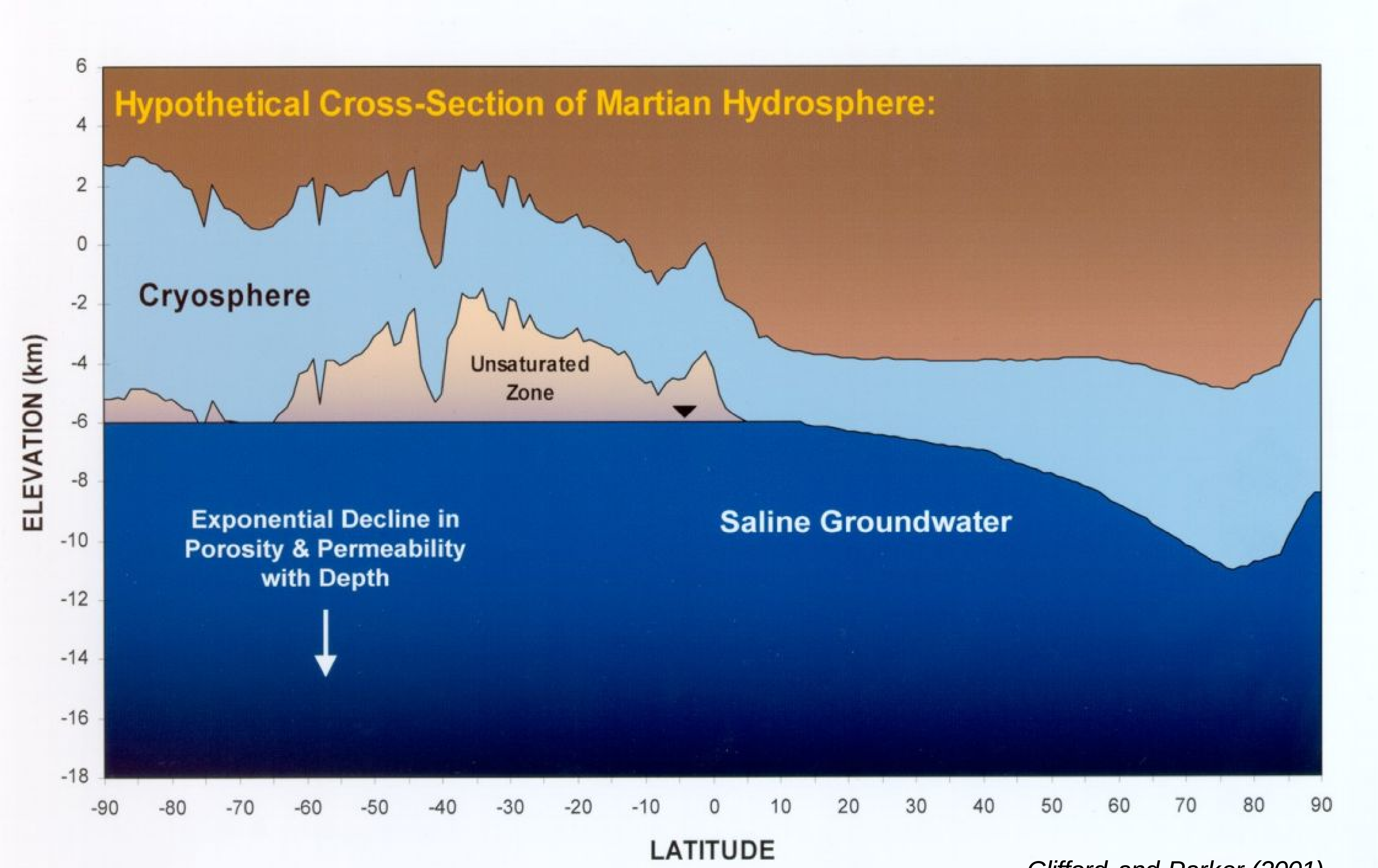
- Deep (Subpermafrost) Aquifers
- Proposed Shallow Aquifer Origins of Gullies and RSL
- RSL and Surface Brines
- Subglacial Lakes in the SPLD

Summary

Final Thoughts on Planetary Protection: *"Above all else, do no harm"*

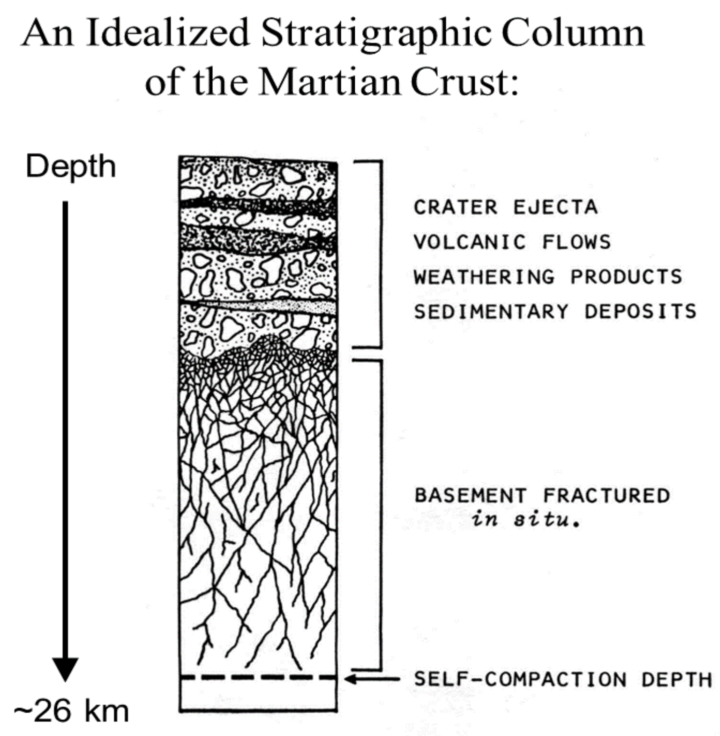
References

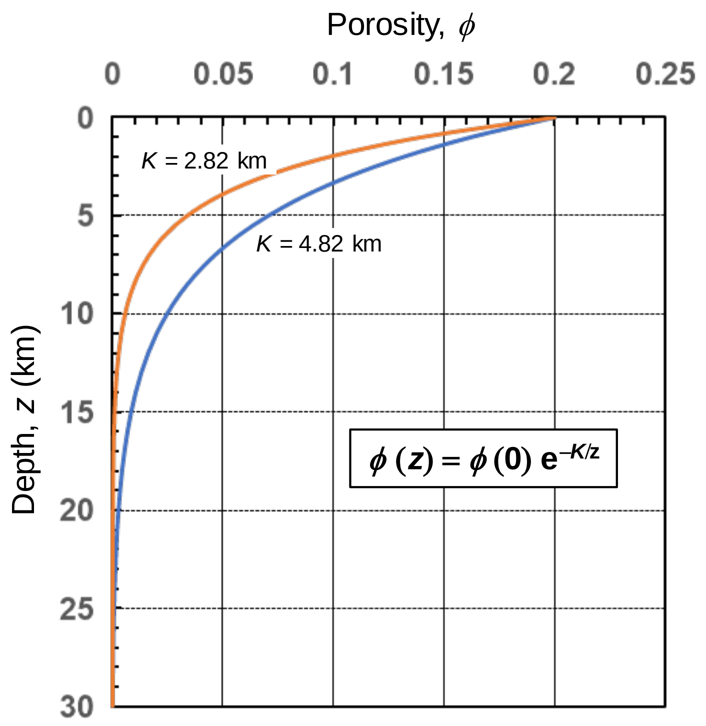
Deep (Subpermafrost) Aquifers



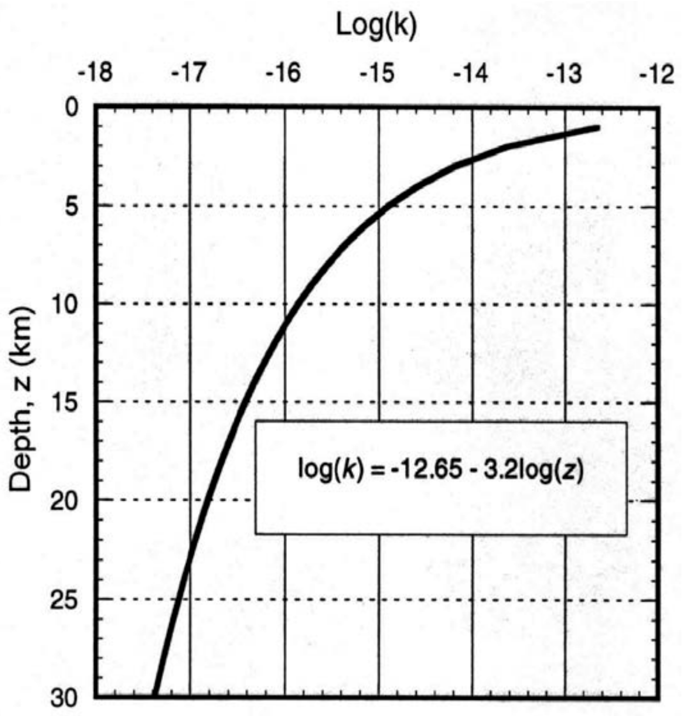
Clifford and Parker (2001)

Gravitationally-Scaled, Globally-Averaged Porosity & Permeability Profiles for Mars



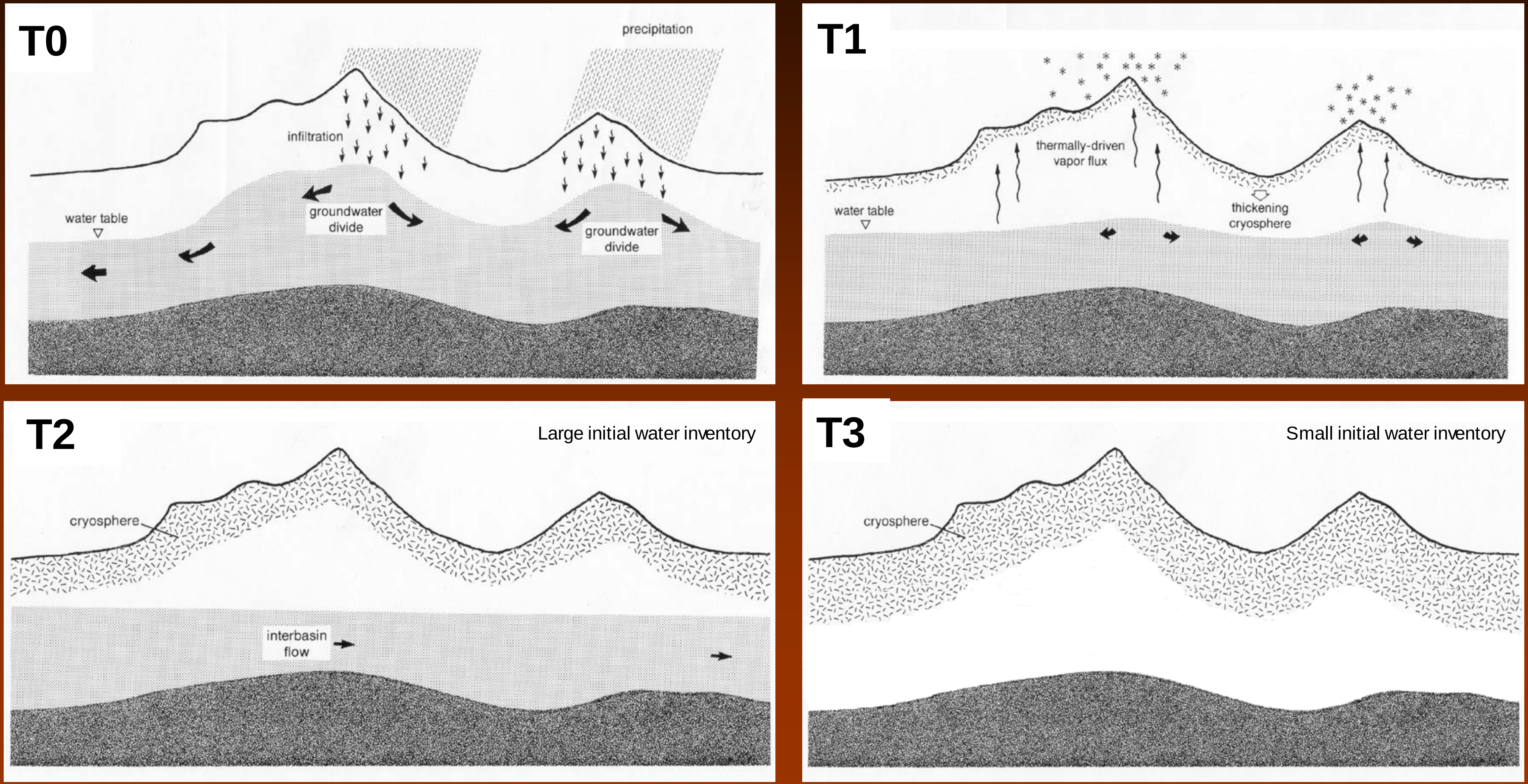


Globally-averaged variation of crustal porosity with depth based on the gravitationally-scaled models previously applied to the Moon (Clifford, 1993; Weiss and Head, 2017).

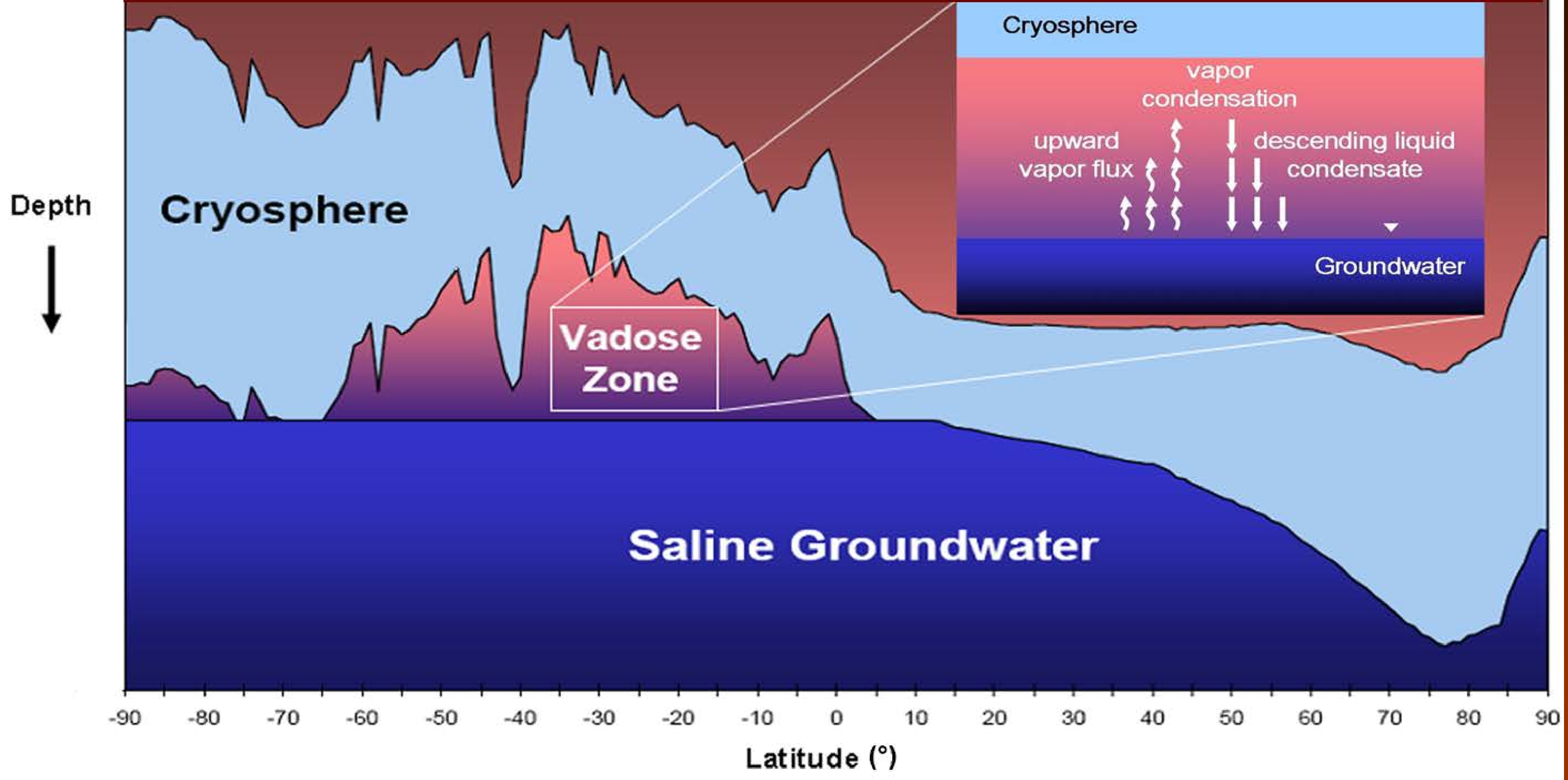


Globally-averaged variation of crustal permeability with depth, based on a gravitationally-scaled relationship previously derived for the Earth by Manning and Ingebritsen (1999) (Carr 2000, Clifford & Parker 2001),

Temporal Evolution of the Martian Hydrosphere



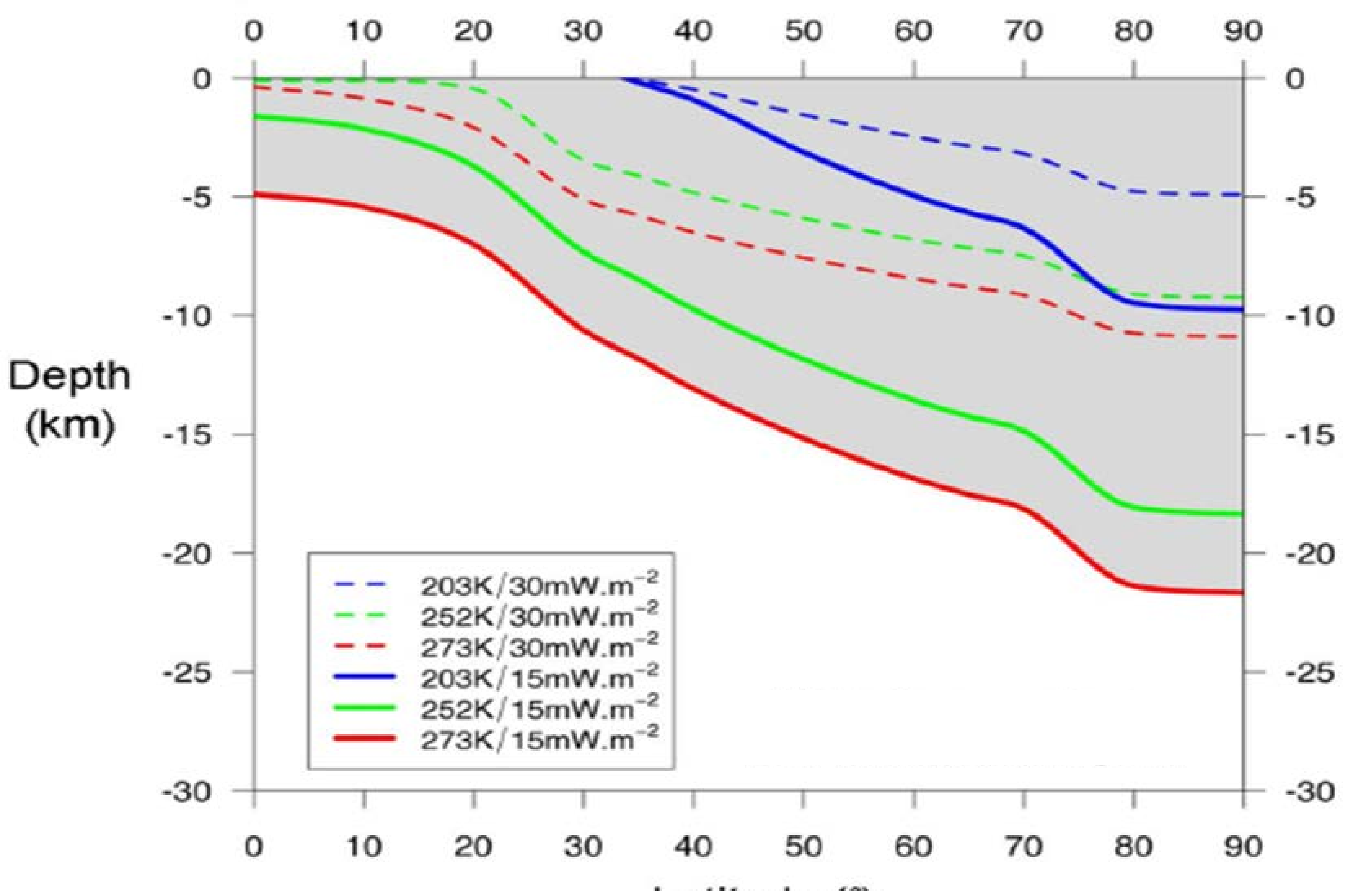
Hypothetical Pole-to-Pole Cross-Section of the Martian Crust



Depth to the Base of the Cryosphere

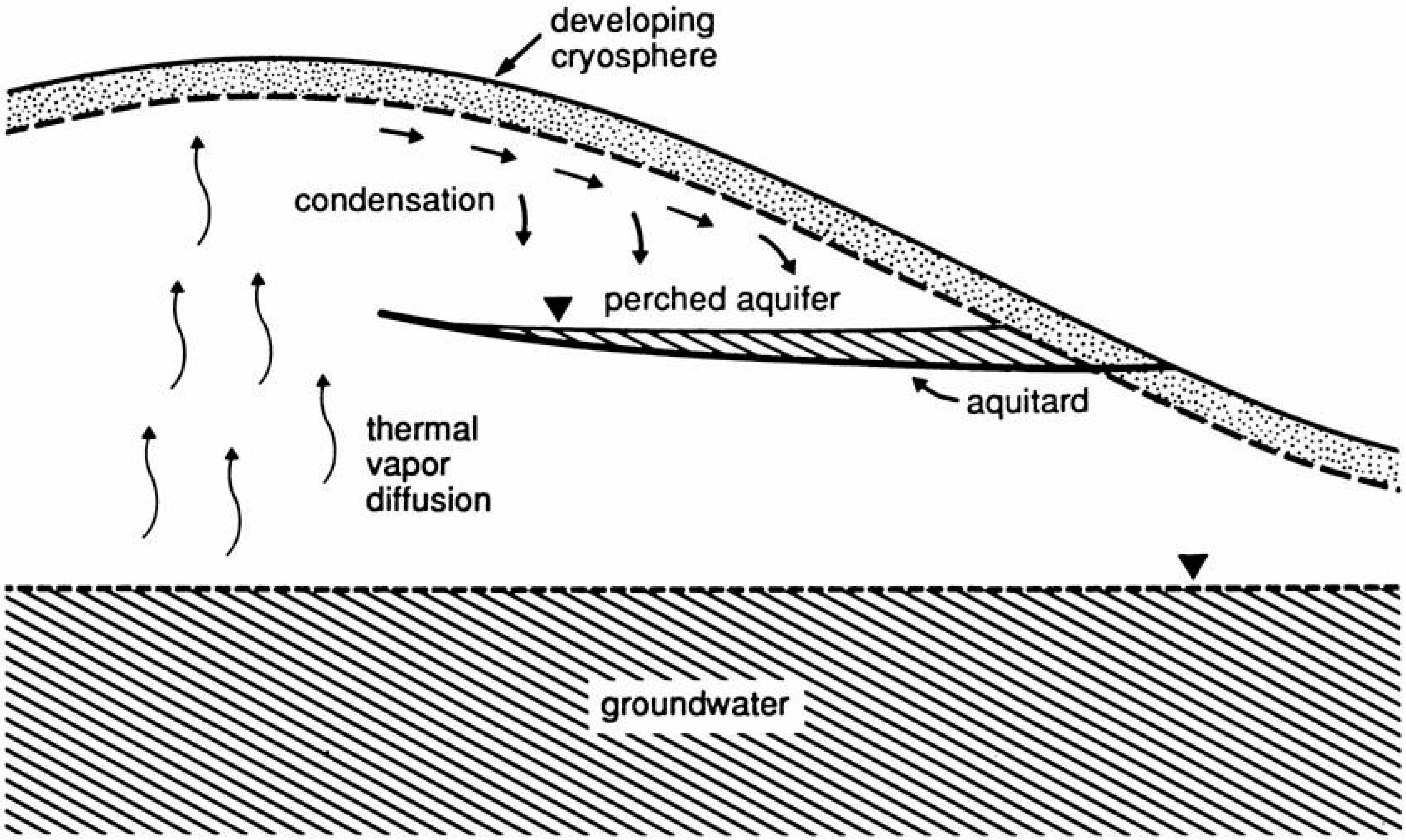
$$Z = k(T)\,\frac{(T_s - T_{fp})}{Q_g}$$

T_s - Mean annual surface temperature
T_{fp} - Freezing point of groundwater
Q_g - Geothermal heat flow
$k(T)$ - Temperature-dependent thermal conductivity of cryosphere



Clifford et al. (2010)

Illustration of Possible Development of Perched Aquifers from Subpermafrost Low-Temperature Hydrothermal Convection



Geophysical Techniques for the Detection of Subpermafrost Groundwater

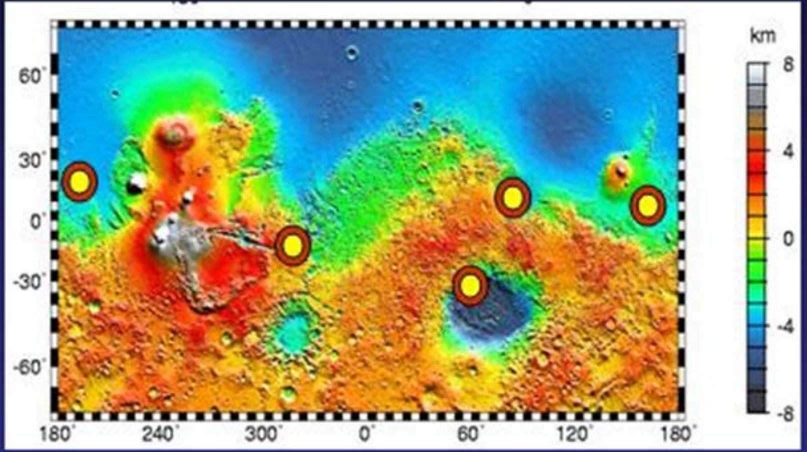
- The dielectric loss and scattering properties of Martian subsurface effectively preclude orbital radar sounders, like MARSIS and SHARAD, from detecting groundwater at depths in excess of ~100-200 m (Clifford et al., 2010; Stillman and Grimm, 2011).

- Analysis of the InSight magnetometer data suggests the existence of an electrically conductive crust, consistent with the presence of groundwater (Yu et al., 2020); however, analysis of the Insight seismic data suggests that the propagation characteristics of the Martian crust are intermediate between those of the Moon (dry) and Earth (wet) (van Driel et al., 2021).

- The geophysical technique with the best promise of detecting subpermafrost groundwater is probably time-domain electromagnetic sounding conducted on the surface by a lander or rover (Grimm, 2002, 2003; Grimm et al., 2009).

Optimal Locations for the Geophysical Detection of Subpermafrost Groundwater (Clifford and Parker, 2001)

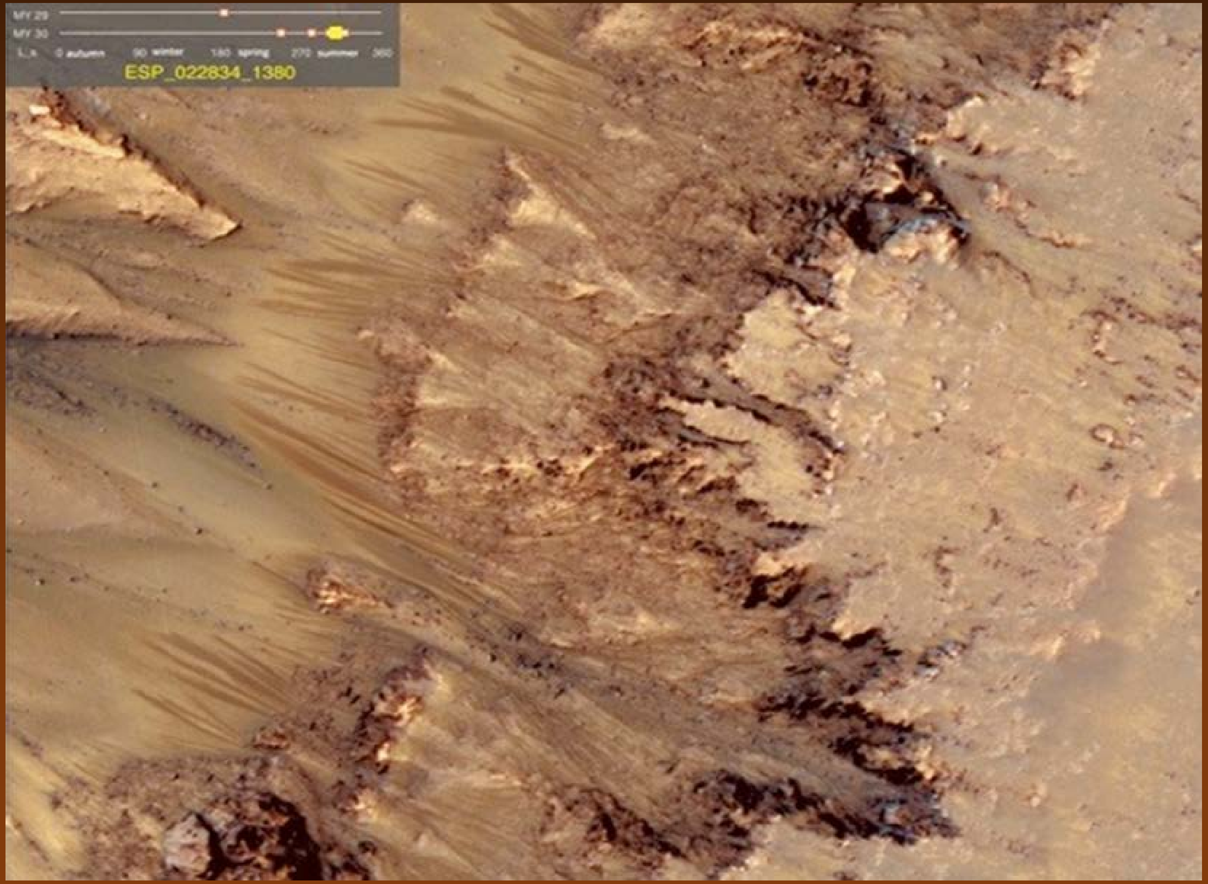
- All else being equal, the locations that provide the best opportunity for detecting subpermafrost groundwater are those that combine low latitude (minimizing the thickness of frozen ground) and low elevation (minimizing the depth to a groundwater table in hydrostatic equilibrium).
- Realistically, local variations in crustal heat flow and thermophysical properties may cause significant variations 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

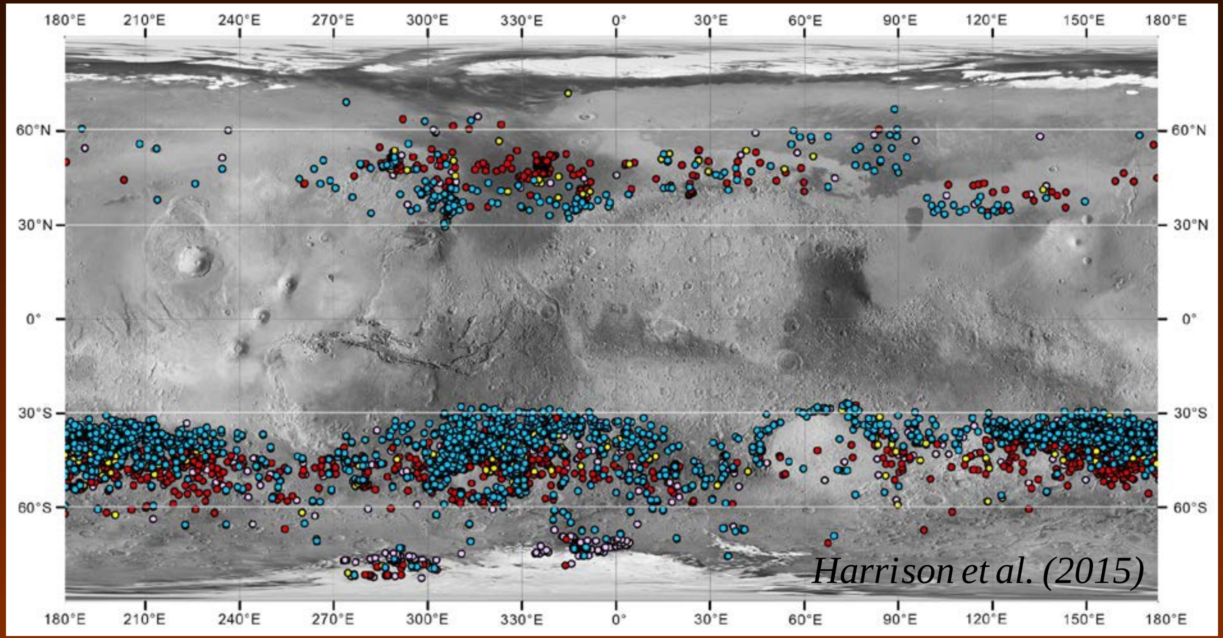
[a] All latitude and longitude ranges represent approximate maximum extensions.
[b] Smith *et al.* (1999).

Proposed Shallow Aquifer Origin of Gullies and RSL



Characteristics of Martian Gullies

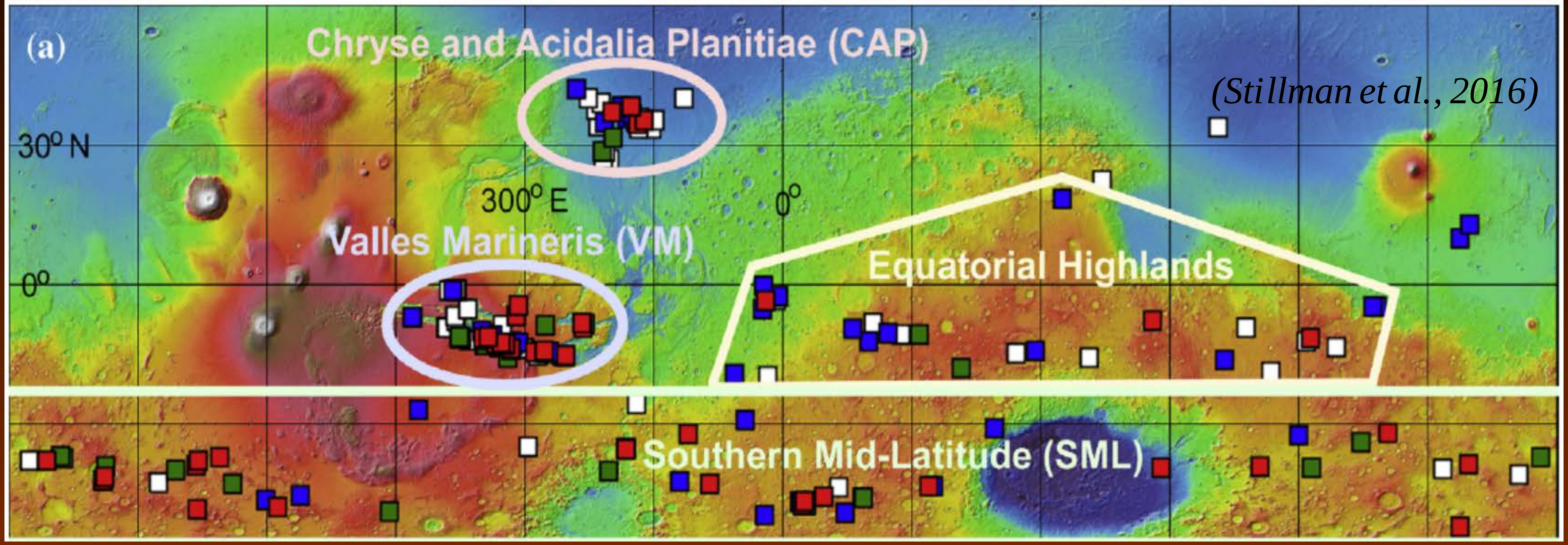
(Malin and Edgett, 2000; Harrison et al., 2015)



- Morphology suggests fluvial origin and "young" age.
- Appear to emanate from shallow (~100-500 m) depths.
- Found in both hemispheres (although mostly in southern) with the majority occurring between 30° and 70° latitude.
- From 30° - 40° latitude, gullies preferentially occur on poleward-facing slopes, but generally face equatorward above 40° latitude.
- Exhibit no obvious association with areas of known geothermal activity (e.g., Tharsis and Elysium).
- Origin has been attributed to shallow aquifers, liquid CO_2, and dry mass-wasting.

Characteristics of RSL

(McEwen et al., 2011, Rummel et al., 2014; Stillman et al., 2016)



- Recurring slope lineae (RSL) are narrow (0.5-5 m), abundant (>10), recurring dark markings on steep slopes (>25°).
- They are concentrated in southern hemisphere (30°S to 50°S), favoring equator-facing slopes, they form and incrementally grow in late spring to summer, then fade or disappear by fall.
- They recur at nearly same locations in multiple Mars years.
- Exhibit no obvious association with areas of known geothermal activity (e.g., Tharsis and Elysium).
- Origin has been attributed to seasonal surface brines, the discharge of shallow aquifers, and dry mass-wasting. Spectrographic analysis has revealed the presence of perchlorate salts, which is consistent with the presence of brine.

Gullies Formed by Discharge from Thin Shallow Aquifer, Mantled by Dry, Low-Thermal Conductivity Soil (Mellon and Phillips, 2001)

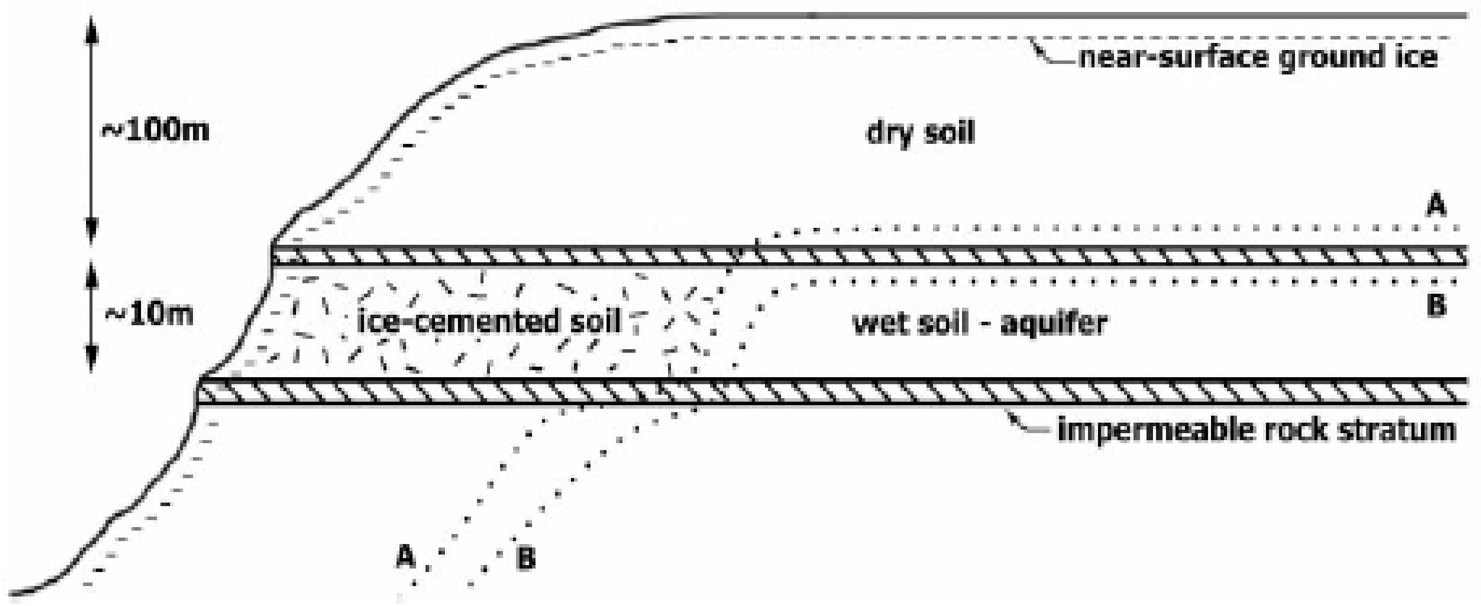
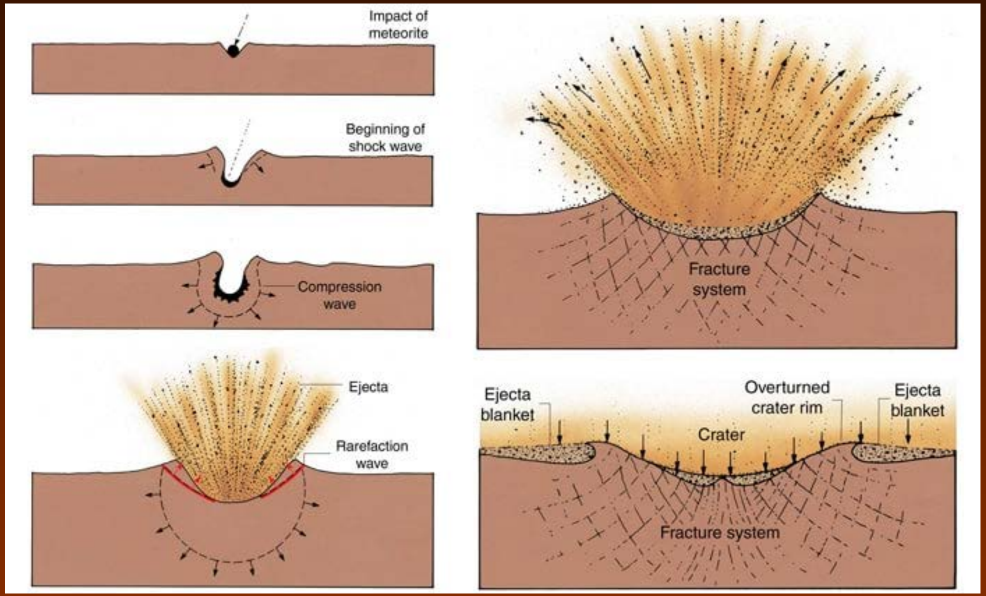


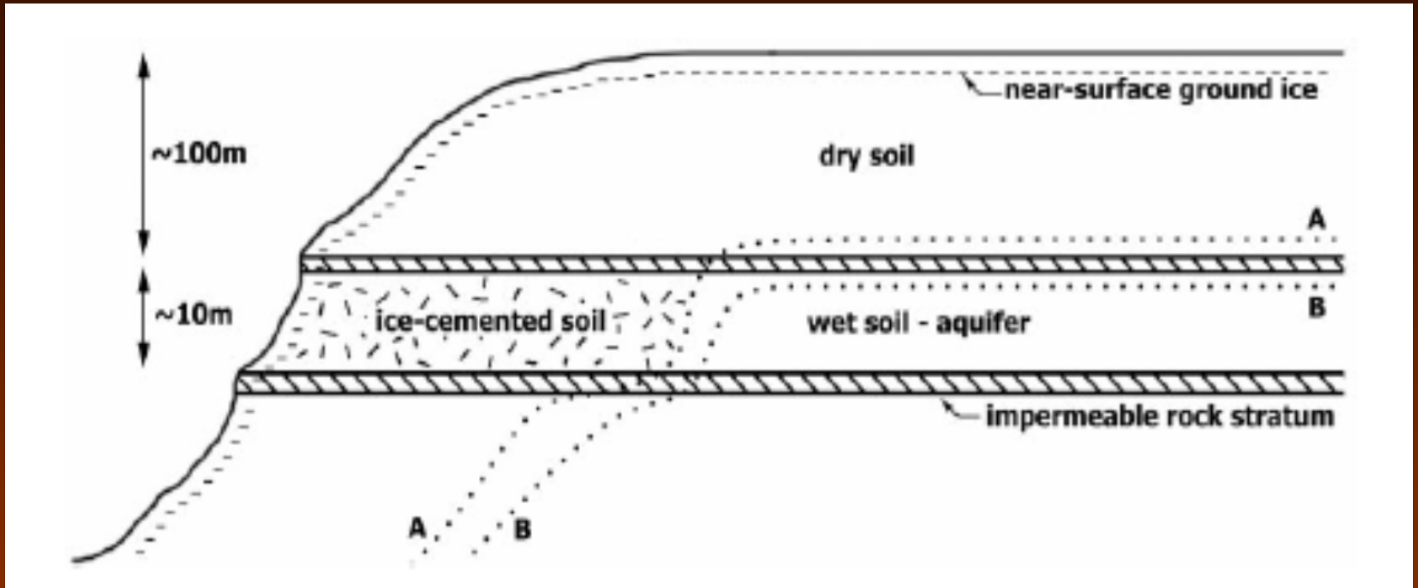
Figure 11. Conceptual model of trapping and freezing of groundwater. Strata of impermeable rock trap a permeable soil unit saturated with water. Toward the slope, water in the aquifer saturates the permafrost with ice, preventing liquid water from escaping. Orbitally driven oscillations in the mean annual surface temperature cause partial freezing of the water in the aquifer, which in turn increases the water pressure until the ice-saturated permafrost fractures, allowing water to escape to the surface. "A" and "B" indicate the position of melting isotherms at different times during orbital cycles. Enclosing the aquifer opposite the slope (on the right, not shown) can be accomplished by a higher thermal conductivity soil layer, upturned rock strata, or gradual merging of the rock units.

Model assumptions:

- Aquifer existed prior to impact.
- Aquifer is confined by an impermeable layer, which is mantled by dry (ice-free) low-thermal conductivity soil in order to produce a steep geothermal gradient that allows liquid water to survive at shallow depth.

Difficulties with the Mellon and Phillips (2001) Model

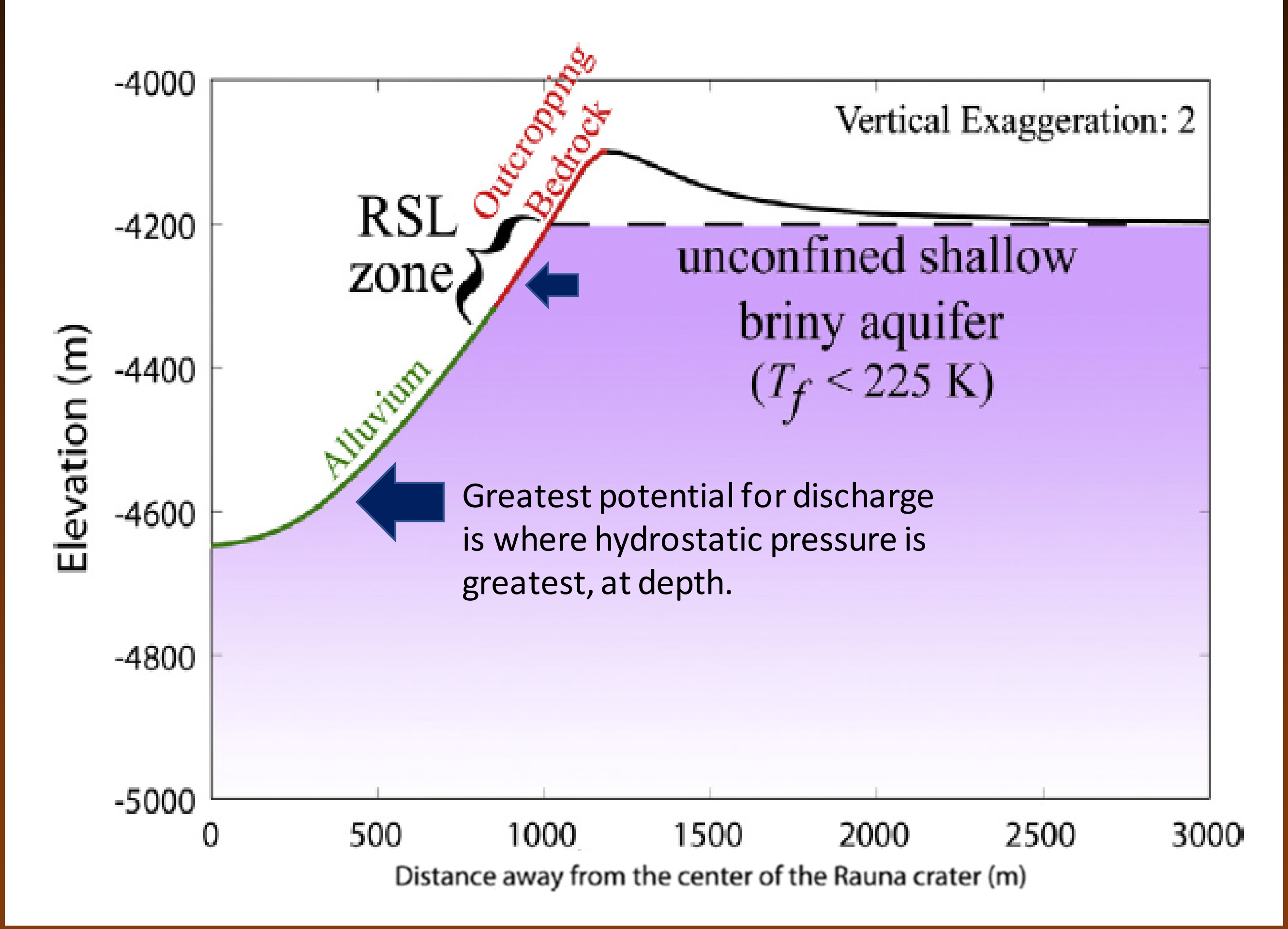




Christiansen and Hamblin (1995)

- No hydrologically viable way to create and replenish such a confined, shallow aquifer.
- The impact that created the crater would have fractured the surrounding region to multi-km distances, destroying any originally impermeable confining layer – allowing the groundwater to infiltrate the initially dry soil and saturate it with ice, lowering its thermal conductivity and resulting in the retreat of the 273K geotherm to multi-km depths.

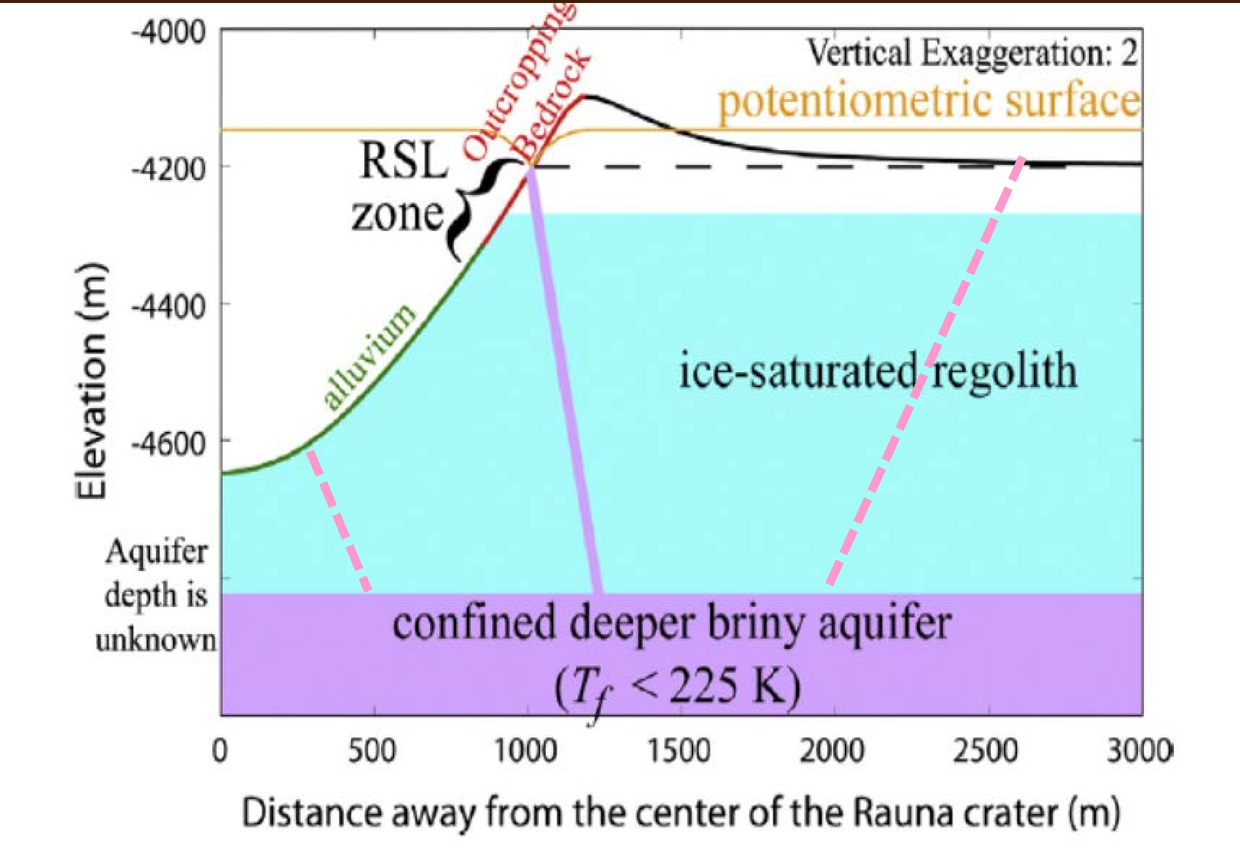
Additional Difficulties with the Shallow Aquifer Hypothesis



After Stillman et al. (2016)

- Discharge can only occur when the freezing point of the groundwater is lower than the local mean annual surface temperature – however, most gullies occur at latitudes where current mean annual temperatures are <200 K (lower than the freezing point of a perchlorate brine).
- Within a crater, the hydrostatic pressure of groundwater is greatest near the bottom, making the largest discharges more likely there, rather than near the crater rim – yet, no such relationship is observed.
- Nunes et al. (2010) examined SHARAD observations of numerous gully sites and found no evidence consistent with the presence of shallow groundwater.

Difficulties with Shallow Discharges from a Deep Subpermafrost Aquifer



After Stillman et al. (2016) and Abotalib and Heggy (2019).

- Although physically more probable than the existence of a shallow aquifer, shallow discharges from a pressurized subpermafrost aquifer should occur anywhere a fracture provides a conduit to the surface. There is no *a priori* reason why such fractures should occur only near the top of a crater rim or local slope.
- Because the hydrostatic pressure driving a discharge is greatest at low elevation, the largest discharges should preferentially occur there – such a relationship has not been observed.

Schematic of Fracture Distribution at Meteor Crater

(Kumar and Kring, 2018)

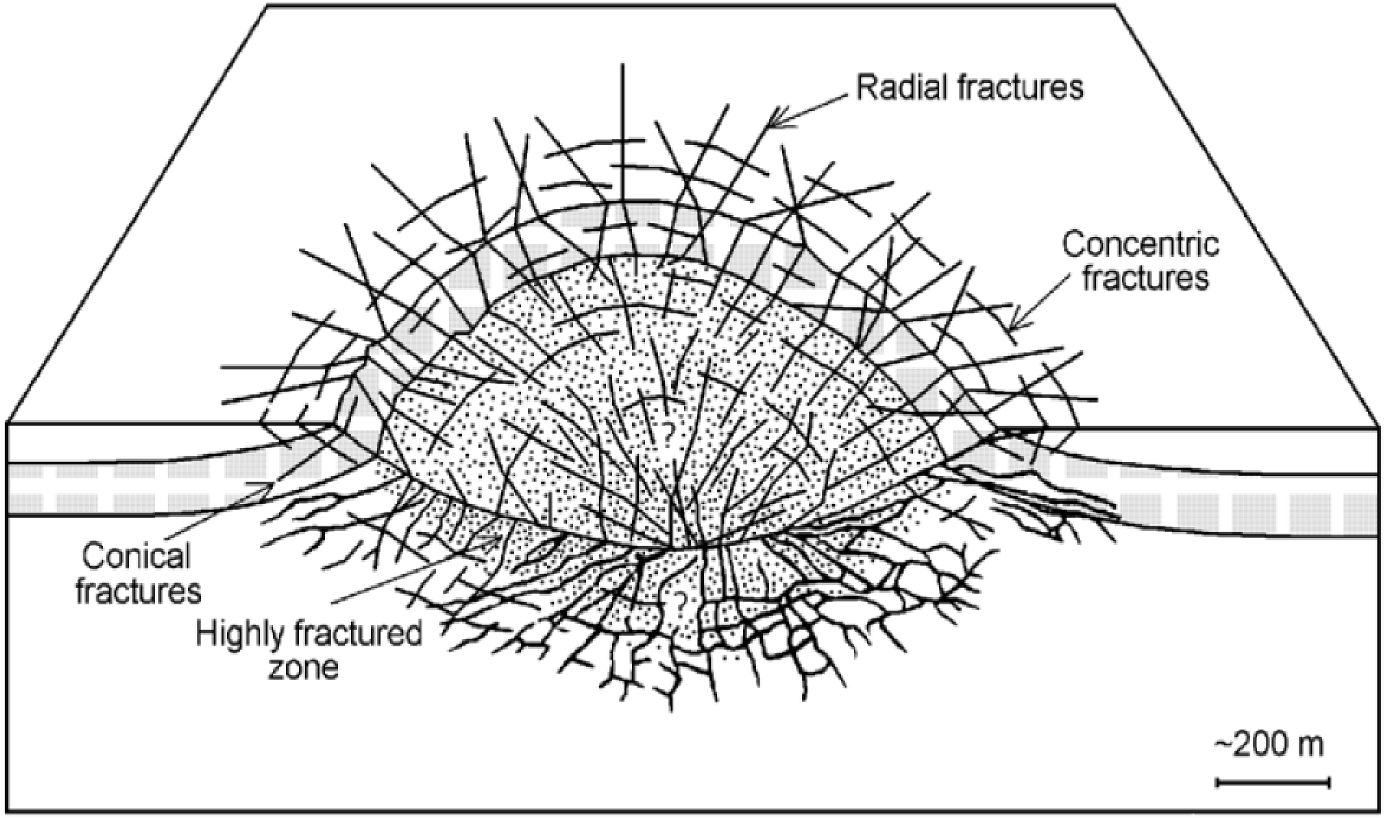


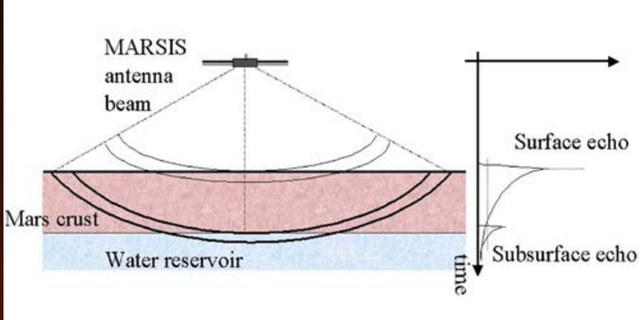
Figure 5. A schematic diagram showing the crater wall fractures.

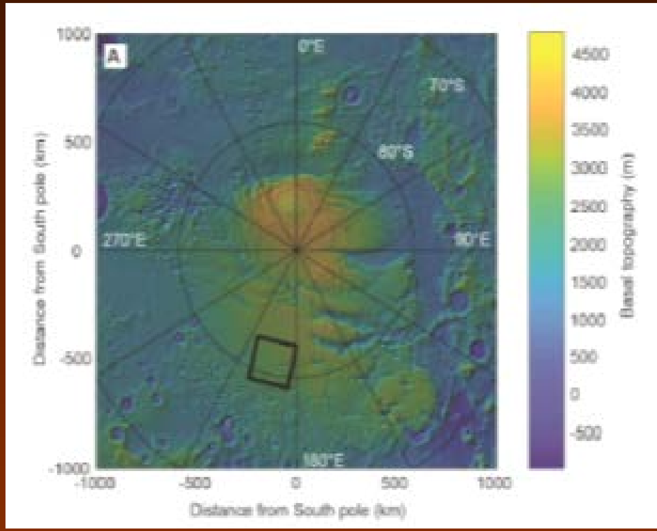
RSL and Surface Brines

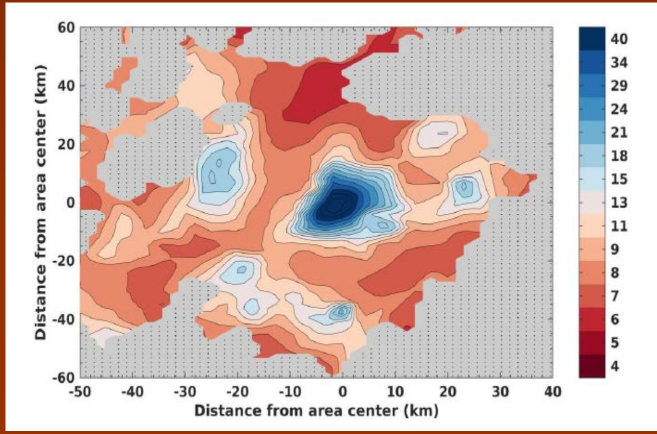
- If RSLs originate from briny seasonal flows, then it represents a significant concern -- because it is by the seasonal downslope propagation of these dark streaks that RSL are identified.
- However, the geochemical and atmospheric conditions that are thought to contribute to the occurrence of RSLs could also exist on horizontal surfaces where there is no flow. If so, it could make them difficult to identify – raising the possibility that lander and rover spacecraft have already contaminated seasonally-active surface brines.
- The ground penetrating radars on the Perseverance and the ExoMars rovers will conduct temporal investigations of the dielectric properties of the regolith to determine whether they are consistent with the presence/diurnal formation of brines.
- A high-res orbiting polarimetric synthetic aperture imaging radar, such as that proposed as part of the Mars Orbiter for Resources, Ices, and Environments (MORIE, selected as one of NASA's 2019 Planetary Mission Concept Studies, Calvin et al., 2021), is probably the best approach for identifying seasonally active surface brines, before selecting a site for a lander/rover mission.

Subglacial Lakes in the SPLD

(Orosei et al., 2018; Lauro et al., 2021)







- MARSIS has detected a localized region (~20 km in diameter) at the base of the south polar layered deposits (SPLD) (~1.5 km below the surface), which has been interpreted as a subglacial lake or patch of water-saturated sediment.

- Given the low mean annual temperature of the SPLD, as well as estimates of the thermal conductivity of the polar ice and local geothermal heat flux, it has been argued that the presence of the lake is best explained by a perchlorate brine (freezing point ~203 K).

- On Earth, hypersaline lakes form when water evaporates from a body faster than it can infiltrate the bed -- concentrating any dissolved salts that might be carried into the lake by surface runoff. But a lake at the base of the SPLD doesn't experience evaporative losses and loses water solely by infiltration into the underlying bedrock.

- A more plausible explanation for the existence of the basal lake is a relatively fresh body of water formed by the presence of a local geothermal anomaly (Sori and Bramson, 2019).

Summary

Likely locations of:

- Fresh (or nearly fresh) water: (1) As thin films of liquid covering pore walls and as perched aquifers within the subpermafrost vadose zone (z > several km), and (2) as subglacial lakes in the SPLD (z > 1.5 km).
- Brine: (1) Seasonally occurring at the surface, at latitudes < 50º latitude and (2) hypersaline groundwater (z > several km).

Best geophysical detection methods:

- For surface brines and shallow aquifers (z< 100-200 m): hi-res orbital polarimetric synthetic aperture imaging and sounding radar.
- For subpermafrost groundwater: Time-domain electromagnetic sounding conducted on the surface by a lander or rover.

Final Thoughts on Planetary Protection: *"Above all else, do no harm"* (Hyppocratic Oath)

- To minimize the likelihood of contaminating potentially habitable Martian environments with terrestrial life, PREVCOM (2006) argued that – where our existing knowledge of Mars is ambiguous, incomplete, or seriously contested, we should err on the side of caution, placing the burden of proof on establishing that a region is non-special, rather than special.
- By this reasoning, should we later find that some Martian environments are more hostile to the survival of terrestrial life than previously thought, spacecraft cleanliness standards, and any limitations on potential landing sites, can always be relaxed.
- On the other hand, if we underestimate the ability of Martian environments to support terrestrial life, then the mistake may be irreversible – with potential consequences not only for the integrity of our life-detection investigations, but also for the long-term survival of the very life we seek to detect.

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