Purpose of Paper:
Model the evolution and distribution of water and its transport in the subsurface on Mars

“This conclusion is based on only two assumptions: (1) that the physical properties of the Martian crust, including porosity, permeability, and crustal thermal conductivity, are no different than those which characterize the Earth and the Moon, and (2) Mars possesses an inventory of water that exceeds the pore volume of the cryosphere by as little as a few percent. Given these conditions, basic physics dictates that the process of surface deposition, basal melting, groundwater flow, and the thermal transport of H2O, will thermodynamically and hydraulically link the atmosphere, surface, and subsurface reservoirs of water on Mars into a single self-compensating system.” (p. 11,010)

1. What is the structure of the cryosphere on Mars?:
   - key parameters to model: 1) porosity with depth (scaled from Moon) and 2) thermal structure [thermal conductivity, melting temperature (effect of salts?), geothermal heat flux (globally averaged value of 30 mW m⁻²)]
   - the distribution of ground ice is controlled by the local surface temperature and the magnitude of the geothermal gradient

2. Is there groundwater in the subsurface of Mars?
   - “once the pore volume of the cryosphere has been saturated with ice, any remaining water will drain to saturate the lowermost porous regions of the crust.” Very little additional water in excess to the pore volume is needed to develop a widespread groundwater system (~10 GEL).

<table>
<thead>
<tr>
<th>Basal Melting/Groundwater Freezing Temperature (K)</th>
<th>$Q_e = 15$ mW m⁻² (High $k$ Equatorial Regolith)</th>
<th>$Q_e = 30$ mW m⁻² (Low $k$ Equatorial Regolith)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Phi(0.20)$</td>
<td>$\Phi(0.35)$</td>
</tr>
<tr>
<td>273</td>
<td>585</td>
<td>1025</td>
</tr>
<tr>
<td>252</td>
<td>565</td>
<td>990</td>
</tr>
<tr>
<td>203</td>
<td>205</td>
<td>360</td>
</tr>
</tbody>
</table>

$^*$From Clifford et al. (2010)

Pore volumes reflect the integrated porosity of the crust, expressed in terms of a global equivalent layer (GEL) of water (in m), between the surface and the depth of the indicated isotherm, based on a porosity profile given by equation (5). Pore volumes are listed for two combinations of lithospheric heat flow and low- (0.1 W m⁻¹ K⁻¹) and high-$k$ (1.0 W m⁻¹ K⁻¹) models of the desiccated equatorial regolith which have been chosen to represent the likely minimum and maximum extents of the cryosphere at these latitudes. On Earth, there is evidence of hydraulic continuity extending down to a depth of ~10 km [Manning and Ingebritsen, 1999]. Gravitational scaling this result to Mars suggests that the crust will remain permeable to a depth of ~26.5 km. For reference purposes, the total pore volume of the Martian crust, integrated down to this depth, is 615 m for $\Phi(0.20)$ and 1060 m for $\Phi(0.35)$. The actual values of crustal porosity are likely to exhibit significant spatial variability [Clifford, 1993; Clifford and Parker, 2001].
Crustal sources of atmospheric water:

**TABLE 6. Crustal Sources and Potential Contributed Volumes of Atmospheric Water**

<table>
<thead>
<tr>
<th>Crustal Source</th>
<th>Volume, km³</th>
<th>Equivalent Layer, m H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sublimation of ground ice [Fleming et al., 1984]</td>
<td>2.7–5.6 x 10⁶</td>
<td>20–40</td>
</tr>
<tr>
<td>Catastrophic floods [Carr, 1987; Baker et al., 1991]</td>
<td>0.75–6.5 x 10⁷</td>
<td>50–450</td>
</tr>
<tr>
<td>Volcanism [Greeley and Schield, 1991]</td>
<td>2.5 x 10⁸</td>
<td>15</td>
</tr>
<tr>
<td>Impacts [this work]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excavation/erosion²</td>
<td>1.5–3.0 x 10⁷</td>
<td>100–200</td>
</tr>
<tr>
<td>Hydrothermal circulation¹</td>
<td>1.9 x 10⁷</td>
<td>130</td>
</tr>
<tr>
<td>Totals</td>
<td>0.47–1.2 x 10⁸ km³</td>
<td>315–830 m</td>
</tr>
</tbody>
</table>

*Calculation assumes a crustal inventory of 500–1000 m of water within the top 10 km of the crust and a global crustal density equivalent to that found in the cratonic highlands.

**Processes of replenishment of equatorial ground ice (water table to base of cryosphere):**
1. thermal vapor diffusion (most important)
2. seismic pumping
3. hydrothermal convection

**Transport of water through the cryosphere:**
1. thermal vapor diffusion (will continue until the cryosphere is saturated with ice)
2. liquid phase transport (capillary action)
3. thermal regelation (transport of solid phase)

**3. Is groundwater globally connected and does it flow on a global scale?**
- At the kilometer-scale, “virtually all groundwater systems on Earth may be considered hydraulically interconnected.” (due mostly to crustal fractures; avg. crustal permeability on Earth is 10⁻² darcies).
- Carr (1979) estimated permeabilities of 10³ darcies for outflow channels, comparable to permeabilities of gravel and permeable basalt on Earth. Carr’s estimate likely too high.

**Groundwater flow and polar basal melting, “...an inevitable consequence of polar deposition”:**
- an insulating layer (such as the polar cap) will cause the base of the cryosphere (the melting isotherm) to rise to maintain thermal equilibrium.
- can get a **mounded water table** below the polar cap (assuming many things) as basal melting progresses, which will drive groundwater flow away from the pole.
- Basal melting can also help to explain continued deposition of polar layers and the youthful age of the polar cap. (How would polar erosion from obliquity cycles affect this?)

**Questions:**
- “...does the present planetary inventory of H₂O exceed, by more than a few percent, the quantity of water required to saturate the pore volume of the cryosphere?” (p. 11,011)
- How permeable is the martian crust?
- Is a global groundwater system geologically reasonable?
- Is this system “essentially a closed loop”?*
- Was early Mars warm and wet?
- How can we test the hypothesis of a global groundwater system?
- What is the current heat flux of Mars? How has it evolved with time?