DISCHARGE-DRIVEN HYDROGEOLOGY OF MODERN MARS.

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Introduction. In spite of abundant evidence for groundwater on early Mars [e.g., 1-4] and recent fluid-like surface flow [e.g., 5-9], the distribution—or even existence—of contemporary groundwater has remained theoretical [e.g., 10-12]. Here we consider the requirements for the depth, extent, and composition of aquifers discharging as Recurring Slope Lineae (RSL), assuming the latter are indeed water flows. We then discuss the implications for global hydrogeology of both RSL and outflow channels as manifestations of recent groundwater discharge. Finally, we lay out future tests for groundwater discharge and storage capacity. Aquifers provide the most stable and shielded environments for microorganisms on Mars, but groundwater must move in order to supply nutrients and remove waste from microbial colonies. Without recharge, such life-sustaining fluid transport must be driven by intermittent groundwater discharge.

Subsurface Structure of RSL Sites. RSL grow incrementally, which is *prima facie* evidence of fluid flow in a porous medium [13,14]. Lengthening occurs when surface temperatures are high and the temperature interval over which RSL are active suggests seasonal release of meltwater or brine [15-17]. Our water-volume estimates >1 m^3 per m of headwall [14,15] are too large to be sourced by atmospheric condensation or subsurface vapor diffusion and imply a groundwater source. We adopt the working hypothesis that RSL are spring discharges and explore implications for subsurface structure.

The martian cryosphere likely averages several km thick (see below), but in order for aquifers to discharge at RSL sites, the cryosphere must be thin or absent due to salt freezing-point depression [16], insulation by low thermal conductivity, or higher heat flow. The first explanation is most likely for RSL in Chryse and Amazonis Planitiae (CAP), where discharge temperatures suggest an aquifer temperature comparable to the mean annual surface temperature ~225 K. Southern Midlatitude (SML) RSL, however, require larger changes in the subsurface, because the apparent freezing point ~273 K [8] is much higher than the mean surface temperature. Thermal blanketing or higher heat flow must contribute to thinning or removing the cryosphere locally Many SML RSL are associated with surficial units [8] that suggest sublimating volatiles, akin to remnants of latitude-dependent mantle [17]. These units may have high porosity following ice loss and provide thermal insulation. In Ganges and Juventae Chasma sand sheets covering the bases of RSL-producing inselbergs could provide the same function [18]. RSL in Valles Marineris (VM) become active at temperatures intermediate between CAP and SML, and thus could be due to a combination of freezing-point depression and enhanced thermal gradient.

Global Hydrogeology of Mars. The appearance of chaos and outflow channels during the Hesperian is interpreted as collapse of the surface under artesian pressure and subsequent massive groundwater discharge [19]. This indicates a thickening cryosphere and transition from an unconfined [20] to a confined state. Outflow-channel formation has occurred intermittently into the late Amazonian [9,21], likely triggered by magmatic melting of deep ground ice or injection of juvenile water.

The modern hydrogeology of Mars is therefore dominated by the cryosphere, whose thickness depends on latitude, heat flow, thermal conductivity, and freezing-point depression [10,22]. For contemporary heat flow <20 mWm^{-2} [23], desiccated, low thermal conductivity regolith, and an intermediate freezing-point depression (252 K, NaCl eutectic), the thickness of the cryosphere varies from ~2 km at the equator to ~18 km at the poles. The thickness is relatively constant at latitude <20°.

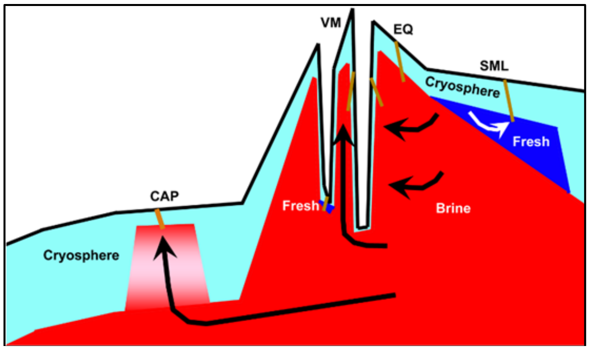

Fig. 1. Conceptual model of present-day discharge-driven groundwater flow on Mars. Groundwater is static unless cryosphere is breached, which occurs infrequently on scales of ~100 km, leading to massive outflows (not shown), or frequently on km-scales, leading to slow leakage from RSL. Water may reach the surface via fractures (brown) below locally thinned cryosphere. Freshwater over brine may be indicated by freezing temperatures of SML vs most other RSL. Alternatively, fresh vs. briny regions could be separated laterally by impermeable units.

An extant hydrological cycle [10] would involve subsurface infiltration through basal melting of the polar caps, fluid and vapor transport toward the equator, evaporation at low latitudes, and closure through precipitation at the poles. We now know that basal melting of the polar caps does not occur under contemporary heat flow [25], so the circuit cannot be completed. Instead, we propose a <u>discharge-driven</u>

model for the global hydrogeology of Mars (**Fig. 1**). Our perspective is that hydrogeology, like many other crustal features of Mars, has probably changed little throughout the Amazonian. If there was any unsaturated porosity below the cryosphere [10], it would have been driven to the highest elevation due to relaxation of the water table, assuming good global connectivity. In this case the head would be relatively uniform around the planet at probably several km above datum. This poses a problem in that the hydraulic pressure would exceed the lithospheric pressure for elevations < −2 km (assuming minimum elevation −5 km, water-table elevation 3 km, and rock density 2.5 g cm^{-3}), which presumably would lead to breakouts. Alternatively, groundwater could be strongly compart-mented. This restricts global equalization of head; instead, hydraulic heads follow the base of the lithosphere. An intermediate state is likely, with sufficient connectivity that parts of the crust are poised for breakout (needing say, a magmatic intrusion), but sufficiently compartmented that lateral head variations are statically maintained. When a discharge site (outflow or RSL) is introduced, the static configuration is broken and flow begins. Healing of the cryosphere shuts off flow to the site (for RSL, there is also a seasonal melting and freezing of thin ice dams).

Since Mars presently has no recharge mechanisms, discharge of H_2O must be incorporated into the near-surface ice reservoir or lost to space. Outflow channels released some 40 m Global Equivalent Layer [GEL; 25], but this was dominantly during the Hesperian. We crudely estimate the RSL loss at ~10^6 m^3 per Mars year, by assuming that the global area of RSL is about twice the ~$2x10^7$ m^2 [26] of VM RSL, and that the saturated thickness is 5-cm saturated thickness at 50% porosity [15]. Assuming further that RSL have been active at comparable levels, if not the same locations, throughout the Amazonian leads to ~21 m GEL discharge since 3 Ga. We have ignored evaporation, which could result in a water budget several times larger [14], and it is likely that RSL experience surface controls (obliquity) on their activity or even that they have not been active over the full Amazonian. The total discharge from outflow channels and RSL since the Hesperian is likely <60 m. The D/H-derived Hesperian-Amazonian loss to space is ~60 m GEL, exclusive of magmatic degassing, and the reservoir of atmospherically exchangeable (mobile) ground ice is ~30 m GEL [12,25]. Therefore groundwater discharge can exist on geologically modern Mars yet not dominate the near-surface H_2O budget.

Tests of the Model. Groundwater models [e.g., 27] can evaluate the flow and solute transport expected for the very small, gradual drawdown due to RSL, punctuated by larger changes during rare outflow-channel formation. Simultaneously, minimum flow rates can be related to the energy and mass requirements of chemolithoautotrophic organisms [28] for different assumptions of groundwater chemistry, metabolic redox reaction, and biome activity state.

NASA's the "follow the water" strategy has largely been abandoned or diverted to the study of ancient water-rock interactions exposed at the surface. We must continue to seek actual liquid water by determining if RSL are water flows and by subsurface geophysical investigation. The former will require not just dedicated orbital or long-range ground imaging, but in situ sampling. RSL are challenging to target and access because of the small areas on which they are found, their occurrence on steep slopes, and their incomplete surface coverage. However, only very simple instrumentation is required to assess the water content and salinity of RSL. Electromagnetic sounding [29] is the optimum approach to assessing the depth and thickness of aquifers (radar is quickly absorbed or scattered in the uppermost crust and seismic requires greater resources and has less sensitivity). Passive EM sounding only requires simultaneous measurement of ambient electric and magnetic fields and is suitable for probing groundwater at depths of kilometers or more. Active EM sounding uses a transmitter [30] and can achieve high resolution in the shallower subsurface, which will be particularly useful in the areas outside of craters containing RSL in order to measure aquifer properties.

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