THE EVOLUTION AND FATE OF GROUNDWATER ON MARS: THE INFLUENCE OF MODELING ASSUMPTIONS AND CONSISTENCY OF PREDICTIONS WITH OBSERVATIONAL CONSTRAINTS.

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Introduction: The initial inventory, evolution and ultimate fate of groundwater on Mars has important implications for understanding the geological, hydrological and mineralogical evolution of the planet, as well as the potential survival of native Martian life.

Here, we discuss and contrast two models of the hydrologic evolution of Mars (Clifford [1] and Grimm and Painter [2]) in an effort to explain the basis for their differing conclusions regarding the likely survival and distribution of present-day groundwater. The predictions of both models are then compared against the observational evidence as a potential test of their validity.

The planetary inventory of H_2O and implications for the persistence of groundwater. Based on the geomorphic interpretation of a wide variety of Martian landforms, and a conservative estimate of the volume of water required to erode the outflow channels, Carr [3, 4] has estimated that, at the time of peak outflow channel activity (~2-3 Ga), Mars possessed a planetary inventory of water equivalent to a global equivalent layer (GEL) ~0.5–1 km deep. As the outflow channels significantly post-date the period when the most efficient mechanisms of planetary water loss (impact erosion and hydrodynamic escape) were thought to be active (>4 Gya) [5], it is expected that the bulk of this water still survives on Mars today, 90-95% of which is believed to be stored in the subsurface, as either ground ice or groundwater [1, 4].

The fraction of the Martian inventory of water that is held in these two volatile reservoirs, depends on the relative size of the planetary inventory of water vs. the pore volume of the cryosphere. If the inventory of water exceeds what can be stored as ice within the pore volume of the cryosphere, then the excess will exist as groundwater, saturating the lowermost porous regions of the crust [1].

Although the outflow channels provide persuasive evidence that Mars once possessed a sizable inventory of groundwater, it is possible that today such a reservoir no longer survives – a potential consequence of the cold-trapping of a once-large inventory into the pore volume of the thickening cryosphere, as the planet's internal heat flow declined with time [1].

Recent estimates of Martian geothermal heat flow, suggest a present-day value only half as great as previously thought [6], effectively doubling previous estimates [1, 7] of the expected thickness of the cryosphere (and, thus, the depth to any surviving reservoir of groundwater). This most recent analysis suggests that the zonally-averaged thickness of the cryosphere may vary from ~0 - 9 km at the equator to ~10 – 22 km at the poles, depending primarily on the geothermal heat flux, availability of potent freezing point depressing salts (such as perchlorate) and temperature-dependent themal conductivity of the crust [6].

Combining reasonable estimates of crustal porosity with this calculated range of cryosphere depths suggests that, for a present-day heat flow of ~15 mW m^{-2}, the total pore volume of the Martian cryosphere is sufficient to cold-trap ~0.5 km GEL of H_2O -- equivalent to Carr's [3, 4] lower estimate of the planetary inventory of water. However, if the planetary inventory is as great as Carr's maximum estimate of a ~1 km GEL, then up to several hundreds of meters of groundwater may still survive at depth.

Hydrologic evolution of a water-rich Mars. Clifford [1] and Clifford and Parker [7] have examined the thermal and volatile evolution of a water-rich Mars, arguing that, if the inventory of H_2O exceeds the pore volume of the cryosphere by more than a few percent, then a planetary-scale subpermafrost groundwater system will necessarily result – a system whose existence may have played a critical role in the long-term climatic and hydrologic evolution of Mars.

According to this model, under the climatic conditions that have prevailed throughout most of Martian geologic history, the H_2O that is lost from the equatorial regolith by the sublimation of ground ice, is ultimately transported by the atmosphere and cold-trapped at the poles. Given an initially ice-saturated cryosphere, the deposition and retention of ice at the poles (or any other location, such as Tharsis) will result in the rise of the melting isotherm at the base of the cryosphere, the onset of basal melting, and downward percolation of meltwater into the underlying global aquifer.

Given geologically reasonable values of large-scale crustal permeability ($\geq 10^{-15}$ m^2), the gradient in hydraulic head created by the melting of ice at the base of the cryosphere (and, ultimately, the base of the polar layered deposits themselves) will lead to the development of groundwater mounds at both poles, capable of driving the equatorward flow of a significant volume of groundwater (~1-10 km GEL H_2O, depending on the effective permeability of the crust) over the course of the planet's history [1, 7].

At equatorial and temperate latitudes, the presence of a geothermal gradient will result in a net discharge of the groundwater system as vapor is thermally pumped from the warmer (higher vapor pressure) depths to the colder (lower vapor pressure) near-surface crust. By this process a gradient as small as 15 K km^{-1} could drive the vertical transport of 1 km GEL of water to the freezing front at the base of the cryosphere every 10^6– 10^7 years, or the equivalent of a 10^2-10^3 km GEL of water over the 4.5 billion year history of the planet. This potential supply exceeds the maximum amount of ice potentially lost by equatorial submimation by more than two orders of magnitude, ensuring that equatorial ground ice will persist (at some depth) until the reservoir of underlying groundwater is exhausted. By this process, any excess vapor, beyond that required to keep pace with submilmation, will simply recondense and infiltrate back to the groundwater table [1].

In response to the planet's declining geothermal heat flow, the progressive cold-trapping of H_2O into the growing cryosphere is expected to have significantly depleted the original inventory of groundwater – a development that might well explain the apparent decline in outflow channel activity observed during the Amazonian. As noted earlier, the implications of this evolution for the present state of groundwater range from an initial inventory that has now been completely assimilated by the growth of the cryosphere, to the continued survival of a subpermafrost reservoir equal to several hundred meter GEL – most probably confined to low- to mid-latitudes by the encroachment of a thick polar cryosphere [6].

An alternative view. This scenario for the hydrologic evolution of Mars has recently been challenged by Grimm and Painter [2] who, based on their own analysis of the evolution of the Martian hydrosphere following the transition to a colder climate, find that the survival of groundwater beneath an ice-rich cryosphere would have been short-lived – a consequence of the diffusive instability of H_2O at low latitudes, which they calculate would have led to the effective dessication of the equatorial regolith in just a few hundred million years.

Their anaylsis further suggests that, if groundwater persists anywhere on Mars today, it will most likely be at mid- to high-latitudes, where it will be present as thin films of adsorbed liquid coating pore walls, beneath a many km-thick temperate and polar cryosphere.

A number of factors contribute to the differing predictions of the Grimm and Painter [2] model. First and foremost is their assumption of a significantly smaller planetary inventory of water (~75 m GEL, or roughly 8-16% of the inventory estimated by Carr [3, 4]), which is rapidly sublimed away at equatorial latitudes. This result is favored by their adoption of a uniform 10 μm pore size, dismissal of the potential role played by natural diffusion-inhibiting barriers, and failure to consider the potential replenishment of sub-permafrost groundwater by the recycling of sublimed H_2O back into the crust by the process of basal melting. Rather, they assume that any H_2O sublimed from the equatorial regolith is irreversibly lost from the planetary inventory of water by exospheric escape.

While the individual merit of many of these assumptions can be debated, the ultimate test for the viability of any model of the hydrologic evolution of Mars is its consistency with respect to the observationnal evidence. In this respect, the predicted rapid dessication of the equatorial regolith, just a few hundred million years following the inferred transition to a colder climate at the end of the Noachian, appears to fail – as it runs counter to the geologic evidence that the peak in outflow channel activity did not occur until ~1-2 billion years later [5]. This inconsistency is further aggravated by the fact that virtually all of the outflow channels originate at equatorial latitudes – indicating that groundwater at low-latitudes at this time was abundant. Indeed, Carr's estimate of a ~0.5 - 1 km GEL planetary inventory of H_2O, is not an estimate of Mars' initial inventory of water (i.e., @4.5 Ga), but the inferred inventory at the time when the bulk of the outflow channels were formed (~2-3 Ga).

This suggests that the predicted rapid dessication of the equatorial regolith is an artifact of Grimm and Painter's model assumptions, rather than an accurate description of reality – although the dessication of the equatorial regolith (and potential disappearance of groundwater) sometime during the Amazonian cannot be ruled out.

If groundwater does still survive on Mars, the expected thickness of the polar cryosphere is likely to confine its occurrence to low- to mid-latitudes, with lower latitudes having the added benefit of minimizing the thickness of frozen ground – optimizing the potential detection of groundwater by geophysical exploration techniques [6].

References: [1] Clifford, S. M. (1993) JGR 98, 10973-11016. [2] Grimm, R. and # Painter (2009), GRL, in press. [3] Carr, M. H. (1986) Icarus 68, 187-216. [4] Carr, M. H. (1996) Water on Mars, Oxford University Press. [5] Tanaka, K. (1986) JGR 91, 139-158. [6] Clifford et al., (2009), JGR-Planets, in press. [7] Clifford, S. M. and T. J. Parker (2001) Icarus 154, 40-79.