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Tharsis recharge: A source of groundwater for Martian outflow channels

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[1] The large martian outflow channels terminating in Chryse Planitia are remnants of flooding events involving the localized discharge of millions of cubic kilometers of subsurface water, more than can be regionally stored in the crust. We use a dynamic groundwater model to demonstrate that snowpack or glaciers on the Tharsis rise, formed during periods of high obliquity when ice was stable at low latitudes, may have provided an efficient source of recharge and hydraulic head for the circum-Chryse outflow channels. Water is discharged through the outflow channels several times faster in Tharsis recharge models than in comparable South Pole recharge models. *INDEX TERMS:* 6225 Planetology: Solar System Objects: Mars; 1829 Hydrology: Groundwater hydrology; 1821 Hydrology: Floods. **Citation:** Harrison, K. P., and R. E. Grimm (2004), Tharsis recharge: A source of groundwater for Martian outflow channels, *Geophys. Res. Lett.*, *31*, L14703, doi:10.1029/2004GL020502.

1. Introduction

[2] While it is generally accepted that the circum-Chryse outflow channels of Mars were carved by groundwater discharge through disruptions in a cryosphere [*Carr*, 1979], quantitative descriptions of their formation remain poorly constrained. In particular, estimates of sediment-water ratio (SW) – which determines the volume of water necessary to carve a channel of known dimensions – vary from 10^{-4} [*de Hon et al.*, 2003] to 0.67 [*Komar*, 1980], yielding a range of 3×10^6 to 2×10^{10} km^3 of water required to erode the channels. SW values even slightly less than the maximum lead to water volumes exceeding the regional storage capacity of the crust, implying that aquifer recharge is required.

[3] *Clifford and Parker* [2001] proposed that basal melting of a South Polar ice cap recharged a global aquifer, providing a supply of groundwater to the outflow channels. The model does not, however, explain the development of water-related features above the recharge zone (e.g., outflow channels flanking Valles Marineris Chasmata [*Carr*, 2002; *Coleman et al.*, 2003] and possible intra-Chasmata lacustrine deposits [*Carr*, 2002]). We propose that recharge at the Tharsis rise, which was largely in place by the late Noachian [*Phillips et al.*, 2001], provides a high elevation source of discharge to the outflow channels and further constrains postulated hydrologic links to the circum-Chryse outflow channels [*Baker et al.*, 2001].

[4] There is substantial qualitative support for past atmospheric delivery of water to Tharsis and its infiltration into the regional aquifer. Evidence for periodic climate change on Mars, revealed by Mars Global Surveyor and Mars Odyssey, demonstrates the transient nature of martian volatile dynamics. The martian obliquity (currently 25.2°) undergoes high amplitude (~10°) oscillations with a period of about 0.1 Myr [*Ward*, 1992]. Its fundamentally chaotic nature precludes accurate extrapolation to times earlier than a few Myr ago, but statistical calculations [*Laskar et al.*, 2004] suggest a most probable value of 45° over the last few Gyr. At these obliquities, climate models predict an equatorial zone in which surface ice is perennially stable [*Jakosky and Carr*, 1985; *Mellon et al.*, 1997; *Haberle et al.*, 2003]. Warm polar summers lead to sublimation of polar ice which precipitates at low latitudes, particularly at high topographic elevations. This mechanism may have operated as far back as the Noachian: *Carr and Head* [2003] suggest basal melting of low- to mid-latitude ice sheets at high obliquities as a source of water for valley networks.

[5] Infiltration of precipitation over Tharsis was likely aided by volcanic activity which may have thinned the cryosphere [*Tanaka et al.*, 2002], perhaps melting it through in places [*Wilson and Head*, 2002]. A further advantage of Tharsis recharge is its proximity to the westernmost outflow channels (including the largest, Kasei Valles).

2. Model

[6] We support our hypothesis of Tharsis recharge with numerical simulations that quantitatively constrain the large-scale dynamics of groundwater supply to the outflow channels. We use MODFLOW [*Harbaugh et al.*, 2000] to model an initially saturated global martian aquifer cast in a Lambert equal-area projection, with the South Pole, Tharsis, and the circum-Chryse outflow channels at approximately the same distance from the model boundary (Figure 1). Our assumption of total initial saturation (due to precipitation over an unconfined Noachian aquifer) influences initial outflow channel discharge, but does not affect discharge induced by aquifer recharge, the focus of these models. Hydraulic head at the lateral boundary is fixed to the elevation of the lowest outflow channel so that discharges are not inflated by flow driven by fixed boundary head. Upper and lower model boundary elevations are determined by the martian topography (from MGS MOLA data), with the Amazonian volcanic shields removed. An impermeable cryosphere offsets the upper model boundary to some depth below the topography determined by geothermal heat flux and surface temperature. In recharge regions, however, the upper model boundary is set to coincide with the martian surface, since geothermal heat (possibly in conjunction with

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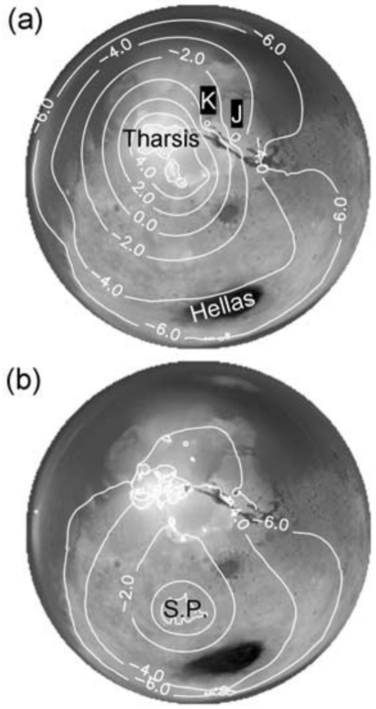

Figure 1. Contours of hydraulic head (in km relative to martian datum) in a global martian aquifer (Lambert equal-area projection). TH and SP models are shown at 270 Myr in (a) and (b), respectively. Note higher head gradients in (a), indicating a stronger influence from Tharsis recharge than from South Pole recharge in (b). In (a), "K" and "J" designate Kasei/Echus and Juventae outflow sources. In (b), complex contours over Tharsis are due to drainage of the highest parts of the aquifer. "S.P." designates South Pole.

ice sheet formation) is assumed to have lifted the melting isotherm to this elevation. The lower model boundary is also offset from the topography, but to a depth determined by pore-space compaction due to lithostatic pressure. Surface discharge is permitted through nine modeled outflow channel sources at elevations corresponding to the pre-disruption cryosphere base. The surface area of each finite difference cell is approximately 3000 km^2.

[7] Recharge is applied in separate models to regions centered at the South Pole and Tharsis. South Pole recharge is applied to model cells within 750 km of the pole [*Clifford and Parker*, 2001], while Tharsis recharge is applied, for the purposes of comparison, to regions whose surface elevation exceeds 5.8 km, thereby yielding approximately the same total area as that of South Pole recharge. In both cases, recharge is applied at a constant rate of 2×10^{-10} m.s^{-1} [*Clifford and Parker*, 2001], but infiltration actually occurs at a lower, variable rate determined by permeability and hydraulic head gradient (excess recharge is assumed to evaporate or become surface runoff). Groundwater flow beneath a confining cryosphere is relatively insensitive to small changes in recharge over time scales significantly less than the transit time between recharge and discharge locations (a few 100 Myr in these models), therefore a time-averaged recharge rate is suitable.

[8] The hydrologic and thermal conditions of *Clifford and Parker* [2001], which include a Hesperian geothermal heat flux of 95 mW.m^{-2}, surface temperatures of the present day, and an exponential decay of porosity with depth, are simulated with both South Pole and Tharsis recharge models (SPC and THC). We also construct revised South Pole and Tharsis recharge models (SP and TH) with improved, more conservative parameter values, including a lower geothermal heat flux (30 mW.m^{-2}) suggested by lithosphere thicknesses derived from gravity-topography relationships [*McGovern et al.*, 2002], and surface temperatures representing the average of obliquity extremes. In all models, we use the *Manning and Ingebritsen* [1999] permeability-depth function scaled to martian conditions, giving $\log k = -12.65 - 3.2 \log z$, where z is in km. However, the thermal properties of the revised models yield a thicker cryosphere which engulfs the most permeable upper parts of the aquifer, yielding a factor of four decrease in average permeability. The revised model porosity n is derived from the permeability through the Kozeny-Carman equation [*Saar and Manga*, 1999], giving $\log n = -1.65 - 0.8 \log z$. This function falls more steeply than that of [*Clifford and Parker*, 2001] and together with the thinner aquifer results in an order of magnitude lower total storage.

[9] All outflow channel sources begin discharging at the start of the simulation and are shut off simultaneously once their combined discharge production has met a particular quota. The duration of outflow activity for a larger quota can be found simply by continuing the simulation until that quota is met. Furthermore, each quota corresponds to a specific SW, allowing us to investigate with one simulation any ratio below the assumed maximum value of 0.67. A drawback of this approach is that information regarding individual discharge quotas and starting times is ignored, so each source is unlikely to produce the expected proportion [e.g., *Carr*, 1996] of the total discharge over a given time period. We tested models with individual quotas and found a maximum difference in discharge of a factor of two. At present, we prefer the combined approach since it provides a straightforward test of recharge requirements, and because local dynamics of discharge initiation and cessation are poorly constrained.

[10] We limit the models to physically reasonable time periods by noting that the circum-Chryse outflow channels formed between the end of the Noachian 3.5 Gyr ago and the end of the Hesperian between 2.9 and 3.3 Gyr ago [*Hartmann and Neukum*, 2001]. Estimates of individual outflow event durations are as low as days to months [*Carr*, 1996], but require high peak discharge rates and the maximum SW. Recent work suggests lower discharge rates [*Williams et al.*, 2000; *Hassett et al.*, 2002] which, in combination with likely lower SW values, imply considerably longer periods of outflow channel formation. A maximum duration of outflow activity of 400 Myr, dictated by the estimated length of the Hesperian, provides conservative bounds on parameters of interest such as SW, permeabilities, and recharge rates.

3. Results

[11] The TH model produces five times more discharge than the SP model over the assumed length of the Hesperian (400 Myr). Stronger TH model hydraulic head gradients efficiently drive groundwater from Tharsis to the outflow

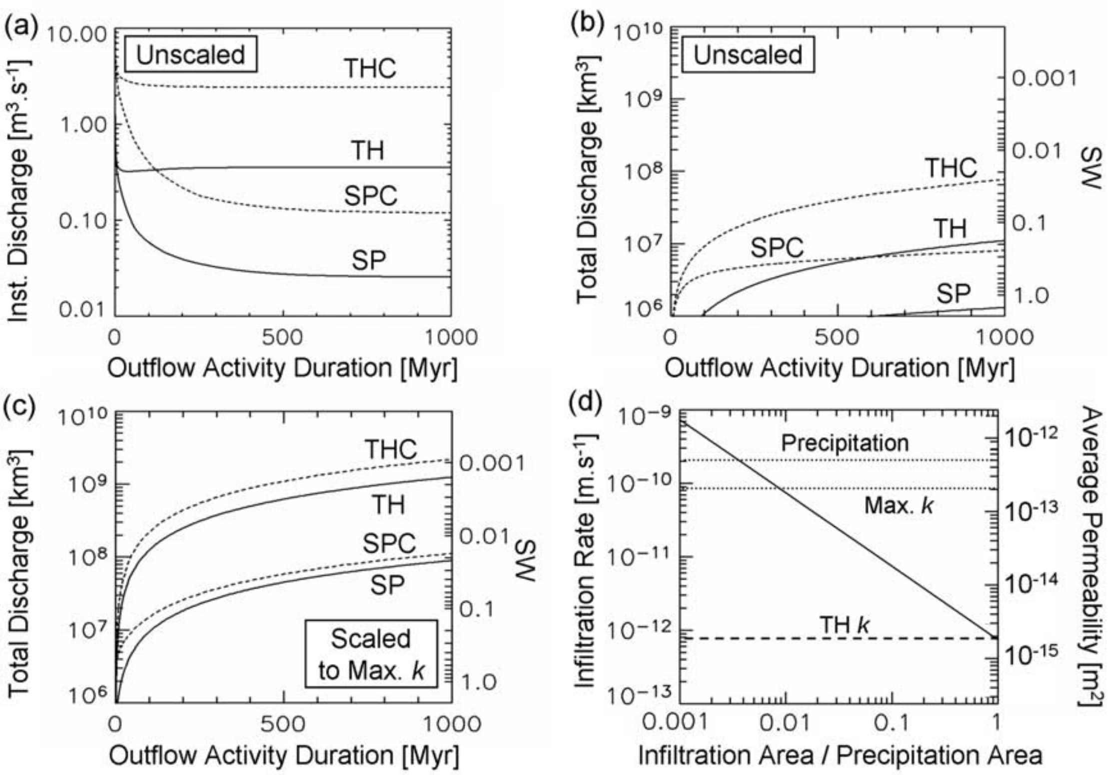

Figure 2. (a) Instantaneous discharge (summed over outflows) vs. outflow activity duration for TH, SP, THC, and SPC models. (b) Total discharge, with corresponding SW values on right ordinate. Dashed and solid lines distinguish models with *Clifford and Parker* [2001] and revised properties, respectively. (c) Total discharge from models scaled to a likely maximum average aquifer permeability of 2×10^{-13} m^2. (d) Infiltration rate required to conserve steady state TH model flux given a reduction in infiltration area. Required average permeability appears on right ordinate. Dotted lines indicate upper bounds imposed by applied precipitation ("Precipitation") and likely maximum average permeability ("Max. *k*"). Dashed line indicates TH average permeability ("TH *k*").

sources, and the minimum discharge quota (determined by SW = 0.67) is reached after 270 Myr (Figure 1). The SP model meets the minimum quota after 3.6 Gyr, vastly exceeding reasonable time constraints. The ratio of TH and SP model discharges increases slightly with average permeability as indicated by models scaled to 2×10^{-13} m^2 (Figure 2), a likely upper bound (derived from a terrestrial estimate [*Manning and Ingebritsen*, 1999]). At this value, 400 Myr of TH model outflow activity corresponds to SW = 3.9×10^{-3}, close to the lowest martian estimates [*de Hon et al.*, 2003].

[12] Large SPC model discharge rates (Figure 2) seem to suggest a strong South Pole recharge influence, but this is not the case. The high porosities of this model mean that low discharge quotas are met by groundwater from the large initial inventory of the Tharsis aquifer. At lower SW values, the correspondingly higher discharge quotas require aquifer recharge which, in the steady state, produces an outflow discharge of 0.12 m^3.s^{-1}, a third that of the TH model. Overall, the THC model is the most efficient, producing in 400 Myr six times the discharge of the SPC model and 40 times that of the SP model. We note that hydraulic pressure in both the SPC and THC models exceeds, in places, the lithostatic overburden of the cryosphere, which we must assume remains undisrupted in these regions. This difficulty further supports the low geothermal heat fluxes of the TH and SP models, in which this problem does not arise.

[13] Note that greater permeabilities permit faster infiltration. At the maximum permeability, however, steady state infiltration in the TH model is less than half the applied rate, so enough water is still available for recharge.

4. Discussion and Conclusions

[14] We consider some quantitative aspects of Tharsis recharge. Recharge may occur through the direct infiltration of precipitation near volcanic intrusions sufficiently shallow and hot to melt the cryosphere. The localized nature of this process means that infiltration takes place only through some fraction of the precipitation area. If the infiltration area is reduced without increasing the infiltration rate (i.e., at fixed permeability), the total flux into the aquifer decreases and discharge requirements can be met only if the outflow sources remain active longer. In particular, if the TH model infiltration area is reduced to 68% of the modeled size, the minimum discharge requirement will just be met within the allowed 400 Myr of outflow activity.

[15] To conserve outflow channel activity duration, and therefore the flux into the aquifer, a reduction in infiltration area must be accompanied by a corresponding increase in infiltration rate, achieved by increasing the permeability. Figure 2d shows infiltration rates required to maintain the steady state TH model flux (0.36 m^3.s^{-1}) for a range of infiltration areas (normalized to the precipitation area). The

upper bound on infiltration rate (8.3×10^{-11} m.s^{-1}) is imposed by the maximum permeability, rather than the applied precipitation, and corresponds to an infiltration area covering only 0.9% of the precipitation area.

[16] If basal melting of an ice sheet occurred, our conservative thermal properties require an equatorial ice sheet thickness of about 3 km. With the likely elevated geothermal heat at Tharsis, however, the equilibrium thickness is likely to be significantly smaller. Water contributing to ice sheet growth comes from polar sources in the form of north and south ice caps or a primordial northern ocean as described by *Clifford and Parker* [2001]. Precipitation over Tharsis at the modeled rate builds a 1 km ice sheet in 0.15 Myr. Other work [*Mischna et al.*, 2003], when extrapolated in time, implies a period of 0.05 Myr, shorter than a single obliquity cycle [*Ward*, 1992]. The preserving effect of lag deposits during unfavorable obliquities might allow basal melting to re-initiate after much shorter delays during subsequent obliquity extremes, increasing the chances of long-term accumulation.

[17] To summarize, Tharsis is several times more efficient than the South Pole as a source of recharge supplying groundwater to the circum-Chryse outflow channels. This estimate is conservative since the Tharsis recharge area, chosen to match that of the South Pole, covers less than a tenth of the Tharsis rise. By virtue of its position and elevation, Tharsis imposes greater hydraulic head gradients at the outflows and provides a relatively short, direct route for groundwater flow. Recharge is made possible by high planetary obliquities which give rise to surface temperatures and atmospheric circulation conducive to equatorial precipitation and stability of ice. Faults trending radially from Tharsis toward the outflow channels suggest enhanced hydrologic connectivity between the two regions.

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