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Recharge mechanism of near-equatorial hydrogen on Mars: Atmospheric redistribution or sub-surface aquifer

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[1] The geographical distribution of water-equivalent-hydrogen (WEH) near the equator of Mars was compared with the topography and distribution of atmospheric water vapor to constrain possible recharge mechanisms of near-surface water (<1 m of the surface). Recharge through a subsurface conduit provided by an aquifer, although possible, seems less likely than recharge through the atmosphere. Although the spatial distribution of WEH does not correspond to the current distribution of water vapor in the atmosphere, several terrestrial analogs indicate that dynamics of atmospheric circulation during periods of higher obliquity prior to the present epoch can qualitatively account for the observed WEH distribution. *INDEX TERMS:* 5410 Planetology: Solid Surface Planets: Composition; 5416 Planetology: Solid Surface Planets: Glaciation; 5445 Planetology: Solid Surface Planets: Meteorology (3346); 6225 Planetology: Solar System Objects: Mars; 3665 Mineralogy and Petrology: Mineral occurrences and deposits. **Citation:** Feldman, W. C., J. W. Head, S. Maurice, T. H. Prettyman, R. C. Elphic, H. O. Funsten, D. J. Lawrence, R. L. Tokar, and D. T. Vaniman (2004), Recharge mechanism of near-equatorial hydrogen on Mars: Atmospheric redistribution or sub-surface aquifer, *Geophys. Res. Lett.*, *31*, L18701, doi:10.1029/2004GL020661.

1. Introduction

[2] Two separate types of hydrogen reservoirs have been identified on Mars. The first exists at latitudes poleward of ±50° and is sufficiently rich that it has been identified as deposits of water ice [*Feldman et al.*, 2002; *Boynton et al.*, 2002; *Mitrofanov et al.*, 2002; *Tokar et al.*, 2002; *Prettyman et al.*, 2004]. The second covers vast areas at mid- to equatorial latitudes and has been identified with hydrated minerals [*Feldman et al.*, 2002, 2004a, 2004b; *Basilevsky et al.*, 2003]. While the existence of hydrogen reservoirs at high-latitudes has been predicted for some time [*Farmer and Doms*, 1979; *Fanale et al.*, 1986; *Mellon and Jakosky*, 1993], those at near-equatorial latitudes were unexpected. Their recharge mechanism is likewise not known, but two distinct possibilities exist: from the surface intersection of a global water table [*Clifford*, 1993], or from a redistribution of near surface water through the atmosphere. If recharge comes through the atmosphere, then it is important to determine its relevant time scale. The purpose of this study is to detail the observed distribution of water-equivalent hydrogen (WEH) at mid- to equatorial latitudes in order to determine the most likely conduit for transport of water molecules from the high latitudes, where water ice is presently stable, to the equator, where it is presently unstable.

2. The MONS Data Set

[3] The first presentation of a global map of CO_2 frost-free epithermal neutron counting rates from the Mars Odyssey Neutron Spectrometer (MONS) was given in *Feldman et al.* [2004a]. The procedure to reduce the raw neutron data to lower-limit WEH abundances using Monte Carlo Neutron simulations, was detailed in *Prettyman et al.* [2004]. Resultant maps of WEH abundances from data acquired between 19 Feb. 2002 and 20 April 2003, are shown in Figures 1a–1c. Polar orthographic projections (Figure 1a) were constructed by smoothing the time-integrated counts within $1^\circ \times 1^\circ$ quasi-equal-area pixels using a 4° radial box-car filter. The two cylindrical near-equatorial projections were smoothed using a 1.5° radial box-car filter. Whereas the maps in Figures 1a and 1b use linear scales, that in Figure 1c uses a logarithmic scale. A dual-scale presentation was deemed necessary because the linear scale best presents the relatively high abundances at high latitudes and the logarithmic scale best presents the relatively low abundances at near-equatorial latitudes.

3. Characteristics of Near-Equatorial WEH Deposits

[4] Inspection of the map in Figure 1b shows two separate hydrogen reservoirs that maximize near Arabia Terra and Medusae Fossae at close to 9.5 ± 1.5% WEH by mass. They are connected to a longitudinally-extended reservoir that follows the zero-km elevation contour [*Feldman et al.*, 2004a] before connecting to the northern high-latitude reservoir along the western margin of Tharsis and through Elysium Mons. Figure 1c shows a separate C-shaped lane of relative maximum WEH that nearly encloses a relative minimum in Solis Planum, following parts of Valles Marineris on the north and the cordillera that almost completely envelops Solis Planum on the south. A last zone of relative maximum sits atop a tear-shaped highland zone within western Xanthe Terra that straddles the equator at −55°E. This zone is cut off from direct subsurface contact with the high-latitude southern water-rich zone by deep valleys that form part of Valles Marineris. Also shown are relative minima of about 2% by mass WEH that occur in Solis Planum, Argyre and Hellas basin, Isidis

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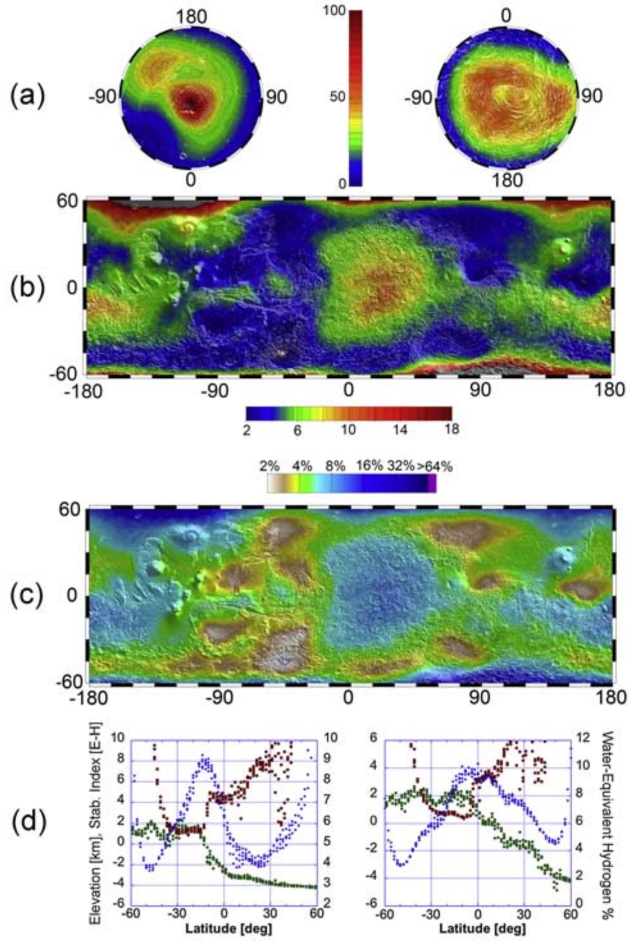

Figure 1. The geographic distribution of water-equivalent-hydrogen (WEH) on Mars. The topmost panel gives an overlay of WEH using a linear color scale, and a shaded relief map of Mars derived from MOLA topography data northward of +60° latitude on the left and −60° latitude on the right. The second panel from the top gives the same overlay using a cylindrical projection between +60° and −60° latitude. The third panel down gives the same data using a logarithmic color scale. And the lowest panel shows two meridional cuts through the WEH distribution (in blue), the topography measured using MOLA (in green), and the atmospheric humidity relative to the stability boundary between epsomite and hexahydrite (in red).

and Utopia Planitia, northern Acidalia, Echus Chasma, Chryse Planitia, and Cerberus.

[5] Meridional cuts through the two largest equatorial WEH reservoirs near Medusae Fossae (−180° < Longitude < −170°) and Arabia Terra (20° < Longitude < 30°) are compared in Figure 1d with corresponding cuts through the topography [*Smith et al.*, 1999] and the predicted atmospheric relative humidity [*Feldman et al.*, 2004b] for which epsomite ($MgSO_4.7H_2O$) is stable relative to less hydrous Mg sulfates (e.g., hexahydrite, $MgSO_4.6H_2O$, and kieserite, $MgSO_4.H_2O$). Note that the WEH contours follow the topography between the highlands in the south and the lowlands in the north. In addition, comparison with the theoretical relative humidity that gives a quantitative index for the stability of epsomite shows that both WEH abundances maximize at the break between relatively low values of stability in the south and high values in the north.

[6] The zonally-averaged distribution of equatorial WEH is compared with the annually- and zonally-averaged atmospheric water-vapor abundance [*Smith*, 2002] in Figure 2. Their maxima are seen to be offset in latitude. Whereas the WEH abundance maximizes at 10°S, the water vapor maximizes at about 25°N. Their offset is sufficiently pronounced to suggest that present-day WEH deposits near the equator are not in diffusive equilibrium with the present atmosphere.

4. Implications of Observations

[7] In support of a water-table recharge mechanism, it is striking that both large-scale equatorial WEH reservoirs straddle a constant topographic contour (at zero km) and occur at nearly antipodal longitudes [*Feldman et al.*, 2004a]. Both of these longitudes overlay negative gravity anomalies [*Phillips et al.*, 2001], which may indicate subsurface basins that provide a relatively low-permeability conduit for water. Their broad, yet nearly constant topographic altitude can also be understood in terms of a hydrologic head at southern latitudes driven by the residual, south-polar water ice cap [*Clifford*, 1993]. The existence of such a water table has been suggested as a credible explanation for gully-like features found between about 30° and 50° latitude in both hemispheres [*Malin and Edgett*, 2000; *Mellon and Phillips*, 2001; *Heldmann and Mellon*, 2004]. We note though that most of these gullies are found where the epithermal neutron data indicate low WEH content. This lack of correlation may reflect 1) the fact that gullies emerge from steep slopes that are on average ~250 m below the adjacent surface [*Heldmann and Mellon*, 2004], reflecting a water table well below the ~1 m epithermal-neutron sensitivity depth for WEH, or 2) that the gullies represent features related to local climatic micro-environments [*Christensen*, 2003; *Head et al.*, 2003], the scale of which is well below the spatial resolution of the NS.

[8] In support of an atmospheric conduit for WEH, we note that two of the observed relative maxima in WEH

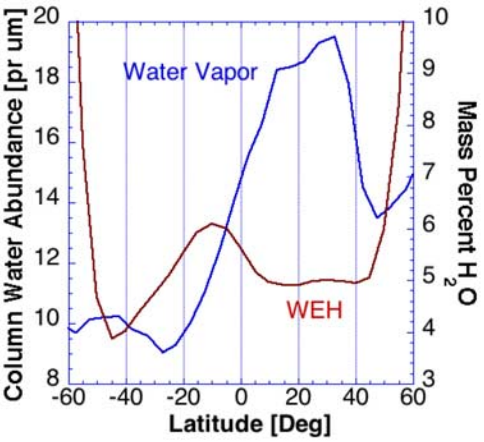

Figure 2. Zonal and annual averages of the water-equivalent-hydrogen (in red) and the atmospheric water-vapor column density (in blue).

abundance, namely the high terrain that completely surrounds Solis Planum, and the high plateau in Xanthe Terrae at −55°E and 0°N, are effectively isolated from a subterranean connection to both high latitude water-rich reservoirs on Mars. Both can only be recharged through the atmosphere. A simple orographic explanation for the atmospheric recharge of the other near-equatorial reservoirs is also likely. Figure 1d shows that the WEH abundance (blue dots) closely follows the topography (green dots) on the north-facing slope of the southern highlands. If the atmospheric moisture supply is from the north, as shown in Figure 2 [see also *Smith*, 2002], then dehydration of atmospheric moisture caused by atmospheric cooling with altitude, can cause more extensive frost deposits at night than evaporation during the day, and consequent long-term hydration of the uppermost 1 to 2 m of soil. The time scale for this hydration may be hundreds to thousands of years [*Mellon and Jakosky*, 1993]. This explanation could also apply to enhanced WEH on the western flanks of the Tharsis plateau near Olympus, Arsia, and Pavonis Mons, and on the western flank of Elysium Mons. The relative dearth of WEH nestled between Ascraeus Mons, Olympus Mons, and Alba Paterra could then be due to a 'moisture-shadow' effect as observed in many locations on Earth.

[9] Another related possibility is that the WEH shown in Figure 1b reflects buried water ice that was delivered to equatorial latitudes through the atmosphere from the residual water-ice polar caps prior to the present epoch during periods of higher obliquity [*Mellon and Jakosky*, 1995; *Mischna et al.*, 2003; *Head et al.*, 2003]. In order to survive to the present, this ice would have to be isolated from the atmosphere by a very low permeability diffusive barrier. Geological evidence from the Antarctic Dry Valleys, a hyperarid cold polar desert analog of Mars, suggests that ice can survive for millions of years beneath a sublimation till less than several tens of cm thick [*Marchant et al.*, 2003].

[10] This last explanation has both supporting and detracting factors. A supporting factor is that deposition during a previous high-obliquity phase would tend to populate terrains that straddle the equator (as observed) because the times of highest obliquity would likely average over all solar-areocentric longitudes of perihelion [see *Mischna et al.*, 2003, Figure 14]. Such deposition would bring with it the seeds for its own survival. Periods of high obliquity should be accompanied by both a high global humidity driven by greater solar insolation at high latitudes, extensive ice deposition at equatorial latitudes, and a more vigorous dust cycle [*Mischna et al.*, 2003]. Subsequent evaporation of the resultant dusty water-ice deposit would form a low-permeability lag cover, thereby isolating the remaining water ice from diffusive contact with the atmosphere [*Head et al.*, 2003]. It is conceivable that a mosaic of small islands of buried water ice left over from periods of deposition prior to the present epoch appear as large contiguous deposits when viewed by a large field-of-view instrument such as the MONS, as shown in Figure 1b. However, a potential problem with this explanation is that the pattern of ice deposition at high obliquities [see *Mischna et al.*, 2003, Figure 8] does not match the pattern of WEH abundances shown in Figure 1b. A potential solution is that ice ages between the present and 5 Ma driven by obliquities ranging up to 35°, left lag deposits extending only to about 30° of the equator, which are presently desiccated [*Head et al.*, 2003] yet sufficiently thick to prevent observation of residual buried water-ice from orbit by leakage neutrons.

5. Conclusions

[11] Based on the foregoing arguments, the full range of observations favors the supply of WEH to near-equatorial surface soils through the atmosphere rather than through a subsurface water table. However, these observations and their rationale are qualitative only. They need to be validated by quantitative GCM simulations coupled with laboratory measurements of the dehydration/rehydration rates of many different hydrous minerals at Martian conditions, and of water-vapor transport, deposition, and retention in possible soil stratigraphies. Specifically, are reaction rates sufficiently rapid to follow climate variations thought to change in response to variations in the orbital elements of Mars, which occur on a 50 to 100 thousand year time period [*Laskar et al.*, 2004]? Regardless, we cannot rule out a combination of both an atmospheric and subsurface moisture supply that may depend on geographic location. It is also possible that near-surface water ice is isolated from rapid diffusive exchange with the atmosphere by relatively impermeable sublimation residues, such as those seen in parts of the Antarctic Dry Valleys [*Marchant et al.*, 2003]. If also present within the upper few tens of cm of the surface, then such deposits could preserve near-surface water ice that is predicted to form at more equatorial latitudes during periods of higher obliquity in earlier epochs [e.g., *Mellon and Jakosky*, 1995; *Mischna et al.*, 2003].

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