SECLAR RETENTION OF TROPICAL GROUND ICE ON MARS. R.E. Grimm1, K.P. Harrison2, M.R. Kirchoff2, and D.E. Stillman1. 1Southwest Research Institute, 1050 Walnut St. #300, Boulder, CO 80302 (grimm@boulder.swri.edu), 2Consultant, Denver, CO.

Introduction. Mars has been extremely efficient at retarding sublimation loss of subsurface H2O. Adapting a new three-reservoir model for D/H evolution [1], we calculate loss of 20-80 m Global Equivalent Layer (GEL) of H2O since the early Hesperian: the portion lost during the Amazonian may be 20 m or less. The 5-km onset diameter of layered-ejecta (formerly rampart) craters at low latitudes indicates depths to ice of 300-400 m [2]: some of these craters appear to be only a few hundred Myr old [3], suggesting that tropical ice today may be found at depths of a few hundred meters, at least in places. The inferred decrease of depth to ice with increasing latitude integrates to loss ~20 m GEL since deep ground ice stabilized. Numerical modeling shows that loss is slowed by (in priority order): (1) higher obliquity, (2) smaller initial H2O inventory or near-surface porosity, (3) smaller heat flux, and (4) smaller pore radius. The second factor is actually an effect of higher thermal conductivity at lower porosity. We suggest that the restricted pore volume and size are consequences of mineralization following climatic shutoff of a hydrologic cycle on Mars. The bottom of the cryosphere must still be saturated with ice today in order to prevent massive escape [4], which in turn implies that underlying groundwater exists in contact with the cryosphere.

D/H Constraints on H2O Loss. The classical Rayleigh-distillation model of a near-surface H2O reservoir that exchanges with an escapable atmosphere yields only the fractional reservoir loss, which was inferred to be large [5]. However, the absolute loss is derivable in a model that includes a third, unexchangeable reservoir that simply losses H2O to the exchangeable ice and atmosphere [1]. Taking initial D/H enrichment 2-3, atmospheric D/H enrichment 4-7, atmosphere-to-space fractionation factor 0.016-0.33, atmosphere-to-ground fractionation factor 1-1.35, and thickness of the exchangeable H2O layer 10-30 m, we find that 50% of the computed losses lie within 20-80 m GEL. This implies that only a small fraction of the anticipated total storage capacity of Mars’ crust (hundreds of meters GEL [6]) has escaped since “deep,” unexchangeable H2O was emplaced, presumably in the Hesperian. Because the initial D/H enrichments still reflect rocks that have interacted with abundant water [7,8], loss may be biased early, so that the escape after “lockdown” may be much smaller, perhaps 10-20 m GEL. Losses of just a few tens of m GEL are consistent with hydrodynamic escape models [9] and further such constraints may follow from the MAVEN mission [10].

Ice-Table Constraints on H2O Loss. Layered (fluidized) impact crater ejecta blankets on Mars have long been attributed to mobilization of subsurface H2O [11]. From an initial sample of 20 single-layered ejecta (SLE) craters, crater counts on the ejecta blankets of 5 yield age upper bounds <1 Ga (300-Ma median including alternative chronologies) [3]. Ultimately we will analyze 200 SLE sites, but these initial results point to the possibility that SLE craters may be forming up to the present, and so their H2O source may be contemporaneous. A minimum diameter ~5 km for layerd-ejecta craters implies a depth to ice of 300-400 m in the tropics [2]. Our numerical models for sublimation loss (see below) indicate that a Gaussian function with σ=30° is a reasonable representation of ice-table depth as a function of latitude. Because only a fraction of impact craters are SLE, however, the ice table at low latitude is likely to be spatially heterogeneous around this latitudinal variation (another objective of our 200-crater study). For 5-10% porosity (see below) and 300-600 m depth-to-ice at the equator, the sublimation loss is 8-32 m GEL. This is in the same range as the D/H losses (inferred above) since any hydrological cycle on Mars ended.

Together, the D/H and ice-table constraints indicate that loss of H2O on Mars in the Hesperian-Amazinian is entirely attributable to sublimation of tropical ground ice to depths of several hundred meters.

H2O Transport Model. We used the computer code MarsFlo [4,12], a three-phase simulator for water migration in partially frozen porous media. Conservation of H2O (as ice, liquid and vapor) and CO2 (in the gas phase and dissolved in liquid water) are coupled to a heat transport equation. Multiphase flows are described by generalizations of Darcy’s Law and the van Genuchten relative permeability and capillary pressure relationships. Classical binary diffusion and Knudsen flow describe the gas-phase diffusive transport of H2O and CO2 [13,14]. Diffusion coefficients are calculated from temperature, pressure, and tortuosity based on the local gas content and porosity.

The model domain is a 2D cross-section of a spherical shell extending from equator to pole and to a depth of 20 km. The 2D formulation and crustal-scale depth allow for lateral groundwater flow if suitable forcing develops. This was an important feature in our early models [4] but the D/H and ice-table constraints restrict allowable loss so much that only vertical vapor diffusion is important. The vertical discretization varies from 5 to 1000 m and the horizontal discretization is 5°. The surface boundary conditions are latitude-
obliquity dependent surface temperature and obliquity-dependent H₂O vapor pressure [15].

The model starts with an abrupt transition at 3 Ga from a denser and warmer atmosphere to the present cold and dry conditions. Heat flow q declines with time [16] to a value that is presently ~60% chondritic (14.4 mWm⁻²) [17]; variations span 50-100% chondritic heat production.

Initial pore volumes are taken to be \( V_0 = 560 \text{ m} \) and 180 m GEL. The baseline configuration of the 560-m model adopts surface porosity \( \phi_0 = 0.2 \) and exponential scale height \( \delta = 2.8 \text{ km} \) [6]; whereas \( \phi_0 = 0.067 \) for the 180-m model. In a series of parameter sweeps, \( \phi_0 \) and \( \delta \) were varied such that GEL remained constant. In the baseline configuration, pore radius \( r_p \) is 10 \( \mu \text{m} \), tortuosity \( \tau = 3 \), and obliquity \( \Theta = 25.2^\circ \), but all were varied.

Results. In the baseline model, tropical ice is completely sublimated in <1 Gyr, resulting in complete groundwater evaporation [4,18] and loss >300 m GEL. Substantial changes in at least two parameters are required to reduce the loss to 20-m GEL, e.g., 1-\( \mu \text{m} \) pore radius and \( \phi_0 = 0.06 / \delta = 11 \text{ km} \) (Fig. 1). The ice-table recession rate does not depend directly on porosity; rather, thermal conductivity increases at smaller porosity, reducing the temperature rise from the surface to the ice table and hence decreasing the vapor pressure. Losses increase roughly as \( q^{0.7}, \phi^{0.8} \), and \( V^{1.3} \). Below pore radii of a few microns, losses decrease due to the transition to Knudsen flow [6,14]. Because all of these dependencies are modest, greater change is effected by parameters that have a greater possible range. Smaller \( V_0 \) is problematic, however, in that the final ice-table depth at low latitude exceeds that inferred from SLE crater excavation.

The cryosphere does not breach in the baseline model for \( \Theta > 30^\circ \) and at higher obliquities loss still varies strongly, \( \sim \Theta^3 \). Using the average obliquity 38° reduces losses to <50 m and loss is <20 m at \( \Theta = 50^\circ \). However, Mars is not inferred to have remained in a high-obliquity state in recent eons [19]. Furthermore, in models with random obliquity variations, excursions to low \( \Theta \) accelerate sublimation to a net loss \( \sim 80 \text{ m} \) GEL.

Discussion. Obliquity is a key parameter in controlling loss, but must be supplemented by lower-than-expected \( r_p, \phi_0, \) or \( q \). Because the uncertainty in the last is less than a factor of 2, we infer that small porosity or pore radius are the other principal contributors to sublimation retardation on Mars. Both could have been reduced during the initial epoch following climate transition, when the interior was still unfrozen but cut off from a hydrologic cycle. In situ water-rock reactions will both remove a portion of the H₂O from subsequent escape and choke the pores.

Finally, the small H₂O volume lost requires that the cryosphere, at least its lower portion, is completely saturated with ice to seal in groundwater. This in turn implies that groundwater on Mars is ubiquitous and in direct contact with the cryosphere.

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![Fig. 1. Variation in sublimation loss (m GEL) as functions of heat flow and crustal porosity function, for 540-m GEL initial reservoir and small (1 \( \mu \text{m} \)) pore radius.](2592.pdf)