SNOWMELT MODEL OF THE FORMATION AND DISTRIBUTION OF SEDIMENTARY ROCKS ON MARS: THICK ATMOSPHERE NOT REQUIRED? Edwin S. Kite[1] , Michael Manga[1] and Itay Halevy[2], [1]Earth & Planetary Sciences, U.C. Berkeley (kite@berkeley.edu) [2]Geological & Planetary Sciences, Caltech.

Summary: We are developing a snowmelt model of the formation and distribution of sedimentary rocks on Mars. Initial results show good correspondence between areas where snowmelt is predicted, and areas where sedimentary rocks are observed.

Background: Geochemical and sedimentological measurements along the Opportunity traverse require overland flow of liquid water, diagenetic alteration, and probably shallow lakes [1]. Geologic and spectroscopic similarities connect this locality to a broad range of rocks in Meridiani and the Valles Marineris [2,3]. To prevent the growth of an impermeable cryosphere, the global groundwater model for the Meridiani rocks requires annually-averaged temperatures above freezing, sustained for >>10^3 years [4,5]. Early Mars climate models have great difficulty in sustaining annually-averaged temperatures above freezing [6,7]. In order to reconcile the climate models with the data, we are exploring snowmelt models in which melt-season temperatures exceed freezing, but mean annual temperatures are similar to today. As in the Antarctic Dry Valleys, perennial ice-covered lakes are possible with liquid water maintained by the seasonal input of latent heat from runoff [8]; as in the Antarctic Dry Valleys, evaporites would accumulate at the floor of such lakes.

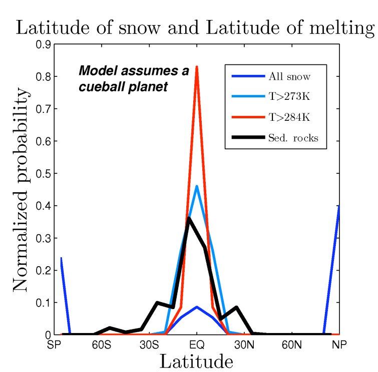
Importance of orbital diversity: We assume that at least some liquid water is required to indurate and lithify sediment [9]. With this assumption, the sedimentary rock record is a wet-pass filter that only records the wettest orbital conditions. Because Mars' chaotic orbital diffusion samples a very wide range of orbital conditions [10], and the sedimentary rock record could have accumulated in a small fraction of Mars history, modelling typical orbital conditions is neither sufficient nor appropriate. We model snowpack temperatures for all orbital conditions and latitudes and then weight the results by the age-dependent probabality distributions of orbital parameters [10].

Modeling target: Our main target is the distribution of sedimentary rocks reported by [11]. This shows an extremely strong equatorial concentration of sedimentary rocks (64% within 10° of the equator), and, independently, a strong preference of sedimentary rocks for low elevations. These effects are robust to the exclusion of Valles Marineris, and are strengthened by the exclusion of Late Hesperian and younger material.

Major model assumptions: We assume the atmosphere is thin enough that the effect of long-distance transport of energy by the atmosphere on snow temperature can be neglected. We asssume that eccentricity e, obliquity ϕ and longitude of perihelion Lp are not strongly correlated over long intervals. We neglect seasonal thermal inertia. We assume dusty snowpack albedo of 0.28, near the low end of the observed range [12,13]. We consider only horizontal, unshadowed surfaces. Our 1D column thermal model includes only the most important terms in the surface energy balance (conduction, radiation, sublimation and greenhouse forcing): we currently ignore sensible heat transfer to the atmosphere and assume zero wind and 25% surface-layer humidity. These are generally optimistic assumptions, in that they favor melting.

Eliminating cold traps: what are the "wettest" orbital conditions?: Dusty snow would melt on a flat surface at Mars' equator today. Perennial equatorial snow does not occur, however, because ice is stored in polar cold traps. Theory, observation and experiments agree [14-16] that in almost all cases, water ice is removed from the vicinity of the surface to cold traps at least as fast as orbitally-paced shifts in ice stability. We assume that snow only persists through the warmest season at locations that minimize the annual-averaged sublimation loss rate (approximately, the "coldest" locations), and we only consider the melting predictions for those locations. The optimal orbital conditions for snowmelt are then those that maximize the annual peak temperature at the locations of minimum annual-averaged sublimation rate. Neglecting topography, these conditions are always: high obliquity, moderate-to-high eccentricity, and longitude of perihelion aligned with equinox, with melting occurring at the equator and at perihelion equinox.

Results for a Mars without topography: For a Mars without topography, for 3.5 Gya solar luminosity and pCO2 = 28 mbar, the model reproduces the strong latitudinal preference shown by the data: the hottest events (most favorable for runoff) occur overwhelmingly at the equator.

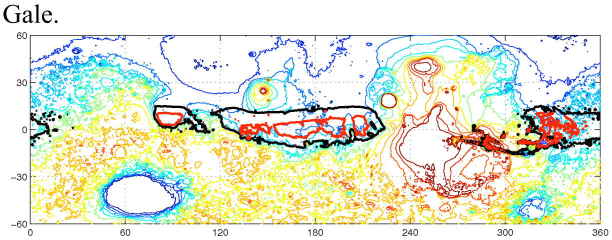


However, sedimentary rocks also have a strong longitudinal clumpiness, with sedimentary rocks found preferentially at low elevations for a given latitude band.

Pressure and the role of elevation: We are unable to find melting solutions for < ~10 mbar atmosphere on Early Mars. The vigorous free convection at these low pressures leads to strong evaporative cooling of the snowpack. (This is not relevant for thin-film melting, for which the temperature of the regolith need not be strongly affected by sublimation). Higher pressures add downgoing longwave radiation, and, at least as important, suppress evaporative cooling [17]. As noted before [18] this means that we should expect snow-filled depressions rather than snow-capped mountains on a Mars with a thin atmosphere, as observed for Amazonian deposits at high and low latitude [19,20].

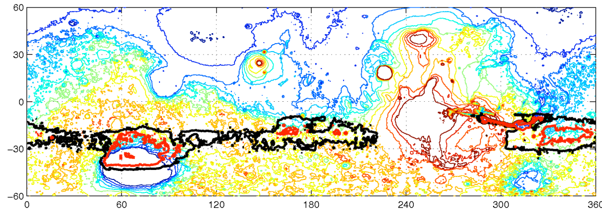
Putting this together, we interpolate our results for different pressures (equivalently, elevations) and latitudes onto MOLA topography. To do this, we need to define a percentage of planet surface area that has perennial water ice snow (today, ~1%), otherwise all the snow will go to 1 pixel. The exact locations will continue to be refined (for example, by an improved treatment of the atmosphere) and are preliminary.

Preliminary results for optimal orbital conditions: At orbital conditions that are optimal for melting on a cueball planet, the 8% contour encloses the outflow channel source regions, the floors of the Valles Marineris, and most of Meridiani Planum. It also encloses a broad region along the dichotomy boundary between Gale and Olympus Mons. The most favorable 1% of Mars for snowmelt under the optimal orbital conditions includes many regions previously identified as maxima of sedimentary rock accumulation, including MSL target Gale.



Thick red contour: 2%. Outer black contour: 8%.

Preliminary results for orbital conditions chosen to produce melting in the "alluvial fanbelt": The Terby/Hellas cluster of sedimentary rocks near 30°S indicates that snowmelt must have occurred under a wider range of orbital conditions, not just the optimal conditions. In order to reproduce this cluster, we pick $e = 0.15$, $Lp = 90°$, $\phi = 60°$. These conditions are slightly less favorable for melting than the optimal case. The 2% of Mars most favorable for perennial snow now encloses two of the three alluvial fan clusters identified by [21], plus Bakhuysen and the Terby/Hellas cluster.



Pros and cons of the snowmelt model: *Pro:* Equatorial craters are observed to cold-trap relict ice in the present epoch [20]. The snowmelt model naturally reproduces the observed equatorial concentration of sedimentary rocks, does not require a thick atmosphere nor a strong greenhouse effect on Early Mars, and does not require the majority of sedimentary rocks to have been eroded away since the Hesperian. We predict that mean annual surface temperatures at the Meridiani landing site were 50°C colder than in the global groundwater model, more consistent with climate models [7]. If Mars climate once supported annually-averaged T>273K, then it must have passed through climate conditions amenable to snowmelt en route to the present state. The converse is not true.

Con: The geochemistry of Meridiani requires significant interaction between acidic water and basalt [1]. Only small volumes of postdepositional diagenetic fluids are required [22,23], but it is not obvious that even these constraints can be met by a model where water-rock interaction is limited to snowmelt-fed streams, shallow groundwater, and ice-capped, perennial lakes. We welcome collaboration on this, and other tests.

References: [1] McLennan, S. M., & J.P. Grotzinger (2008), The sedimentary rock cycle of Mars, in Bell, J., ed. *The Martian Surface,* Cambridge University Press. [2] Bibring, J.P., et al. (2007), *Science* 317, 1206-1210, [3] Andrews-Hanna, J.C. (2010) *JGR* 115, E06002, [4] Andrews-Hanna, J.C., et al. (2007) *Nature* 446, 163-166 [5] Andrews-Hanna, J. C., & K. W. Lewis (in press) *JGR.,* doi:10.1029/2010JE003709 [6] Haberle, R.M. (1998) *JGR* 103, 28, 467–28, 479 [7] Wordsworth, R., et al. (2010), *Icarus* 210, 992-997 [8] McKay, C.P., et al. (1985), *Nature* 313, 561-562, doi:10.1038/313561a0 [9] Lewis, K. W., et al. (2008) *Science* 322 (5907), p. 1532-1535. doi: 10.1126/science.1161870. [10] Laskar, J., et al. (2004) *Icarus* 170, 343-364. [11] Malin, M.C., et al. (2010), *Mars* 5, 1-60, doi:10.1555/ mars.2010.0001 [12] Kereszturi, A., et al. (2011), *Plan. & Space Sci.* 59(1), 26-42. [13] Vincendon, M., et al. (2010), *JGR* 115, E10001, doi:10.1029/2010JE003584 [14] Schorghofer, N., & O. Aharonson (2005) *JGR.* 110, E05003. [15] Mellon, M.T., et al. (2009), *JGR* 114, E00E06, doi:10.1029/2009JE003418. [16]Hudson, T.L., & Aharonson, O. (2008) *JGR* 113, E09008, doi:10.1029/2007JE003026, 2008 [17] Hecht, M.H. (2002), *Icarus* 156, 373-386.[18] Fastook, J.L., et al (2008) *Icarus* 198, 305-317. [19] Armstrong, J.C. et al (2005), *Icarus* 174, 360-372. [20] Shean, D. E. (2010) *GRL,* 37, L24202, doi:10.1029/2010GL045181. [21] Kraal, E.R., et al. (2008), *Icarus* 194, 101-110. [22] Madden, M.E.E., et al (2009) *Geology* 37, 635-638. [23] Berger, G. (2009), *Am. Mineral.* 94, 8-9, 1279-1282.