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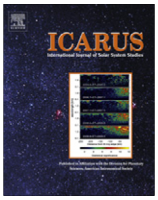

Seasonal melting and the formation of sedimentary rocks on Mars, with predictions for the Gale Crater mound

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ABSTRACT

A model for the formation and distribution of sedimentary rocks on Mars is proposed. In this model (ISEE-Mars), the rate-limiting step is supply of liquid water from seasonal melting of snow or ice. The model is run for a $O(10^2)$ mbar pure CO_2 atmosphere, dusty snow, and solar luminosity reduced by 23%. For these conditions snow melts only near the equator, when obliquity and eccentricity are high, and when perihelion occurs near equinox. These requirements for melting are satisfied by 0.01–20% of the probability distribution of Mars' past spin–orbit parameters. This fraction is small, consistent with the geologic record of metastable surface liquid water acting as a "wet-pass filter" of Mars climate history, only recording orbital conditions that permitted surface liquid water. Total melt production is sufficient to account for observed aqueous alteration. The pattern of seasonal snowmelt is integrated over all spin–orbit parameters and compared to the observed distribution of sedimentary rocks. The global distribution of snowmelt has maxima in Valles Marineris, Meridiani Planum and Gale Crater. These correspond to maxima in the sedimentary-rock distribution. Higher pressures and especially higher temperatures lead to melting over a broader range of spin–orbit parameters. The pattern of sedimentary rocks on Mars is most consistent with a model Mars paleoclimate that only rarely produced enough meltwater to precipitate aqueous cements (sulfates, carbonates, phyllosilicates and silica) and indurate sediment. This is consistent with observations suggesting that surface aqueous alteration on Mars was brief and at low water/rock ratio. The results suggest intermittency of snowmelt and long globally-dry intervals, unfavorable for past life on Mars. This model makes testable predictions for the Mars Science Laboratory *Curiosity* rover at Gale Crater's mound (Mount Sharp, Aeolis Mons). Gale Crater's mound is predicted to be a hemispheric maximum for snowmelt on Mars.

1. Introduction

The early Mars climate problem has bedevilled generations of scientists (Sagan and Mullen, 1972; Kasting, 1991; Haberle, 1998; Wordsworth et al., 2013): What allowed widespread sedimentary rocks and valley networks on a planet in a distant orbit around a faint young star? What caused that environment to deteriorate? Climate models struggle to maintain annual mean temperatures $\overline{T} \gtrsim 273$ K on early Mars (Haberle, 1998; Wordsworth et al., 2013). Seasonal melting can occur for annual maximum temperatures $T_{max} \gtrsim 273$ K, which is much easier to achieve. Therefore, seasonal melting of snow and ice is a candidate water source for surface runoff and aqueous mineralization on Mars. Surface temperatures reach ~300 K at low latitudes on today's Mars. However, seasonal melting of surface-covering, flat-lying snowpack does not occur because of (1) evaporative cooling and (2) cold-trapping of snow and ice near the poles or at depth. Reduced solar luminosity for early Mars makes melting more difficult (Squyres and Kasting, 1994).

Milankovitch cycles exert a strong control on Mars ice temperatures (Toon et al., 1980). Melting is favored when snow is darkened by dust, when evaporative cooling is reduced by increased pressure, and when the solid-state greenhouse effect is strong (Toon et al., 1980; Clow, 1987). Equatorial snowpacks should form at high obliquity (Jakosky and Carr, 1985), so melt could contribute to the observed low-latitude erosion. Orbital change shifts the locations of cold-traps in which subsurface ice is most stable (Schorghofer and Forget, 2012). Melting on steep slopes is a candidate water source for young midlatitude gullies (e.g., Costard et al., 2002; Hecht, 2002). For example, Williams et al. (2009) modeled melting of relatively clean snow overlain by a thin, dark lag deposit. They found melt rates ~1 $kg/m^2/h$ on steep slopes, and argue that this is sufficient to form gullies through either fluvial or

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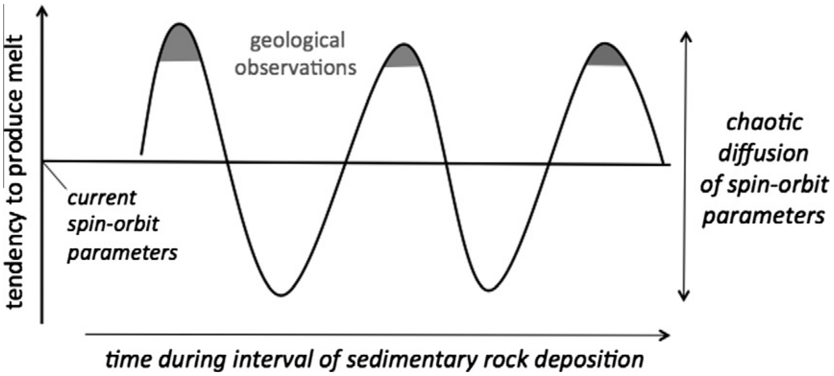

Fig. 1. Motivation for this paper. Mars underwent tens to thousands of spin–orbit oscillations during the interval of sedimentary-rock deposition. Three are shown schematically in this sketch. Mars orbital parameters vary over a wide range, resulting in a correspondingly wide range in tendency to melt. The geologic record of metastable surface liquid water is a wet-pass filter of Mars climate history. Because of the evidence for orbital pacing of sedimentary rock accumulation (Lewis et al., 2008), transient warming events are not shown, but may have been critical for generating geomorphically effective runoff – see Section 8.4.

debris-flow incision. The Laboratoire de Météorologie Dynamique (LMD) General Circulation Model (GCM) has been used to simulate the early martian hydrological cycle, including melting, for selected orbital parameters (Fastook et al., 2012; Wordsworth et al., 2013).

This paper has two purposes:

- To extend the global snowmelt models with a new model, ISEE-Mars (Ice and Snow Environment Evaluator for Mars). For the first time, ISEE-Mars integrates a model of snowpack temperatures over all spin–orbit parameters, while keeping track of cold-traps. Chaotic diffusion in the Solar System makes it almost certain that Mars' obliquity (ϕ) has ranged 20 times more widely than Earth's obliquity over billion-year periods, and that Mars' eccentricity has had a long-term variance twice that of the Earth (Touma and Wisdom, 1993; Laskar and Robutel, 1993; Laskar et al., 2004; Laskar, 2008). These wide swings cause large variations in insolation and propensity to melt (Fig. 1).
- To understand the water source for sedimentary rock formation on Mars (Malin and Edgett, 2000; Squyres et al., 2004). We focus on the hypothesis that supply of water from seasonal melting was the limiting step in the formation of sedimentary rocks on early Mars. Existing evidence for snowmelt-limited sedimentary rock formation is discussed in Section 2.

If surface liquid water availability was the only limiting factor on sedimentary rock formation, then the spatial distributions of liquid water availability and sedimentary rock detections should correspond to each other. Section 3 analyzes the global sedimentary rock distribution. In the only previous global model of sedimentary rock formation on Mars, Andrews-Hanna et al. (2007) tracked groundwater flow in a global aquifer that is recharged by a broad low-latitude belt of precipitation. Groundwater upwelling is focused in low-lying areas, generally consistent with the observed distribution of sedimentary rocks (Andrews-Hanna et al., 2010; Andrews-Hanna and Lewis, 2011). Their model assumes $\overline{T} > 273$ K, in order to avoid the development of an impermeable cryosphere. Especially in light of the Faint Young Sun predicted by standard solar models, temperatures this high may be unsustainable for the long periods of time required to form the sedimentary rocks (Haberle, 1998; Tian et al., 2010). We assume instead that liquid water is supplied from locally-derived snowmelt, rather than a deep global aquifer (Sections 4 and 5). Groundwater flow contributing to shallow diagenesis is restricted to local aquifers perched above the cryosphere. Annually-averaged and planet-averaged temperatures remain similar to today's, which reduces the required change in climate forcing from the present state. If Mars' climate once sustained $\overline{T} > 273$ K, then it must have passed through climate conditions amenable to snowmelt en route to the modern desert (McKay and Davis, 1991). The converse is not true.

Sections 3-5 emphasize the model, Sections 6-8 emphasize comparison to geologic data. ISEE-Mars predictions for different paleoclimates are compared to global data in Section 6. Section 7 makes testable predictions for Mount Sharp[1] in Gale Crater (Milliken et al., 2010; Grotzinger et al., 2012), which is the objective of the Mars Science Laboratory (MSL) *Curiosity* rover. The discussion (Section 8) compares three models for sedimentary rock formation: our snowmelt model, the global-groundwater model (Andrews-Hanna et al., 2010), and the ice-weathering model (Niles and Michalski, 2009). We conclude in Section 9. The most important results are shown in Fig. 12 and Fig. 16

The scope of our paper is forward modeling of snowmelt production as a function of (unknown) early Mars climate parameters. We do not attempt to physically model the processes running from snowmelt production to sedimentary rock formation, beyond a qualitative discussion in Sections 7 and 8. A computationally inexpensive 1D model allows us to sweep over a large parameter space. The trade-off is that 1D models cannot track the effect of topographically-forced planetary waves on the atmospheric transport of water vapor, which controls snow precipitation (Colaprete et al., 2005; Vincendon et al., 2010). Any 1D snow location prescription is therefore an idealization.

2. Snowmelt hypothesis

Liquid water is required to explain sedimentary rock texture and bulk geochemistry along the Mars Exploration Rover *Opportunity* traverse across Meridiani Planum, and there is strong evidence for extending this conclusion to other light-toned, sulfate-bearing sedimentary rocks on Mars (Bibring et al., 2007; McLennan and Grotzinger, 2008; Murchie et al., 2009a). The hypothesis in this paper is that the water source for sedimentary rocks on early Mars was seasonal melting, and that liquid water was infrequently available so that melt availability was the limiting factor in forming sedimentary rocks. "Sedimentary rocks" is used to mean units comprised of chemical precipitates or siliciclastic material cemented by chemical precipitates, usually sulfates. These are recognized from orbit as light-toned layered sedimentary deposits (Malin et al., 2010) that

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[1] Mount Sharp is the informal name of Gale's mound that is used by NASA and the MSL Project. The formal name is Aeolis Mons. We use Mount Sharp in this paper.