PUNCTUATED VOLCANISM, TRANSIENT WARMING AND GLOBAL CHANGE IN THE LATE NOACHIAN—EARLY HESPERIAN. I. Halevy[1] and J. W. Head III[2], [1]Center for Planetary Science, Weizmann Institute of Science, Israel (Itay.Halevy@Weizmann.ac.il), [2]Department of Geological Sciences, Brown University, Providence, RI, USA.

Introduction: Profound changes occurred on Mars during the transition between the late Noachian and early Hesperian epochs [1]. Among others, these changes include the formation of the majority of known valley networks and outflow channels [2-4], the deposition of massive sulfate-bearing deposits [e.g., 5, 6] and a pronounced peak in the volcanic flux, accompanied by a change in the style of volcanism [7, 8]. Suggestions that this volcanic activity maintained a warmer climate and an active hydrological cycle through the radiative effect of volcanically emitted greenhouse gases, such as CO_2 and H_2O [9], and SO_2 [10, 11], have been challenged on various accounts [12-15]. Here, by analogy to terrestrial volcanism, we stress the punctuated, rather than continuous, nature of the volcanic eruptions at the Noachian–Hesperian transition and argue that this episodicity gave rise to transient warming and hydrological activity, and to the formation of associated geological, geochemical and mineralogical records.

Punctuated Volcanism in the Late Noachian–Early Hesperian: The areal extent and thickness of Martian volcanic units has been previously used to estimate their volumes, and in combination with constraints from crater chronology, their rate of eruption [7, 16]. This reveals a pronounced peak in volcanic fluxes in the late Noachian and early Hesperian [7, 17]. Slope indicators, such as valley network and lava flow directions, suggest that $\sim 3\times 10^8$ km^3 of Tharsis magmas had been largely emplaced by the end of the Noachian [9]. Hesperian volcanism is volumetrically dominated by $\sim 3\times 10^7$ km^3 of the Hesperian Ridged Plains flood-basalt-like deposits [7, 18]. Central source complexes (paterae) are also characteristic of Hesperian volcanism and include a substantial pyroclastic component [8]. Fine-grained mantling units, interpreted to be related to pyroclastic airfalls erupted from the centers of volcanism or other, now-buried vents, are widespread [7]. Finally, volumetrically significant dikes and radial graben systems surrounding Tharsis also contribute to the total volume of eruptive magma [17, 19]. In summary, variably explosive late Noachian–early Hesperian lavas, which resurfaced >30% of the planet, were emplaced at average rates ~1 km^3 yr^{-1}. Based on estimates of the volatile content of Martian basalts, an accumulated equivalent of a few hundred millibars of CO_2 and H_2O was degassed, as well as a few tens of millibars of SO_2 and other trace gases [20].

The above rate estimates represent averages over hundreds of millions of years. Actual effusion rates of dike-like ridges closely associated with the Hesperian Ridged Plains may have been comparable to terrestrial flood basalt eruption rates, 10^5–10^6 m^3 s^{-1} [21], approximately 3,000–30,000 times the average flux. If values even an order of magnitude lower than these represent typical volcanic eruption rates, then to maintain an average flux of ~1 km^3 yr^{-1} over the late Noachian–early Hesperian, volcanic eruptions need to have occurred only ~0.3–3% of the time. Depending on a typical eruption duration, this implies that volcanic eruptions were separated by thousands or even millions of years of quiescence.

Consequences of Punctuated Volcanism: The emission of greenhouse gases associated with late Noachian–early Hesperian volcanism has been previously suggested to have warmed the surface of early Mars and allowed the existence of liquid water [e.g., 9]. However, model attempts at explaining overland flow on early Mars are complicated by the formation of CO_2 clouds, which increase the fraction of solar radiation reflected to space and cool the planet [12]. Although CO_2 clouds also scatter infrared radiation and may, under certain conditions, have a net warming effect [22], three-dimensional climate models suggest a multibar CO_2 atmosphere is required [23], in disagreement with recent estimates of volcanic outgassing on Mars [13, 14]. A long-lived, CO_2-dominated greenhouse may also be inconsistent with geomorphological and geochemical evidence for transient, rather than prolonged, aqueous conditions [2, 24, 25].

The climatic effect of atmospheric SO_2 is the topic of recent debate. Partial pressures of SO_2 between ~2 and 85 μatm were found to warm the surface by ~5–25°C in a three-dimensional model [19]. However, the negative radiative effect of sulfate aerosols, which are the main products of SO_2 photolysis and subsequent reaction under Mars' atmospheric conditions, were not examined in this study. With the effect of sulfate aerosols included in a single-column, coupled photochemical-radiative transfer model, it was shown that an increase in the atmospheric abundance of SO_2 results in cooling, rather than warming [15]. However, the photochemical model in this study provided only the concentrations of atmospheric constituents in a steady-state. That is, the time-dependent concentrations of gaseous and condensed species of interest (SO_2 and sulfate aerosols), was not investigated. The *e*-folding time of SO_2 to photolysis and oxidation following a volcanic eruption has been found in another photochemical study to be hundreds of years [26]. Two implications are that for a single, strong volcanic episode *i)* the full negative radiative effect of sulfate aerosols develops only after tens to hundreds of years, and *ii)* depending on the relative dynamics of SO_2 and sulfate aerosol removal from the atmosphere, the maximal achievable cooling effect may never be enough to overcome the warming effect of SO_2.

We envision phases of late Noachian–early Hesperian volcanism, during which large volumes of lava were erupted at high rates, punctuated by long intervals of quiescence. Between these phases of punctuated volcanism, the climate would be cold and dry, in accordance with the apparent inability of a moderately thick CO_2-dominated greenhouse to maintain mild conditions on the early Martian surface [12, 23]. Water would be mostly locked in ice at and beneath the surface. Low concentrations of SO_2 (ppb or less) and sulfate aerosols would perhaps be maintained in a steady state by the quiescent volcanic outgassing flux.

During phases of punctuated volcanism, the background atmospheric steady state would be episodically perturbed by the emission of large amounts of CO_2, H_2O and SO_2 (Fig. 1). The CO_2 added to an atmosphere that was already strongly absorptive in the CO_2 bands would have little effect on radiative transfer and climate. The H_2O would partition largely into condensed surface reservoirs with relatively little residing in the atmosphere, depending on the climate during and immediately after the eruption. The SO_2 emitted during these phases of punctuated volcanism would initially accumulate in the atmosphere. Based on the lifetime of SO_2 in atmospheric chemistry models of volcanic eruption into the Martian atmosphere [26, 27], it would take decades for an appreciable fraction of the SO_2 to be converted to sulfate aerosols. During these decades, the surface could be warmed by as much as 25°C [19], perhaps not enough for above-freezing mean annual surface temperatures, but enough to explain the predominance of lower-latitude valley networks [17]. We note that removal processes for sulfate aerosols would continue to operate during this time, perhaps lengthening the duration of net warming.

If a volcanic episode persisted, the atmosphere would approach a steady state in which higher SO_2 concentrations were accompanied by high concentrations of sulfate aerosols (Fig. 1). The net cooling effect would plunge the planet back into subfreezing and dry conditions [15]. Once the phase of punctuated volcanism ended, irrespective of whether or not a new steady state was reached, the SO_2 would be removed from the atmosphere within tens to hundreds of years and the atmosphere would return to its background steady state. Thus, the duration of warm climatic conditions is bounded by either the lifetime of SO_2 or the timescale

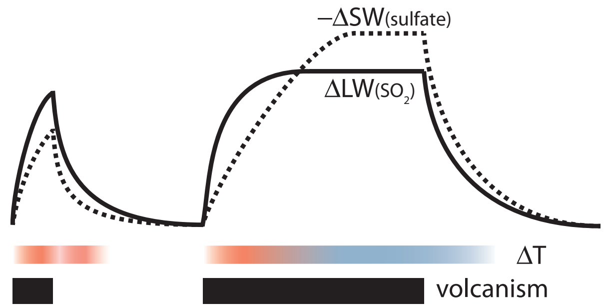

Fig. 1: Schematic effects of punctuated volcanism. Black bars denote eruptive pulses. The solid and broken curves show radiative forcing by SO_2 and sulfate aerosols, respectively. The color bars show the net climatic effect (red, warming; blue cooling; white, cold equilibrium conditions).

to establishment of a new steady state in which cooling by sulfate aerosols cancels out (or exceeds) the warming by SO_2. We estimate that in either case, within 200–300 years at most and possibly much less, the atmosphere would return to a cold and dry state.

Consistency with the Geological Record: The short-lived nature of warming provided by phases of punctuated volcanism is consistent with evidence for transient episodes of liquid water stability at the surface of early Mars, rather than sustained, long-term stability [e.g., 2, 17, 24, 25] and has implications for the hydrological system and cycle [28]. Additionally, given the rate of neutralization of sulfuric acid by chemical weathering [29], evidence for acidic conditions on the surface of Mars [30] is consistent with the rapid production and deposition of sulfuric acid, during brief intervals of volcanic activity. Finally, the occurrence of massive sulfate deposits [5, 6] is also consistent with rapid supply of sulfate.

References: [1] Carr M. and Head J. (2010), *EPSL, 294*, 185. [2] Fassett C. and Head J. (2008), *Icarus, 195,* 61. [3] Fassett C. and Head J. (2008), *Icarus, 198,* 37. [4] Hynek B. et al. (2010), *JGR, 115*, E09008. [5] Gendrin A. et al. (2005), *Science, 307*, 1587. [6] Bibring J.-P. et al. (2006), *Science, 312*, 400. [7] Tanaka K. et al. (1992), in *Mars*, Arizona, 11. [8] Greeley R. and Spudis P. (1981), *Rev Geophys Space Phys, 19*, 13. [9] Phillips R. et al. (2001), *Science, 291*, 2587. [10] Postawko S. and Kuhn W. (1986), *JGR, 91*, D431. [11] Halevy I. et al. (2007), *Science, 318*, 1903. [12] Kasting J. (1991), *Icarus, 94*, 1. [13] Hirschmann M. and Withers A. (2008), *EPSL, 270,* 147. [14] Grott M. et al. (2011), *EPSL, 308*, 391. [15] Tian F. et al (2010), *EPSL, 295*, 412. [16] Hartmann W. and Neukum G. (2001), *Space Sci Rev, 96*, 165. [17] Head J. and Wilson L. (2011) *LPS XLII*, abstract #1214. [18] Head et al. (2002), *JGR, 107*, 5004. [19] Johnson S. et al. (2008), *JGR, 113*, E08005. [20] Craddock R. and Greeley R. (2009), *Icarus, 204*, 512. [21] Head J. et al. (2006), *Geology, 34*, 285. [22] Forget F. and Pierrehumbert R. (1997), *Science, 278*, 1273. [23] Wordsworth, R. et al. (2011), *4th Mars Atmosphere Workshop*. [24] Tosca N. and Knoll A. (2009), *EPSL, 286*, 379. [25] Halevy I. et al. (2011), *PNAS, 108*, 16895. [26] Johnson S. et al. (2009), *JGR, 114*, E11011. [27] Wong A.-S. et al (2003), *JGR, 108*, E45026. [28] Head, J. (2012) *LPS XLIII*, this mtg. [29] Tosca N. et al. (2004), *JGR, 109*, E05003. [30] Hurowitz J. and McLennan S. (2007), *EPSL, 260*, 432.