CLIMATIC EFFECTS OF PUNCTUATED VOLCANISM ON EARLY MARS. 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: The geological record of Mars shows a pronounced peak in volcanic activity during the transition between the late Noachian and early Hesperian epochs [1]. This peak appears coeval with profound climatic and chemical changes in the surface environment, including the formation of the majority of known valley networks [2-4] and the deposition of massive sulfate-bearing deposits [5]. Suggestions that volcanism maintained a warmer climate and an active hydrological cycle through the radiative effect of volcanically emitted greenhouse gases, such as CO_2, H_2O and SO_2 [6-8], have been challenged on various accounts [9-11]. We consider two previously neglected phenomena: *i)* the punctuated, rather than continuous, nature of volcanic eruptions, and *ii)* the role of preexisting dust grains and volcanic ash as condensation nuclei for sulfuric acid. We suggest that the episodicity of eruption and the timescale for development of a sulfuric acid coating on dust grains resulted in transient warming and hydrological activity, and the formation of associated geological and geochemical records.

Punctuated Volcanism on Early Mars: Geological mapping and crater chronology reveal a major peak in volcanic activity in the late Noachian and early Hesperian, when volcanic units resurfaced >30% of the planet and were emplaced at long-term average rates ~1 $km^3\ yr^{-1}$ [1, 12, 13]. 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 $m^3\ s^{-1}$ [14], 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 occurred only ~0.3–3% of the time. Depending on a typical eruption duration, this implies that eruptions were separated by ~10^2–10^5 years of quiescence.

Based on estimates of the volatile content of Martian basalts [15], an accumulated equivalent of a few hundred millibars of CO_2 and H_2O was emitted, as well as a few tens of millibars of SO_2 [16]. This has been previously suggested to have warmed the surface of early Mars enough for the existence of liquid water [6-8]. 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 [9]. Although CO_2 clouds also scatter infrared radiation and may, under certain conditions, have a net warming effect [17], three-dimensional climate models suggest a multibar CO_2 atmosphere is required [18], in disagreement with recent estimates of volcanic outgassing on Mars [10]. A long-lived, CO_2-dominated greenhouse may also be inconsistent with evidence for transient, rather than prolonged, aqueous conditions [2, 19, 20].

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 [15]. 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. With the effect of pure 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, at the atmospheric steady state [11]. The time-dependent concentrations of gaseous and condensed species of climatic interest (SO_2 and sulfate aerosols) during a volcanic eruption was not investigated. A SO_2 *e*-folding time to photolysis and oxidation of several hundred years [21], implies that for a single, strong volcanic episode *i)* the full cooling effect of sulfate aerosols may develop 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 exceed warming by SO_2.

In addition to the dynamic effects above, the microphysics of sulfate aerosol nucleation and growth are important. Homogeneous nucleation is much slower than condensation onto preexisting nuclei and requires higher degrees of supersaturation. Indeed, under all but the cleanest atmospheric conditions, deposition and condensation of H_2SO_4 onto preexisting nuclei prevents homogeneous nucleation from occurring [22]. Unlike pure H_2SO_4 aerosols, H_2SO_4-coated mineral grains become efficient scatterers of visible radiation only when the coating thickness approaches the radius of the dust nucleus (Fig. 1A). At infrared wavelengths, lensing by the H_2SO_4 coating increases absorption by the aerosols over a spectral range complementary to absorption by CO_2 (Fig. 1B). Thus, with attenuated scattering efficiency at visible wavelengths and increased infrared absorption by aerosols, and including the strong greenhouse effect by gaseous SO_2, volcanic eruptions on early Mars may have had a net warming effect even at the atmospheric steady state. Whether the atmosphere reached this steady state would depend on the duration of the volcanic episode.

Modeling Punctuated Volcanism: To investigate the time-dependent effect of volcanic outgassing into

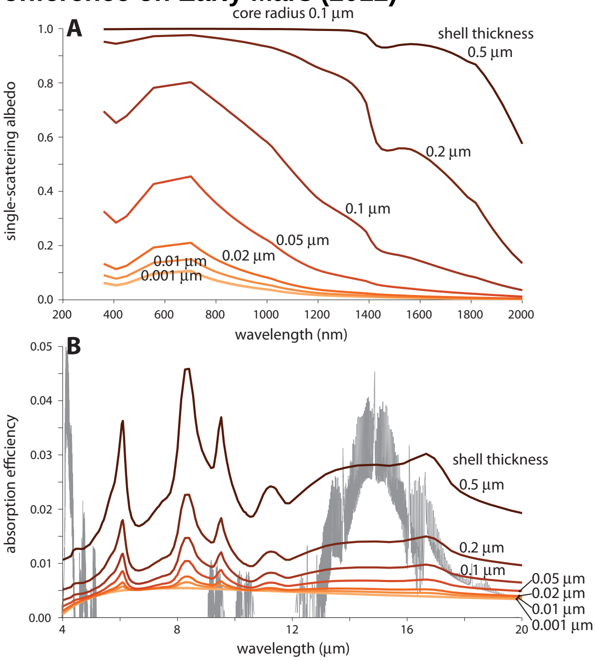

Fig. 1: The optical properties of Mars dust coated by a sulfuric acid solution shell. (**A**) Single-scattering albedo at visible wavelengths. (**B**) Absorption at infrared wavelengths.

the early Martian atmosphere, we developed a dynamic aerosol model. The model includes aerosol nucleation, growth or evaporation, coagulation, transport and lofting of fresh dust. Instead of a full photochemical model, we parameterize SO_2 loss and H_2SO_4 production using published *e*-folding times [21]. We simulate the time-evolution of atmospheric concentrations of SO_2 and H_2SO_4 and of coated, uncoated and pure H_2SO_4 particles during a volcanic eruption. We then use these results in a radiative transfer model to assess the sign and magnitude of radiative forcing provided by the combined effects of greenhouse gases and aerosols. Preliminary results indicate that a rapid rise in SO_2 levels, accompanied by a gradual coating of preexisting mineral dust and volcanic ash, result in net positive radiative forcing during the early eruptive phase.

Climatic Implications: Phases of late Noachian–early Hesperian volcanism, during which large volumes of lava were erupted at high rates, were likely punctuated by long intervals of quiescence. Between these phases of active 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 [9, 18]. Atmospheric dust concentrations under these conditions were likely comparable to the present day. Water would be mostly locked in ice at and beneath the surface. Low concentrations of SO_2 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,

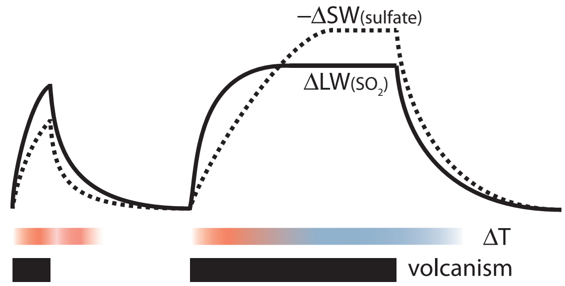

Fig. 2: Schematic effects of punctuated volcanism. Black bars denote eruptive pulses. The solid and broken curves show radiative forcing by SO_2 and sulfate aerosols, respectively. The color bars show the net climatic effect (red, warming; blue, cooling; white, cold equilibrium conditions).

H_2O and SO_2 (Fig. 2). The SO_2 emitted during these phases of punctuated volcanism would initially accumulate in the atmosphere and then be gradually converted into H_2SO_4. During this time, the surface could be warmed by as much as 25°C [15], perhaps not enough for above-freezing mean annual surface temperatures, but enough to explain the predominance of lower-latitude valley networks.

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. 2). The net radiative effect would depend on the relative rates of H_2SO_4 condensation onto preexisting dust, H_2SO_4 homogeneous nucleation and lofting of fresh, uncoated dust. Once the eruptive phase ended, irrespective of whether or not a new steady state was reached, the SO_2 would be lost from the atmosphere within decades and the atmosphere would return to its cold, dry state. Thus, the duration of warm climatic conditions is bounded by either the lifetime of SO_2 or the timescale 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, the atmosphere would return to a cold and dry state, consistent with evidence for transient, rather than sustained, episodes of liquid water stability at the early Martian surface [e.g., 2, 14, 19, 20].

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