BASALTIC PLINIAN ERUPTIONS ON MARS: UPDATED MODELS OF CO-ERUPTED TEPHRA, H_2O, SO_2, S_2, H_2S AND PRECIPITATION OF H_2SO_4.

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1. Basic Issues: The current *low atmospheric pressure* on Mars, coupled with the *acceleration due to gravity being ~38% that of Earth*, have predictable consequences [1, 2]. Magma volatile solubility is pressure-dependent, so magma erupting under present conditions on Mars will exsolve more of its volatiles than the same magma on Earth. The *volatiles will expand more*, releasing more energy and essentially *guaranteeing magma fragmentation and basaltic plinian explosive activity*. *Pyroclasts will be smaller* than on Earth and will be *ejected at greater speeds* into eruption plumes. The largest martian volcanoes extend vertically over ~2 scale heights of the atmosphere, so amounts of volatiles released in explosive activity will have been different for lowland and shield volcano summit eruptions.

2. Magma Volatiles: Early studies [1, 2] assumed that, as on Earth, water and CO_2 were the commonest magmatic volatiles on Mars. Newer work [3] shows that, relative to CO_2 and CO, the proportions of SO_2, S_2 and H_2S released from martian magmas increase dramatically as the atmospheric pressure decreases through the range 10 bars to 10 mbars (Fig. 1). Water first increases and then decreases at the lowest pressures. Given that martian atmospheric pressure could have been at least a few bars early in the planet's history [4], *atmosphere loss to present levels must have enormously increased the proportion of sulfur (see Fig. 2) released by eruptions, influencing the reactions between volcanic gases and surface rocks*. We treat elsewhere [5] the chemical formation of sulfuric acid and sulfates. Here we focus on the volcanic input to the process.

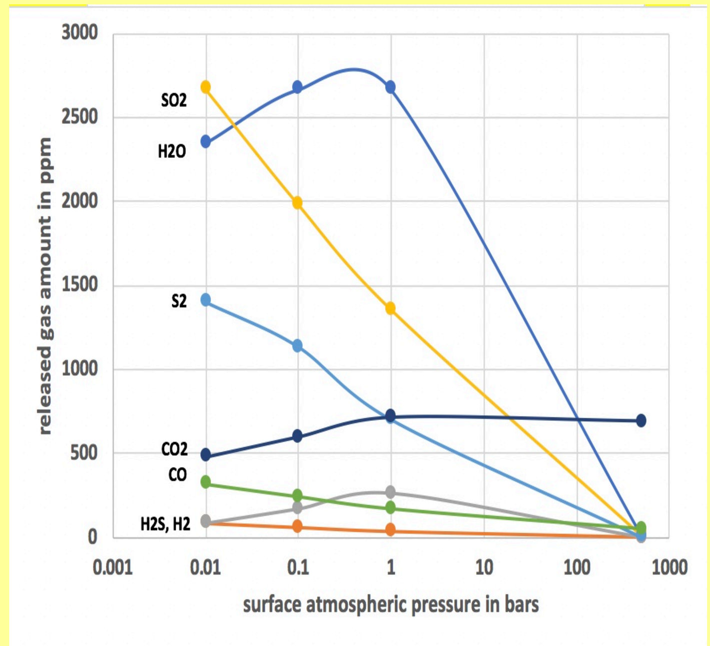

Figure 1. Volatile release from martian magma as a function of pressure.

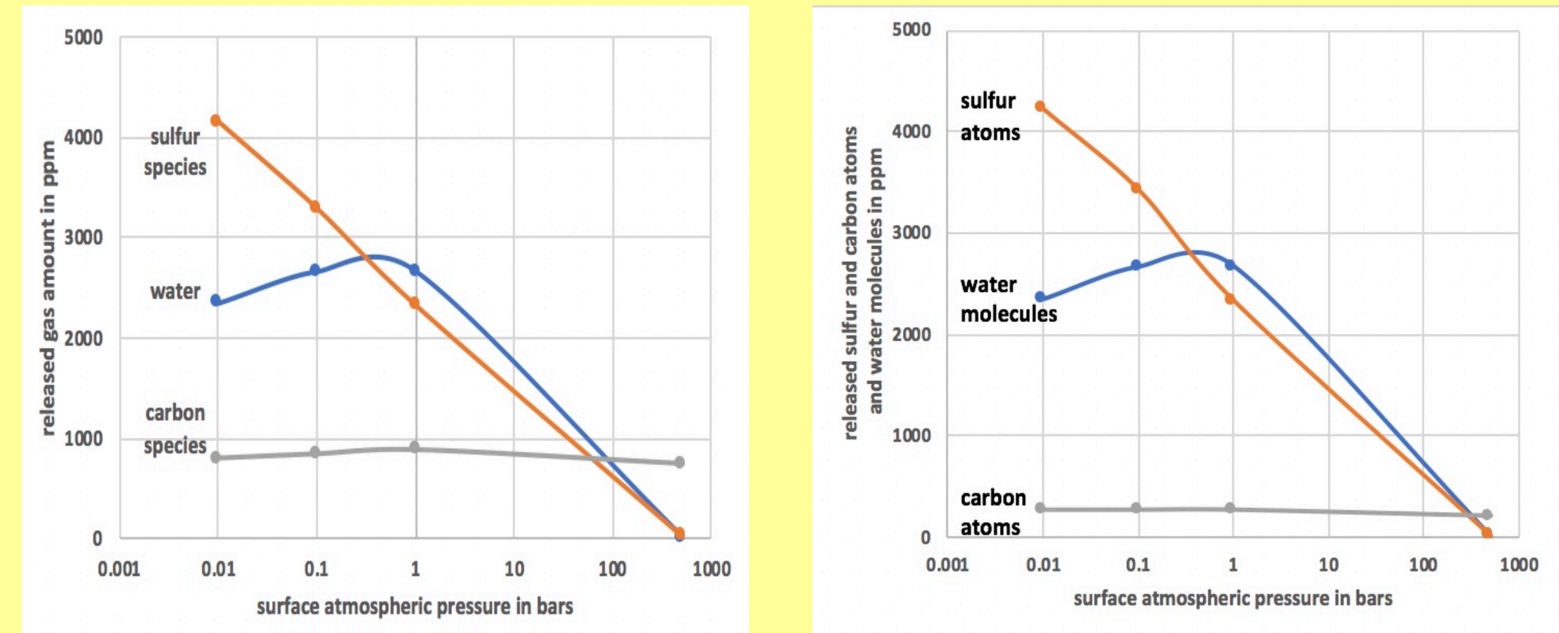

Figure 2. Major volatiles released from martian magma expressed in terms of species (left) and atoms (right).

3. Dynamic Issues: Partial melt segregating into growing dikes moves at ~ meters/year [6] in the mantle. Mafic magma in dikes connected to the surface flows at ~0.1 m/s at depth and gas exsolution and expansion (see Fig. 3) at depths <~3 km increase this to ~1 m/s, [7]. After magma fragmentation at depths ~200 m, the speed of gas and pyroclasts increases to 10s of m/s at the vent [7]. Gas release and expansion is pressure-dependent, and magma pressure approximates lithostatic pressure [8], in turn proportional to depth and acceleration due to gravity, ~38% that on Earth. Thus, all the processes involving subsurface volatile release and expansion take place over vertical distances typically 1/0.38 = ~2.6 times greater on Mars than Earth but at similar speeds until the magma approaches very close to the surface and "sees" the low atmospheric pressure. *Thus, the time scale for geochemical interactions is at least twice as long on Mars. Thermodynamic equilibrium is therefore likely.*

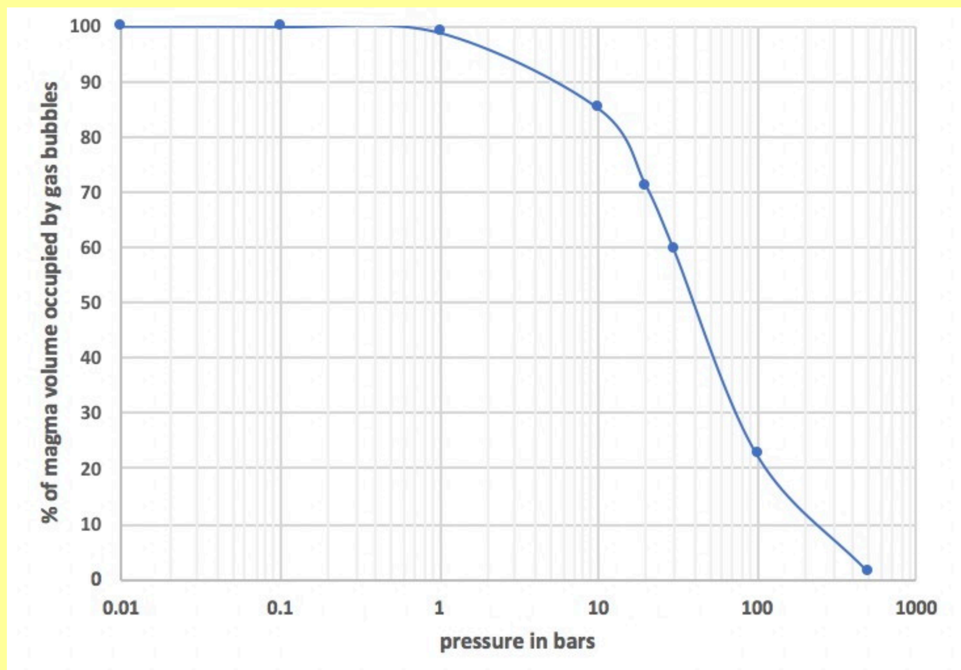

Figure 3: Volume fraction of Mars magma consisting of gas bubbles as a function of pressure.

4. Pyroclast Grain Sizes: The size distribution of clasts from explosive eruptions depends on the depth and pressure at which volatile release begins, the depth at which close packing of bubbles causes the onset of fragmentation, and the atmospheric pressure which dictates when all bubble expansion stops. Using [1] and [9] we estimate that, for the gas species in Fig. 1, *basaltic pyroclast sizes will mainly lie between 10 μm and 5 mm on Mars* (Fig. 4). The corresponding ranges are 10 μm to 200 mm for the Earth and 10 μm to 2 mm for the Moon. Assuming Gaussian particle size distributions, *the smaller range of clast sizes on Mars means that relatively more clasts are present and leads to about a three-fold greater pyroclast surface area available for volatile condensation on Mars than Earth.*

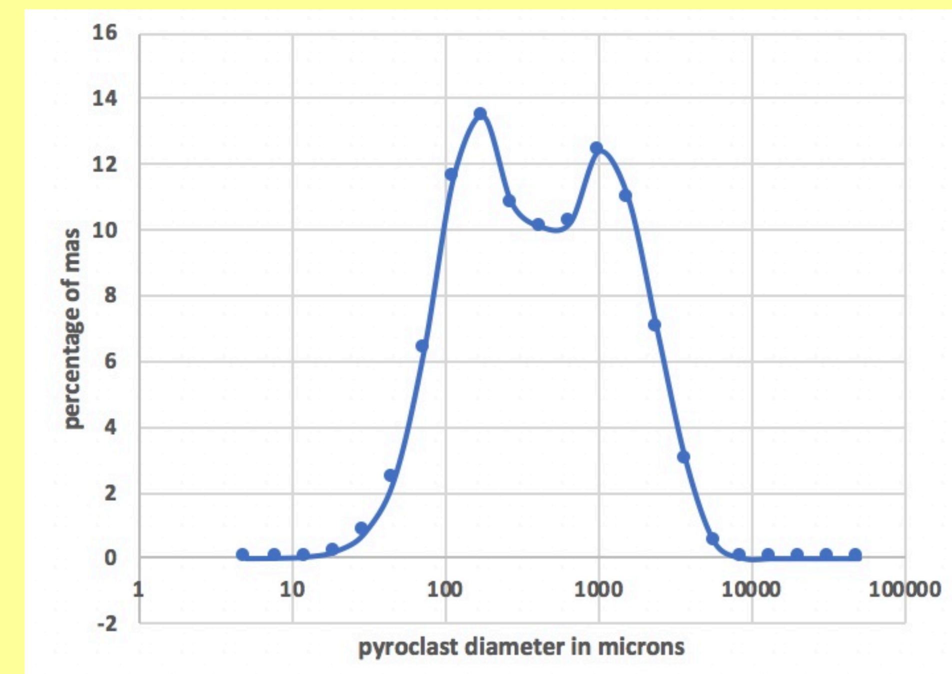

Figure 4. Predicted mass distribution of basaltic pyroclasts in explosive eruptions on Mars.

5. Pyroclast Dispersal From Eruption Plumes: Above ~20 km height in the current Mars atmosphere, gas densities are so low that atmosphere entrainment become very inefficient, the normal rule (plume height) $\propto$ (erupted mass flux)$^{1/4}$ [10] no longer applies, so convecting eruption plumes are not likely to exceed this height on Mars [11]. The mass flux required to reach this height is ~10^6 kg s^{-1} (300 m^3 s^{-1} dense rock equivalent), 10 times smaller than basaltic plinian eruptions rates seen on Earth. *The lower gravity on Mars should lead to magma eruption rates being systematically larger than on Earth by a factor of 5* [1], so almost all explosive eruptions on Mars in current atmospheric conditions should produce plumes reaching ~20 km height (Fig 5.). Large (~5 mm) clasts will take 4-5 minutes to fall within ~20 km of the vent but small (20 μm) clasts falling at ~0.01 m s^{-1} in ~20 m/s winds could travel 40,000 km, twice around the planet. *In earlier, higher-pressure, denser martian atmospheres, rise heights of low mass-flux plumes would have been smaller, and heights of high mass-flux plumes would have been greater (Fig. 5). Pyroclast grainsize distributions would have been coarser, reducing the pyroclast surface area available for chemical reactions.*

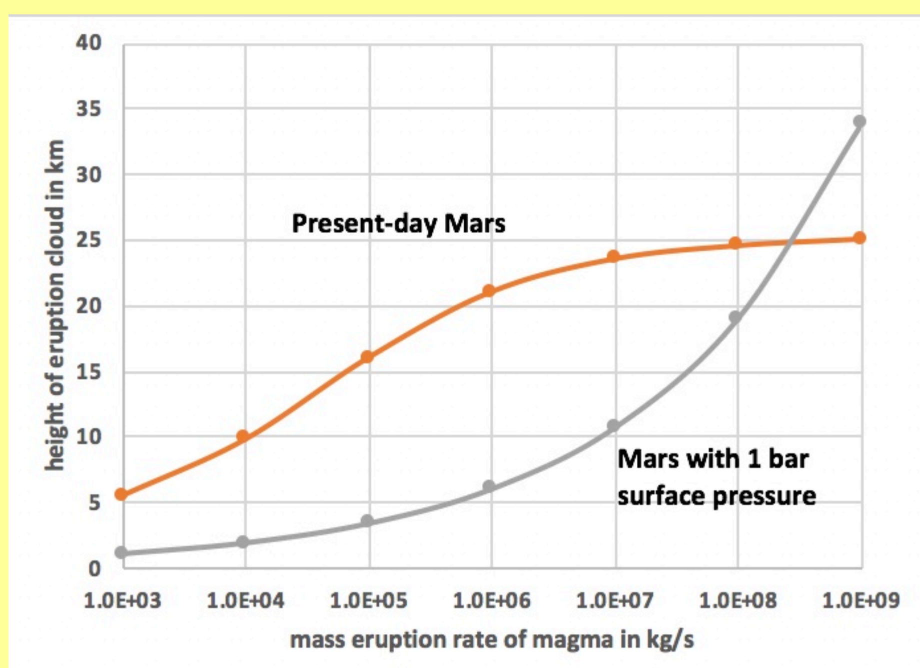

Figure 5. Rise heights of martian eruption plumes under current and ancient atmospheric pressures.

6. Results: Chemical Consequences of Atmosphere Evolution: *The most important result of atmospheric pressure reduction with time on Mars is the increase in the proportion of sulfur compounds in volcanic gases and the potential for the formation of acid-rich pyroclast layers, especially by eruptions at the summits of shield volcanoes.*

The volumes of magma discharged in typical eruptions on Mars are most easily estimated from lava flow volumes. These range from a few tens of km^3 on the flanks of Elysium Mons [12] to ~300 km^3 for a flow originating between Pavonis and Ascraeus Montes in Tharsis [13], but many of the smaller flows are parts of multi-flow eruptions. A better guide to the largest total volumes erupted in single eruptive episodes is the volumes of caldera collapse events. The individual calderas on the summit of Olympus Mons imply that dense-rock equivalent volumes of 412, 425, 518, 462, 750 and 3675 km^3 of magma left the sub-surface reservoir in discrete events [14]. In some cases this magma was intruded to form giant lateral dikes, but in other cases may have been erupted explosively at the surface.

An extreme example is Arsia Mons, where the caldera volume implies that as much as 6500 km^3 of magma may have been erupted in one event. With water and SO_2 contents of 2350 and 2667 ppm, respectively [3], *a conservative erupted magma volume of 5000 km^3 implies that as much as 2 x 10^{16} kg of sulphuric acid could be generated during a single eruption. If this accumulated on pyroclasts deposited over the surface area of the 180 km radius volcano, it would form the equivalent of a layer of concentrated liquid sulfuric acid about 0.5 m deep (e.g. [5]).*

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