EXPLOSIVE VOLCANIC ERUPTIONS INTO THE MARTIAN ATMOSPHERE

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Introduction: Volcanism has been an important geologic process for most of martian history, both because of its contributions to the surface geology as well as its contributions to the martian atmosphere. Volcanoes provide a major pathway by which volatile species are outgassed from planetary interiors, and it is likely that martian volcanoes have contributed significant amounts of H_2O, CO_2, and SO_2 to the atmosphere over geologic time [e.g., 1, 2, 3]. It is estimated that volcanism related to Tharsis alone produced 3 x 10^8 km^3 of volcanic products, which, (assuming 2% magma water content by weight) would imply a release of 1.8 x 10^{19} kg of water vapor, equivalent to a 120-m-thick global layer [1]. Using similar logic and assuming relative amounts of CO_2 and SO_2 based on Hawaiian values, it has been estimated that Tharsis volcanic activity alone would have released the equivalent of a 1.5-bar CO_2 atmosphere and a 1-bar SO_2 atmosphere [1, 2]. Simulations of atmospheres with enhanced SO_2, H_2O, and CO_2 abundances have predicted warming by up to 50-70 K for models with a pulse of SO_2 in combination with water-vapor feedbacks [4]. The total amount of warming to be expected as a result of a volcanic event is highly dependent on the timing and magnitude of the pulse: a large pulse of volcanic gases emitted into the atmosphere over a short period of time is more potent than the same volume over a longer time period [4].

While the sulfur released from passive degassing and effusive eruptions of terrestrial volcanoes per annum is greater than the sulfur released per annum from explosive volcanoes [5], explosive volcanoes often release large quantities of sulfur high into the atmosphere during relatively short time periods, meaning that explosive volcanoes can have large effects on climate [6, 7]. The release of sulfur from these types of eruptions may be greater on Mars, where sulfur solubility in magmas has been interpreted to be greater [3, 4]; low atmospheric pressure enhances sulfur exsolution from erupting magmas [8]; and explosive plinian eruptions of more sulfur-rich basaltic magmas may be more common than on Earth (where such magmas are commonly extruded effusively) [9, 10].

Changes in climate due to these eruptions may have included large relative increases in atmospheric pressure, warming of up to 50-70 K, and surface acidification, leading to conditions where liquid water flow across the surface was possible and precipitation of carbonates was suppressed [2,3,4].

In addition to contributing volatiles from the martian interior, volcanoes have been shown to interact extensively with the martian cryosphere [11, 12]. Volcano-ice interactions can result in enhanced volcanic explosivity and an additional release of water vapor [12]. Volcanoes can also be an important source of small particles, which can have a large effect on the atmosphere [13, 14].

In addition to affecting the evolution of the martian atmosphere, volcanoes have played an important role in shaping many of the geological provinces on Mars. Extensive effusive volcanism has formed many distinctive geological features on Mars, including the large Tharsis and Elysium shield volcanoes, the Hesperian ridged plains, and the young Cerberus fissure flood lavas [15, 16, 17]. Evidence of wide-spread explosive volcanism has been more difficult to identify uniquely. The martian highland paterae have been interpreted as the products of explosive volcanism based on their resemblance to terrestrial ash sheets and their friable, erodible surfaces [18, 19]. In addition, several friable layered deposits have been hypothesized to be formed of volcanic ash, such as the Medusae Fossae Formation [18, 20, 21, 22, 23]. Small-scale examples of explosive volcanic activity include pseudo-craters and smooth mantles identified near the tops of volcanoes such as Hecates Tholus and Arsia Mons [24, 25, 26].

Quantitative modeling of explosive eruptions into the martian atmosphere can aid in assessing the affects these eruptions on the atmosphere and the short-term and long-term climate of Mars. Such models can also aid in the interpretation of geological units, especially in cases where the volcanic origin of the unit is in question. Quantitative models of explosive eruptions into the martian atmosphere have been developed over the last few decades by several authors [10, 27, 28]. These models have created a sophisticated framework for determining the rise-heights of inertial and convecting plumes for a limited number of martian atmospheric profiles [10, 27].

Rapid improvement of Mars global circulation models (GCMs) in recent years have now made it possible to extract a large number of realistic climate profiles differing by season, location, altitude, and climate scenario, allowing for the first time detailed simulations of eruptions from specific volcanoes. The inclusion of chemical cycles and photochemistry in the GCM machinery also allows for the modeling of volcanically-derived water and other volatiles from their eruption into the atmosphere through their accumulation, loss, or eventual deposition on the surface.

To this end, we combine a Mars Global Circulation Model (GCM) [29] with a semi-analytical explosive eruption model for Mars [10, 27]. Here we describe several applications of this combination model, focusing on the utility of the model to contribute to the identification of units of geological interest. First we discuss the dispersal of ash from specific volcanoes and the correlation of the resultant ash blankets with putative ash deposits. Second, we discuss the theoretical dispersal of small particles by volcanic processes. Third, we model the deposition of surface ice through the eruption of water vapor from explosive volcanoes.

Methods. The explosive model [10, 26] determines the rise-height of the eruption column and the release heights for volcanic clasts of various sizes based on atmospheric profiles provided by the GCM. The GCM also provides time-dependent wind profiles which transport each particle from its point of departure from the plume to its final deposition on the surface. The GCM accepts both ash particles as well as volcanically-derived water particles as tracers (specified by their mixing ratios). Water particles are permitted to nucleate on dust particles and eventually to accumulate on the surface (if they are stable).

Friable Layered Deposits. Simulations were run from the Hesperian-aged volcano Apollinaris Patera (-8ºS, 174ºE), chosen because of its proximity to the Medusae Fossae Formation, a fine-grained and friable deposit hypothesized to be composed of pyroclastic material [20, 21, 22, 23]. Additional simulations were run from other nearby possible source volcanoes. Each simulation was run for one year. An average mass-flux for a volcanic eruption with a stable convecting plume, 10^6 kg/s, was used in the eruption model to determine the rise-height of the plume. At the point where the clasts were released into the GCM for dispersal, the mass flux was changed to 3.166×10^{10} kg/s in order to erupt the entire volume of the Medusae Fossae Formation in the course of one year [volume of the MFF]/[seconds in a martian year].

This change was made in order to simulate the effects of many short eruptions (days to months) taking place over random times of the year over hundreds of millions of years, or the lifetime of the Apollinaris volcanic center. The presence of a magnetic anomaly associated with the volcano, together with an early Hesperian surface crater-age date, would suggest a fairly long-lived period of activity for the volcanic center [29, 30, 31].

Production of Small Particles. Simulations were run from several of the martian volcanoes to determine the dispersal of small grains (~20 μm) based on theoretical estimates of grain-size distributions [10]. Thin layers of small grains are known to prevent accurate measurements by remote sensing instruments, especially in visible and near-infrared wavelengths [33]. Small particles are also important for aeolian abrasion, saltation, and the initiation of dust storms [34]. Simulations were run from Olympus Mons. As the tallest volcano on Mars, Olympus Mons has one of the greatest potentials for the wide dispersal of small grains. Simulations were run for a typical volcanic eruption with a mass flux of 10^6 kg/s and a duration of ten days. The eruption was again distributed over one martian year [10^6 kg/s]/[days in a martian year/10 days] to encompass the effects of different seasonal wind regimes.

Eruption of Water Vapor. Simulations were run from Elysium Mons modeling the explosive eruption of water vapor. A magma water content of 2% was assumed, with a mass flux of 10^6 kg/s, and a duration of ten days, as above. In this case the eruption took place during martian spring. Because ice deposits are permitted to sublime, year-long averages cannot be equated to ten-day eruptions as they were above. A simulation run continuously through one year showed that deposition and sublimation of ice remained close to steady-state.

Results.

Friable Layered Deposits. Eruptions from Apollinaris Patera result in an ash distribution that matches the distribution of the Medusae Fossae Formation fairly well (**Figure 1**). The distribution is best matched if the ash particles are of slightly lower density (700 kg/m^3, equivalent to a pumice), if the eruption was strong (high plume height), and if the fragmentation was aggresive, favoring a particle-size distribution that is weighted towards the smaller sizes. The results shown are for particles less than 160 μm. Other nearby volcanoes have much higher vents, giving them a wider dispersal. Any of these could have contributed material to the Medusae Fossae Formation. However, none of these distributions explains the preferential accumulation of material to the west of the Tharsis rise (**Figure 1**).

Production of Small Particles. Results of the Olympus Mons simulation are shown in **Figure 2**. During a single eruption, a volcano such as Olympus Mons could create and disperse very small particles over an area of thousands of square kilometers. Similar areal dispersal is observed for other volcanoes with high altitude vents, such as the Tharsis Montes and

Elysium Mons, but the particular shapes of the distributions depend on the regional winds. Most of the dispersal is concentrated towards low latitudes due to the locations of the major volcanoes. A single, moderately-sized eruption (mass flux: 10^6 kg/s) would create a layer of 20μm ash only micrometers thick; however, larger eruptions (mass flux: 10^7-10^9 kg/s) would create deposits of correspondingly larger thicknesses (hundreds of microns to tens of centimeters), depending on whether or not a convecting plume could be sustained. Repeated eruptions over hundreds of millions of years from many volcanoes would result in large accumulations of small particles, due to the relatively slow weathering processes on Mars [35].

Eruption of Water Vapor. Eruptions from Elysium Mons result in an ice deposit which is much more localized than similar ash dispersal simulations (**Figures 1, 3**). In terrestrial eruptions, both atmospheric and volcanically-derived water will nucleate as ice crystals on volcanic ash particles [36]. If the water or ice reaches the surface without subliming, it may accumulate into a deposit which is a mixture of water, ice, and ash (muddy rain) [36]. Water released during martian eruptions may also be deposited with ash, likely as ice [37]. During the simulated eruption, the water released from the volcano settles to the ground forming millimeters of ice. Much of this ice quickly sublimes away, but if it were codeposited with ash or quickly buried, it would be possible for some of it to be preserved [38]. This kind of process could contribute to the deposition of ice and the formation of water-related features where they would not be ordinarily expected based on normal atmospheric water vapor distributions.

Conclusions: An explosive volcanic model and a Mars global circulation model were combined and applied to several diverse geological problems: the formation of the friable layered deposits, specifically the Medusae Fossae Formation; the production of small particles important in the initiation of martian dust storms and the saltation and suspension of abrasive particles; and the formation of water clouds and ice deposits as a result of volcanically-derived water. The addition of the global circulation model to the explosive model aides in the modeling of specific volcanoes to solve geologically relevant questions. The ability of GCMs to track the evolution of atmospherically relevant volcanic gases expands the potential uses of explosive volcanic models to include paleoclimate scenarios.

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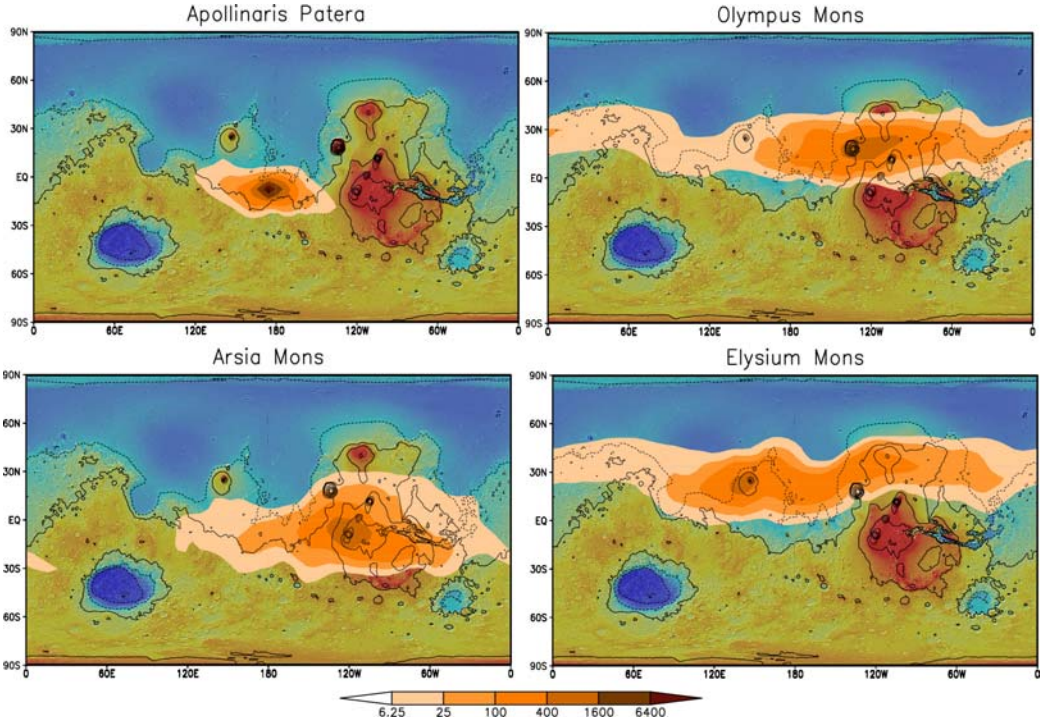

Figure 1. Simulated ash distributions erupted from Apollinaris Patera and other possible sources for the Medusae Fossae Formation. The other volcanoes produce wide-spread ash deposits, some of which overlap with the MFF (particularly the ash deposit of Arsia Mons). However, an eruption from Apollinaris Patera would deposit most of its material in the Medusae Fossae Formation, without a large amount of material deposited elsewhere. Contours are in meters (depth).

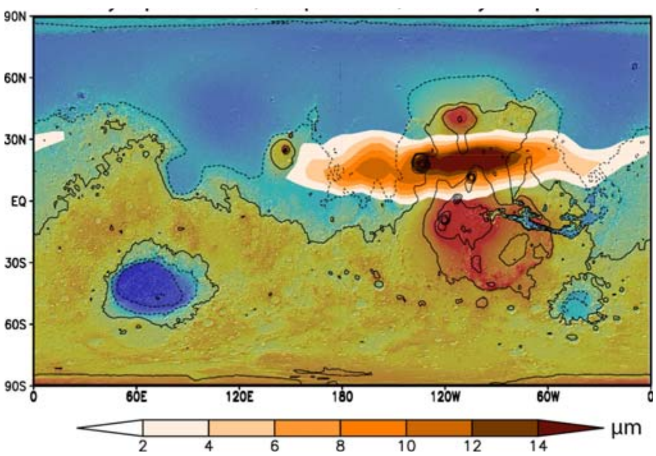

Figure 2. Following a ten day eruption of moderate mass eruption rate (10^6 kg/s) from Olympus Mons, several micrometers of small particles have accumulated for thousands of kilometers around the edifice. This eruption was averaged over a year to include wind regimes that prevail during different seasons.

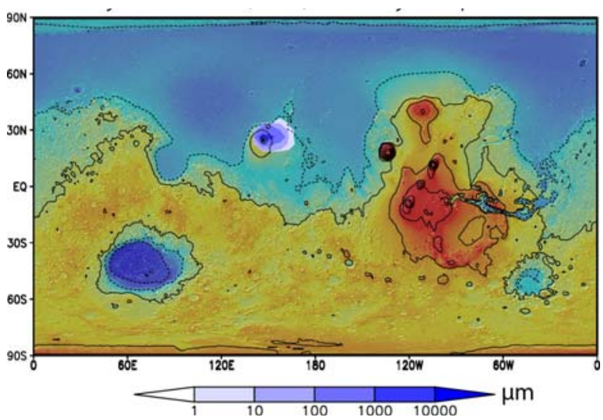

Figure 3. An eruption of water ice from Elysium Mons. The water ice tends to keep a steady state during the eruption of the volcano, subliming away rapidly after the volcano has ceased erupting. If the ice were codeposited with ash, it is possible that the ice could be protected from sublimation and would accumulate into ice-rich layers.