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# Shape of cinder cones on Mars: insight from numerical modelling of ballistic pathways

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## Abstract

Morphometric observations of Martian cinder cones [1] show that their shapes do not correspond to values previously predicted on theoretical grounds. Our study addresses this inconsistency by numerical modeling of tephra particle ejection and dispersal around the vent under Martian environmental conditions, and comparing the results with real morphologies of Martian cinder cones.

## 1. Introduction

For a long time, the evidence of small-scale monogenetic explosive eruptions on Mars was poor due to non-adequate image resolution, precluding any detailed investigations. However, theoretical considerations predicted that cones should be wider and lower on Mars than on Earth [2-4]. Recent studies have significantly improved our knowledge about these edifices and their real morphologies [e.g., 1,5]. These studies revealed inconsistencies of real observations with previously established theoretical predictions about the cone shapes [1].

Tephra particles forming cinder cones are produced by magma degassing and associated fragmentation [4]. Two main models exist to describe the exact mechanism of fragmentation [e.g. 4,6], but both models lead to the generation of a wide size range of pyroclasts that are ejected from a vent by explosive eruptions. While the finer particles are entrained in buoyant convective plumes and are transported far away from the vent by wind transport, the coarser size fractions (> ~1 cm) are mostly ejected by ballistic paths [7] to the vicinity of the vent where they forming a cinder (scoria) cone. The distribution of ejected material depends on particle size and density, initial speed, and the angle of ejection from the vent [7]. This is only valid; however, until a critical mass or volume of material is reached after which the cone flank attains the angle of repose (~30°) and avalanching of tephra takes over as the main process determining the shape of the cone. It was demonstrated by M. Kleinhans and colleagues [8] that the angle of repose depends on gravity, but nevertheless it is very similar on Earth and Mars [8]. Topographic measurements [1] show that cinder cones on Mars do not reach this angle anywhere along their flanks.

## 2. Method

Ballistic pathways of particles were calculated for a log-normal distribution of particle sizes with a peak at 4 cm and a density of 850 $kg/m^3$. They were ejected with various initial velocities (see legend in Figure 1 for details) under different ejection angles, using a gravitational acceleration of 3.71 $m/s^2$, an atmospheric pressure of 0.01 $kg/m^3$, and an atmospheric drag of 0.7). The clasts are emplaced where they land and accumulate over time without any other post-landing processes considered.

## 3. Results

A comparison of particle ejection by magma ascent and fragmentation under Martian and terrestrial conditions reveals that the distance a particle is ballistically transported away from the vent is much larger on Mars than on Earth. Therefore, the ejected material is dispersed over a much larger area on Mars, and Martian cinder cones should be wider (larger basal diameter), consistent with observations [1,5]. Consequently, the amount of material needed to build a steep cone with flank slopes attaining the angle of repose dramatically increases and is actually not reached at the observed Martian cones. Hence, it is possible to reconstruct the process of cone formation by particle ejection from the initial vent and subsequent deposition. The results of this approach are visible on Fig. 1, which shows modeled and real cross-sectional profiles of cones. The model stopped, when the maximum observed height of the real cones was reached. If the particles are ejected with an initial velocity of 46 m/s (as observed for terrestrial cinder cones [9]), a steeper and smaller cone is formed than actually observed on Mars. Such a cone with the required height would reach the angle of repose, inconsistent with observations. When the velocity is increased by a factor of two (as predicted, e.g., by [2] and [10]), the result is a broader and flatter cone, consistent with the observation that cone flank slopes on Mars stay below the angle of repose.

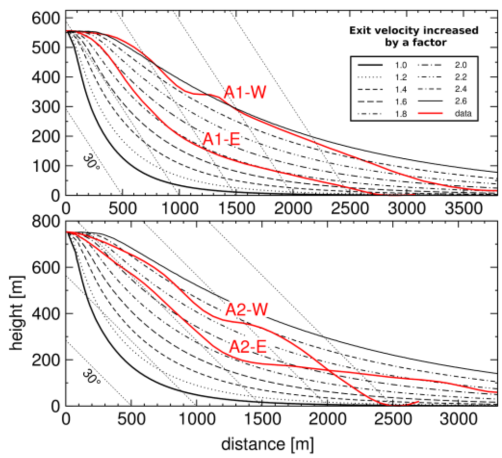


**Figure 1**: Real cone profiles (in red) of two Martian cones (upper panel: A1; lower panel: A2, each with western [“W”] and eastern [“E”] flank) in the Ulysses Colles cone field in comparison with modeled profiles (black lines; representing different ejection velocities). When exact terrestrial values on current martian environments used (black bold solid line), resulting shape is not in agreement with observations. Therefore the increasing of initial ejection velocities is necessary (dashed lines). The best fit is obtained when initial velocities were increased by factor of ~2, as predicted by [2].

## 4. Summary and Conclusions

We note that the cinder cones of Ulysses Colles do not reach the critical angle of repose because of an insufficient amount of ejected material. This is in contrast to the common situation on Earth, where the angle of repose is typically reached causing downward avalanching of scoria particles on cones flanks. The cones on Mars did not reach the angle of repose, and therefore their morphological shape preserves a record of environmental conditions at the time of eruption and hence preserves information about ejection velocities (if erosional degradation of these relatively young edifices is considered negligible). This offers an opportunity to examine basic parameters controlling cone formation by numerical modeling more deeply.

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