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Explosive volcanic eruptions on Mars: Tephra and accretionary lapilli formation, dispersal and recognition in the geologic record

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Abstract

Explosive volcanic eruptions, potentially involving large amounts of magmatic and entrained water, are thought to have been very important in the Noachian and Hesperian periods earlier in Mars history, and basaltic plinian eruptions are likely to have occurred throughout martian history. Previous treatments of explosive volcanic plumes on Mars have simply extrapolated plume models for the Earth's atmosphere to Mars. Taking account of known limitations to the applicability of this approach, which suggest that convective plumes may be capable of reaching only ~20 km height on Mars, we introduce the concept of inertial plumes, capable of carrying clasts to much greater heights and dropping them into the lower atmosphere over a wide area. Atmospheric circulation patterns guarantee wide dispersal and thick deposits of tephra resulting from both types of eruption. The presence of large amounts of water in convecting explosive eruption plumes can also lead to condensation of water on small particles and the consequent accretion of other particles as the smaller particles fall through the plume, producing accretionary lapilli. Formation of accretionary lapilli significantly alters the spatial distribution and grain sizes of pyroclastic fall deposits from those involving discrete juvenile clasts with negligible clast interactions. We model the eruption and dispersal of tephra, and the formation of accretionary lapilli on Mars under current atmospheric conditions and explore the consequences of this for the geometry and grain size of deposits formed from explosive eruption plumes. We show that explosive eruptions can produce thick widespread deposits of ash and lapilli similar to those thought to have produced mantling deposits in several regions of Mars. We develop a detailed example that shows that local hydrovolcanic explosive eruptions and solely magmatic eruptions originating from the nearby Apollinaris Patera could have emplaced tephra and accretionary lapilli in the Columbia Hills region of the Mars Exploration Rover Gusev site. If the atmospheric pressure was higher early in Mars' history than now, eruptions would have led to somewhat more extensive pyroclast dispersal than under current conditions.

Keywords: Mars; explosive eruptions; tephra; lapilli; volcanoes

1. Introduction

Volcanism has been an important process on Mars throughout its history, generally decreasing in significance as a function of time (Tanaka et al., 1992). During the last half of the history of Mars, volcanic activity has been largely centered on the Tharsis and Elysium

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regions, producing huge shield volcanoes and their associated extensive aprons of lava flows and potential basaltic plinian eruptions (e.g., Wilson and Head, 1994). Earlier in the history of Mars, some of the large volcanic edifices known as paterae (e.g., Hadriaca and Tyrrhena Paterae) were characterized by low constructs and large central craters, strongly suggesting that eruption styles were different in this early period (Greeley et al., 2000). Large expanses of fine-grained deposits mantling subjacent cratered terrain also characterized this period (e.g., Grant and Schultz, 1990; Moore, 1990; Fassett and Head, in press), and these distinctive attributes led many to interpret these early edifices and deposits as being related to specific styles of explosive volcanism that appeared to be dominant during this time, in contrast to the largely effusive nature of the later shield-building eruptions (Carr, 1973; Greeley and Spudis, 1981; Greeley et al., 2000). Higher volatile contents and/or the incorporation of groundwater into the eruptions were thought to be the major causes of the early distinctive explosive eruption style (e.g., Greeley and Crown, 1990; Crown and Greeley, 1993; Robinson et al., 1993). Numerous investigators have developed models for explosive eruptions on Mars and the emplacement of airfall and pyroclastic flow deposits (e.g., see Wilson and Head, 1994, and references therein; Kieffer, 1995; Hort and Weitz, 2001; Glaze and Baloga, 2002) and others have discussed the relationship of models and specific deposits on Mars (e.g., Hynek et al., 2003).

Early application to Mars of eruption plume models developed for the Earth suggested that such plumes should rise much higher in the atmosphere of Mars for a given mass eruption rate (Wilson and Head, 1994). However, Glaze and Baloga (2002) pointed out that some of the assumptions made in these models about the mechanism of entrainment of atmospheric gases are not justified above ~20 km in the atmosphere of Mars, so that high discharge-rate eruptions generating plumes that might have been expected to convect to much greater heights will not behave entirely as predicted. Although we recognize the uncertainties and incomplete aspects of modelling convective plumes in variable atmospheres, we will use this value of 20 km as a limiting value; we infer that, for sufficiently high magma mass fluxes and eruption speeds, explosive eruptions on Mars may instead produce structures more analogous to the umbrella-shaped plumes on Io (Cook et al., 1979; Glaze and Baloga, 2000; Cataldo et al., 2002; Geissler, 2003; Zhang et al., 2003), where gas–particle interactions are minimal except near the surface. We therefore model separately the dispersal of pyroclasts on Mars from convective *plumes* rising to heights up to ~20 km, and *inertial plumes* rising to greater heights.

Furthermore, most treatments of the formation of fall deposits from volcanic eruption plumes on Mars (e.g., Mouginis-Mark et al., 1982, 1988; Kusanagi and Matsui, 1998; Hort and Weitz, 2001) have assumed that individual clasts were transported through, and fell from, such plumes as discrete objects with negligible mutual interactions. However, it is well established that the formation of accretionary lapilli, a mechanism that allows small particles to fall much more rapidly as members of clusters than as individuals, is an important factor in determining the spatial thickness and grain size variations in fall deposits on Earth (e.g., Veitch and Woods, 2001 and references therein). We therefore also explore the nature of this process in the martian environment. We begin by exploring factors influencing the nature of all long-lived, relatively steady discharge rate explosive eruptions on Mars under current atmospheric conditions.

2. Physics of steady explosive eruptions on Mars

The nature of an explosive volcanic eruption depends most strongly on the amount of volatiles released from the magma during its ascent, the key threshold being the release of enough volatiles to ensure that the magma is disrupted into a spray of pyroclasts entrained in the liberated gas. Gas expansion as the pressure decreases is the main source of energy causing high eruption speeds. The gas expansion is accommodated by a mixture of the increase in speed of the gas–pyroclast mixture and the widening toward the surface of the conduit or fissure (Wilson and Head, 1981; Mitchell, 2005). It is likely that in the vast majority of eruptions under current martian conditions, the vent cannot flare outward toward the surface sufficiently rapidly to allow the pressure in the erupting jet of volcanic gas and entrained pyroclasts to decrease to the atmospheric pressure (e.g., Glaze and Baloga, 2002; Mitchell, 2005). Instead the eruption is choked, with the pressure in the vent being the value at which the velocity of the gas–pyroclast mixture is equal to the speed of sound in that mixture. The speed of sound, U_s, in the gas–pyroclast mixture is given with sufficient accuracy (Wilson and Head, 1981) by

$$U_s^2 = (n\ Q\ T/m)\{1 + [((1-n)\ m\ P_v)/(n\ Q\ T\rho_m)]\}^2, \tag{1}$$

where n is the exsolved mass fraction of the major volatile in the magma, here assumed to be dominated by water vapor with molecular weight m equal to 18.02 kg/kmol, Q is the universal gas constant, 8314 J kmol^{-1}