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Explosive volcanic activity on Venus: The roles of volatile contribution, degassing, and external environment

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ABSTRACT

We investigate the conditions that will promote explosive volcanic activity on Venus. Conduit processes were simulated using a steady-state, isothermal, homogeneous flow model in tandem with a degassing model. The response of exit pressure, exit velocity, and degree of volatile exsolution was explored over a range of volatile concentrations (H_2O and CO_2), magma temperatures, vent altitudes, and conduit geometries relevant to the Venusian environment. We find that the addition of CO_2 to an H_2O-driven eruption increases the final pressure, velocity, and volume fraction gas. Increasing vent elevation leads to a greater degree of magma fragmentation, due to the decrease in the final pressure at the vent, resulting in a greater likelihood of explosive activity. Increasing the magmatic temperature generates higher final pressures, greater velocities, and lower final volume fraction gas values with a correspondingly lower chance of explosive volcanism. Cross-sectionally smaller, and/or deeper, conduits were more conducive to explosive activity. Model runs show that for an explosive eruption to occur at Scathach Fluctus, at Venus' mean planetary radius (MPR), 4.5% H_2O or 3% H_2O with 3% CO_2 (from a 25 m radius conduit) would be required to initiate fragmentation; at Ma'at Mons (~9 km above MPR) only ~2% H_2O is required. A buoyant plume model was used to investigate plume behaviour. It was found that it was not possible to achieve a buoyant column from a 25 m radius conduit at Scathach Fluctus, but a buoyant column reaching up to ~20 km above the vent could be generated at Ma'at Mons with an H_2O concentration of 4.7% (at 1300 K) or a mixed volatile concentration of 3% H_2O with 3% CO_2 (at 1200 K). We also estimate the flux of volcanic gases to the lower atmosphere of Venus, should explosive volcanism occur. Model results suggest explosive activity at Scathach Fluctus would result in an H_2O flux of $\sim 10^7\ \mathrm{kg\ s^{-1}}$. Were Scathach Fluctus emplaced in a single event, our model suggests that it may have been emplaced in a period of ~15 days, supplying $1\text{–}2 \times 10^4$ Mt H_2O to the atmosphere locally. An eruption of this scale might increase local atmospheric H_2O abundance by several ppm over an area large enough to be detectable by near-infrared nightside sounding using the 1.18 μm spectral window such as that carried out by the Venus Express/VIRTIS spectrometer. Further interrogation of the VIRTIS dataset is recommended to search for ongoing volcanism on Venus.

1. Introduction

Volcanoes and their deposits are some of the most widespread and recognisable geological features in Venus' surface record (Crumpler and Aubele, 2000; Ford et al., 1993; Head et al., 1992; Ivanov and Head, 2011). Volcanic landforms include clusters of small shield volcanoes ranging from <1 km to 10s of km in diameter ('shield fields'), large volcanoes up to ~1000 km in diameter, steep-sided domes, isolated calderas not associated with an obvious edifice, and stress-induced surface deformation features known as coronae and novae (Head et al., 1992) thought to be associated with shallow magma bodies (McGovern and Solomon, 1998). The broad variety of volcanic features on Venus suggests a corresponding variety of processes responsible for their formation.

Whether or not explosive eruptions occur on Venus has been the subject of debate (e.g. Fagents and Wilson, 1995; Glaze et al., 2011; Thornhill, 1993), as the conditions affecting the physical processes of eruption on Venus are very different to those on Earth. Lava flows have been recognised globally, while pyroclastic density currents and fallout deposits are apparently rare or absent. It has proved difficult to determine the nature of these less common volcanic deposits seen in the radar imagery of Venus and confirmation of an

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explosive origin has so far mostly proved to be controversial (Campbell and Rogers, 1994; Grosfils et al., 2011; Keddie and Head, 1995; McGill, 2000). One recent exception is a proposed pyroclastic deposit known as Scathach Fluctus, identified by Ghail and Wilson (2013). This pyroclastic interpretation was arrived at via a combination of radar characteristics, flow morphology, and flow interaction with other geomorphological features.

Establishing whether explosive volcanism occurs on Venus might yield further clues concerning subsurface conditions on Venus and would better inform our understanding of atmospheric processes such as the apparent SO_2 variations detected by Pioneer Venus (Esposito, 1985), and later Venus Express (Marcq et al., 2012). In terms of atmospheric interactions, understanding the heights that explosive plumes might achieve is also key. Our study aims to better understand the eruptive behaviour of volcanoes on Venus through consideration of the factors affecting these processes.

1.1. *Explosive volcanism*

The processes resulting in terrestrial explosive volcanism have been widely documented in numerous articles on magma ascent dynamics (e.g. Papale et al., 1998; Papale and Polacci, 1999; Wilson et al., 1980; Woods, 1995) and the magma degassing behaviour that leads to it has been extensively modelled (Lesne et al., 2011; Newman and Lowenstern, 2002; Witham et al., 2012). Whether or not explosive volcanism results in a buoyant plume has also been extensively described in previous work on eruption column physics (Sparks, 1986; Valentine and Wohletz, 1989; Wilson et al., 1978; Woods, 1988, 1995; and others). A parcel of magma that decompresses sufficiently and exsolves enough of the volatile gas phase to initiate fragmentation within the conduit, either when the gas volume fraction in the mixture exceeds a critical value (Sparks, 1978), or the magma suffers brittle failure and fragments (Gonnermann and Manga, 2003; Tuffen and Dingwell, 2005), is then emitted from the vent into the overlying atmosphere as a volcanic plume, initially in a momentum-driven ‘gas thrust’ regime. The column will collapse into a fountain unless enough atmospheric gas can be entrained, heated by the clasts within the plume, expand, and become buoyant. The column is then considered to be in a buoyancy-driven ‘convective’ regime, and will continue to rise and expand until it reaches the level of neutral buoyancy. At this level, the column spreads laterally in an ‘umbrella’ region.

The first application of subaerial plume modelling under Venus conditions was carried out by Thornhill (1993); the minimum initial parameter values required for explosive activity were identified by applying the model of Woods (1988) to Venusian environmental conditions. A case study by Robinson et al. (1995) applied the same model to Ma’at Mons and suggested that explosive volcanism could have been responsible for the elevated atmospheric SO_2 concentrations detected by Pioneer Venus (Esposito, 1985). A further suite of studies estimated the overall plume height attainable by explosive volcanic eruption columns over a range of boundary conditions similar to those chosen for this study (Glaze, 1999), and with circular vs. linear vent geometries (Glaze et al., 2011). In this study we link a conduit flow dynamics model, not previously carried out under Venusian conditions, via a jet decompression model, with an established plume dynamics model, which has previously been applied to Venus (Glaze et al., 1997). In addition to this, our model includes CO_2 as an accessory volatile species to H_2O. Previous models only included H_2O but on Venus CO_2 may be of comparatively greater significance in terms of plume dynamics than on Earth when considering the potentially smaller concentration of magmatic H_2O (see Section 1.3) making its inclusion an important innovation.

When conducting an investigation into what may characterise the eruptive style of volcanoes, a broad array of environmental, chemical, and physical factors must be considered. The physical and chemical properties of the atmosphere into which erupted material is injected have a strong control on plume behaviour and cause the process of plume generation to be different on Venus than Earth as do the material properties and the volatile load of the magma.

Table 1
Physical and chemical data for the atmospheres of Venus, Earth, and Mars for comparison. The atmospheric compositions are given in mole fractions with ~0 meaning undetermined but very small. Data from Taylor (2010).

	Venus	*Earth*	*Mars*
Atmosphere			
Molecular weight (g)	43.44	28.98 (dry)	43.49
Surface temperature (K)	730	288	220
Surface pressure (MPa)	9.2	0.1	0.0007
Mass (kg)	4.77×10^{20}	5.30×10^{18}	$\sim 10^{16}$
Composition			
Carbon dioxide	0.96	0.0003	0.95
Nitrogen	0.035	0.770	0.027
Argon	0.00007	0.0093	0.016
Water vapour	~0.0001	~0.01	~0.0003
Oxygen	~0	0.21	0.0013
Sulphur dioxide	150 ppm	0.2 ppb	~0
Carbon monoxide	40 ppm	0.12 ppm	700 ppm
Neon	5 ppm	18 ppm	2.5 ppm

1.2. *Environmental conditions on Venus*

Venus has a dense CO_2-dominated atmosphere enshrouded in thick sulphuric acid clouds. The atmospheric composition of Venus is provided in Table 1 alongside those of Earth and Mars for comparison. At the mean planetary radius (MPR, ~6051.8 km) the atmospheric pressure is ~9.2 MPa and its temperature is ~730 K due to the high atmospheric density and intense greenhouse effect (Seiff et al., 1985). These factors inhibit explosivity by inhibiting magma fragmentation due to vesiculation, and reducing the plume-atmosphere boundary temperature contrast, respectively. Both the pressure and temperature are strongly altitude dependent, however, and diminish rapidly with altitude into conditions more conducive to plume buoyancy (see Fig. 1). The altitude of the surface of Venus ranges between ~-2 and ~+9 km of the MPR.

The chemical composition of the atmosphere is an important factor since the presence of water vapour can influence column dynamics by releasing latent heat and therefore enhancing buoyancy (Glaze et al., 1997) above the altitude at which it condenses within the plume. This effect, however, is not significant in volcanic plumes on Venus because the atmosphere contains negligible water vapour (see Table 1). The value of the constant g (acceleration due to gravity) is slightly smaller on Venus, 8.41 m s^{-2} as opposed to 9.81 m s^{-2} on Earth, resulting in a smaller effect on pressure and column momentum flux on Venus than on Earth.

1.3. *The characteristics of Venus magmas*

The chemical composition of magma is important when modelling conduit processes because it affects the viscosity and fluid dynamic response of the decompressing magma flow (Sparks, 1978). With the exception of one anomalous site (Venera 13, which detected alkalic rocks), the bulk geochemical analyses carried out by the Russian Venera and Vega landers (Table 2), at sites located on lava plains and flows characteristic of most (> 70%, Ivanov and Head, 2011) of the planetary surface, are consistent with a weathered basaltic surface composition (Treiman, 2007). Indeed, the numerous shield volcanoes evident on Venus appear analogous to basaltic shield volcanoes and seamounts on Earth. Steep-sided domes have

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