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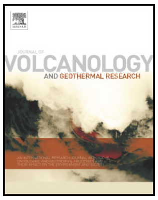

New approaches to inferences for steep-sided domes on Venus

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ABSTRACT

New mathematical approaches for the relaxation and emplacement of viscous lava domes are presented and applied to steep-sided domes on Venus. A similarity solution approach is applied to the governing equation for fluid flow in a cylindrical geometry for two distinct scenarios. In the first scenario, dome relaxation is explored assuming a constant volume of fluid (i.e. lava) has been rapidly emplaced onto the surface. Cooling of lava is represented by a time-variable viscosity and singularities inherent in previous models for dome relaxation have been eliminated. At the onset of relaxation, bulk dynamic viscosities lie in the range between 10^{10}–10^{16} Pa s, consistent with basaltic-andesite to rhyolitic compositions. Plausible relaxation times range from 5 to 5000 years, depending on initial lava viscosity. The first scenario, however, is only valid during the final stages of dome relaxation and does not consider the time taken for lava to be extruded onto the surface.

In the second scenario, emplacement and growth of a steep-sided dome is considered when the volume of lava on the surface increases over time (i.e. time-variable volume approach). The volumetric flowrate may depend on an arbitrary power of the dome thickness, thus embracing Newtonian as well as other rheologies for describing terrestrial and planetary mass flows. The approach can be used to distinguish between basic flowrate models for fluid emplacement. The formalism results in radial expansion of a dome proportional to $t^{1/2}$, consistent with the diffusive nature of the governing equation. The flow at the front is shown to thicken as the front advances for a constant rate of lava supply. Emplacement times are intimately correlated with the bulk rheology. Comparison of the theoretical profiles with the shape of a typical dome on Venus indicates that a Newtonian bulk rheology is most appropriate, consistent with prior studies. However, results here suggest a bulk dynamic viscosity of 10^{12}–10^{13} Pa s and emplacement times of approximately 2–16 years. Both scenarios investigated give emplacement times significantly less than prior estimates and compositions consistent with basaltic andesite.

1. Introduction

Fig. 1 shows a Magellan radar image and topography for a putative lava dome on Venus. Pavri et al. (1992) identified 145 such domes and Stofan et al. (2000) identified an additional 30. These domes are thought to be volcanic in origin (Head et al., 1991) and to have formed by the flow of viscous fluid (i.e., lava) on the surface. The 175 domes examined by Stofan et al. (2000) range from 19 to 94 km in diameter, and have estimated thicknesses as great as 4 km.

A key issue surrounding the Venus steep-sided domes is their composition. Despite studies by several investigators, a significant conundrum persists: high viscosity lavas are implied by the need to sustain the extremely thick flows (1–4 km) (e.g., Head et al., 1991), whereas low viscosity lavas are needed to provide the relatively "smooth" upper surface (e.g., Stofan et al., 2000). If, for example, these domes are composed of evolved magmas analogous to andesites or rhyolites, this would have profound implications for volcanism on Venus, which is thought to be fundamentally basaltic (Surkov et al., 1984; Barsukov et al., 1986.).

There are also numerous secondary science issues that have implications for sub-surface magma ascent and local surface stress conditions. These include the duration of emplacement (how long the conduit remained open and capable of supplying lava), the volumetric flow rate (how rapidly lava was supplied to the surface), the rheology (how did the fluid behave, including the effects of crystallization), and the role of rigid crust in influencing flow and final morphology. Due to a host of physical processes, such as formation of crystals within the lava, cooling, fracturing, and entrainment of a crust, the bulk rheology of the domes during emplacement is unclear. Although a Newtonian flow rate is often assumed for simplicity, other rheologies are also admissible (McKenzie et al., 1992), particularly Bingham (e.g., Skelland, 1967) and empirically derived flow rates (e.g., Baloga et al., 1995, 2001; Bruno et al., 1996; Glaze et al., 2002; Lavallée et al., 2007; Cordonnier et al., 2009).

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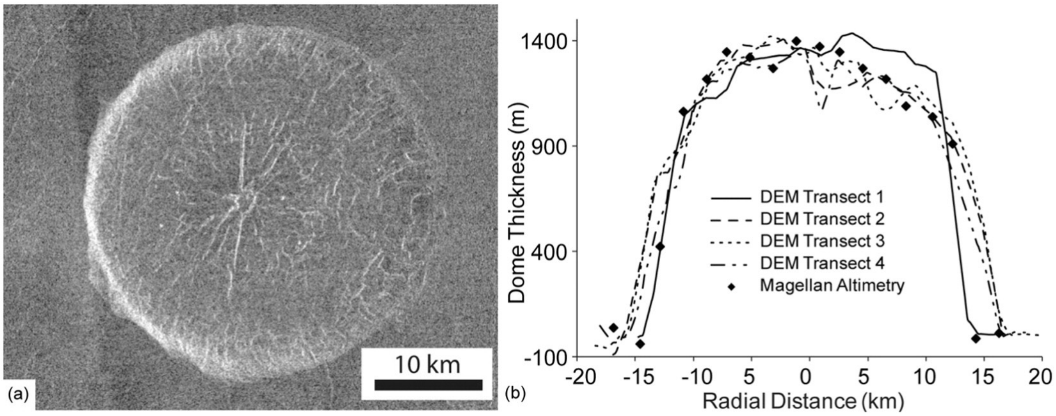

Fig. 1. (a) Magellan image of a typical steep-sided dome in Rusalka Planitia at 3°S, 151°E. (b) Topographic data for the dome shown in (a) with ~20× vertical exaggeration. The four transects depict the topography of the dome as taken from a digital elevation model generated from stereo Magellan images (Gleason, 2008). DEM sampling is less than 300 m (actual resolution is on the order of 1 km). DEM transects are from South to North (Transect 1), West to East (Transect 2), Northwest to Southeast (Transect 3), and Southwest to Northeast (Transect 4). The dome exhibits a diameter between 29 km and 34 km (radius of ~14 km to ~17 km). The black diamonds indicate Magellan altimetry data from orbit 1277 (McKenzie et al., 1992).

In an attempt to address these key questions, several previous theoretical studies (McKenzie et al., 1992; Sakimoto and Zuber, 1995; Neish et al., 2006a,b) have attempted to model the emplacement of steep-sided domes as laminar axisymmetric viscous gravity currents of Newtonian fluid following Huppert (1982) and Huppert et al. (1982). Similarly, studies of the spreading of other viscous fluids such as terrestrial salt extrusions have also been undertaken (Talbot, 1998). Huppert et al. (1982) explore the radial expansion of an axially symmetric viscous flow for both a constant volume of fluid and a flow fed by a constant volume flux. The Huppert (1982) model assumes, a priori, a Newtonian fluid. Based on the limited data available for Venus domes, a Newtonian rheology cannot be precluded. Indeed, "fitting" of theoretical curves for a Newtonian fluid (Huppert, 1982) to the data in Fig. 1b resulted in a final shape that closely matched that of steep-sided Venus domes (McKenzie et al., 1992). In addition, non-Newtonian rheological effects due to cooling, crystallization, and crustal growth, are unlikely to dominate emplacement unless the chilled crust of the lava begins to control the dynamics of emplacement, which is not supported by dome morphology (Stofan et al., 2000). Given the high surface temperatures on Venus, the thermal gradient between erupted lava and its surroundings is small enough that the crust is unlikely to control emplacement (Bridges, 1997).

McKenzie et al. (1992) indicate that the dome will stop spreading when the lava cools and calculate a time constant for this cooling of 650–7400 years. McKenzie et al. (1992) assume that this cooling took place after all the lava was on the surface. Thus, this time constant can be interpreted as the scale over which the interior of the dome remained warm and ductile enough to 'relax'. Using this time constant, lava viscosities range from 10^{14}–10^{17} Pa s, and based on work by Webb and Dingwell (1990), the corresponding lava temperatures of 610–700 °C are consistent with dry rhyolite magma. Thus, McKenzie et al. (1992) conclude that the steep-sided domes on Venus are more likely rhyolitic in composition.

Sakimoto and Zuber (1995) attempted to use a numerical scheme to solve the Huppert (1982) constant volume system in r and t with a viscosity that is uniformly time-dependent throughout the flow as it is being emplaced. These authors use $\nu = kt^b$ as a model for the viscosity change (see Eq. (10), in Sakimoto and Zuber (1995)), claiming "k is the initial viscosity", which can be true only in the $b = 0$ case of a constant viscosity. Because this viscosity model is zero at $t = 0$, the initial velocity (Eq. (10), in Sakimoto and Zuber (1995)) must be infinite (except for $b = 0$). This violates their assumption of the lubrication theory on which the Huppert (1982) approach is based and no indication of the extent or consequences of this violation are given. The paper also states that they look for solutions for $b < 1$. By their Eq. (20), the dome thickness is infinite initially (except for $b = 0$), being clearly nonphysical and violating the assumption of the lubrication theory for some undetermined time. Because the model for viscosity has dimensions of viscosity only for the $b = 0$ case, conclusions about the emplacement differences for basalt, andesite, and rhyolite compositions are also contentious.

Both McKenzie et al. (1992) and Sakimoto and Zuber (1995) use the form of the Huppert (1982) model that is appropriate for finding the radial profile shape of a fixed volume of fluid on a flat surface, e.g., a volume of Newtonian liquid instantaneously dropped onto a surface. However, the particular similarity solution for constant volume employed by McKenzie et al. (1992) and Sakimoto and Zuber (1995) results in an infinite flow rate at $t = 0$. Therefore, the range of t values over which the models are valid is not clear from these studies.

In summary, prior applications of fluid dynamic arguments to the Venus domes still leave many questions unanswered. There remain issues concerning the nature of the lava rheology, bulk viscosity for the Newtonian case, composition, emplacement time, confidence in the underlying mathematical treatment, and reconciliation with dimensional and morphologic indicators.

Here, two different analytical techniques are applied in order to revisit the theoretical approach to modeling dome emplacement. Each approach, when applied to actual Venus dome topography, leads to estimates of emplacement time and admissible rheology ranges. In the first approach, dome relaxation is investigated by reassessing the constant volume scenario examined by Huppert (1982) and Sakimoto and Zuber (1995). The method presented here also involves a similarity solution, but unlike the Huppert (1982) approach, the solution neutralizes the inherent singularity at time $t = 0$, and is applicable to scenarios where a constant fluid viscosity is considered, as well as to those that require any form of a time-dependent viscosity. In Section 3 we consider a viscosity that grows exponentially with time and is parameterized by a single time constant. Using this approach, it is shown that the constant volume solution is only applicable to the very final stages of dome relaxation, and thus it cannot be used to constrain lava viscosity at the time of eruption. In the second approach, dome emplacement is investigated assuming an increasing volume of lava on the surface. This is done by applying a technique based on Babu and van Genuchten (1980). This approach satisfies the plausible boundary condition of a constant lava supply rate and produces a flow front advance rate that reflects the expanding areal coverage associated with the cylindrical geometry and the diffusive nature of the flow dynamics. The time-variable volume approach is valid throughout dome emplacement and can be used to place constraints on erupted lava viscosities.