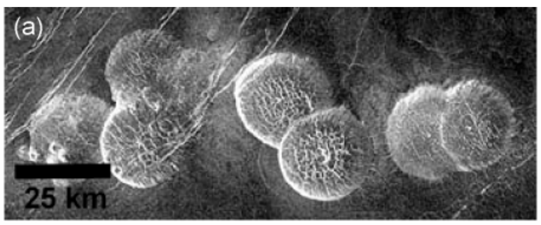
A NEW APPROACH TO INFERENCES FOR PANCAKE DOMES ON VENUS. L. S. Glaze[1], S. M. Baloga[2] and E. R. Stofan[2], [1]NASA Goddard Space Flight Center (Code 698, Greenbelt, MD 20771; Lori.S.Glaze@nasa.com), [2]Proxemy Research (20528 Farcroft Lane, Laytonsville, MD 20882; Steve@proxemy.com, Ellen@proxemy.com).

Introduction: Figure 1 shows a radar image and topography for flat-topped, steep-sided "pancake" domes on Venus. At least 145 such domes have been identified on Venus [1] and are thought to be volcanic in origin [2]. Based on analysis of the dome surfaces, [3] suggested that only the late stage surface fractures are preserved, indicating entrainment and annealing of fractures during emplacement, consistent with a basaltic composition.



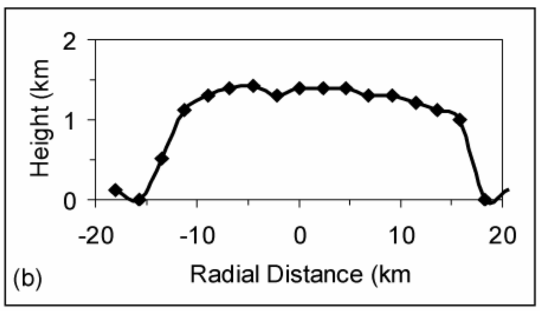


Fig 1. (a) Magellan image of domes SE of Alpha Regio. (b) Magellan altimetry of a typical dome in the Rusalka region.

Previous studies have attempted to model the emplacement of these domes [e.g., 4, 5] as a laminar axisymmetric viscous gravity current of a Newtonian fluid [6, 7]. There are, however, several significant fundamental shortcomings in the model presented in [6, 7]. These are semi-analytic methods based on similarity solutions that satisfy unlikely boundary conditions (i.e., increasing volume flow rates). Even for a constant effusion rate, the suspect treatment of singularities leads to a flow front advance that goes as $t^{1/8}$ [6,7] instead of $t^{1/2}$ as shown earlier in [8] with singularities neutralized. Moreover, most formulations consider the fluid to be isothermal.

Due to a host of physical processes, such as the cooling, formation, 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, particularly Bingham (e.g., [9]) and emprically derived flow rates (e.g., [10, 11, 12, 13]). Baloga et al. [10] indicate that letting n = 1 in (1), below, results in a flow that glides on a thin basal layer, essentially a limiting case of the Bingham flow rate. Typical values of n for empirically derived flow rates for terrestrial mass flows cluster around 1.5.

Here we present a method for inferring bulk rheology from topographic profiles of domes. A widely referenced (but little known to the volcanology community) contribution by Babu and Van Genuchten [8] presents an innovative perturbation solution to the radial formulation of the so-called Boussinesq equation for fluid flow. This approach allows accurate and nonsingular approximations to be made near the origin to avoid this problematic singularity and allows for solutions to within 0.1% of the flow front. The most significant advantage of the Babu and Van Genuchten approach is the ability to distinguish a flow's rheology based solely on the shape of the flow surface.

Approach: The equation describing the radial expansion of a fluid with a gently sloping free upper surface is given by the continuity expression

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rh^{n}\frac{\partial h}{\partial r}\right)=\frac{\partial h}{\partial t} \quad (1)$$

where r and h are the radial and vertical variables, respectively, t is time, and the value of n is indicative of the fluid rheology. The radial variable, r, can have values ranging from 0 (origin) to $r_f(t)$ at the flow front.

To solve the boundary value problem when the steady state volume flux, Q, at the origin is given, equation (1) is transformed to an ordinary differential equation. To find the similarity solution by perturbation, the parameter, ε, is defined as

$$\varepsilon = 1/(n+1) \quad (2)$$

A new independent variable, x, and dependent variable P, are defined as

$$x=\left(\frac{r^{2}}{4t}\right)\left[\varepsilon\,\Phi\left(\frac{Q}{4\pi\varepsilon}\right)^{1-\varepsilon}\right]^{-1} \quad (3)$$

$$P \equiv h^{n+1}4\pi\varepsilon/Q$$

$$\Phi \equiv 1+\varepsilon\,\Phi_{1}+\varepsilon^{2}\,\Phi_{2}+\ldots \quad (4)$$

The constants in (4) are found to be $\Phi_1 \sim 0.5775$, and

$\Phi_2 \sim 0.7455$, by requiring that $x = 1$ at the the flow front, r_f. Equation (1) can now be rewritten as

$$\frac{d}{dx}\left(x\frac{dP}{dx}\right) + \Phi\, x\frac{dP^{\varepsilon}}{dx} = 0 \qquad (5)$$

From [8], the similarity solution of (5) is

$$P(x;\varepsilon) = \exp\left[\left(\varepsilon + \varepsilon^2 + ...\right)\int_0^x \frac{dy}{\ln y}\right]\cdot \left[-\ln x + \varepsilon P_1(x) + \varepsilon^2 P_2(x) + ...\right] \qquad (6)$$

where

$$P_1(x) \equiv x - 1$$

$$P_2(x) \equiv x(x-1) + \ln x \int_0^x \frac{2(1-y) + \int_y^1 \frac{1-t}{t\ln t}dt}{\ln y}dy + \int_x^1 \frac{1-y}{\ln y}dy - x\int_x^1 \frac{1-y}{y\ln y}dy \qquad (7)$$

Application: The examples shown here use the approximation from [8] to evaluate $P(x)$ for $0 \le x \le 0.1$. A Romberg numerical integration scheme was used to evaluate all the integrals in (6) and (7) to find values of $P(x)$ for $0.1 < x < 1$. For illustration purposes, a dimensionless volume flux of $Q = 50$ is used.

Assuming a Newtonian rheology as in [10, 11] with $n = 3$ in (1), Figure 2 shows the solution for a radially spreading fluid at four times. The small peak near the origin is a numerical artifact of the approximation used near the singularity. However, even with this small artifact, the overall "shape" of the flow surface, as well as the aspect ratio at the final time, is very similar to the example shown in Figure 1b for a steep-sided pancake dome on Venus.

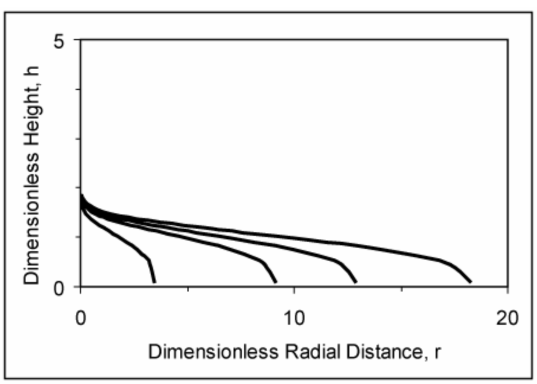


Fig 2. Axially symmetric Newtonian fluid flow profiles at dimensionles times, t = 5, 35, 70, 140 from left to right, respectively.

Perhaps the most intriguing aspect of the solution described here is that the topographic profiles for different rheologies have distinctly different shapes (Fig 3). The most distinct differences are between the limiting Bingham "basal glide" and Newtonian flow rates. The basal glide flow has a concave upward surface that gently slopes from the origin to the flow front. This shape is not at all consistent with the altimetry data presently available for the pancake domes (e.g. Fig 1b). However, the Newtonian flow rate produces a concave downward surface that is characterized by an essentially flat top and a steep flow front, very similar to that observed on Venus.

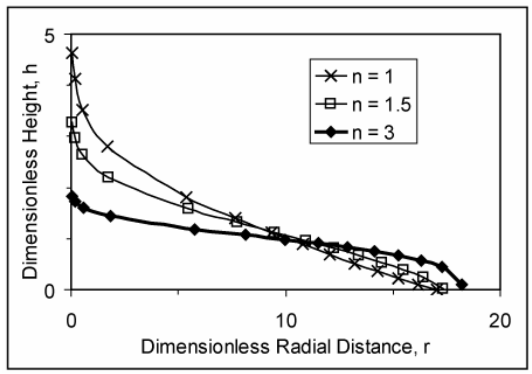


Fig 3. Upper free surface at t = 140 for three volume flow rates as defined by the n values shown. All other boundary conditions are the same.

Conclusions: This new approach has broad potential for modeling lava domes with a simple algorithm that does not require complicated finite difference schemes. The approach has the added advantage that it can be used to distinguish between basic flow rates for fluid emplacement. Based on this very preliminary assessment, the pancake domes on Venus are consistent with a Newtonian bulk rheology.

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