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The spreading of variable-viscosity axisymmetric radial gravity currents: applications to the emplacement of Venusian 'pancake' domes

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The Magellan images of Venus have revealed a number of intriguing volcanic features, including the steep-sided or 'pancake' domes. These volcanic domes or flows have morphologies that suggest formation by a single continuous emplacement of lava with a higher viscosity than that of the surrounding basaltic plains. Numerous investigators have suggested that such high viscosity is due to high silica content, leading to the conclusion that the domes are evidence of evolved magmatic products on Venus. However, viscosity depends on crystallinity as well as on silica content: high viscosity could therefore also be due to a cooler (and therefore higher crystal content) lava. Models of dome emplacement which include both cooling and composition factors are thus necessary in order to determine the ranges of crystallinity and silica content which might lead to the observed gross dome morphologies. Accordingly, in this study domes are modelled as radial viscous gravity currents with an assumed cooling-induced viscosity increase to include both effects. Analytical and numerical results indicate that pancake dome formation is feasible with compositions ranging from basaltic to rhyolitic. Therefore, observations of gross dome morphology alone are insufficient for determining composition and the domes do not necessarily represent strong evidence for evolved magmatism on Venus.

1. Introduction

The Venusian 'pancake' domes were first identified in the Magellan images of Venus. They have been catalogued and characterized by Pavri *et al.* (1992) as steep-sided flat-topped circular-plan-view high-volume domes of probable volcanic origin ranging from 10 km to nearly 100 km in diameter with mean diameters and heights of about 24 km and 700 m, respectively (figure 1). Pavri *et al.* (1992) documented 145 domes in a survey covering 95% of Venus' surface and suggested that their morphology implies a high effective viscosity and formation by a single continuous episode of lava emplacement. They went on to suggest two models to account for the formation of lavas with high apparent viscosities. In the first model, a compositionally evolved magma is the result of differentiation similar to that in terrestrial continental locations. The second model suggests enhanced basaltic bubble growth that could lead to Venusian equivalent of a terrestrial ignimbrite eruption. A similarity between the morphologies of Venusian domes and terrestrial silicic domes is mentioned – specifically terrestrial steep-sided circular to irregular features with flat or near-flat summits. McKenzie *et al.* (1992) used Magellan altimetry data (figure 2) to suggest that

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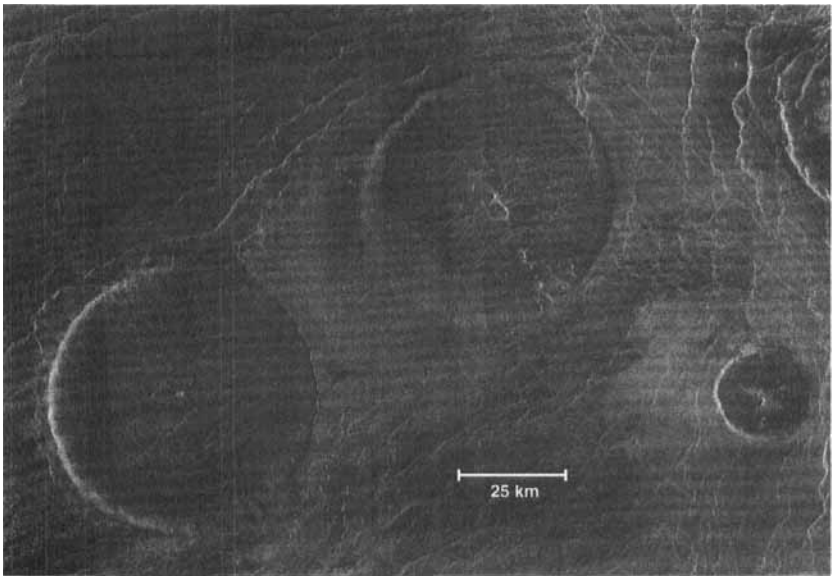

FIGURE 1. Three steep-sided domes in Tinatin Planitia (12° N, 8°) with approximate radii of 31 km, 29 km, and 10.3 km. Magellan image from C1-MIDR 15N009. Illumination is from the left.

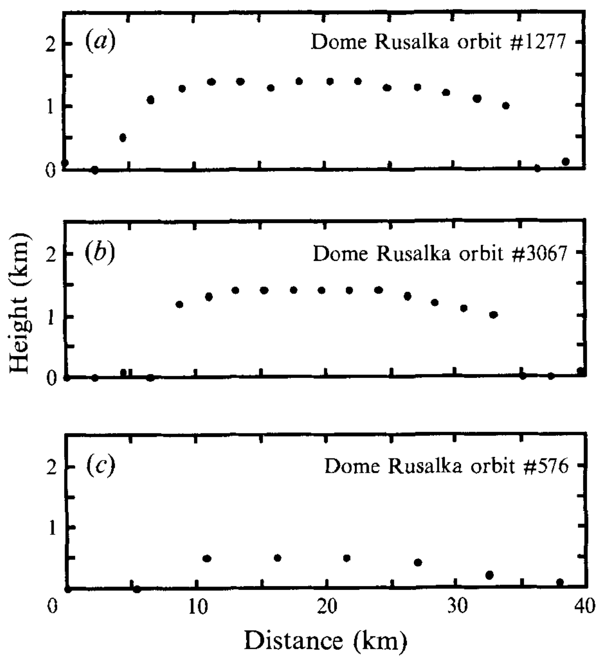

FIGURE 2. Altimetry data from the Venus domes in Rusalka region: (*a*, *b*) two different orbital passes over a dome at 3° S latitude, 151° longitude; (*c*) another dome at 30 °S latitude and 12° longitude. Data points are individual altimetry footprints (about 2 km for *a*, *b* and 5 km for *c*), with a height resolution of approximately 100 m. Processed data courtesy of Dan McKenzie.

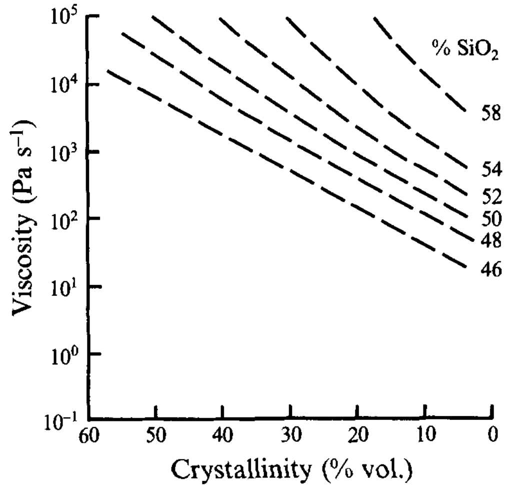

FIGURE 3. Magmatic dynamic viscosity ($\mu = \rho\nu$) as a function of crystal content and composition (after Marsh 1981).

morphology is best fit by radial spreading of a constant-viscosity Newtonian fluid, with a high effective viscosity that is the possible result of a silicic composition. However, as Pavri *et al.* mention, the Venusian domes are remarkably circular in plan view and have very large volumes and low aspect ratios. There are no indications, such as breakout flows or morphologic boundaries, that emplacement involved more than one flow per dome. The radar properties of the domes are more similar to that of the surrounding basaltic plains than to terrstrial silicic domes (Ford & Pettengill 1992; Plaut *et al.* 1994), and in many ways the domes are reminiscent of terrestrial basaltic seamounts (Sakimoto 1994; Bridges & Fink 1994). However, in spite of the high volumes and low aspect ratios that would be uncharacteristic of terrestrial silicic domes, the apparently high effective viscosity of the domes compared to the surrounding basaltic plains has prompted several suggestions that the Venusian pancake domes are the best evidence for evolved magmatism (higher silica content) on Venus (Fink, Bridges & Grimm 1993; McKenzie *et al.* 1992; Pavri *et al.* 1992). While the suggested silicic compositions (Fink *et al.* 1993; McKenzie *et al.*, 1992; Pavri *et al.* 1992) cannot be ruled out, there is an oft-neglected dual dependency of viscosity on crystallinity as well as silica content that raises the question of whether a high silica content is a requirement to explain the observed morphology of the domes. Namely, high viscosity could also be due to the eruption of a cooler (and therefore higher crystal content) lava. Additionally, recent textural and additional morphologic studies have suggested that the Venusian pancake domes are not texturally similar to terrestrial silicic domes (Stofan *et al.* 1995; Anderson 1994). Figure 3 shows how a given viscosity may result from different combinations of crystallinity and composition, with the limitation that flows with crystal content higher than 50–60 % are not expected to erupt (Marsh 1981), but this content may be reached by subsequent cooling. Models of dome emplacement which include both cooling and composition factors as well as variations in initial crystallinity are thus necessary in order to determine the ranges of crystallinity and silica content which might lead to the observed gross dome morphologies.

Many lava flow studies to date have not included the effects of cooling on lava flow effective viscosity, modelling flows as fluids of constant or near-constant viscosities (e.g. Pavri *et al.* 1992; Fink & Zimbelman 1990; Huppert 1982). However, neglecting the cooling-induced viscosity increase may lead to estimates of effective flow viscosities that are orders of magnitude higher than eruption viscosities. More accurate estimates of flow bulk viscosities or effective viscosities are obtained when a cooling-induced viscosity change is considered. Experimental work on radial viscous gravity currents with a strongly temperature-dependent viscosity shows that approximating flows with a constant internal temperature distribution and bulk viscosity distribution might be reasonable (Stasuik, Jaupart & Spinks 1993). Differences in initial crystal content for otherwise similar compositions can be modelled by an appropriate increase in viscosity (as previously discussed, and illustrated in figure 3). This study assumes a Newtonian temperature-dependent rheology, since the temperature effects on the rheology are expected to be greater than the non-Newtonian effects. The Newtonian model is an easier model to work with, and is often used for lava flow modelling in order to keep the problem tractable even when non-Newtonian effects are expected to be present. In this problem, it is possible that non-Newtonian effects could approach the importance of temperature effects in the later stages of cooling before the flow comes to a halt, since increasing crystal content drives increasingly non-Newtonian behaviour. Since dome morphology is expected to preserve primarily the effects of the late thermal and material characteristics of the flow, they could have noticeable effects on the flow rheology and thus the flow morphology. However, since the thermal, compositional, and non-Newtonian effects on rheology are all similar, they cannot be uniquely extracted from observations of dome morphology alone. This study will examine the largest effect (thermal), in conjunction with the compositional effect in order to clarify what possible compositional conclusions, if any, we can make from morphology observations, and the non-Newtonian effects will be considered in later treatments.

Griffiths & Fink (1993) have suggested that surface cooling and crustal effects should be considered in the modelling of lava flows and domes. It has been shown that, on Venus, the convective cooling efficiency of the atmosphere is greater than that on Earth, and that volcanic flows should therefore form a surface crust more quickly than on Earth (Gregg & Greeley 1993). However, this accelerated crustal formation actually favours the thermal longevity of the flow, since subsequent cooling must then be through conductive cooling through the crust, and conductive heat transport is less effective than radiative or convective. Since conductive cooling is driven by the temperature difference, two factors will favour slower cooling of Venus flows compared to terrestrial flows. First, the ambient temperatures of the Venus surface are much higher than those on Earth. Second, while the initial heat losses of flows on Venus through convective cooling will be higher than on Earth, subsequent losses will be lower, and flows will have a larger heat budget with accompanying higher temperatures than any given distance from the vent when compared to terrestrial flows with similar properties. These two factors together will reduce the temperature gradient driving the conductive heat losses, and increase the heat budget of the flows still further, while slowing the growth of the crust as a thermal and physical boundary layer. As a result, we should expect flows on Venus to crust over more quickly, but then to cool and crystallize more slowly and thus travel farther at higher temperatures than flows of similar composition on Earth (Gregg & Greeley 1993; Sakimoto & Zuber 1995). For this investigation, crust formation is thus not considered a primary factor in flow morphology for the bulk of the flow, and the contribution of the bulk effective viscosity is expected to exceed the contribution of possible crust formation in the control of gross flow morphology.

It is interesting to note that the role of crystallization in the rheological evolution of cooling lavas is sometimes misunderstood. Magmas and lavas, their aboveground counterparts, are impure substances and solidify or melt over a range of temperatures bounded by the solidus – the temperature of complete crystallization – and the liquidus – the temperature of completely crystal-free melt. The gap between these temperatures varies in magnitude from around 400 °C for periodities to less than 175 °C for andesites, gabbros, and more silicic magmas (Marsh, 1981). Crystallization proceeds very slowly in the temperature regimes near the solidus and liquidus, but the bulk of the crystallization, and thus the most rapid increases in viscosity apparently occur over a range of 50 °C or less. Lavas with over approximately 55 % crystals are not thought to erupt or flow (maximum packing is in the range of 50–60 % crystals) (Marsh 1981), and so the occasionally heard statements about particular lavas that 'erupted near the solidus' are erroneous. Most terrestrial lavas contain between 25 % and 55 % crystals (an equivalent temperature range of only 50°) (Marsh 1981), while the Hawaiian basaltic lavas used most frequently as planetary analogues average around 5–15 % crystals. For lavas with moderate crystal content, the viscosity increases moderately as the lava cools and crystallizes. However, as the crystal content approaches maximum packing, the viscosity increases to effectively infinite values over only a few degrees of temperature and a very short range of crystallinity (5 % or so), so that the magma becomes – rheologically – a solid (Marsh 1981). The implications for Venus domes are thus apparent: instead of requiring a more viscous silicic lava to erupt at moderate crystallinities and cool 10–100 °C before halting to form a pancake dome, we can also postulate a basaltic lava similar in composition to the surrounding plains that has simply cooled to a greater (than the average plains lava) crystallinity which then erupts and cools a moderate amount. The resulting domes would not be expected to be as abundant as plains lavas since the temperature range for higher crystallinity lavas is smaller than the temperature range for less crystallized lavas. The magma spends less time in the temperature range of the more crystallized states than it does in the lower crystallinity temperature ranges, and is thus less likely to erupt with a high crystal content (Marsh 1981). This crystal-rich basalt hypothesis for pancake domes has the advantages of requiring no special mechanisms for magmatic differentiation and production of silicic melts (which is not thought to be necessary for the rest of Venusian volcanism), nor does it require extremely rapid cooling or vesiculation mechanisms of average plains-type basalts.

The problem of a radially spreading Newtonian fluid on a horizontal surface has been previously considered and partially solved in Huppert's similarity solutions for selected constant-viscosity cases (Huppert 1982; Huppert *et al.* 1982) and has been widely used in interpreting the morphology of the Venusian 'pancake' domes (e.g. McKenzie *et al.* 1992; Pavri *et al.* 1992). However, the contribution of cooling to final morphology is omitted if the viscosity of the fluid is held constant over the emplacement time, as Huppert's solution requires. Accordingly, we have solved the problem of a radially spreading variable-viscosity Newtonian fluid on a horizontal surface both numerically and analytically (for some selected cases). For ease of comparison to previous results, the flow problem formulation (up to equation (7)) is in the same manner as Huppert (1982) and Huppert *et al.* (1982). This study treats the viscosity of the flow as an emplaced volume where eruption time is short compared to the cooling and emplacement time, since the pancake dome morphology suggests that they were emplaced as a single unit (Pavri *et al.* 1992). This allows treatment of the dome viscosity as a time-dependent property only, and neglects spatial variations in viscosity. A parallel but independent study (Bercovici 1994) considers the possible influence of radial variations in viscosity on morphology, and predicts morphologies with a flatter top and steeper sides than seen in similarity solutions such as Huppert's and this study. However, the altimetric resolution of the Venus domes is rather coarse, and the problems of resolving a sharp slope change in a radar return reduce the reliability of the returns at the dome margins, making it difficult – if not impossible – to rule in favour of either model's results on the basis of final morphology alone. However, both models require fluids of much lower initial viscosities for pancake dome formation than the constant-viscosity model.

2. Theory

Spreading of the liquid is governed by the ratio of the horizontal gradient of the hydrostatic pressure to the viscous retarding force

$$\frac{\partial^2 u}{\partial z^2} = \frac{g}{\nu}\frac{\partial h}{\partial r} = \frac{1}{\rho}\frac{\partial p}{\partial r}, \tag{1}$$

where $u(r, z, t)$ is the radial velocity, ν is kinematic viscosity, and $h(r, t)$ is flow height. The pressure distribution in the flow is given by

$$p = p_0 + \rho g(h - z), \tag{2}$$

where p_0 is the constant pressure at the surface, ρ is the density of the fluid, h is flow height, and g is the acceleration due to gravity. If the boundary conditions of no slip (zero velocity) at the base of the flow,

$$u(r, 0, t) = 0, \tag{3}$$

and the approximation that shear stress at the top of the flow is negligible,

$$\frac{\partial u}{\partial z}(r, h, t) = 0, \tag{4}$$

are required, then the radial velocity,

$$u(r, t) = \frac{1}{2}\frac{g}{\nu}\frac{\partial h}{\partial r} z(2h - z), \tag{5}$$

is known from the well-known approximation of lubrication theory (first solved by Reynolds 1886). The continuity equation for incompressible flow applied to a vertical plane of radius r in the fluid yields

$$\frac{\partial h}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left(r \int_0^h u \, \mathrm{d}z\right) = 0. \tag{6}$$

The substitution of (5) into (6) yields the nonlinear parabolic (Ames 1982) partial differential equation for $h(r, t)$,

$$\frac{\partial h}{\partial t} - \frac{1}{3}\frac{g}{\nu}\frac{1}{r}\frac{\partial}{\partial r}\left(r h^3 \frac{\partial h}{\partial r}\right) = 0, \tag{7}$$

which may also be stated as

$$\frac{\partial h}{\partial t} = \frac{g}{12\nu}\nabla_r^2 h^4, \tag{8}$$

where ∇_r^2 is the radial gradient, or (after Spence & Turcotte 1985)

$$\frac{\partial h}{\partial t} = \frac{1}{3\mu}\nabla \cdot (h^3 \nabla p). \tag{9}$$

3. Analytic solution for fixed volume release

Equation (7) may be solved with a similarity solution for the release of a fixed volume of fluid at the origin at time $t = 0$ for a time-dependent viscosity of the form

$$\nu = kt^{\beta}, \tag{10}$$

where ν is kinematic viscosity, k is initial viscosity, t is time and β is a constant. This formulation of the viscosity function reduces to constant viscosity for $\beta = 0$. The analytic solution developed here will turn out to be valid only for $\beta < 1$, so a numeric solution will be tested against the analytic solution for small β-values and then used for solutions with larger β-values. Physically, a β-value less than 1 translates loosely into a flow that stops only when its source of material is cut off (sometimes called a 'volume-limited' flow), where a flow with a β-value larger than 1 would theoretically cool, increase in viscosity, and eventually stop regardless of activity at the vent (sometimes called a 'cooling-limited flow'). However, the cooling-limited/volume-limited terminology implies a simpler interaction between the thermal, rheologic and vent activity histories of the flow than is generally possible, and thus can be potentially confusing, if not misleading regarding the thermal and velocity states of the flow. Thus, it will not be used here. Ideally, viscosity should be a function of radius (i.e. McBirney & Murase 1984) and strain rate or velocity gradient as well as time, but this simpler time-dependent formulation is an advance over previous constant-viscosity theoretical approaches as well as being convenient, and will be appropriate for flows where eruption is rapid relative to emplacement time, as was discussed earlier. Few data for lava viscosity as a function of time exist. The data of Fink & Zimbelman (1990) for basalt flows are shown in figure 4, with equation (10) plotted for several β-values. From examination of figure 4, it is apparent that equation (10) with $1 < \beta < 2$ is a reasonable fit for cooling basaltic lavas. Temperature-dependent fits with β slightly less than 1 can also be fit to the data, but such flows will not cool sufficiently to stop from viscous causes, and so are not considered in this study. A schematic of the analytical problem is shown in figure 5. In an approach similar to that of the constant-viscosity problem (Huppert 1982; Huppert *et al.* 1982), we assume the dimensionless similarity variable

$$\eta = \left(\frac{3\nu}{gV^3}\right)^{1/8} rt^{(\beta-1)/8}, \tag{11}$$

the solution form

$$h = \frac{V}{r^2}H(\eta), \tag{12}$$

and a global continuity equation

$$V = 2\pi \int_0^{r_N(t)} rh(r,t)\,\mathrm{d}r, \tag{13}$$

where H and η are similarity solution variables and V is the volume of the flow. Substitution of (11) and (12) into (7) and carrying out the indicated partial deriatives yields

$$[\eta^{-8}H^3(\eta H' - 2H)]' - \left(\frac{\beta-1}{8}\right)H' = 0, \tag{14}$$

where $f' = \mathrm{d}f/\mathrm{d}\eta$. If we assume that the flow is of finite thickness at $r = 0$, then

$$H(0) = H'(0) = 0. \tag{15}$$

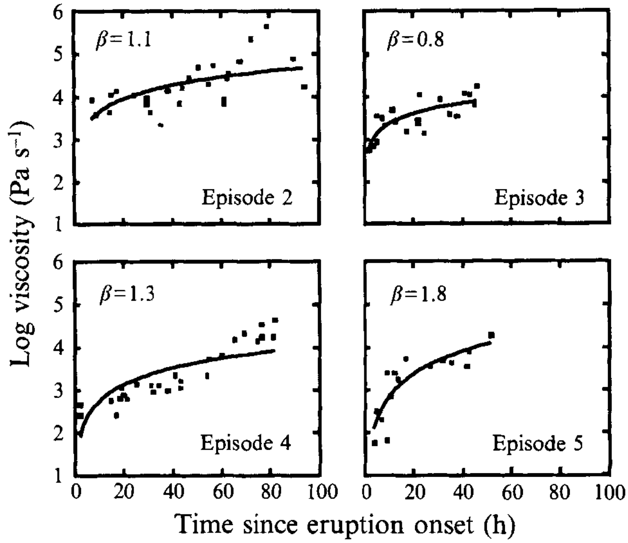

FIGURE 4. Best-fit viscosity functions (equation (10)) to the calculated dynamic viscosity *vs*. time data of Fink & Zimbelman (1990) for four flows of the 1983 eruption of Puu Oo, Kilauea volcano, Hawaii.

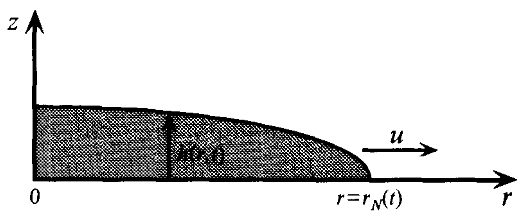

FIGURE 5. Schematic of radial flow flow model. Height is a function of radius and time and the radial extent r_N is the flow front position at any given time.

Integration of (14) and application of (15) yields

$$H^2(\eta H'-2H)-\left(\frac{\beta-1}{8}\right)\eta^8 = 0. \tag{16}$$

A solution of (16) for $\beta < 1$ is

$$H = (\tfrac{3}{16})^{1/3}(1-\beta)^{1/3}\eta^2(\eta_N^2-\eta^2)^{1/3}, \tag{17}$$

where η_N is the value of η at $r = r_N(t)$, the radial extent of the flow. The value of η_N,

$$\eta_N = \left(\frac{1024}{81\pi^3(1-\beta)}\right)^{1/8}, \tag{18}$$

is obtained from equation (13). The radial extent,

$$r_N = \eta_N\left(\frac{gV^3}{3k}\right)^{1/8} t^{(1-\beta)/8}, \tag{19}$$

is calculated from equation (11) using an explicit finite differencing routine similar to that of Olson (1990). The height of the centre is given by

$$h(0,t) = \left(\frac{3kV}{4\pi g}\right)^{1/4} t^{(\beta-1)/4}. \tag{20}$$

4. General numerical solution

The above analytical solution is valid only for the stated source conditions, for $\beta \leqslant 1$ and the assumed viscosity function (equation (10)). For other conditions, it is simpler to find a more general numerical solution. Consider the dome formation problem as stated above, with the addition of a source flux Q at a source location r_p. As before, the radial velocity away from the source for large aspect ratios ($h \ll r$) is known from the lubrication theory approximation as

$$u(r,t) = \frac{1}{2}\frac{g}{\nu}\frac{\partial h}{\partial r} z(2h-z). \tag{21}$$

The horizontal dome flux q is then

$$q = \int_0^h u(r,t)\,\mathrm{d}z. \tag{22}$$

Substitution of (21) into (22) and integration yields

$$q = -\frac{1}{12}\frac{g}{\nu}\frac{\partial h^4}{\partial r}. \tag{23}$$

The continuity equation for a dome with a point source of lava is

$$\frac{\partial h}{\partial t} = -\boldsymbol{\nabla}_r \cdot \boldsymbol{q} + Q\delta(r-r_p), \tag{24}$$

where Q is the source flux, δ is the boundary layer thickness, and r_p is the source location. Substitution of (23) into (24) yields

$$\frac{\partial h}{\partial t} = \frac{1}{12}\frac{g}{\nu}\nabla_r^2 h^4 + Q\delta(r-r_p). \tag{25}$$

Equation (25) may be made dimensionless by using the length scale Q/ν and time scale H^3/Q where H is a reference dome height. Using the dimensioness variables, $h^* = h\mu/Q\rho$, $t^* = tQ/H^3$, and $r^* = r\mu/Q\rho$, equation (25) becomes

$$\frac{\partial h^*}{\partial t^*} = \frac{1}{12}\frac{g}{\nu}\frac{H^3\rho}{\mu}\nabla_r^{*2} h^{*4} + \delta(r^*-r_p^*). \tag{26}$$

The Galileo number, Ga, is the ratio of gravitational forces to viscous forces and is expressed as

$$Ga = \frac{H^3 g\rho^2}{\mu^2} \tag{27}$$

so that equation (26) may be rewritten as

$$\frac{\partial h^*}{\partial t^*} = \frac{Ga}{12}\nabla_r^{*2} h^{*4} + \delta(r^*-r_p^*). \tag{28}$$

Numerical solutions to equation (28) are calculated using a finite difference routine similar to that of Olson (1990).

5. Results and discussion

The analytical and numerical results are shown in figure 6. For $\beta < 1$, the analytical and the numerical results are identical within the resolution of the models. The redundancy of the analytical results are a necessary confirmation of the numeric

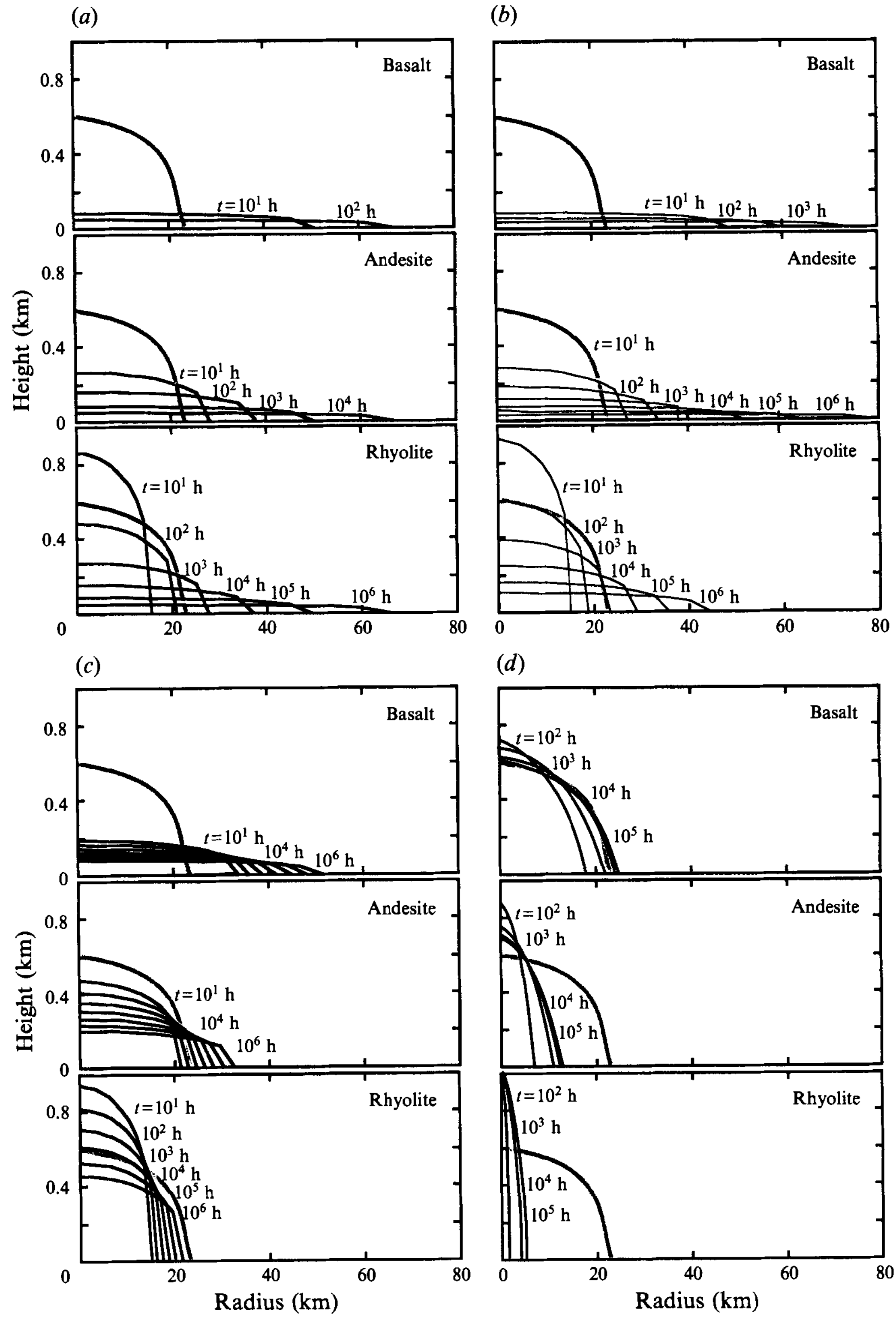

FIGURE 6. Model results plotted for a trio of lava compositions as a series of radial height profiles at successive times. Times should be considered relative rather than absolute, due to emplacement

results, which then extend the solution to higher β-values. Since the analytic solution is valid for $\beta < 1$, numerical results only are shown for $\beta \geqslant 1$. Each trio of plots is a series of radial dome height profiles for successive times for three lava compositions. Initial crystal content was assumed to be in the same 10–20% range as typical terrestrial values. The short spreading times are the result of the instantaneous lava emplacement and subsequent spreading assumed in the model, and should be considered a relative (rather than absolute) indication of the emplacement time required for different compositions. It was assumed that the lava was emplaced in a single episode. The only variable that changes from one set of plots to the next is β, which is indicative of the relative amount of cooling during emplacement. Recall that equation (10), $\nu = kt^{\beta}$, defines the viscosity function where k is the initial viscosity, and t is time. The grey stippled line in each plot is the profile of a typical Venusian dome with a volume of the material erupted equivalent to that of the model. Figure 6(*a*) illustrates dome emplacement for a constant-viscosity or $\beta = 0$ lava. The solution is the same as that found in Huppert (1982), where the material continues to flow indefinitely until halted by some outside force. From figure 6(*a*) it is clear that with little or no viscosity increase during emplacement, a high initial viscosity is needed to produce the required Venusian dome morphologies and that some factor neglected in this study would have to be responsible for halting the flow of material. Figures 6(*b*) and 6(*c*) show the emplacement of lavas with $\beta = 0.25$ and $\beta = 0.75$. Here also, the lava continues to flow indefinitely, but decelerates as the result of an effective viscosity increase as would occur during cooling. As in figure 6(*a*), outside forces are required to halt the flow, and a high initial viscosity is required to form the morphologies observed for Venusian pancake domes. Figure 6(*d*) shows dome emplacement for $\beta = 1.5$, which is in the range of values previously fit to the terrestrial experimental cooling data. In this set of plots the effective viscosity increase is sufficient to decelerate the flow appreciably – very little motion has occurred in the last time step, no measurable motion occurs in the next time step (10000 years), and the flows have come to a halt. This illustrates the essential difference between the constant-viscosity models, in which flows do not halt, and this model, where viscosity increases with time, and flows can halt. To obtain fits to a constant-viscosity model, the morphology must be fit to a still-moving profile. Here, the flow has stopped, and the final shape may be compared with the Venusian domes, which are presumably not moving either. For this viscosity increase, which may be accomplished with a conservative 10% initial crystals and 80–100° of cooling in a basalt (figure 3), this model reproduces the morphologies observed for Venus pancake domes. For the initial crystal content of about 10% and the equal amounts of cooling implied by the β-fits to the basaltic data (equation (10) and figure 4), the basaltic model is a better fit to the Venus dome morphology than the more silicic models. However, by varying the initial crystal content, the magnitude and rate of the viscosity increase, and the composition, most of the spectrum of terrestrial rheologies will produce the range of observed pancake dome aspect ratios and gross shapes. It is easier to produce domes with the basaltic compositions and typical terrestrial crystallinities with the cooling functions assumed for this model, but it should be noted that these results are based on a basaltic cooling function and that while a rhyolite function is predicted by figure 3 to have the same form and possibly a

mechanisms. (*a*) The predicted dome height for constant viscosity lavas; (*b*, *c*) the predicted dome heights for limited lava cooling; and (*d*) predicted dome heights for sufficient cooling to halt the flow. Grey stippled line is a Venus dome with a typical aspect ratio with the same volume as the lava released for all the domes illustrated here. See text for further explanation. (*a*) $\beta = 0$, (*b*) $\beta = 0.25$, (*c*) $\beta = 0.75$, (*d*) $\beta = 1.50$.

similar exponent, the prediction has not yet been tested. Thus, this study cannot rule out a silicic composition for the domes. However, this model does allow us to postulate a basaltic lava of the same composition as the surrounding plains that has cooled to a somewhat enhanced pre-eruption crystallinity which then erupts and cools a moderate amount, instead of requiring a more viscous silicic lava to erupt at moderate crystallinities and cool many degrees to form a pancake dome. This crystal-rich basalt hypothesis for pancake domes has the advantages of requiring no special mechanisms for magmatic differentiation and production of silicic melts (which is not thought to be necessary for the rest of Venusian volcanism), nor does it require extremely rapid cooling or vesiculation mechanisms of average plains-type basalts. However, it is also quite apparent that it is impossible to distinguish between a compositionally driven viscosity increase and thermally driven viscosity increase from large-scale morphological data alone, and that other factors (such as direct sampling, coupled cooling and flow models with empirically determined lava rheologies, or small-scale morphology studies) will have to be used to resolve the issue of pancake dome composition.

A more realistic physical representation of the process of lava flow emplacement will require more sophisticated numerical techniques than those used here. The assumption of variable flow properties such as viscosity even for low Reynolds numbers means that the temperature and flow equations are coupled, and anything but the most simple geometries are impossible to satisfactorily treat analytically without losing important problem parameters. Further research in this area using established tools of computational fluid dynamics (CFD) is thus underway in order to treat a variety of flow geometries as well as the coupled equations for the temperature and flow fields for both Newtonian and non-Newtonian rheological models.

6. Conclusions

The results of this study demonstrate that similar volcanic dome morphologies may be produced by different combinations of initial viscosity, initial crystal content, and viscosity increases with time, and that the cooling-induced increase in lava viscosity during emplacement may strongly affect the final dome morphology. Thus, large-scale dome morphology should not be used as the sole indication of the dome composition. In particular, Venusian pancake domes can probably be formed of a broad range of materials, including basaltic lavas, and are not necessarily good evidence for evolved magmatic products on Venus.

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