Magma Compaction, Gas Exsolution and Decompression in Volcanic Conduits

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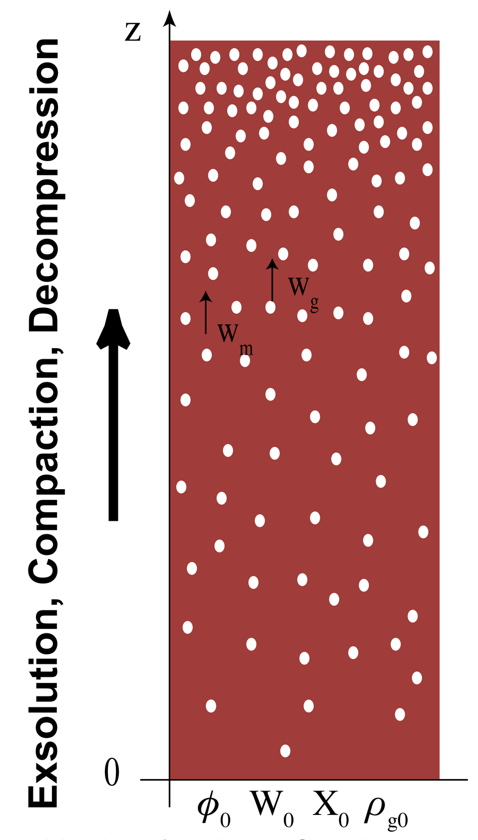
Gas content, exsolution and segregation from magma strongly influence the dynamics of a volcanic eruption. Recently, magma compaction has been shown to exert a control on gas content and segregation in viscous silicic magmas (Michaut et al, 2009) although gas decompression and exsolution were neglected. Dynamics of magma and gas mixtures in volcanic conduit are often studied using homogeneous models, where both phases move at the same velocity, or two-phase flow models, where both phases are at the same pressure, hence where no compaction occurs. However, compaction and inter-phase drag influence gas pressure as well as gas exsolution and decompression; and hence they exert a control on gas velocities and eruption dynamics.

In order to study this complex interplay between compaction, exsolution, inter-phase drag and decompression and its influence on gas and magma dynamics, we extend the two-phase flow theory of Bercovici and Ricard (2003) to take into account gas exsolution from magma matrix as well as gas compressibility. Gas solubility is considered to be a function of gas pressure only and exsolution occurs at equilibrium. The gas is considered perfect and is in the form of bubbles; the drag between phases follows Stoke's law, assuming a constant number of bubbles.

We identify two dimensionless numbers: the first one characterizes the viscous resistance to flow and compaction; the second one characterizes the drag between phases.

We start with a negligible gas volume fraction and compare the results of steady-state two-phase flow models with two limiting cases: homogeneous flow and single-pressure two-phase flow.



X: dissolved gas fraction
ϕ: gas volume fraction
P: Pressure
w: vertical velocity
μ_m : magma viscosity
ρ: density
b_0: characteristic bubble radius
C_g: gas sound speed
subscripts g: gas, m: magma
0: values at z=0

Model, assumptions and equations

Steady-state mass conservation of magma and compressible gas

$$\frac{w_m}{W_0} = \frac{(1-\phi_0)(1-X_0)}{(1-\phi)(1-X)}$$

$$\frac{\Delta w}{W_0} = \frac{(1-\phi_0)(1-X_0)}{(1-\phi)(1-X)} - \frac{\phi_0}{\theta\phi} + \beta_m \frac{1-\phi_0}{\theta\phi}\frac{X-X_0}{1-X}$$

where: $\beta_m = \rho_m/\rho_{g0}$, $\Delta w = w_m - w_g$, $\rho_g = \rho_{g0}\theta$

Steady-state 1-D dimensionless equations for magma compaction and decompression

where we use a drag coefficient deduced from a micromechanical model based on Stoke's law for a constant number of bubbles: $c = c^*\phi^{1/3} = \frac{3\mu_m\phi^{1/3}}{b_0^2}$

a difference in pressure between phases given by: $\Delta P = P_m - P_g = \frac{4\mu_m}{3\phi^{1/2}}\frac{dw_m}{dz}$

a dissolved gas fraction X given by the solubility law: $X = sP_g^\nu = X_0\theta^\nu$ with ν = 0.5 (H_2O in rhyolite), 0.7 (H_2O in basalt)

(E1) $$\frac{d\theta}{dz} = -\theta + \frac{\beta_m D}{\phi^{2/3}}\left(\frac{(1-\phi_0)(1-X_0)}{(1-\phi)(1-X)} - \frac{\phi_0}{\theta\phi} + \beta_m\frac{1-\phi_0}{\theta\phi}\frac{X-X_0}{1-X}\right)$$

(E2) $$\eta\frac{d}{dz}\left((1-\phi)\left[\frac{1+\phi^{1/2}}{\phi^{1/2}}\right]^n \frac{d}{dz}\frac{(1-X_0)(1-\phi_0)}{(1-X)(1-\phi)}\right) - \frac{1}{\beta_m}\frac{d\theta}{dz} = 1-\phi+\frac{\theta\phi}{\beta_m}$$

with n=1, and height nondimensionalized by: $L = \frac{C_g^2}{g}$

Comparison with

1- Homogeneous flow (no phase separation): $\Delta w = 0$

Same equations for w_m and (E2), θ given by:

$$\theta = \frac{\phi_0}{\phi}\frac{(1-\phi)}{(1-\phi_0)}\frac{(1-X)}{(1-X_0)} + \beta_m\frac{(1-\phi)}{\phi}\frac{(X_0-X)}{(1-X_0)}$$

2- Single-pressure two-phase flow (no compaction): $\Delta P = 0$

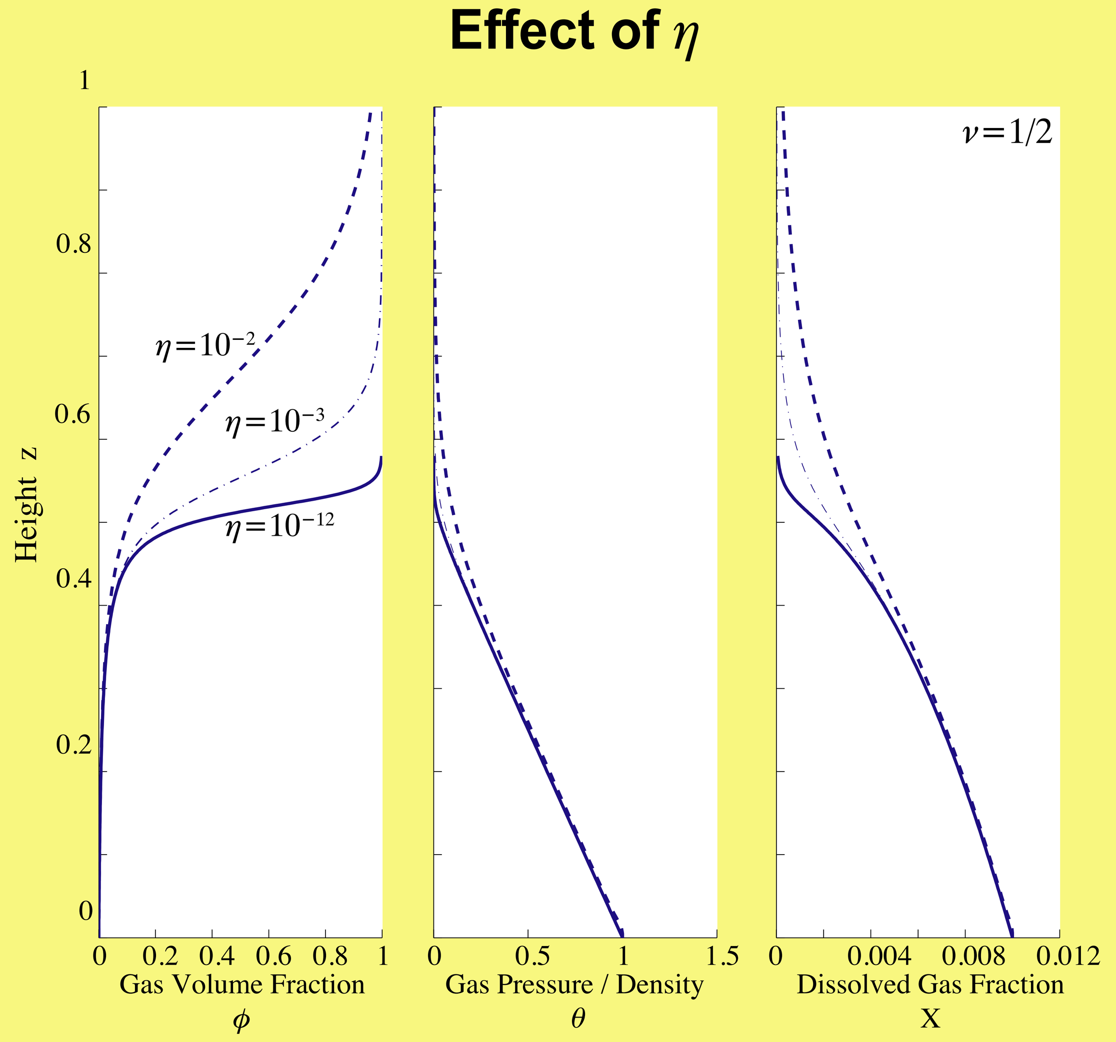
Same equations except for (E2) where n=0.

Dimensionless numbers : For magma and gas mixtures:

Viscous resistance to flow and compaction $\eta = \frac{\mu_m W_0 g}{3\rho_m C_g^4}$ — $10^{-8} < \eta < 10^{-16}$

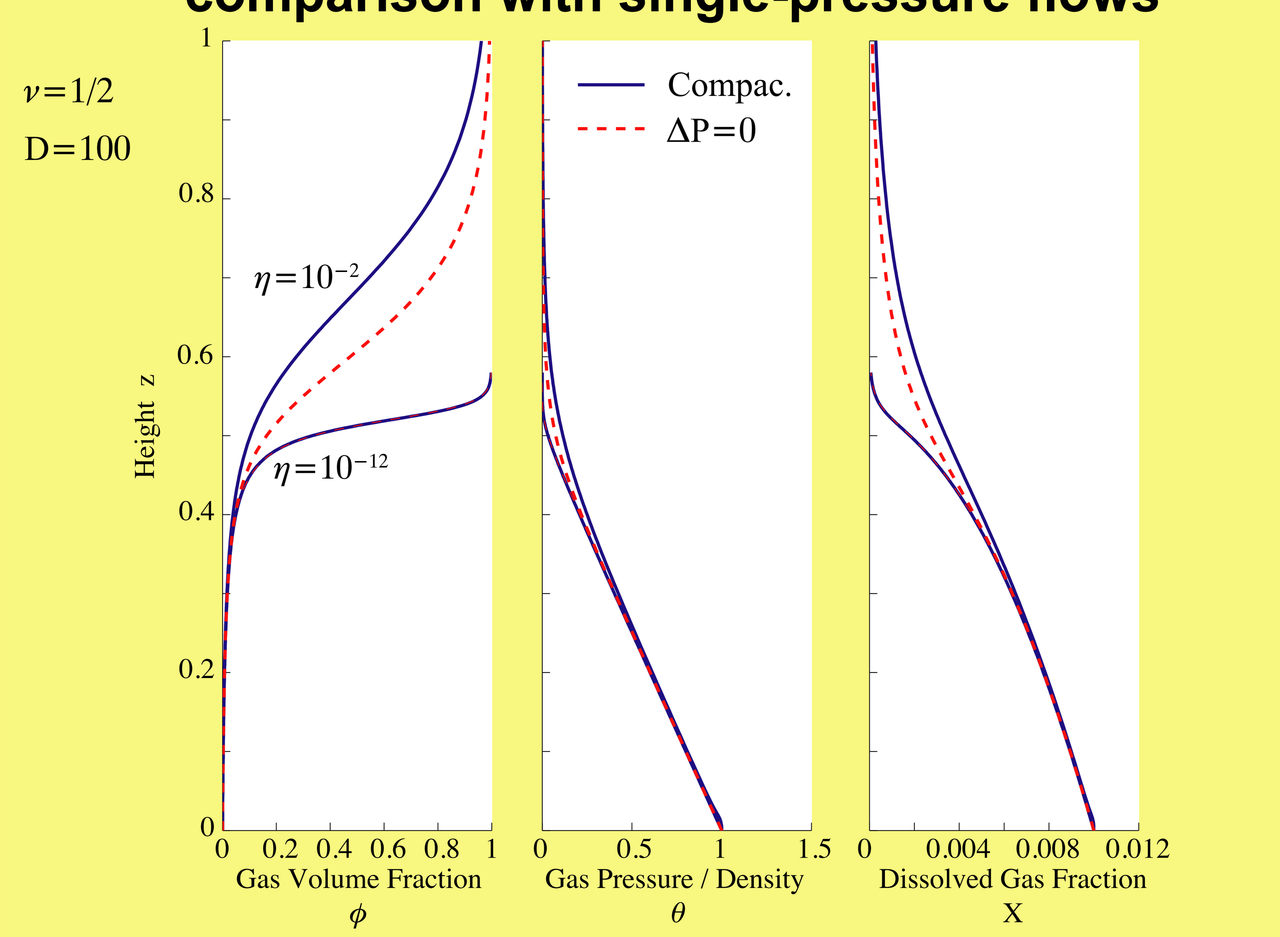
Dimensionless Drag $D = \frac{c^* W_0}{\rho_m g} = \frac{3\mu_m W_0}{b_0^2\rho_m g}$ — $0.1 < D < 10^8$

Effect of η



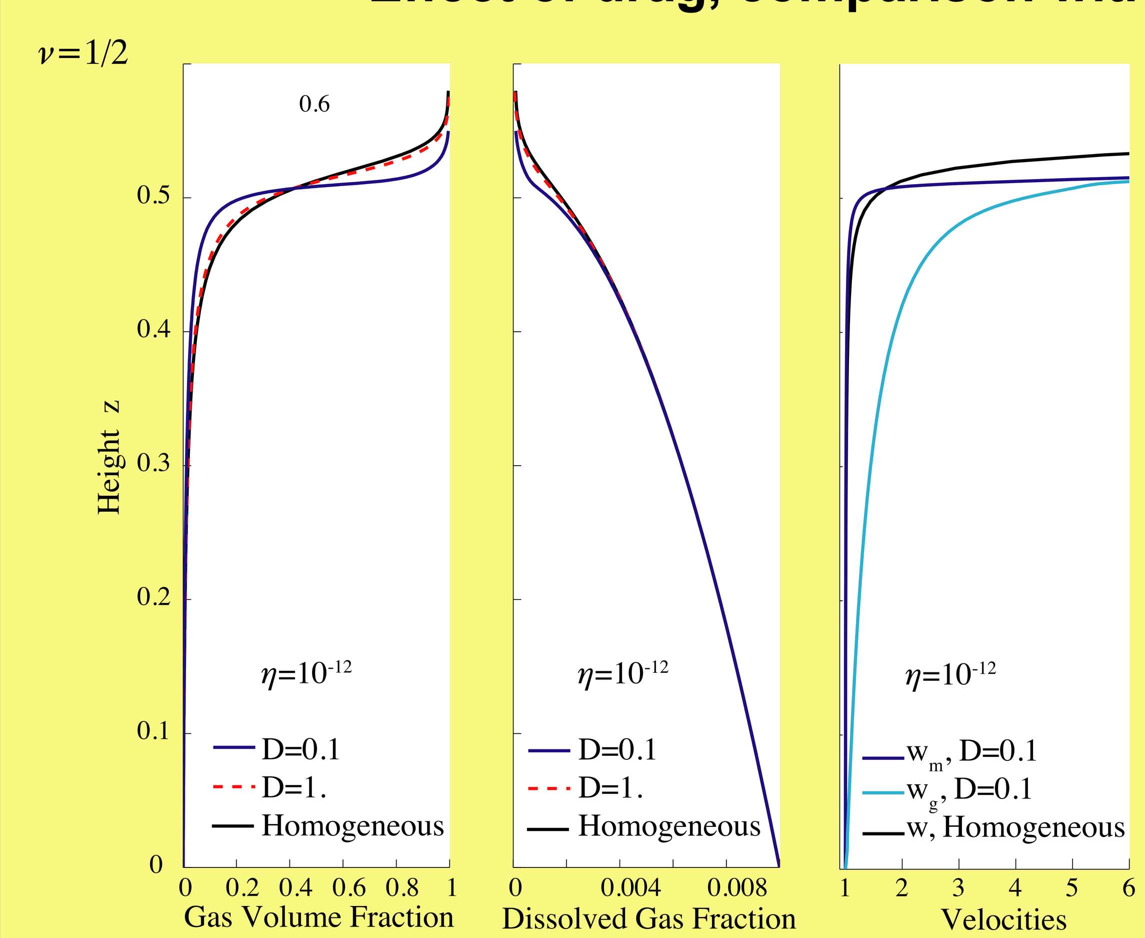
Starting with negligible amount of gas in magma, gas exsolution and decompression occur over a characteristic distance that decreases with η.

Effect of compaction comparison with single-pressure flows

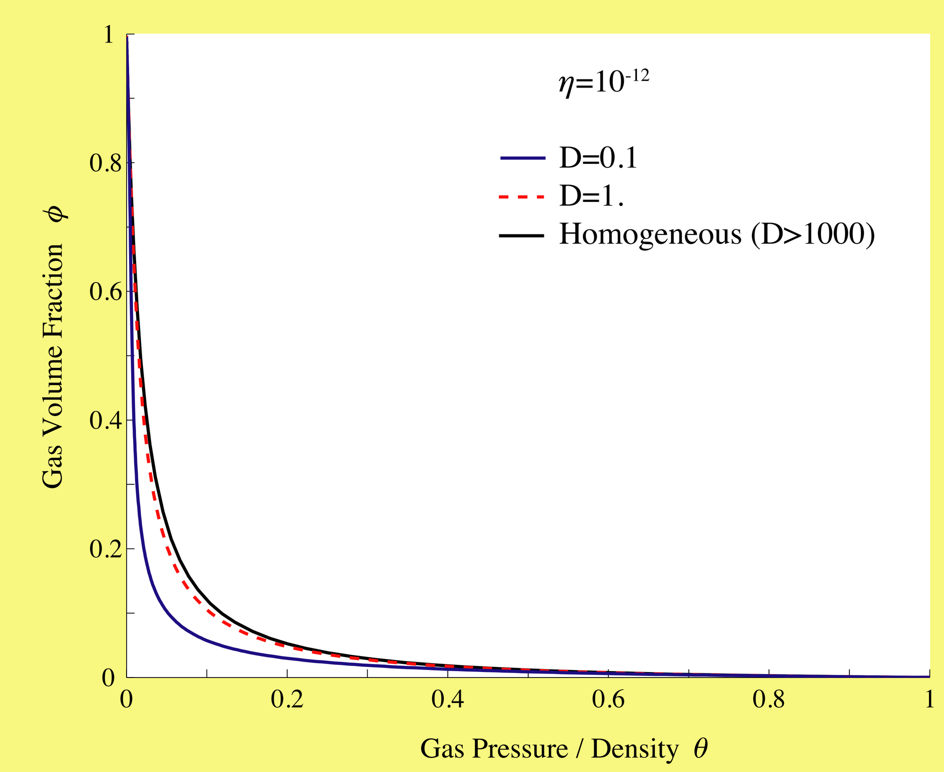


Compaction leads to larger gas pressure at a given depth, hence it delays exsolution. The increase in gas content with height is smaller relative to a single-pressure flow, but, for ϕ_0=0, the difference decreases as η increases.

Effect of drag, comparison with homogeneous flows



As the amplitude of the drag decreases, gas velocity increases and gas expels more rapidly. But, for smaller D, gas pressure (θ, hence X) is lower at a given height, and decompression and exsolution occur then over a shorter distance.

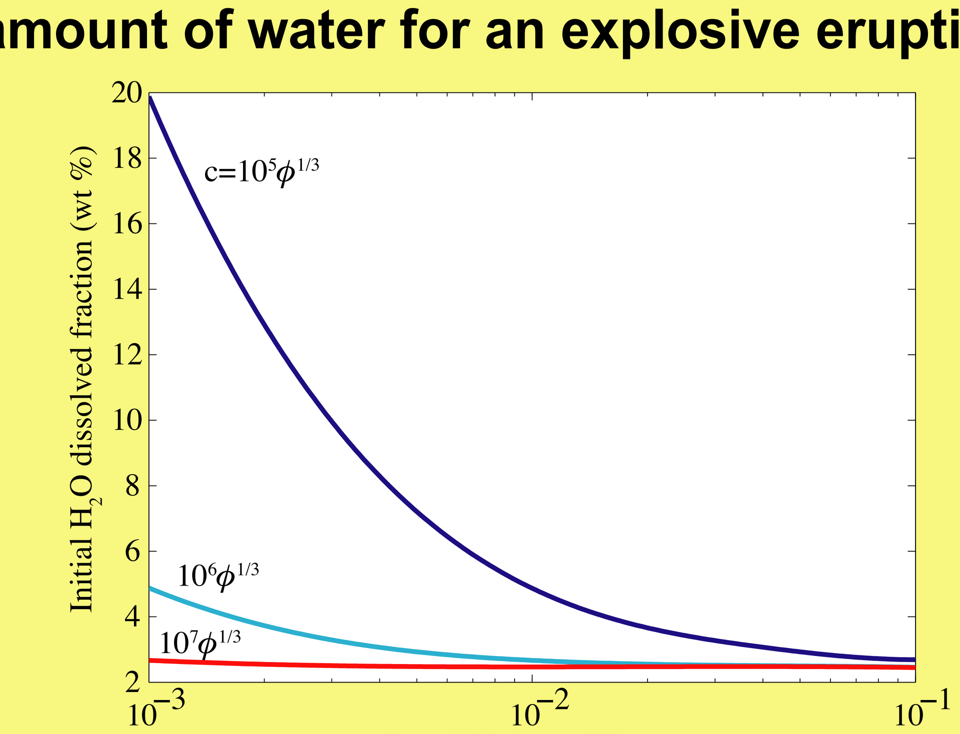


For a given gas pressure, ϕ is smaller for smaller D. Hence, for a given exit pressure and initial volatile fraction, there will be less gas at the exit for a two-phase flow relatively to a homogeneous flow.

Application: amount of water for an explosive eruption, example of Venus

On Venus, the atmospheric pressure is large: P_{atm}=9 MPa, and prevents extensive gas exsolution and decompression.

X=6.8 10^{-8} $P^{0.7}$ (for water in basaltic magmas)
μ_m=1 Pa s
ρ_m=2900 kg/m^3
ϕ_0=0
g=8.87 m/s^2
C_g^2=4.6 10^5 m^2/s^2
Exit Condition:
ϕ=75% at P=P_{atm}



The amount of water dissolved in basaltic magmas required for an explosive eruption on Venus Lowlands is much larger for a two-phase flow than for a homogeneous flow (~ 2.44 wt%), for relevant values of initial velocity and drag coefficient: explosive eruptions are definitely unlikely.

Conclusions

Compaction delays gas exsolution and decompression, as in the case of two-phase turbulent flow of gas and ash mixtures (Bercovici and Michaut, 2010), but this effect becomes negligible for relevant magma viscosities, if ϕ_0=0.

As the inter-phase drag decreases, gas velocity increases and gas pressure decreases, increasing exsolution and leading to a more rapid volatile expel from magma.

For a given exit pressure and dissolved volatile fraction the two-phase model leads to a decrease in the amount of gas at the exit relatively to a homogeneous flow, and hence more dissolved gas is required for an explosive eruption. Explosive eruptions are thus even less likely to occur on Venus.

Bibliography

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