Ascent and Compaction of Gas-rich Magma, Effects on Eruption Dynamics

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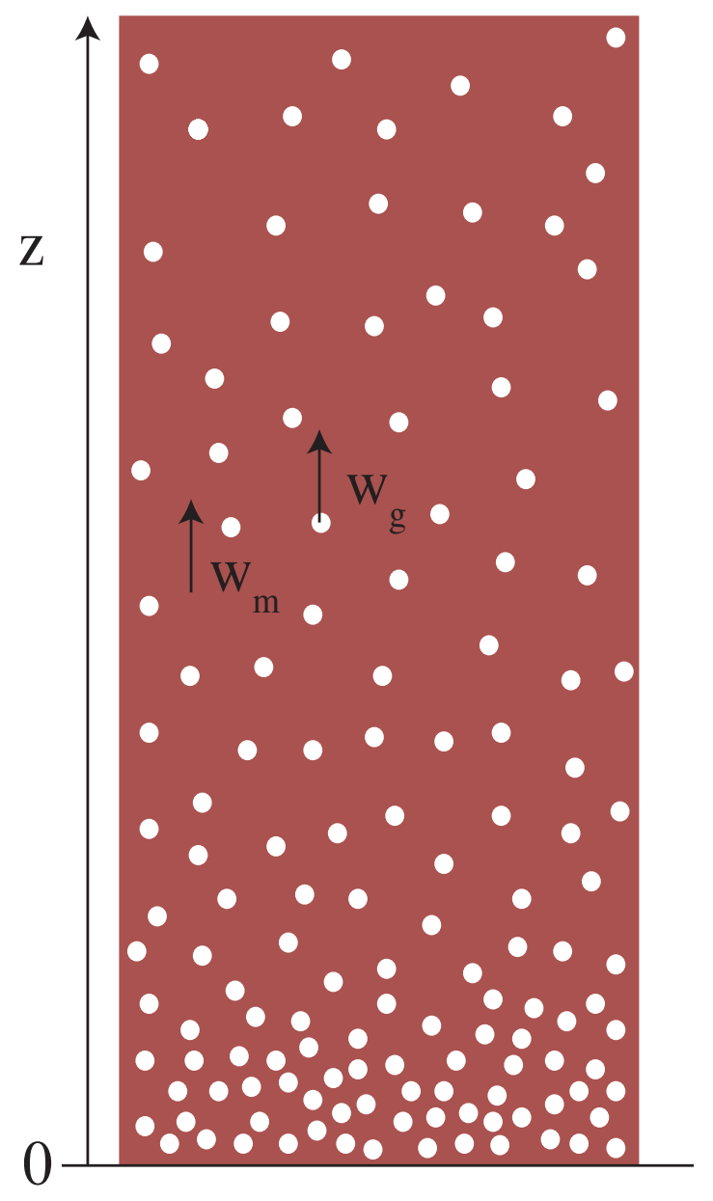
Gas segregation from magma is a crucial process in a volcanic conduit as it strongly influences the dynamics of an eruption. We use the two-phase flow theory developed by Bercovici et al (2001) to study how gas-rich magma compacts and gas segregates as magma ascends to the surface.

We consider the effects of hysteretic magma permeability, where the permeability depends on the history of gas volume fraction evolution and not only on a given gas volume fraction.

Results in a steady-state regime show that gas volume fraction and permeability decrease substantially with height as magma ascends and compacts in the conduit. In the case where the permeability is hysteretic, however, if the ascent velocity is small enough, the permeability profile shows a step where a low-permeability plug of degassed magma sits on top of vesiculated magma. This plug acts as a trap for gas rising from depth.

Time-dependent solutions in the form of solitary waves show indeed that gas pulses are far more concentrated in gas if the permeability is hysteretic, for a given amount, or flux, of gas. Such gas-rich pulses allow for more powerful eruptions and have important consequences on eruption dynamics and eruptive cycles.



Mixture of Gas (g) and Magma (m)

ϕ Volume fraction of gas

k(ϕ) Permeability in m^2

μ_m Magma viscosity, μ_g Gas viscosity

ρ_m Magma density, ρ_g Gas density

w vertical velocity

$\Delta q = q_m - q_f$

MASS CONSERVATION (MAGMA & GAS)

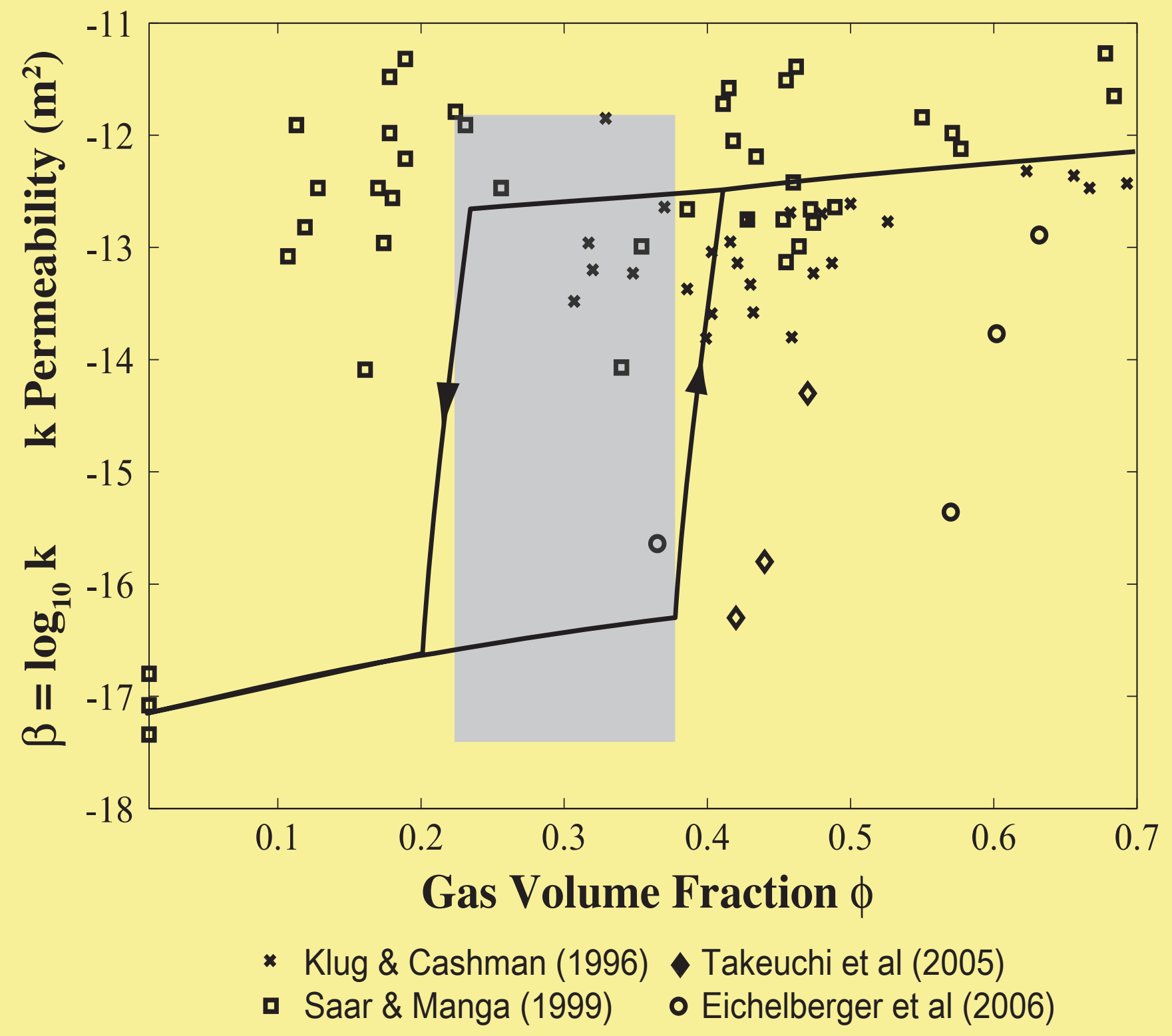
$$\frac{\partial(1-\phi)}{\partial t}+\frac{\partial}{\partial z}((1-\phi)w_m)=0$$

$$\frac{\partial\phi}{\partial t}+\frac{\partial}{\partial z}(\phi w_g)=0$$

1-D EQUATION FOR GAS SEGREGATION AND MAGMA COMPACTION

$$\underbrace{\frac{4}{3}\frac{\partial}{\partial z}\left(\frac{1-\phi^2}{\phi}\frac{\partial w_m}{\partial z}\right)}_{\text{MAGMA DEFORMATION}}-\underbrace{(1-\phi)\frac{\Delta\rho g}{\mu_m}}_{\text{BUOYANCY}}-\underbrace{\frac{\mu_g}{\mu_m}\frac{\phi}{k(\phi)}\Delta w}_{\text{INTERFACIAL DRAG}}=0$$

MAGMA PERMEABILITY HYSTERESIS

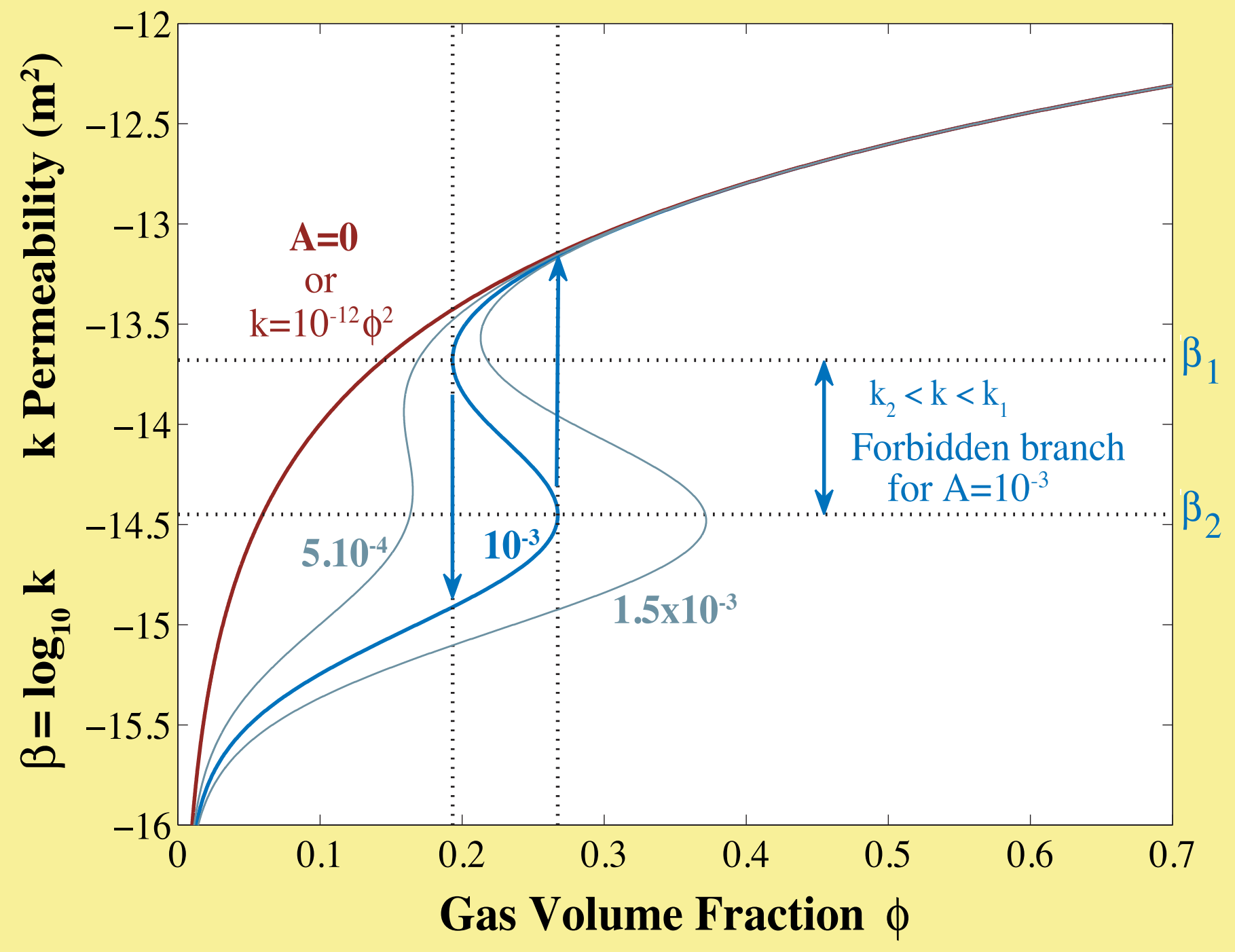


$$\phi = A\beta^2\times\exp^{-\left(\frac{\beta-b_1}{\Delta\beta}\right)^2}+10^{\frac{\beta-b_2}{2}}$$

$b_1 = -14.5$

$b_2 = -12$

$\Delta\beta = 0.5$



Hysteresis increases with increasing value of A.

STEADY-STATE REGIME

At z=0, the mixture is injected with a velocity W=w_m=w_g, and a given fraction of gas ϕ_i.

$$B=\frac{\Delta\rho g k_0}{\mu_g W}\qquad \nu = 4\mu_m/3\mu_g\quad k_0 = 10^{b_2}$$

Far from z=0, at z=∞, magma deformation is complete and the volume fraction of gas ϕ_∞ is given by:

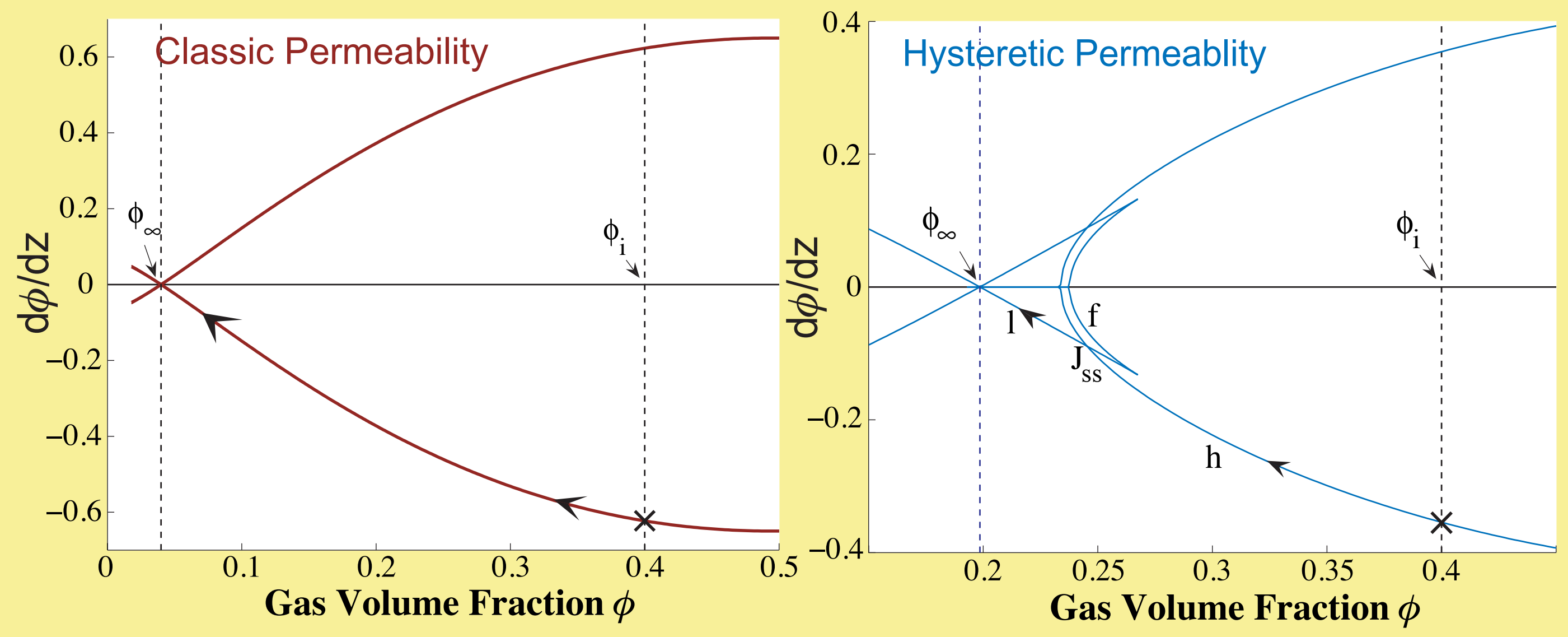
$$\phi_\infty-\phi_i+(1-\phi_\infty)^2 B\frac{k(\phi_\infty)}{k_0}=0$$

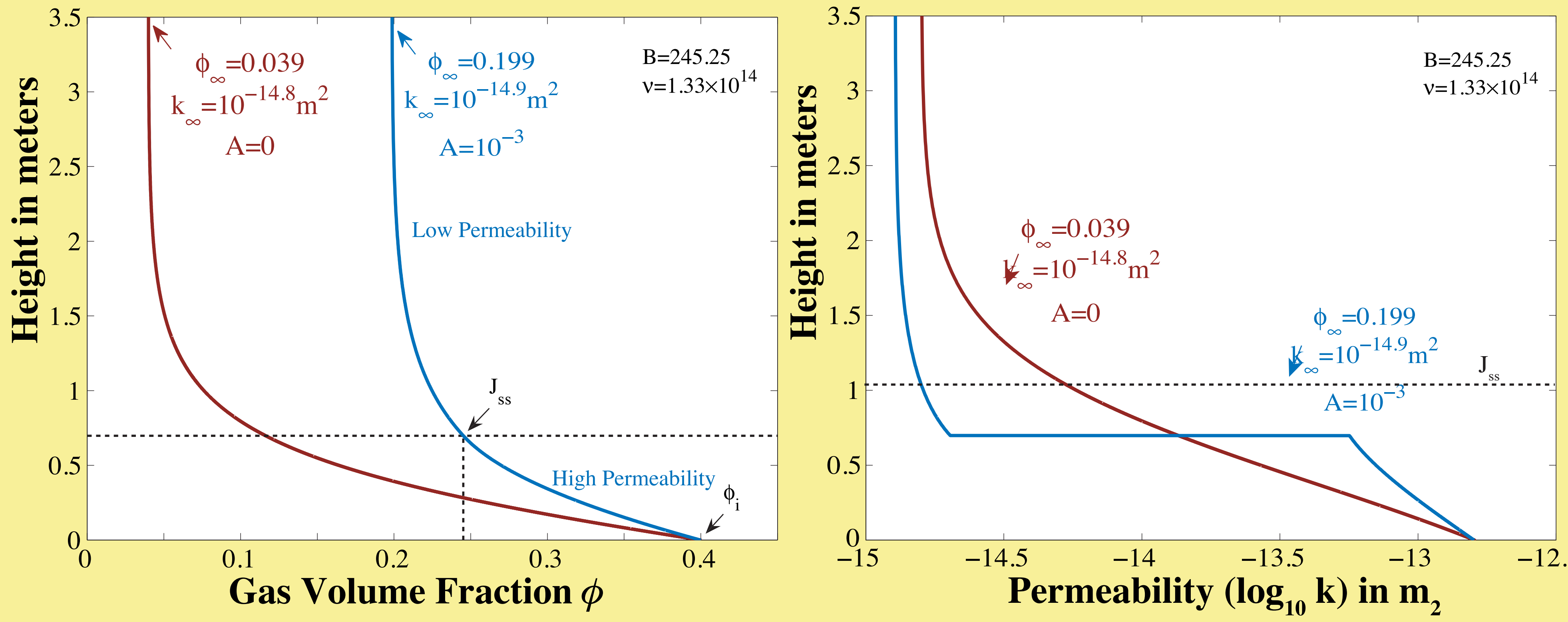
ϕ as a function of z is given by integration of:

$$\frac{d\phi}{dz}=\pm\left(\frac{2}{k_0\nu(1-\phi_i)}\right)^{1/2}\frac{(1-\phi)\phi}{(1+\phi)}\times$$

$$\left[B\left(\phi-\phi_\infty+\log\frac{\phi}{\phi_\infty}\right)+\int_{\phi_\infty}^{\phi}\frac{k_0}{k(\phi)}\frac{(1+\phi)(\phi-\phi_i)}{\phi(1-\phi)^2}d\phi\right]^{1/2}$$

COMPACTION OF ASCENDING MAGMA





Compaction of magma and gas segregation lead to a progressive decrease in gas volume fraction and to a decrease in permeability with height. The distance over which compaction occurs is very small: ~ 0.1 to 10 m

For a hysteretic permeability, if B (i.e. W) is small enough, the value of f at infinity reaches the low permeability branch and the permeability drops dramatically at a given height, such that a low-permeability plug sits on top of a gas-rich magma.

TIME-DEPENDENT REGIME: SOLITARY WAVE

$\phi = \phi(\eta)$ η=z-ut u: wave velocity

Far from η=0, at η=∞, the background fraction of fluid is $\phi = \phi_0$, the maximum value of ϕ in the wave is ϕ_{max}.

In the reference frame of the mean flow: $(1-\phi)\,w_m + \phi\,w_g = 0$

Nondimensionalisation using the compaction length δ, and a characteristic time for compaction τ:

$$\delta = \left(\frac{4\mu_m k_0}{3\mu_g}\right)^{1/2}\qquad \tau = \frac{\delta\mu_g}{k_0\Delta\rho g}$$

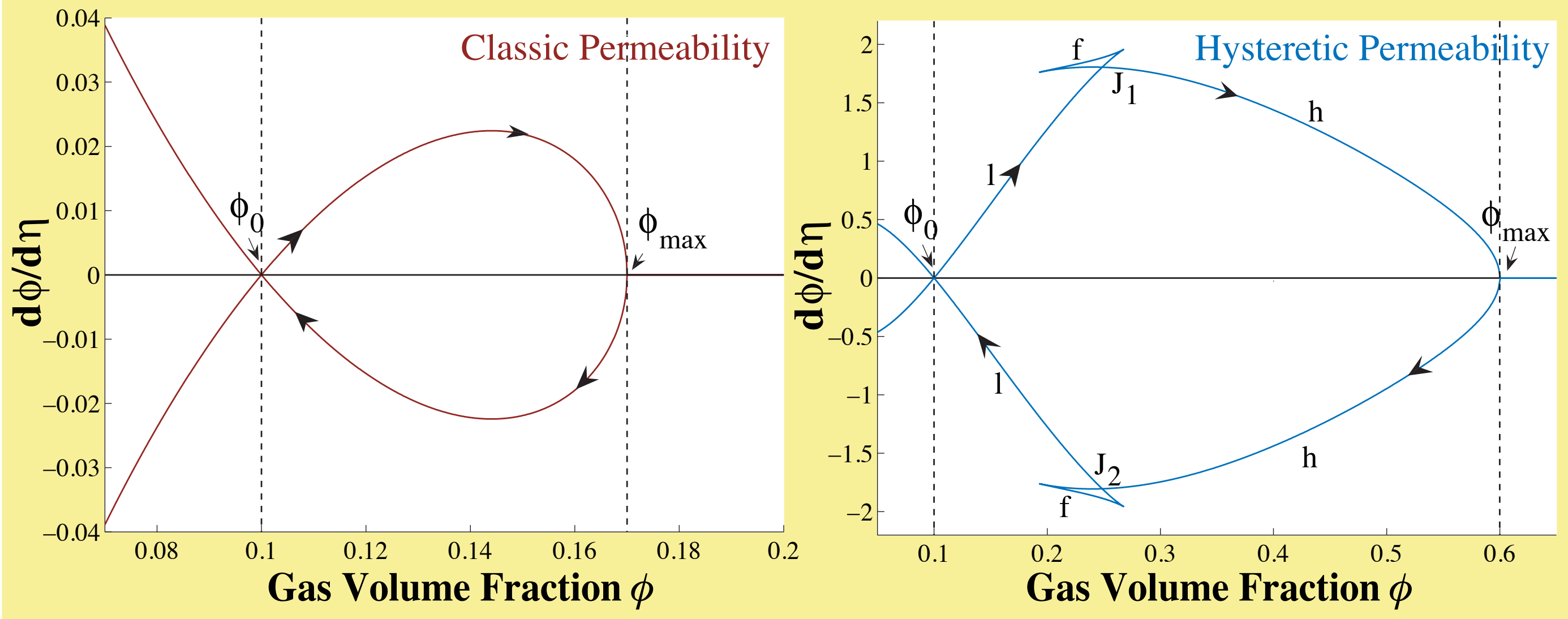
ϕ as a function of η is given by integration of:

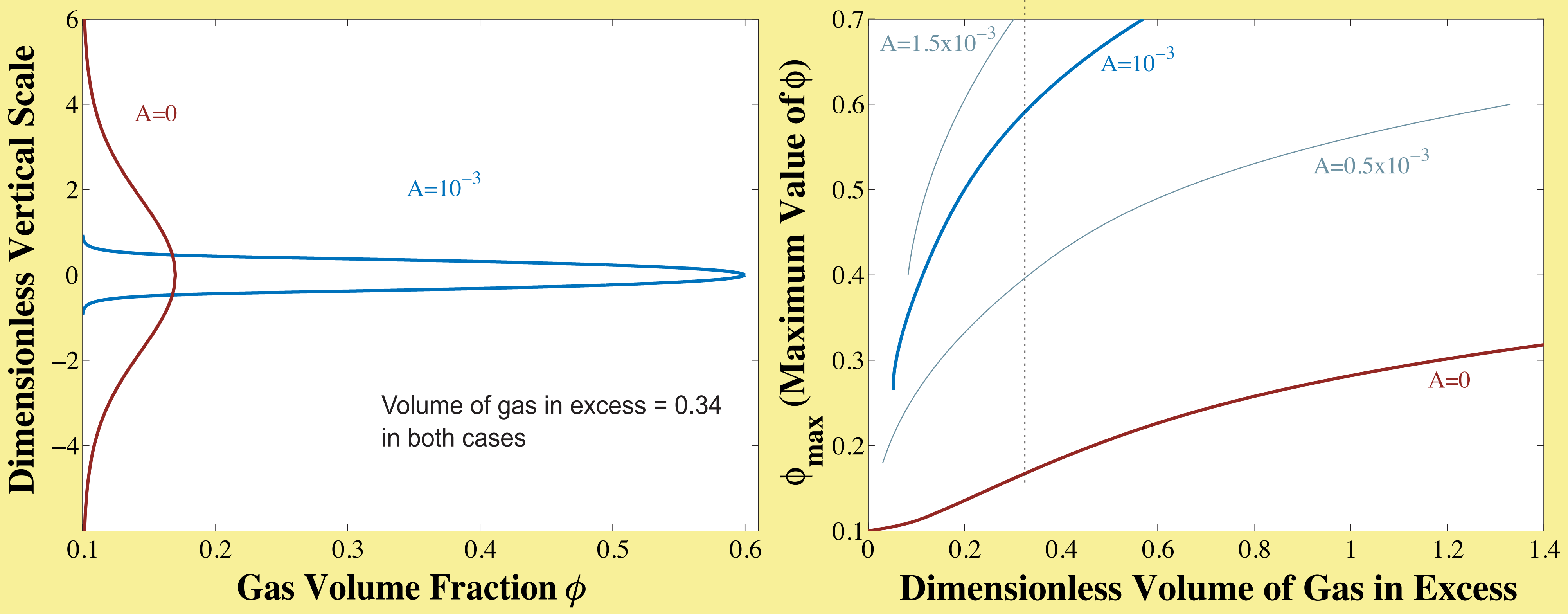
$$\left(\frac{d\phi}{d\eta}\right)^2=\frac{\phi^2(1-\phi)^2}{(1+\phi)^2}\frac{2}{u+C}$$

$$\int_{\beta_0}^{\beta}\left(-\frac{1+\phi}{\phi}+10^{b_2-\beta}\frac{(u\phi+C)(1+\phi)}{(1-\phi)^2\phi}\right)\frac{d\phi}{d\beta}d\beta$$

where C is given by: $C=(1-\phi_0)^2 10^{\beta_0-b_2}-u\phi_0$

TRANSPORT OF A GAS PULSE THROUGH THE DEGASSED MAGMA





In both cases, a transient gas pulse can be transported through a solitary wave of gas within the magma.

But, for a given volume of gas, the gas pulse is thinner and has a higher amplitude, i.e. is more concentrated in gas, for a higher value of A, i.e. a “larger” hysteresis.

A low-permeability plug of degassed magma can form by compaction and gas segregation over a short distance (0.1 to 10 m) in a volcanic conduit during the slow ascent of a gas-rich magma.

In the case of a hysteretic permeablity, the permeability drops dramatically, and the plug acts as a trap for gas rising from depth.

An additional gas pulse, released by a transient episode of exsolution for instance, is transported through a solitary wave in the magma, for both the classic and hysteretic permeability. But the wave is much more concentrated in gas and much thinner in the hysteretic case, allowing for more powerful eruptions.

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