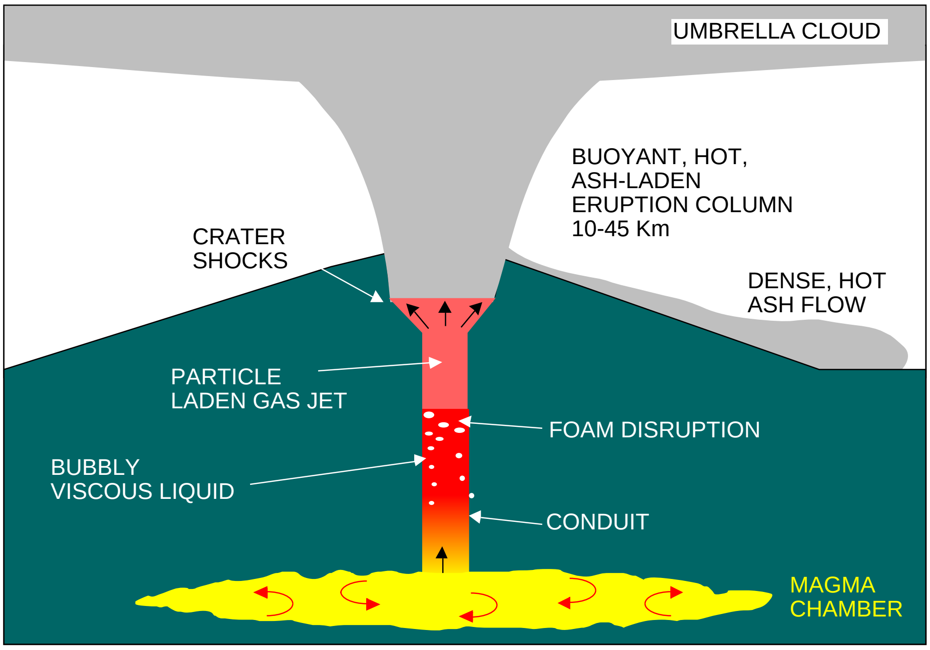
8. EXPLOSIVE VOLCANISM


UMBRELLA CLOUD

BUOYANT, HOT,
ASH-LADEN
ERUPTION COLUMN
10-45 Km

CRATER
SHOCKS

DENSE, HOT
ASH FLOW

PARTICLE
LADEN GAS JET

FOAM DISRUPTION

BUBBLY
VISCOUS LIQUID

CONDUIT

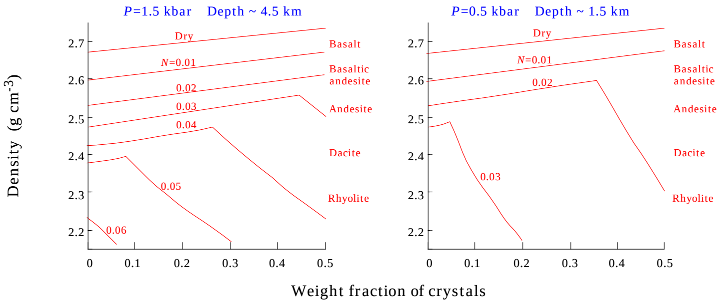
MAGMA
CHAMBER

---

1. Magma chamber processes

Pressure increases in the magma chamber due to tectonic movement, crystallization, gas release..., which eventually leads to disruption of the surrounding country rock and a potential eruption.

(e.g. H^2, Sparks and Turner, 1982 and 1983)

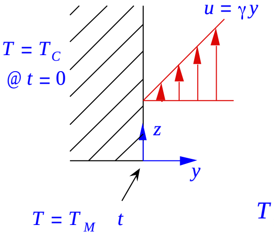


Density of wet magma as a function of the weight fraction of crystals for various total weight fractions of water N .

2. Dry magma ascent

i) Dry magmas ascend up a conduit very much like long gravity currents, under an interplay of fluid mechanics, thermodynamics and elasticity.

a) Fluid mechanics and thermodynamics



$T = T_H\ @\ t = 0$

HOT SHEAR FLOW IN CONTACT WITH A COLD WALL

- LOCAL RATE OF FREEZING $v(z, t)$
- <u>INSTANTANEOUS</u> DISTANCE FROM WALL y

$$T_t - vT_y + \gamma\, y T_z = \kappa T_{yy} \quad (y > 0) \quad \text{ADVECTION-DIFFUSION}$$

$$T_t - vT_y = \kappa T_{yy} \quad (y < 0) \quad \text{DIFFUSION}$$

$$Lv = -\kappa c \left[T_y\right]_-^+ \quad \text{INTERFACIAL B.C.}$$

$$T = T_M \quad (y = 0)$$

$$T = T_H \quad (y \to \infty \ \text{ OR } \ t = 0,\ y > 0 \ \text{ OR } \ z = 0,\ y > 0)$$

$$T = T_C \quad (y \to -\infty \ \text{ OR } \ t = 0,\ y < 0\ )$$

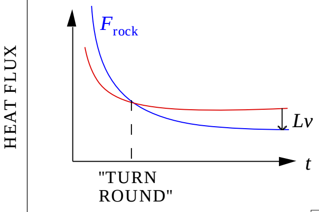
SOLVE SEMI-NUMERICALLY TO ALLOW FOR $\gamma(t)$

(BRUCE AND H^2, 1989)

$$Lv = F_{\text{rock}} - F_{\text{melt}}$$

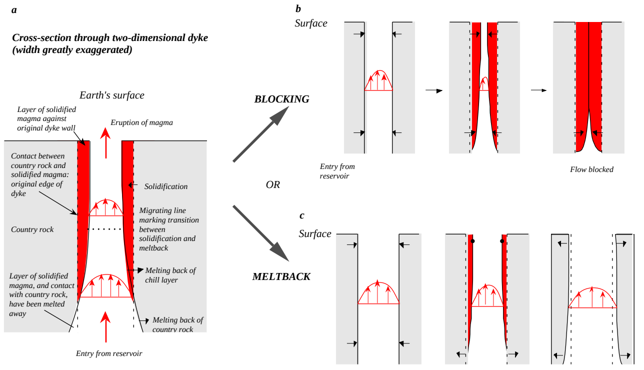
$v > 0$ FREEZING

$v < 0$ MELTING



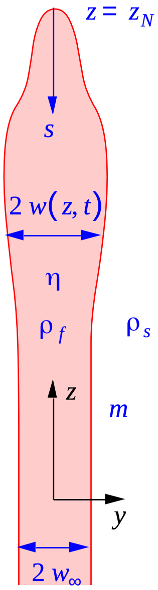
LARGE z, SMALL t	$F_{\text{rock}} > F_{\text{melt}}$	FREEZING
SMALL z, LARGE t	$F_{\text{rock}} < F_{\text{melt}}$	MELTING

Does turnaround point reach the top of the channel before it freezes up?



The evolution of a two-dimensional dyke
a. *State at an instant during initial development*
b. *Development during blocking*
c. *Development of turnaround and meltback.*

b) Fluid mechanics and elasticity



2-D SOLUTION

SOURCE FLUX q (constant)

$$\frac{\partial w}{\partial t} + \frac{\Delta\rho\, g}{3\eta}\frac{\partial w^3}{\partial z} = \frac{1}{3\eta}\frac{\partial}{\partial z}\left(w^3 \frac{\partial\, \Delta P}{\partial z} \right)$$

BUOYANCY ELASTICITY

$$w_\infty = \left(\frac{3\,\eta v}{\Delta\rho\, g} \right)^{\frac{1}{2}} \quad \text{with propagation rate} \quad v = \frac{q}{2\,w_\infty}$$

solve numerically for $w(s = z - vt)$

$$q = 2.5\,m^2 s^{-1} \qquad w_\infty \approx 0.5\,m, \quad v \approx 2.5\,ms^{-1}$$

ii) For "wet" magmas, small exsolved vapour bubbles travel with the magma,

$v_b \sim 10^{-15\text{ to }-6}\text{cm s}^{-1} << v_m \sim 10^{1\text{ to }4}\text{cm s}^{-1}$ with ν increasing by 10 for every 1 wt % of volatiles exsolved.

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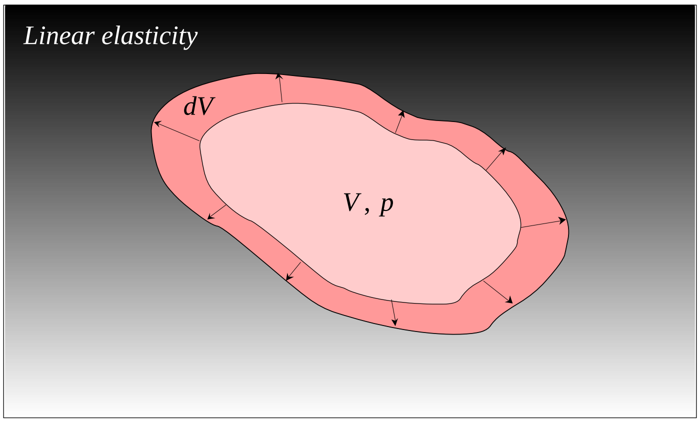
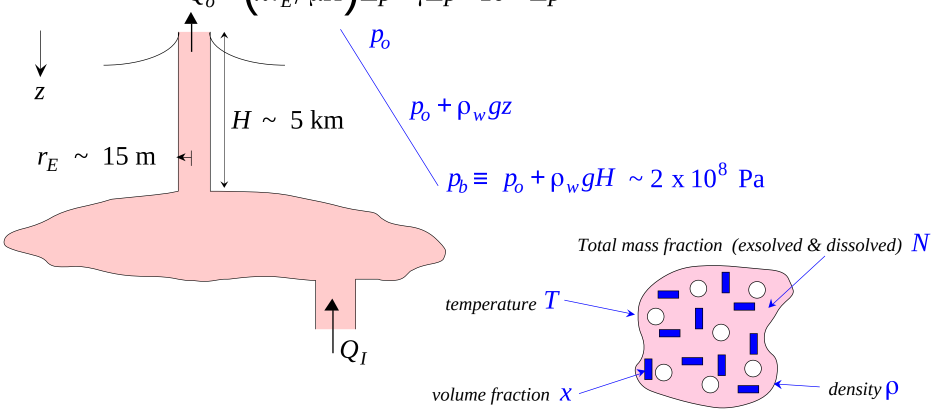
3. Wet magma ascent



β : *bulk modulus* $\qquad \dfrac{Vdp}{\beta} = dV \qquad (*)$

Most general equation $\qquad f(p\,;\underset{\sim}{x})\,dp = dV \qquad (\quad)$

$$Q_o = \left(\pi r_E^2/\mu H\right)\Delta p \equiv \gamma\Delta p \sim 10^{-6}\Delta p$$



Mass conservation $$\frac{d}{dt}(\rho V) = \rho\frac{dV}{dt} + V\frac{d\rho}{dt} = Q_I - Q_0 \equiv Q \qquad (1)$$

Density relationship $$\rho = \rho\left[p, T, x(T), N\right] \qquad (2)$$

$$\frac{dV}{dt} + \frac{V}{\rho}\frac{\partial\rho}{\partial p}\frac{\partial p}{\partial t} = \frac{Q}{\rho} - \frac{V}{\rho}\frac{\partial\rho}{\partial t}\frac{dT}{dt} \qquad (3)$$

Rock elasticity $Vdp = \beta_r\, dV$ (β_r rock bulk modulus ~ 10^{10} Pa) (*)

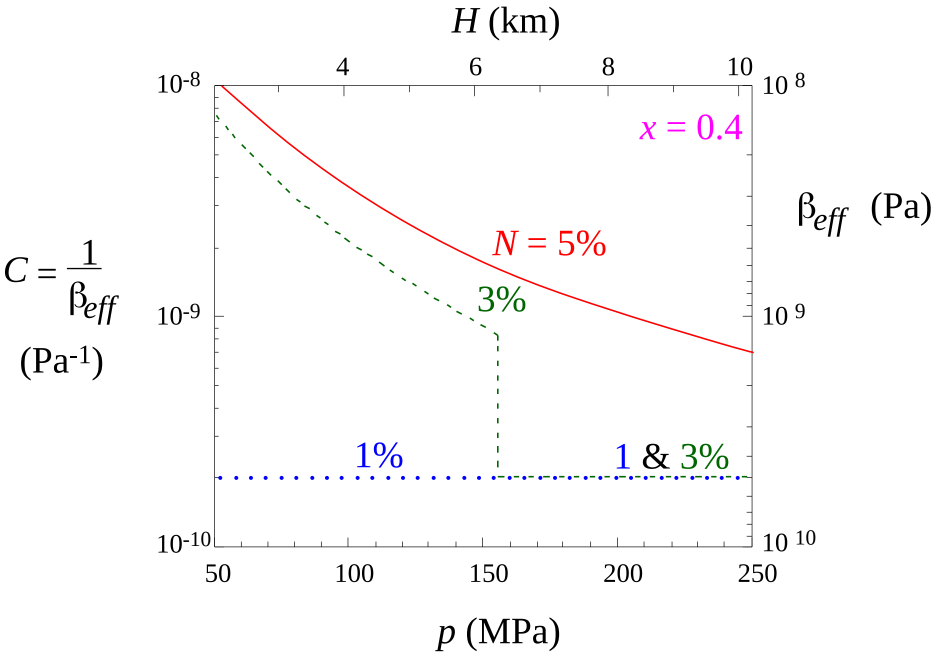
$$V\left[\frac{1}{\beta_r} + \frac{1}{\rho}\frac{\partial\rho}{\partial p}\right]\frac{dp}{dt} = \frac{Q}{\rho} - \underbrace{\frac{V}{\rho}\frac{\partial\rho}{\partial T}\frac{dT}{dt}}_{\text{effective thermal expansion}} \qquad (4)$$

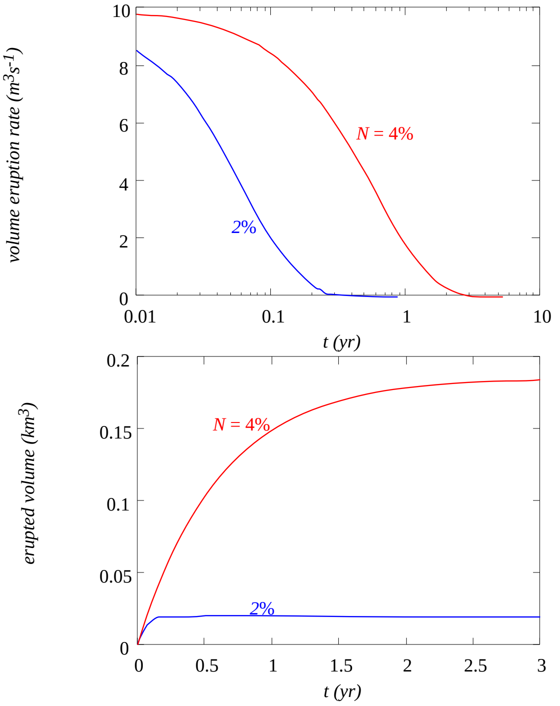
$$\left(V/\beta_{eff}\right)\frac{dp}{dt} \equiv \qquad (**)$$

Solubility $$n = N - sp^{1/2}(1-x) \qquad (5)$$

n mass fraction of exsolved volatiles; s solubility constant ~ 3 x 10^{-6} $\mathrm{Pa}^{-1/2}$

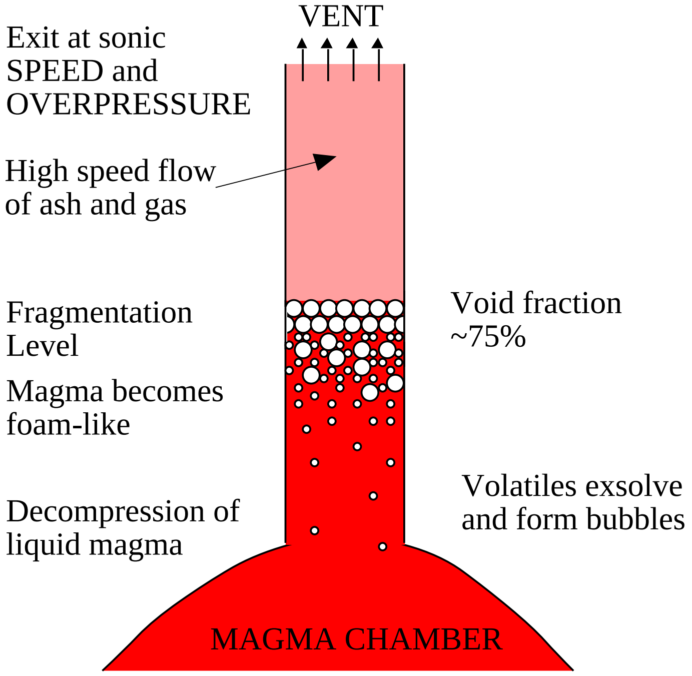
Density relationship $$\rho = \left[\underbrace{\frac{n\mathrm{PT}}{p}}_{\text{(gas)}} + (1-n)\left(\underbrace{\frac{x}{\sigma_c}}_{\text{(crystals)}} + \underbrace{\frac{1-x}{\sigma_m}}_{\text{(melt)}}\right)\right]^{-1} \qquad (6)$$





H^2 & Woods (2002, 2003)

4. Steady conduit dynamics



VENT

Exit at sonic SPEED and OVERPRESSURE

High speed flow of ash and gas

Fragmentation Level

Magma becomes foam-like

Decompression of liquid magma

Void fraction ~75%

Volatiles exsolve and form bubbles

MAGMA CHAMBER

Equations for steady homogeneous flow in pipe

mass conservation $\rho u A = Q$ (1)

momentum conservation $\rho u \frac{du}{dz} = -\frac{dp}{dz} - \rho g - f$ (2)

friction

density $1/\rho = (1-n)/\rho_s + nRT/p$ (3)

solid + gas

volatile content $n = n_0 - sp^{1/2}$ Henry's law (4)

constant

friction $f \sim \frac{1}{12}\mu u / r^2$ (viscous liquid) (5a)

$\sim 0.001\rho u^2/r$ (~ 0) (turbulent gas) (5b)

void fraction $\phi = \left[1 + \frac{(1-n)\,p}{nRT\rho_s}\right]^{-1}$ (6)

fragmentation at about $\varphi = 75\%$

(1), (2), and (3) $$\frac{dp}{dz}\left(1-\frac{u^2}{a^2}\right)=-\rho g-f \qquad (7)$$

where sound speed $$a^2 = dp/d\rho = a^2(p) \qquad (8)$$

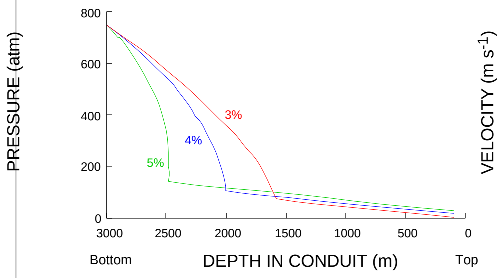
with $$a \approx 0.95\,(n_0 RT)^{1/2} \qquad (9)$$

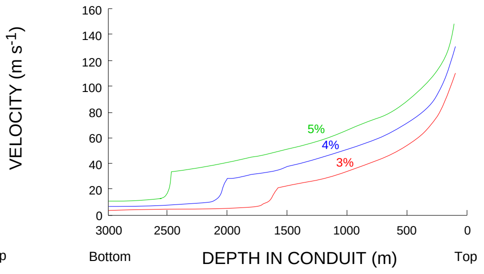
Integrate equations from

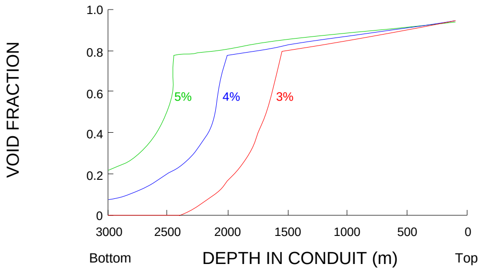
$p = p_0$ $(z = 0)$ (in chamber) (10)

$p_e = p_a$ OR $u = a$ $(p_e > p_a)$ $(z = H)$ (at surface) (11)

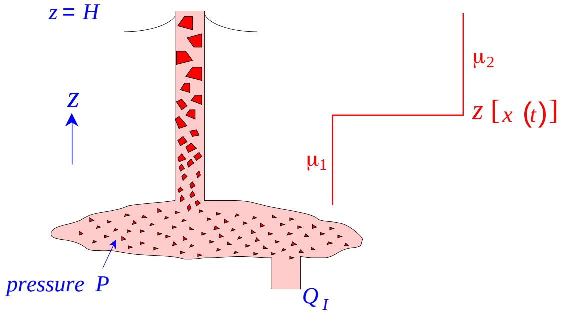
exit pressure

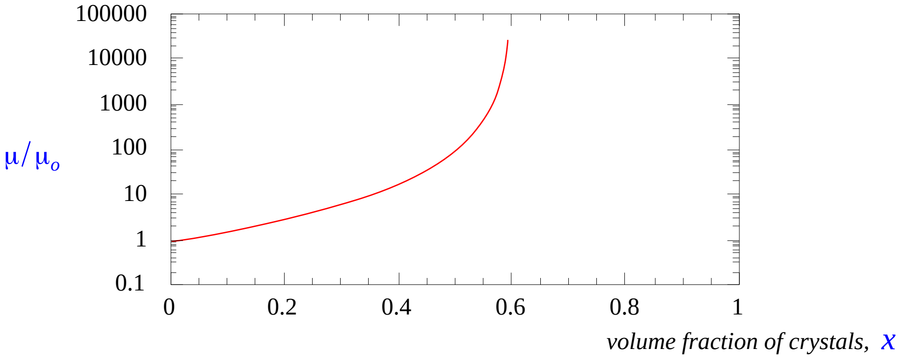






5. Crystals in conduits





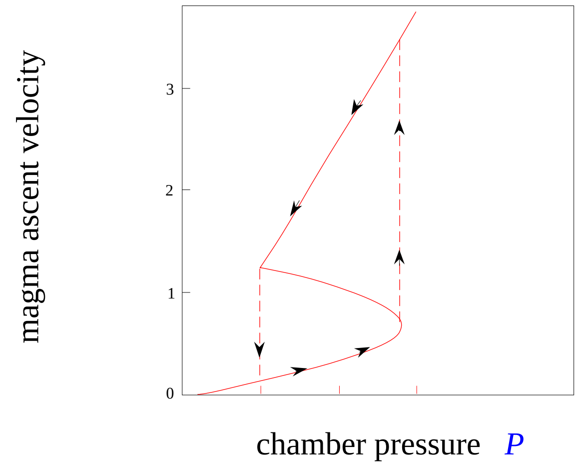
mass conservation $\frac{\partial}{\partial t}\rho + \frac{\partial}{\partial z}\rho w = 0$ $w(z,t)$: *vertical velocity*

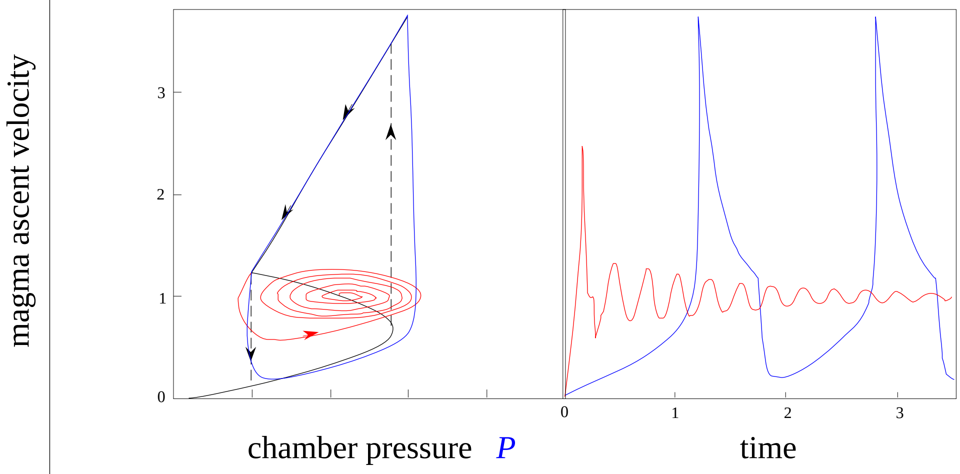
momentum conservation $\frac{\partial p}{\partial z} = -\rho g - \frac{8\mu w}{r_E^2}$

crystal growth $\frac{\partial x}{\partial t} + w\frac{\partial x}{\partial z} = 4\pi\Gamma\phi r^2 = (36\pi\phi)^{1/3}\Gamma x^{2/3}$

number density of crystals $\phi\,(z, t)$;
crystal radius $r\,(z, t)$;
constant linear crystal growth rate Γ

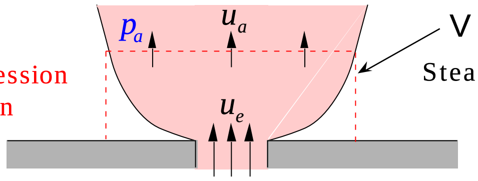
boundary conditions $z = 0$ $\frac{dP}{dt} = \frac{\beta}{V}(Q_I - Q_0)$; $x = x_o$
$z = H$ $p = p_{atm}$


magma ascent velocity
3
2
1
0
chamber pressure P


magma ascent velocity
3
2
1
0
chamber pressure P
0
1
2
3
time

Melnik (1999)

6. Simple decompression phase over flat ground



Decompression region

V

Steady, no entrainment, gravity or friction

Sonic speed $a \sim 0.95(n_o RT)^{1/2}$ and overpressure $5 < p_e / p_a < 100$

$$\nabla.(\rho \mathbf{u}) = 0 \qquad \text{(cty)} \quad (1)$$

$$\rho(\mathbf{u}.\nabla)\mathbf{u} = -\nabla p \qquad \text{(momentum)} \quad (2)$$

$$\rho(\mathbf{u}.\nabla)\left[C_v T + p/\rho + u^2/2\right] = 0 \qquad \text{(enthalpy)} \quad (3)$$

Integrating over a control volume, V

$$(1) \qquad \rho u A = Q \qquad (4)$$

$$(2)\&(4) \qquad u_a = u_e + A_e(p_e - p_a)/Q \qquad (5)$$

$$\approx 1.8(n_o RT)^{1/2} \approx 250 - 400 \ \mathrm{ms}^{-1}$$

$$(3)\&(5) \qquad T_a \approx T_e \approx 10^3 \ \mathrm{K}$$

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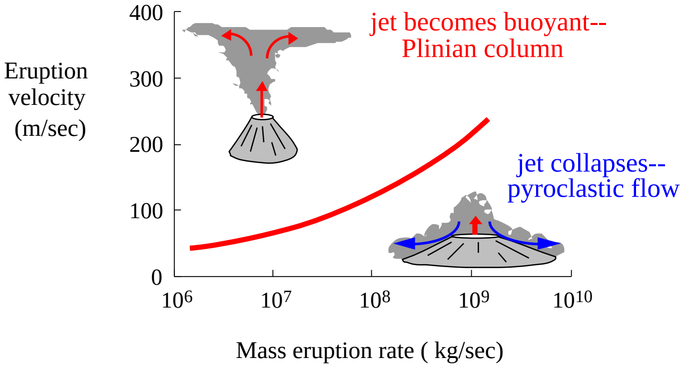
7. The physics of eruption columns

Conversion of thermal energy to potential energy in dense, hot, decelerating jet.

If mixture becomes less dense than air before upward momentum exhausted → BUOYANT PLUME

If not, jet collapses → GROUND HUGGING ASH FLOW

Quantitative analysis in terms of entraining plume models of Morton, Taylor and Turner (1956)

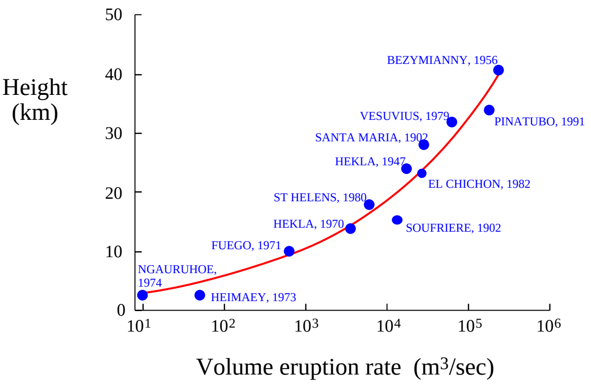


Using standard atmospheric values

$$H = 0.0082 Q^{1/2}$$

$$Q = \rho_e c_e V_e \left(T_e - T_a\right)$$

Q : Thermal energy production rate (kW)



8. Important concepts

- Pressure increase in magma chambers
- Dry magmas ascend under influence of pressure release, fluid mechanics, thermodynamics and elasticity
- Wet magmas exsolve water vapour as they rise
- At fragmentation level, liquid film surrounding gas bubbles fracture and material evolves from a bubbly liquid (with solids) to an ash-laden gas (with small pockets of liquid) at around $\phi = 75\%$
- Eruption decompresses to enter atmosphere between 250 and 400 m s^{-1}
- Large base velocity and small flux produces buoyant plume,
  while small base velocity and large flux produces pyroclastic flows
- Energy in natural events greatly dominates that in those due to man (controlled or otherwise)
- 12 of the 16 largest volcanic eruptions in the last 200 years occurred at sites believed to be inactive

Lecture 8. Explosive Volcanism

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