The role of particle-scale processes on eruption dynamics

Michael Manga

Department of
Earth and Planetary Science
University of California, Berkeley

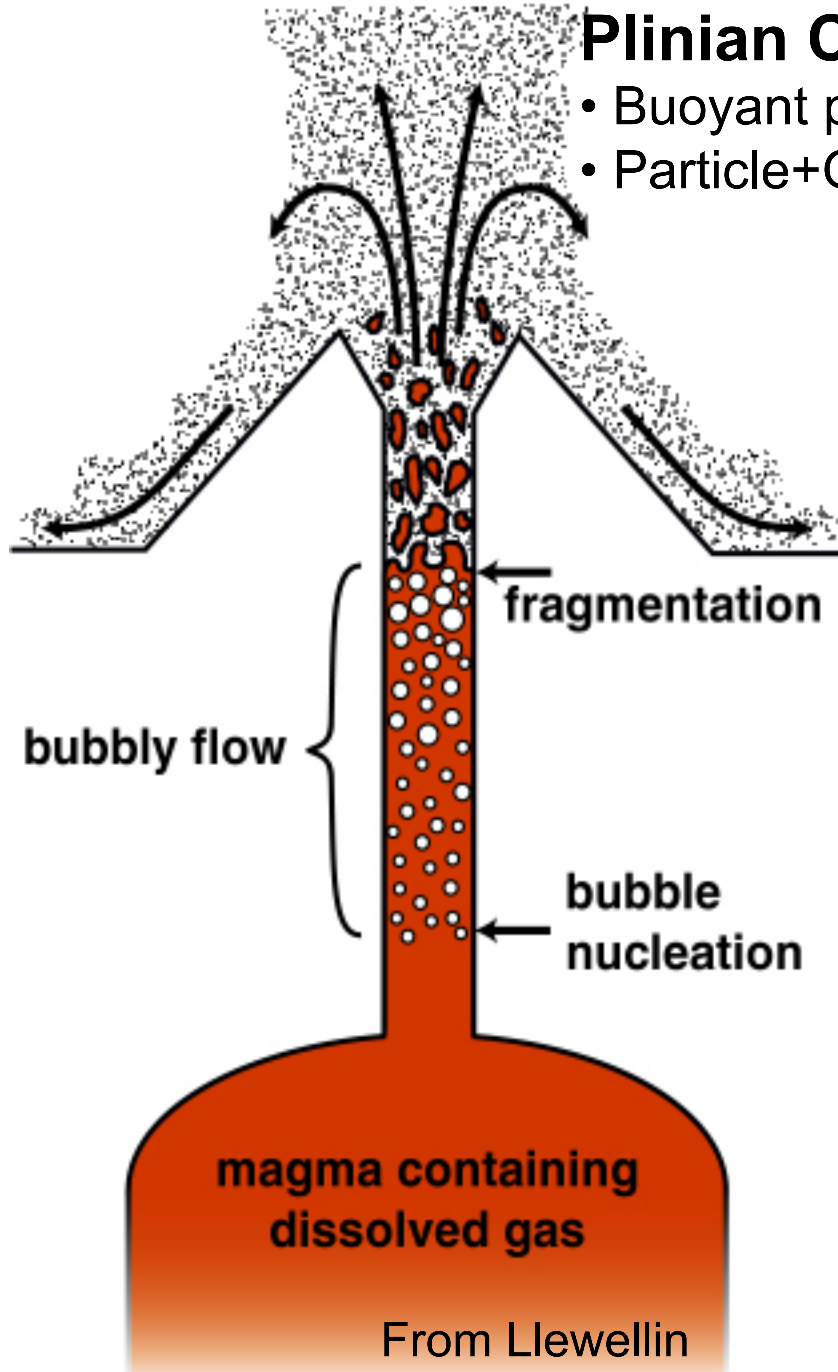
Simulations by Josef Dufek (now GA Tech), Helge Gonnermann (Rice)

Experiments by Ben Andrews (now Smithsonian), Bruno Cagnoli (now INGV, Rome) Marcel Staedter, Daniel Standish, Jason Wexler, Ameeta Patel, Wylie Stroberg, Rebecca Carey (UC Berkeley)

Mutiphase flows in explosive eruptions

Pyroclastic Flow
- Particulate gravity current
- Particle+Gas Flow
- Interaction with water

Plinian Column
- Buoyant plume
- Particle+Gas Flow



From Llewellin

Challenge

- Wide range of length and time scales
- Many critical processes occur at the scale of particles and bubbles

- How to integrate the micro- and macro-scale mass, momentum and heat transfer?

Challenge

- Wide range of length and time scales
- Many critical processes occur at the scale of particles

- How to integrate the micro- and macro-scale mass, momentum and heat transfer?

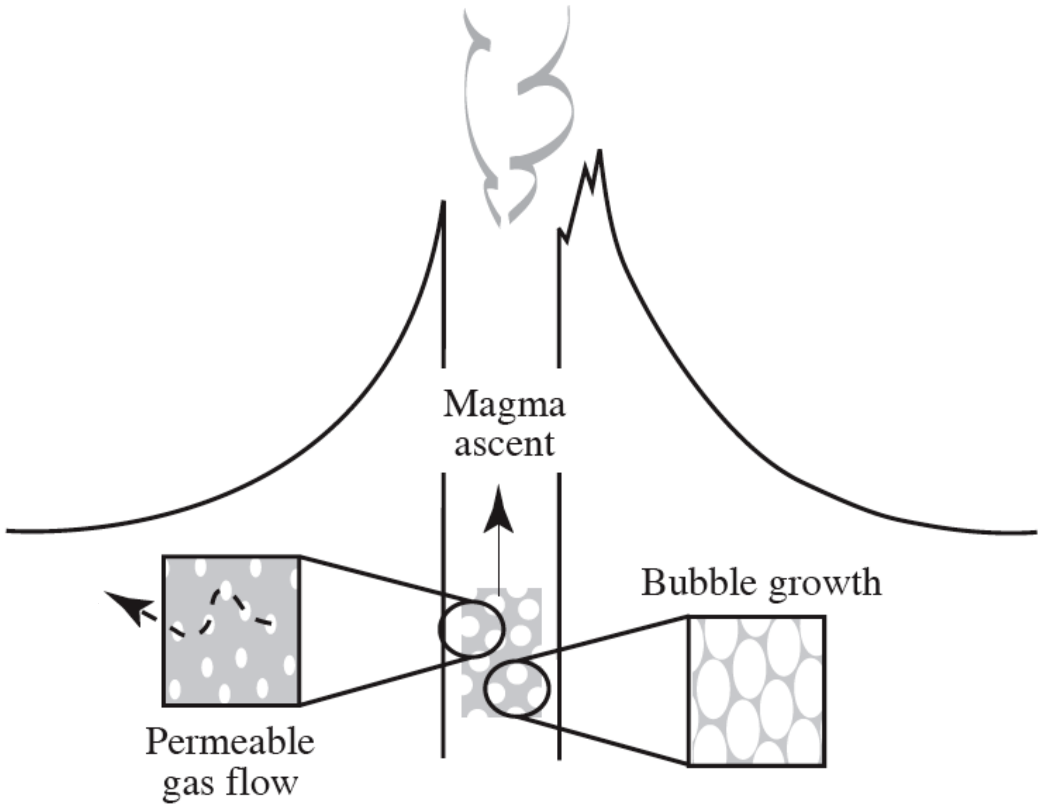
Today: 1) Review conceptual approach used in modeling and then our attempts to 2) use laboratory experiments to develop models for the micro-scale

Prior to fragmentation

- Nucleation and growth of bubbles
- Creating of permeability
- Feedback on rheology and melt composition

Numerical model

Solve equations for conservation of mass, momentum, energy at two scales



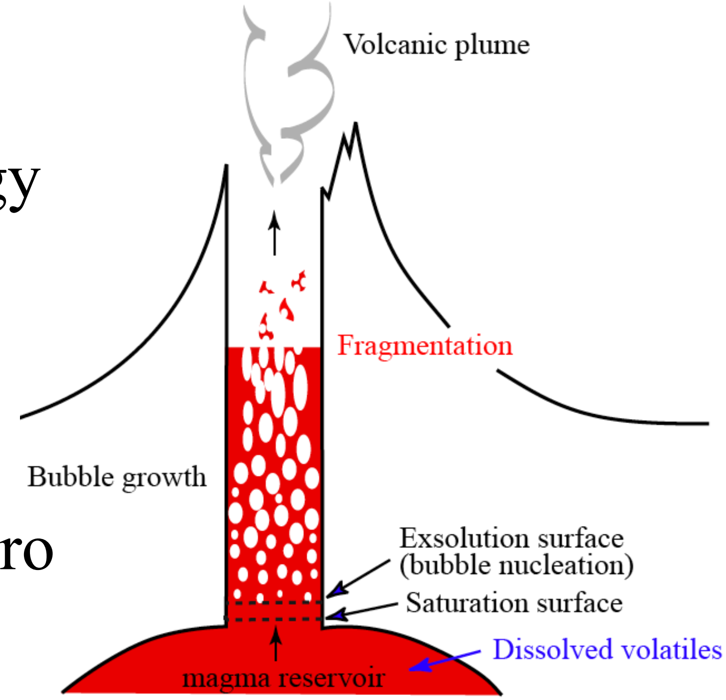
1) Conduit flow:
magma (bubbles+ melt) is locally homogeneous

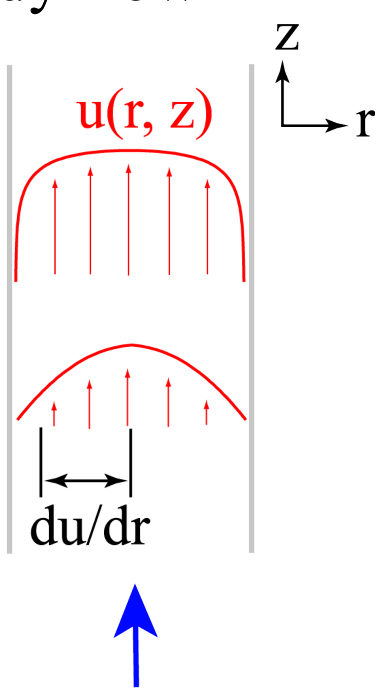
2) Bubble-scale:
Solve for growth of bubbles, determine rheology

Feedbacks between scales through temperature, pressure

Conduit flow

- conservation of mass, momentum, energy
  (include viscous dissipation;
density, rheology from subgrid model)
- non-turbulent, no fragmentation,
- “single” phase magma (melt + bubbles)
- cylindrical conduit , radial velocity is zero
- steady flow





Q_{mass} = const.

$$-\frac{r}{2}\left(\frac{\partial p_m}{\partial z} + \rho g\right) = -\eta \frac{du_z}{dr}$$

$$\eta = \eta(\dot{\gamma}, T_m, \phi, R, c_w)$$

$$\frac{DT_m}{Dt} = \left[D_T\left(\frac{\partial^2 T_m}{\partial r^2} + \frac{1}{r}\frac{\partial T_m}{\partial r}\right) - \frac{1}{\rho_m c_{pm}}\left(\sigma_{rz}\frac{\partial u_z}{\partial r}\right)\right]$$

Conduit flow

- conservation of mass, momentum, energy
  (include viscous dissipation; density, rheology from subgrid model)
- non-turbulent, no fragmentation, cylindrical conduit
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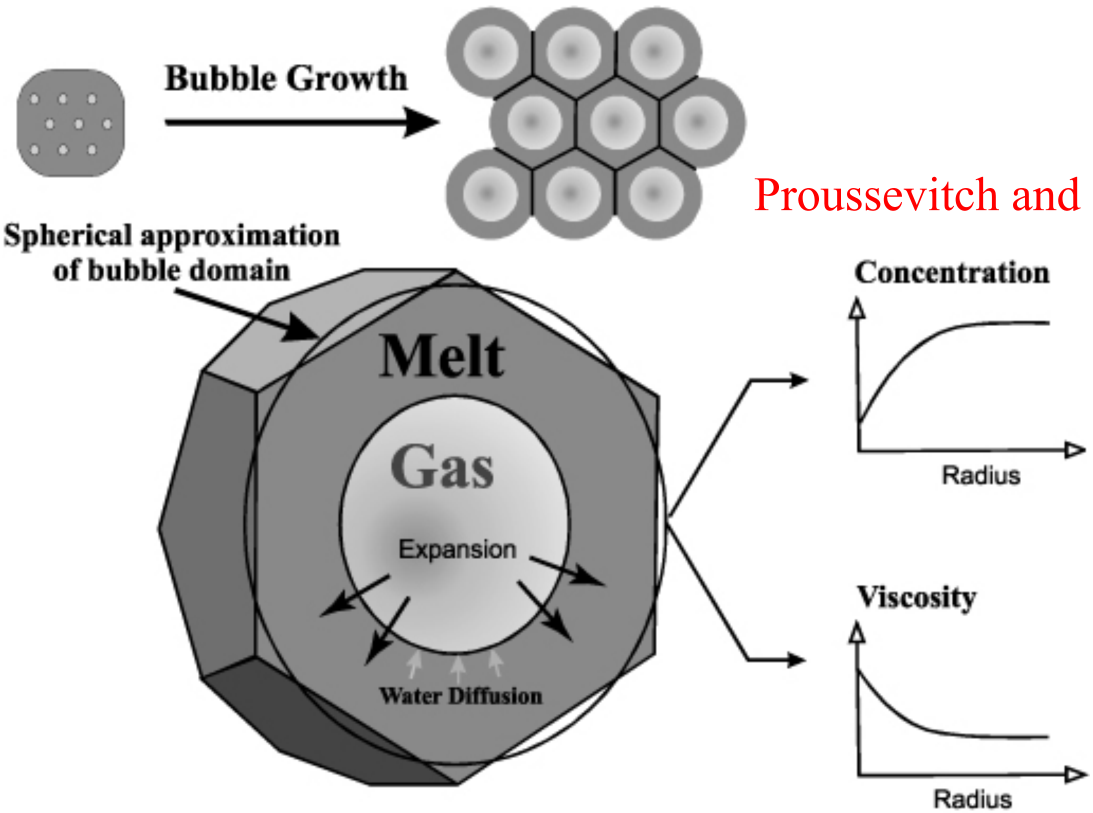
Subgrid model: Volatile exsolution and bubble growth

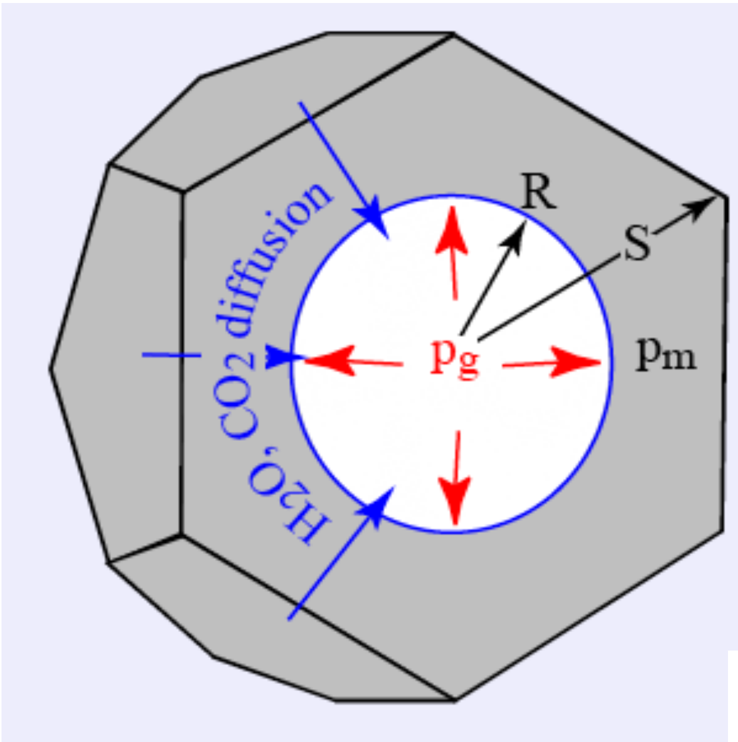


Proussevitch and Sahagian (1998)

Solubility of H_20, CO_2 from Liu et al. (2005)

Diffusivity of H_20, CO_2 from Zhang and Behrens (2000)

Subgrid model: Volatile exsolution and bubble growth



Conservation of mass, momentum and energy, coupled with solubility model and modified Redlich-Kwong equation of state for water-CO_2 mixtures

$$\frac{d}{dt}\left(\rho_g R^3\right) = 3R^2 \rho_m \sum_i D_i \left(\frac{\partial c_i}{\partial r}\right)_{r=R}$$

$$p_g - p_m = \frac{2\gamma}{R} + 12 v_R R^2 \int_R^S \frac{\eta_{melt}(r)}{r^4} dr$$

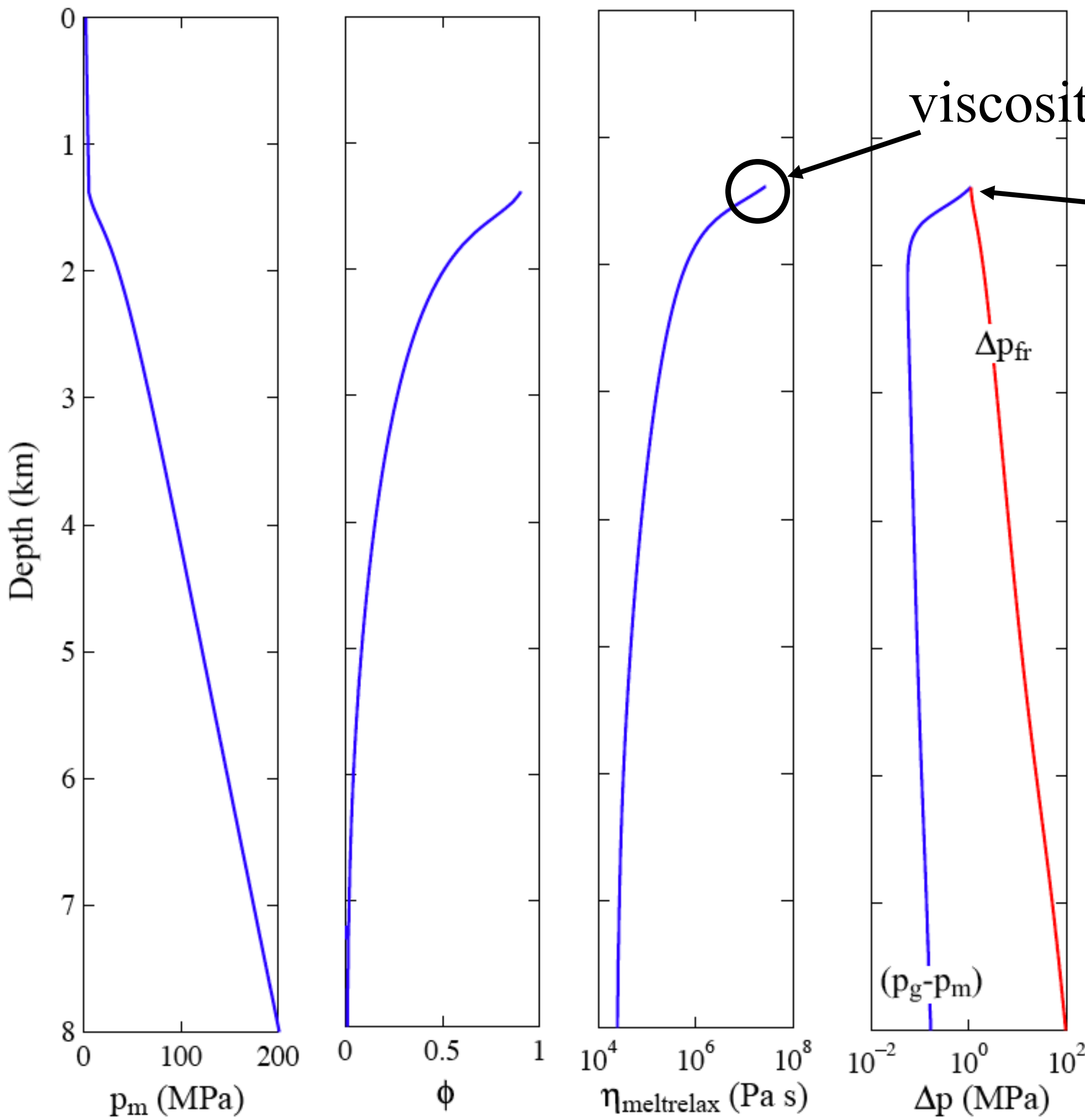
Lensky et al. (2001)

$$\frac{dT_g}{dt} = \Pi \left[\rho_m c_{pm} D_T \left(\frac{\partial T_m}{\partial r}\right)_{r=R} - \sum_i \Delta H_{ev} D_i \rho_m \left(\frac{\partial c_i}{\partial r}\right)_{r=R} + \frac{R}{3}\frac{dp_g}{dt}\right] \quad \Pi = 4\pi R^2 / \left(n \; c_{pg} M_g\right)$$

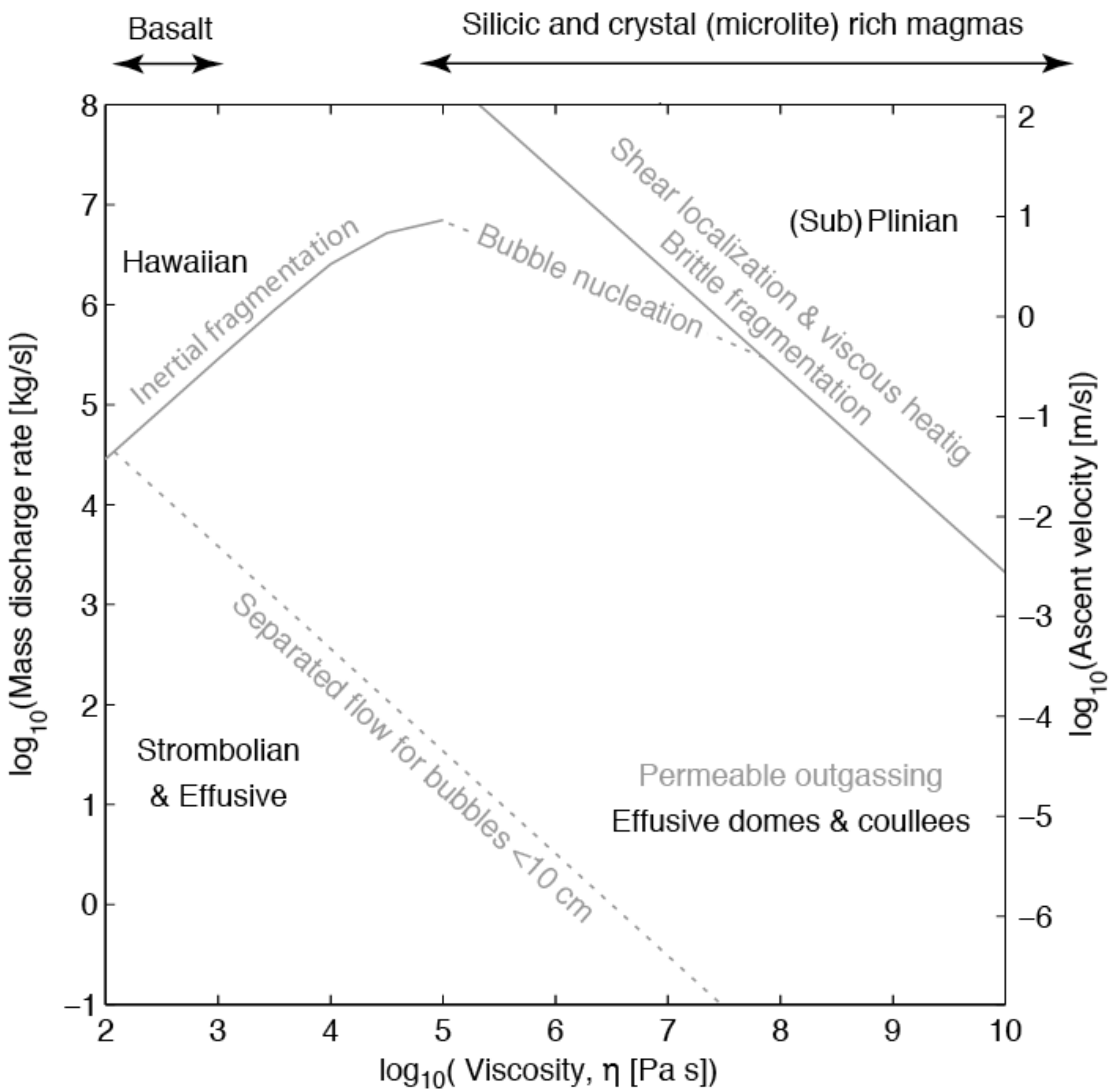
$$\frac{\partial T_m}{\partial t} + v_r \frac{\partial T_m}{\partial r} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(D_T \; r^2 \frac{\partial T_m}{\partial r}\right) + \frac{2\,\eta}{\rho_m c_{pm}}\left[\left(\frac{\partial v_r}{\partial r}\right)^2 + 2\left(\frac{v_r}{r}\right)^2 - \frac{1}{3}\left(\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 v_r\right)\right)^2\right]$$

Bird et al. (1960)

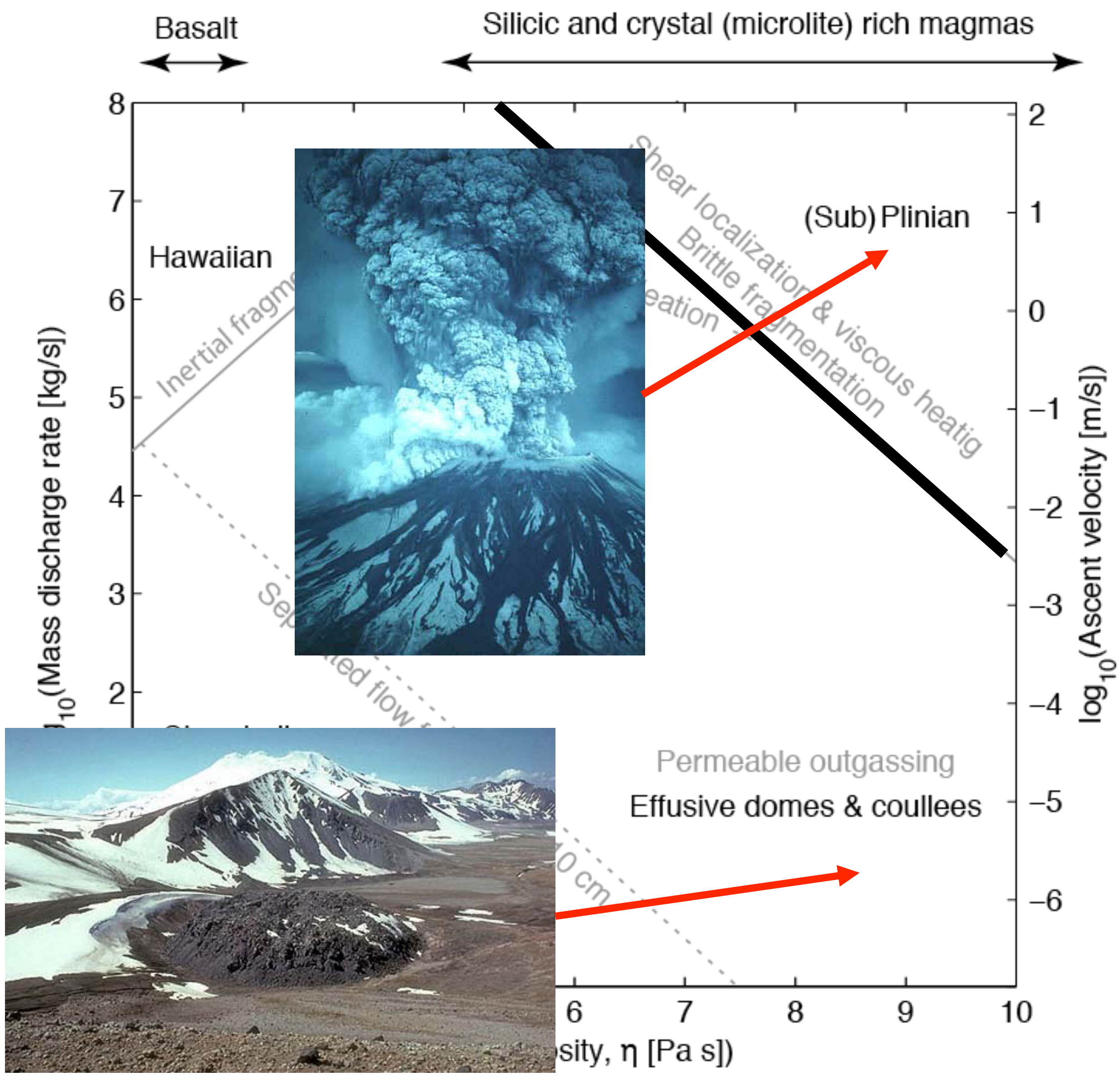
Example: Mount St Helens 1980 conditions



Basaltic eruption styles



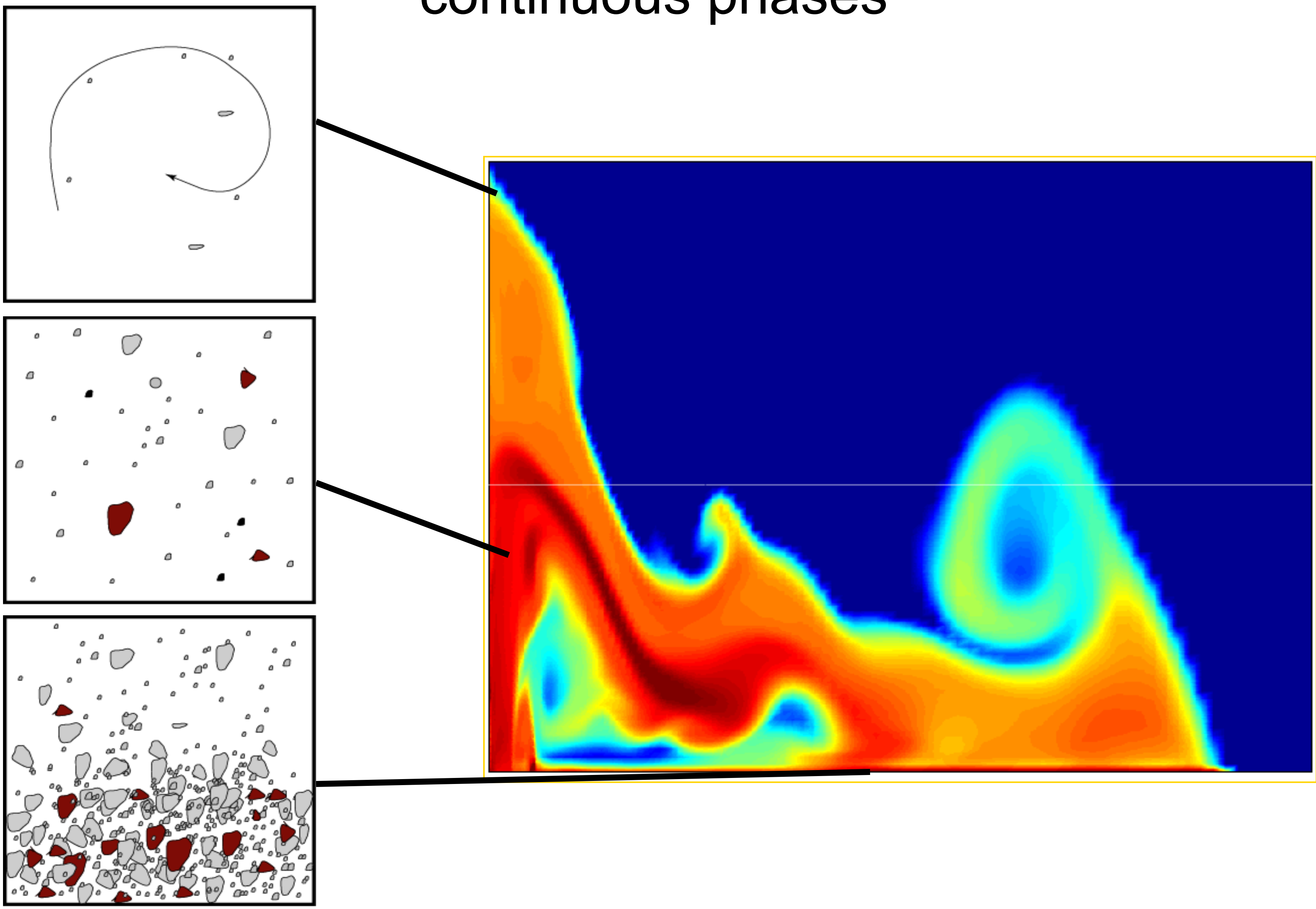
Basaltic eruption styles



Post-fragmentation

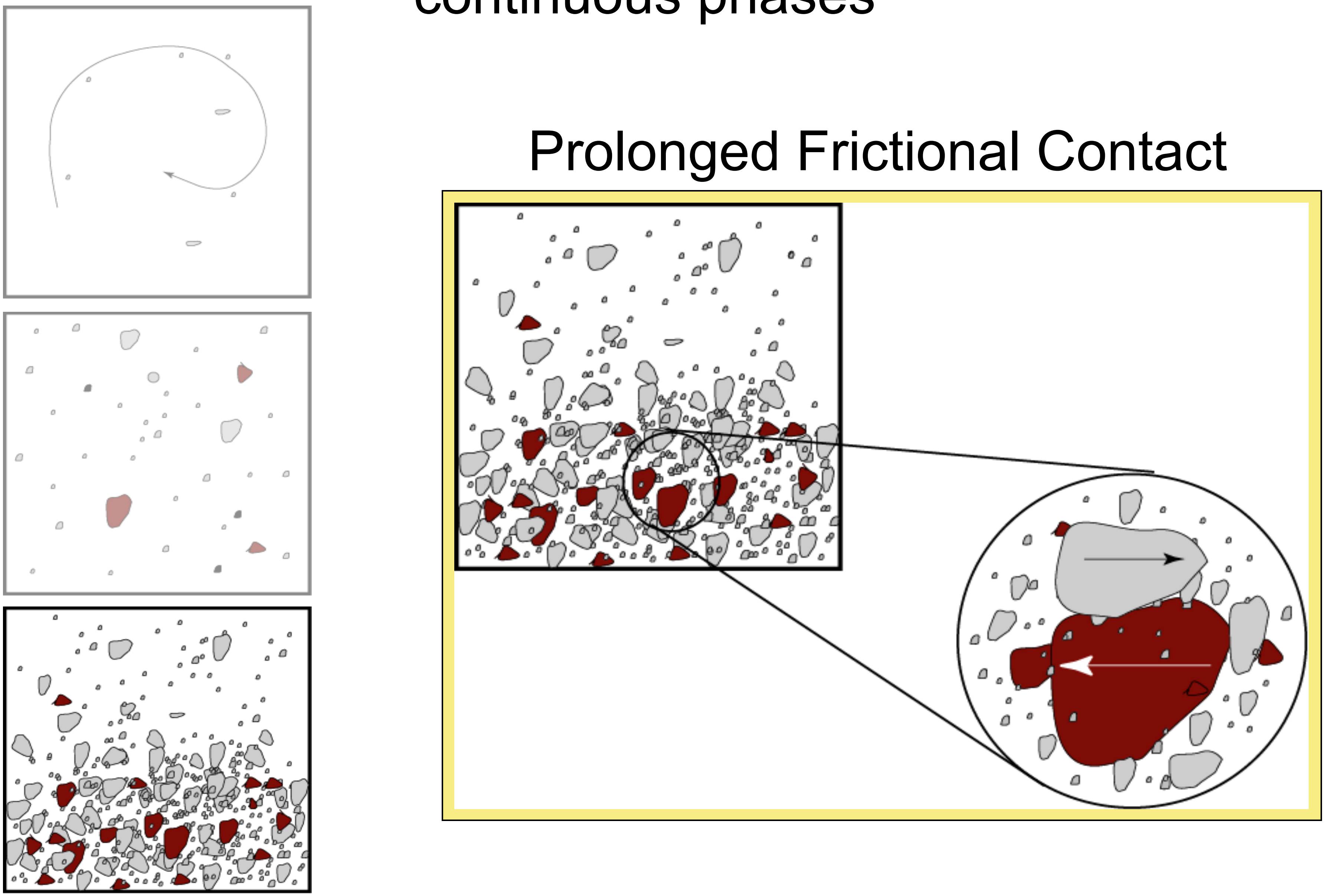
- Collisions transfer momentum
- Collisions caused breakup and comminution
- Agglutination and sticking
- Interaction with boundaries
- Energy exchange

Multiple levels of coupling between discrete and continuous phases

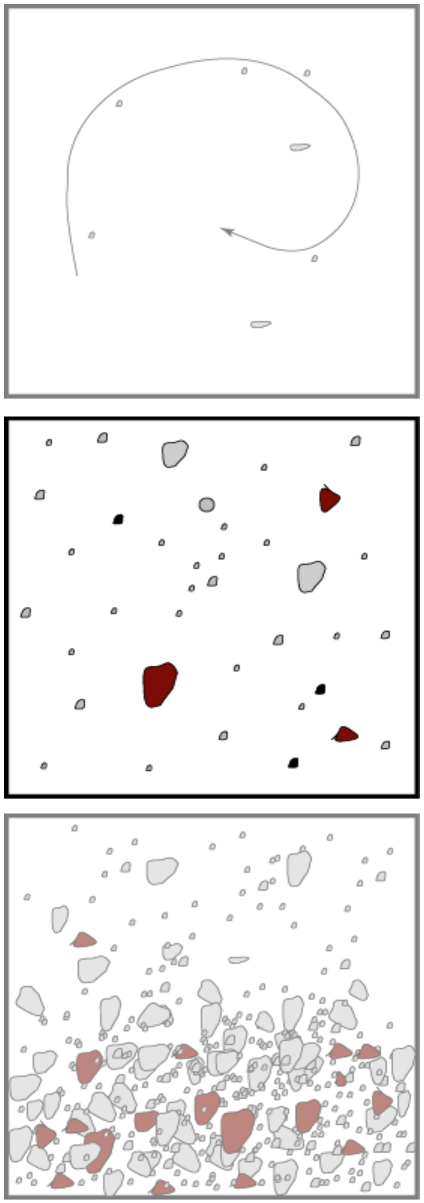


Multiple levels of coupling between discrete and continuous phases

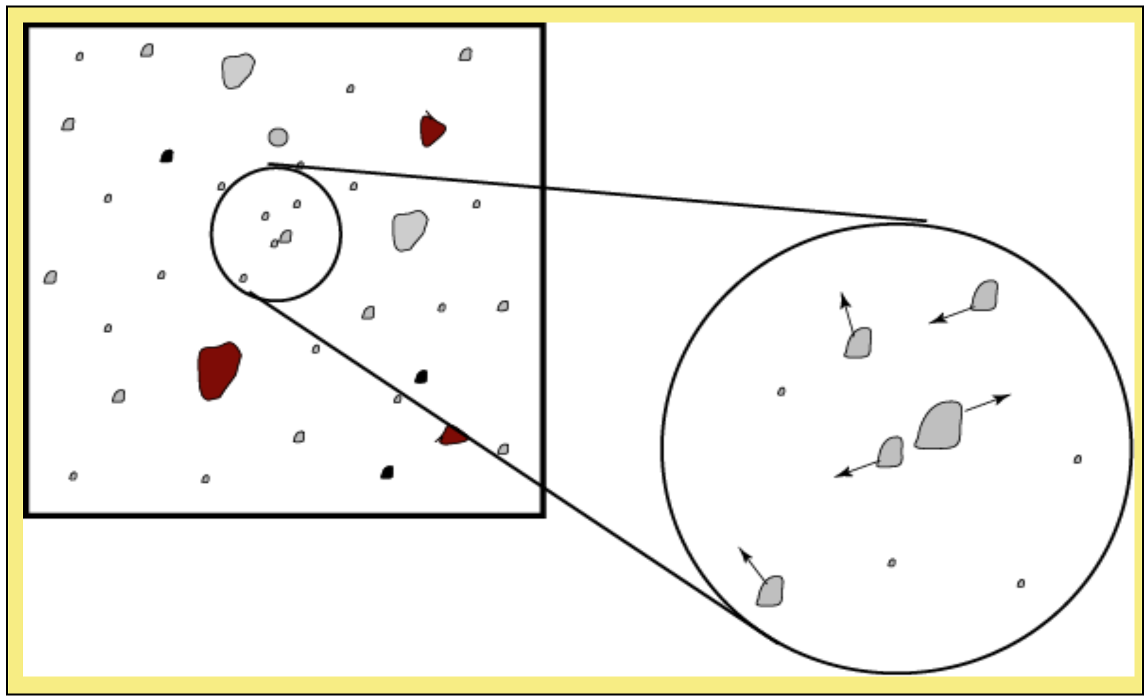
Prolonged Frictional Contact



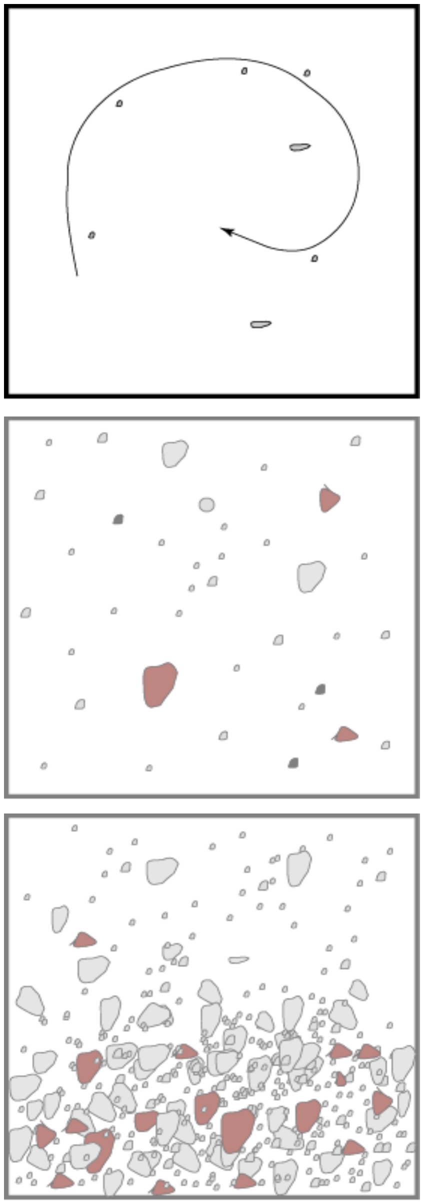
Multiple levels of coupling between discrete and continuous phases



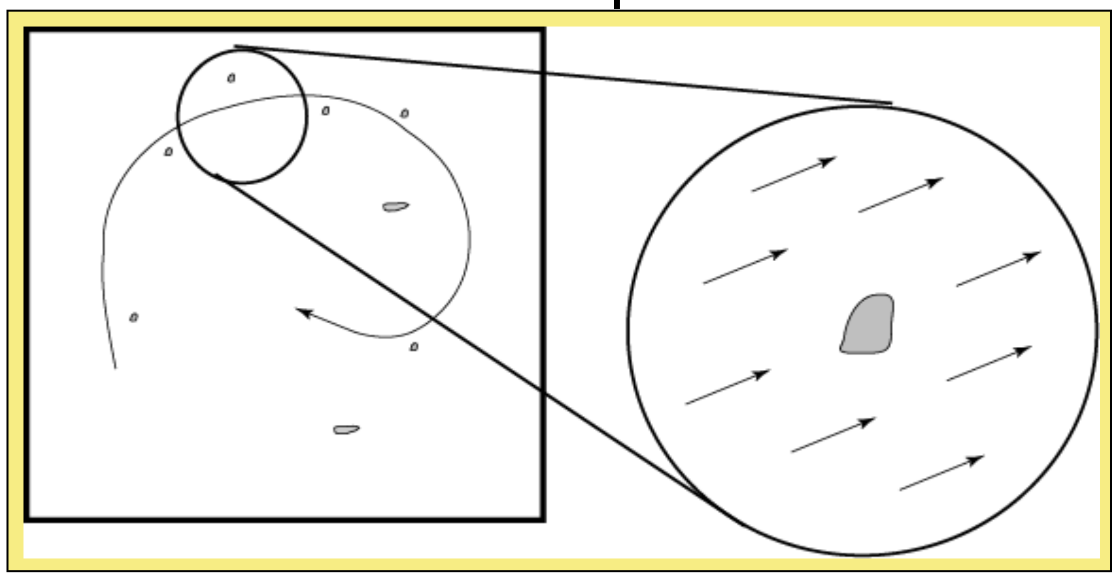
Instantaneous Collisions



Multiple levels of coupling between discrete and continuous phases



$$St = \tau_p/\tau_f$$



Mean field multifluid equations

Continuity

$$\frac{\partial}{\partial t}\left({}^{1}\alpha\,{}^{1}\rho\right)+\frac{\partial}{\partial x}\left({}^{1}\alpha\,{}^{1}\rho\,{}^{1}u_i\right)=0$$

Momentum

$$\frac{\partial({}^{1}\alpha\,{}^{1}\rho\,{}^{1}u_i)}{\partial t}+\frac{\partial({}^{1}\alpha\,{}^{1}\rho\,{}^{1}u_i\,{}^{1}u_j)}{\partial x_i}=$$

$$\left[\frac{N(\alpha,e)}{{}^{\mathbf{p}}\mathbf{M}_{\mathbf{0}}^{\mathbf{2}}}\right]\frac{\partial({}^{1}P)}{\partial x_i}+\left[\frac{1}{\mathbf{Re}}\right]\frac{\partial}{\partial x_i}\left[{}^{1}\tau_{ij}\right]+\left[\frac{1}{\mathbf{St}}\right]({}^{1}u_i-{}^{2}u_i)+\left[\frac{1}{\mathbf{Fr}_{\mathbf{d}}^{\mathbf{2}}}\right]\alpha\hat{e}_g$$

Thermal Energy

$${}^{1}\rho\,{}^{1}\mathrm{c}_{\mathrm{p}}\left[\frac{\partial^{1}\mathrm{T}}{\partial \mathrm{t}}+{}^{1}\mathrm{U}_{\mathrm{i}}\frac{\partial^{1}\mathrm{T}}{\partial \mathrm{x}_{\mathrm{i}}}\right]=\left[\frac{1}{\boldsymbol{Pe}}\right]\frac{\partial^{1}\mathrm{q}}{\partial^{1}\mathrm{x}_{\mathrm{i}}}+\left[\frac{1}{{}^{\boldsymbol{Th}}\boldsymbol{St}}\right]\left({}^{2}\mathrm{T}-{}^{1}\mathrm{T}\right)$$

Details of constitutive models, equations of state, turbulence models, in Dufek and Bergantz, *Theoretical and Computational Fluid Dynamics* (2007)

Mean field multifluid equations

Continuity

$$\frac{\partial}{\partial t}\left({}^1\alpha\,{}^1\rho\right)+\frac{\partial}{\partial x}\left({}^1\alpha\,{}^1\rho\,{}^1u_i\right)=0$$

Momentum

$$\frac{\partial({}^1\alpha\,{}^1\rho\,{}^1u_i)}{\partial t}+\frac{\partial({}^1\alpha\,{}^1\rho\,{}^1u_i\,{}^1u_j)}{\partial x_i}=$$

$$\left[\frac{N(\alpha,e)}{{}^{\mathbf{p}}\mathbf{M}_0^2}\right]\frac{\partial({}^1P)}{\partial x_i}+\left[\frac{1}{\mathbf{Re}}\right]\frac{\partial}{\partial x_i}\left[{}^1\tau_{ij}\right]+\left[\frac{1}{\mathbf{St}}\right]({}^1u_i-{}^2u_i)+\left[\frac{1}{\mathbf{Fr_d^2}}\right]\alpha\hat{e}_g$$

Thermal Energy

$${}^1\rho\,{}^1\mathrm{c}_\mathrm{p}\left[\frac{\partial\,{}^1\mathrm{T}}{\partial \mathrm{t}}+{}^1\mathrm{U}_\mathrm{i}\frac{\partial\,{}^1\mathrm{T}}{\partial \mathrm{x}_\mathrm{i}}\right]=\left[\frac{1}{\boldsymbol{Pe}}\right]\frac{\partial\,{}^1\mathrm{q}}{\partial\,{}^1\mathrm{x}_\mathrm{i}}+\left[\frac{1}{{}^{\boldsymbol{Th}}\boldsymbol{St}}\right]\left({}^2\mathrm{T}\ -\ {}^1\mathrm{T}\right)$$

Numerical implementation adapted from the MFIX (**M**ultiphase **F**low with **I**nterface e**X**change) code developed by US Dept Energy.

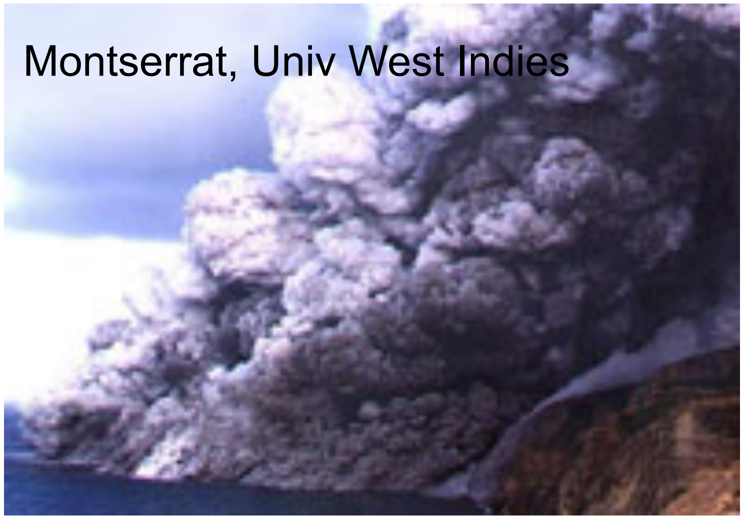
Sub-grid scale thermo-mechanical processes

1) Heat transfer from particles to water

2) Mass and momentum transfer when particles collide with each other

1. Interaction with water

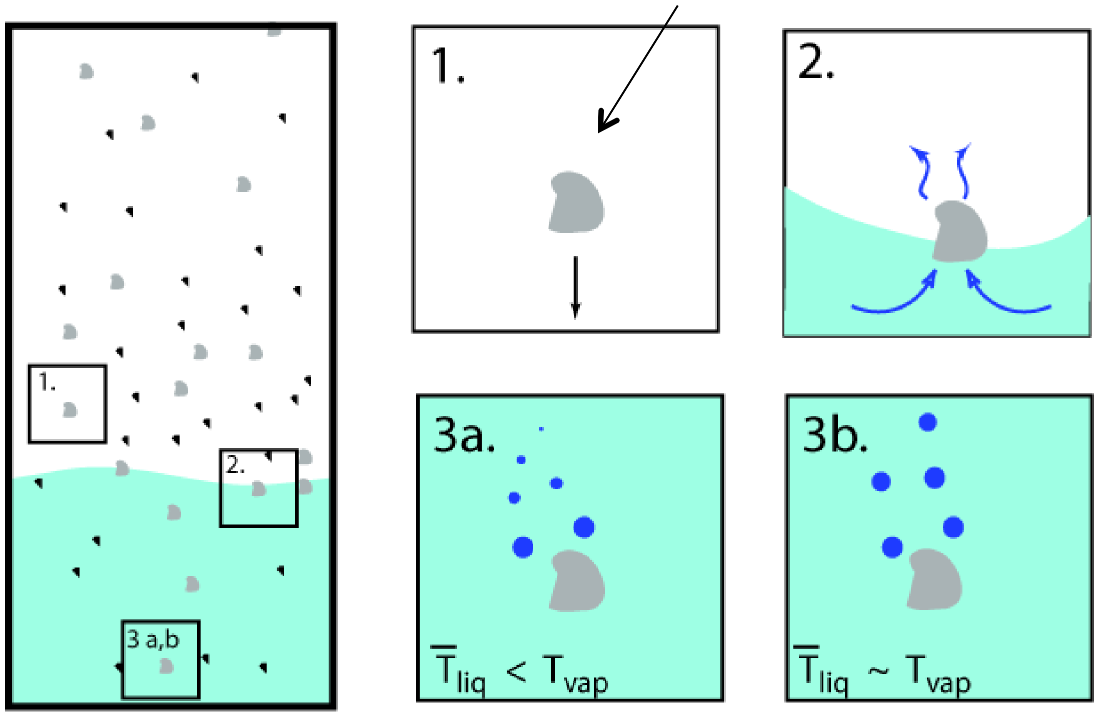
Hot flows, when they enter water, generate steam



- How much?
- How fast?
- Effects of steam generation?

Measurement of steam production rate

Stroberg, Manga and Dufek, *JVGR* 2010

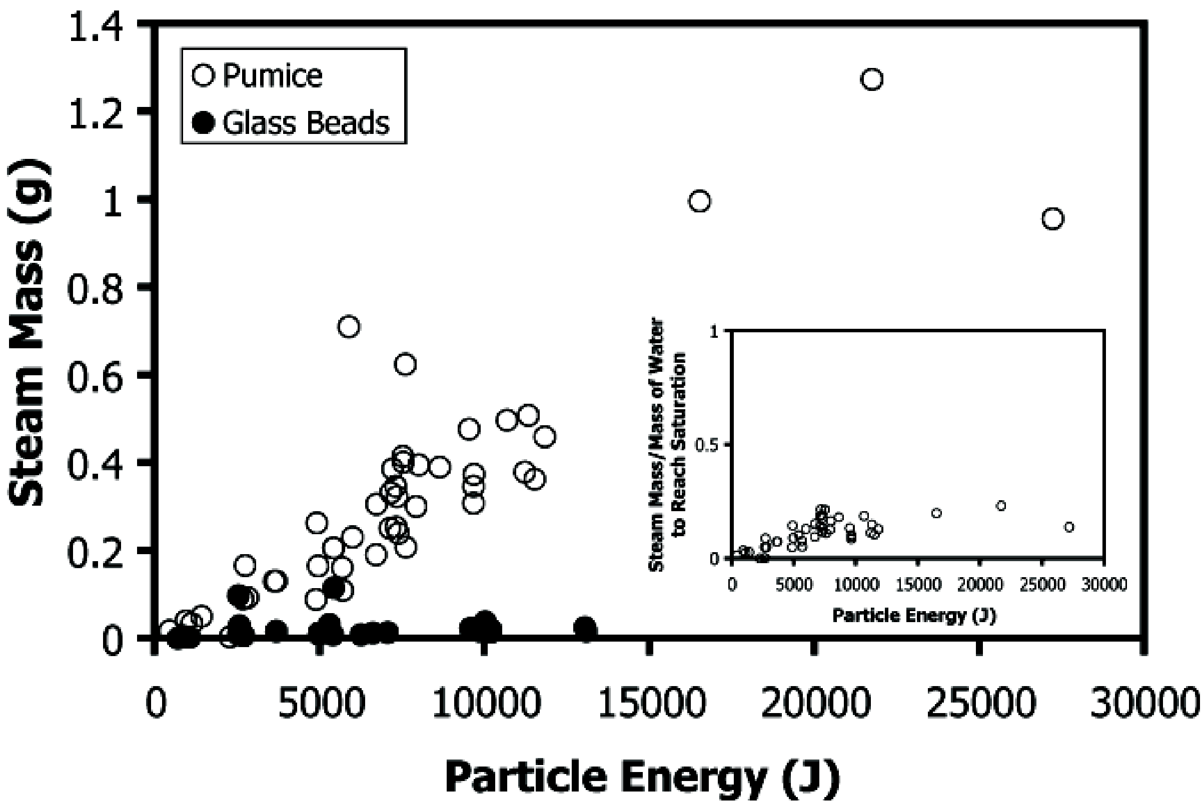


100-700 ^oC
Pumice, glass beads
3 mm - 2 cm

1) Measure mass of stream released
2) Measure time clasts float

(results in Dufek, Manga Staedter, *J Geophys Res* 2007)

Measurement of steam production rate



$$R_v = \frac{\left({}^p\alpha\right)\left(\varepsilon\right)\left({}^p\rho\right)\left({}^p c_p\right)\left({}^pT - {}^wT\right)}{\xi m_p[{}^w c_p({}^bT - {}^wT) + L]} = \frac{6\left({}^p\alpha\right)\left(\varepsilon\right)\left({}^p c_p\right)\left({}^pT - {}^wT\right)}{\xi \pi d^3[{}^w c_p({}^bT - {}^wT) + L]}$$

Multiphase equations

Continuity

$$\frac{\partial}{\partial t}({}^w\alpha\,{}^w\rho) + \frac{\partial}{\partial \boldsymbol{x}_i}({}^w\alpha\,{}^w\rho\,{}^w\boldsymbol{U}_i) = \underbrace{-R_v}_{\text{Mass loss due to phase change}}$$

$$\frac{\partial}{\partial t}({}^g\alpha\,{}^g\rho) + \frac{\partial}{\partial \boldsymbol{x}_i}({}^g\alpha\,{}^g\rho\,{}^g\boldsymbol{U}_i) = \underbrace{+R_v}_{\text{Mass gain due to phase change}}$$

$$\frac{\partial}{\partial t}({}^p\alpha\,{}^p\rho) + \frac{\partial}{\partial \boldsymbol{x}_i}({}^p\alpha\,{}^p\rho\,{}^p\boldsymbol{U}_i) = 0$$

Momentum

$$\frac{\partial}{\partial t}({}^g\alpha\,{}^g\rho\boldsymbol{U}_i) + \frac{\partial}{\partial \boldsymbol{x}_i}({}^g\alpha\,{}^g\rho\,{}^g\boldsymbol{U}_i\,{}^g\boldsymbol{U}_j) = \frac{\partial\,{}^gP}{\partial x_i}\delta_{ij} + \frac{\partial\,{}^g\tau_{ij}}{\partial x_j} + {}^gI_i + {}^g\alpha\,{}^g\rho g_i + \underbrace{R_v\,{}^g\boldsymbol{U}_i}_{\text{Momentum gain to phase change}}$$

$$\frac{\partial}{\partial t}({}^w\alpha\,{}^w\rho\boldsymbol{U}_i) + \frac{\partial}{\partial \boldsymbol{x}_i}({}^w\alpha\,{}^w\rho\,{}^w\boldsymbol{U}_i\,{}^w\boldsymbol{U}_j) = \frac{\partial\,{}^wP}{\partial x_i}\delta_{ij} + \frac{\partial\,{}^w\tau_{ij}}{\partial x_j} + {}^wI_i + {}^w\alpha\,{}^w\rho g_i - \underbrace{R_v\,{}^w\boldsymbol{U}_i}_{\text{Momentum loss due to phase change}}$$

$$\frac{\partial}{\partial t}({}^p\alpha\,{}^p\rho\boldsymbol{U}_i) + \frac{\partial}{\partial \boldsymbol{x}_i}({}^p\alpha\,{}^p\rho\,{}^p\boldsymbol{U}_i\,{}^p\boldsymbol{U}_j) = \frac{\partial\,{}^pP}{\partial x_i}\delta_{ij} + \frac{\partial\,{}^p\tau_{ij}}{\partial x_j} + {}^pI_i + {}^p\alpha\,{}^p\rho g_i$$

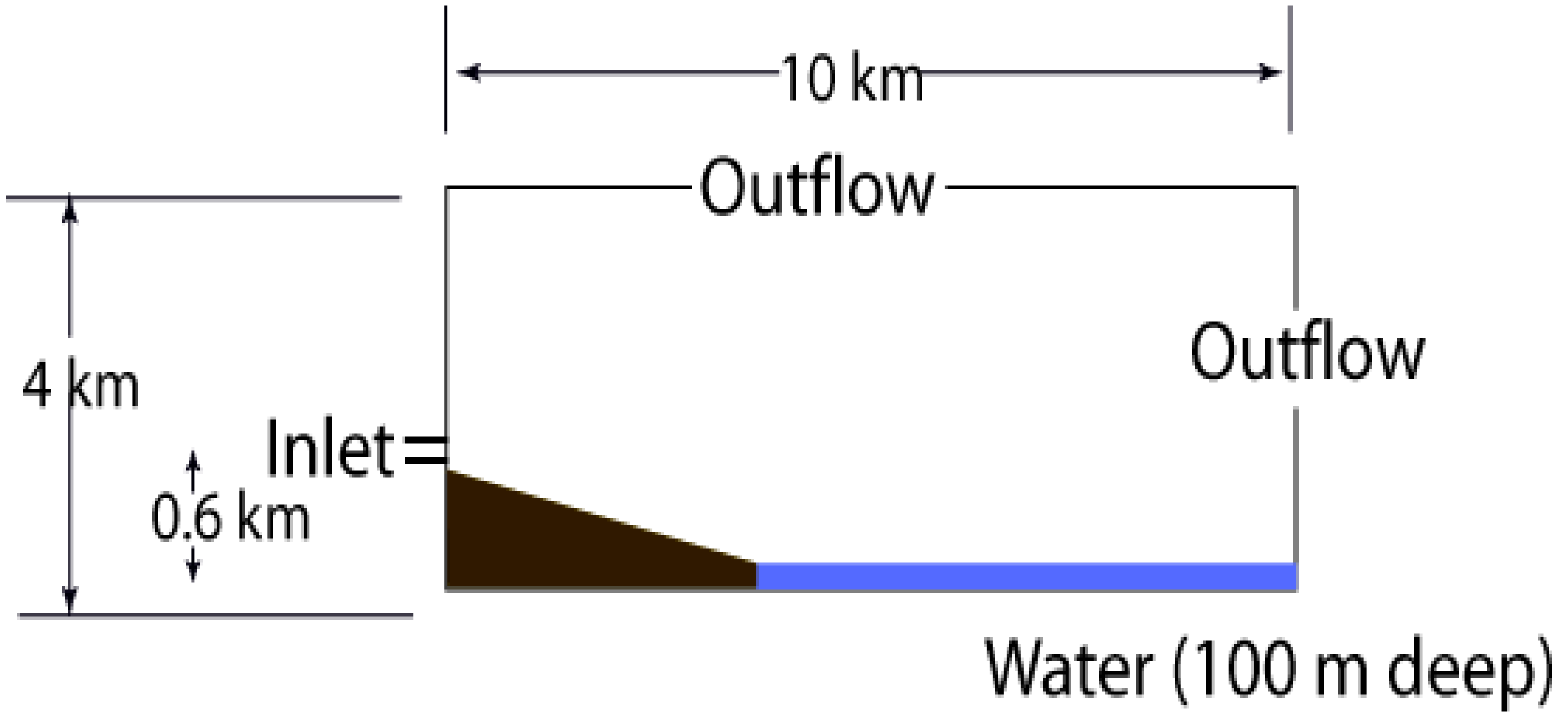
Thermal Energy

$${}^w\alpha\,{}^w\rho\,{}^wc_p\left(\frac{\partial\,{}^wT}{\partial t} + {}^w\boldsymbol{U}_i\frac{\partial\,{}^wT}{\partial \boldsymbol{x}_i}\right) = \frac{\partial\,{}^wq}{\partial \boldsymbol{x}_i} + \overline{H}_{wg} - \underbrace{\overline{H}_{wp}}_{\substack{\text{Mean interphase}\\ \text{heat transfer}\\ \text{(particle - water)}}} - \underbrace{H^s_{wp}}_{\substack{\text{Subgrid interphase}\\ \text{heat transfer}\\ \text{(particle - water)}}} + \underbrace{\overline{S}}_{\substack{\text{Mean field}\\ \text{latent heat of}\\ \text{vaporization}}} + \underbrace{S^s}_{\substack{\text{Subgrid}\\ \text{latent heat of}\\ \text{vaporization}}}$$

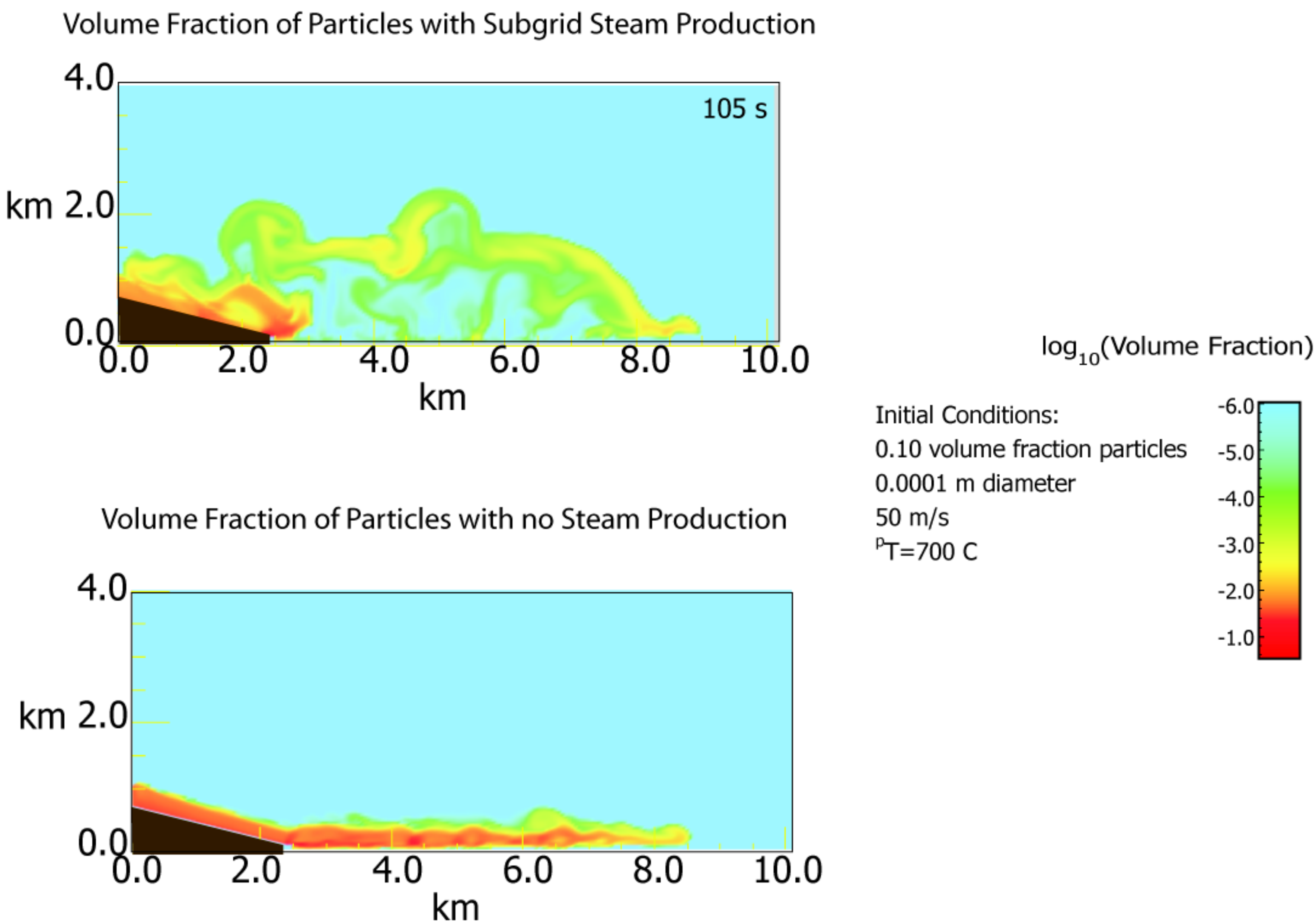
$${}^g\alpha\,{}^g\rho\,{}^gc_p\left(\frac{\partial\,{}^gT}{\partial t} + {}^g\boldsymbol{U}_i\frac{\partial\,{}^gT}{\partial \boldsymbol{x}_i}\right) = \frac{\partial\,{}^gq}{\partial x_i} - \overline{H}_{gp} - \overline{H}_{gw} - \underbrace{\overline{S}}_{\substack{\text{Mean latent}\\ \text{heat of}\\ \text{vaporization}}} - \underbrace{S^s}_{\substack{\text{Subgrid latent}\\ \text{heat of}\\ \text{vaporization}}}$$

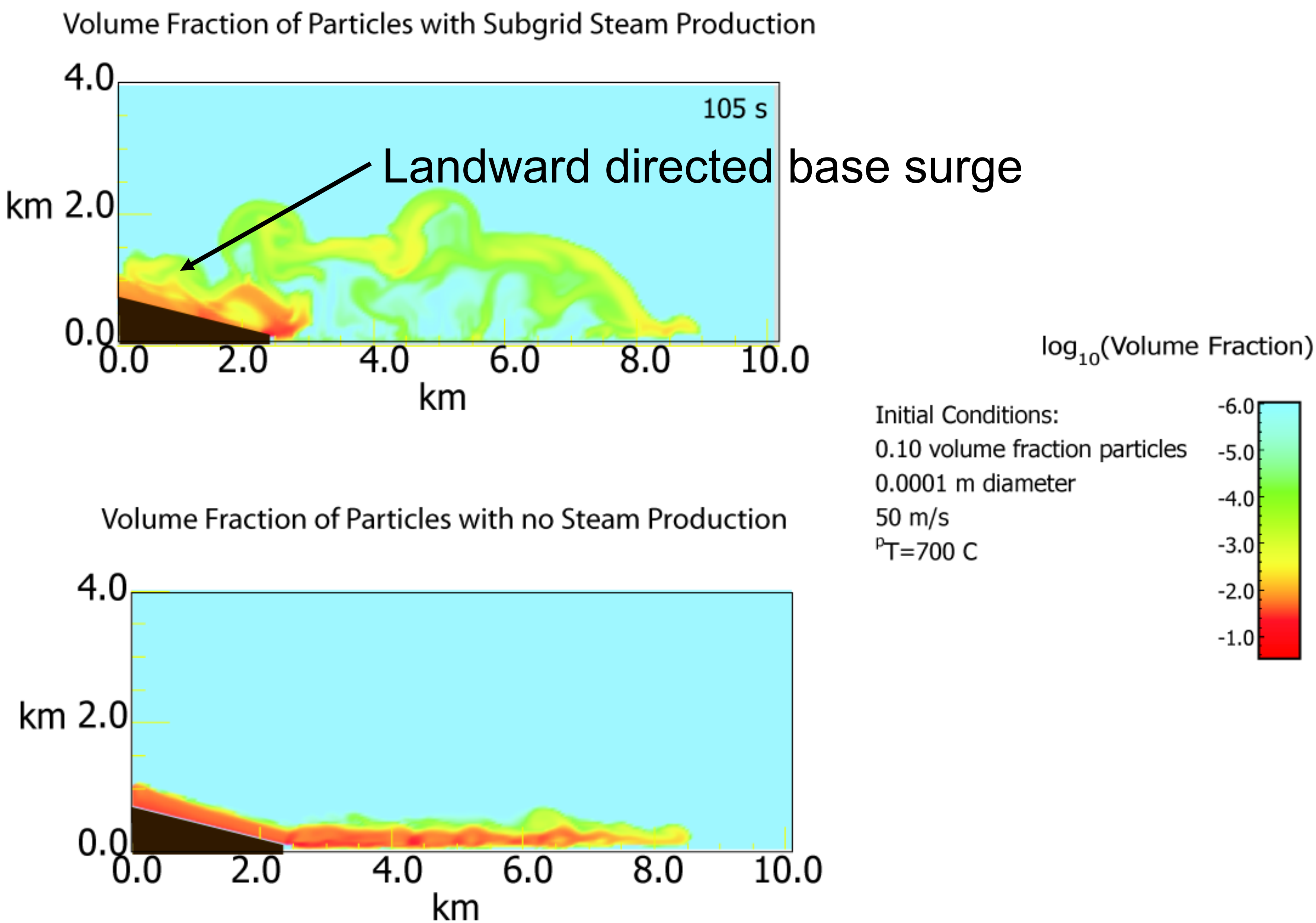
$${}^p\alpha\,{}^p\rho\,{}^pc_p\left(\frac{\partial\,{}^pT}{\partial t} + {}^p\boldsymbol{U}_i\frac{\partial\,{}^pT}{\partial \boldsymbol{x}_i}\right) = \frac{\partial\,{}^pq}{\partial \boldsymbol{x}_i} + \overline{H}_{gp} + \underbrace{\overline{H}_{wp}}_{\substack{\text{Mean interphase}\\ \text{heat transfer}\\ \text{(particle - water)}}} + \underbrace{H^s_{wp}}_{\substack{\text{Subgrid interphase}\\ \text{heat transfer}\\ \text{(particle - water)}}}$$

Application to July 12-13, 2003 littoral blast, Montserrat

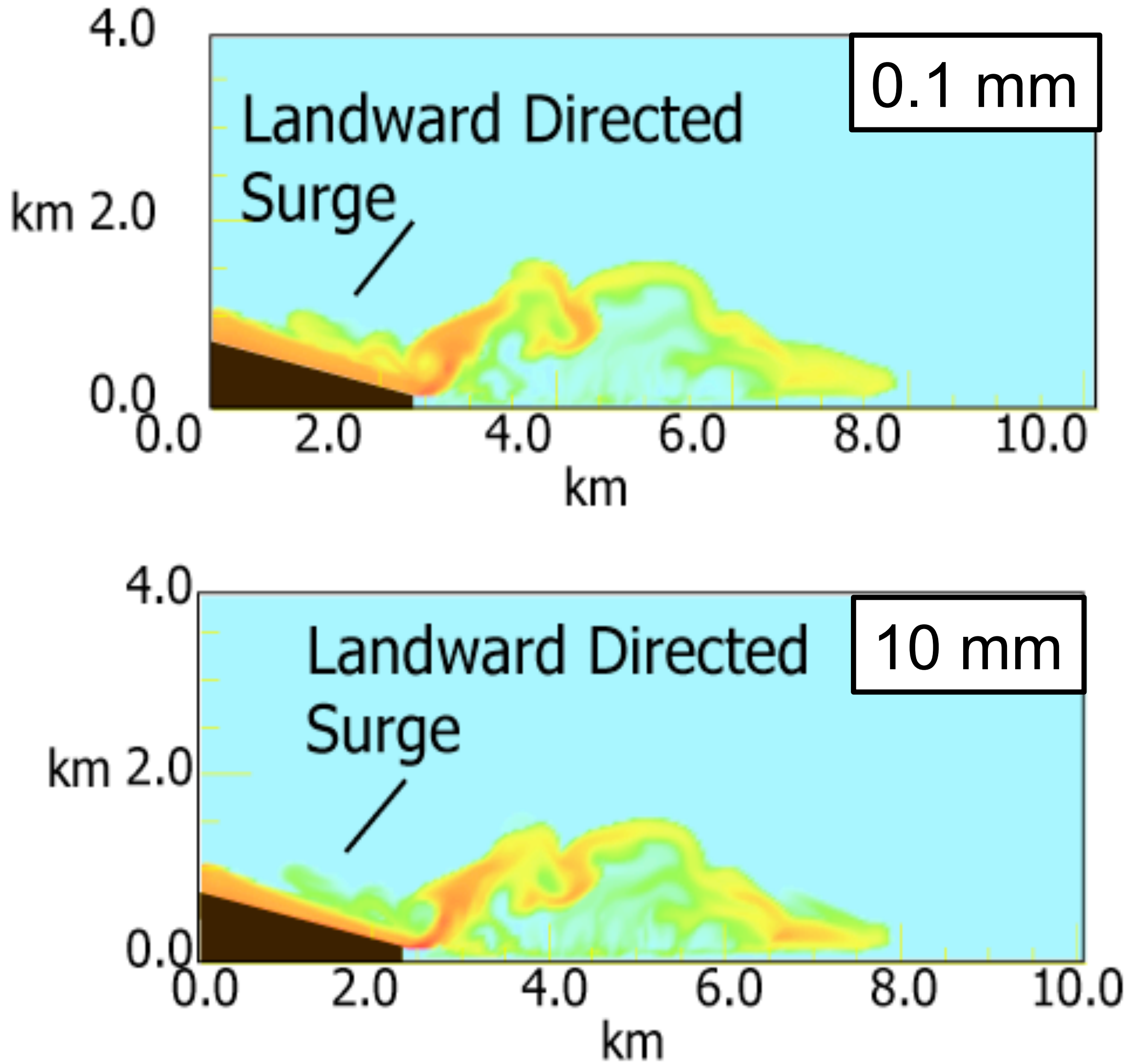


grid 2 m x 10 m; time step , 0.1 s
initial velocity 50 m/s
initial concentration 0.1
initial sizes: 50% is 1 cm, 50% is 0.1 mm
temperature 650 C

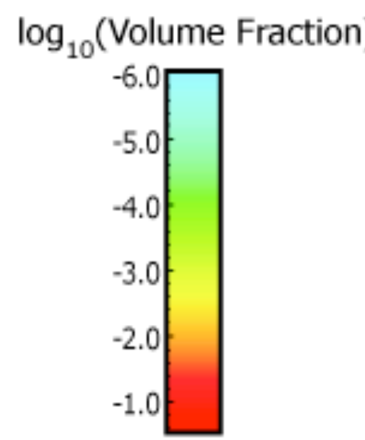

Volume Fraction of Particles with Subgrid Steam Production
105 s
4.0
km 2.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
km
Volume Fraction of Particles with no Steam Production
4.0
km 2.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
km
$\log_{10}$(Volume Fraction)
Initial Conditions:
0.10 volume fraction particles
0.0001 m diameter
50 m/s
^{p}T=700 C
-6.0
-5.0
-4.0
-3.0
-2.0
-1.0

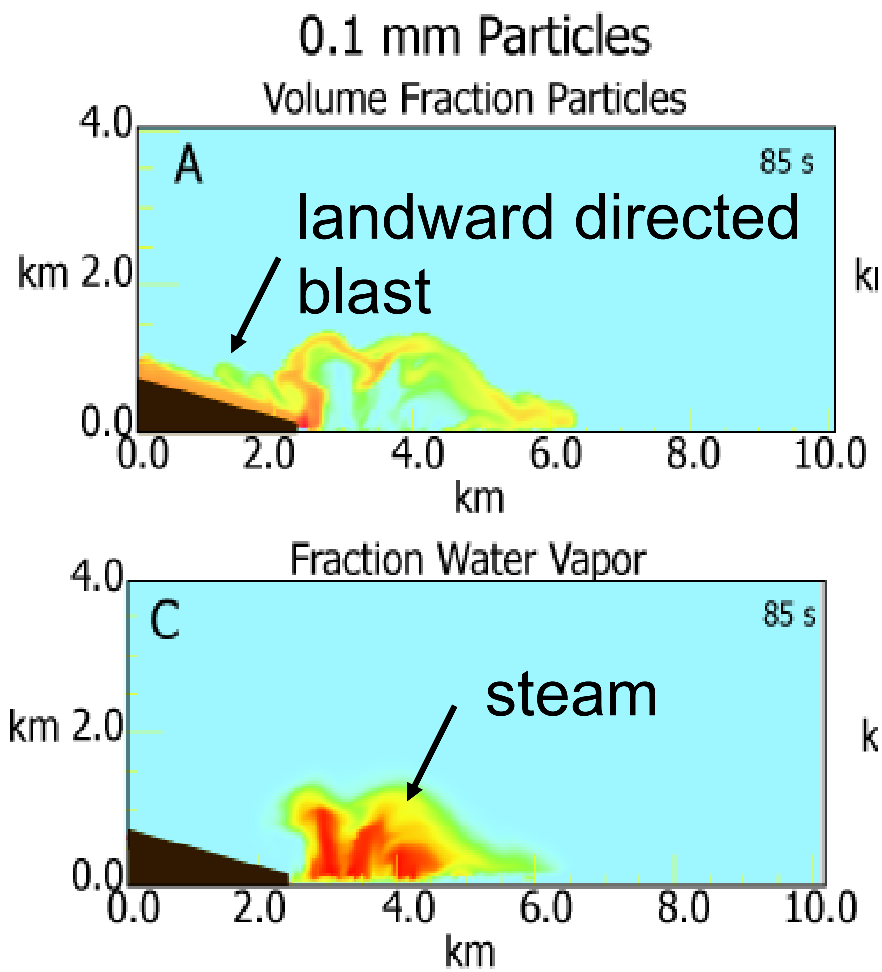


Volume Fraction of Particles with Subgrid Steam Production
105 s
Landward directed base surge
4.0
km 2.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
km
log10(Volume Fraction)
Initial Conditions:
0.10 volume fraction particles
0.0001 m diameter
50 m/s
PT=700 C
-6.0
-5.0
-4.0
-3.0
-2.0
-1.0
Volume Fraction of Particles with no Steam Production
4.0
km 2.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
km



Initial Conditions:
0.10 volume fraction particles
50 % 0.1 mm diameter
50% 10.0 mm diameter
50 m/s
^{P}T=700 C

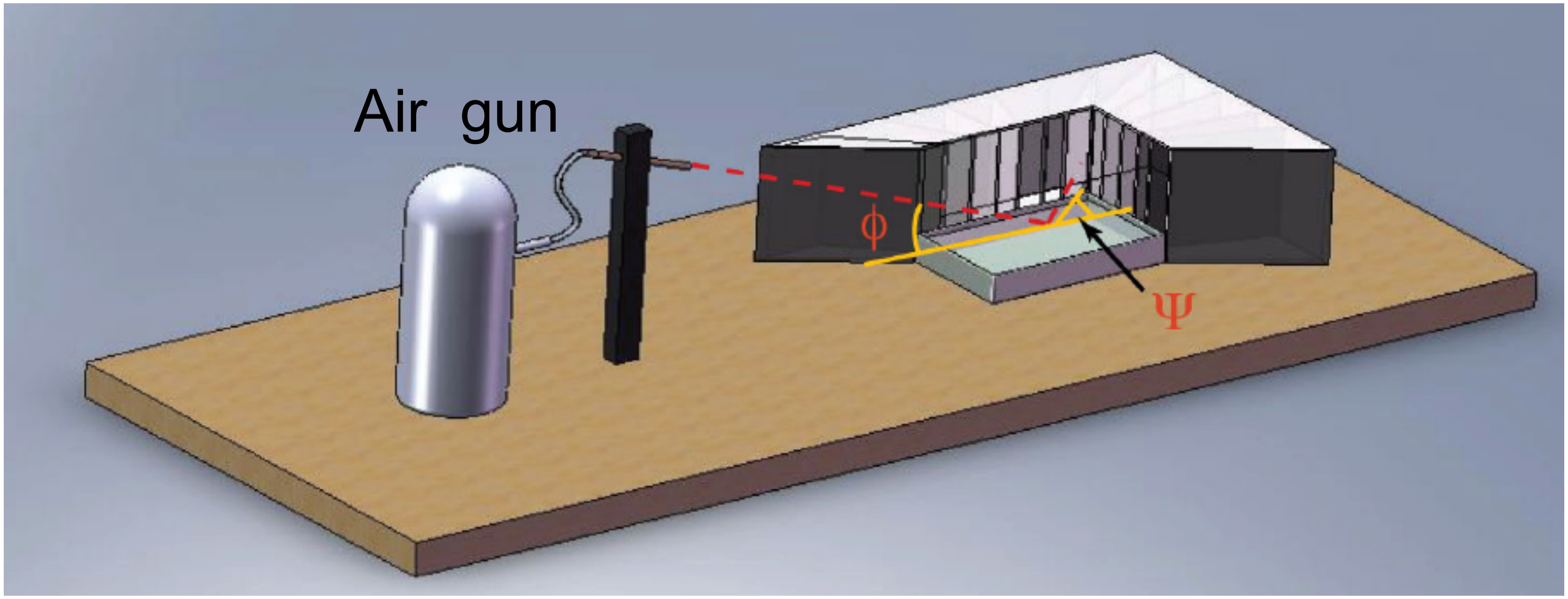




Edmonds and Herd, *Geology* (2005)

- 0.6% flow forms landward-directed base surge (Edmonds et al. (2006) estimate a volume of 0.75%)
- Landward directed flow is dry

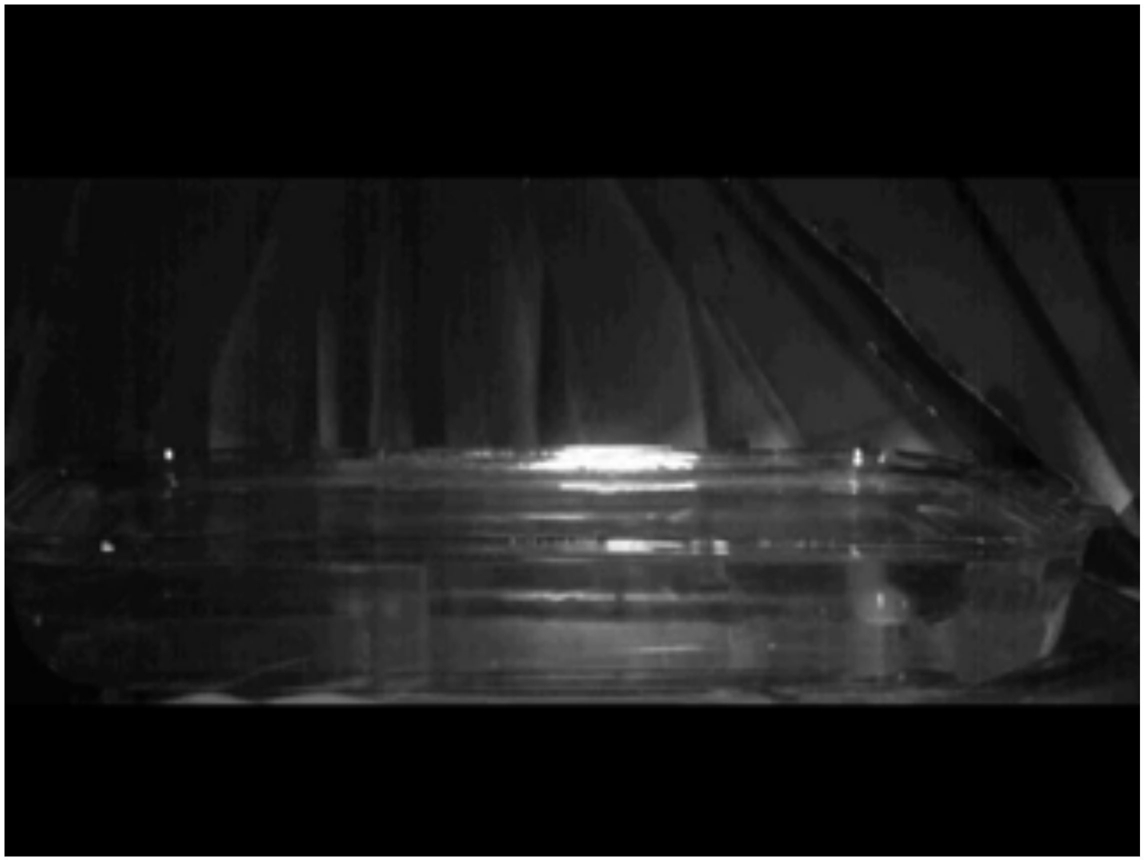
2. Studying particle collisions



Measure velocity before and after collision; whether particle bounces

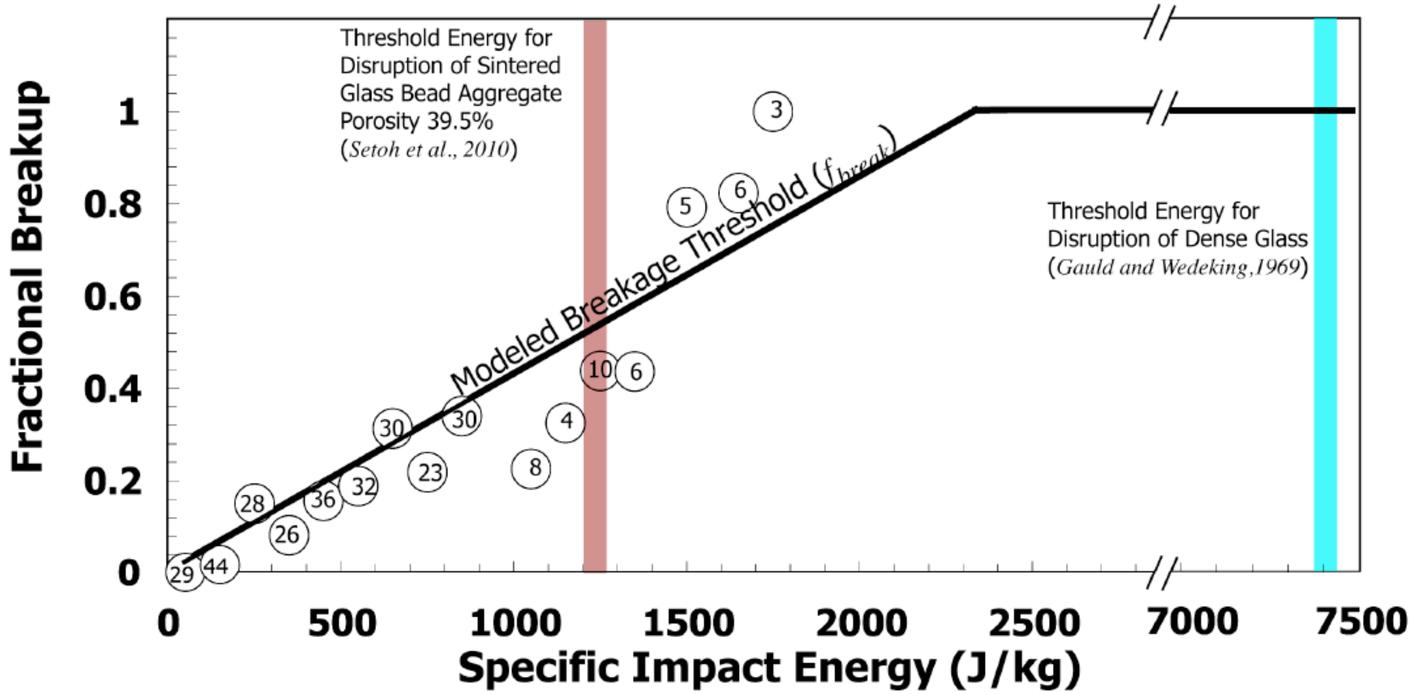
Variables: angle ϕ, velocity, mass, substrate

Example (water substrate)



- Extract quantitative information . . . .

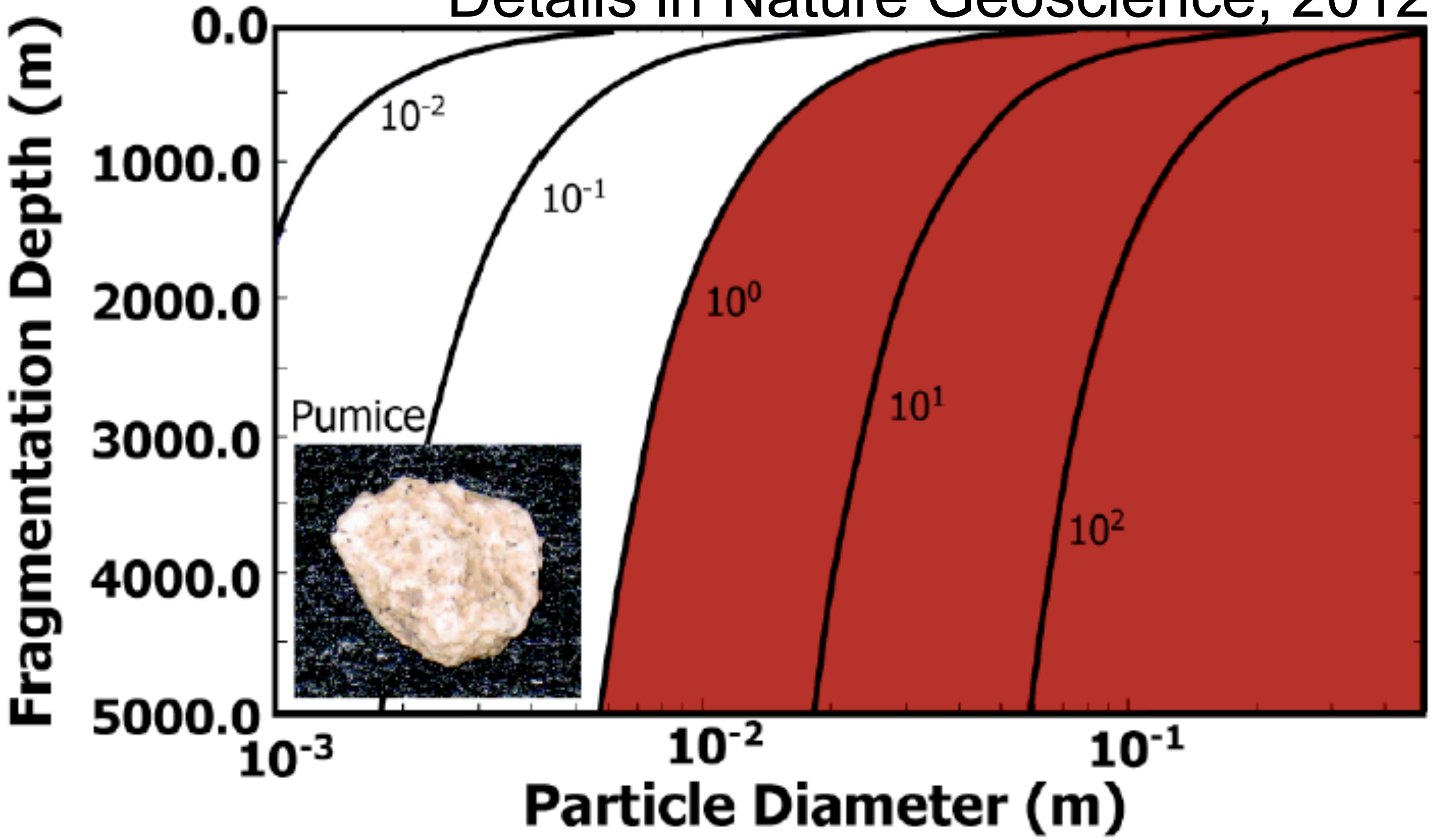
Pumice clasts can break if collisions are energetic enough



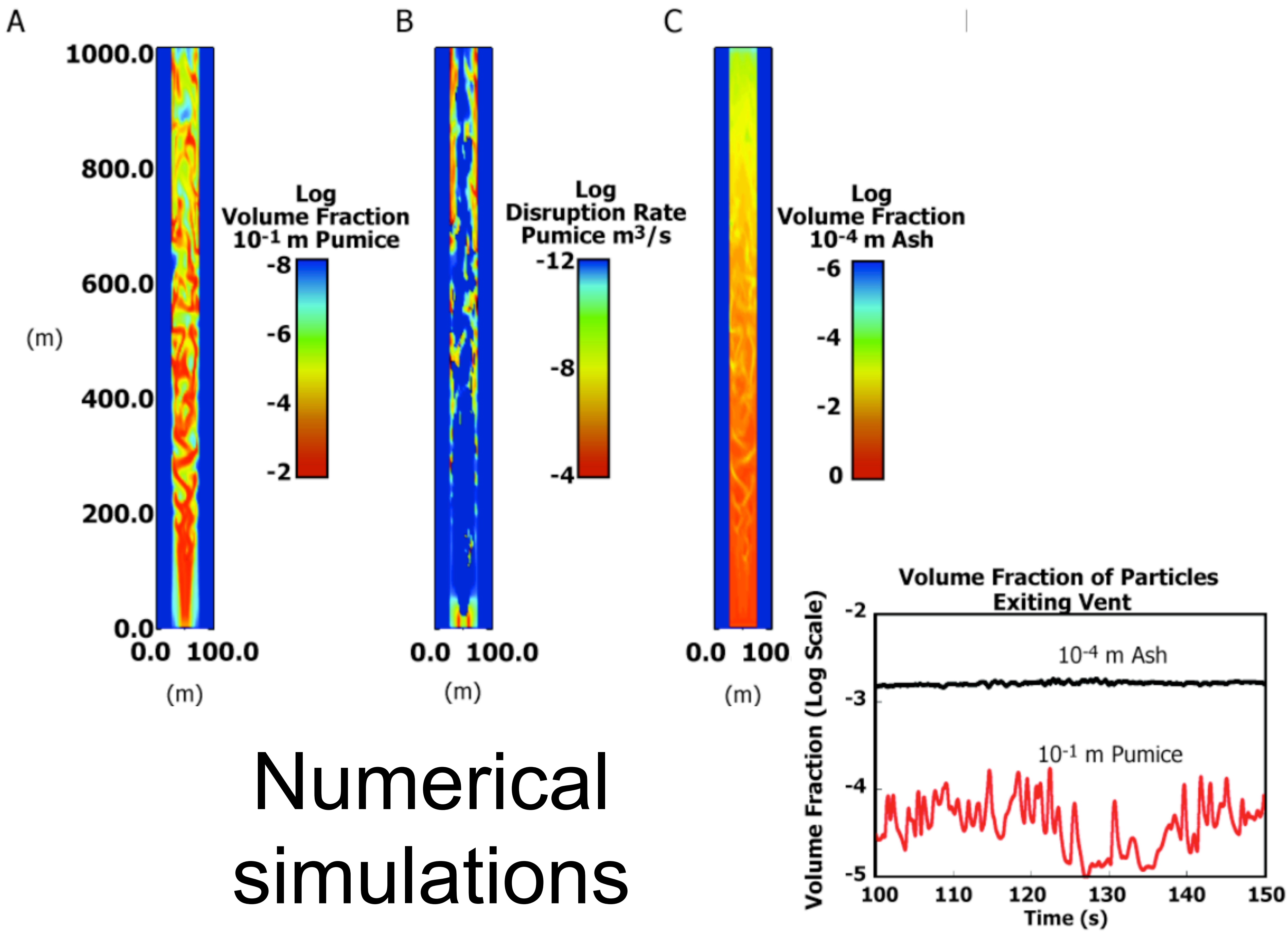
Will large pumice clasts breakup before exiting volcanic conduits?

Analytical model

Details in Nature Geoscience, 2012



- Assumptions: choked flow (exit velocity is the speed of sound in a dusty gas)
- Dissipation of granular energy balanced by production owing to shear



Numerical simulations

Lagrangian particles

Equation of motion of particle

$$\frac{du_i^p}{dt} = F_g + F_s + g\left(\frac{2\rho_p - 2\rho_g}{2\rho_p + \rho_g}\right)\delta_i$$

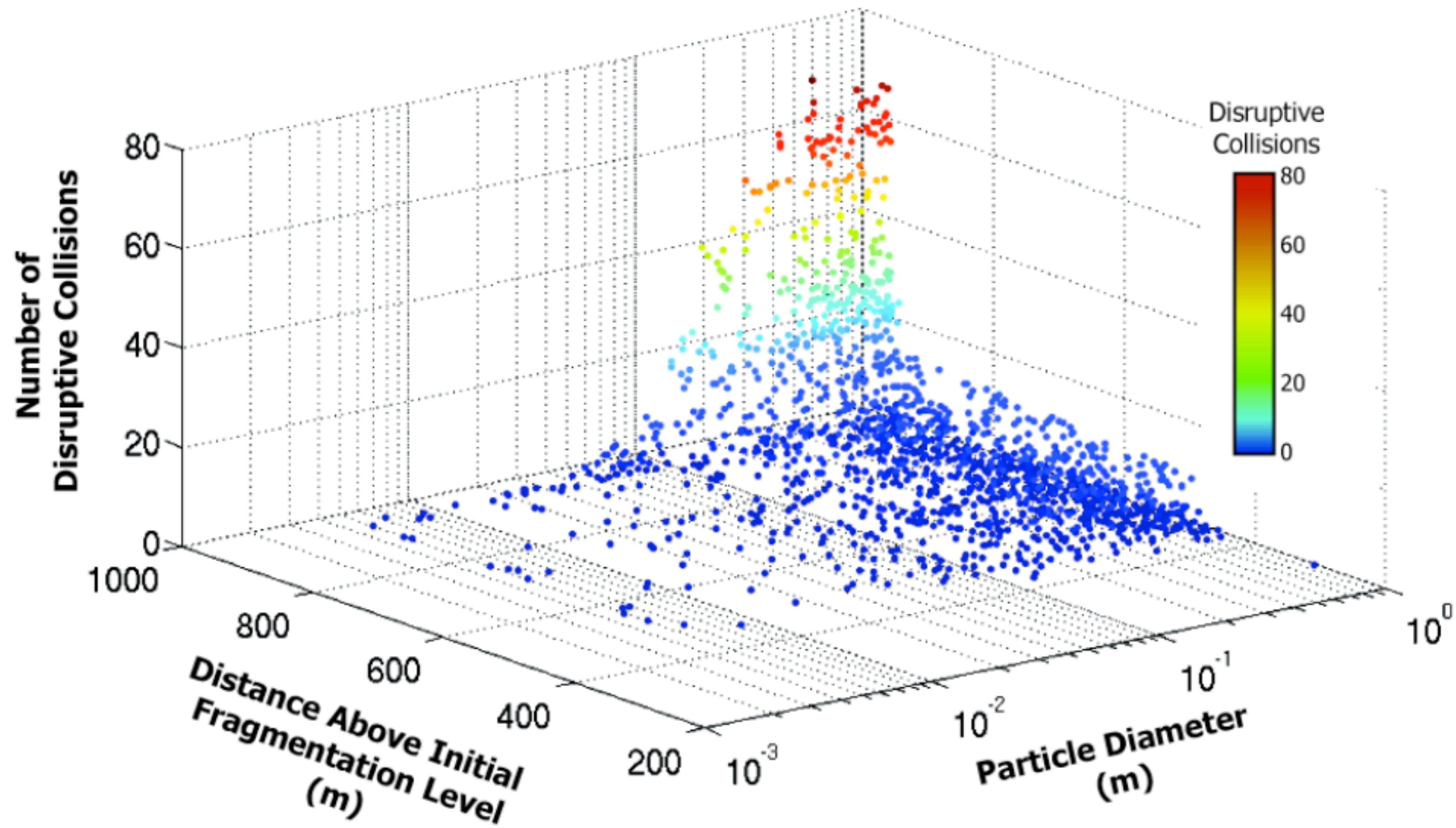
drag from gas

effects of collisions

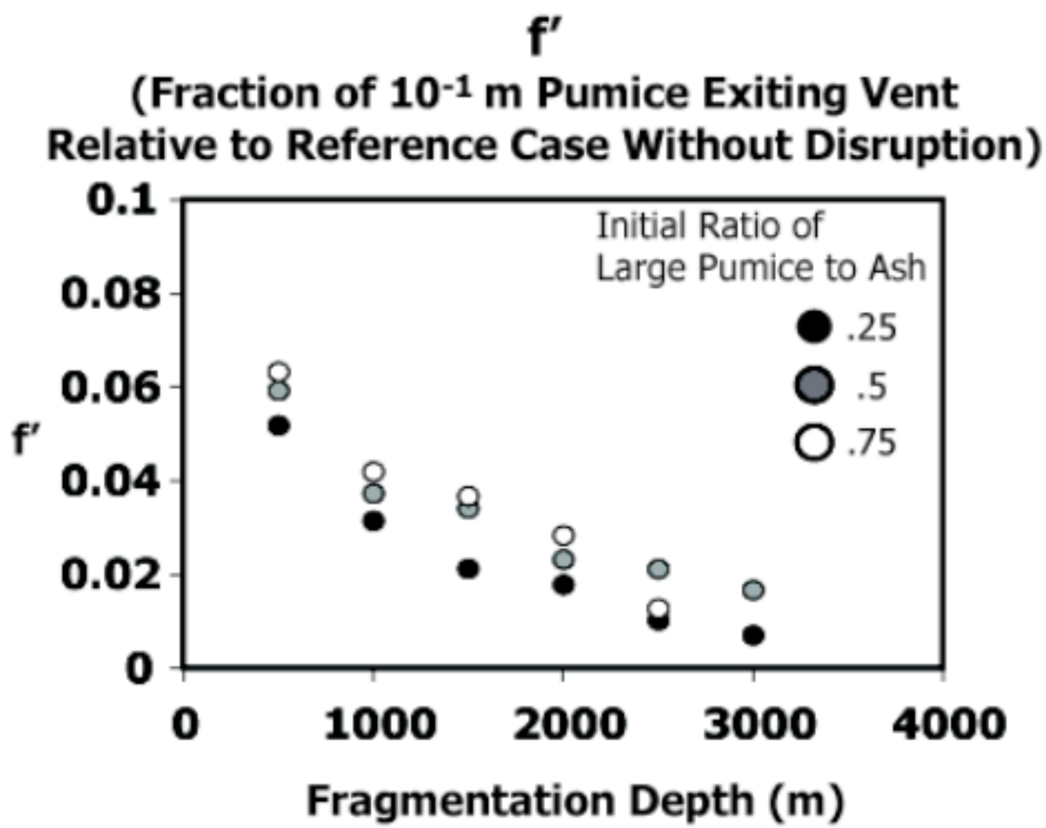
buoyancy force

Detailed expressions in Dufek, Wexler and Manga, *J Geophys Res* (2009)

Lagrangian analysis



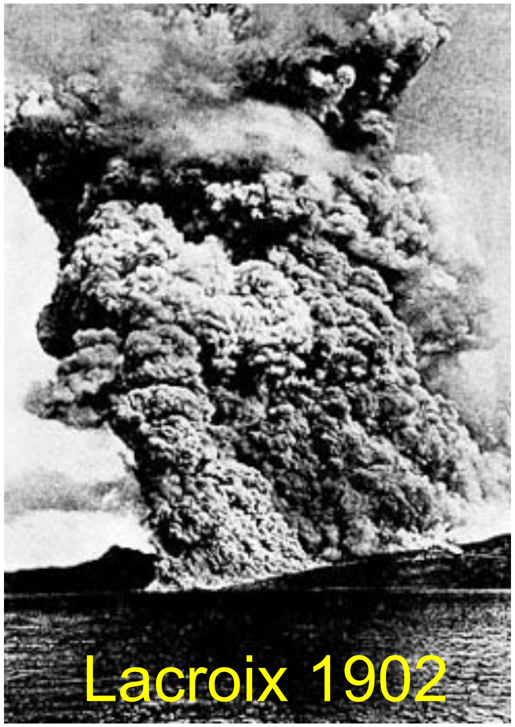
Most large clasts are disrupted for fragmentation > few 100 m

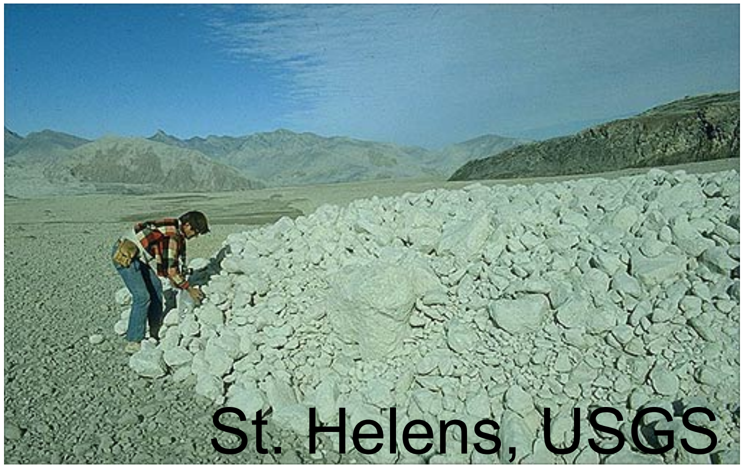


Conclusions

- Steam generation at the scale of particles change flow behavior qualitatively

- Large pumice suggests shallow fragmentation





Conclusions

- Integration models at different scales has a long history (e.g., turbulence) – and necessary for many volcanic processes because of the vast range of length and time scales that matter
- Experimental measurements can be used to link the micro- and macro-scale
- The “new” thermo-mechanical processes and properties (ash production, vaporization of water, boundary conditions) we have included matter in simulations - qualitatively and quantitatively