The mechanics of pyroclastic density currents

Transport processes (not deposits)

The role of particle-scale processes on the large scale dynamics of pyroclastic density currents

Michael Manga

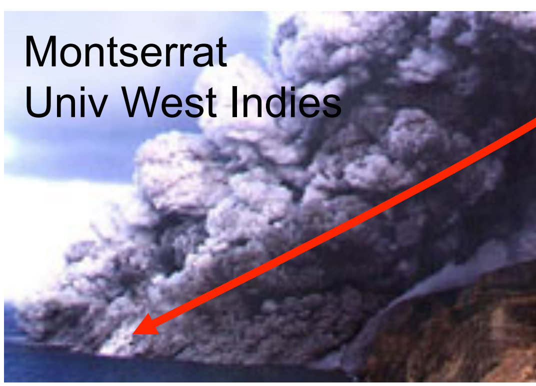
Department of
Earth and Planetary Science
University of California, Berkeley

Interrupt and ask questions anytime

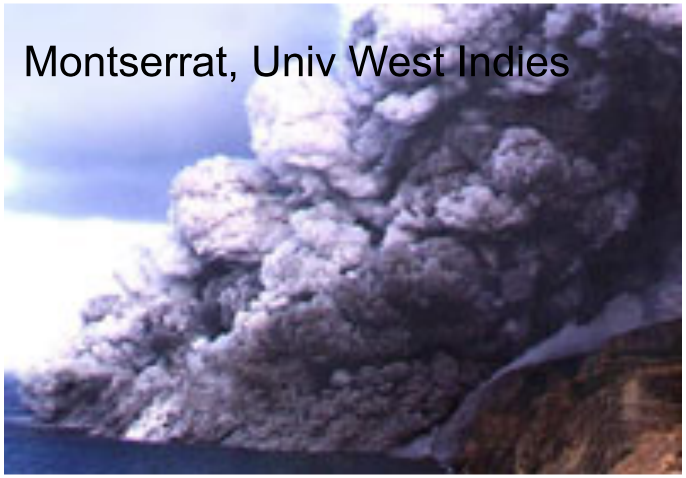
Mutiphase flows in explosive eruptions

Plinian Column
- Buoyant plume
- Particle+Gas Flow

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



Multiphase flows in explosive eruptions



- Controls of particle size?
- How fast?
- How far?
- Internal structure?
- Connect processes to deposits

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?

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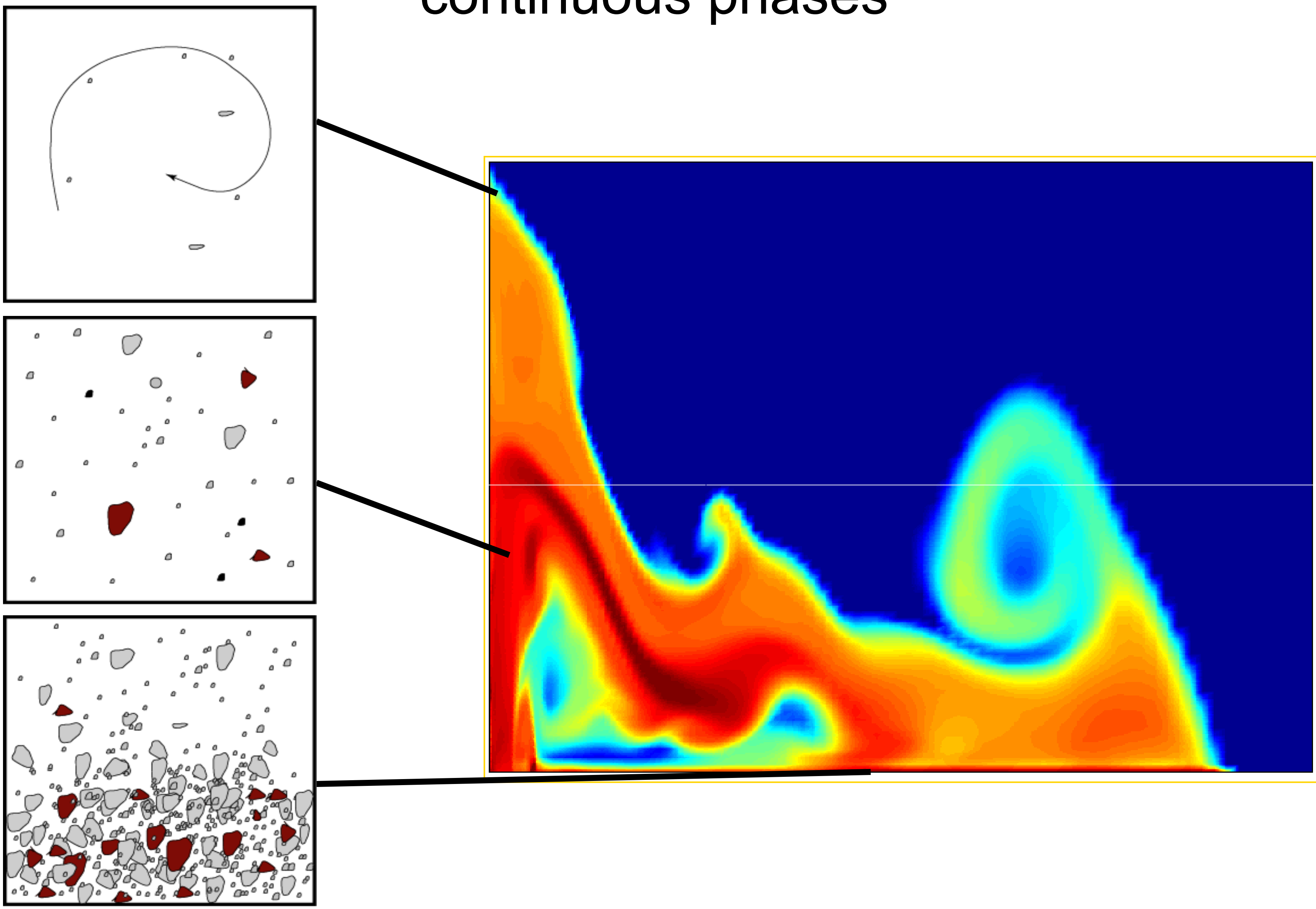
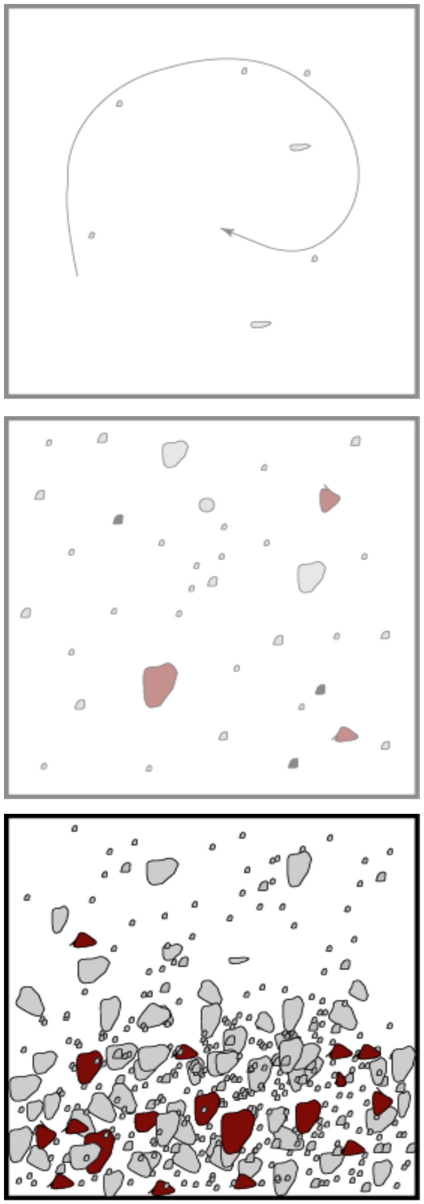
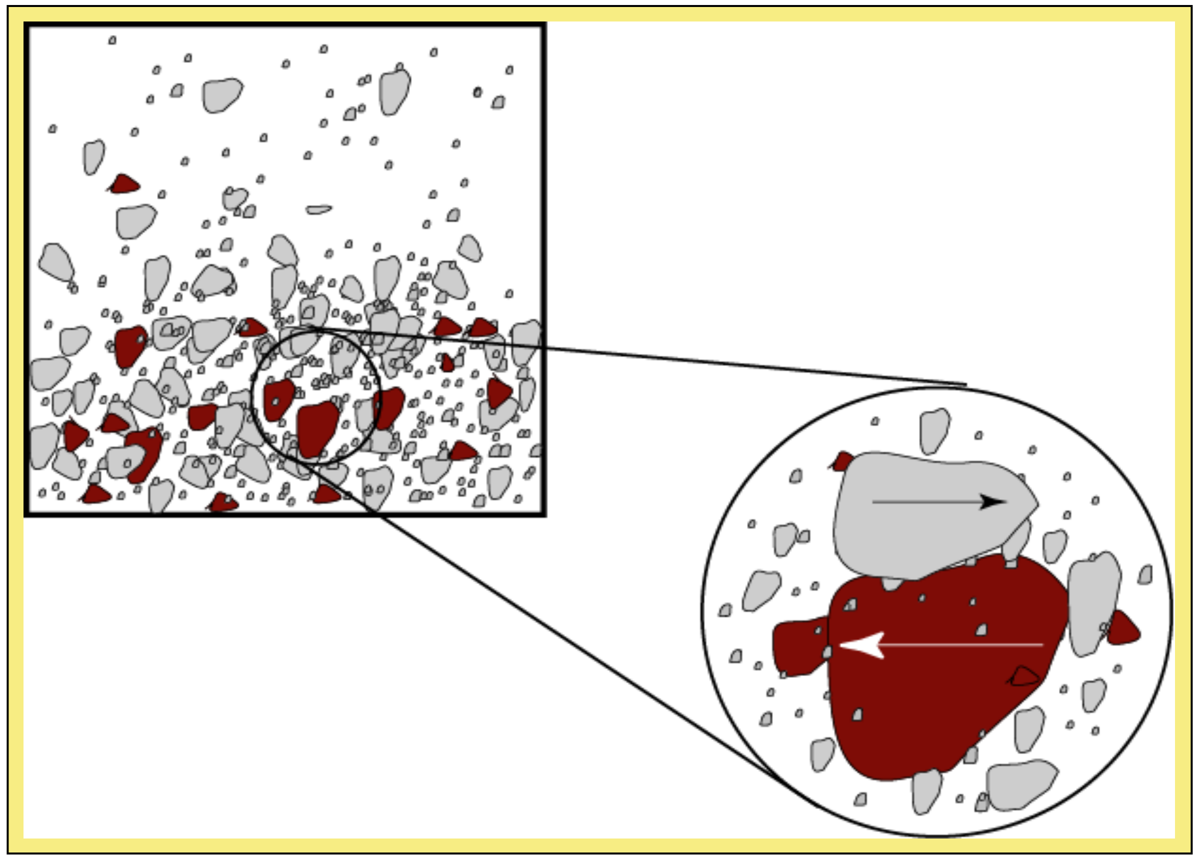
Multiple levels of coupling between discrete and continuous phases



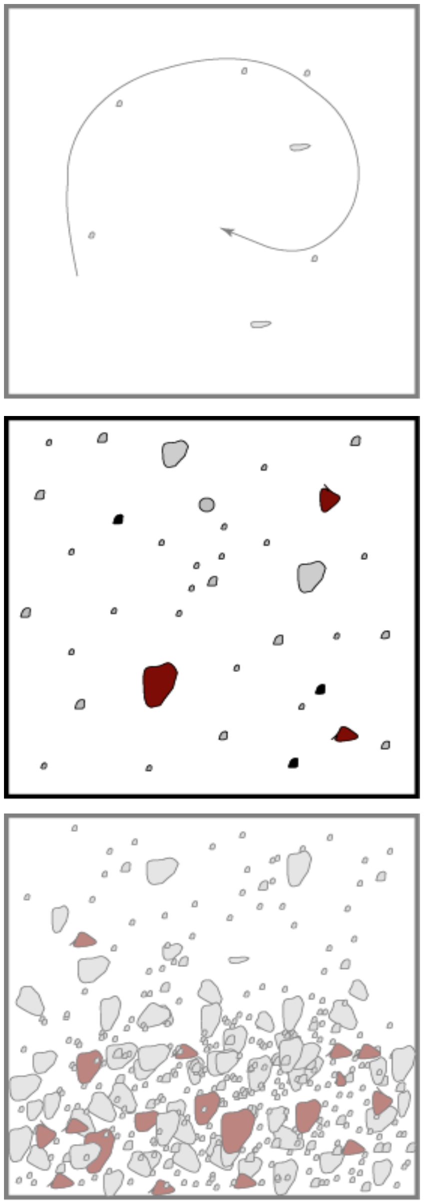
Multiple levels of coupling between discrete and continuous phases



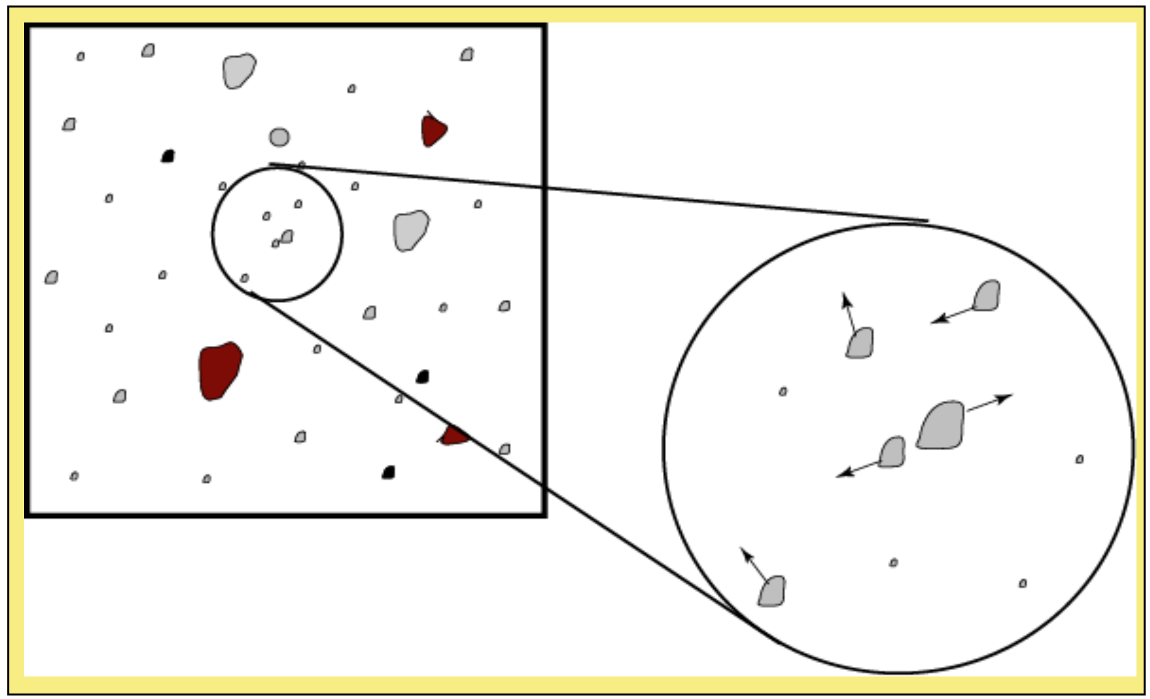
Prolonged Frictional Contact



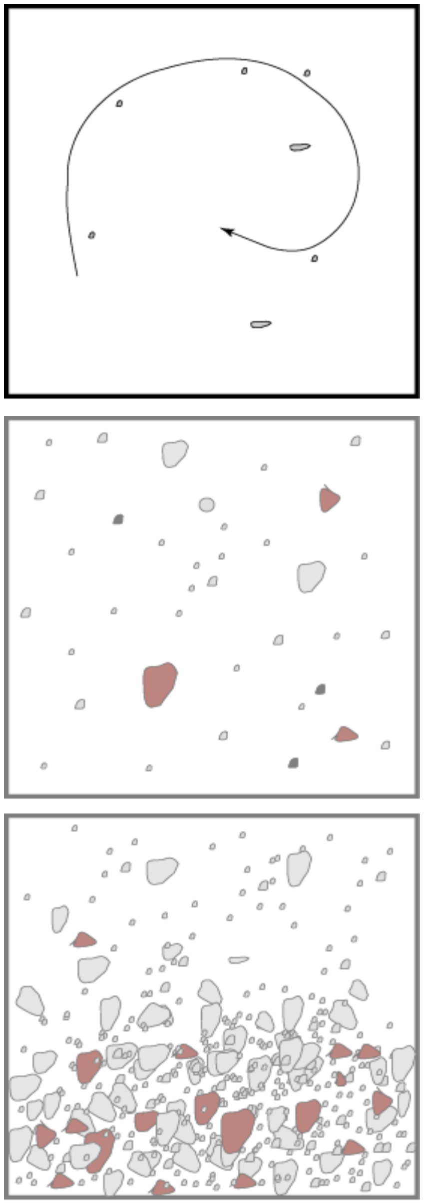
Multiple levels of coupling between discrete and continuous phases



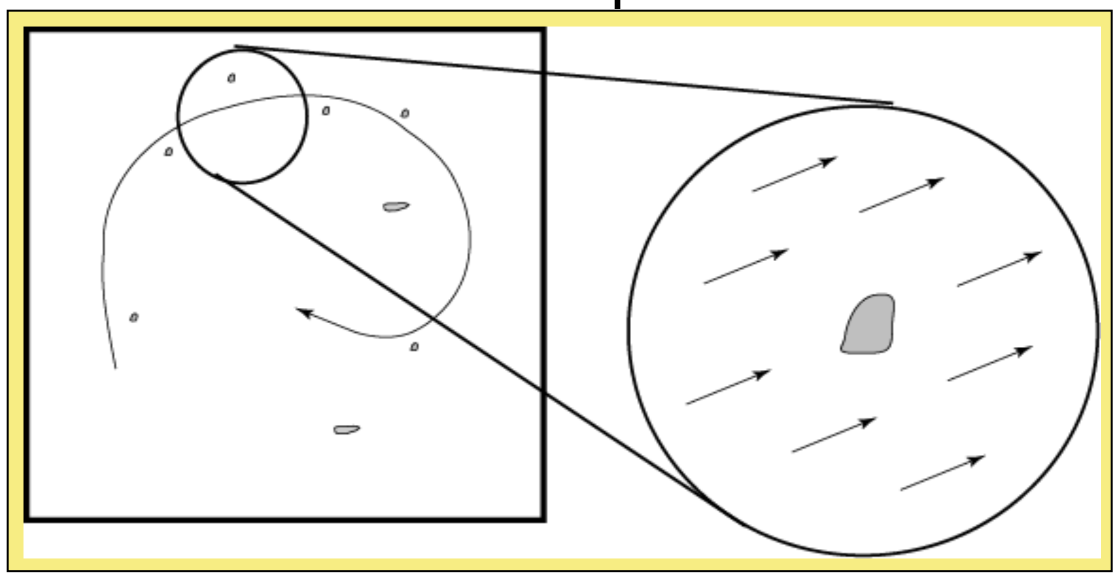
Instantaneous Collisions



Multiple levels of coupling between discrete and continuous phases



$$St = \tau_p/\tau_f$$



Mean field multifluid equations

Continuity

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

Momentum

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

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

Thermal Energy

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

Details of constitutive models, equations of state, turbulence models, in Dufek and Bergantz (2007)

Key: determining closure models

Sub-grid scale thermo-mechanical processes

1) Collisions between particles within pyroclastic flows (and in volcanic conduits in the afternoon)

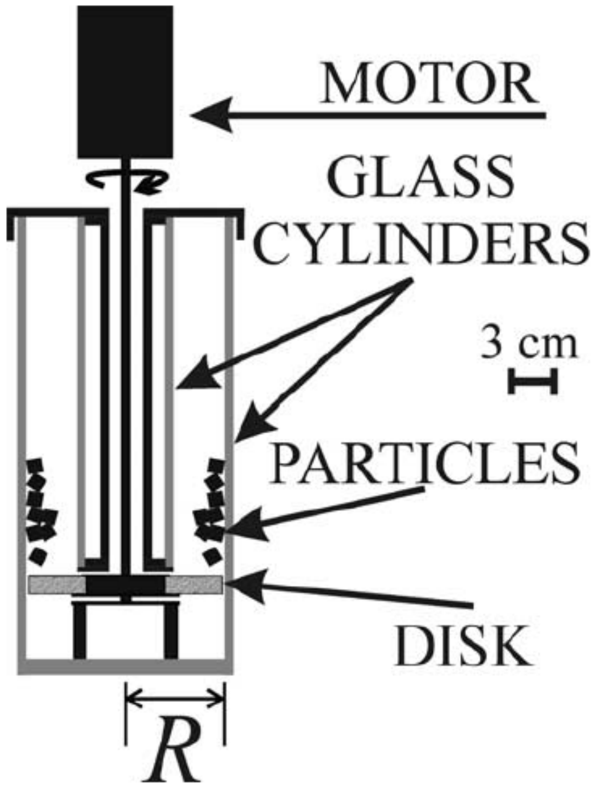
2) Role of boundary conditions (over water vs over land)

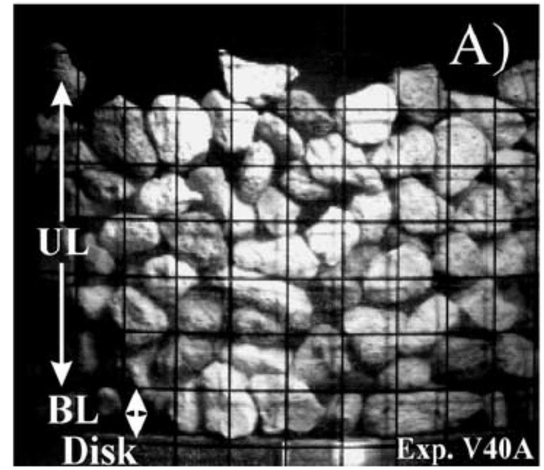
3) Heat transfer from particles to water

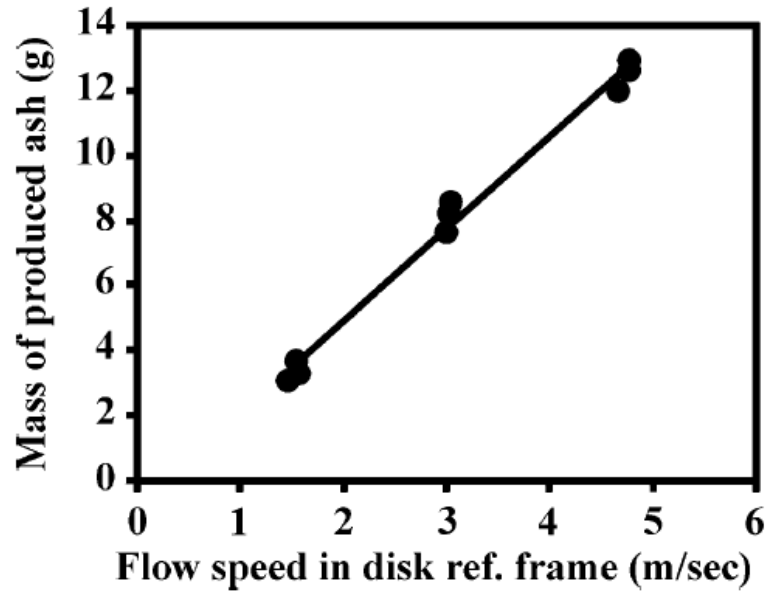
1. How much of this ash is made WITHIN the flow?

Influence on flow mechanics, deposits?

Frictional ash production experiment



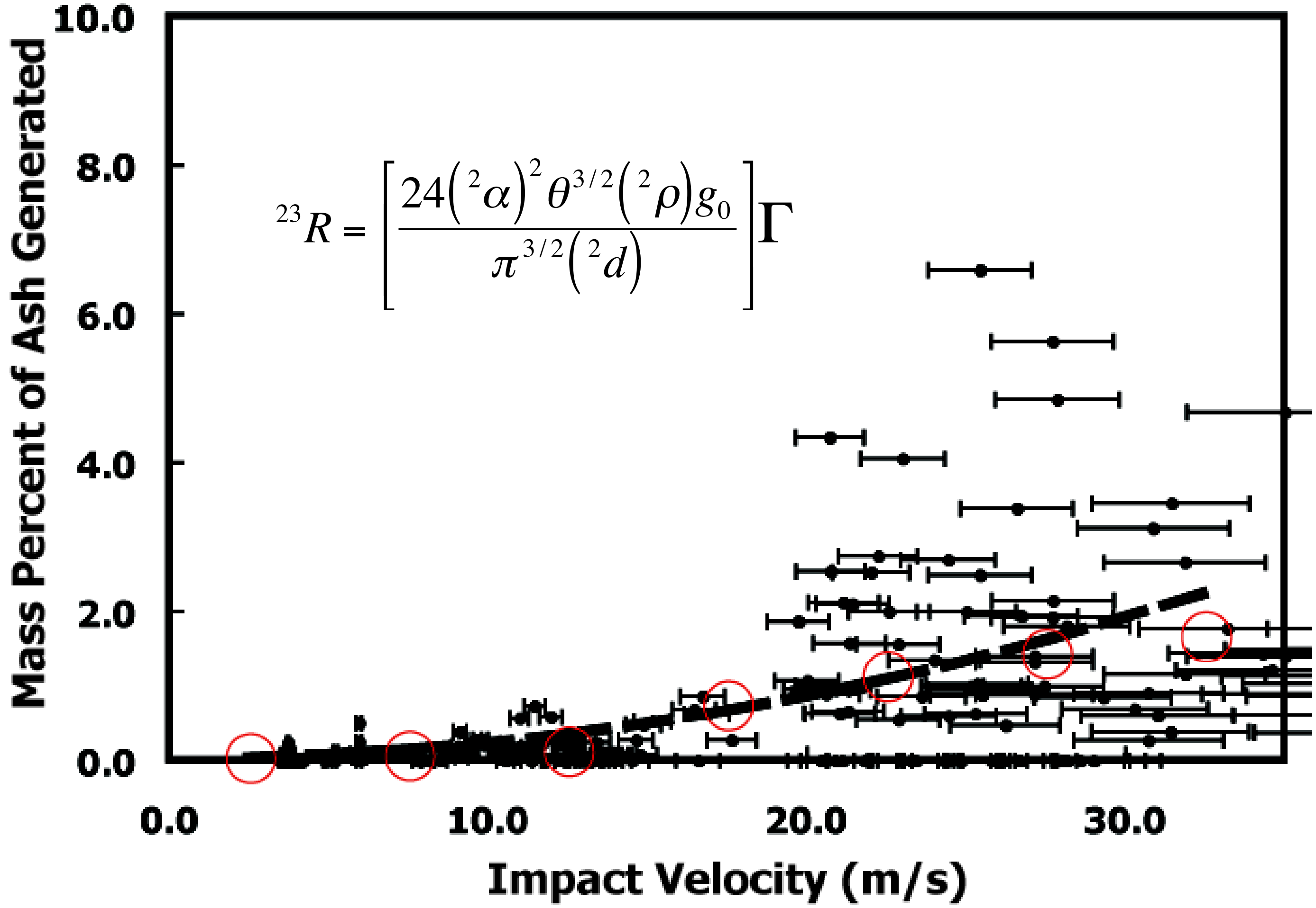




$$^{24}R = \frac{1}{\Delta y}\xi(u)$$

Cagnoli and Manga, *JGR* (2004)

Collisional ash production experiment



Ash, not fractal size distribution (collision energy not large enough)

1. Generating ash within flows

Continuity

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

$$\frac{\partial}{\partial t}({}^2\alpha\,{}^2\rho) + \frac{\partial}{\partial \boldsymbol{x}_i}({}^2\alpha\,{}^2\rho\,{}^2\boldsymbol{U}_i) = \underbrace{-{}^{23}R}_{\text{Mass loss due to collisional ash prodution}} \underbrace{-{}^{24}R}_{\text{Mass loss due to frictional ash prodution}}$$

$$\frac{\partial}{\partial t}({}^3\alpha\,{}^3\rho) + \frac{\partial}{\partial \boldsymbol{x}_i}({}^3\alpha\,{}^3\rho\,{}^3\boldsymbol{U}_i) = \underbrace{+{}^{23}R}_{\text{Mass gain due to collisional ash prodution}}$$

$$\frac{\partial}{\partial t}({}^4\alpha\,{}^4\rho) + \frac{\partial}{\partial \boldsymbol{x}_i}({}^4\alpha\,{}^4\rho\,{}^4\boldsymbol{U}_i) = \underbrace{+{}^{24}R}_{\text{Mass gain due to frictional ash prodution}}$$

Thermal

$${}^g\alpha\,{}^g\rho\,{}^gc_p\left(\frac{\partial\,{}^gT}{\partial t} + {}^g\boldsymbol{U}_i\frac{\partial\,{}^gT}{\partial \boldsymbol{x}_i}\right) = \frac{\partial\,{}^gq}{\partial \boldsymbol{x}_i} - \overline{H}_{g2} - \overline{H}_{g3} - \overline{H}_{g4}$$

$${}^2\alpha\,{}^2\rho\,{}^2c_p\left(\frac{\partial\,{}^2T}{\partial t} + {}^2\boldsymbol{U}_i\frac{\partial\,{}^2T}{\partial \boldsymbol{x}_i}\right) = \frac{\partial\,{}^2q}{\partial \boldsymbol{x}_i} + \overline{H}_{g2}$$

$${}^3\alpha\,{}^3\rho\,{}^3c_p\left(\frac{\partial\,{}^3T}{\partial t} + {}^3\boldsymbol{U}_i\frac{\partial\,{}^3T}{\partial \boldsymbol{x}_i}\right) = \frac{\partial\,{}^3q}{\partial \boldsymbol{x}_i} + \overline{H}_{g3}$$

$${}^4\alpha\,{}^4\rho\,{}^4c_p\left(\frac{\partial\,{}^4T}{\partial t} + {}^4\boldsymbol{U}_i\frac{\partial\,{}^4T}{\partial \boldsymbol{x}_i}\right) = \frac{\partial\,{}^4q}{\partial \boldsymbol{x}_i} + \overline{H}_{g4}$$

Momentum

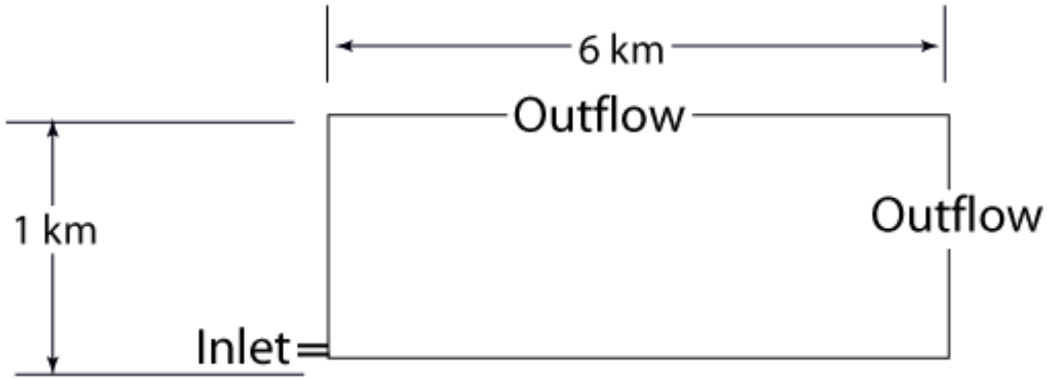
$$\frac{\partial}{\partial t}({}^g\alpha\,{}^g\rho\boldsymbol{U}_i) + \frac{\partial}{\partial \boldsymbol{x}_i}({}^g\alpha\,{}^g\rho\,{}^g\boldsymbol{U}_i\,{}^g\boldsymbol{U}_j) = \frac{\partial\,{}^gP}{\partial x_i}\delta_{ij} + \frac{\partial\,{}^g\tau_{ij}}{\partial x_j} + {}^gI_i + {}^g\alpha\,{}^g\rho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

$$\frac{\partial}{\partial t}({}^2\alpha\,{}^2\rho\boldsymbol{U}_i) + \frac{\partial}{\partial \boldsymbol{x}_i}({}^2\alpha\,{}^2\rho\,{}^2\boldsymbol{U}_i\,{}^2\boldsymbol{U}_j) = \frac{\partial\,{}^2P}{\partial x_i}\delta_{ij} + \frac{\partial\,{}^2\tau_{ij}}{\partial x_j} + {}^2I_i + {}^2\alpha\,{}^2\rho g_i - {}^{23}R\,{}^2U_i - {}^{24}R\,{}^2U_i$$

$$\frac{\partial}{\partial t}({}^3\alpha\,{}^3\rho\boldsymbol{U}_i) + \frac{\partial}{\partial \boldsymbol{x}_i}({}^3\alpha\,{}^3\rho\,{}^3\boldsymbol{U}_i\,{}^3\boldsymbol{U}_j) = \frac{\partial\,{}^3P}{\partial x_i}\delta_{ij} + \frac{\partial\,{}^3\tau_{ij}}{\partial x_j} + {}^3I_i + {}^3\alpha\,{}^3\rho g_i + {}^{23}R\,{}^3U_i$$

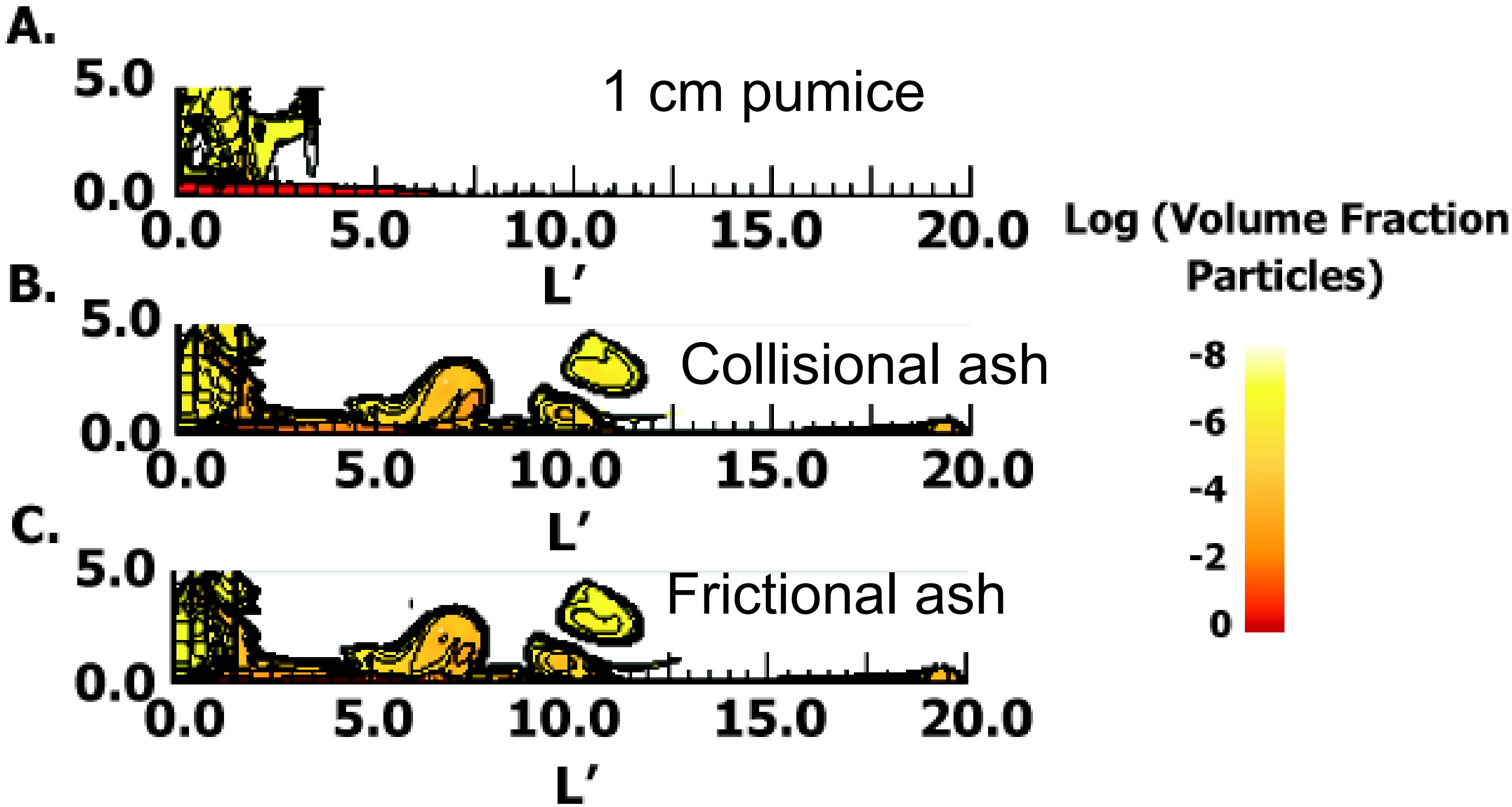
$$\frac{\partial}{\partial t}({}^4\alpha\,{}^4\rho\boldsymbol{U}_i) + \frac{\partial}{\partial \boldsymbol{x}_i}({}^4\alpha\,{}^4\rho\,{}^4\boldsymbol{U}_i\,{}^4\boldsymbol{U}_j) = \frac{\partial\,{}^4P}{\partial x_i}\delta_{ij} + \frac{\partial\,{}^4\tau_{ij}}{\partial x_j} + {}^4I_i + {}^4\alpha\,{}^4\rho g_i + {}^{24}R\,{}^4U_i$$

Model problem



grid 1m x 5 m; time step < 0.1s
initial velocity 50 m/s
initial concentration 0.025
initial size 1 cm
temperature 650 C

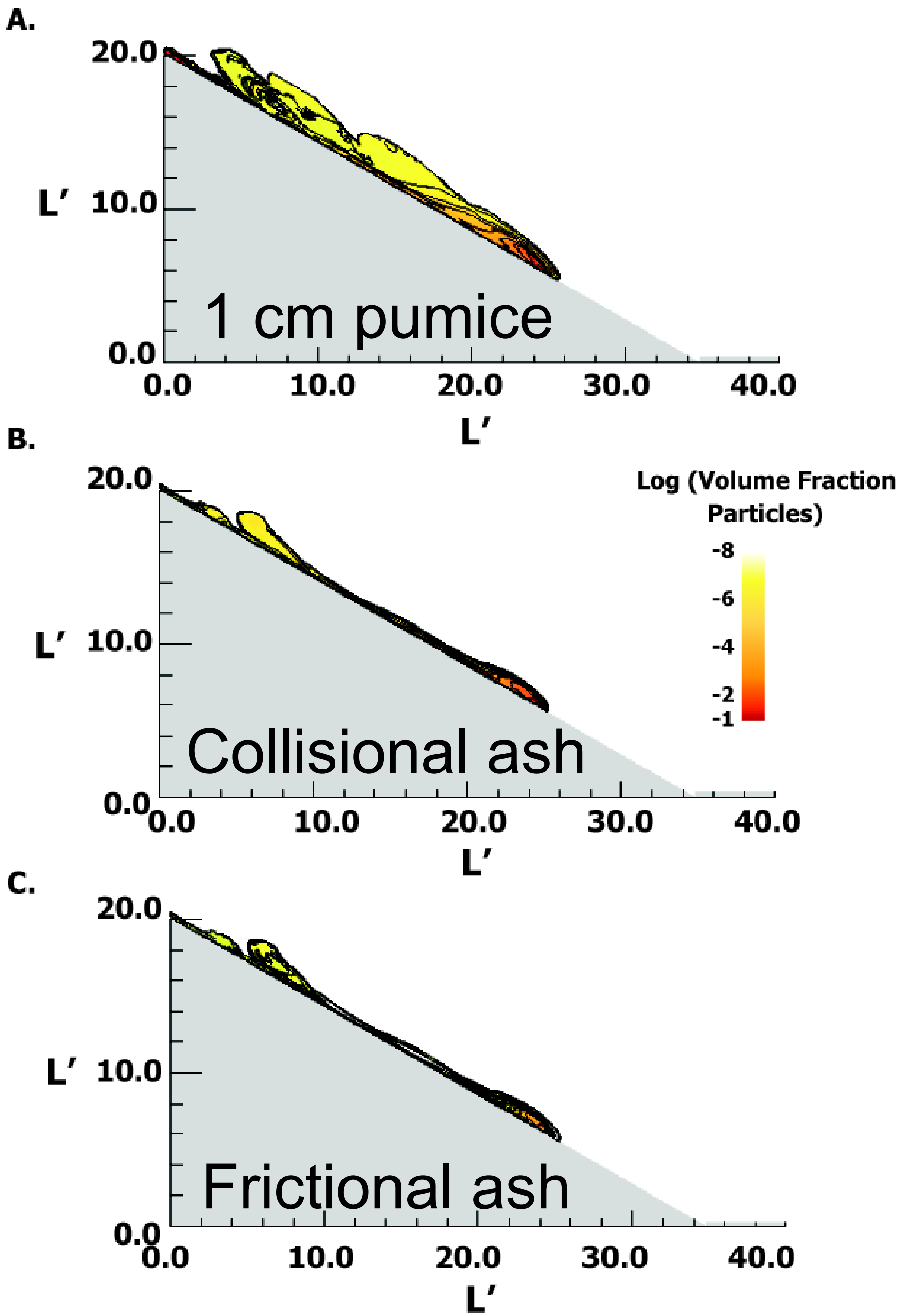
Flow over level terrain



Collisional and frictional ash are well mixed

Travels far beyond pumice

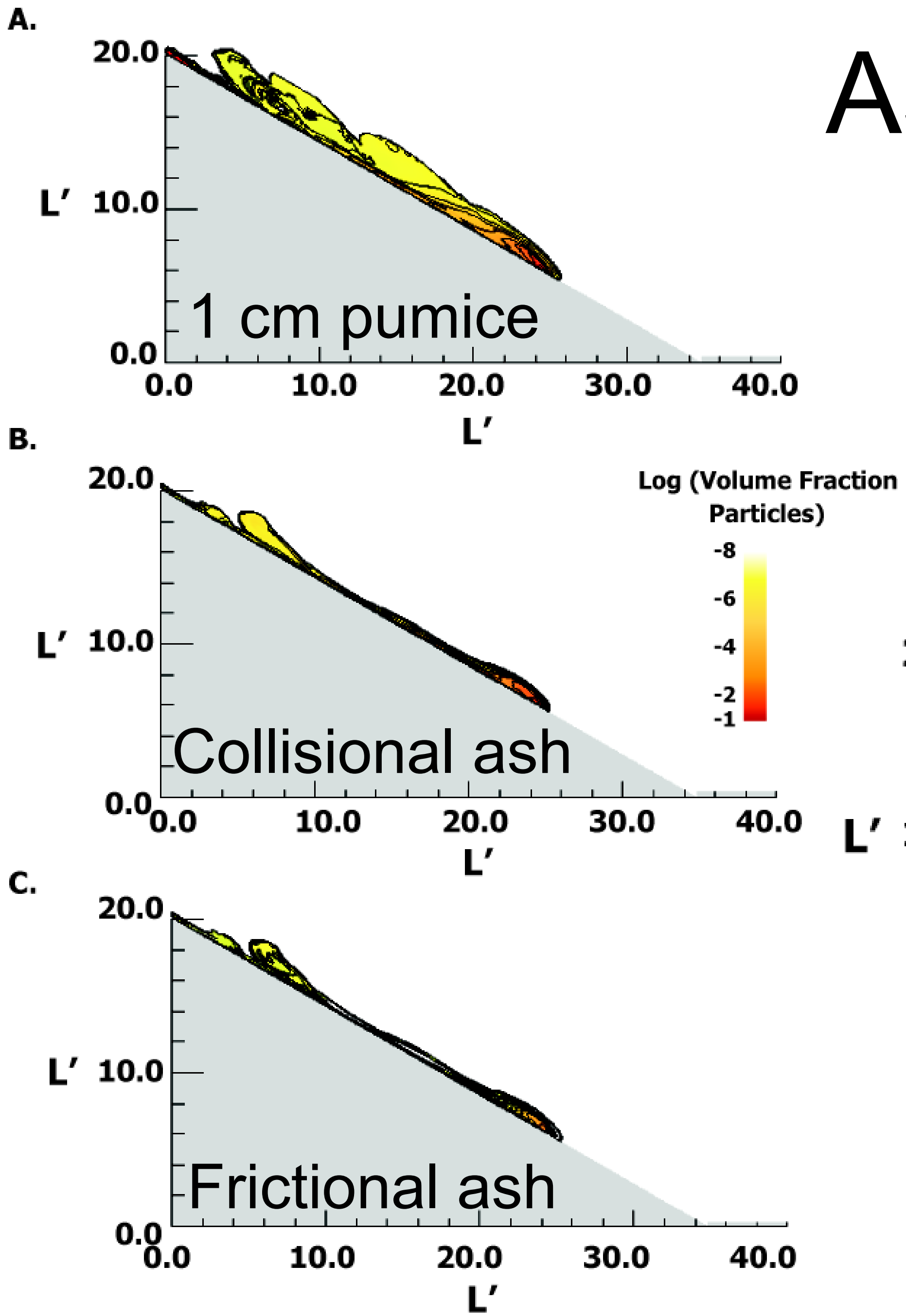
Total ash produced: 7%

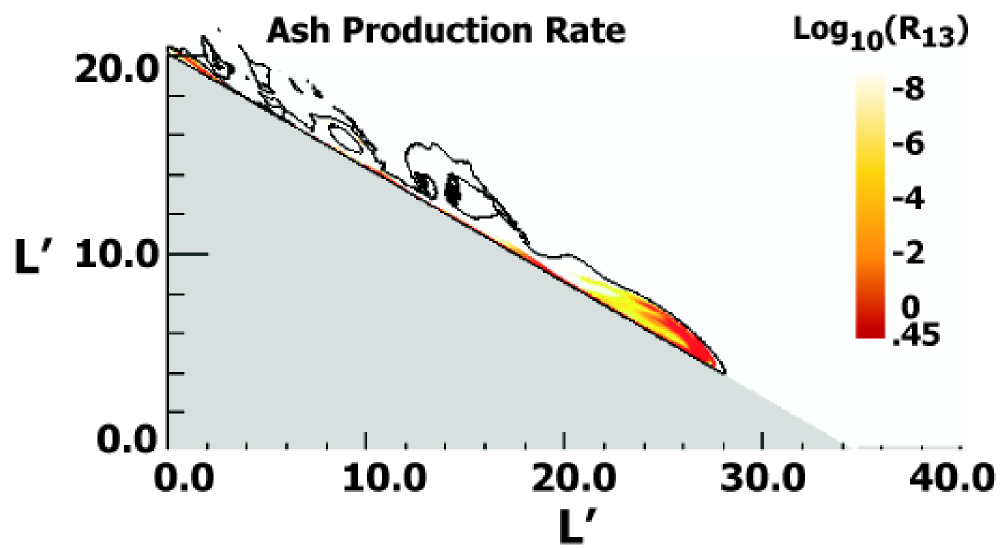


Downslope Accelerating

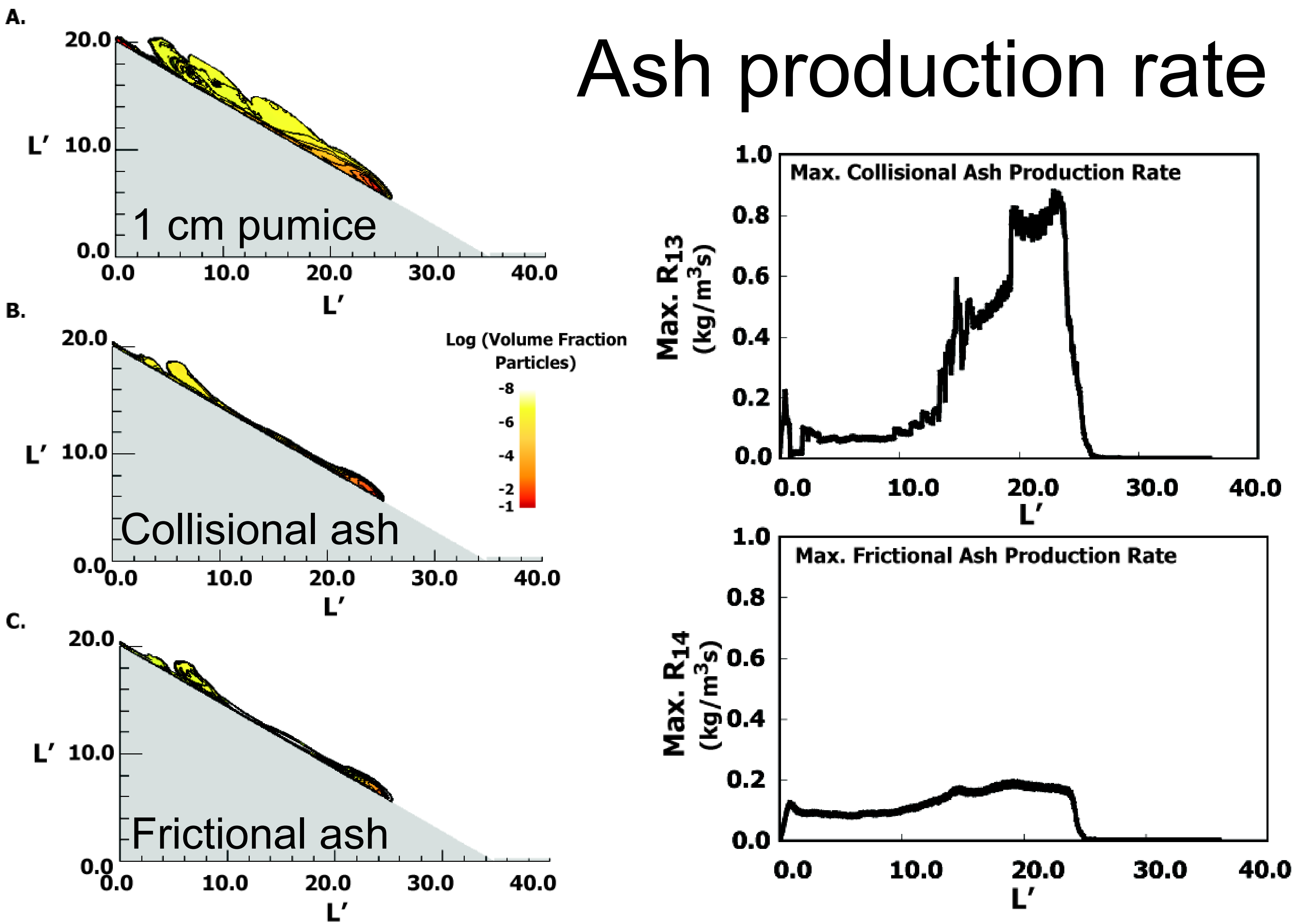
Ash production rate

Ash generated in more energetic part of flow



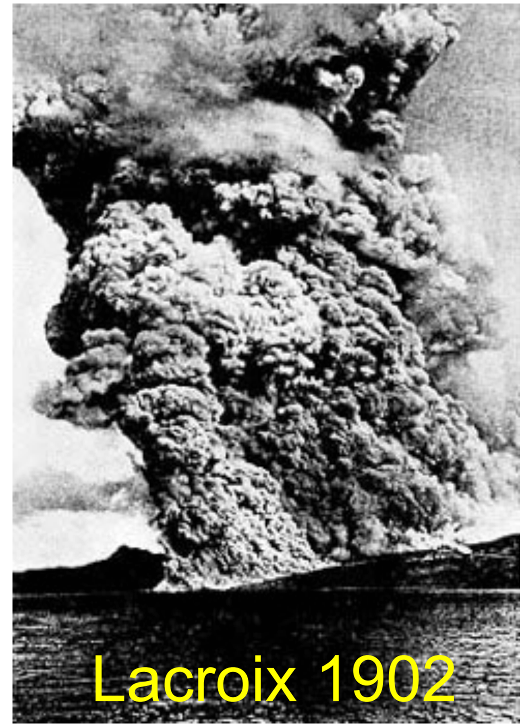


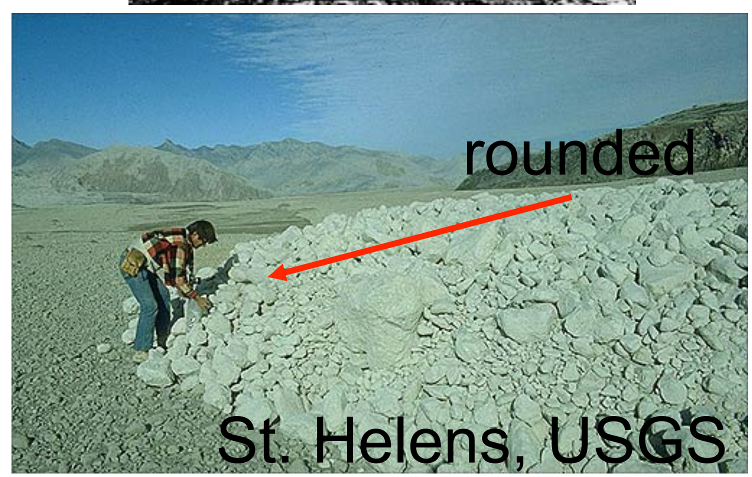
Ash production rate



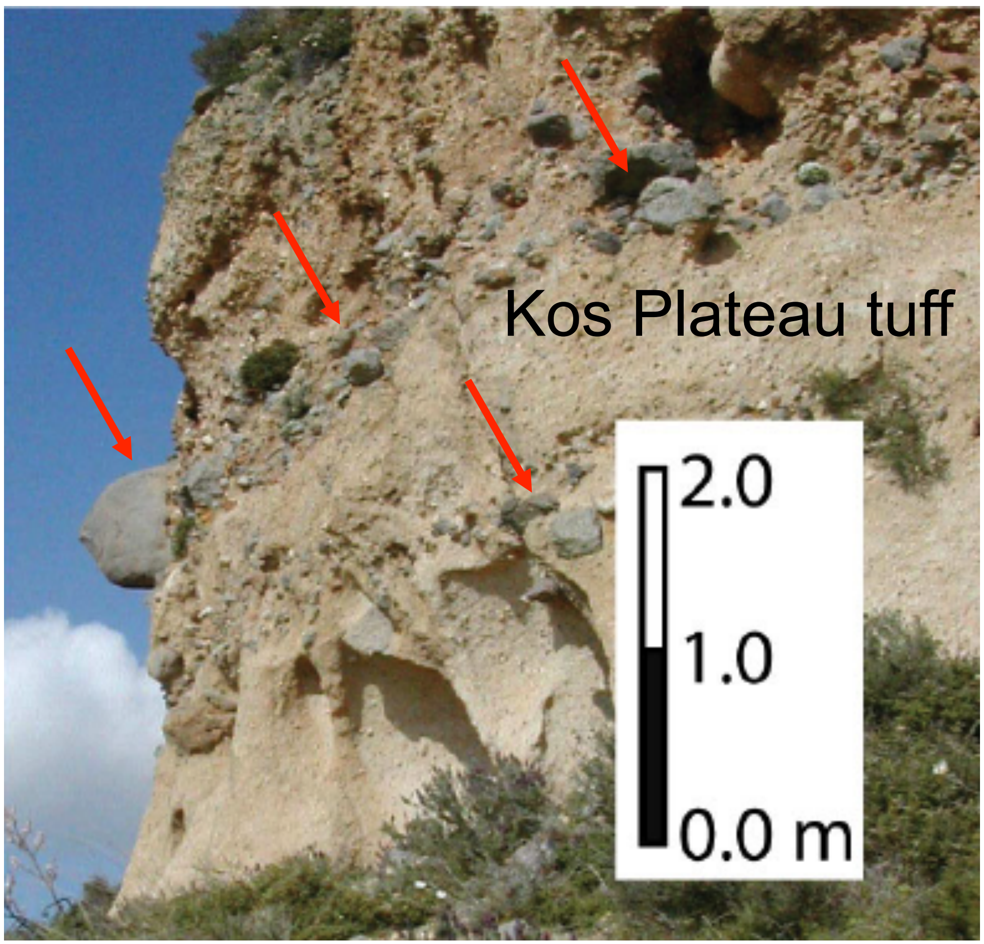
Conclusions

- A few to a few 10s of % of flow is converted to ash
- Ash generation increases runout distance
- Ash generated within flow separates from larger particles (travels faster, higher, farther)
- Origin of rounding of larger clasts

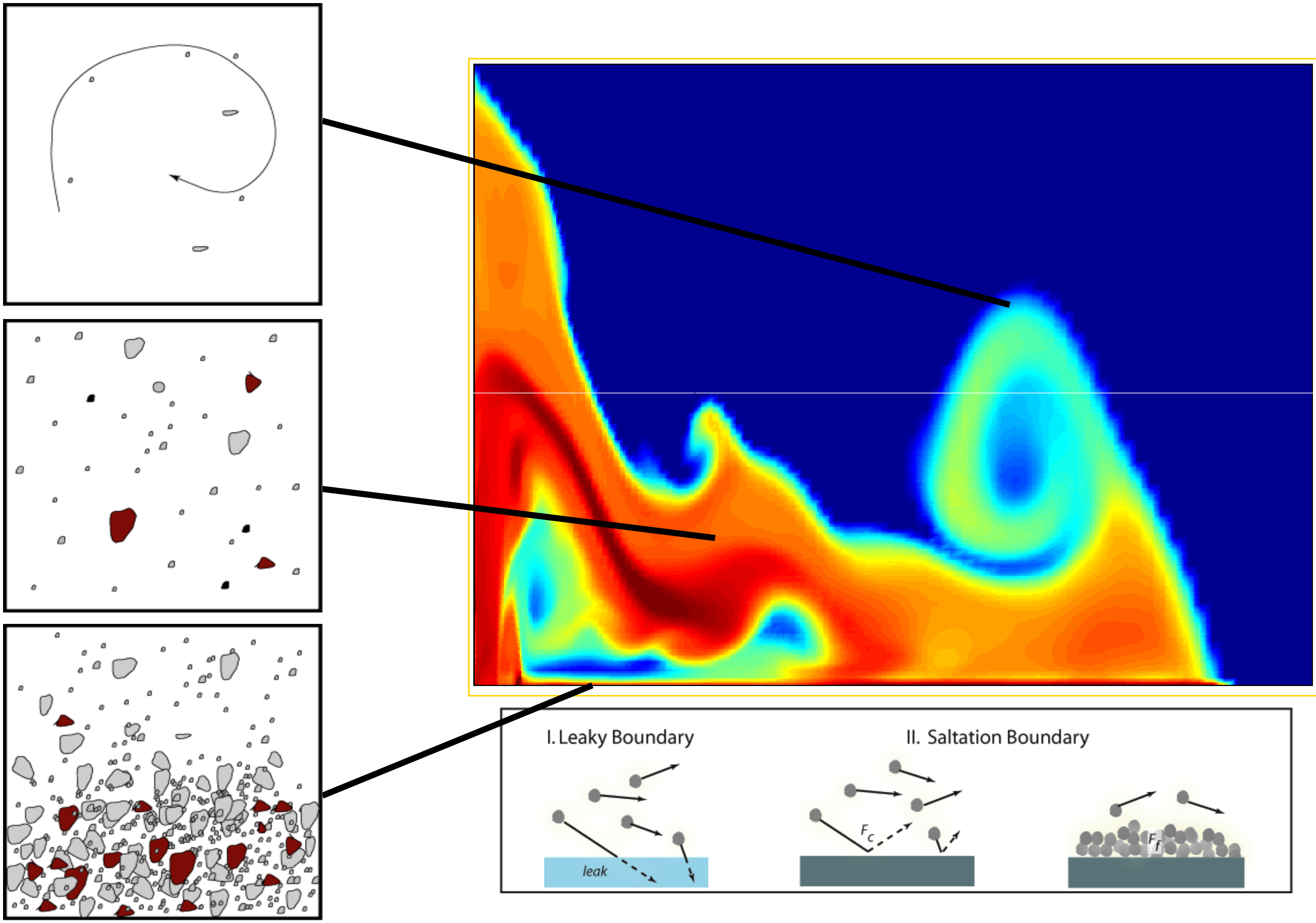




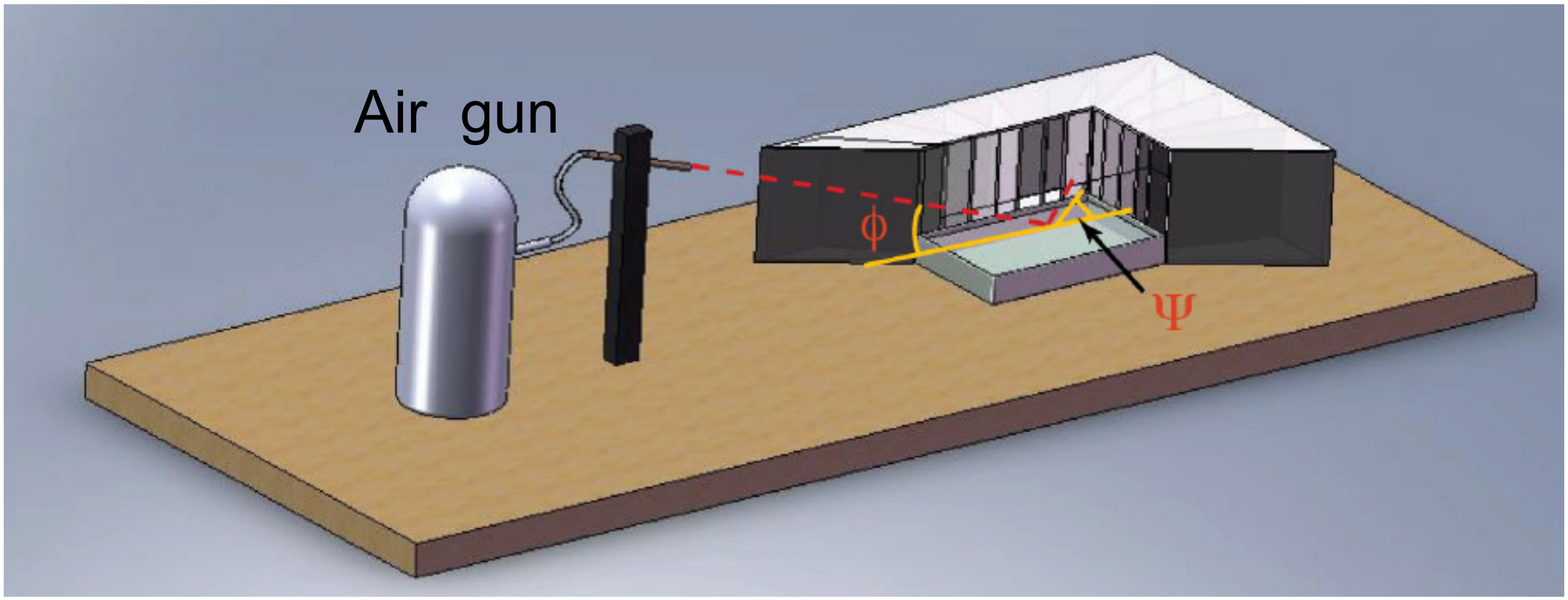
2. Transport capacity of pyroclastic flows: substrate-flow interactions



Role of boundary condition



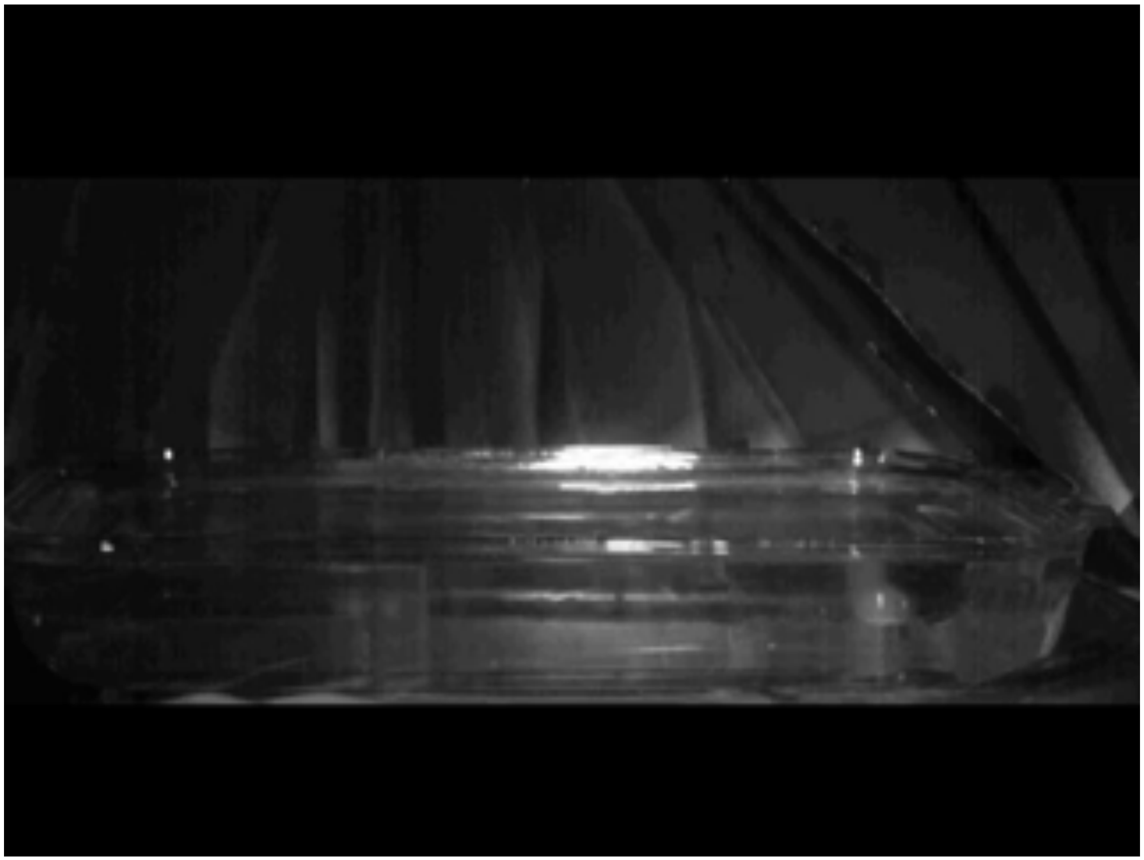
Particle-substrate interactions



Measure velocity before and after collision; whether particle bounces

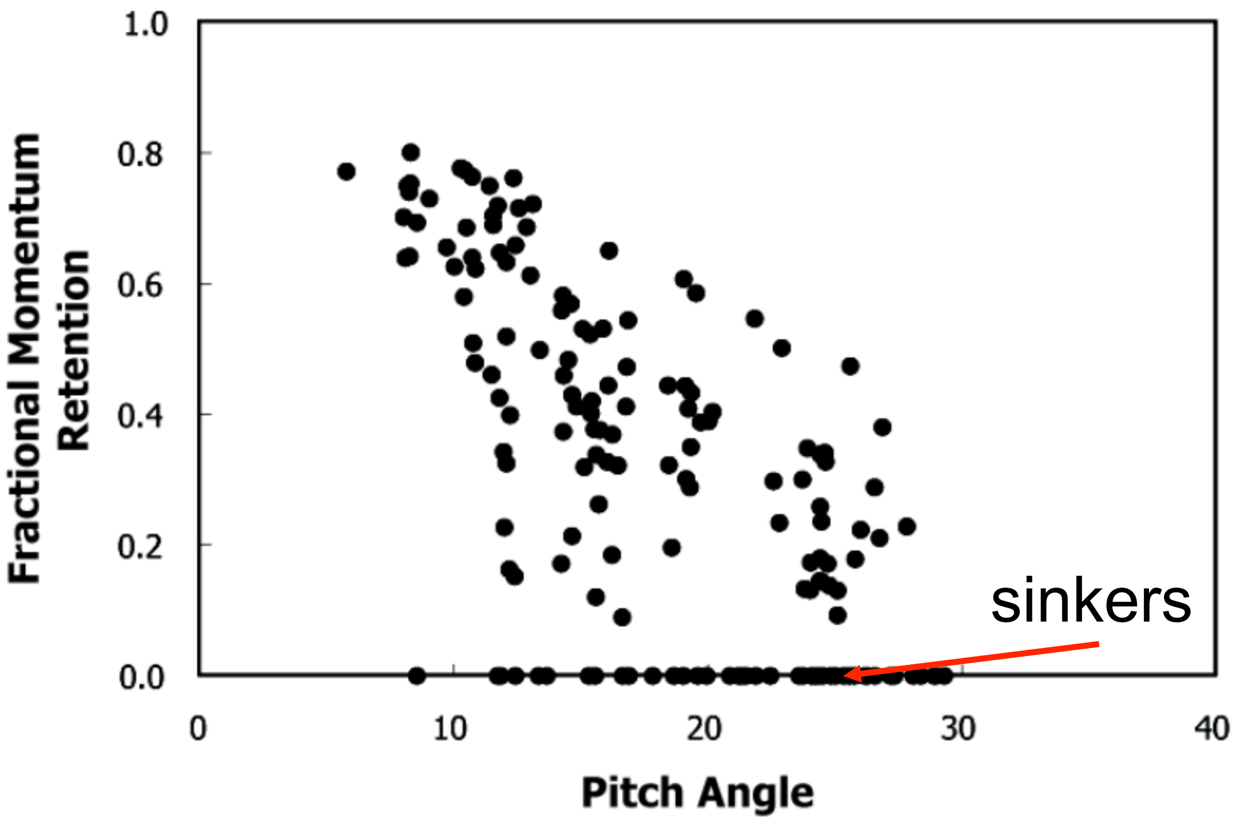
Variables: angle ϕ, velocity, mass, substrate

Example (water substrate)



- Extract quantitative information . . .

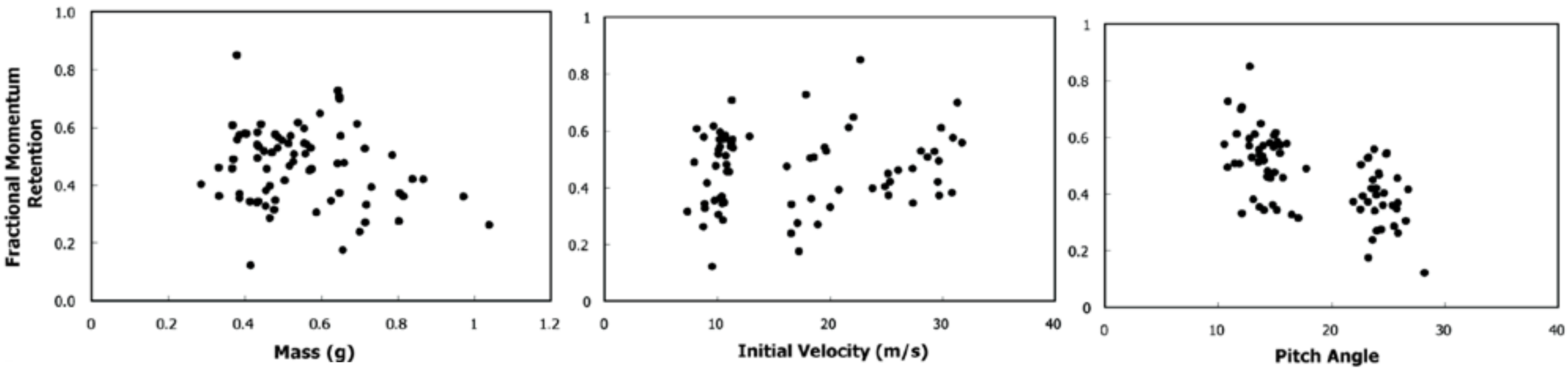
Water substrate



Restitution coefficient: $e = 0.8343 - 0.0291\phi$

Fraction that sink: $S = 9.3755 - 1.9452|V| + 3.1363\phi$

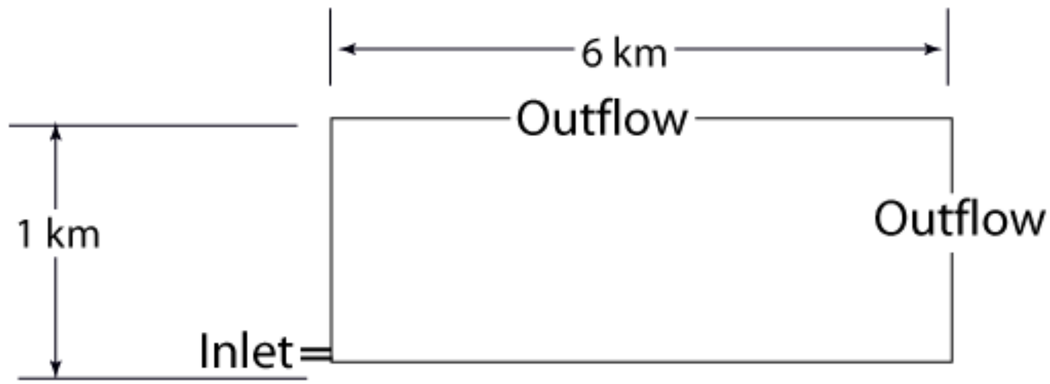
Pumice substrate



No effect of mass, impact velocity

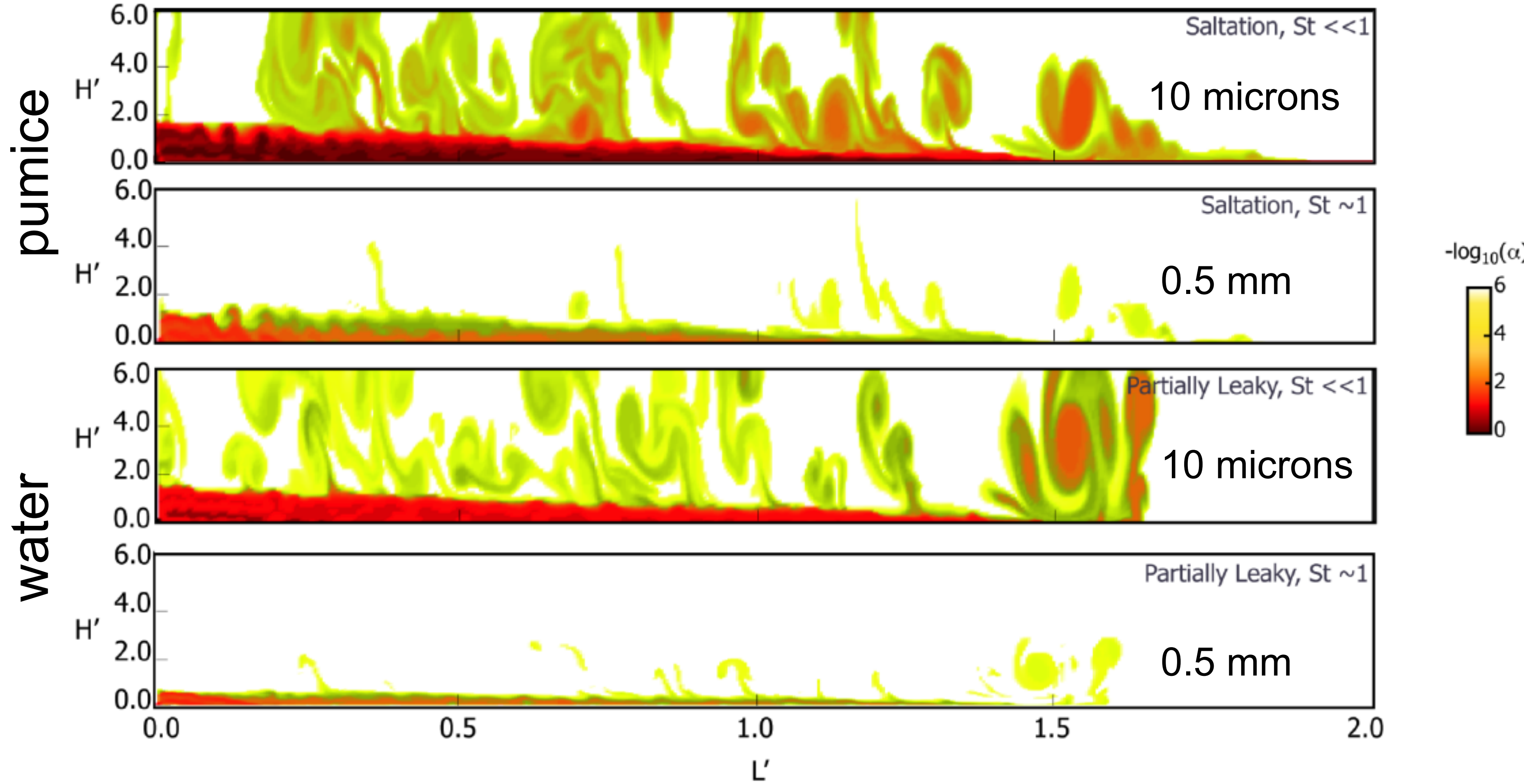
Restitution coefficient: $e = .7307 - 0.0144\phi$

Model problem



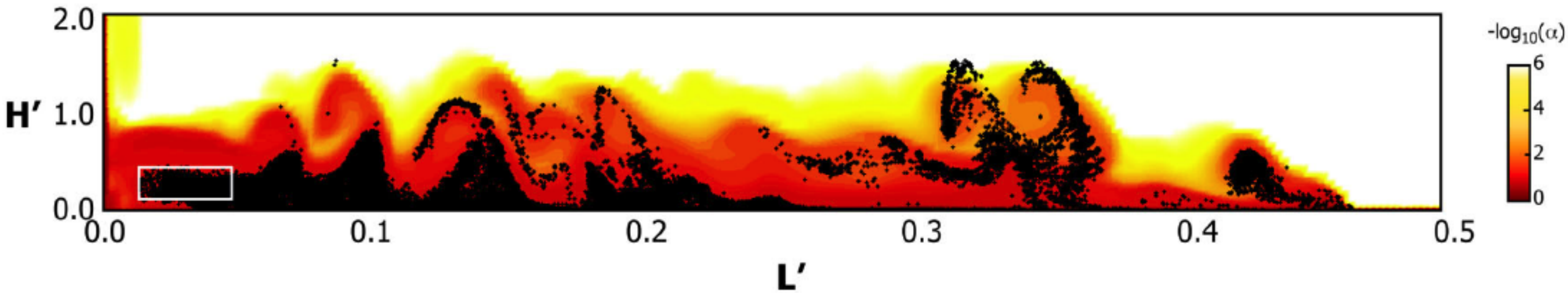
initial velocity 80 m/s
Initial height 100 m
initial concentration 0.025 or 0.40
density 1000 kg/m^3
size: 95% are 10 microns, 5% are 0.5 mm
temperature 700 K; air 300 K

Effect of boundary type



Over land flows develop a dense bed-load region because particles are not lost from the flow

Add Lagrangian tracers

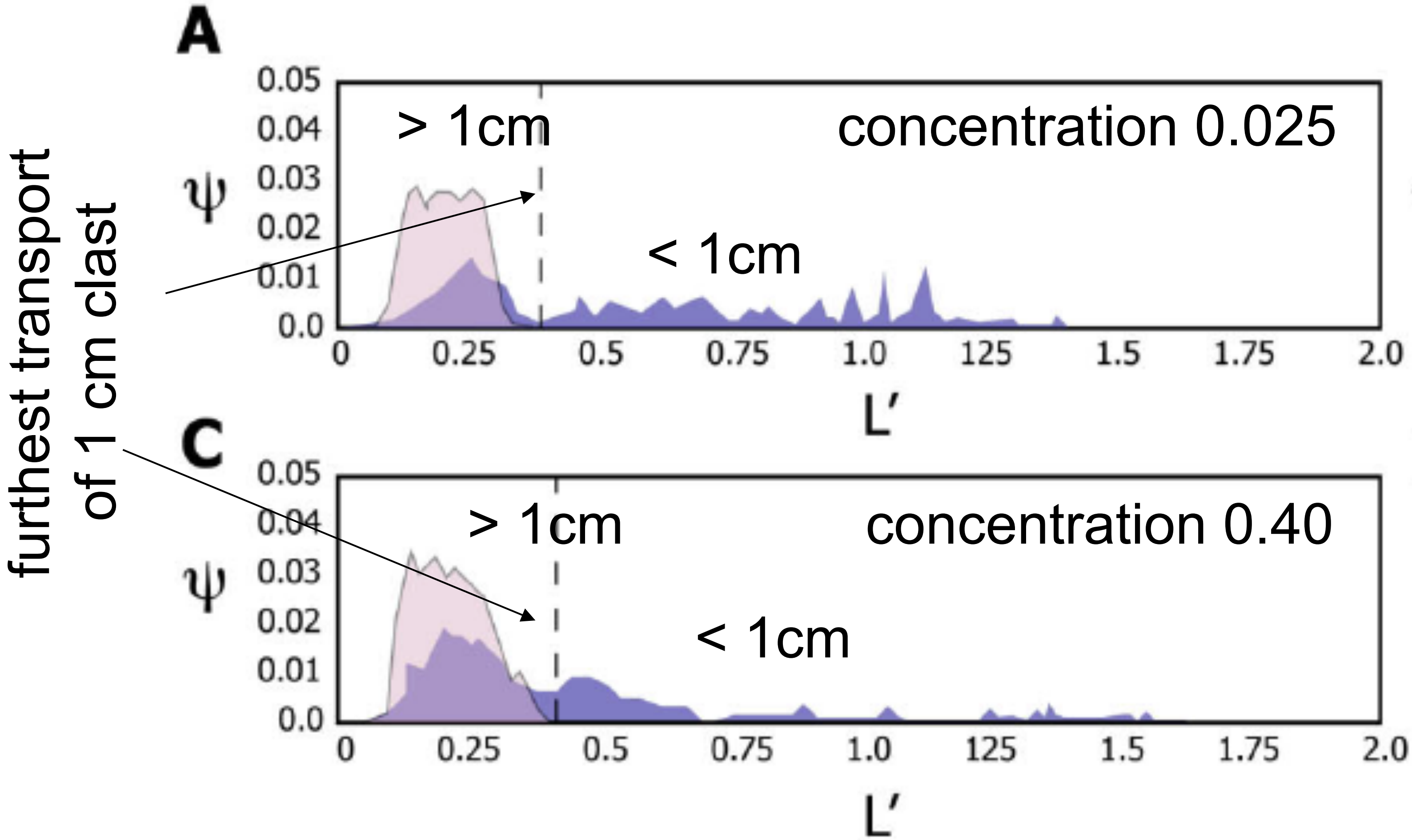


Interact with the flow, but do not affect the flow

Introduced near inlet

Size from 1 micron to 10 m

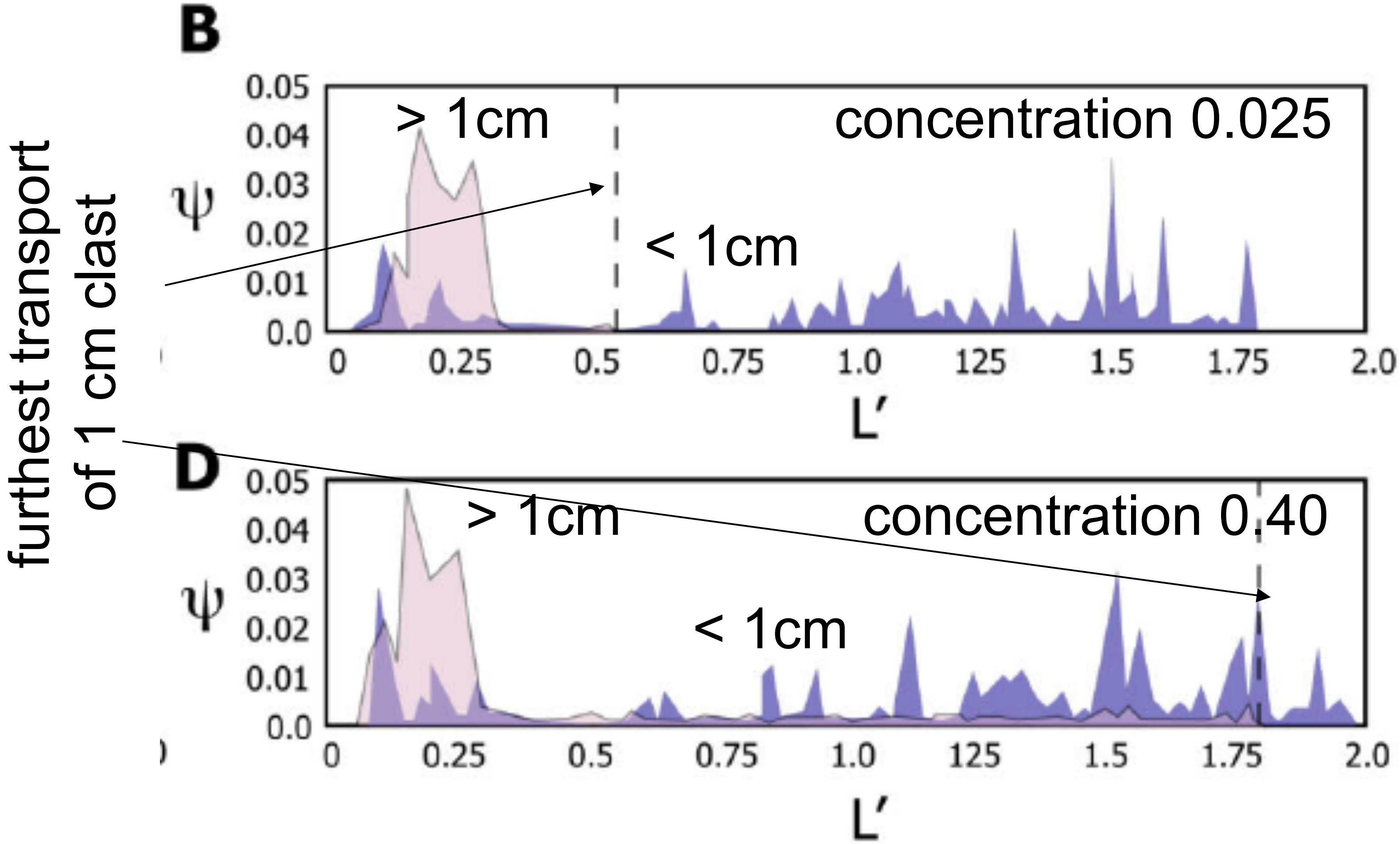
Over water



No concentrated bedload

Concentration has little effect of large clast transport

Over land

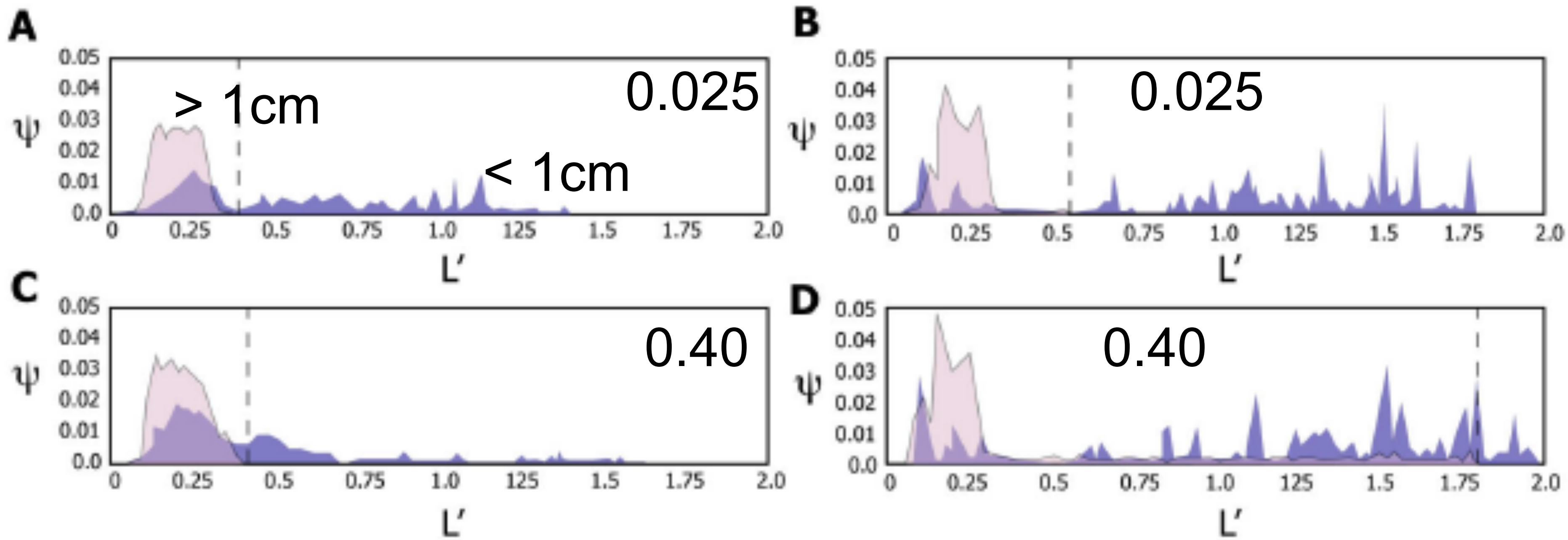


With concentrated bedload, large clasts transported to the end of the flow!

Flows travel further than over water

Over water

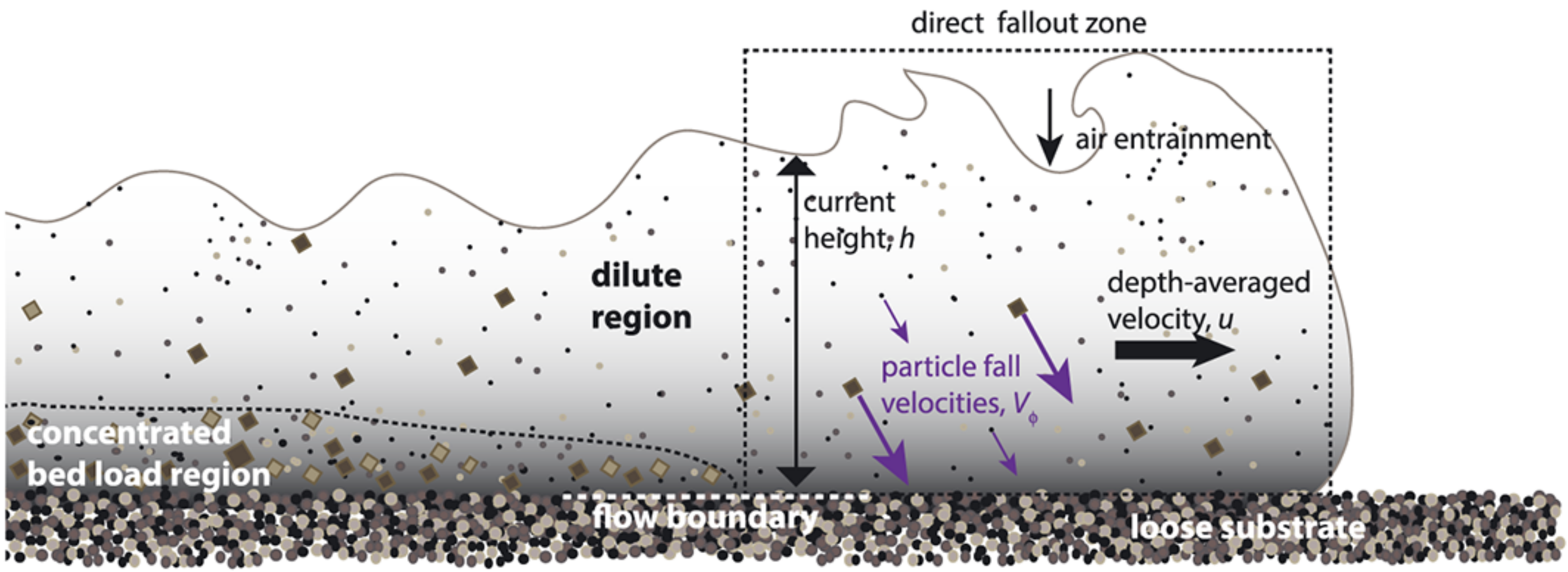
Over land



1) Boundary condition has a small effect for dilute flows

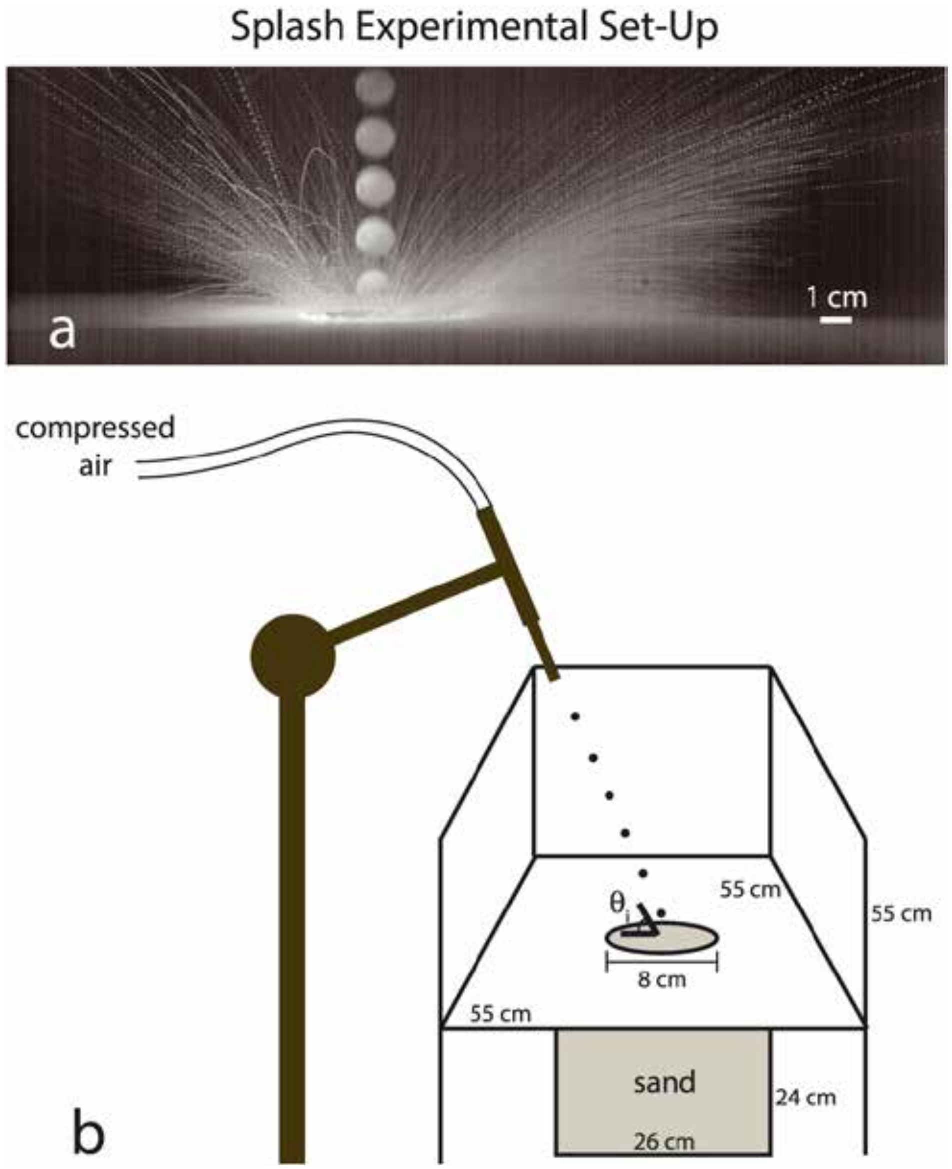
2) Dense flows over land develop a particle-rich bedload which transports large clasts (over water, particles sink and no particle-rich bedload forms)

Adding mass back into the current?

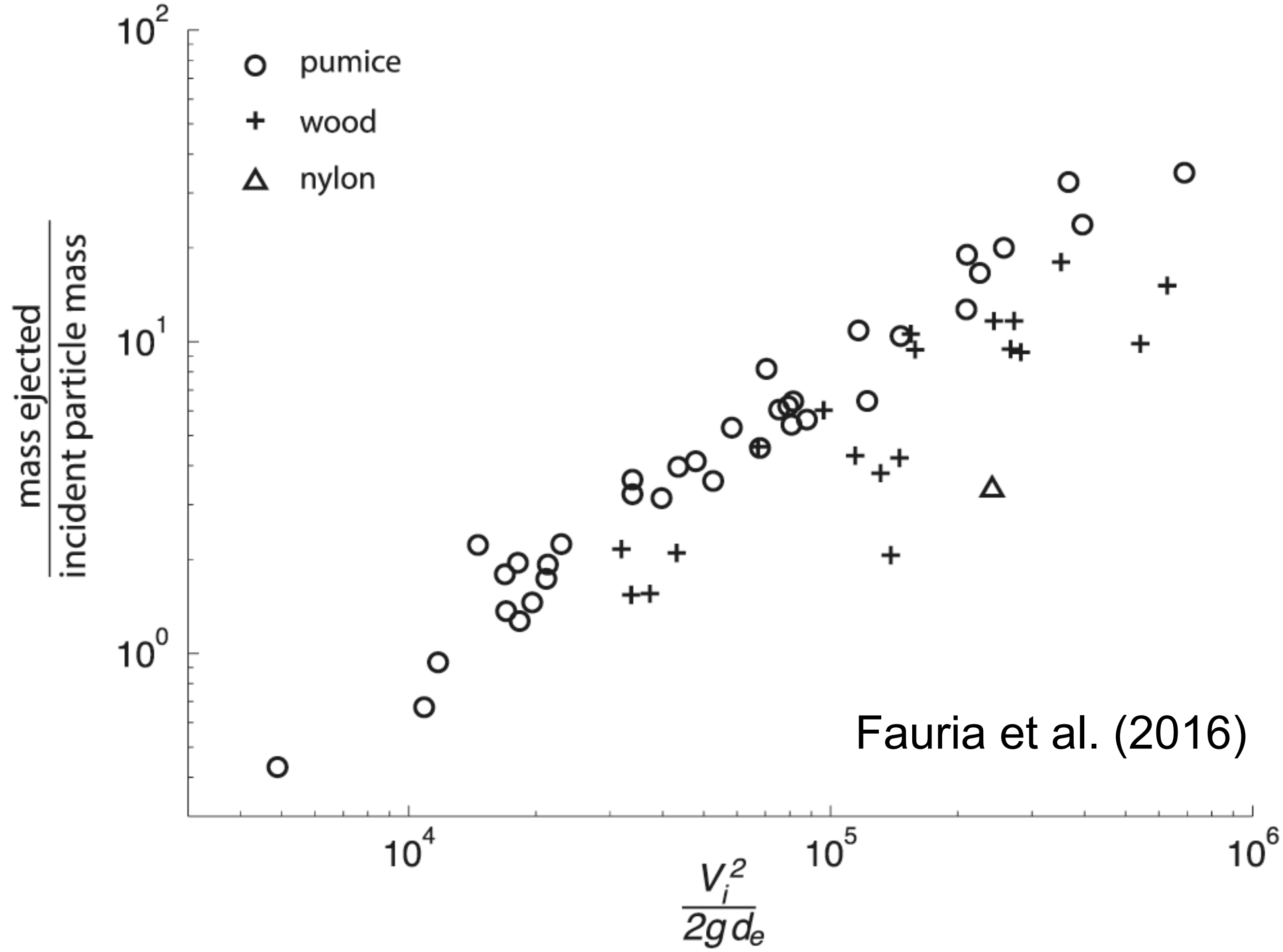


Can settling particles “splash” mass back into the current?

Experiments

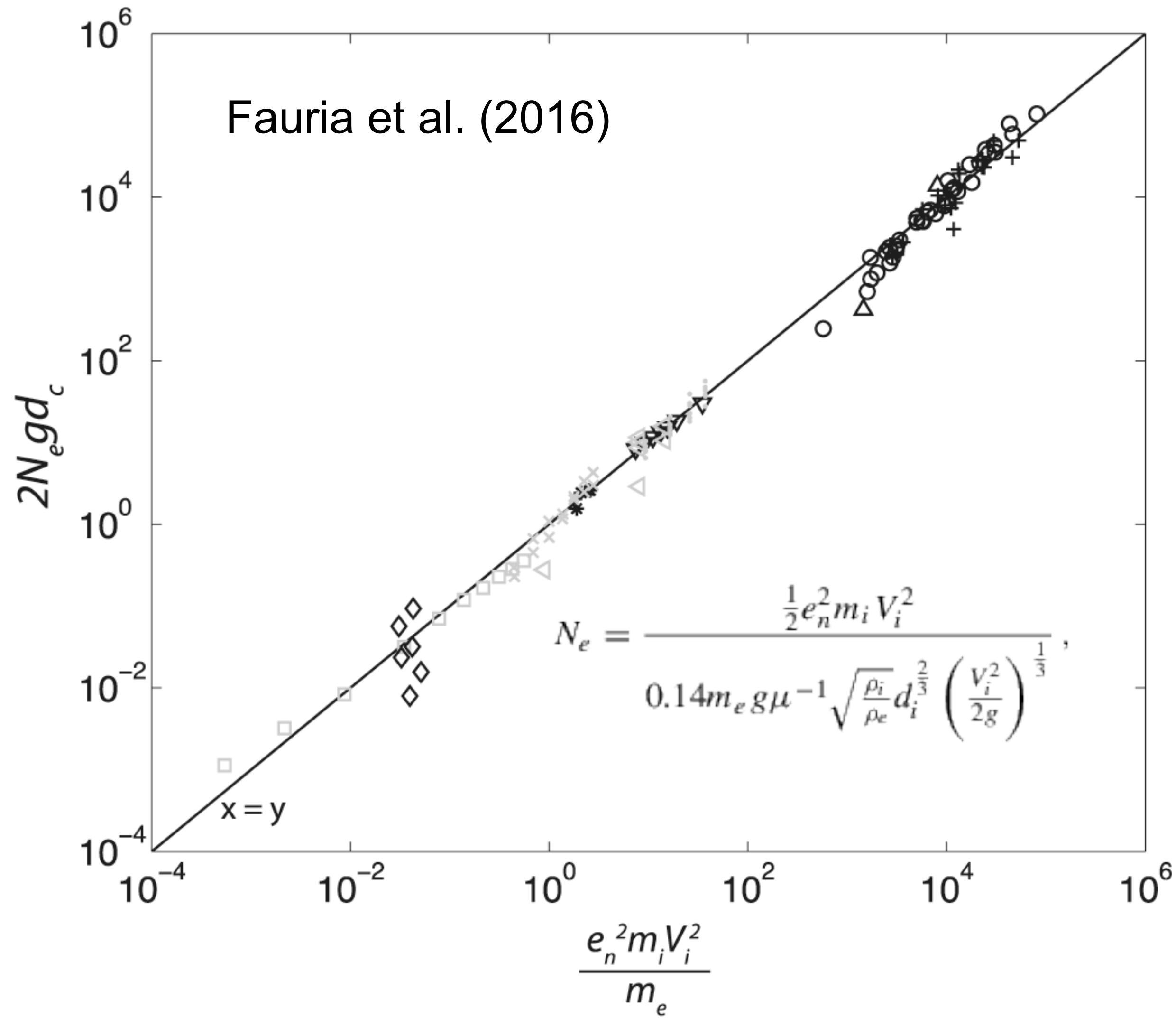


Experiments



Mass ejected can exceed mass of incident particle

Scaling



New and literature data, new scaling law

Density current model

Compute concentration, velocity, temperature as a function of time (and distance)

$$\frac{\mathrm{d}m_a}{\mathrm{d}t} = Eu\rho_a ,$$

Assume turbulent gravity current (e.g., Dade and Huppert, 1995)

$$u = \mathrm{Fr}\sqrt{g'h} ,$$

Allow big particles to settle

$$\frac{\mathrm{d}m_{\phi_2}}{\mathrm{d}t} = \underbrace{\frac{-m_{\phi_2} V_{\phi_2}}{h}}_{\text{settling}},$$

more details in Fauria et al. (2016)

Density current model

Allow small particles to splash

$$\frac{\mathrm{d}m_{\phi_1}}{\mathrm{d}t} = \underbrace{\frac{-m_{\phi_1} V_{\phi_1}}{h}}_{\text{settling}} + \underbrace{\beta V_{\phi_1}^{4/3}}_{\text{splash from } m_{\phi_1}} + \underbrace{\beta V_{\phi_2}^{4/3}}_{\text{splash from } m_{\phi_2}} ,$$

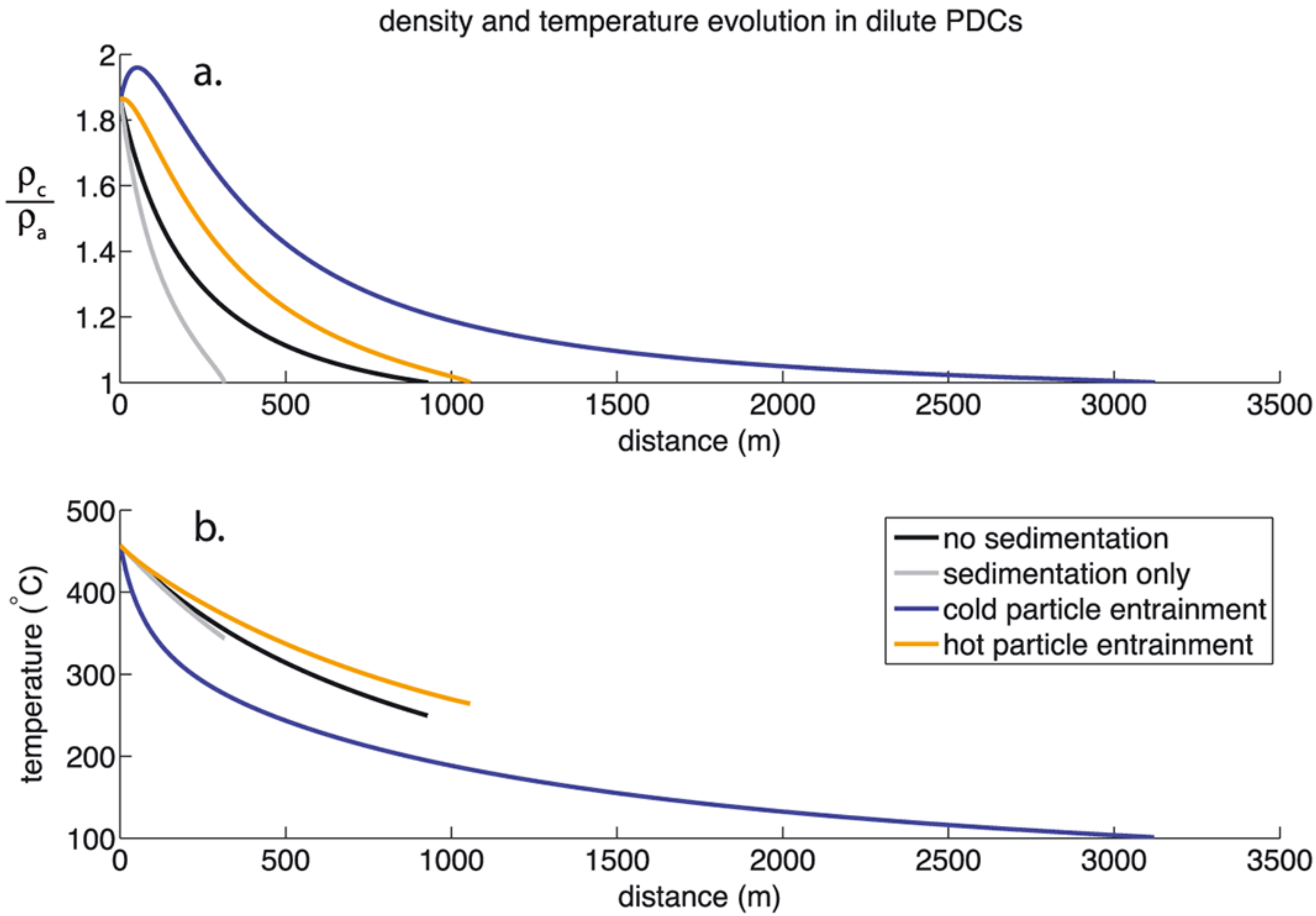
Conserve energy

$$\frac{\mathrm{d}H}{\mathrm{d}t} = \underbrace{\frac{\mathrm{d}m_a}{\mathrm{d}t} C_p^a T_a}_{\text{air entrainment}} - \underbrace{\left(\frac{m_{\phi_2} V_{\phi_2}}{h} + \frac{m_{\phi_1} V_{\phi_1}}{h}\right) C_p^r T_c}_{\text{settling}} + \underbrace{\left(\beta V_{\phi_1}^{4/3} + \beta V_{\phi_2}^{4/3}\right) C_p^r T_e}_{\text{splash}} ,$$

Currents travel until either all particles settle,
or they become buoyant

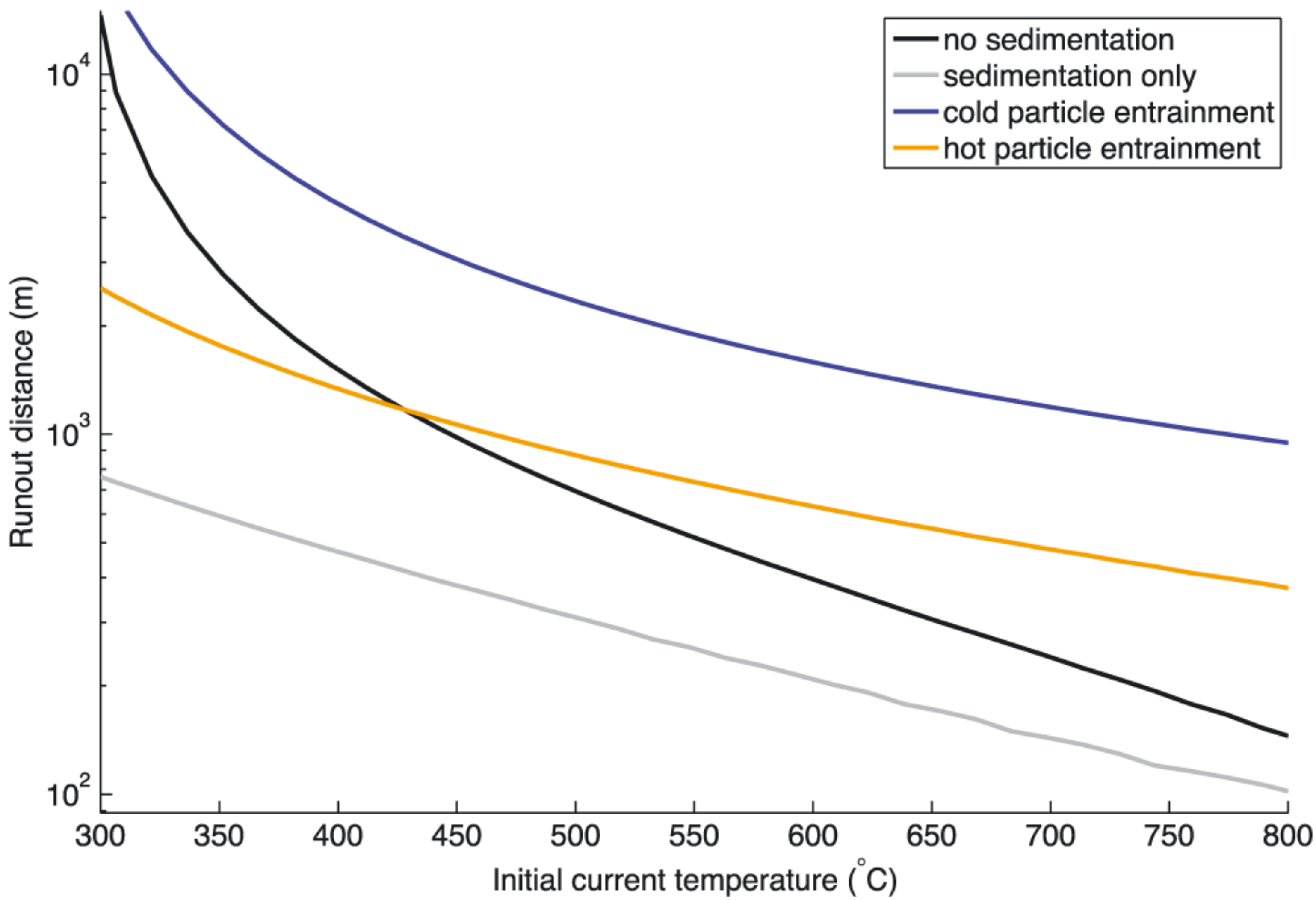
more details in Fauria et al. (2016)

Splash cools flow, increases runout



Fauria et al. (2016)

Splash cools flow, increases runout

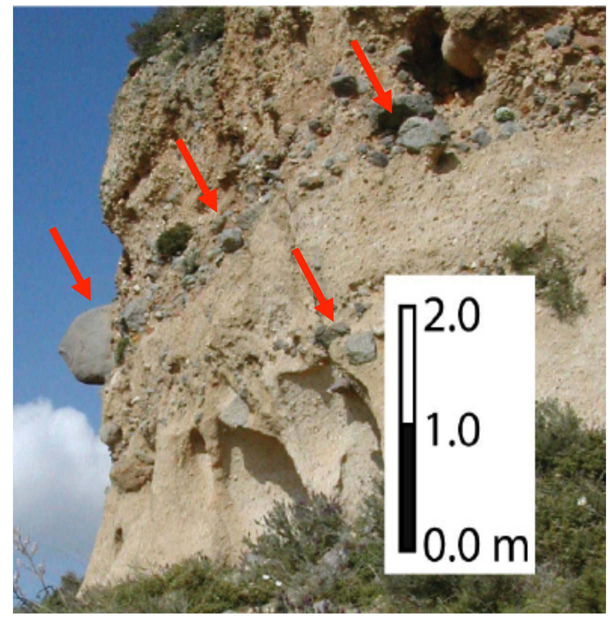


Fauria et al. (2016)

What we learned

Large clast transport is . . .

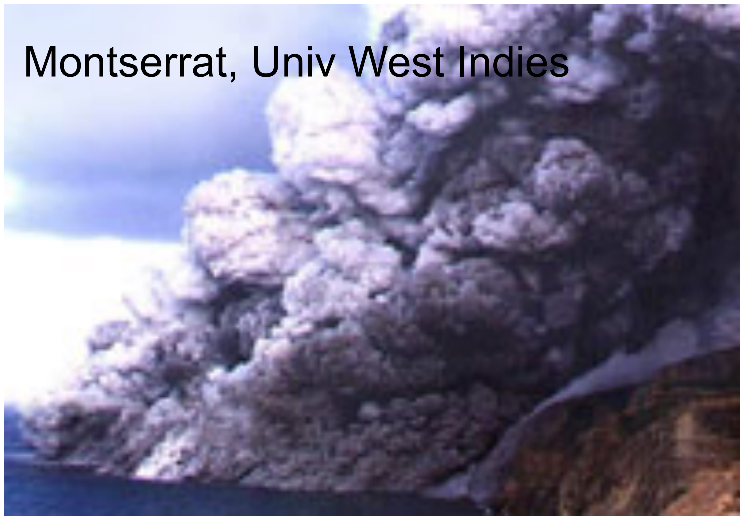
1) dominated by momentum exchange from smaller particles
2) suppressed over water because a dense bedload region does not develop (boundary effect is indirect through the concentration of particles in bedload region)



3) Resuspension can change runnout distance by an order-of-magnitude

3. Interaction with water

Hot flows, when they enter water, generate stream

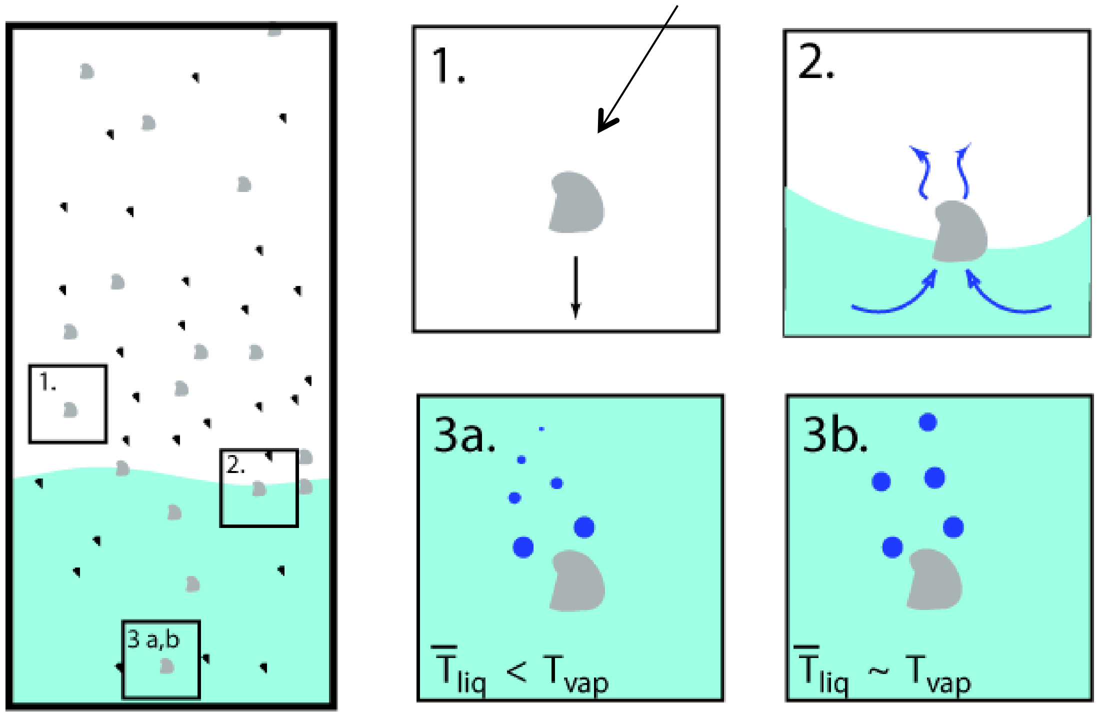


Montserrat, Univ West Indies

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

Measurement of steam production rate

Stroberg, Manga and Dufek, *JVGR* 2010

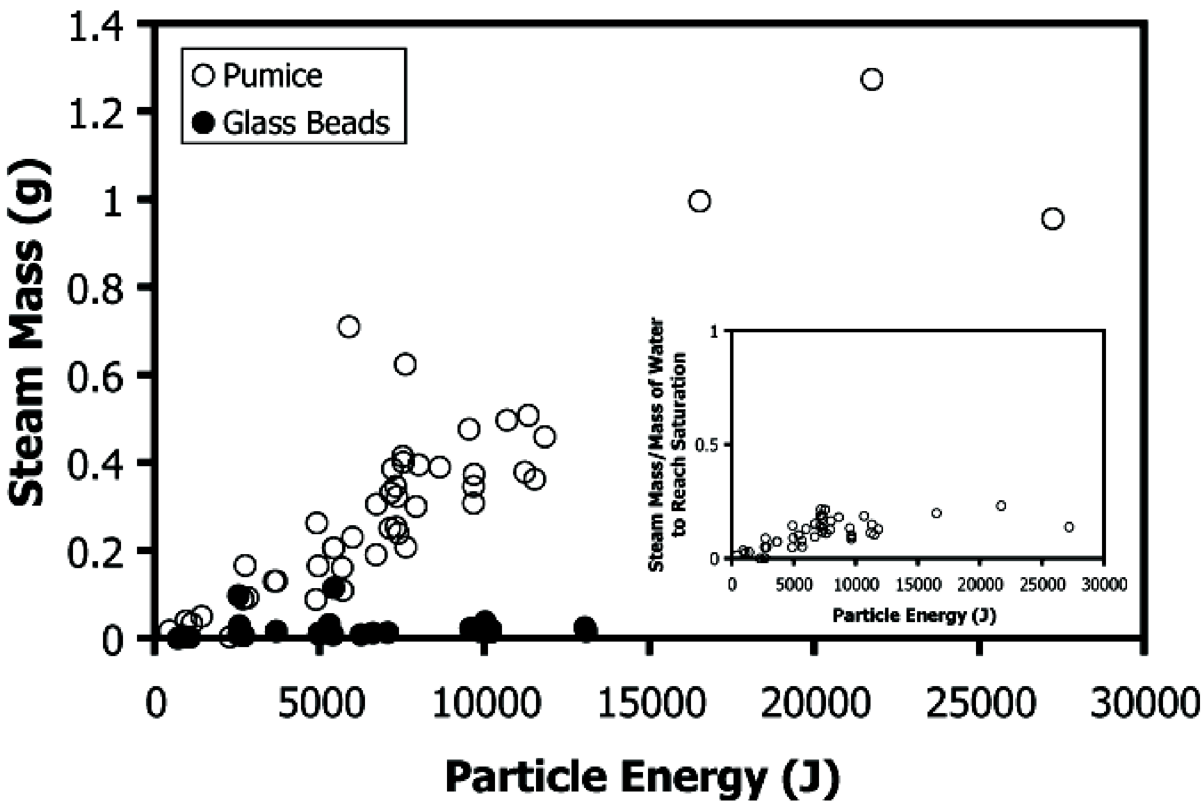


100-700 ^{o}C
Pumice, glass beads
3 mm - 2 cm

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



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

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

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

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

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

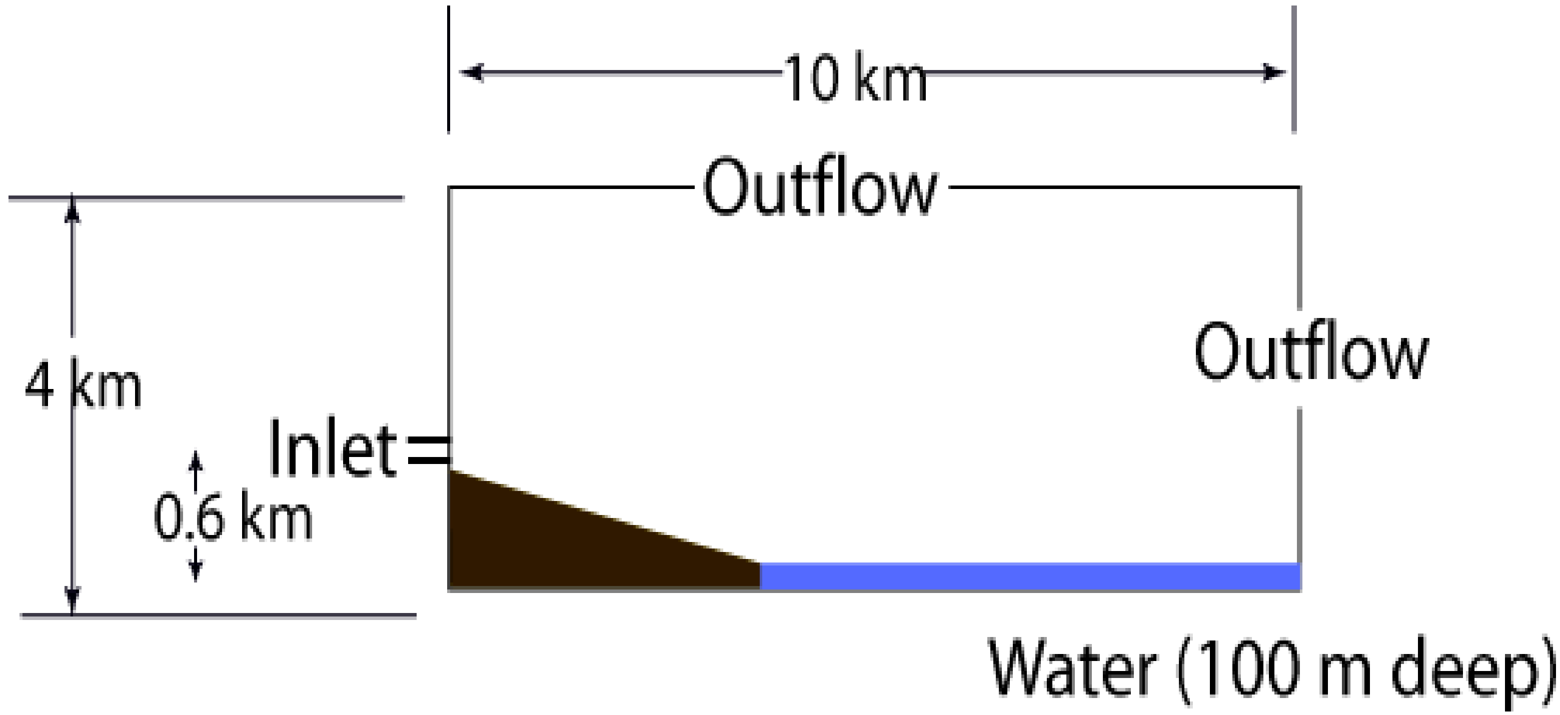
Thermal Energy

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

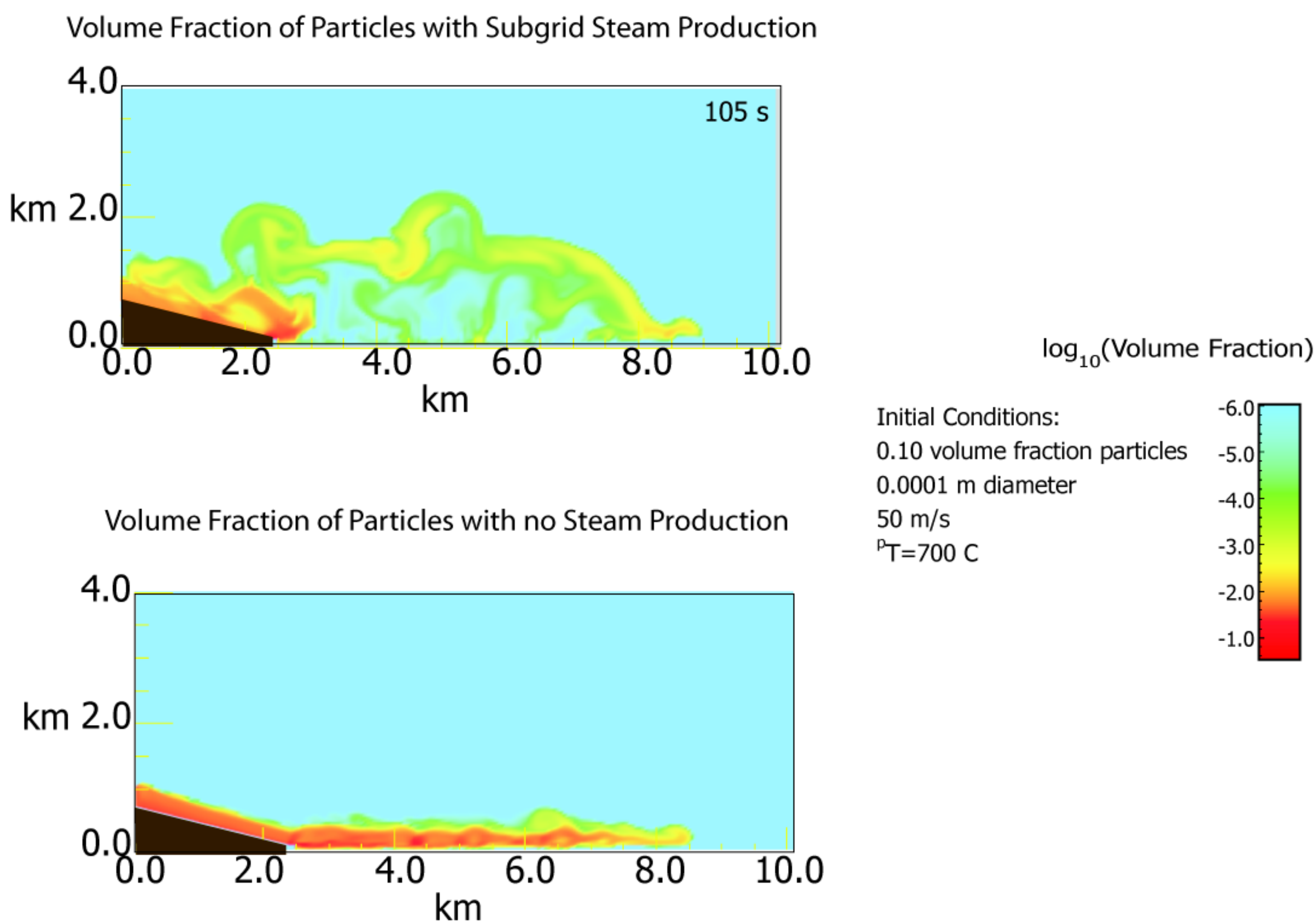
$${}^{g}\alpha\,{}^{g}\rho\,{}^{g}c_p\left(\frac{\partial\,{}^{g}T}{\partial t} + {}^{g}\boldsymbol{U}_i\frac{\partial\,{}^{g}T}{\partial \boldsymbol{x}_i}\right) = \frac{\partial\,{}^{g}q}{\partial x_i} - \overline{H}_{gp} - \overline{H}_{gw} - \underbrace{\overline{S}}_{\substack{\text{Mean latent}\\\text{heat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

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

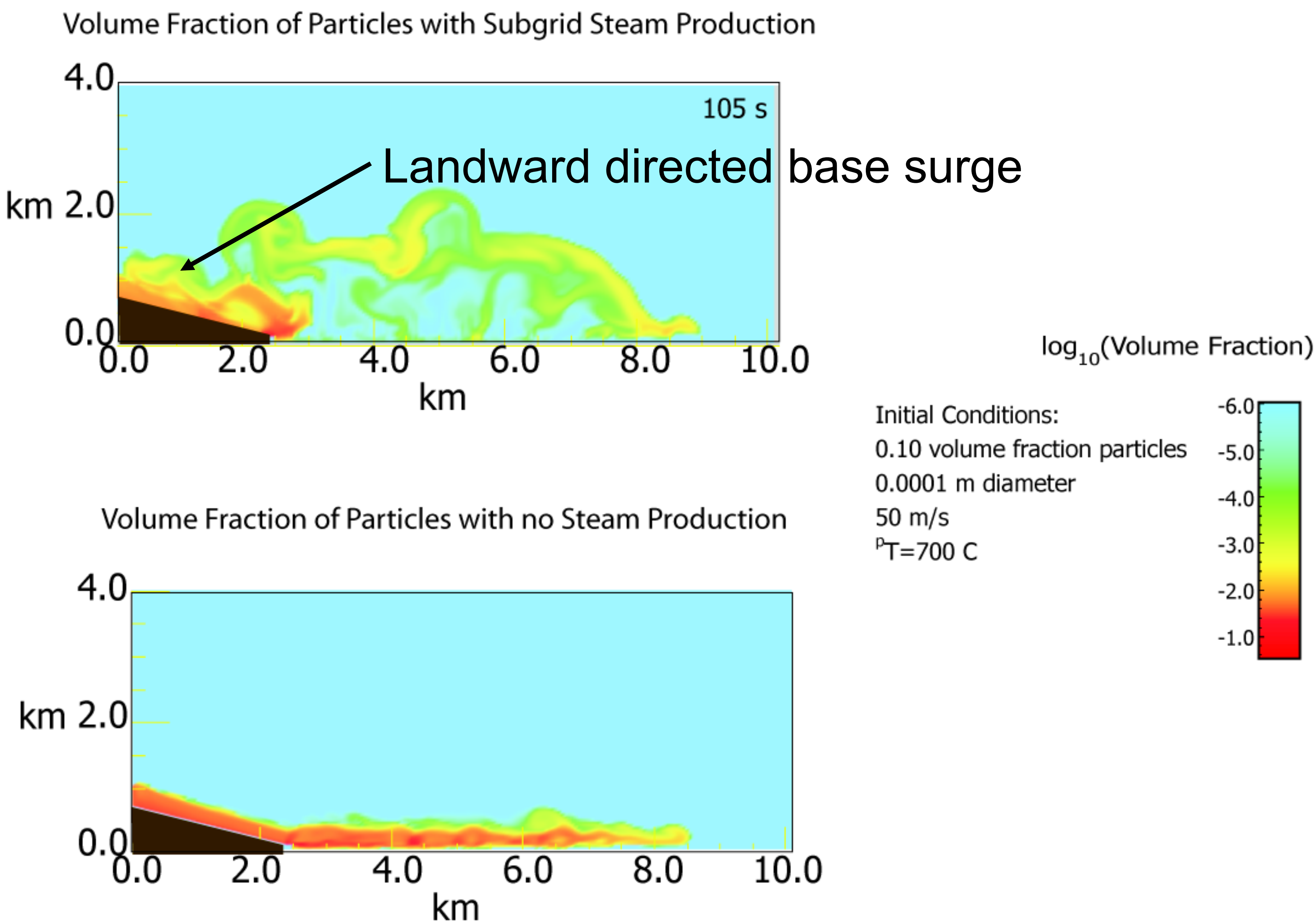
Application to July 12-13, 2003 littoral blast, Montserrat

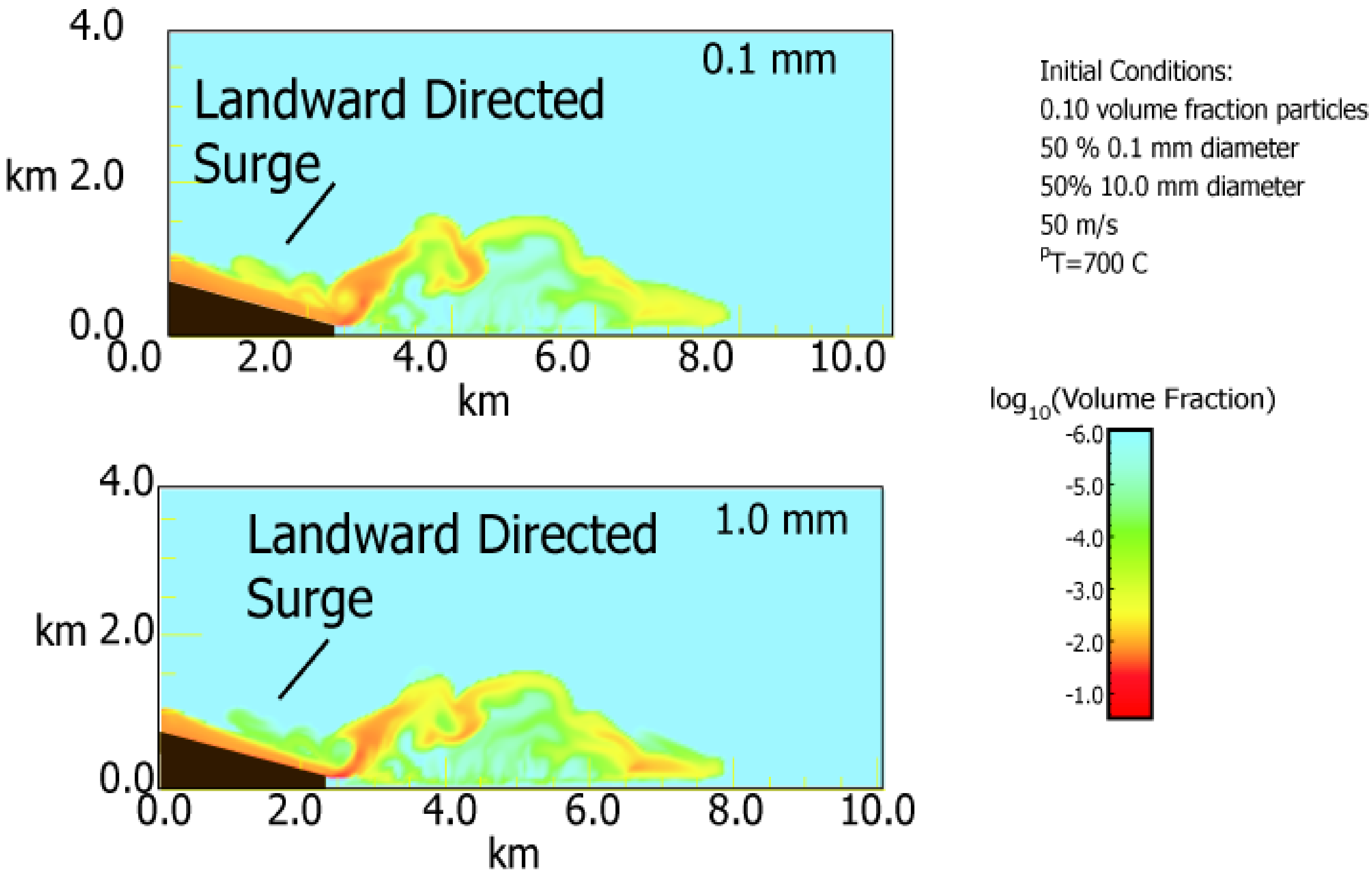


grid 2 m x 10 m; time step , 0.1 s
initial velocity 50 m/s
initial concentration 0.1
initial sizes: 50% is 1 cm, 50% is 0.1 mm
temperature 650 C

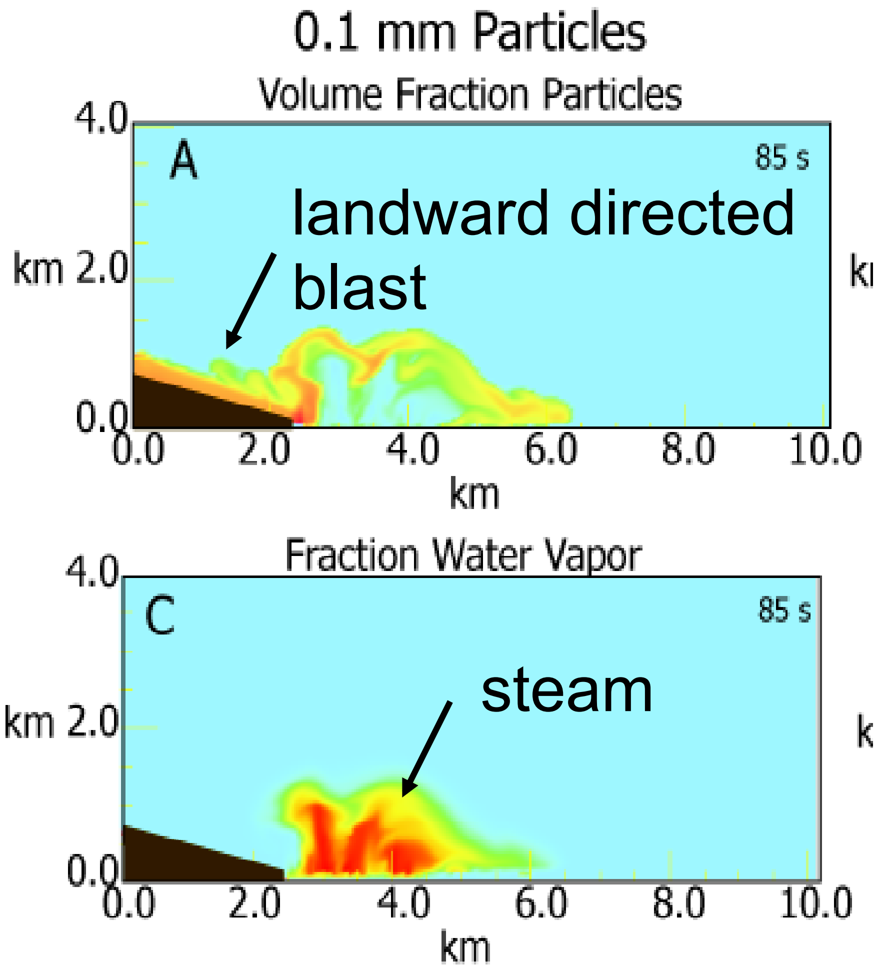


Volume Fraction of Particles with Subgrid Steam Production
105 s
4.0
km 2.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
km
Volume Fraction of Particles with no Steam Production
4.0
km 2.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
km
log10(Volume Fraction)
Initial Conditions:
0.10 volume fraction particles
0.0001 m diameter
50 m/s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


Volume Fraction of Particles with Subgrid Steam Production
4.0
105 s
Landward directed base surge
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



Landward Directed Surge
0.1 mm
Landward Directed Surge
1.0 mm
km 2.0
4.0
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
PT=700 C
log10(Volume Fraction)
-6.0
-5.0
-4.0
-3.0
-2.0
-1.0



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

Conclusions

- Experimental measurements can be used to link the micro- and macro-scale
- Particle-scale thermo-mechanical processes and properties (ash production, vaporization of water, boundary conditions) matter - qualitatively and quantitatively

Suggested reading
Dufek, J. (2016) The fluid mechanics of pyroclastic density currents, *Annual Reviews of Fluid Mechanics*, vol. 48, 459-485