UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département des sciences de la Terre

Volcanic plumes and particle sedimentation

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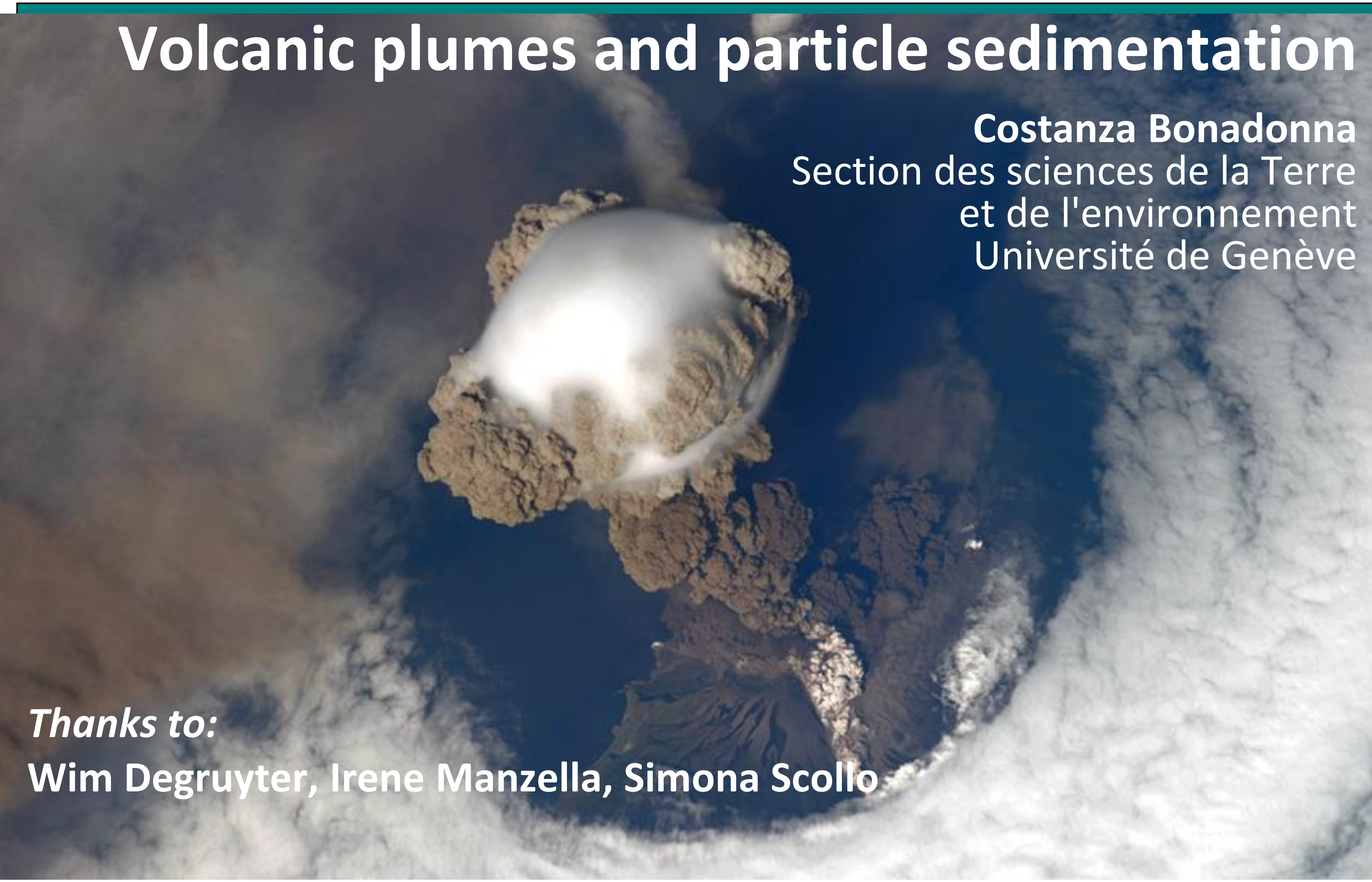
Université de Genève

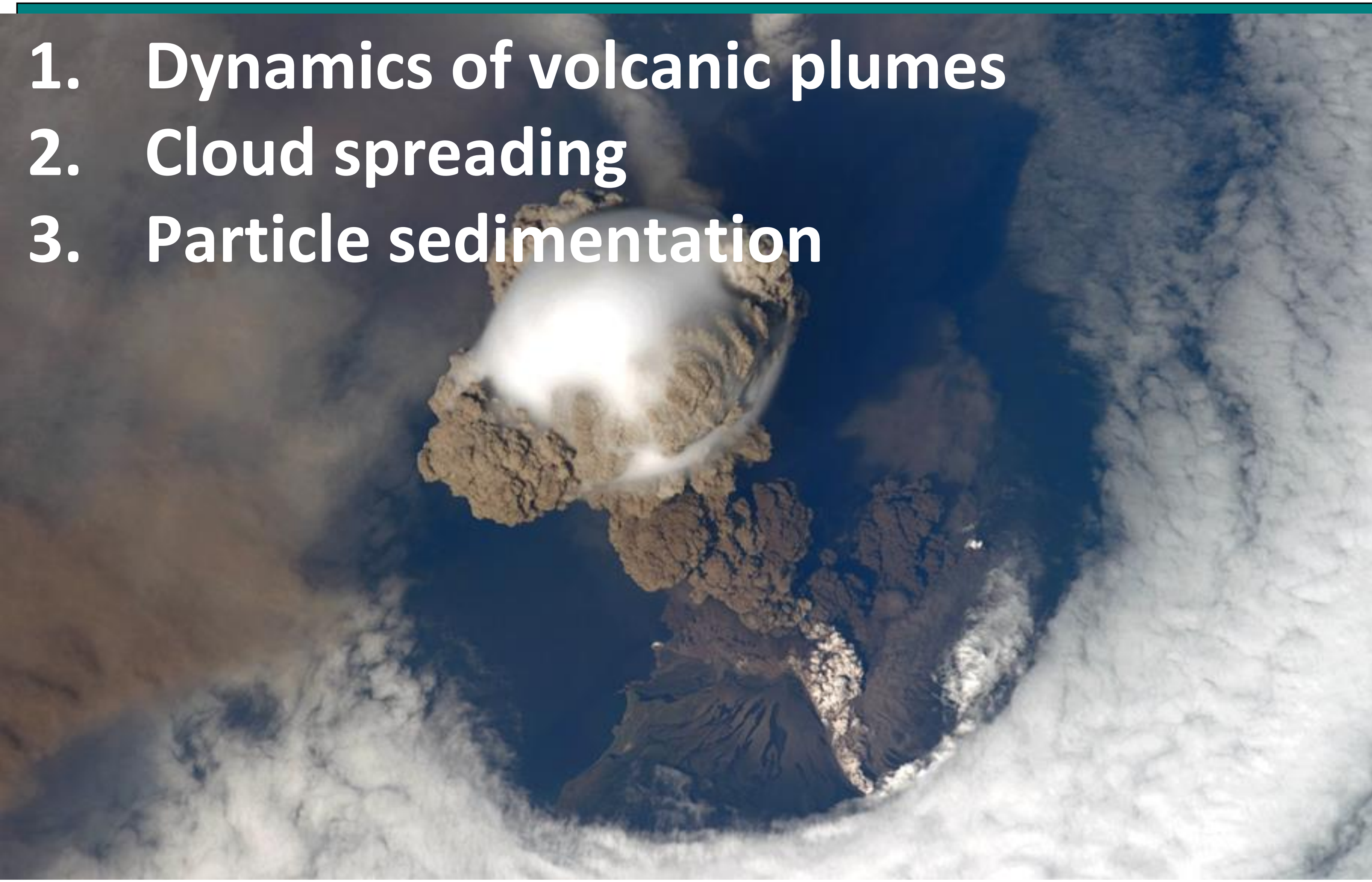


Thanks to:
Wim Degruyter, Irene Manzella, Simona Scollo

Sarychev Volcano June 12, 2009 (NASA/JSC/Image Science and Analysis Laboratory)

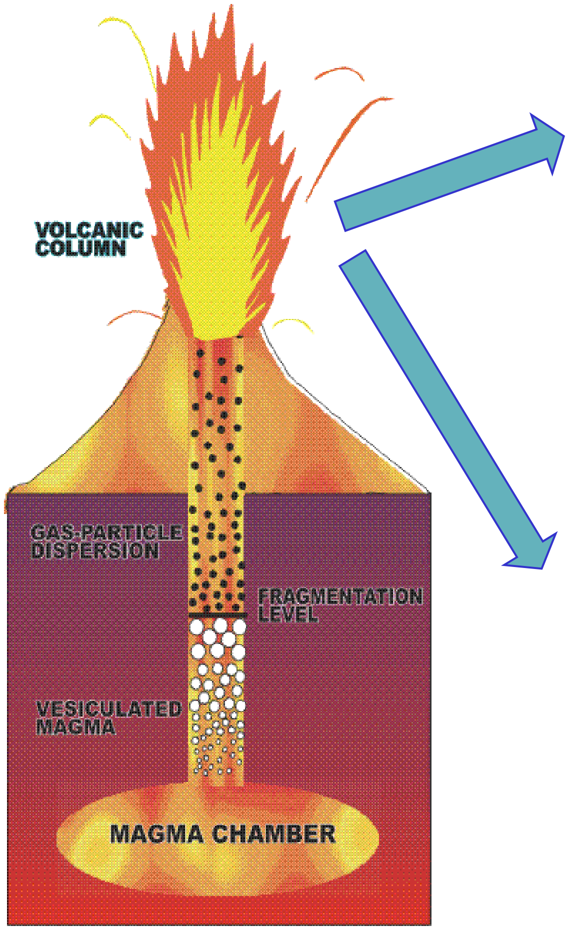
Workshop on Particle Transport, Aarhus, 6-7 November 2014

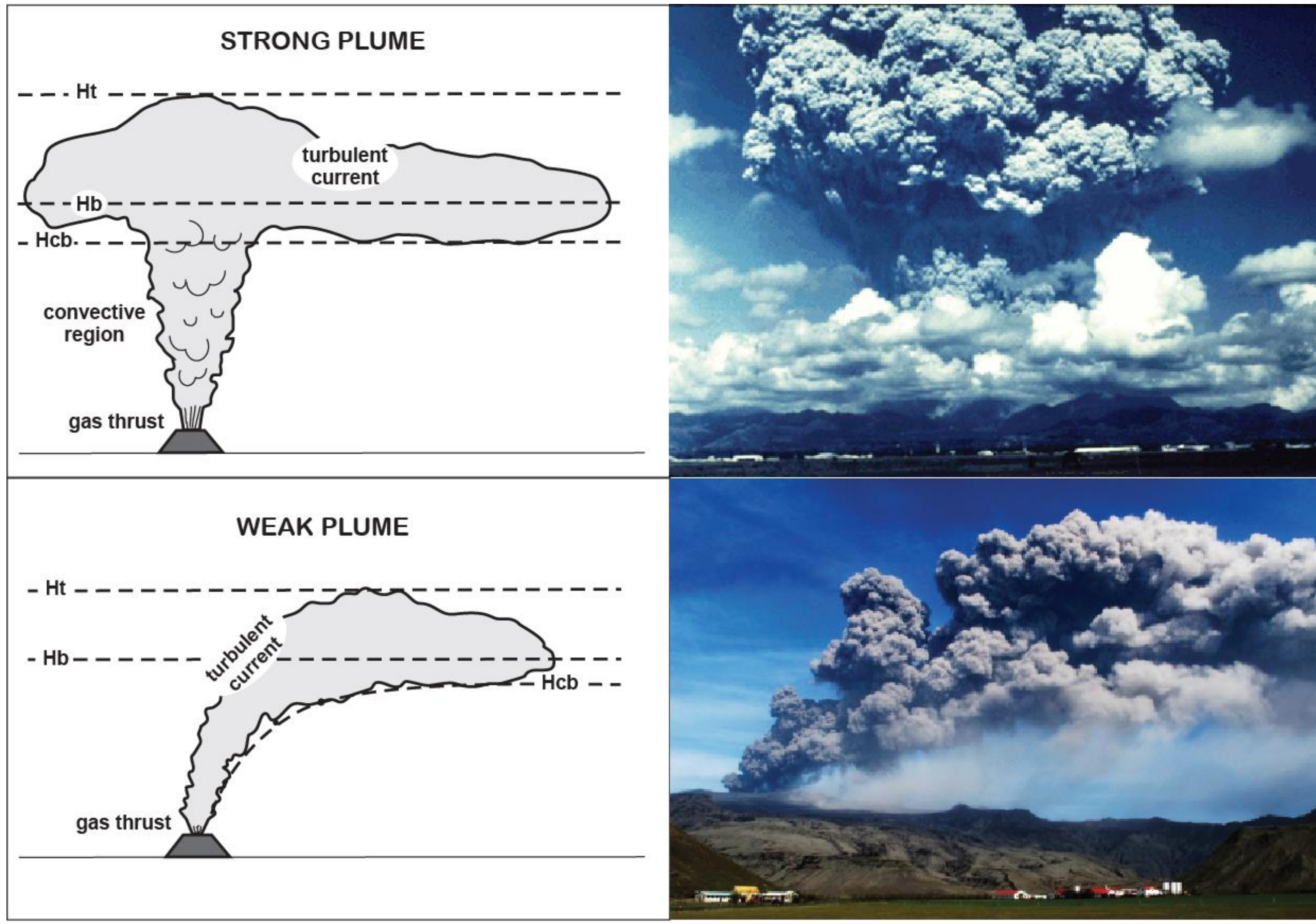
1. **Dynamics of volcanic plumes**
2. **Cloud spreading**
3. **Particle sedimentation**



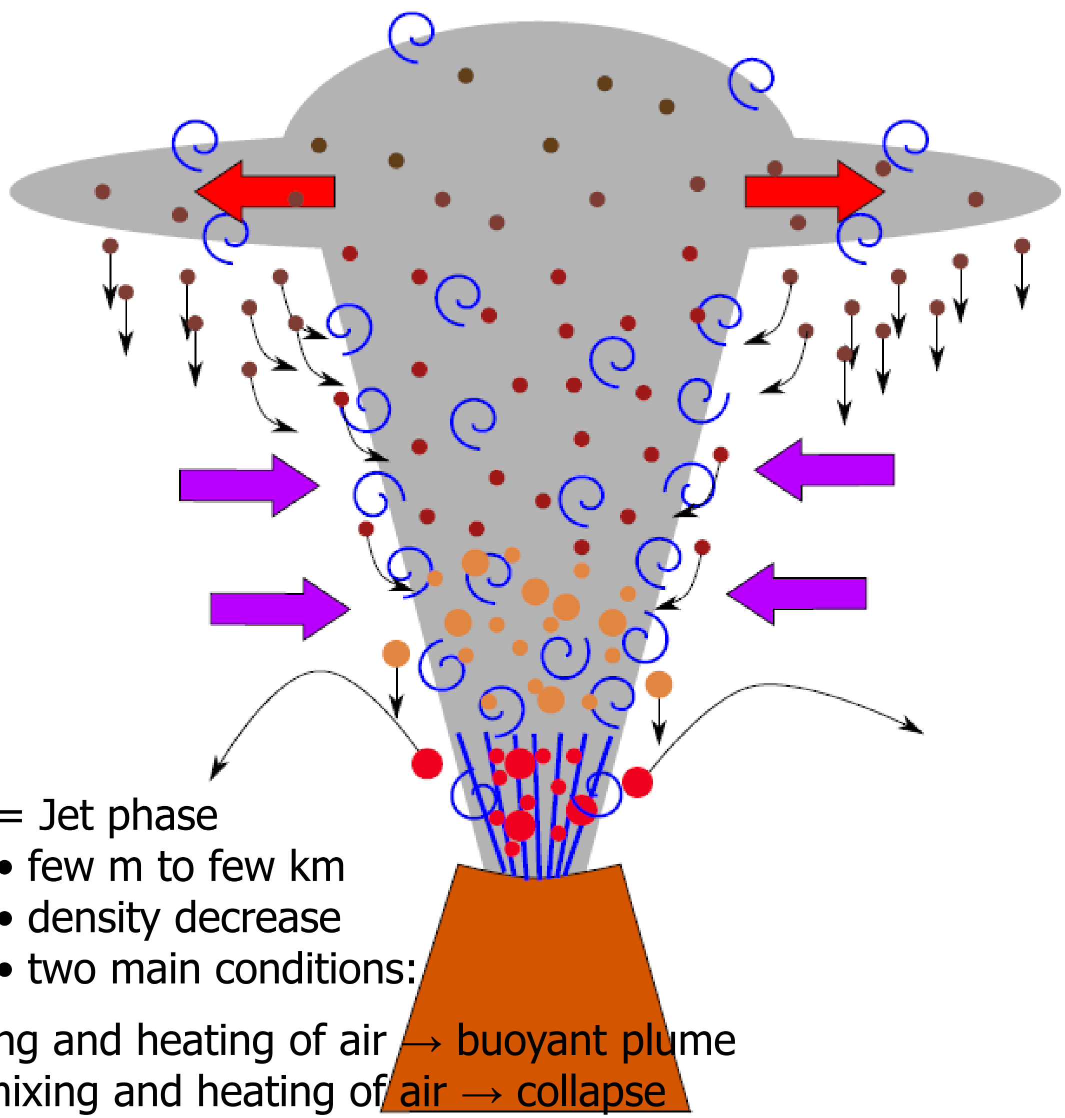
Sarychev Volcano June 12, 2009 (NASA/JSC/Image Science and Analysis Laboratory)

Volcanic Plumes





Volcanic Plumes

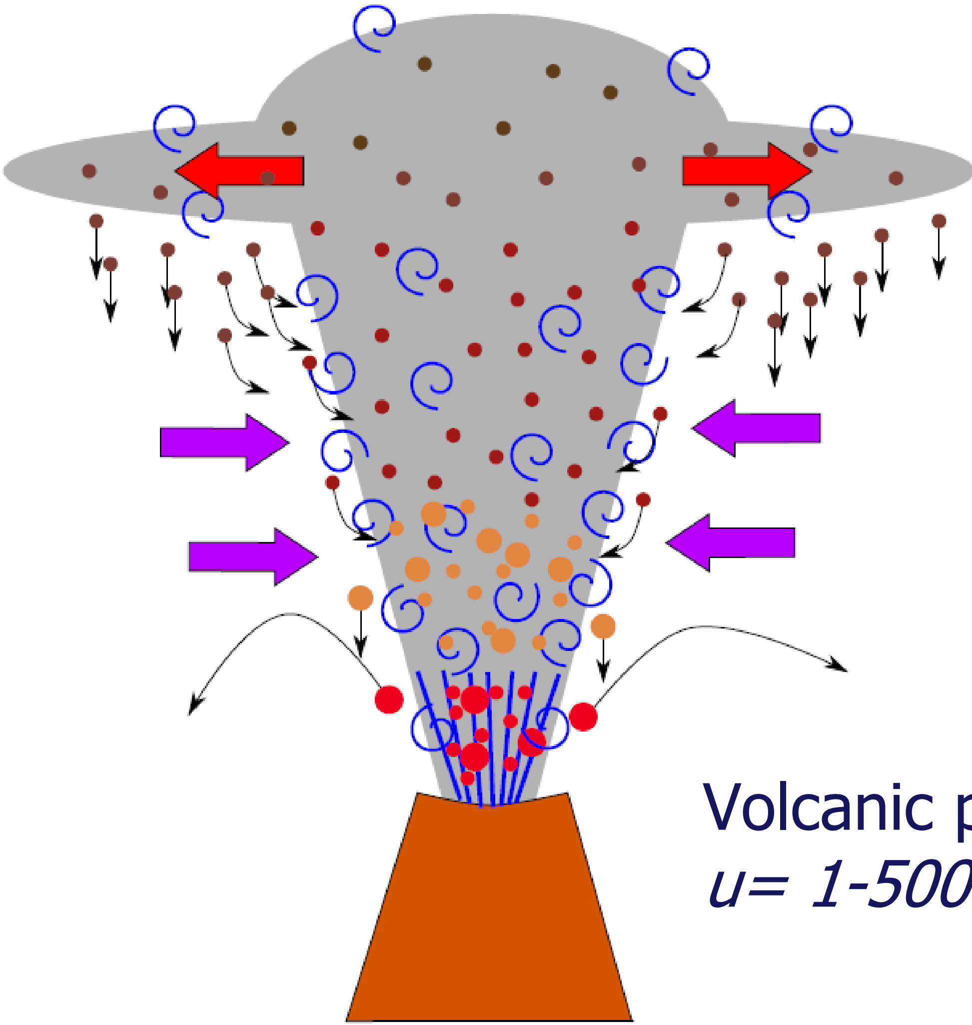


Gas-thrust region = Jet phase

- few m to few km
- density decrease
- two main conditions:

1. enough mixing and heating of air → buoyant plume
2. no enough mixing and heating of air → collapse

Controlling parameters: **vent and conduit geometry**, **volatile content** and **vent exit pressure**



Volcanic plumes:

u= 1-500 m s^{-1}; L= 10-10000 m

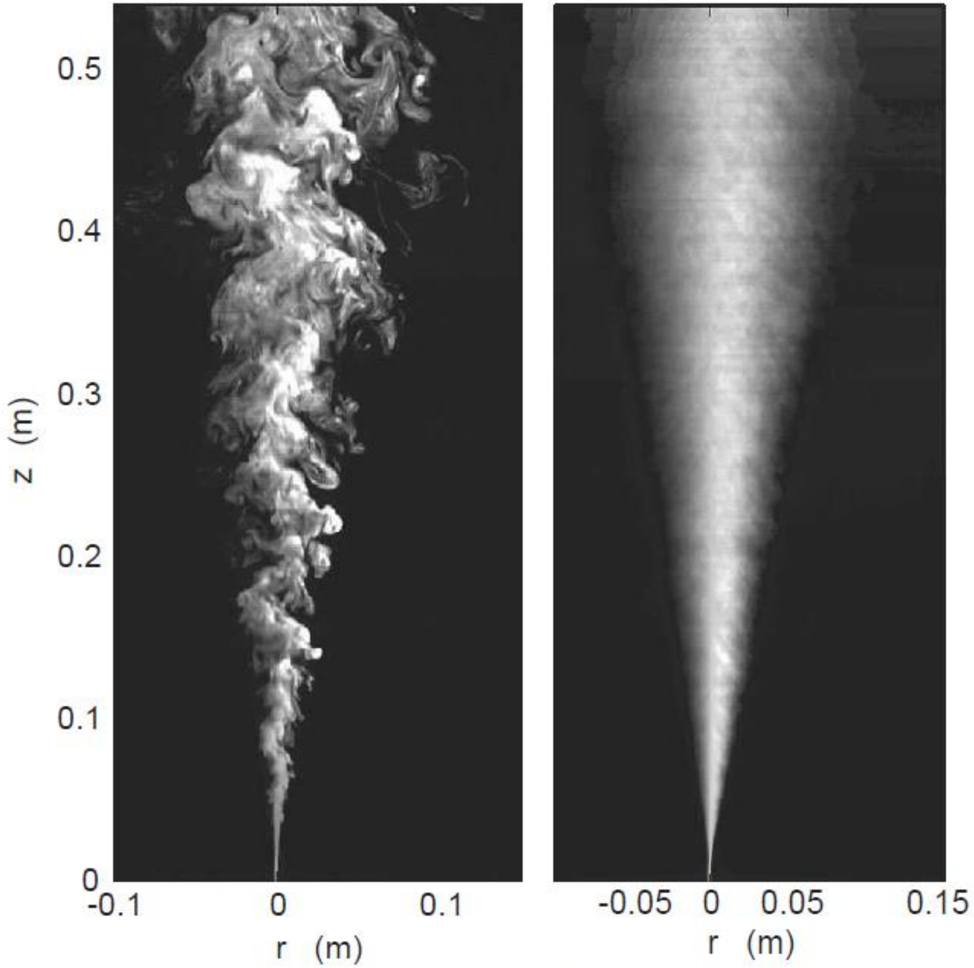
$\rightarrow$ *Re=10^3-10^9*

$\rightarrow$ *turbulent flows*

Modelling Approaches

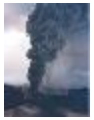
Numerical solution of Navier-Stokes equations – must resolve or parameterize turbulent eddies on a wide range of scales.

Integral model describing variation of averaged plume quantities – look on a time scale longer than eddy turnover time and make assumptions of plume structure and entrainment of ambient fluid.



Scase, M.M., Caulfield, C.P. & Dalziel, S.B. (2008) *J. Fluid Mech.* **600**, 181–199



MASS FLOW RATE

$$Ht = 2^{-5/8}\ \pi^{-1/4}\ \alpha^{-1/2}\ F^{1/4}\ N^{-3/4}\ z_1$$

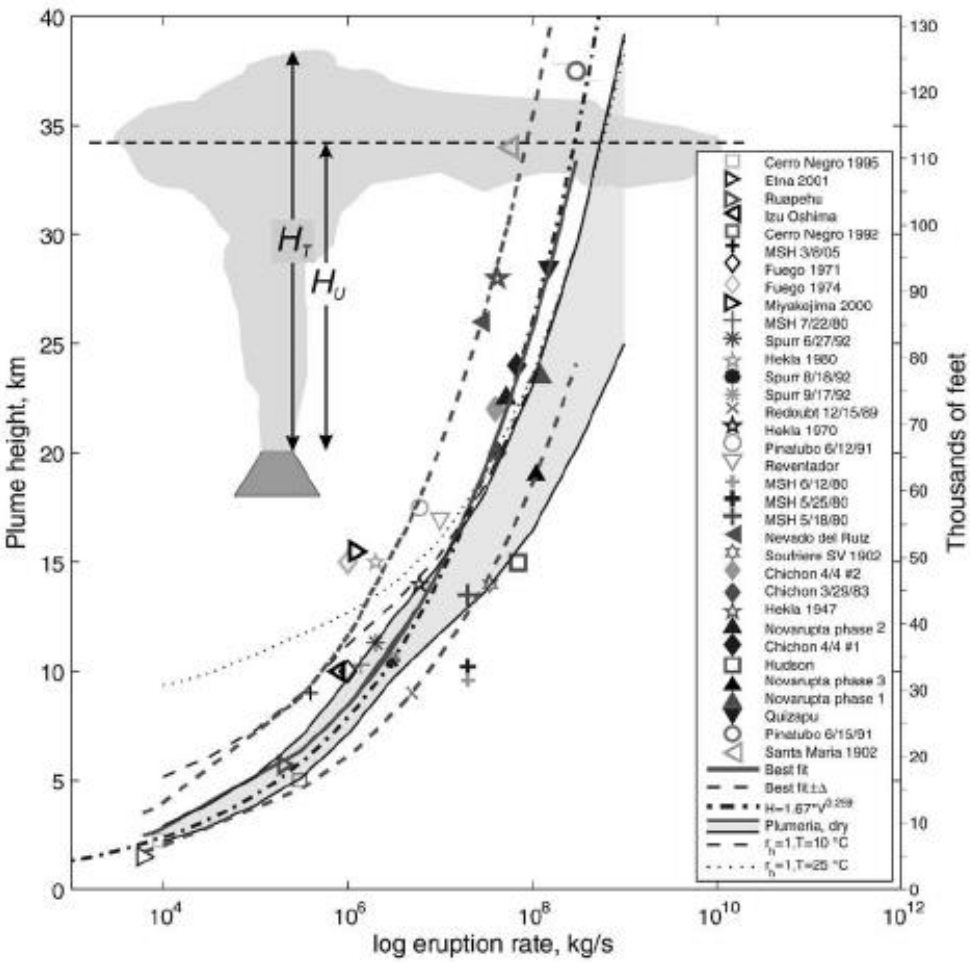
Morton et al. 1956

Empirical equations

$$Ht = 2.00\ [VFR(m^3\ s^{-1})]^{0.241}$$

Mastin et al. 2009

- Mass flow rate from empirical equations can only be constrained within a factor of 10



MASS FLOW RATE

$$\dot{M} = \pi \frac{\rho_{a0}}{g'} \left(\frac{2^{\frac{5}{2}} \alpha^2 \overline{N}^3}{z_1^4} H^4 + \frac{\beta^2 \overline{N}^2 \overline{v}}{6} H^3 \right)$$

H	Plume height
$\overline{N}$	Average buoyancy frequency across the plume height
$\overline{v}$	Average wind velocity across the plume height
z_1	Non-dimensional height
α	Radial entrainment coefficient (best fit: 0.1)
β	Wind entrainment coefficient (best fit: 0.5)
ρ_{a0}	Density of the atmosphere

Degruyter and Bonadonna (2012)

MASS FLOW RATE

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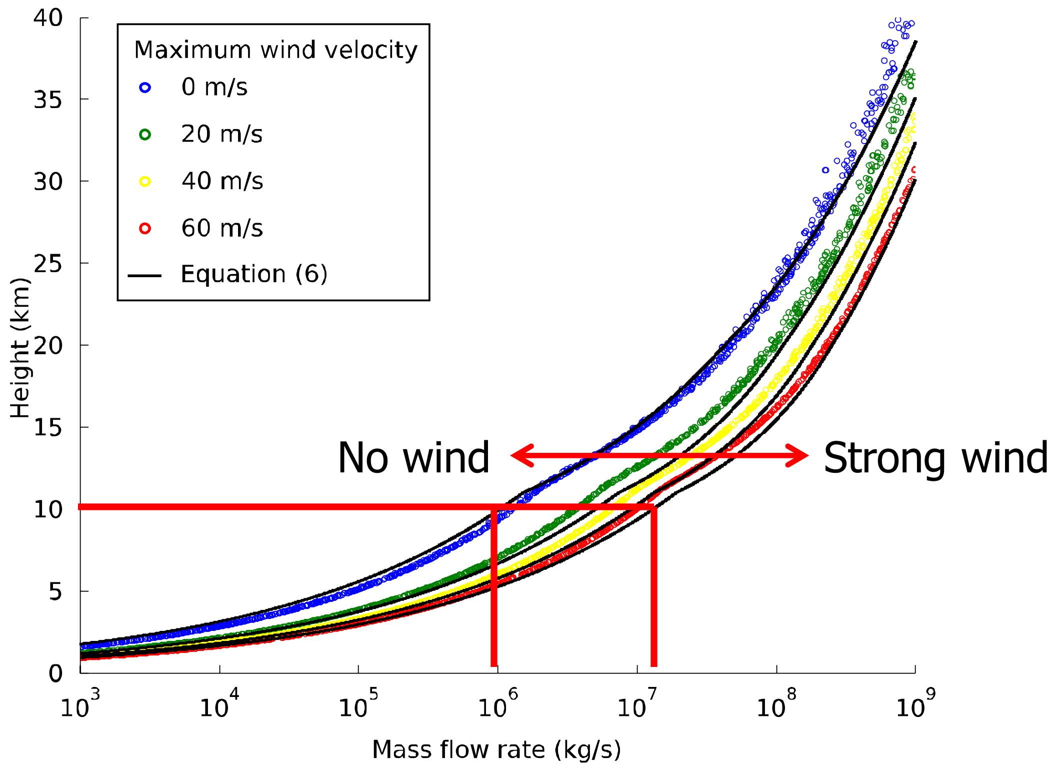
- can account for variability of both source and atmospheric conditions
- remains accurate within a factor of two compared with a 1D plume model

$$\Pi = 6 \frac{2^{\frac{5}{2}} \overline{NH}}{z_1^4 \overline{v}} \left(\frac{\alpha}{\beta} \right)^2$$

wind becomes dominant if the height, buoyancy frequency, and radial entrainment are small and the wind speed and wind entrainment are large

$$\Pi << 1$$



Degruyter and Bonadonna (2012)

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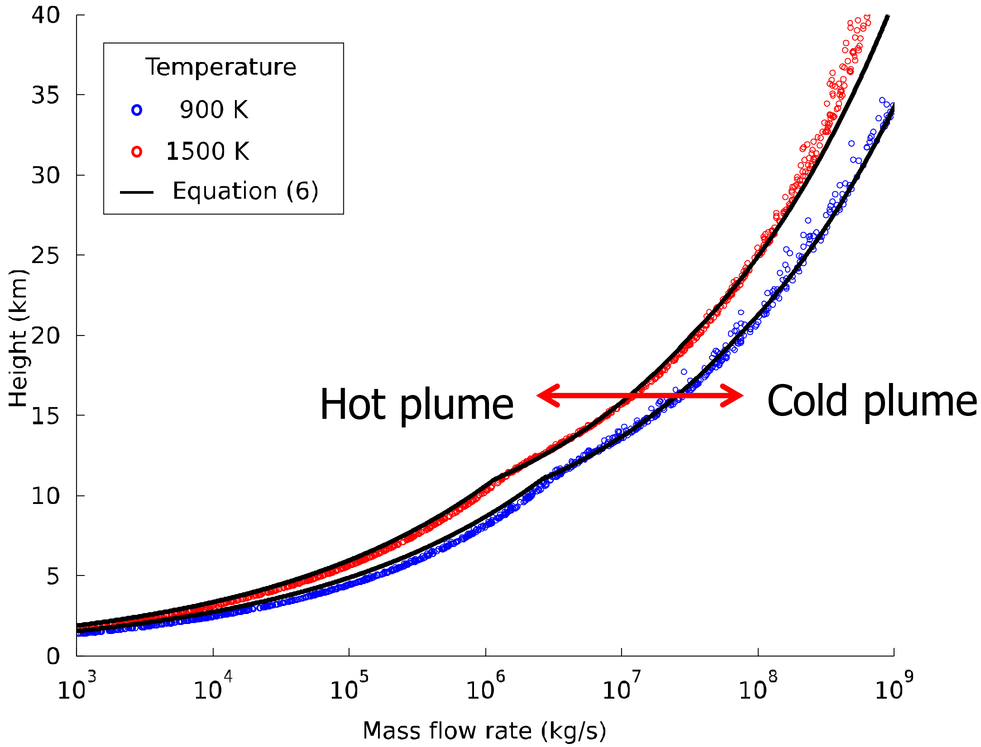
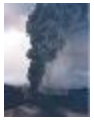


Degruyter and Bonadonna (2012)



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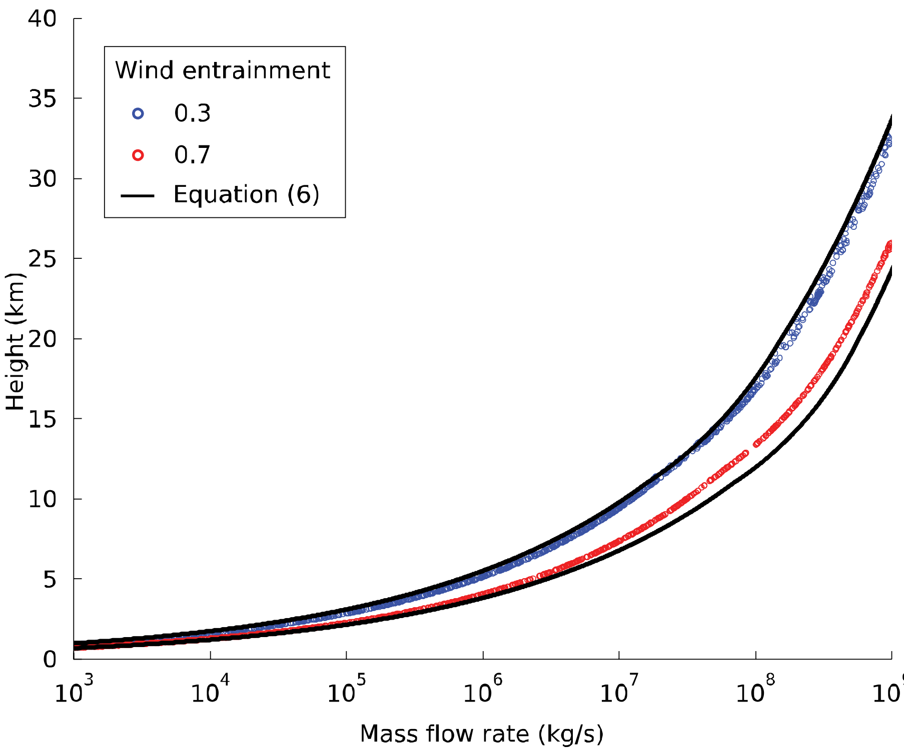
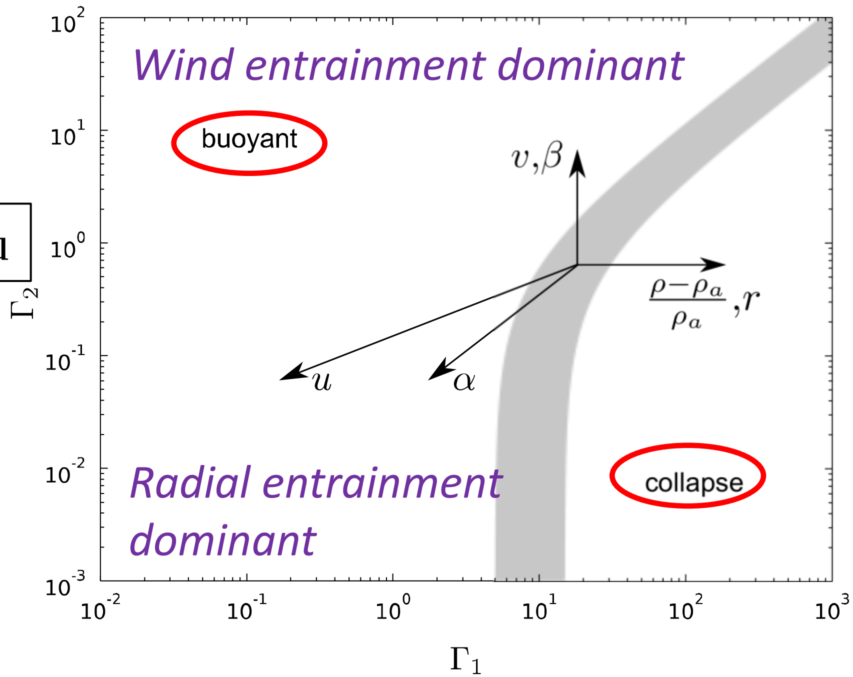


Degruyter and Bonadonna (2012)

Effects of wind on the stability of plumes

Air entrainment due to wind causes a volcanic plume to lower its density at a faster rate and therefore to favor buoyancy

$\beta v/\alpha u$



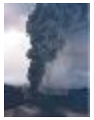
Kinetic energy dominant

$-Ri/\alpha$

Potential energy dominant

Degruyter and Bonadonna (2013)

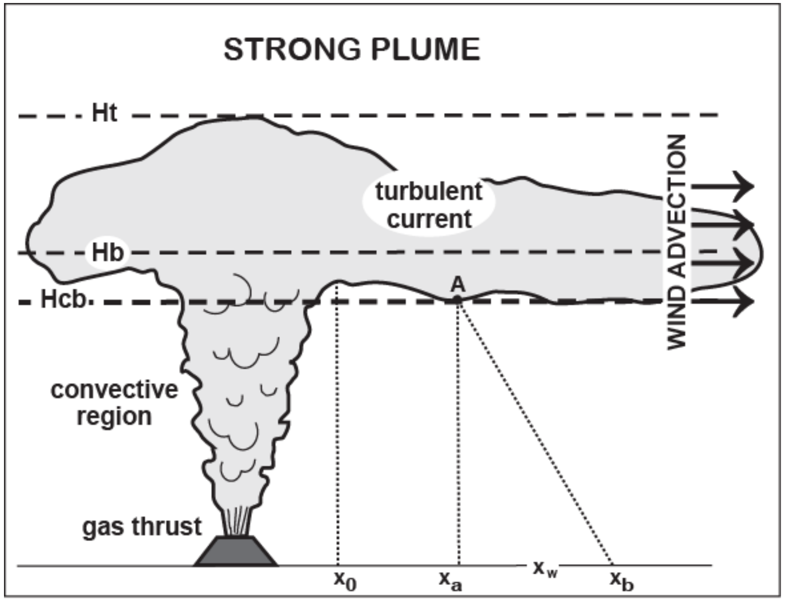


2. Cloud spreading

Sarychev Volcano June 12, 2009 (NASA/JSC/Image Science and Analysis Laboratory)

Cloud spreading



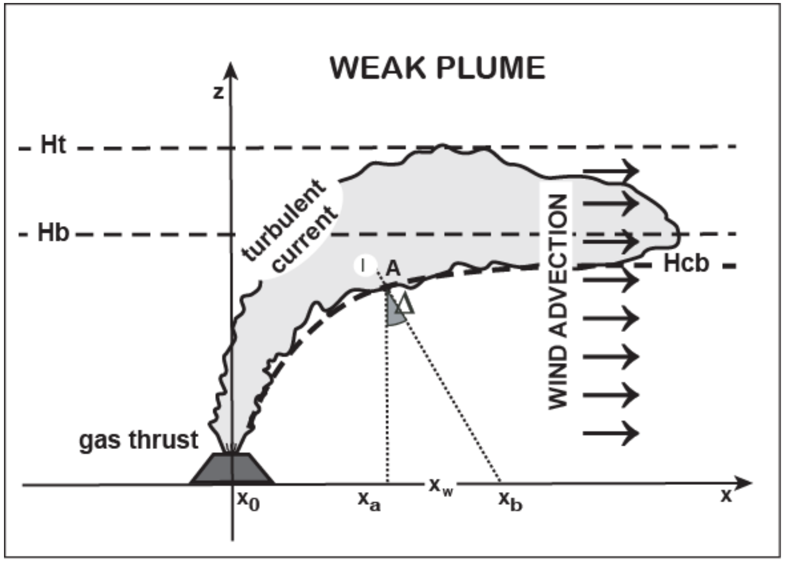
Buoyancy-driven intrusion
→ gravity current spreading

$$u_b = \sqrt{g'h}$$

which scales as $\lambda N h$

$$w = \frac{2x}{1 + a\sqrt{x}}$$

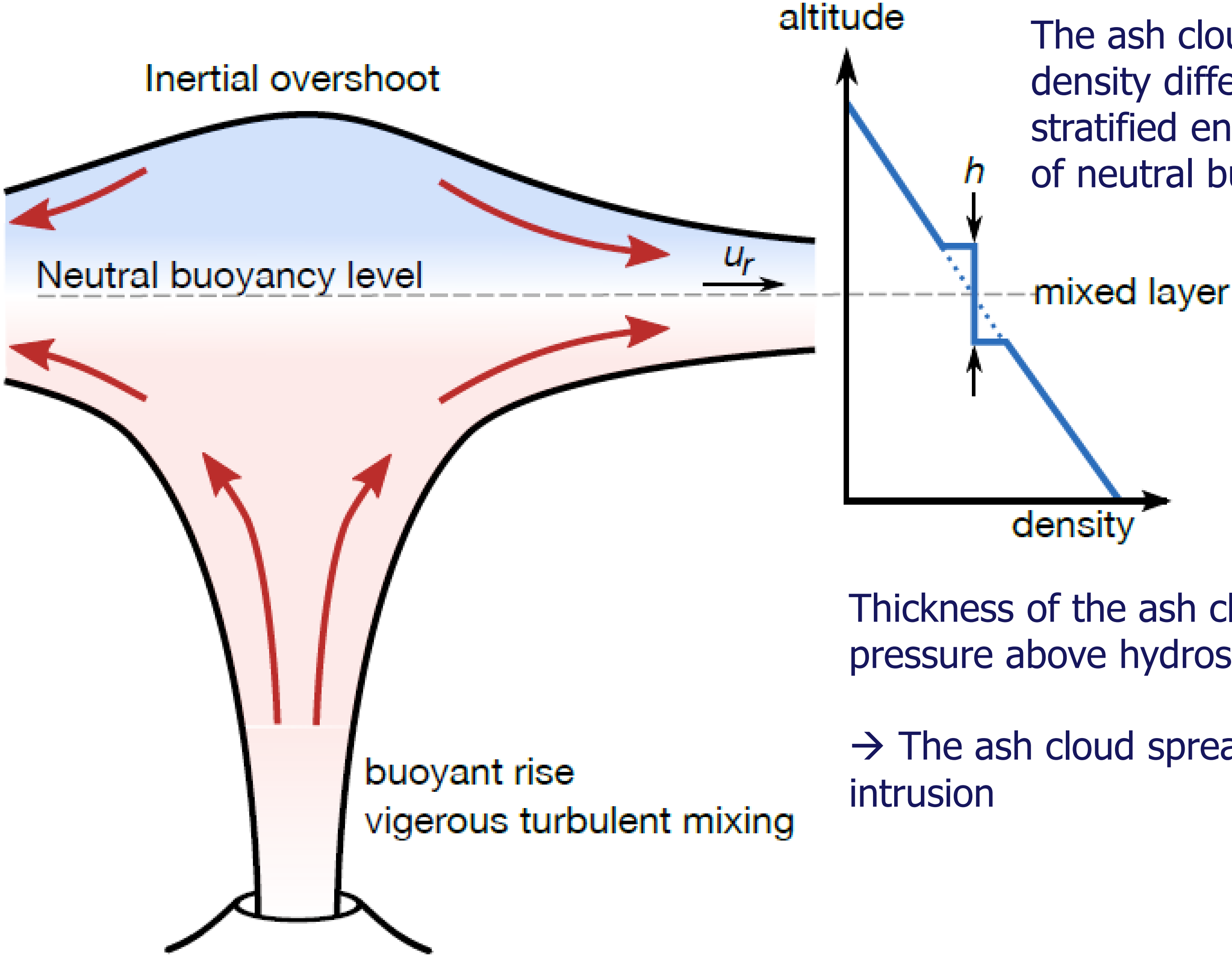
$$\rightarrow \quad a = \frac{u_{wind}}{\sqrt{\lambda N Q / \varepsilon}}$$



turbulent diffusion $w = 4\sqrt{\frac{Kx}{u_{wind}}}$

Bonadonna and Phillips 2003

Buoyancy-driven intrusions



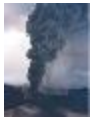
The ash cloud is driven by the density difference due to mixing up a stratified environment around a level of neutral buoyancy

Thickness of the ash cloud determines excess pressure above hydrostatic balance

→ The ash cloud spreads as a turbulent buoyant intrusion

Johnson et al (submitted) 'Modelling Intrusions' J. Fluid Mech.



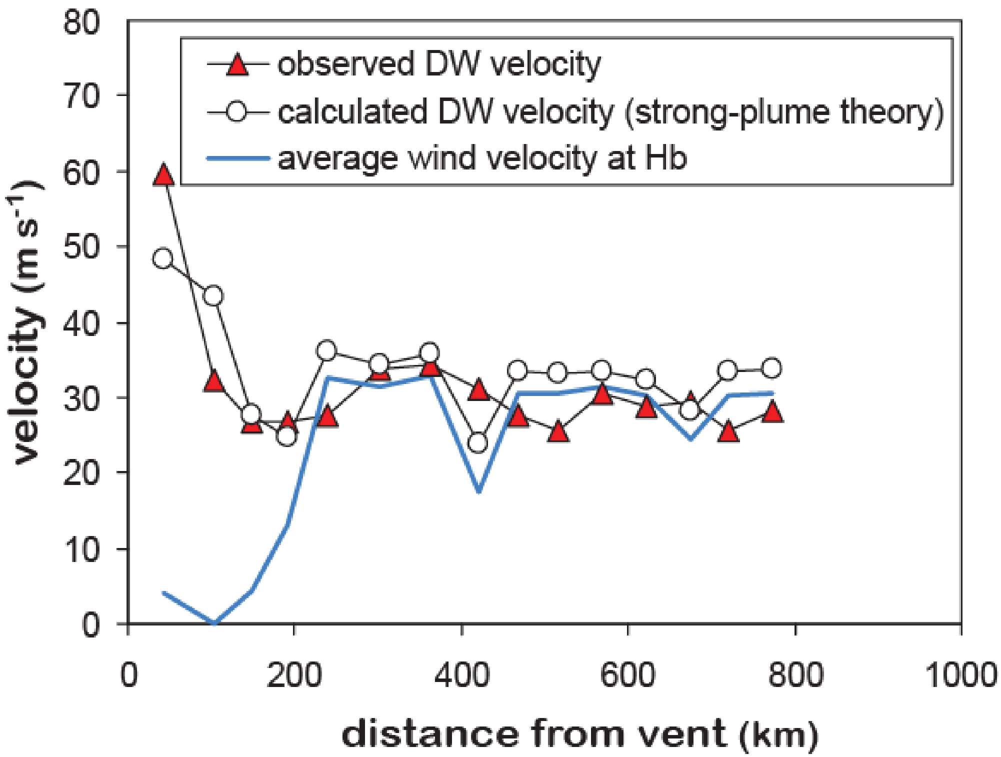
Gravity current

Gravitational spreading velocity is radial and axysimmetric

$$u_b = \sqrt{g' h} = \sqrt{\frac{\lambda N Q}{\varepsilon x}}$$

$$U = u_{wind} + u_b$$

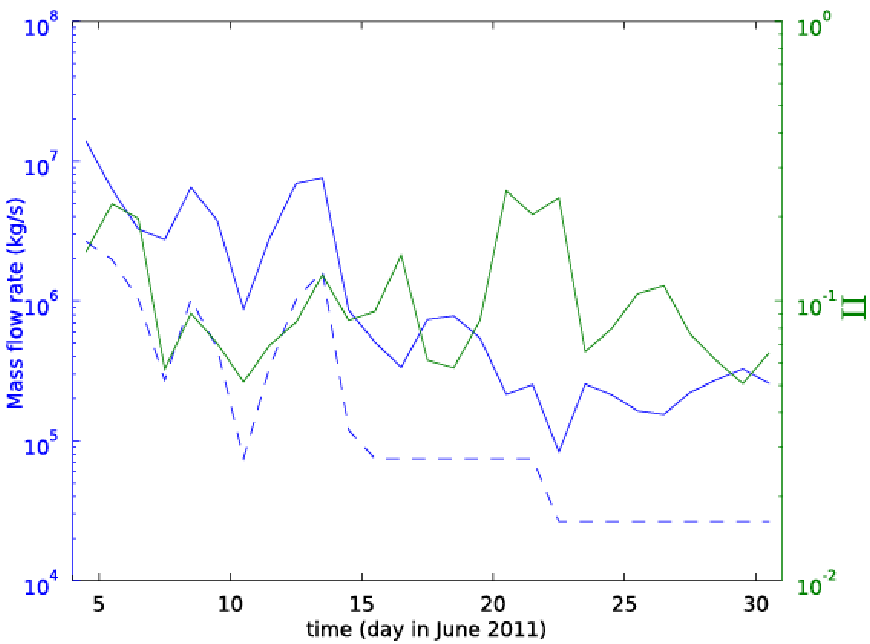
MSH 1980

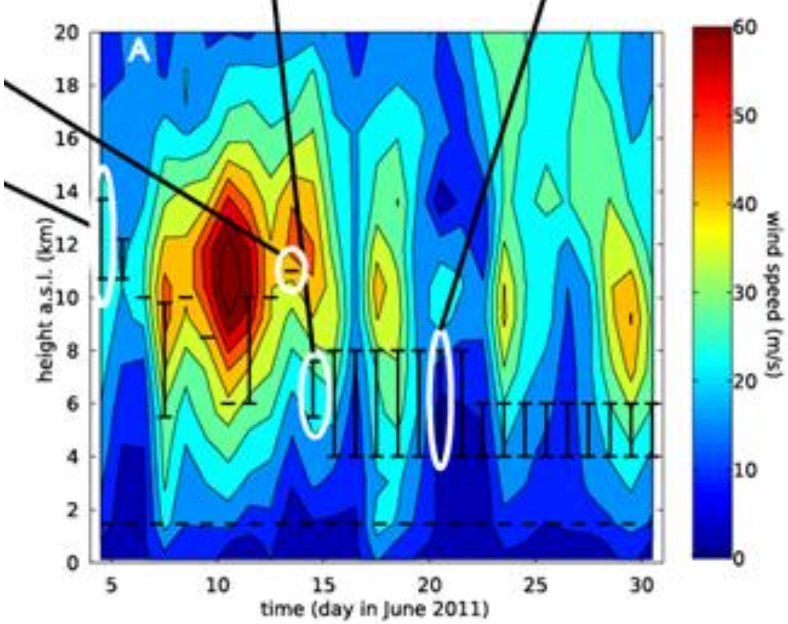


Bonadonna and Phillips 2003

Crosswind spreading

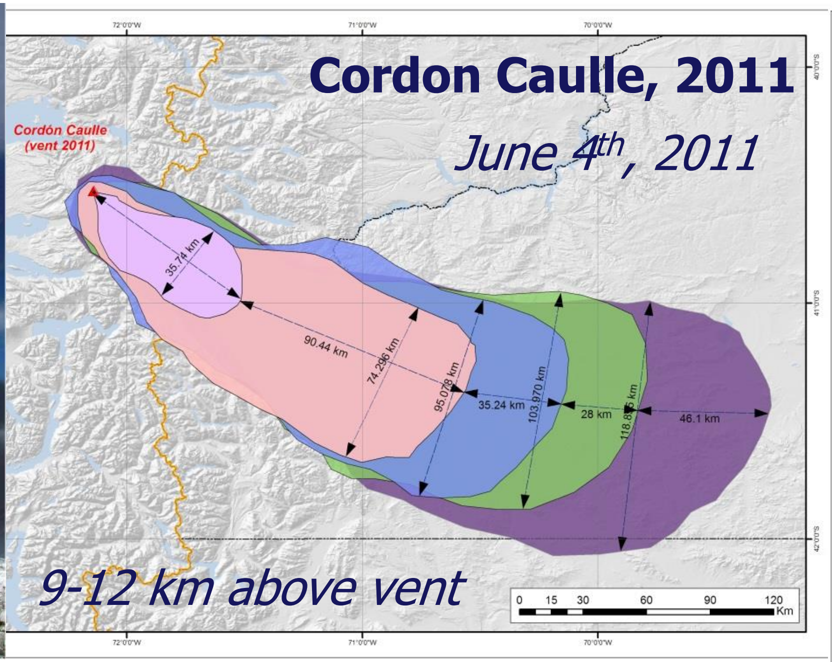
Cordon Caulle, 2011

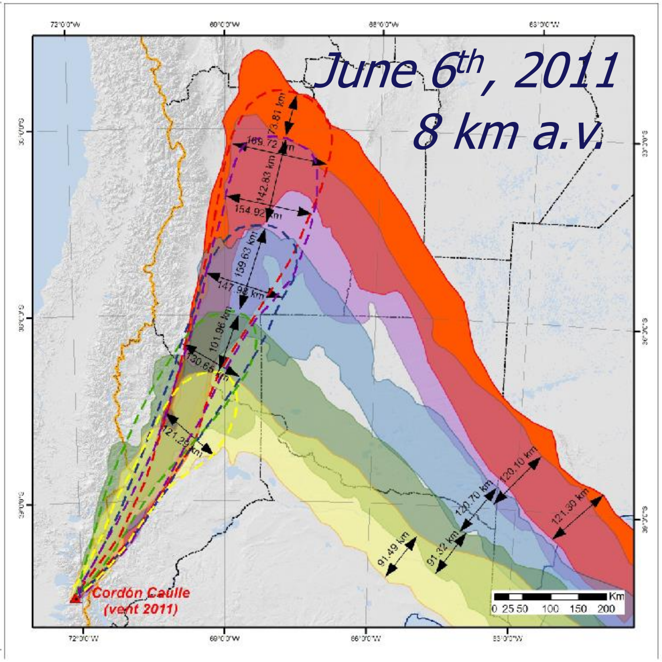


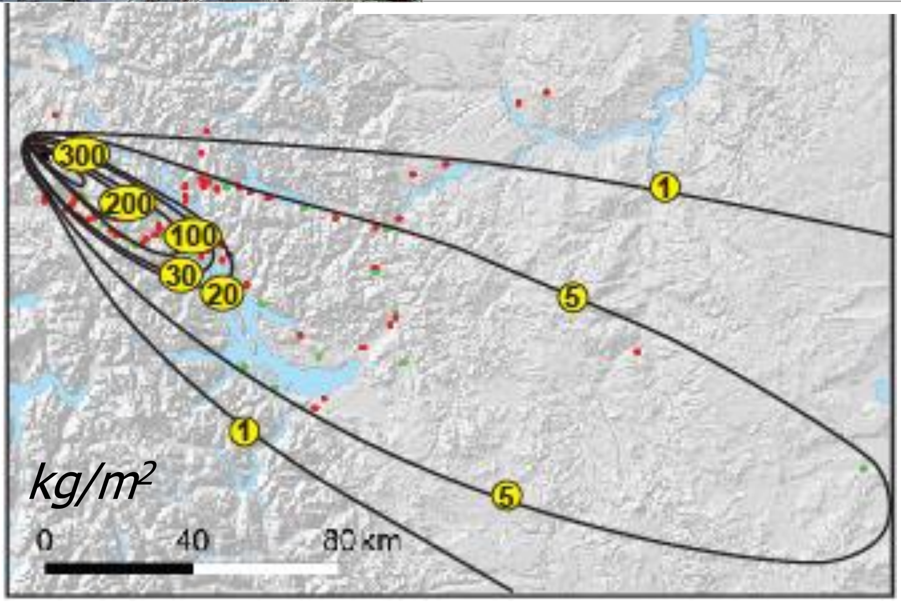


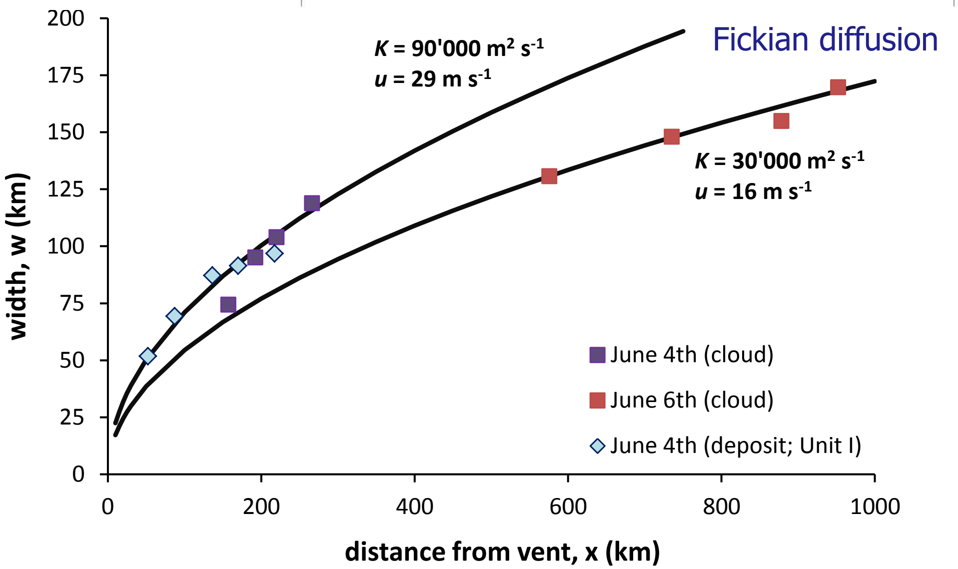
Bonadonna et al. (submitted)

Crosswind spreading









Bonadonna et al. (submitted)

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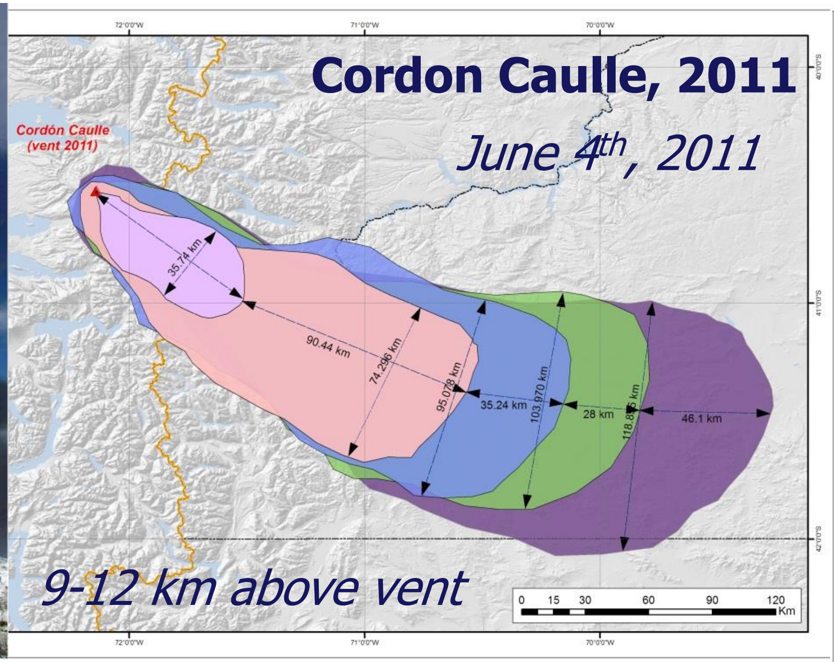
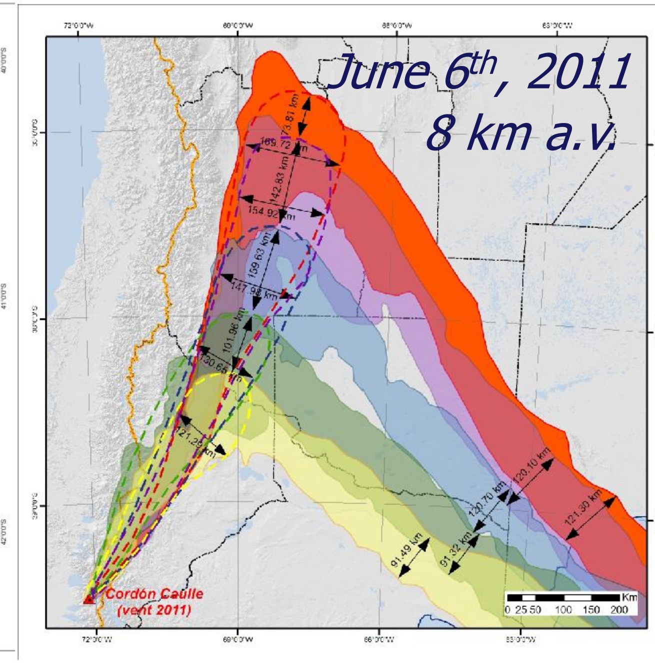
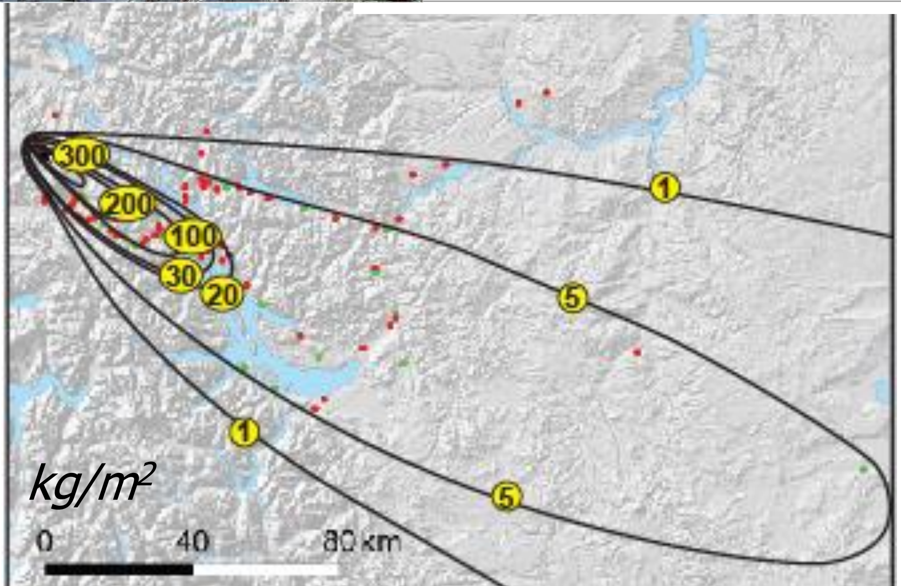
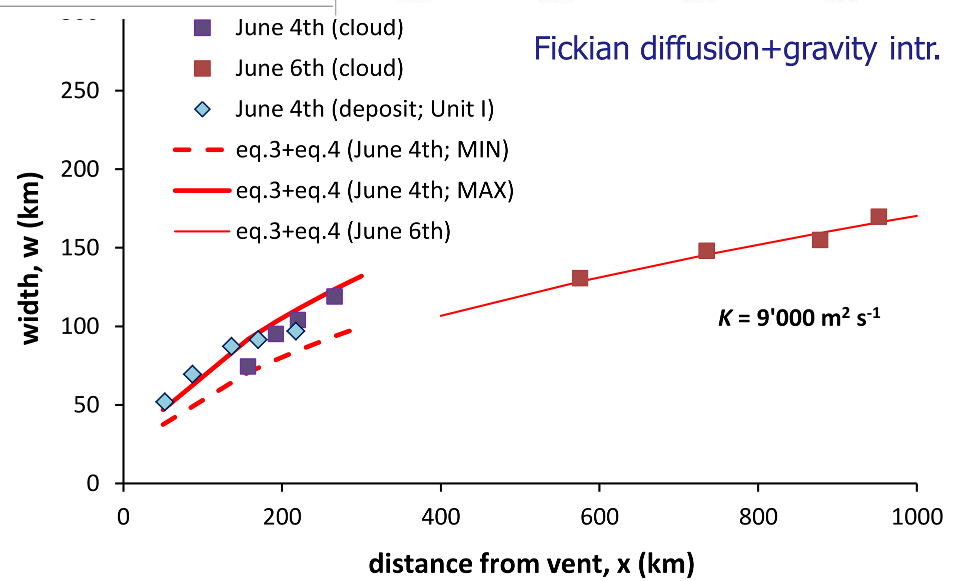


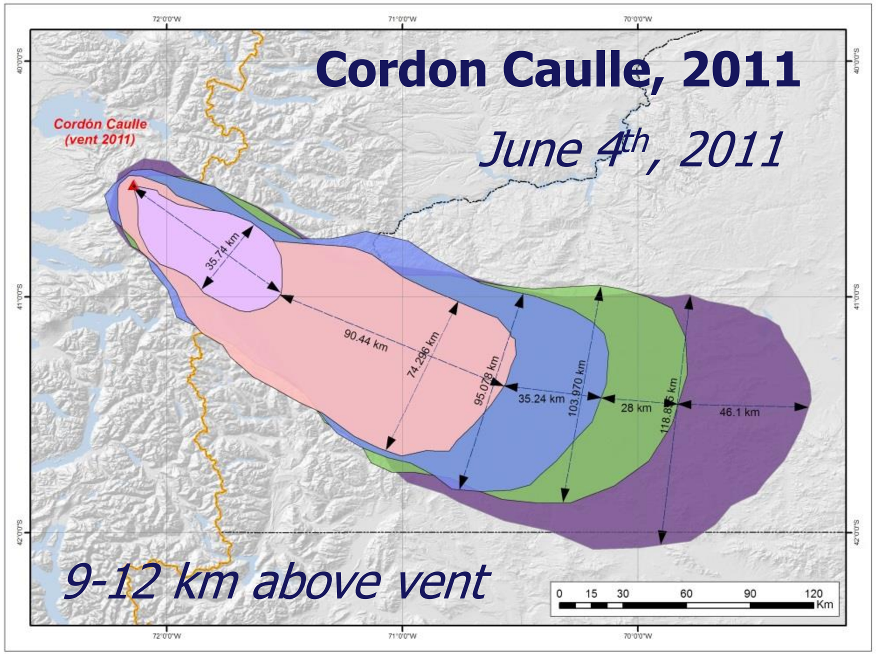






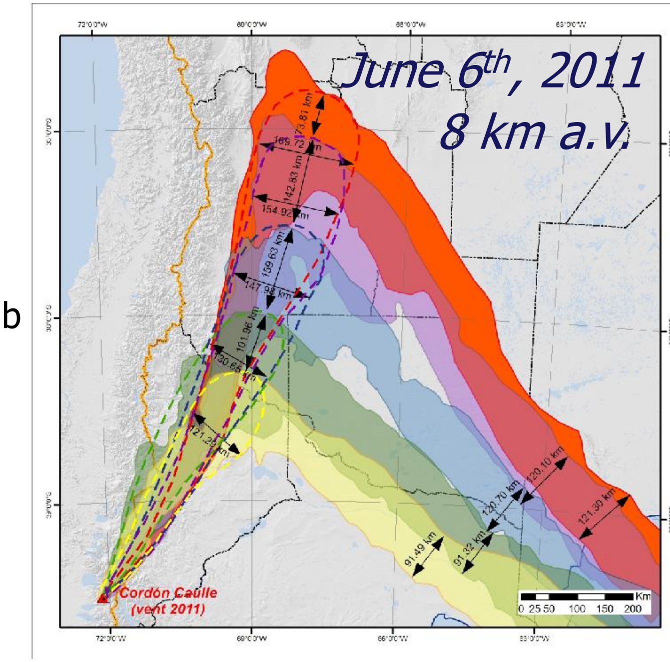
Bonadonna et al. (submitted)

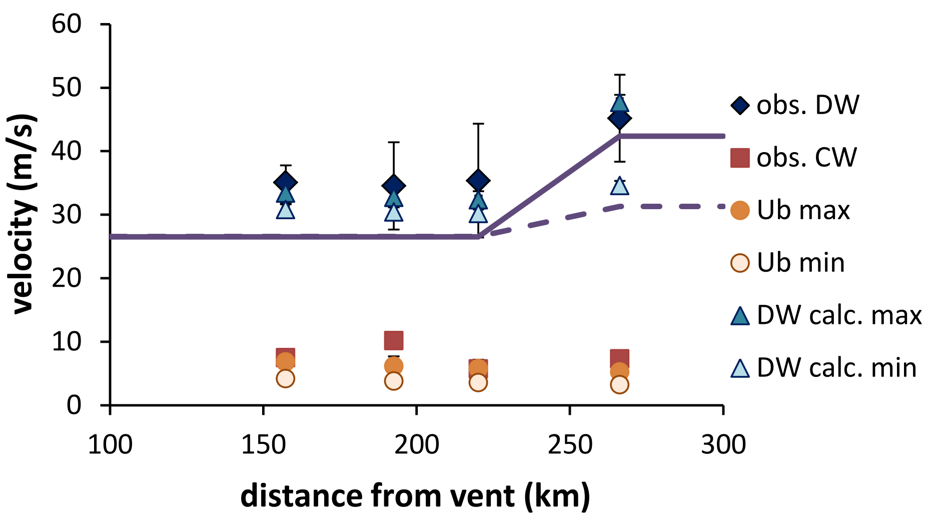
Downwind spreading

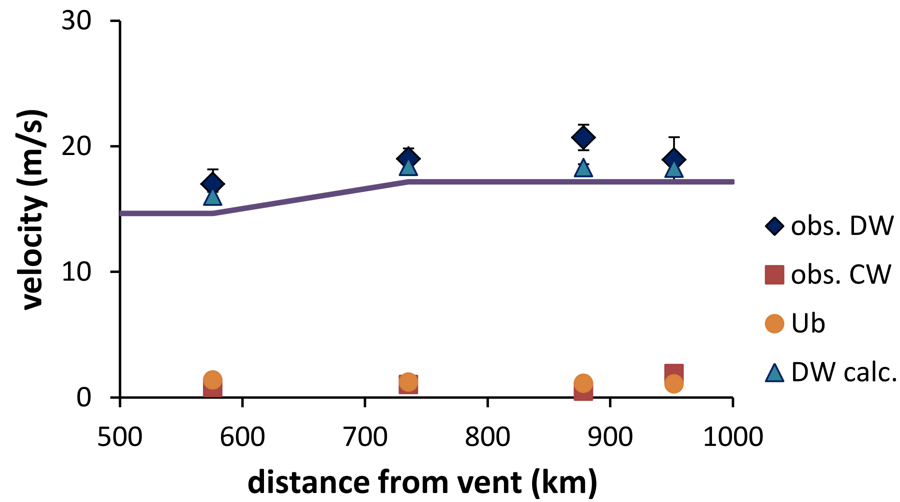


$$u_b = \sqrt{g'h}$$

$$U = u_{wind} + u_b$$

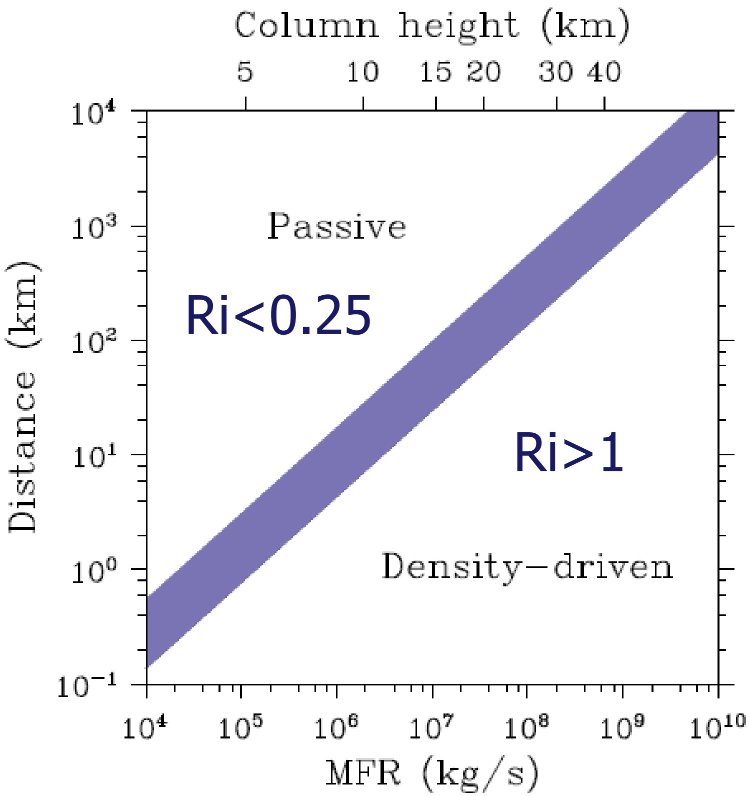






Bonadonna et al. (submitted)

Buoyancy-driven intrusions



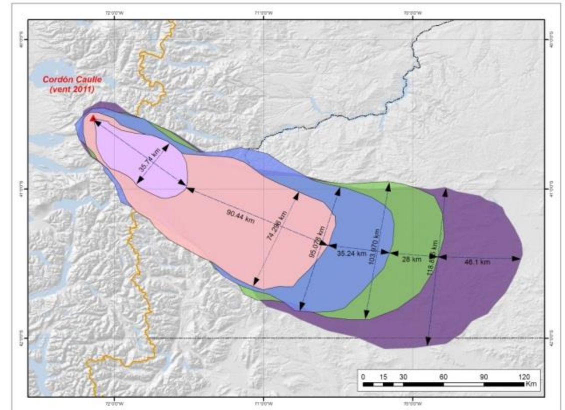
Ri<0.25

Ri>1

Costa et al. 2013

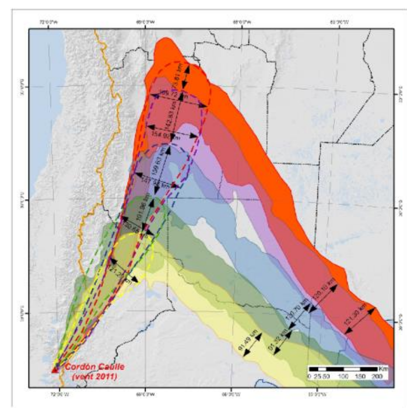
Ri=Ub^2/Uw^2

Cordon Caulle, 2011



June 4th, 2011
9-12 km a.v.

Ri=0.02-0.04
Gravitational spreading →17%



June 6th, 2011
8 km a.v.

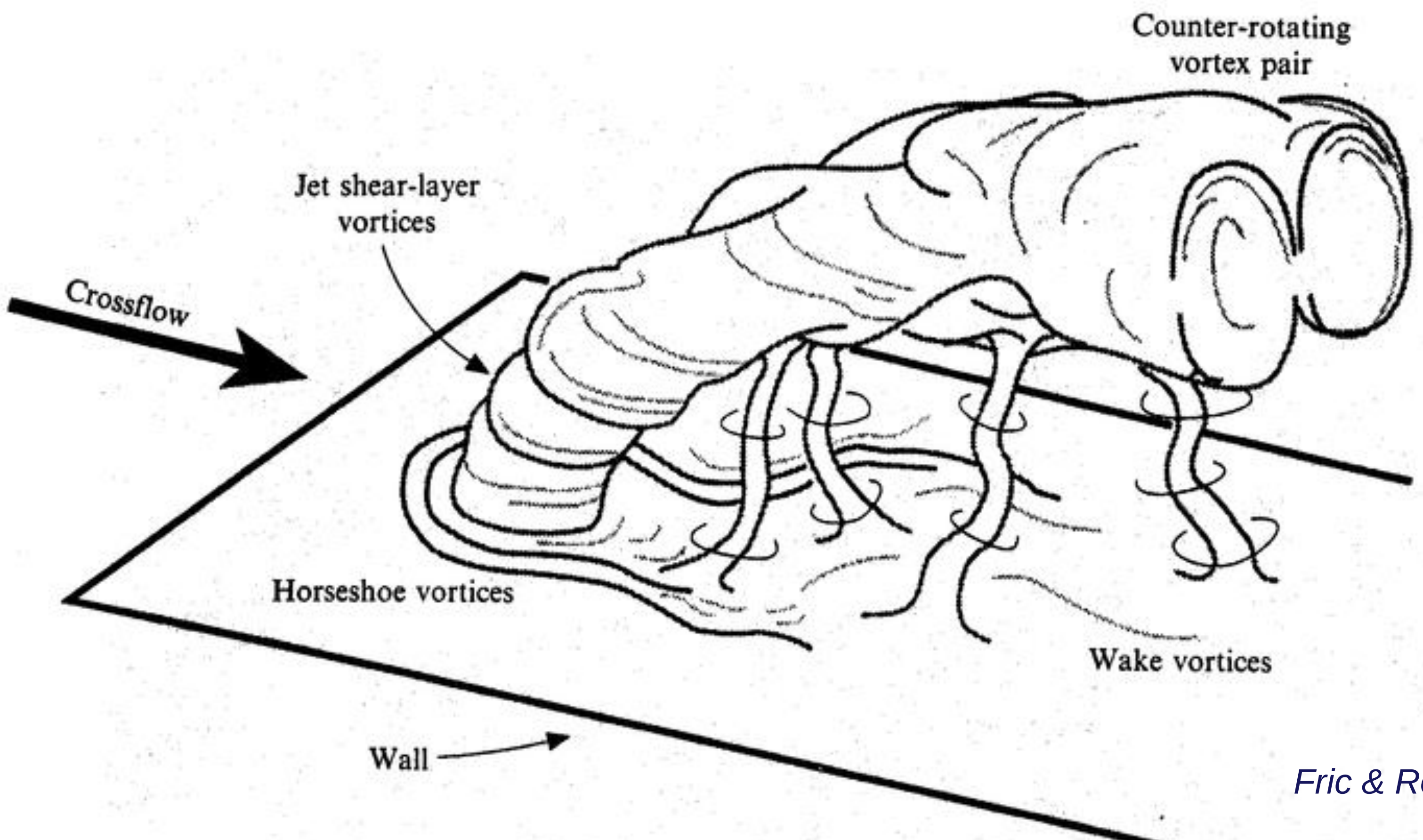
Ri=0.006
Gravitational spreading →7%

Bonadonna et al. (submitted)

Buoyant Plumes in a Cross Flow

➢ The presence of a cross flow increases complexity, and the plume exhibits a variety of vortex structures

➢ They are typically confined to the troposphere



Fric & Roshko 1994

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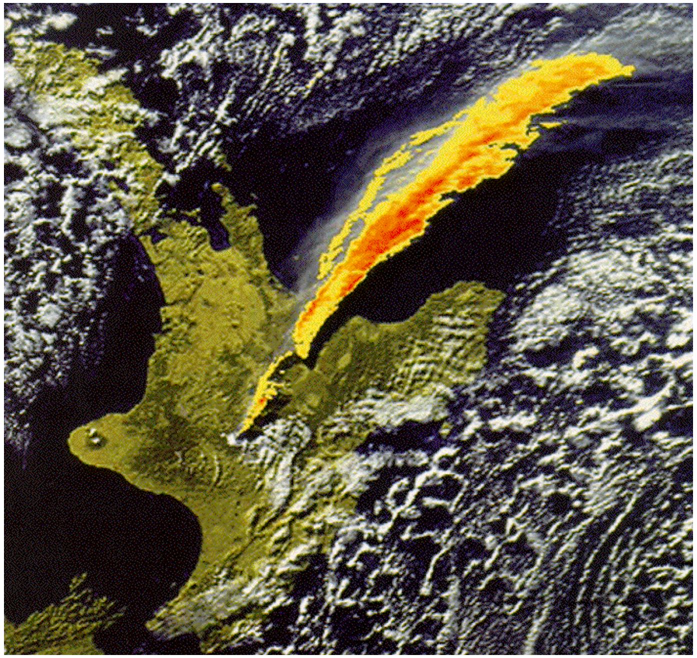
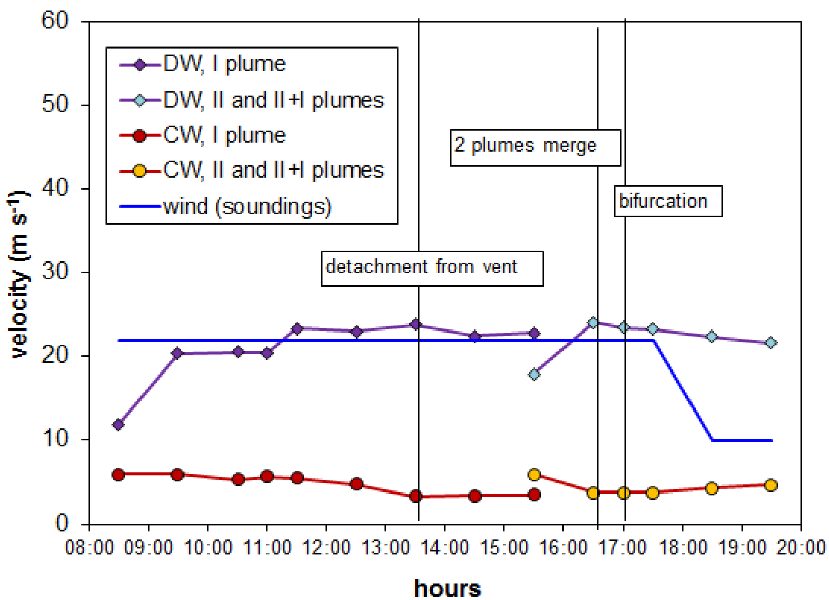
Buoyant Plumes in a Cross Flow

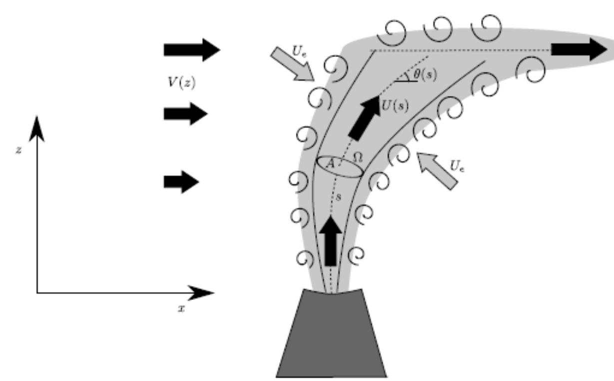



15:30 NZST 17 June 1996

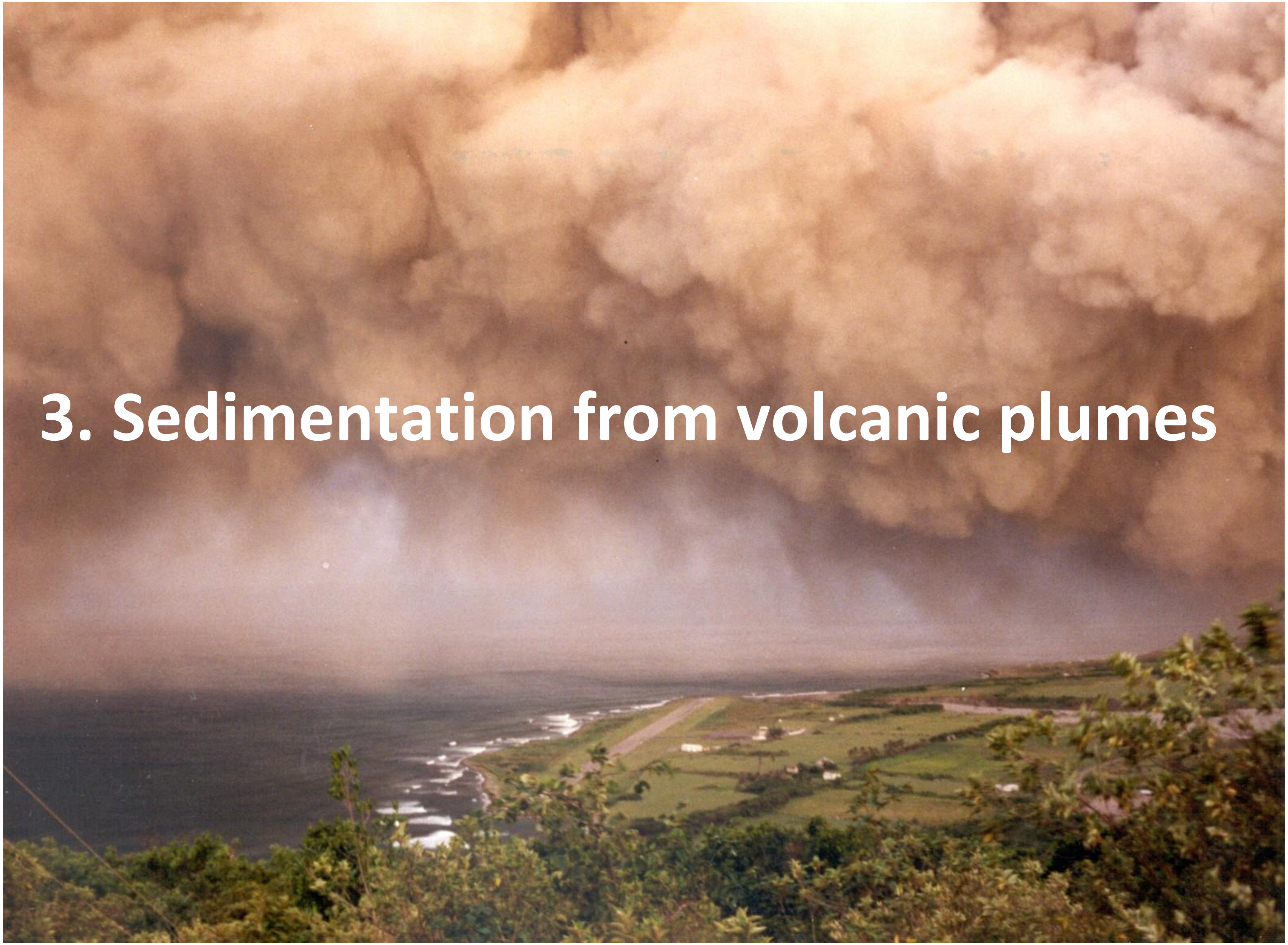




Ruapehu, 1996



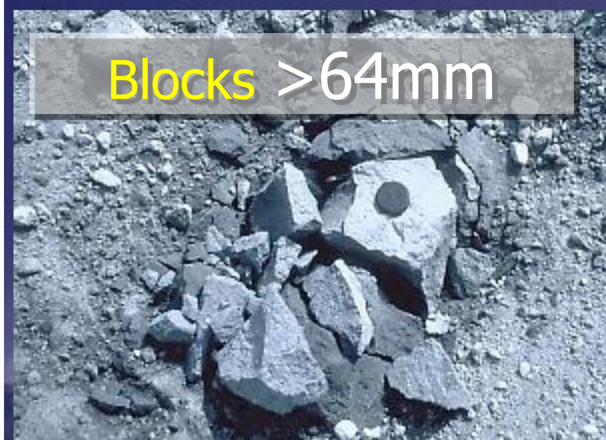
Bonadonna et al. 2005

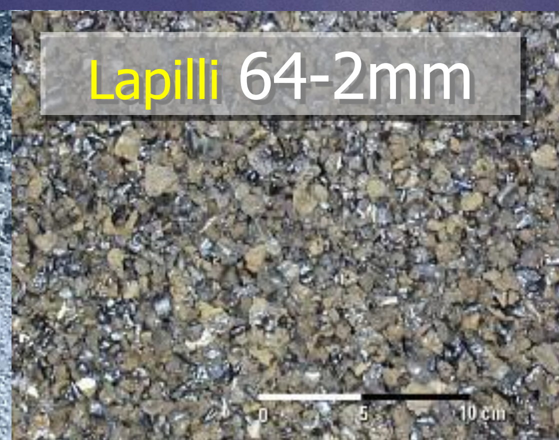


3. Sedimentation from volcanic plumes

TEPHRA

collective term for airborne volcanic ejecta irrespective of size, composition or shape – ***Thorarinsson 1944***





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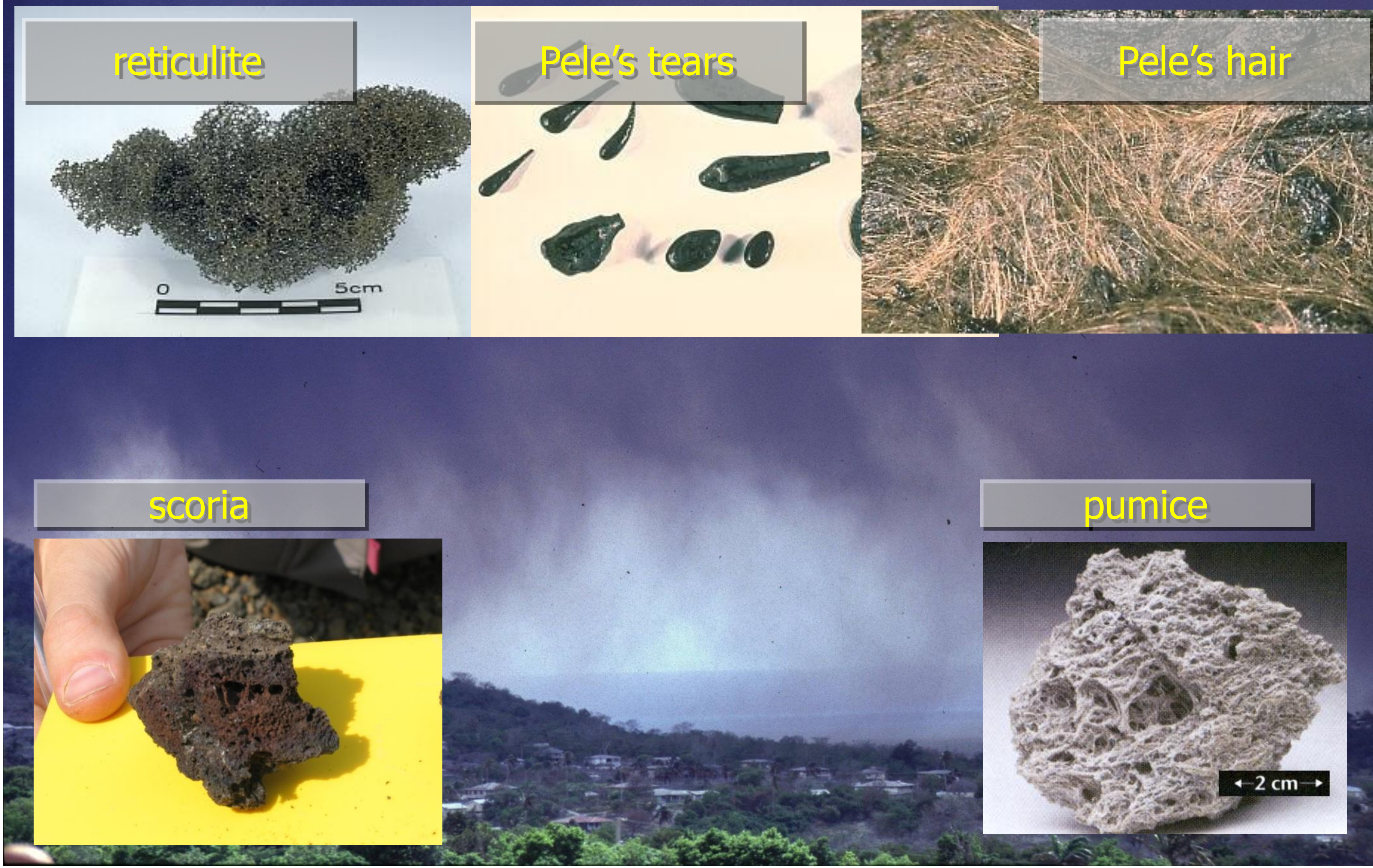

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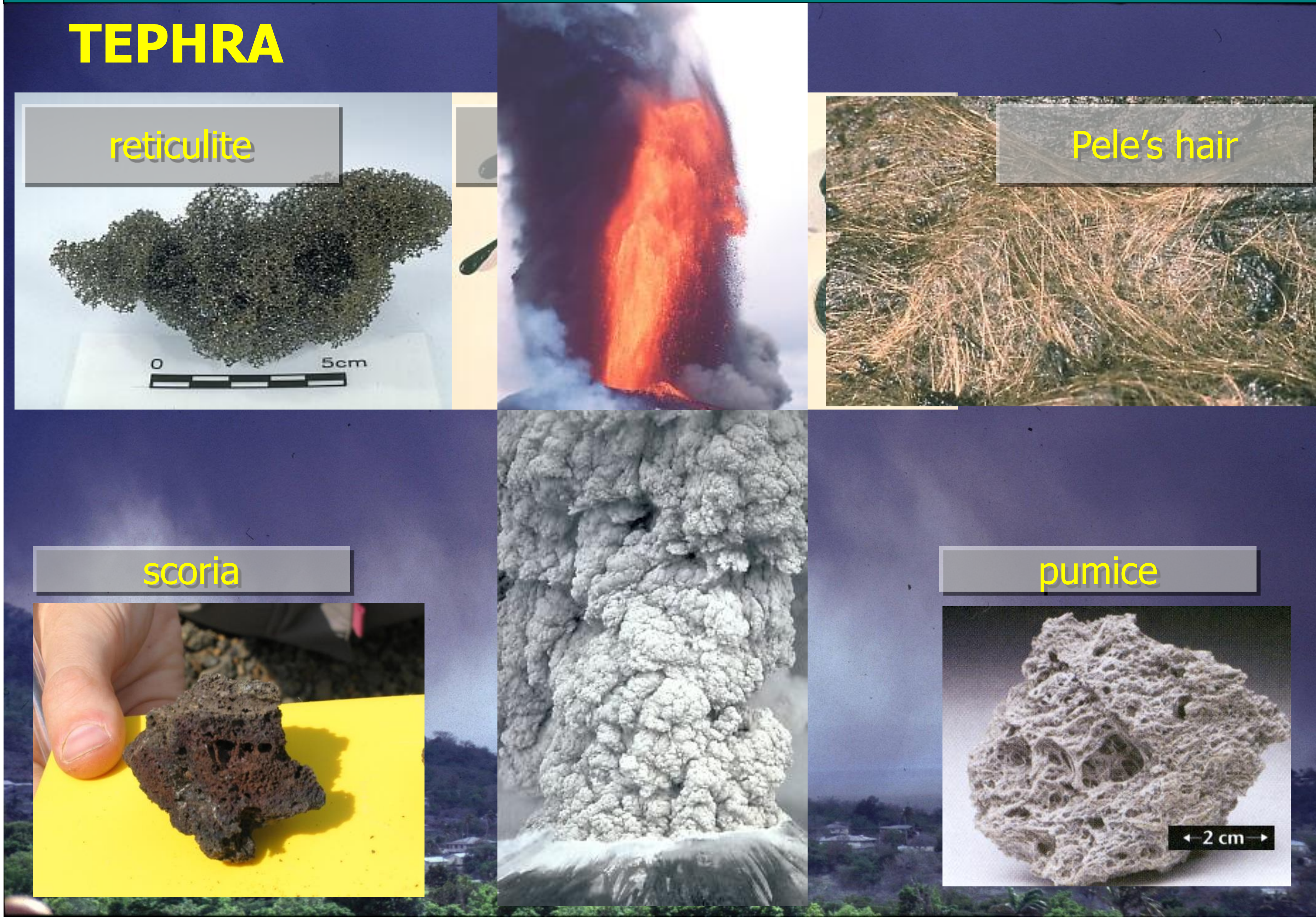
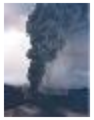
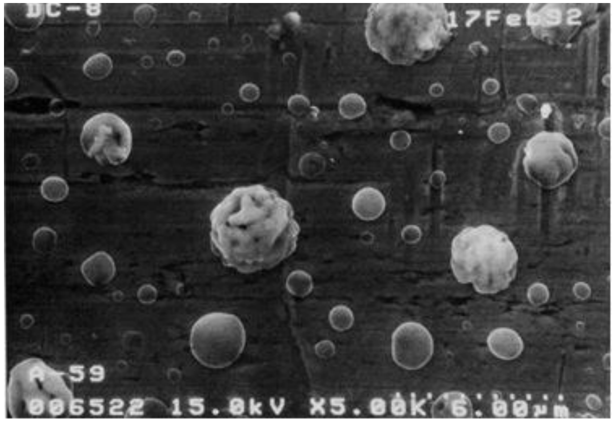
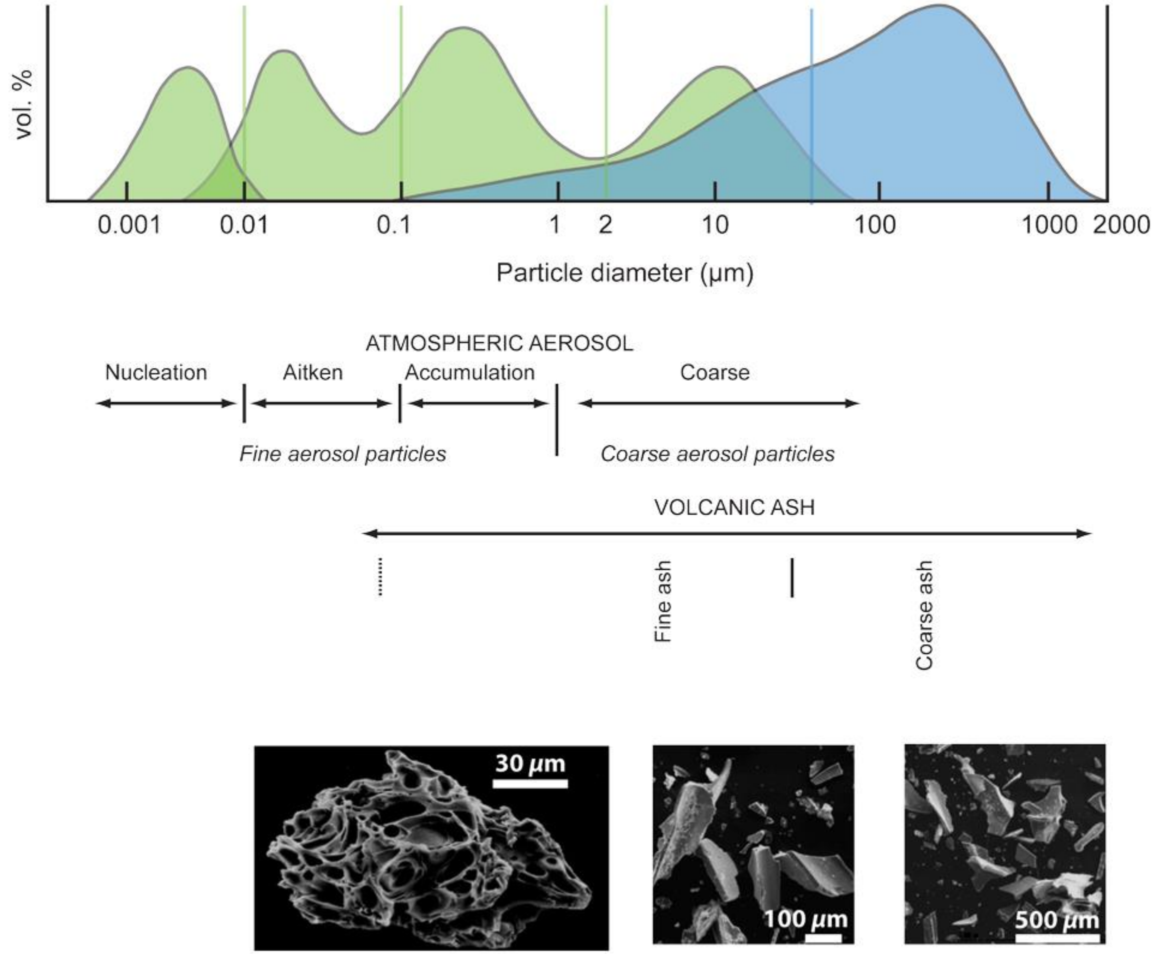


Sedimentation from volcanic plumes

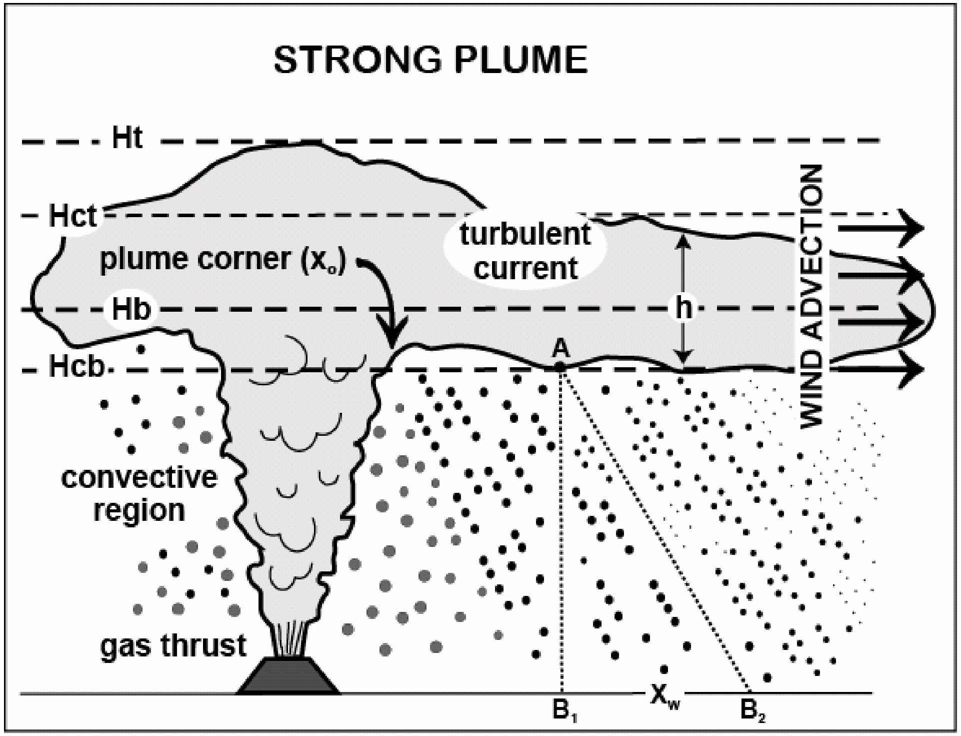






Durant et al. 2010



$$X_o = 0.2\ H_t$$

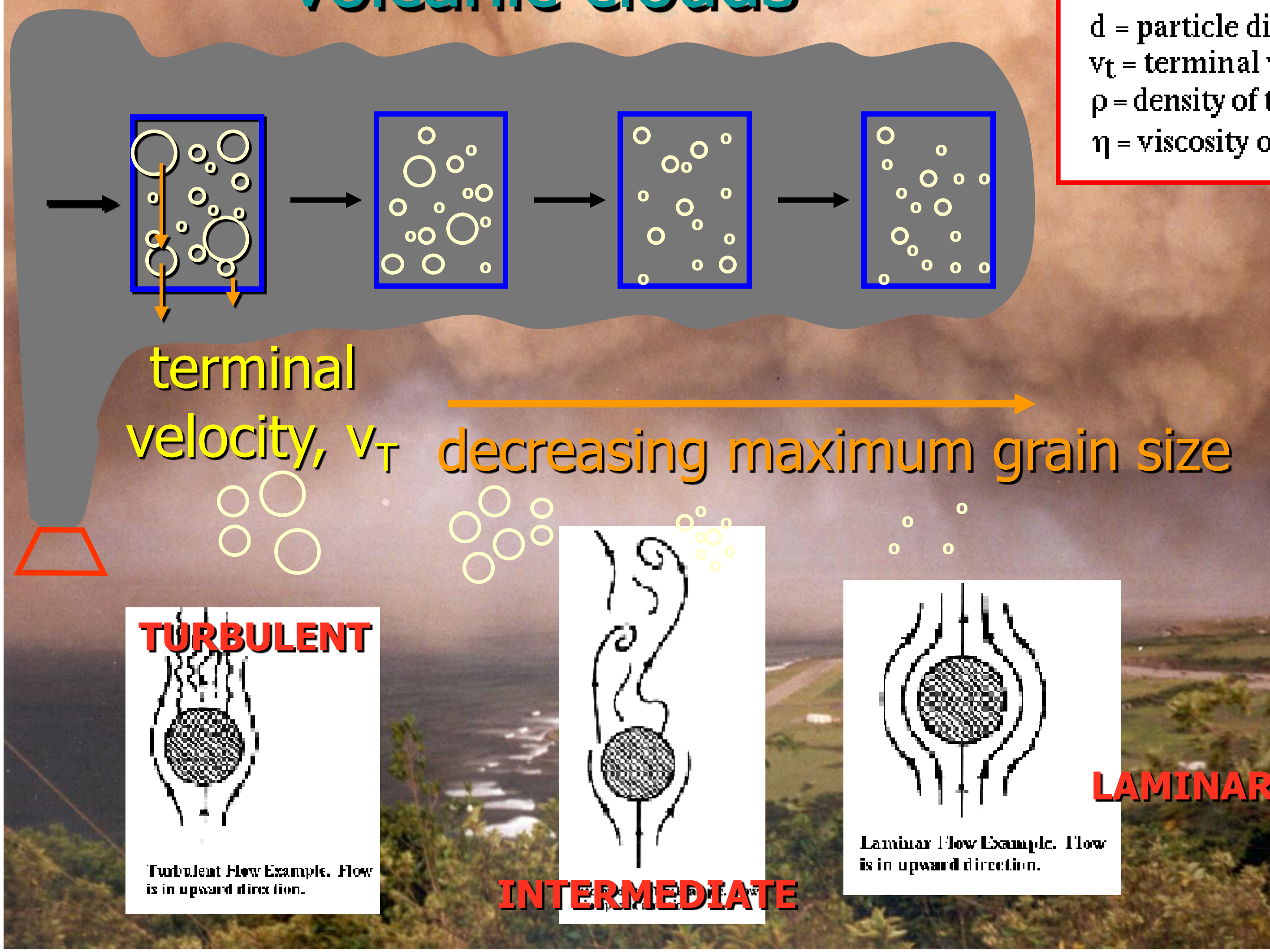
CLASS 1 → coarse fragments ejected from the jet (ballistics) Typically <4km from vent

CLASS 2 → convective region (particles >2cm). Typically <15km

CLASS 3 → umbrella cloud (particle <2cm)

CLASS 4 → fine particles dispersed in atmosphere

Sedimentation from volcanic clouds



Reynolds number (Re):

$$Re = (d * v_t * \rho)/\eta$$

d = particle diameter (μm)
v_t = terminal velocity (cm/s)
ρ = density of the atmosphere (g/cm^3)
η = viscosity of the atmosphere (g/cm-s)

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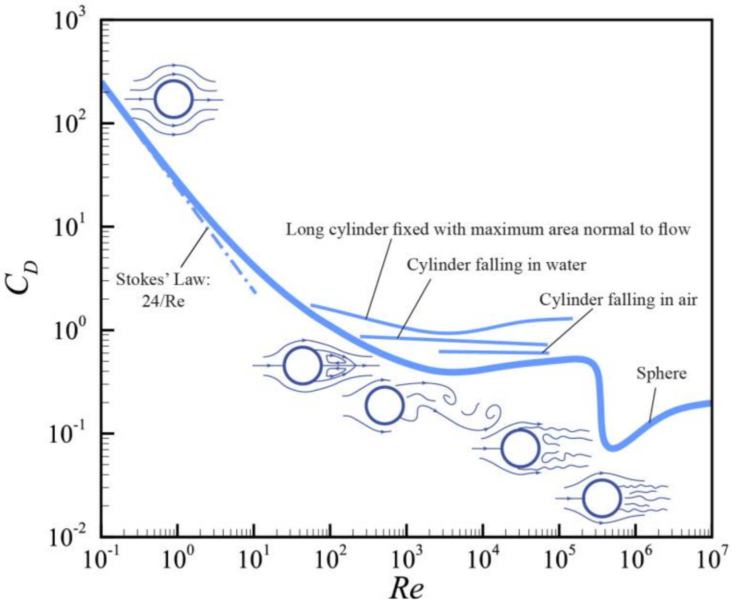
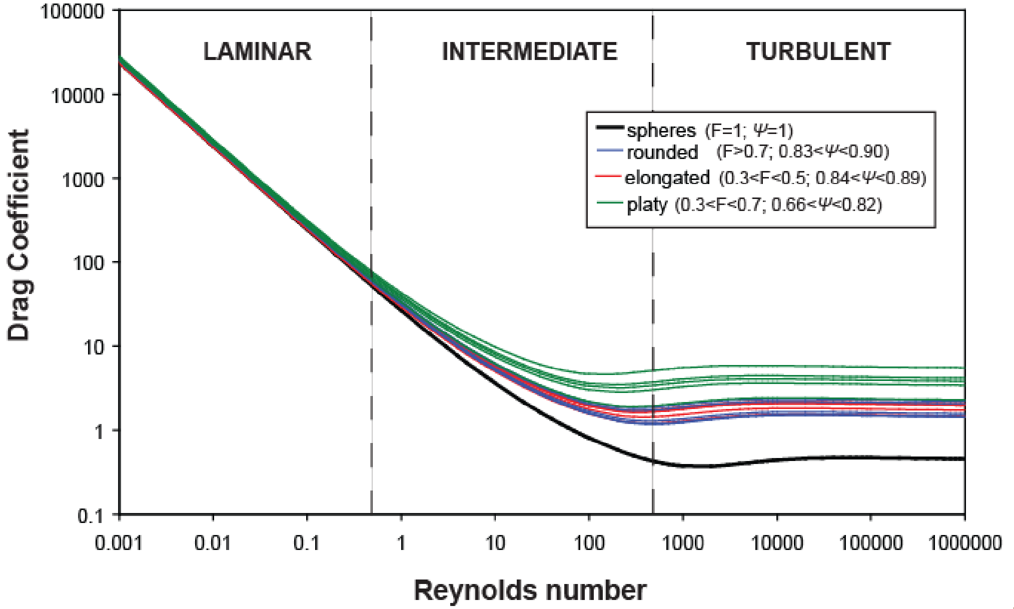
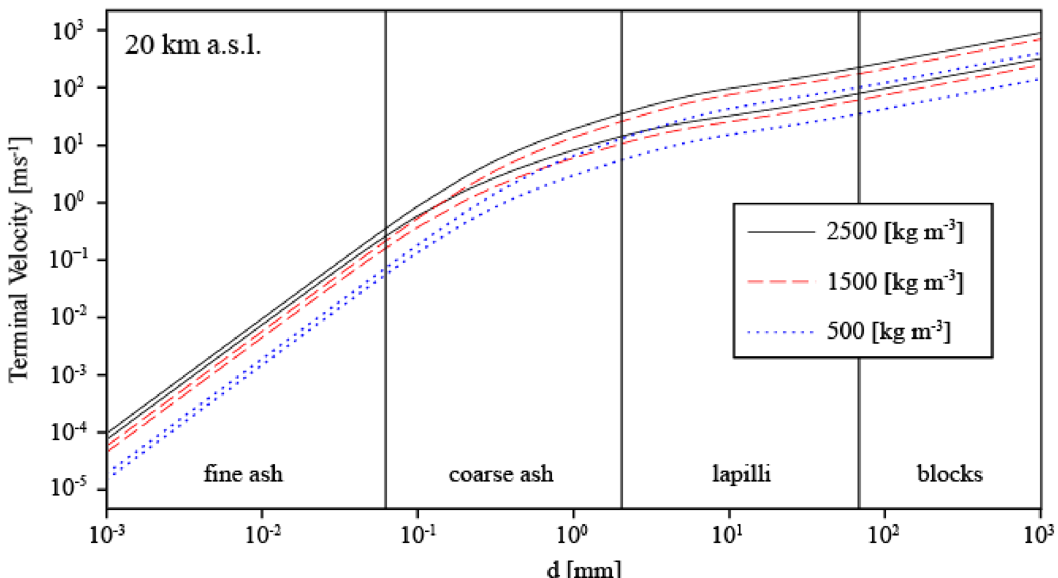
Sedimentation from volcanic plumes

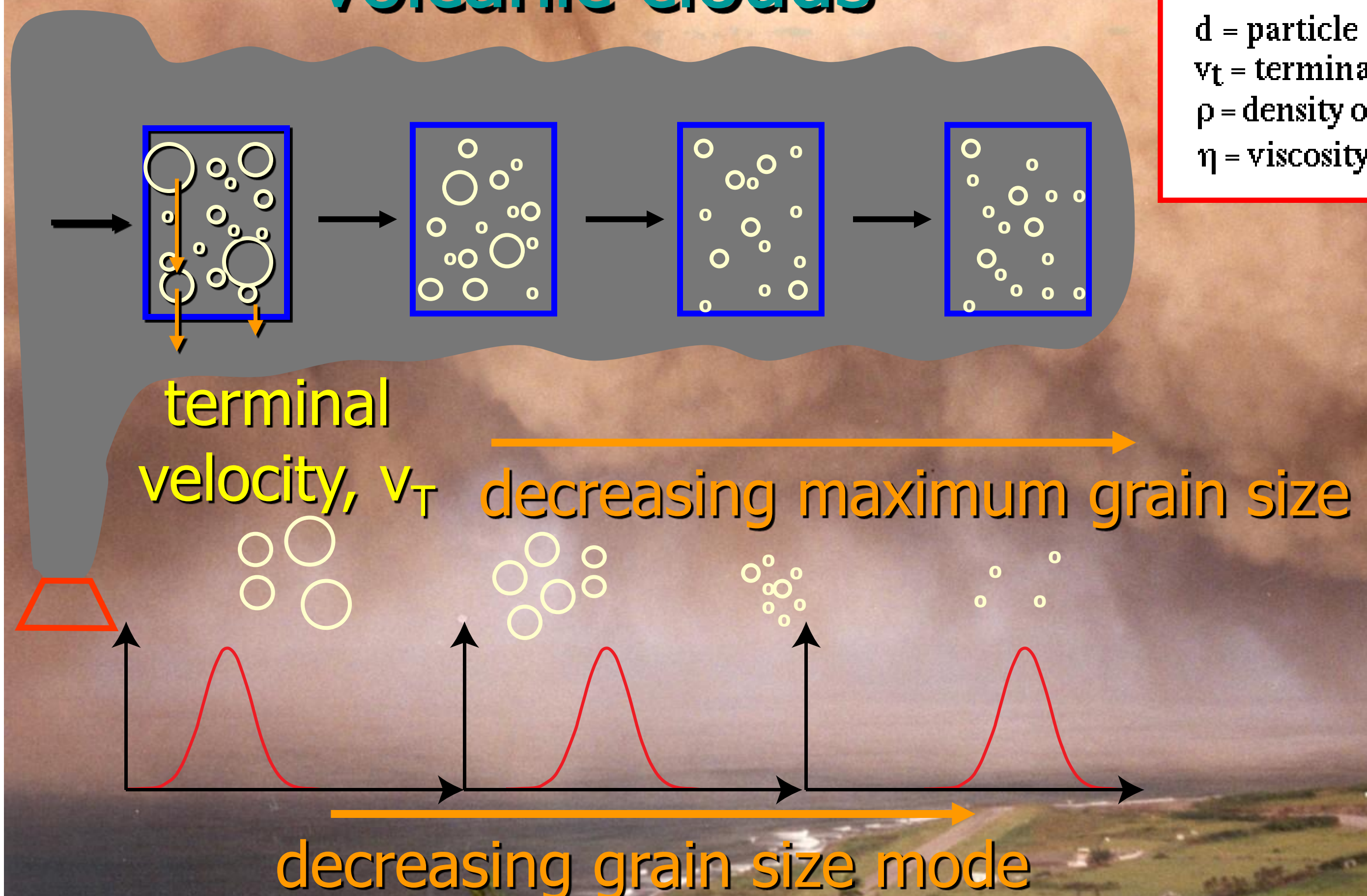






Sedimentation from volcanic plumes

Sedimentation from volcanic clouds

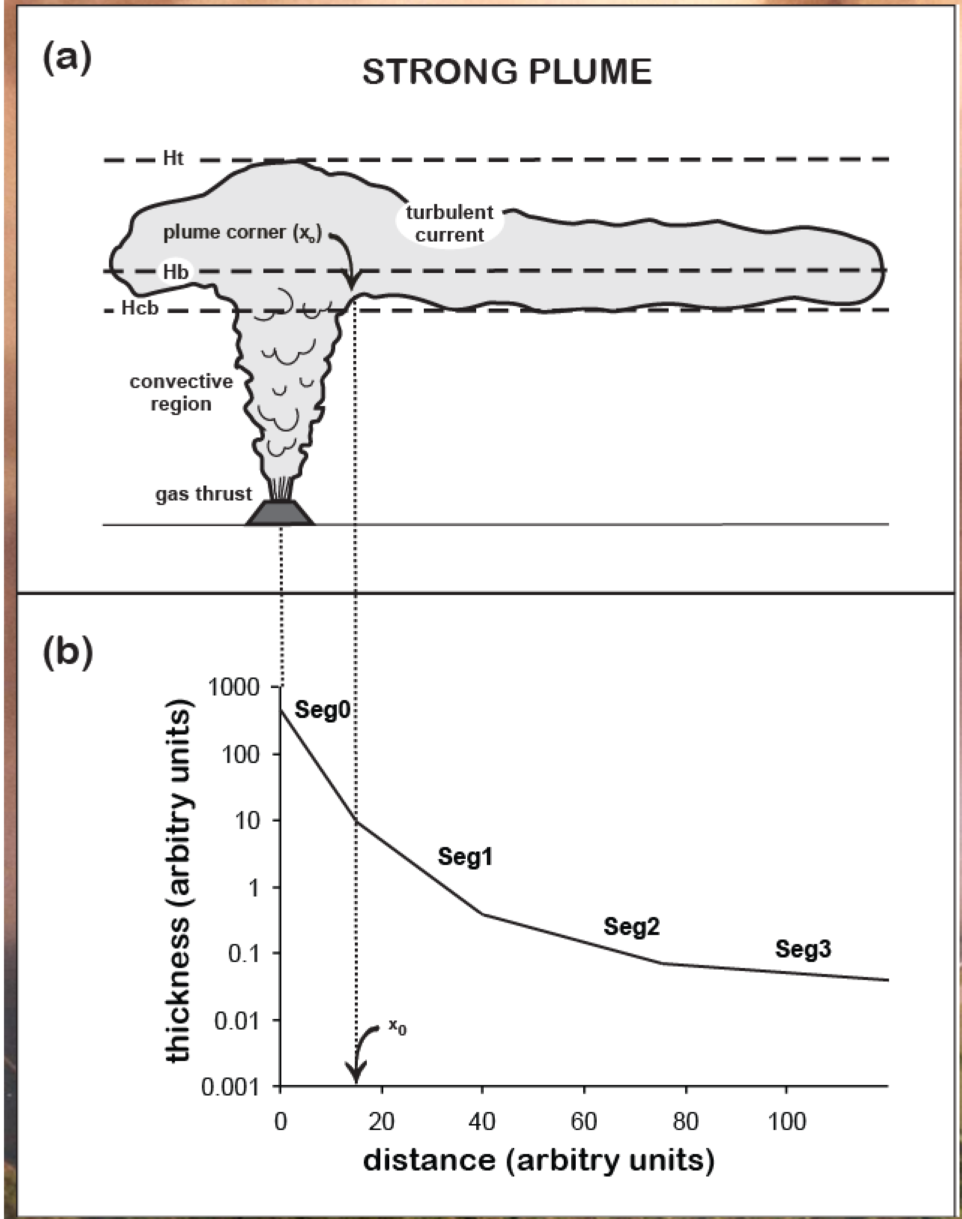


Reynolds number (Re):

$$Re = (d * v_t * \rho)/\eta$$

d = particle diameter (μm)
v_t = terminal velocity (cm/s)
ρ = density of the atmosphere (g/cm^3)
η = viscosity of the atmosphere (g/cm-s)

Sedimentation from volcanic plumes



<u>Segment 0</u>: sedimentation from plume margins

<u>Segment 1:</u>
high-Re particle settling

<u>Segment 2</u>:
intermediate-Re particle

<u>Segment 3</u>:
low-Re particle settling

Bonadonna et al. (1998)

Sedimentation from volcanic clouds

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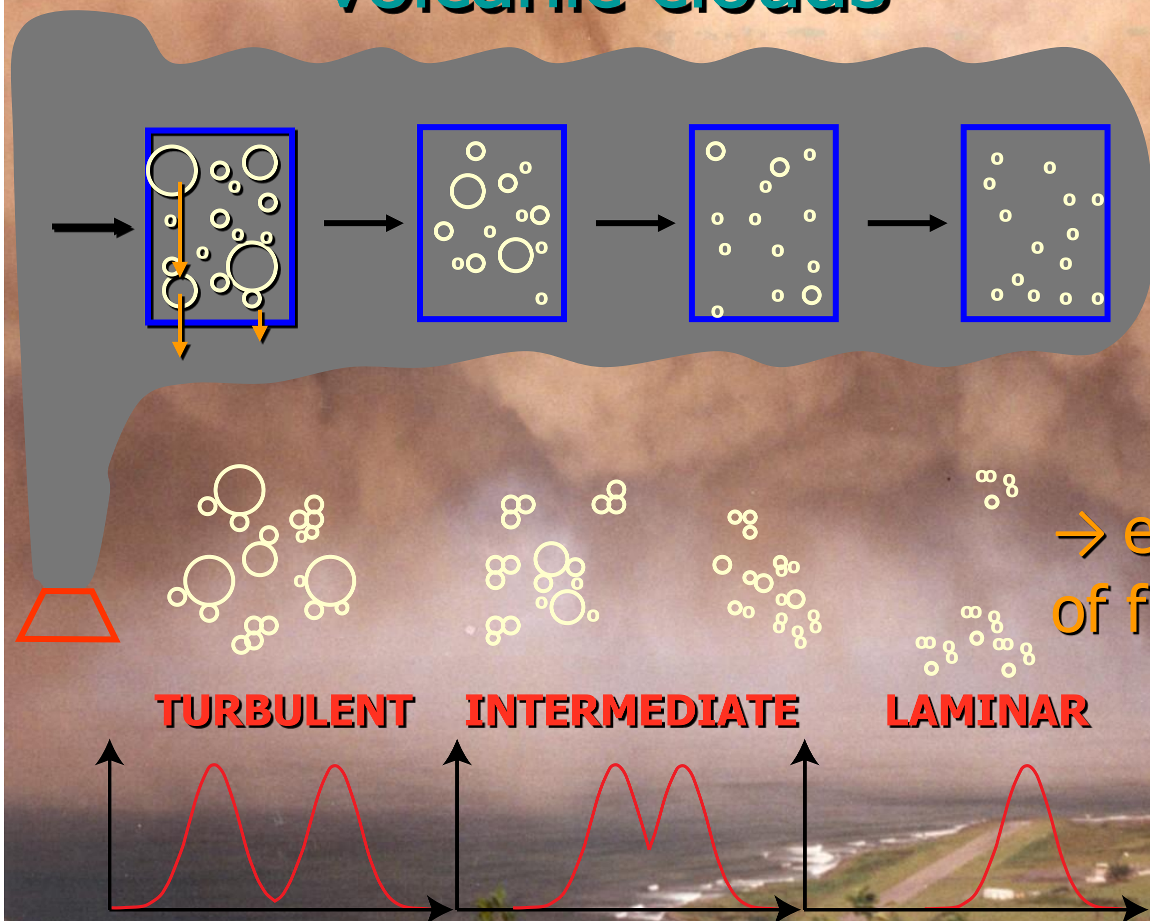
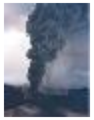
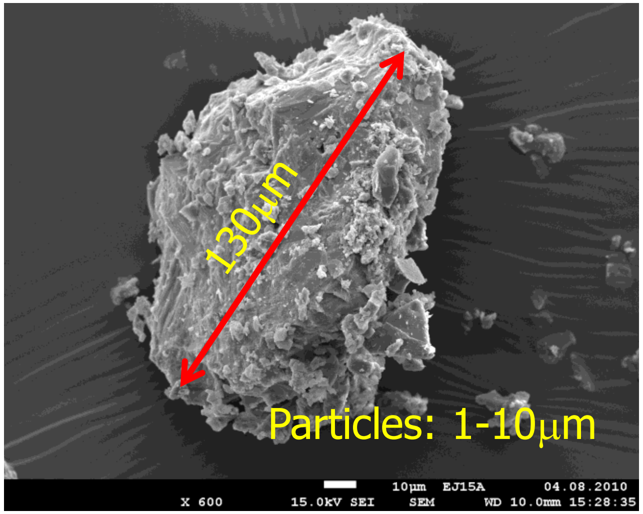


→ enhanced sedimentation of fine ash (<63 µm)

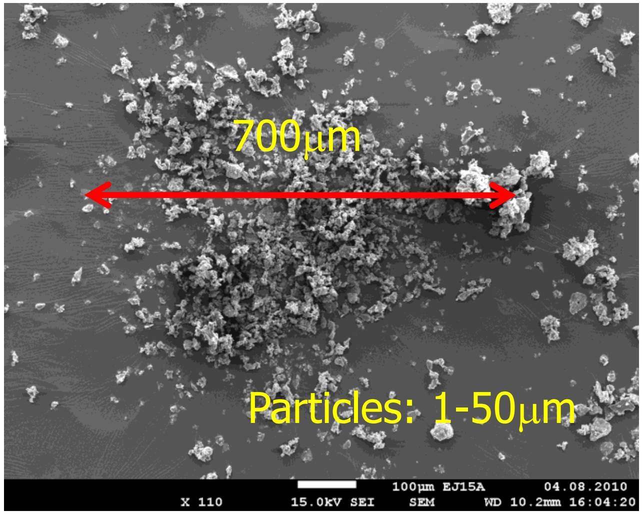


PARTICLE AGGREGATION

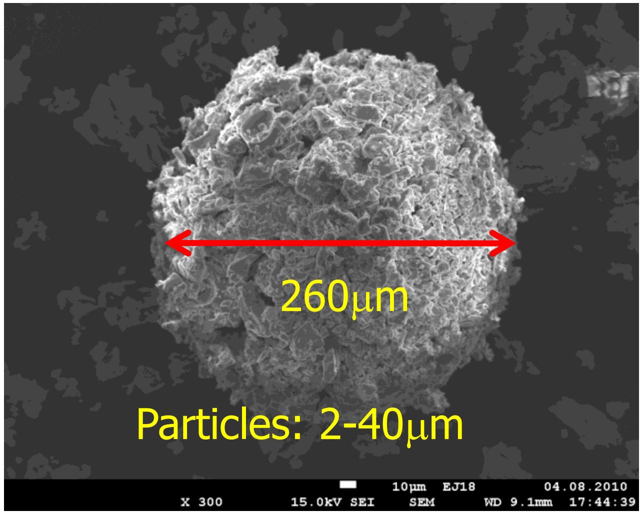
Coated particle



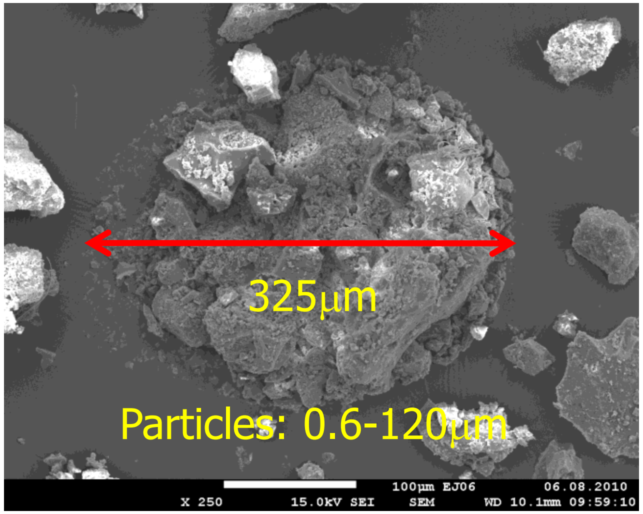
Ash cluster



Poorly-structured pellet



Liquid pellet



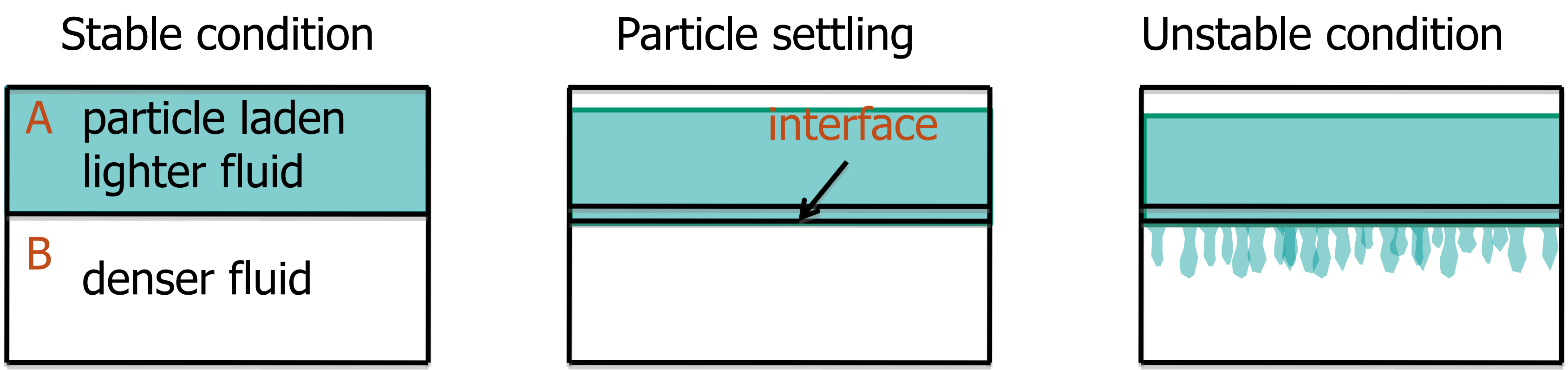
2010 Eyjafjallajökull eruption; Bonadonna et al. 2011

SETTLING-DRIVEN CONVECTION

2010 Eyjafjallajökull eruption

How do fingers form?

- Instabilities occur at the boundary between fluids with different densities
- Formation of vertical instabilities = FINGERS
- Settling fingers: density variations caused by particle settling

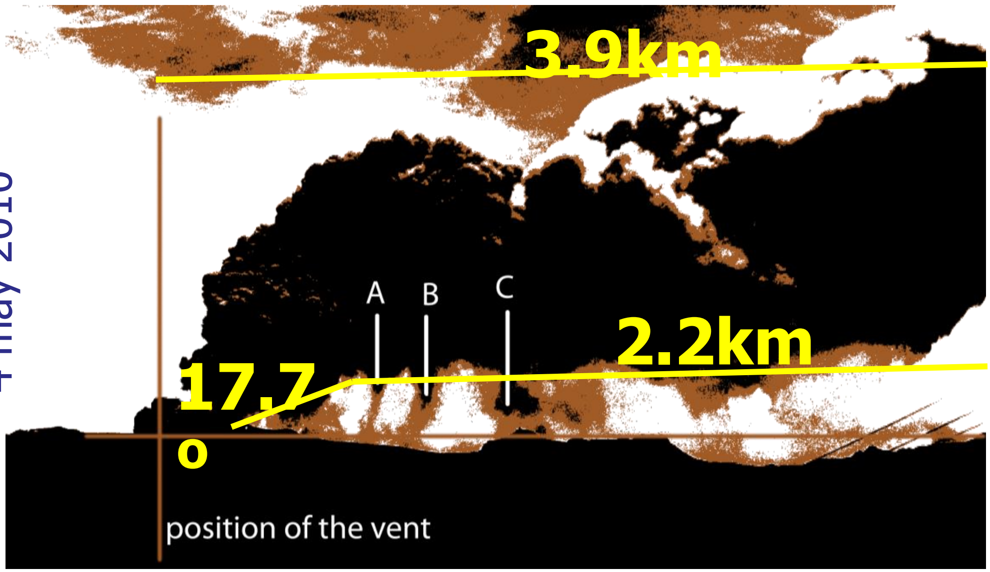


Condition for finger formation : $v_f > v_p$

Particle suspension behaves as a continuum

Sedimentation from volcanic plumes

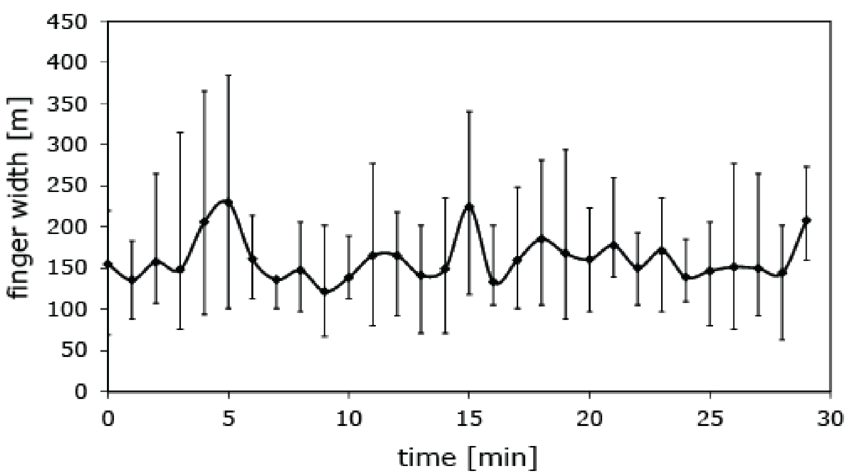
4 may 2010

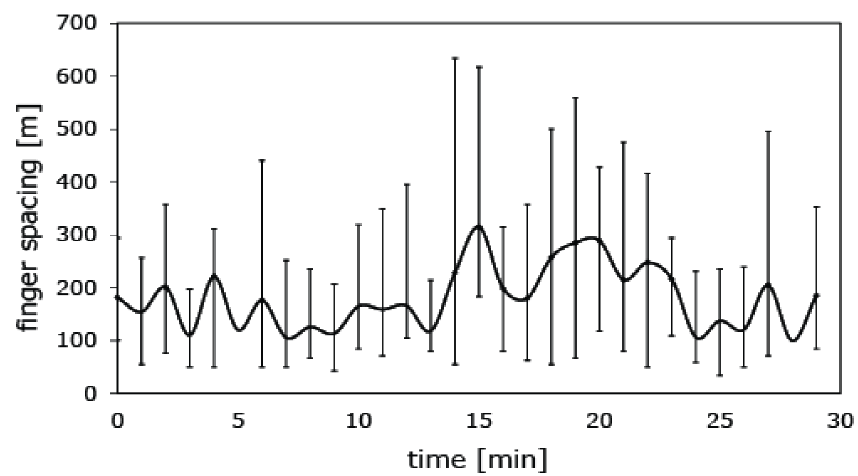


Mean values over 30 minutes observation (4 may 2010):

Cloud lateral speed	=7.9 m/s
Finger width	=161 m
Finger spacing	=180 m
Finger lateral speed	=8.5 m/s
Finger vertical speed	=1.0 m/s

First finger = 1.4km from vent
→ Sedimentation around 10km from vent

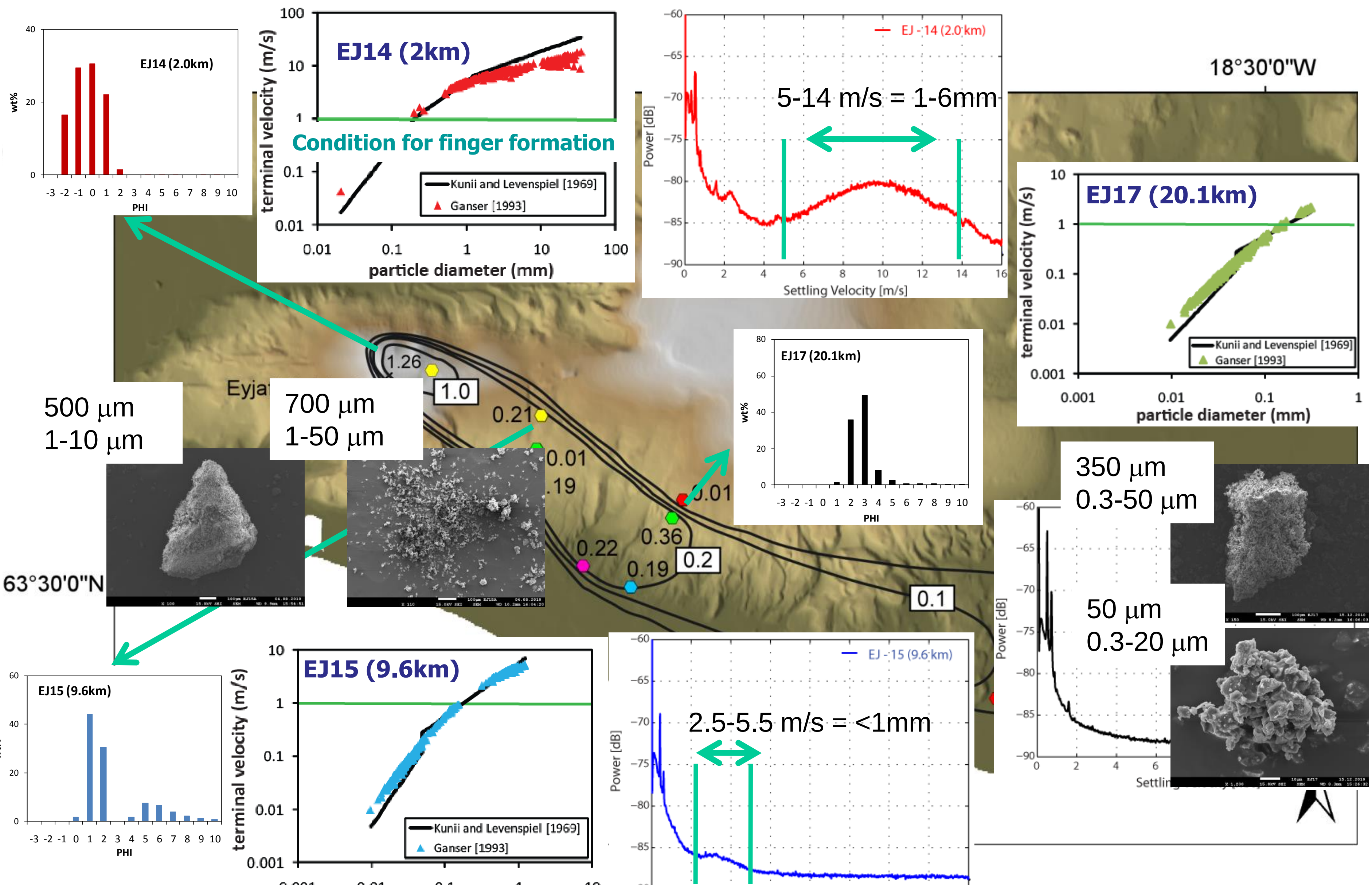




Manzella et al. (submitted)

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département des sciences de la Terre

Sedimentation from volcanic plumes



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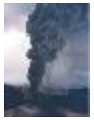
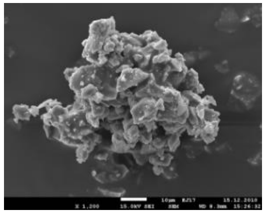
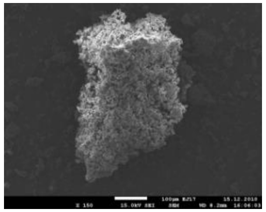


Aggregation / settling-driven instabilities

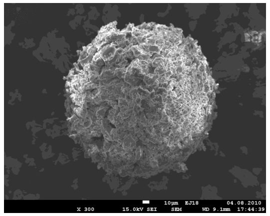
- Terminal velocities (Ganser, 1993):



– PC1 50-600 mm 0.1 - 4 m/s



– PC2 100-700 mm 0.6 - 7 m/s



– AP1 100-400 mm 0.4 - 3 m/s

→ Most PC2 sediment independently of fingers

Manzella et al. (submitted)

Fingers in the lab

Initials conditions:

-Upper layer (particle laden fluid)

Spherical glass beads

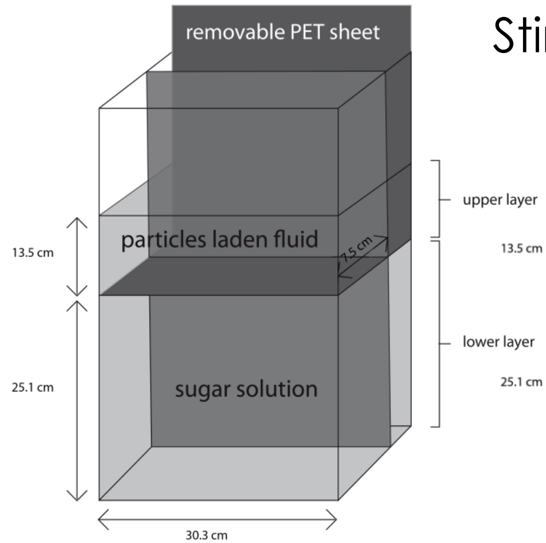
- Diameter = 45 - 63 μm
- Density = 2550 kg/m^3
- Settling velocity ws = 0.88-3.2 x10^{-3} m/s

Conc. part. [g/L]	*density upper layer* ρ_1 *[g/dm^3]*
3	1000.03
4	1000.64
5	1001.25

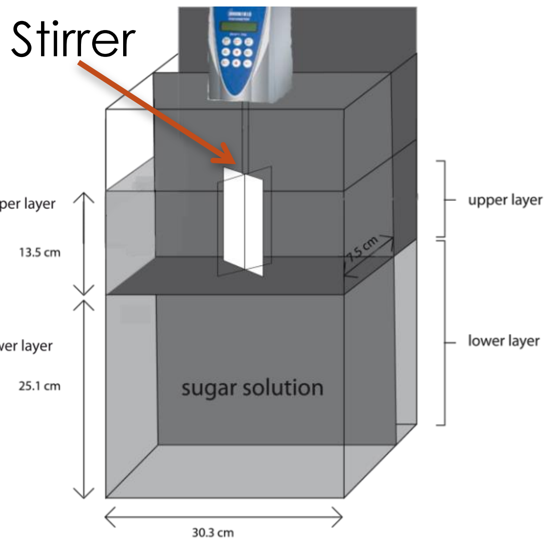
-Lower layer (sugar solution)

Density lower layer ρ_2 = 1008.43 g/dm^3

Unmixed experiment



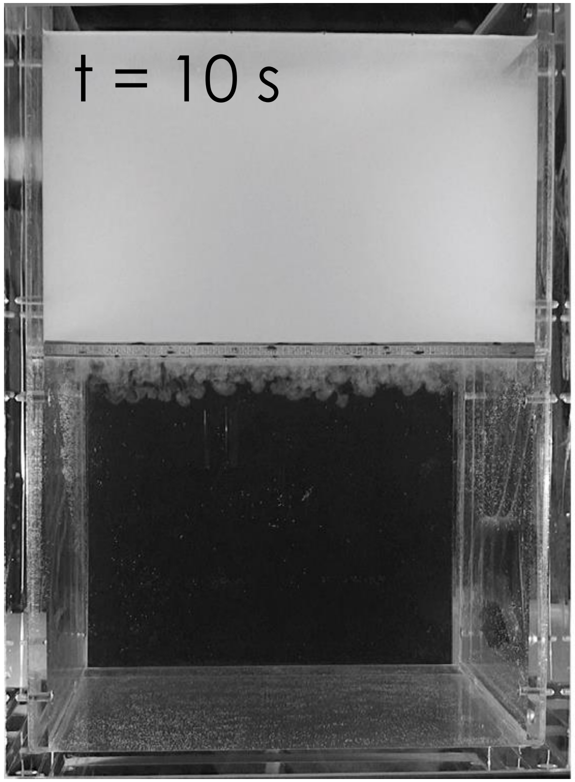
Mixed experiment



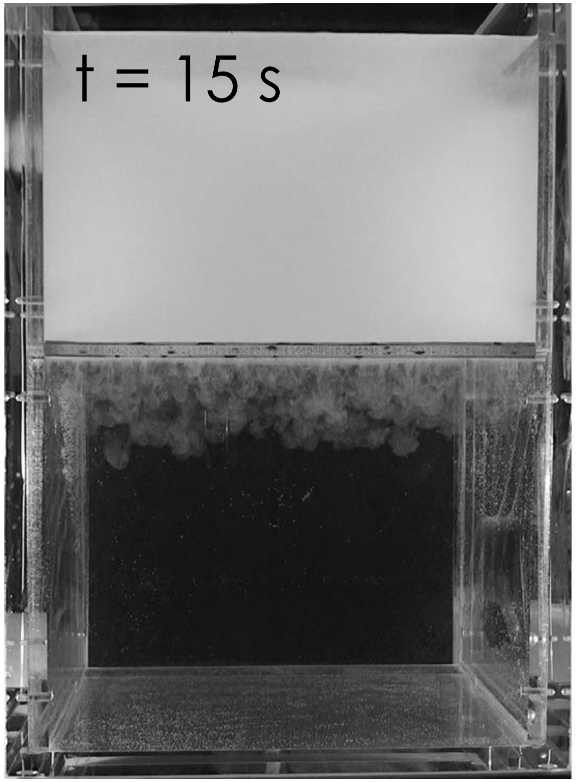
Mean particle concentration in the upper and lower layer are measured as a function of time

Manzella et al. (submitted)

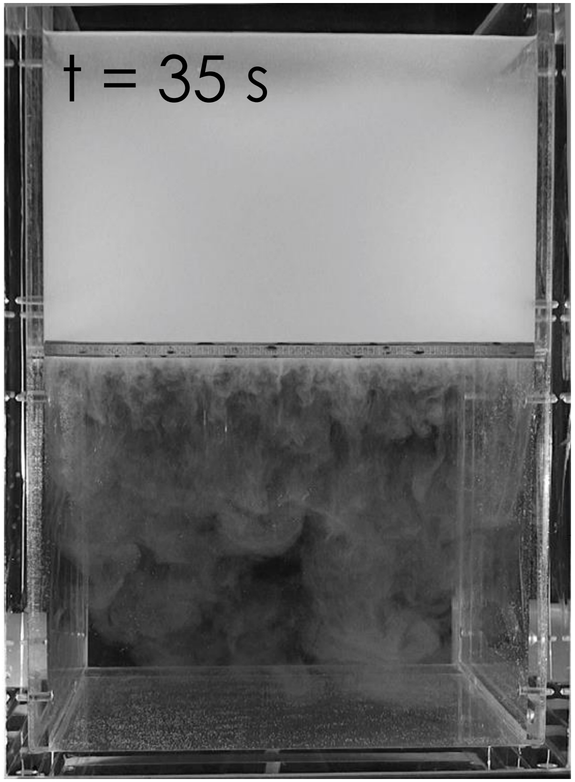
Settling-driven convection: experiments



Fingers just formed and start to propagate downward entraining surrounding fluid



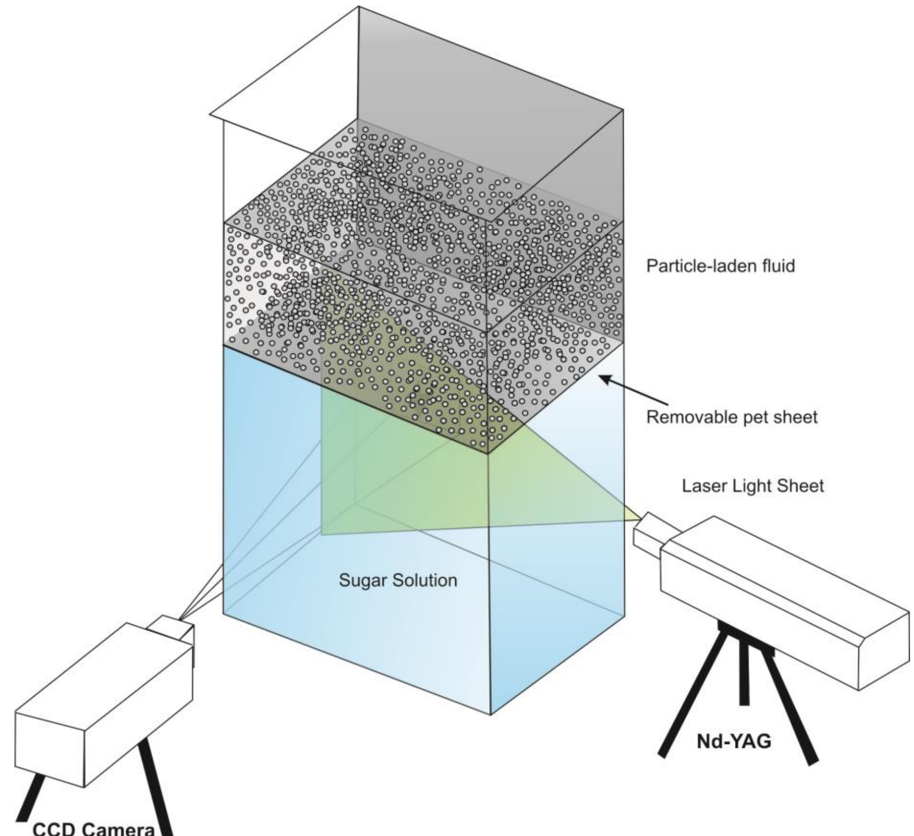
Fingers become larger and start grouping together

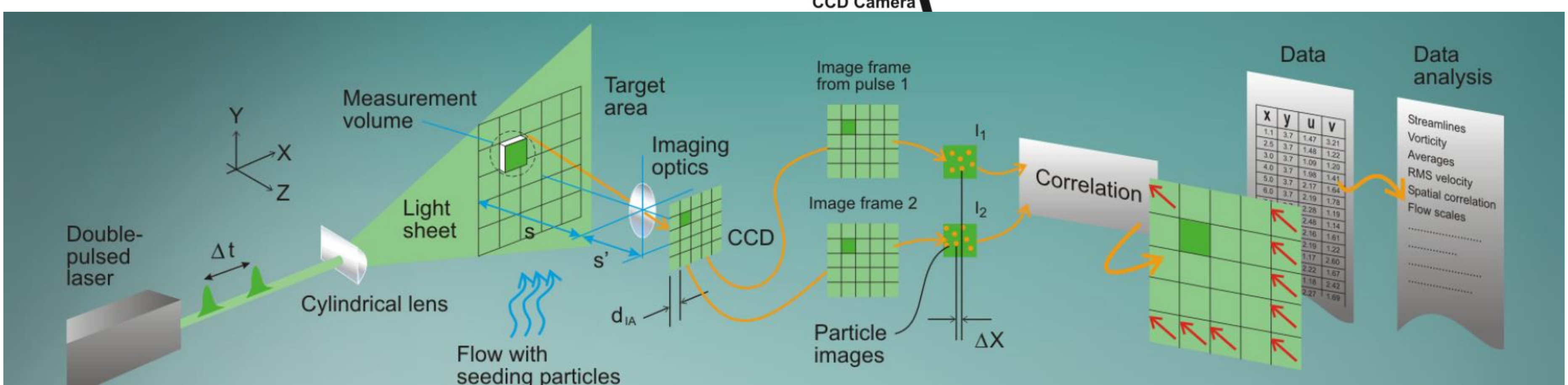


Convective motions take place and control the sedimentation in the lower layer. Fingers are still present

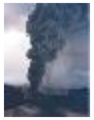
Manzella et al. (submitted)

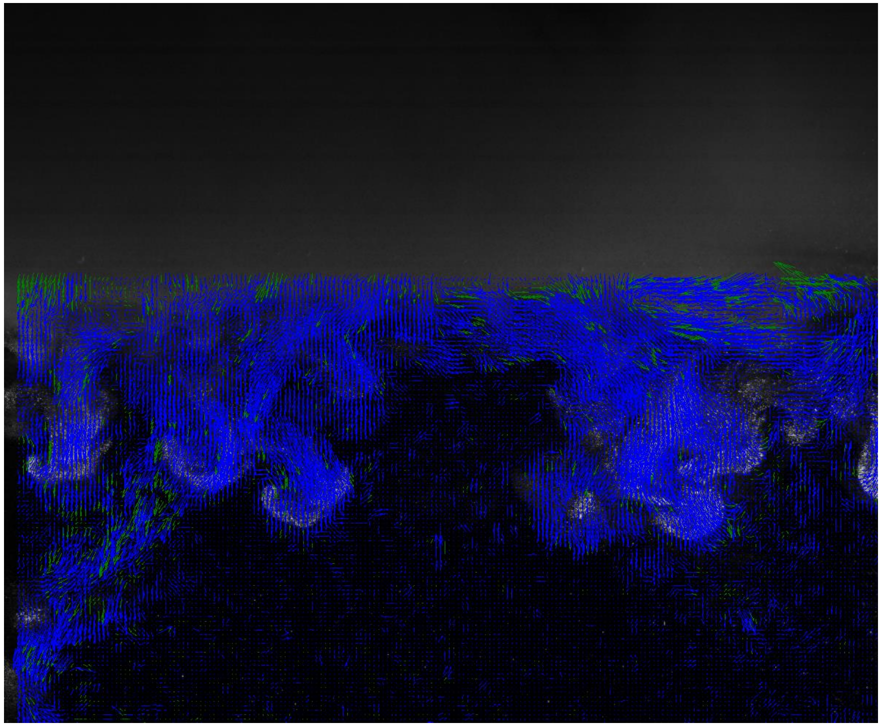
Fingers in the lab with PIV





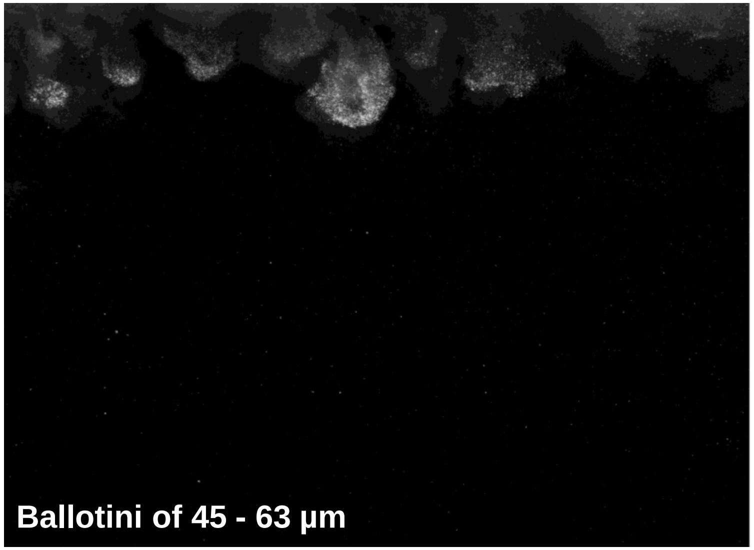
Settling-driven convection: experiments



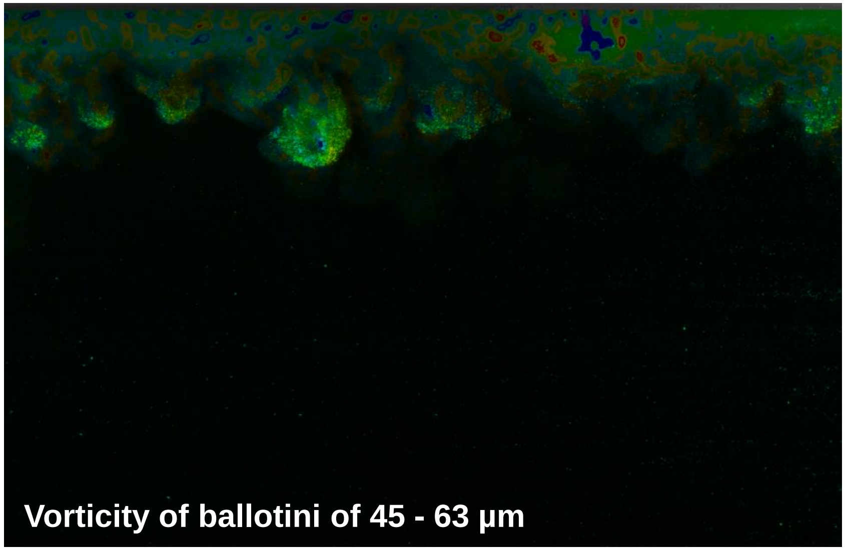


Scollo et al. (in prep.)

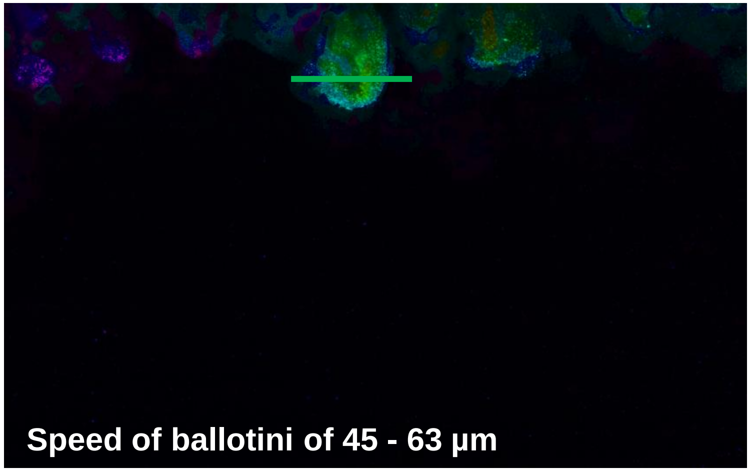
Settling-driven convection: experiments



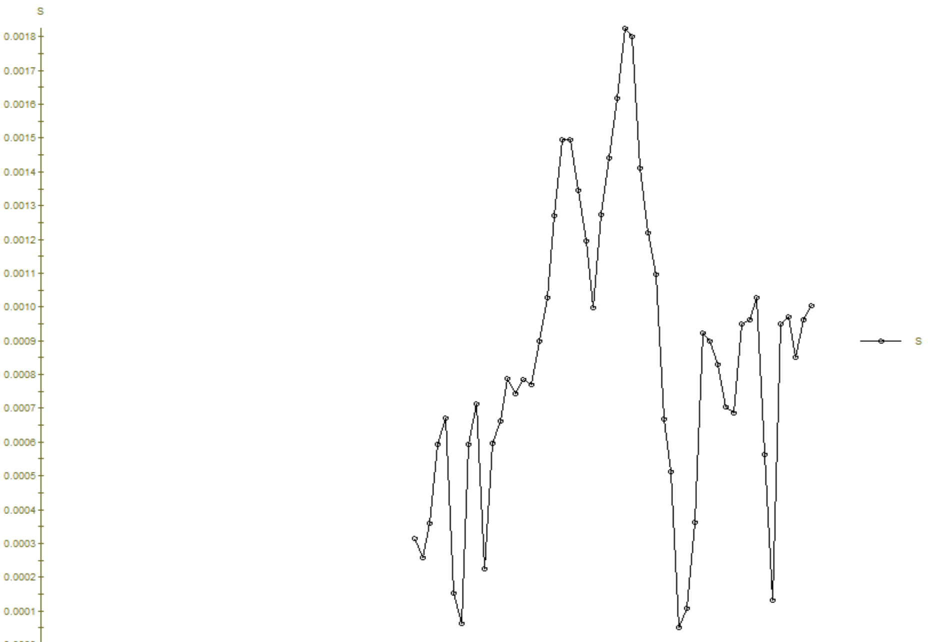
Ballotini of 45 - 63 µm



Vorticity of ballotini of 45 - 63 µm



Speed of ballotini of 45 - 63 µm



Scollo et al. (in prep.)

TAKE-HOME POINTS

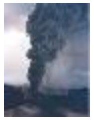
Volcanic eruption columns are intense turbulent plumes that develop from explosive volcanic eruptions
→ strong vs weak plumes, buoyancy-driven intrusion vs turbulent diffusion

Various regimes of tephra fallout → control deposit thinning

Various size-selective sedimentation processes exist that enhance sedimentation of fine ash (<63 μm)
→ particle aggregation, settling-driven convection

THANKS!



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