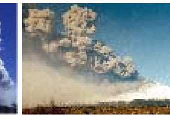
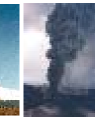


UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Volcanic Plumes

Costanza Bonadonna

Université de Genève

WMO/IAGOS Technical Experts Workshop on Requirements of In□Service Aircraft Aerosol Measurement Systems
Geneva, 22-24 March 2011

WMO IAGOS

OUTLINE

- **Overview of volcanic activity**
- **Volcanic gas**
- **Dynamics of volcanic plumes**
- **Sedimentation from volcanic plumes**
- **Case study: 2010 eruption of Eyjafjallajökull volcano, Iceland**

Acknowledgements: Mathieu Gouhier, Marco Pistolesi, Raffaello Cioni, Armann Hoskuldsson, Riccardo Genco, Maurizio Ripepe

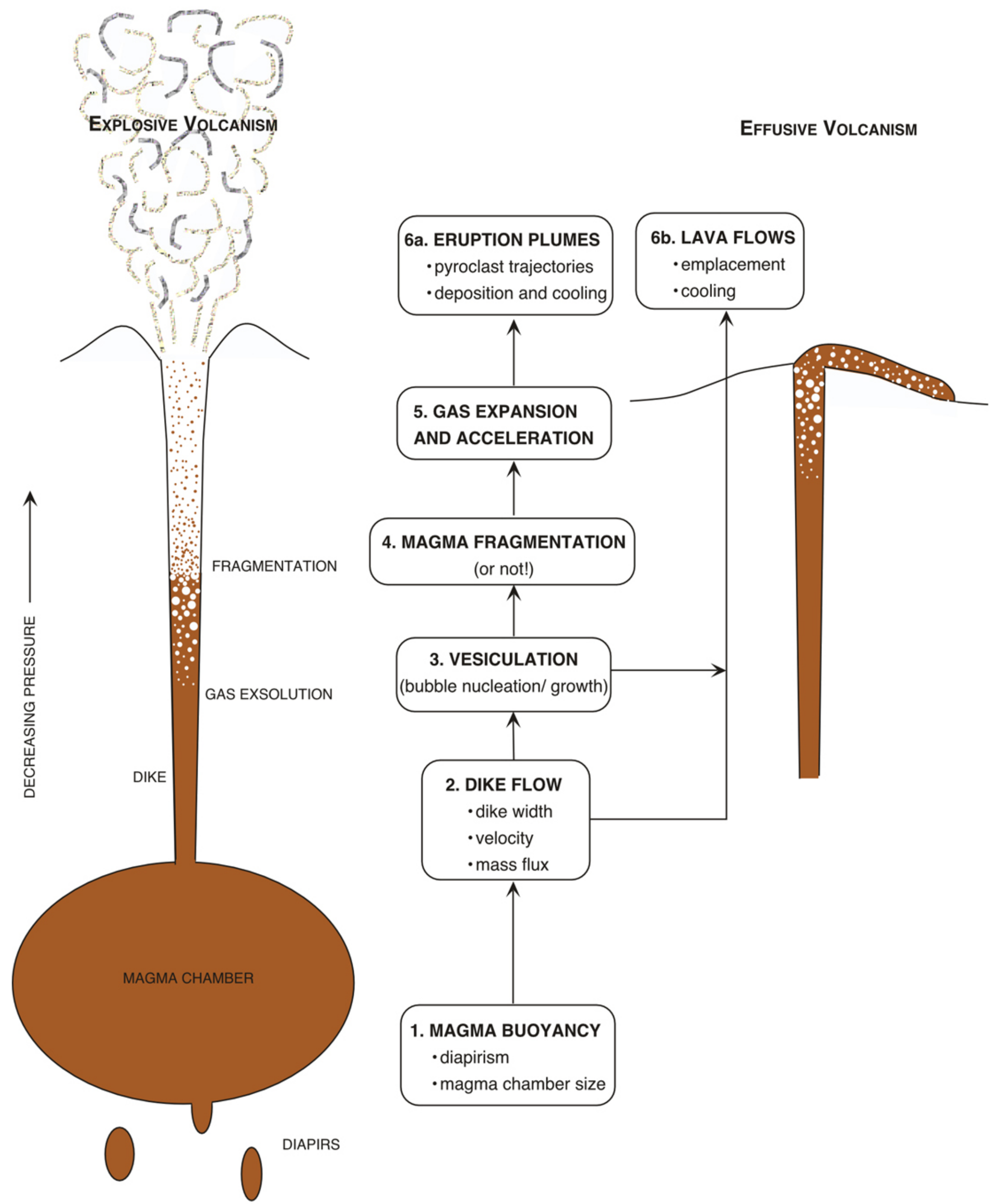
Broad Overview of Volcanic Activity

- Solubility of gas is pressure-dependent. As ambient P drops during ascent, gas exsolves and bubbles nucleate and grow → vesiculation

- Bubbles grow by diffusion, collision/coalescence, and decompression
  - Relative roles depend on magma viscosity, ascent rate, bubble size population

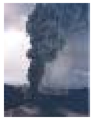
- When fragmentation criteria are met, fragmentation occurs

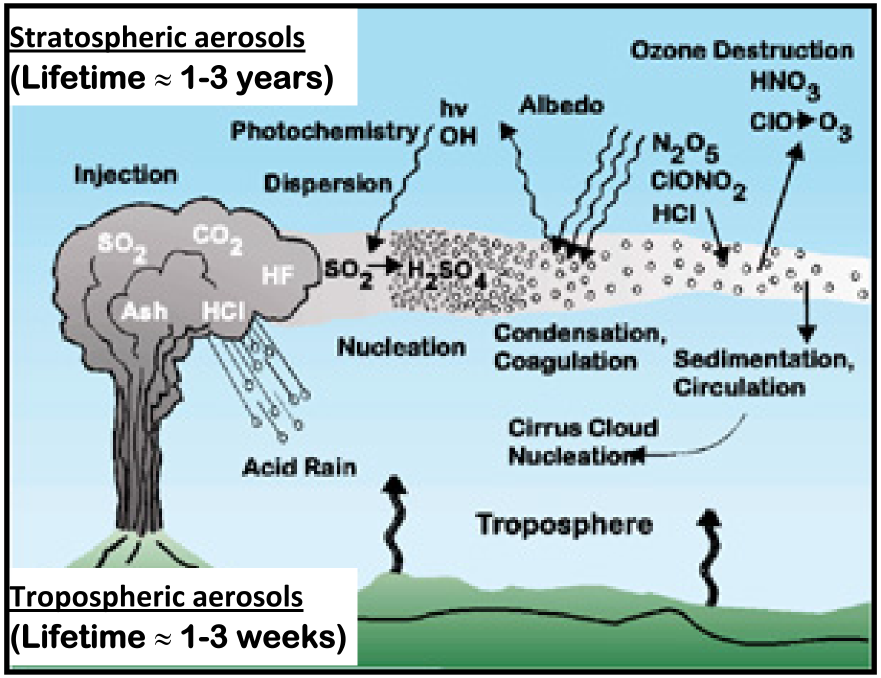
- Expanding gas phase accelerates fragmented magma out of the vent



Volcanic Gas





Most abundant gas:

- **water vapor (H_20)**
- **carbon dioxide ($C0_2$)**
- **sulfur dioxide ($S0_2$)**
- **hydrogen sulfide (H_2S), hydrogen (H_2), carbon monoxide (CO), hydrogen chloride (HCL), hydrogen fluoride (HF), and helium (He)**

e.g., Eyja 2010: 80% H_20, 15% $C0_2$, <3% $S0_2$

$S0_2$ → global cooling, ozone destruction, and polluted air (vog)

(<20 to >10 million tonnes/day)
e.g., Pinatubo 1991: ~20 million tonnes
Kilauea 2002-2006: ~2000 tonnes/day
Eyjafjallajökull 2010: ~3000 tonnes/day

→ conversion of sulfur dioxide (SO_2) to sulfuric acid (H_2SO_4) → SULFATE AREOSOL

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Atmospheric "effectiveness"

Several factors combine to determine injection into the atmosphere

Pinatubo 1991, Indonesia

1. Eruption style

Explosive vs Effusive eruptions

2. Magma volume & chemistry

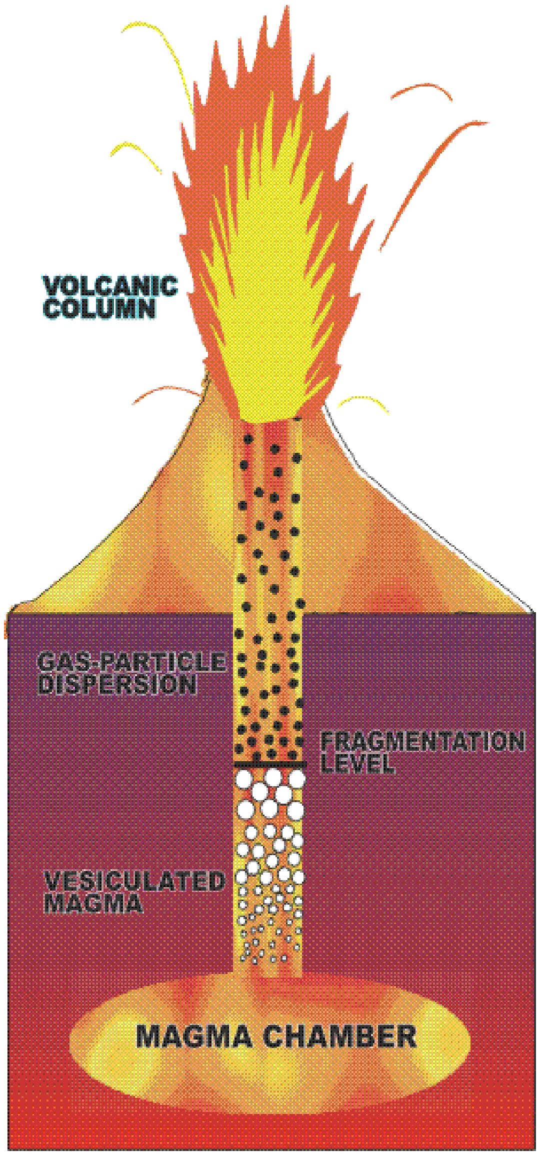
Large eruptions of sulphur-poor magma are less significant than sulfur-rich magmas;
e.g. Mt St Helens - sulfur poor - negligible global effects

3. Latitude

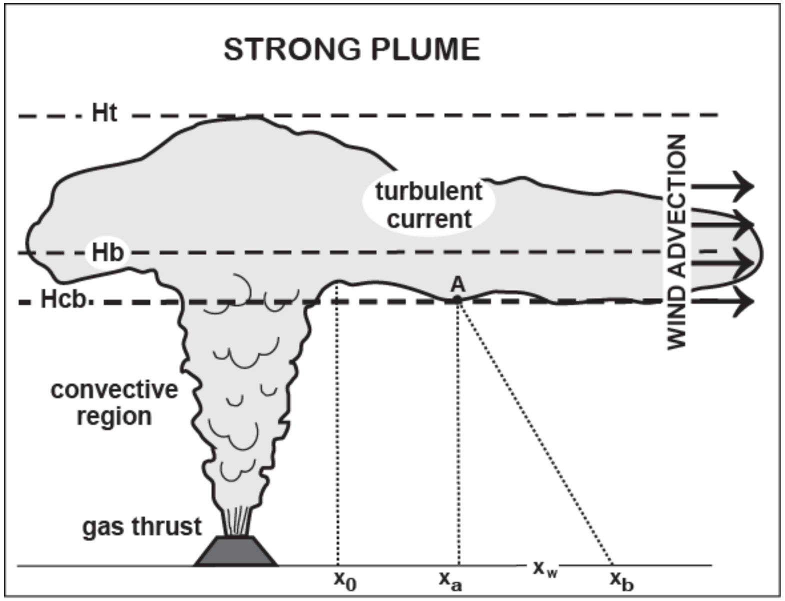
Proximity to the stratosphere: smaller eruptions at high latitude can inject as much SO_2 into the stratosphere as larger eruptions at lower latitudes

Stratospheric dispersal: Aerosols from tropical eruptions have the potential to spread around the globe (e.g., Pinatubo 1991). Atmospheric influence of eruption outside the tropics is contained within the middle and polar latitudes of the hemisphere of origin

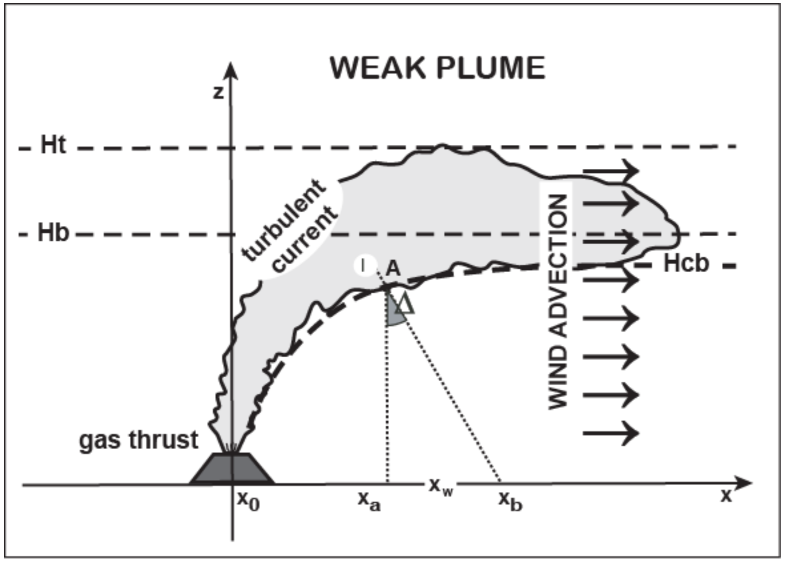
Explosive volcanism



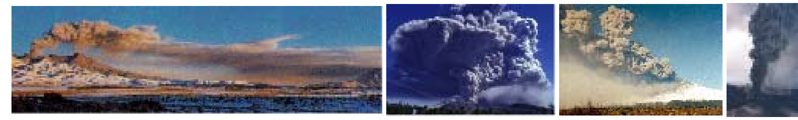
Wind speed < 20 m s^{-1}

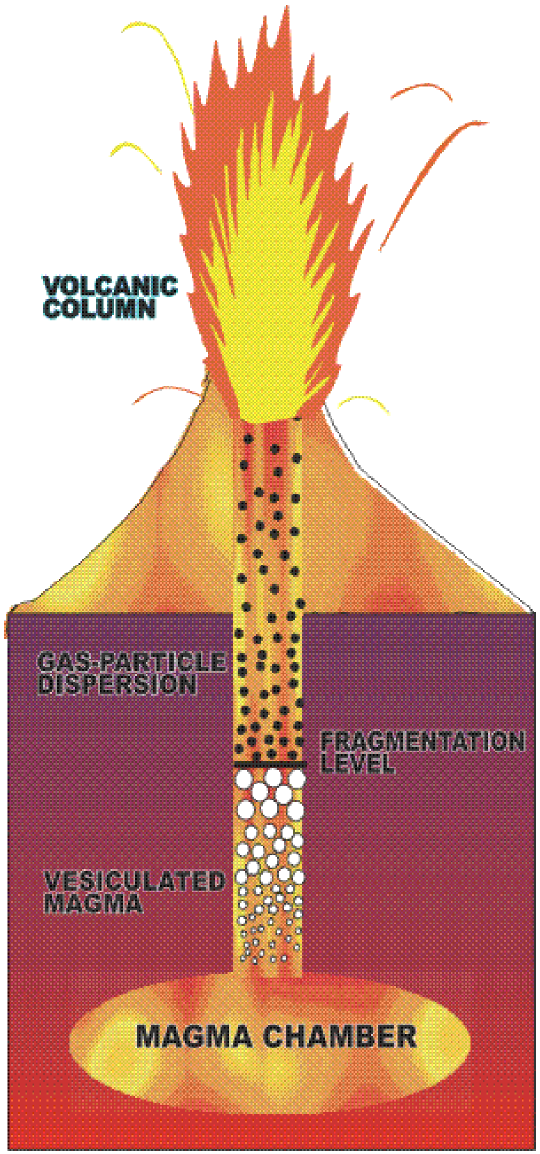


Wind speed > 20 m s^{-1}



Explosive volcanism

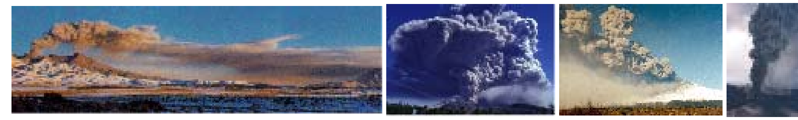


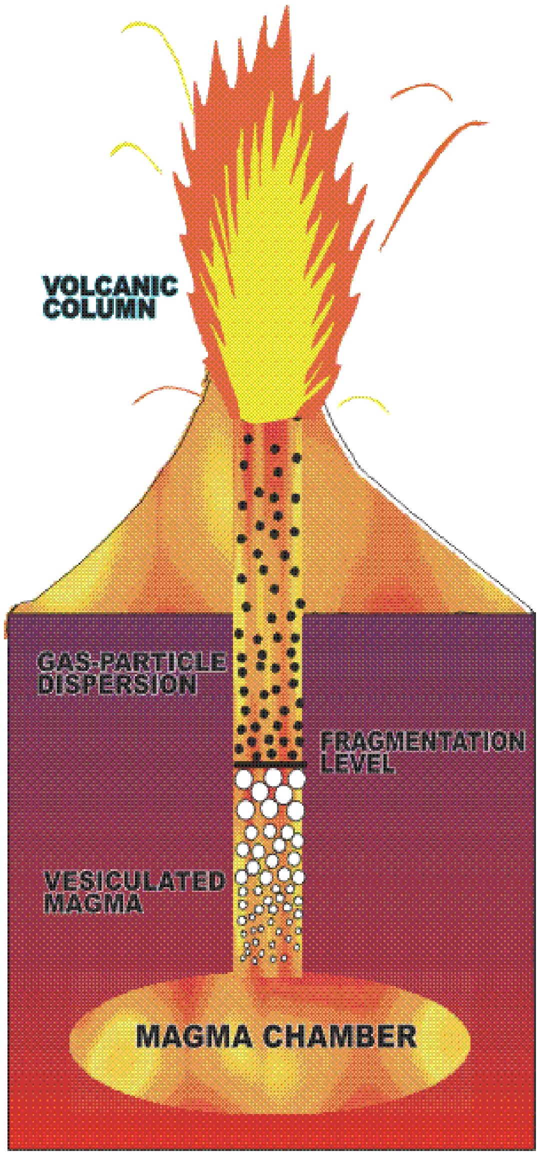


Wind speed < 20 m s^{-1}

Wind speed > 20 m s^{-1}

Explosive volcanism

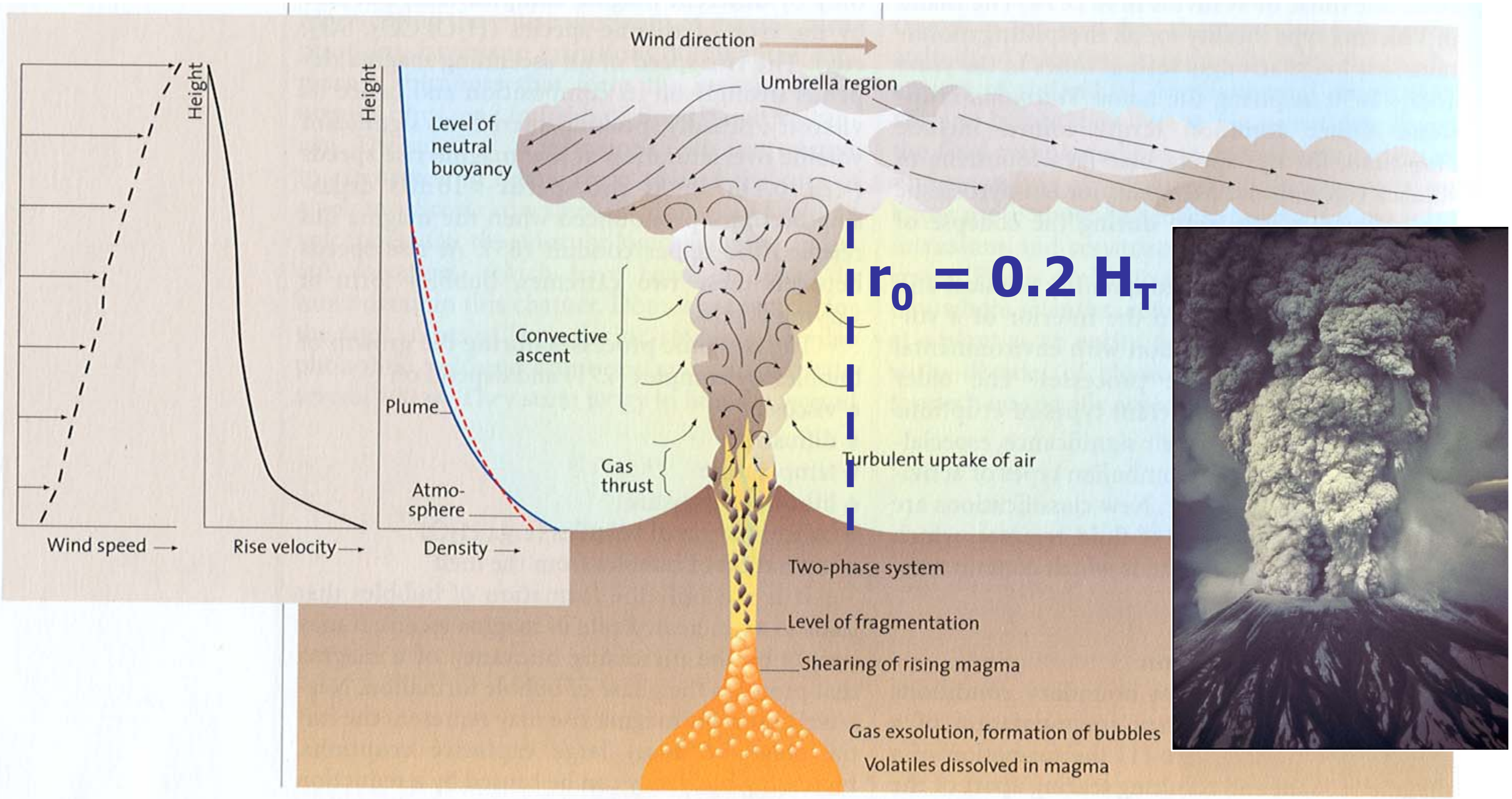




Wind speed < 20 m s^{-1}

Wind speed > 20 m s^{-1}

Strong plumes: Plinian style explosive eruptions



Column height: <45 km
Initial velocities: <400 m/s
Duration: minutes – hours - days
Characteristic features: sustained, high columns, ~ **steady**
Typical solid mass: $10^{11} – 10^{15}$ kg
Typical mass flow rate at vent: $10^{6} – 10^{9}$ kg s^{-1}

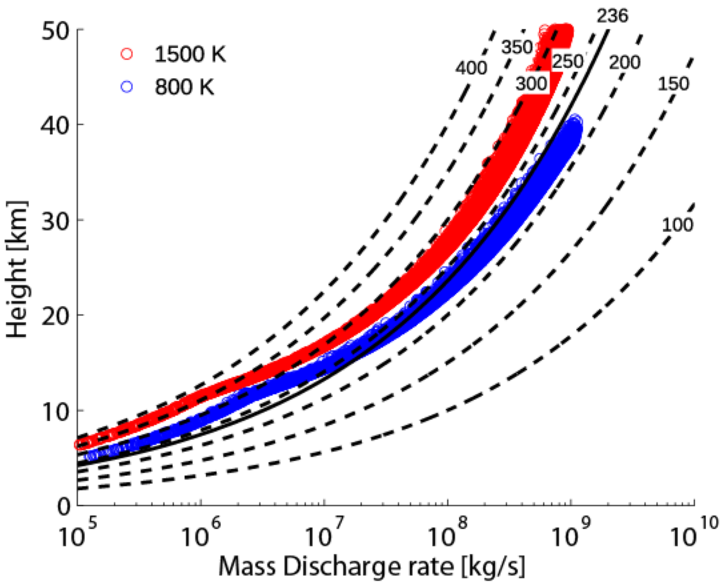
Steady eruption plumes: MASS DISCHARGE RATE

The final height is a function of the rate of release of energy, which is in turn related to the mass eruption rate

$Ht = 8.2\ Q^{0.25}$ → Q = volume flux ($m^3\ s^{-1}$) Wilson et al. 1978

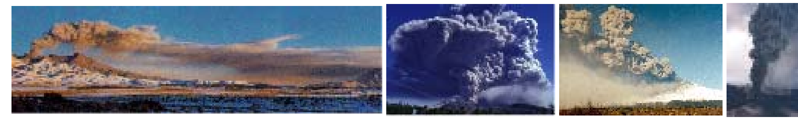
$Ht\ (km) = 0.236\ [MDR(Kg/s)]^{1/4}$ Wilson and Walker 1987

→ **(70% of tot magma heat is transferred to the cloud)**



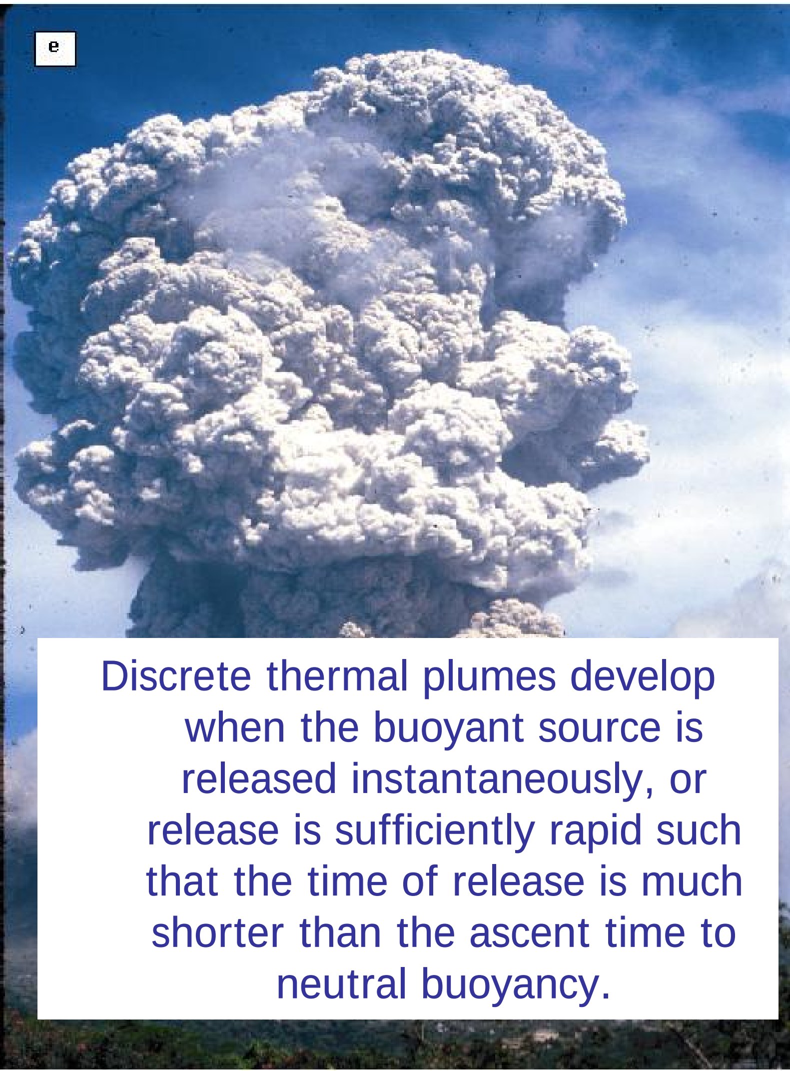
Woods 1988 vs Wilson and Walker 1987

→ **hotter plumes go higher for a same MER**



Discrete thermals

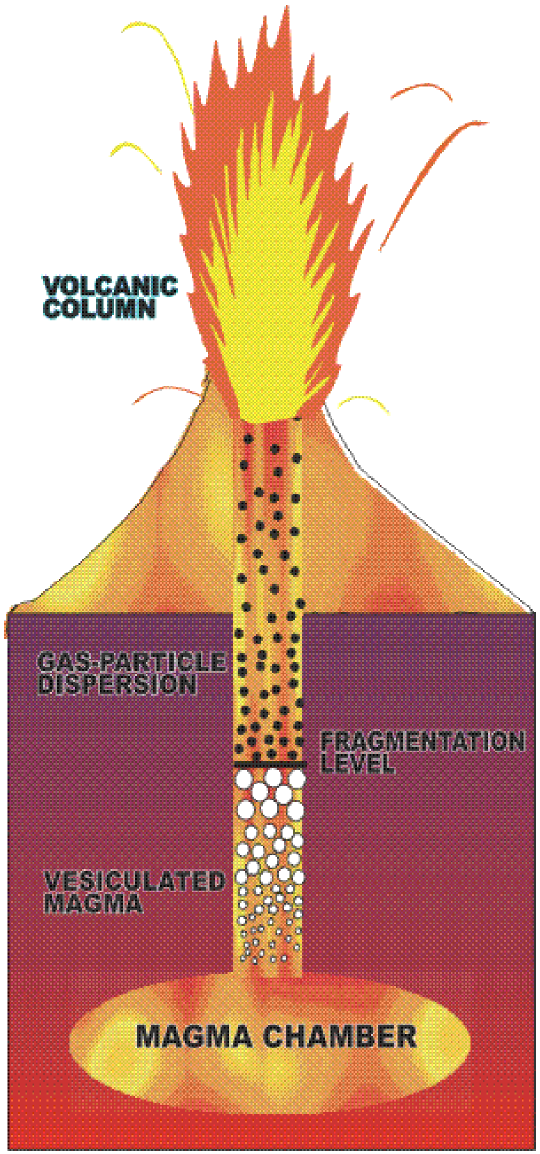
- Magma ascent and vesiculation do not keep up with fragmentation
- Vent conditions are **highly unsteady**, transient & short-lived
- Ejecta and explosion velocities on the order of 100’s of m/s
- Mass erupted for individual events is much less than for Plinian



Discrete thermal plumes develop when the buoyant source is released instantaneously, or release is sufficiently rapid such that the time of release is much shorter than the ascent time to neutral buoyancy.

$$Ht = \gamma\ [M]^{1/4}$$

Explosive volcanism

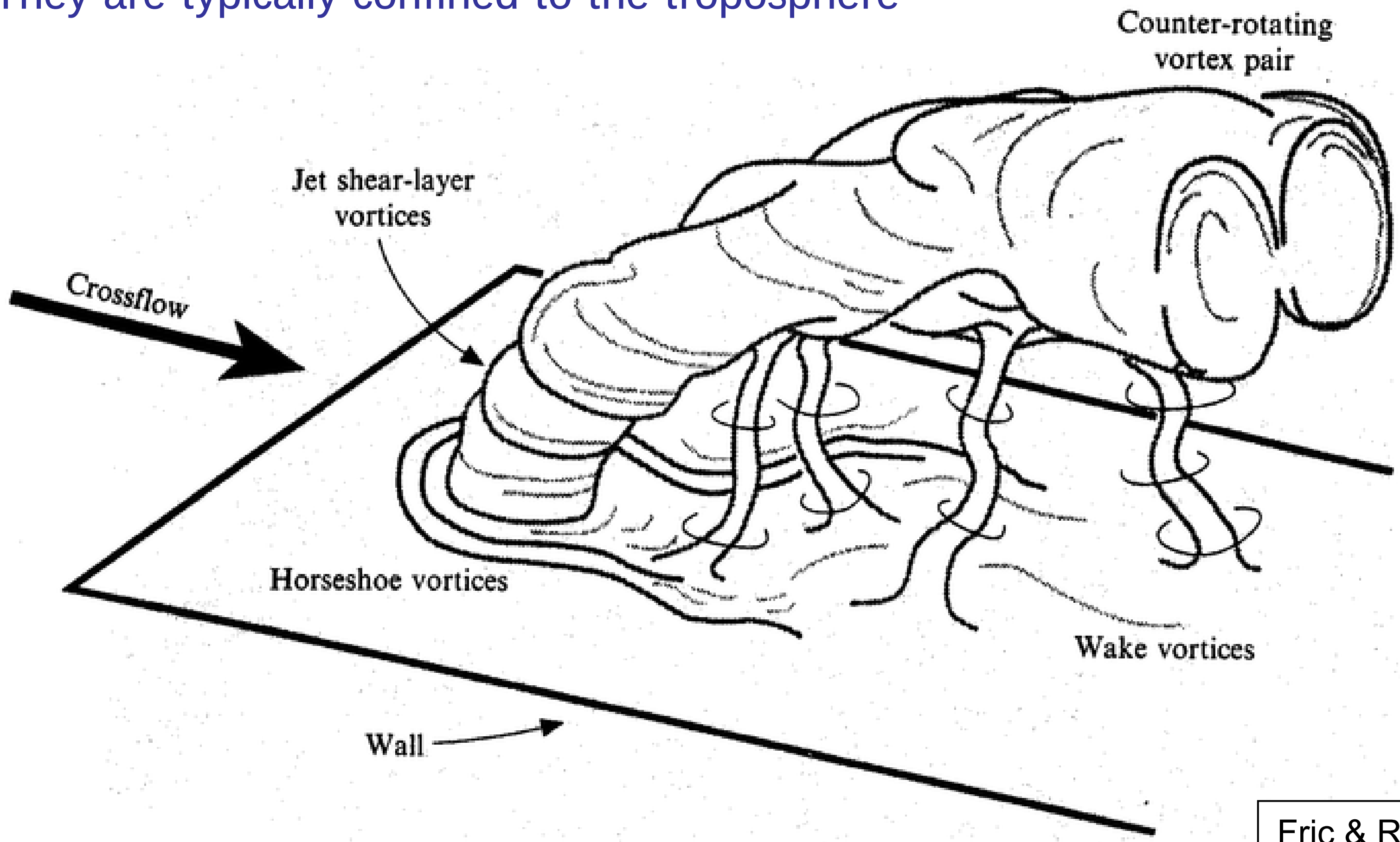


Wind speed < 20 m s^{-1}

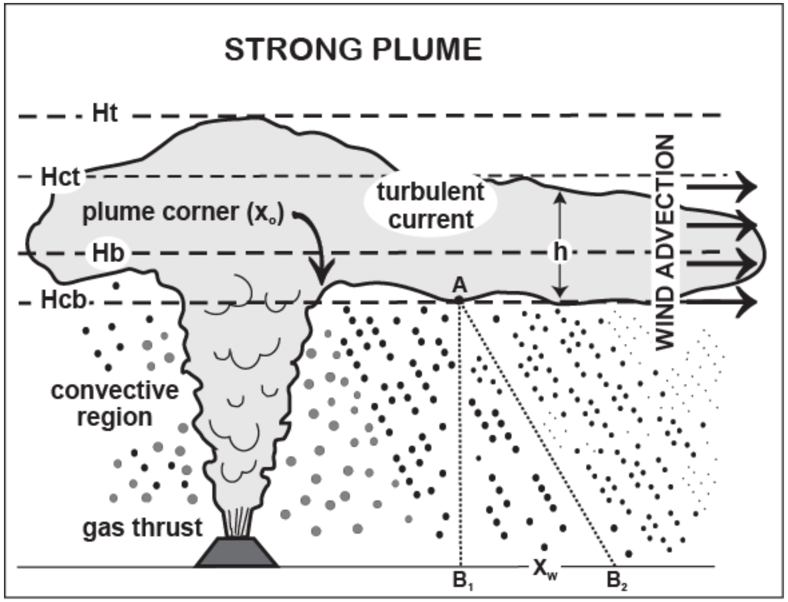
Wind speed > 20 m s^{-1}

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



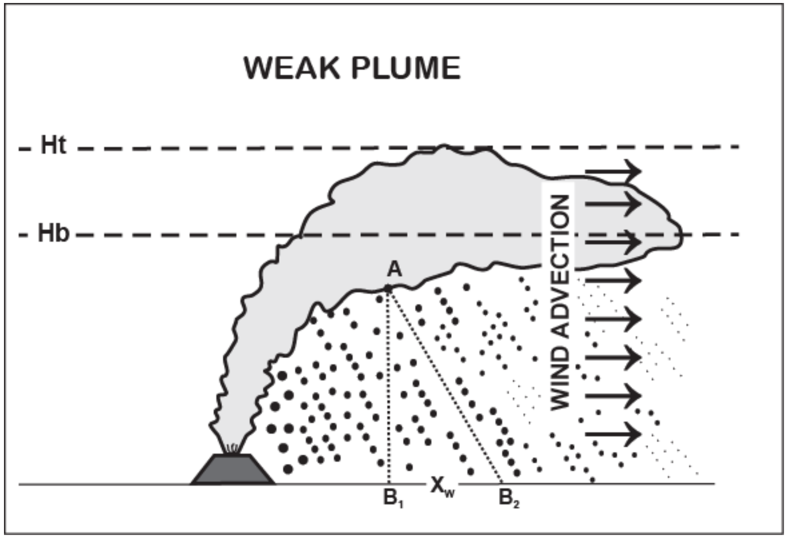
Fric & Roshko 1994



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

CLASS 2 → convective region (2-10cm). Typically <15km. $\mathbf{X_o = 0.2\ H_t}$

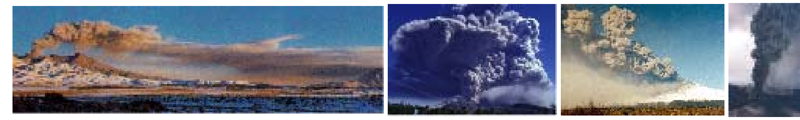
CLASS 3 → umbrella cloud (<2cm)

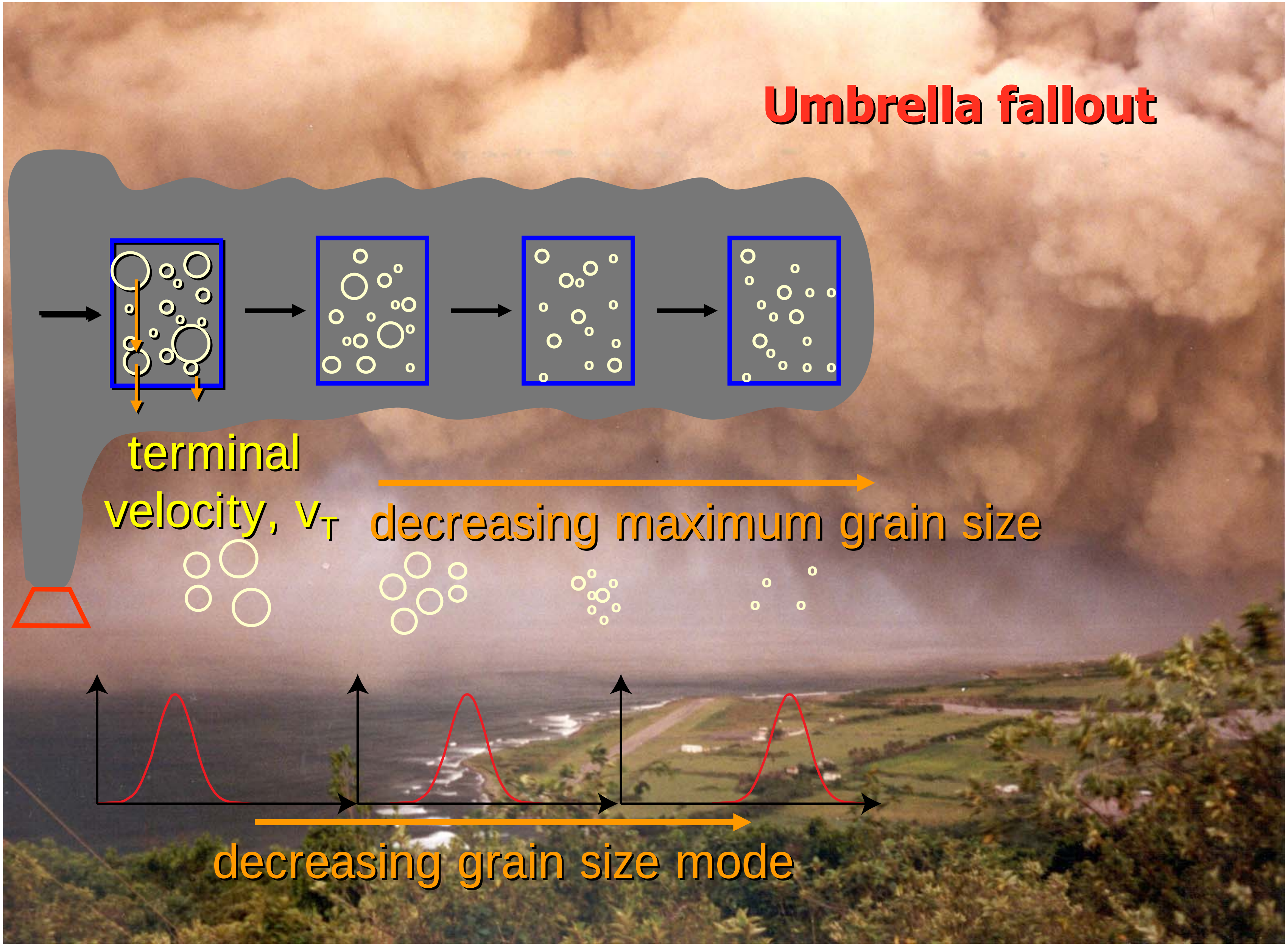


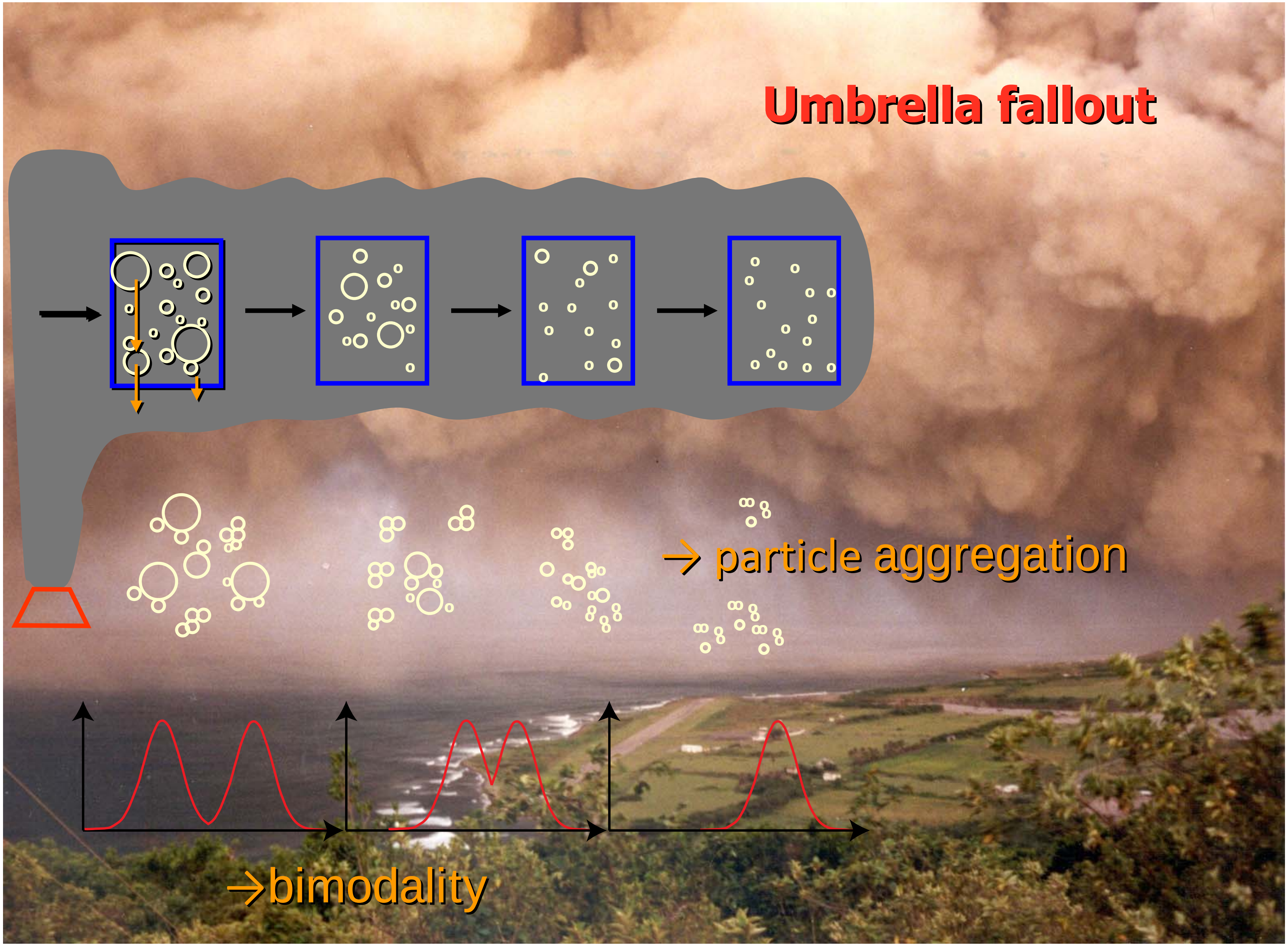
CLASS 1 → Blocks and bombs (>6cm). Typically <0.5km from vent.

CLASS 2 → bent-over region (0.1-6cm). Depends on plume energetics (e.g. Ruapehu 96: 30km from vent)

CLASS 3 → horizontal region (<0.1cm)

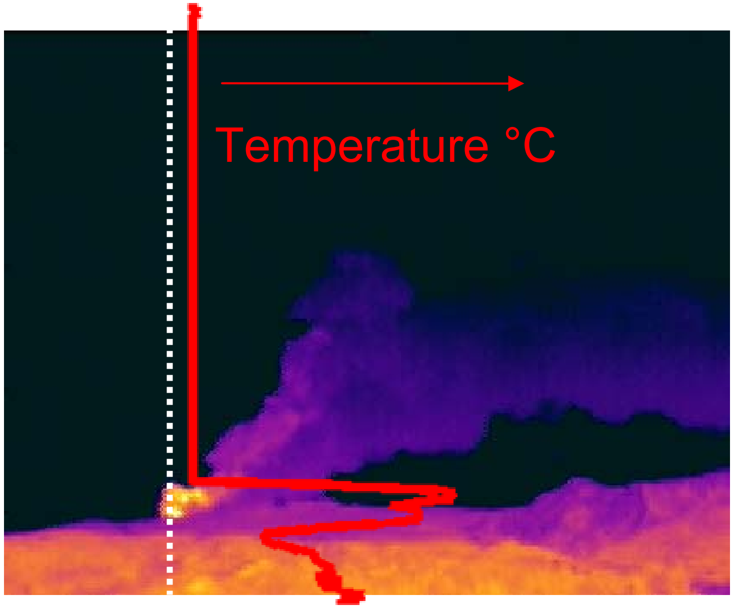


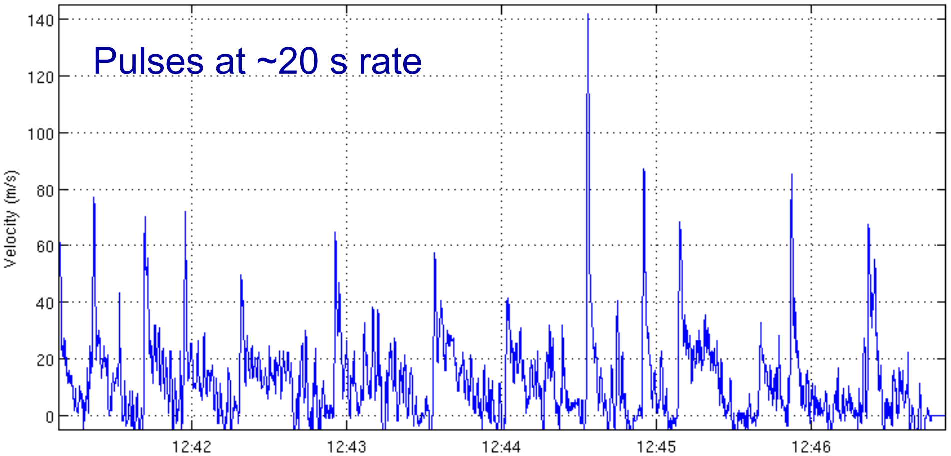

Umbrella fallout
terminal
velocity, v_T
decreasing maximum grain size
decreasing grain size mode

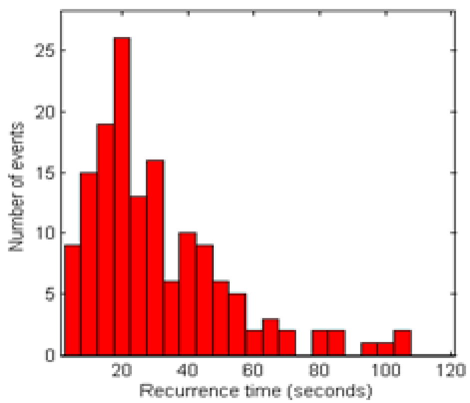

Umbrella fallout
→ particle aggregation
→bimodality

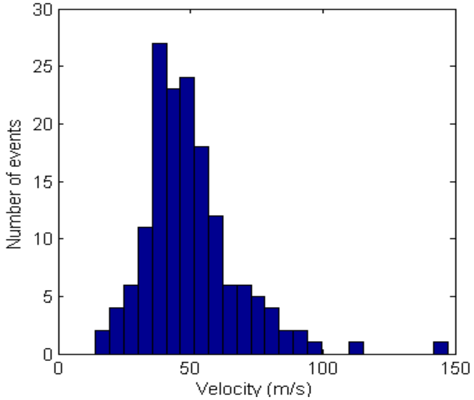
Thermally-derived plume velocity

- FLIR A-20 Uncooled Thermocamera
- 50 frames per second at 16 bits
- Distance from the vent ~ 8.2 km

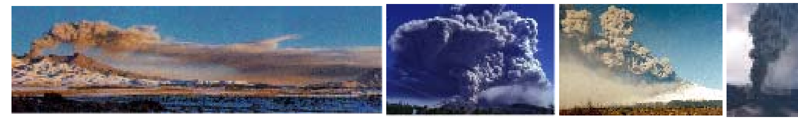


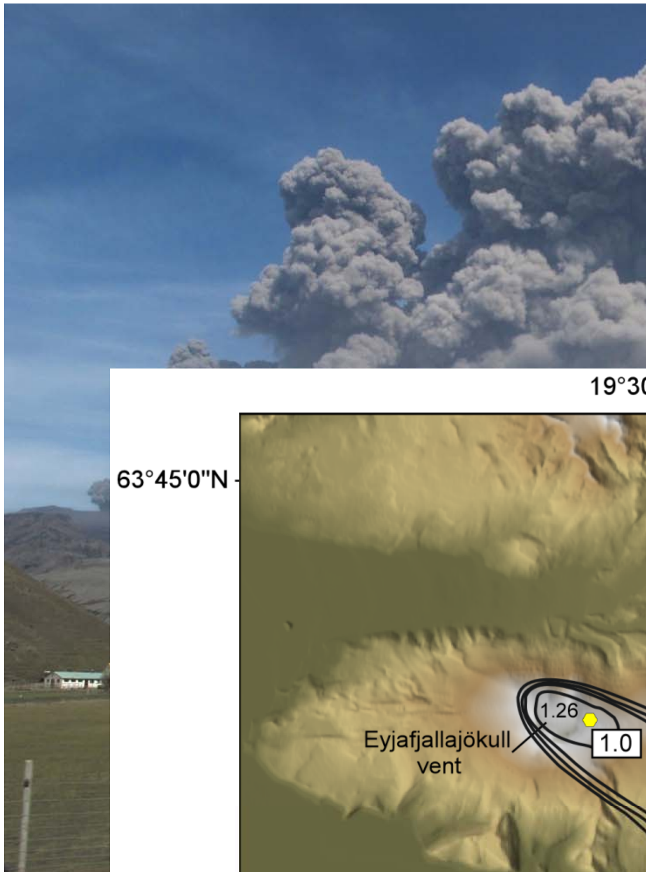


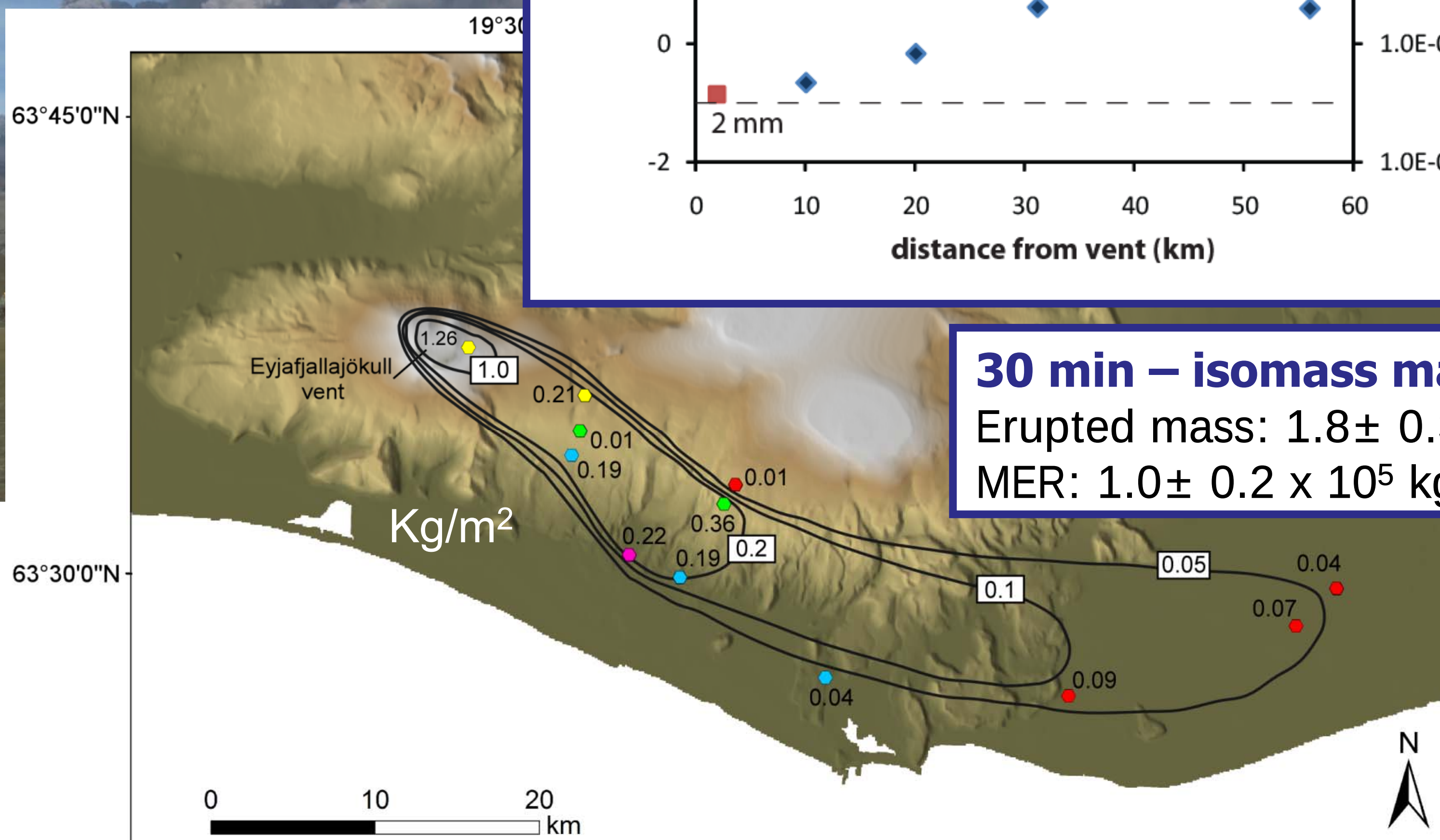


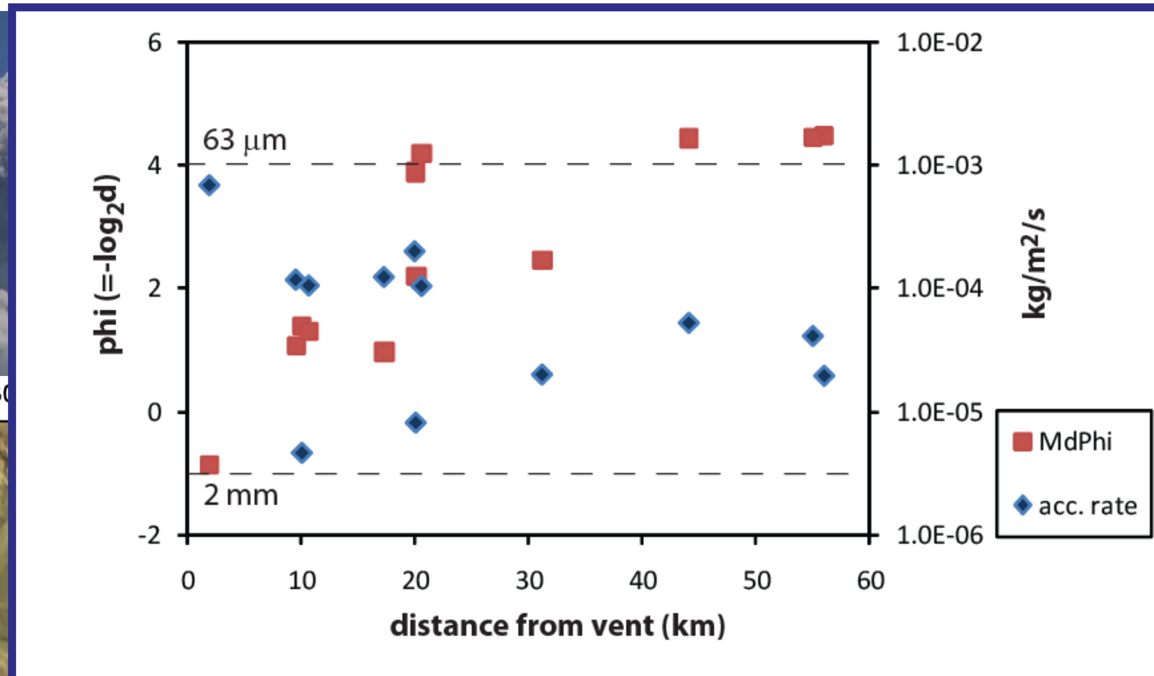


Sedimentation during the 2010 Eyjafjallajökull eruption









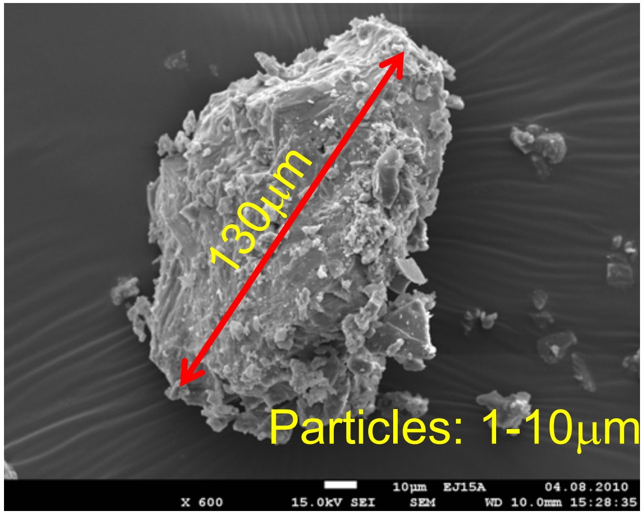
30 min – isomass map

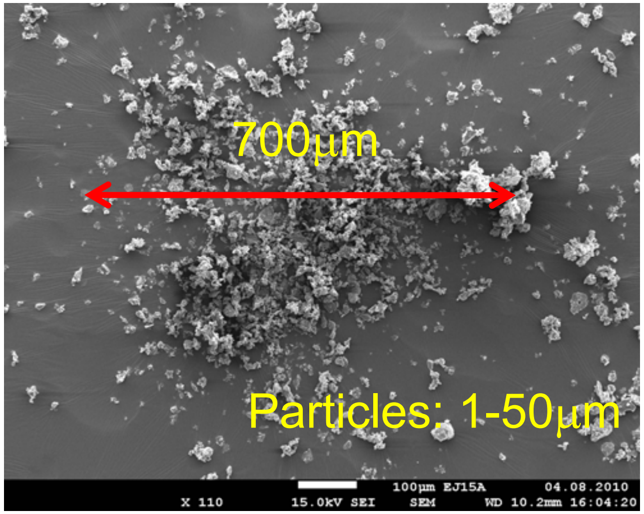
Erupted mass: $1.8 \pm 0.3 \times 10^8$ kg

MER: $1.0 \pm 0.2 \times 10^5$ kg s^{-1}

PARTICLE AGGREGATION

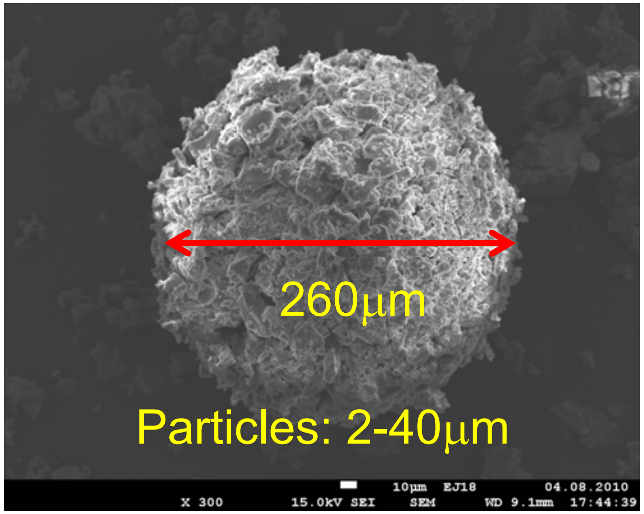
10 km, 5 May 2010

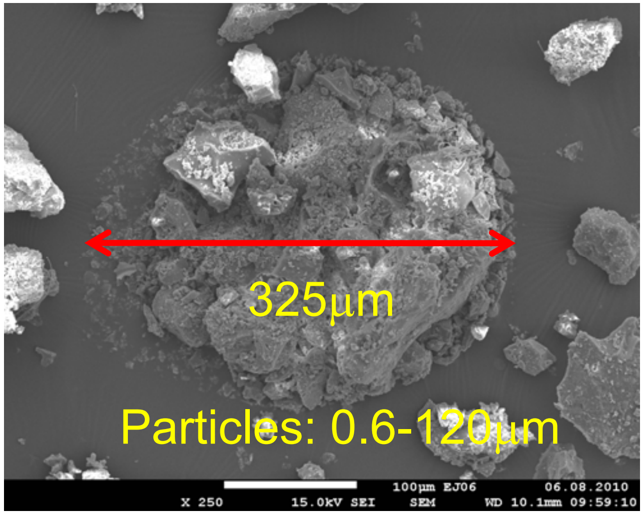




10 km, 5 May 2010

56 km, 6 May 2010

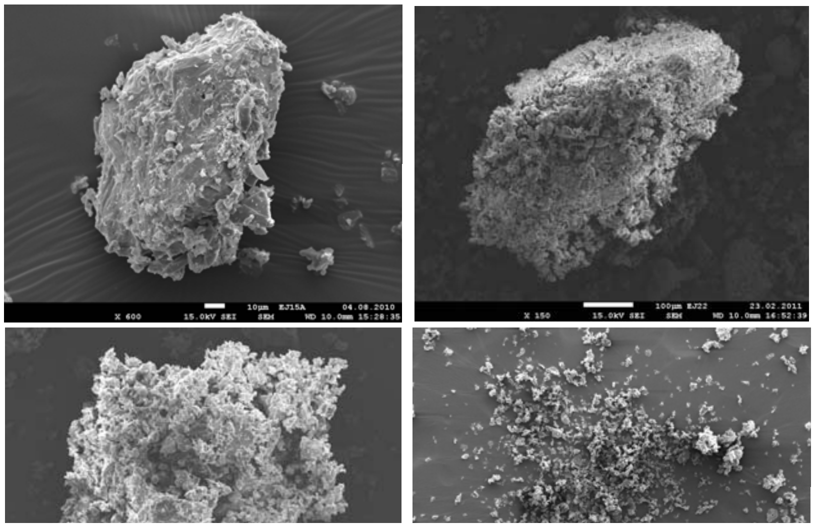


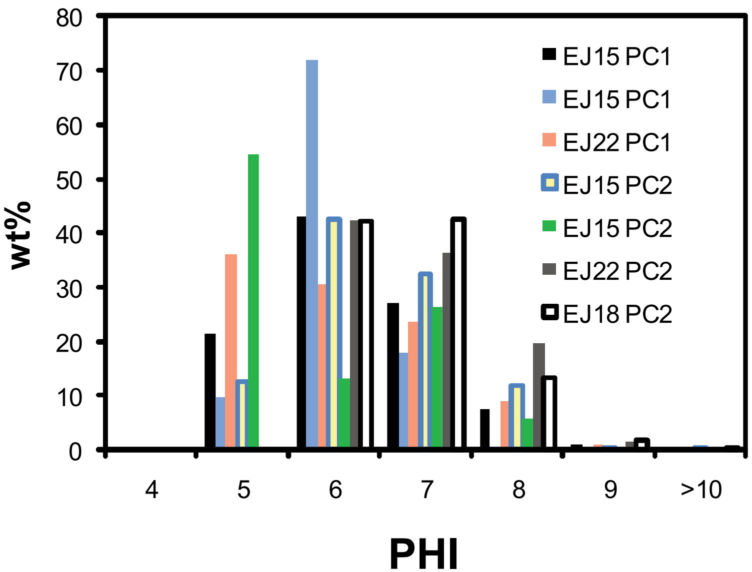


20 km, 4 May 2010

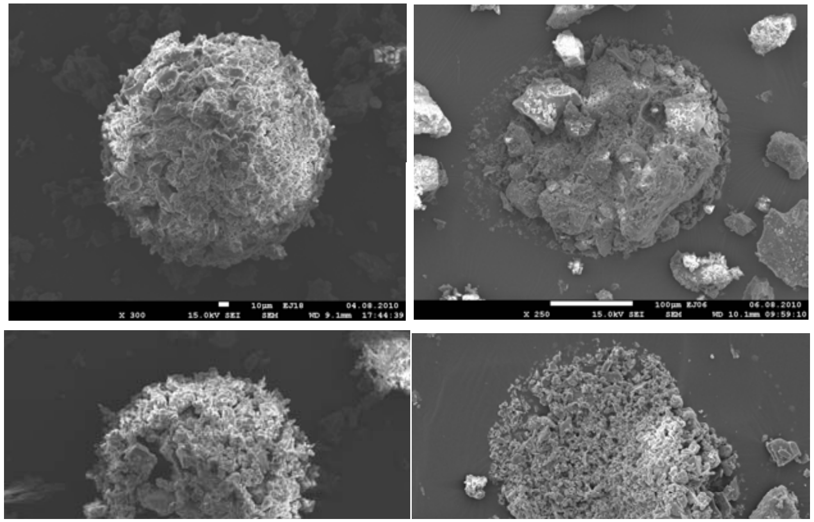
PARTICLE AGGREGATION

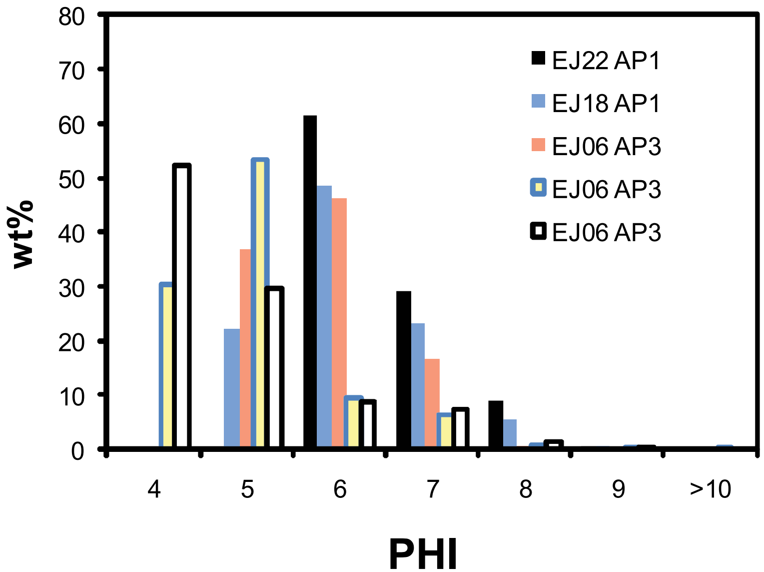
Particle clusters





Accretionary pellets

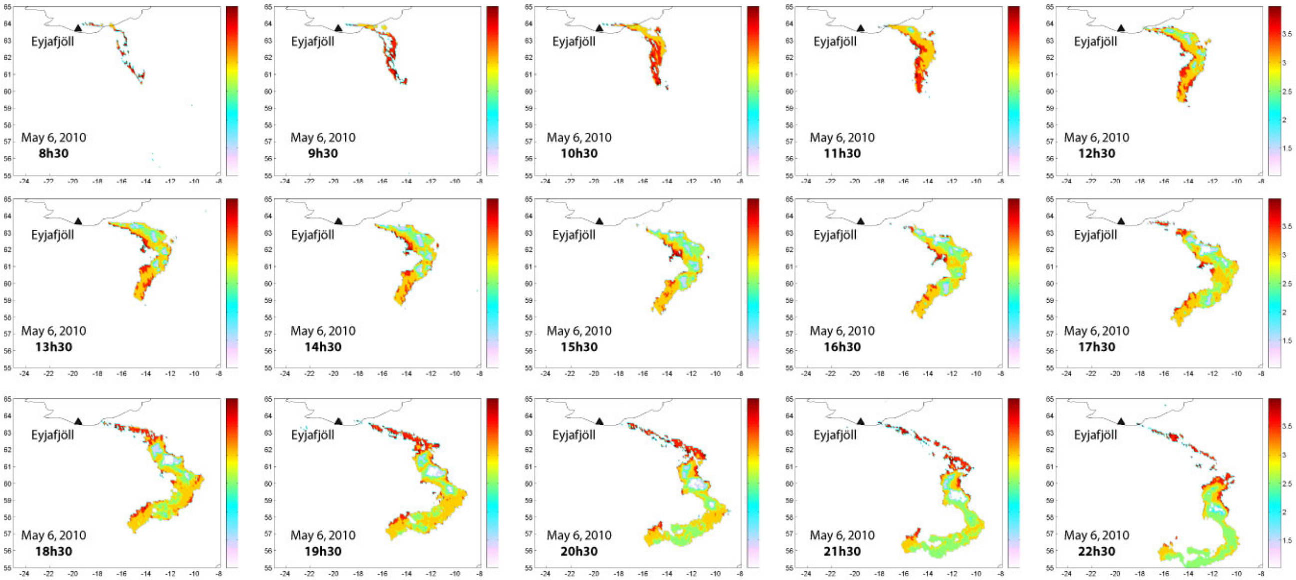


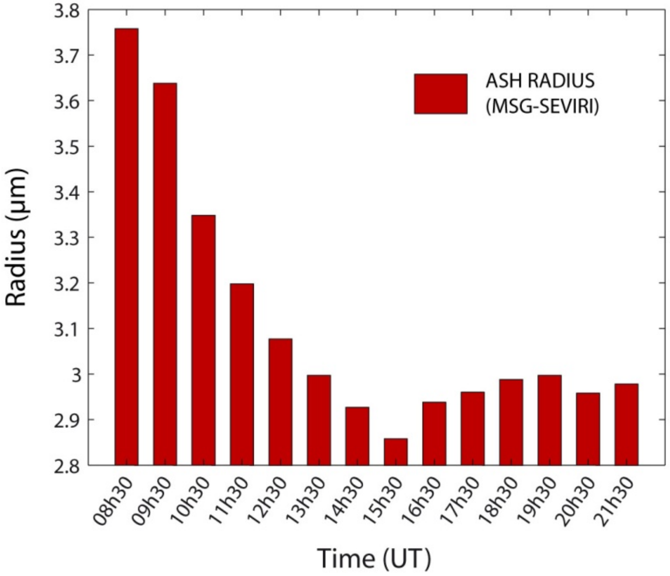


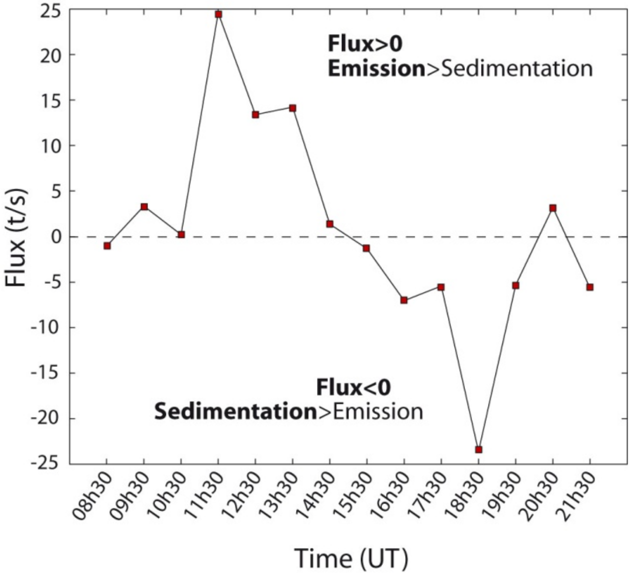
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Sedimentation during the 2010 Eyjafjallajökull eruption

6 May 2010, MSG-SEVIRI

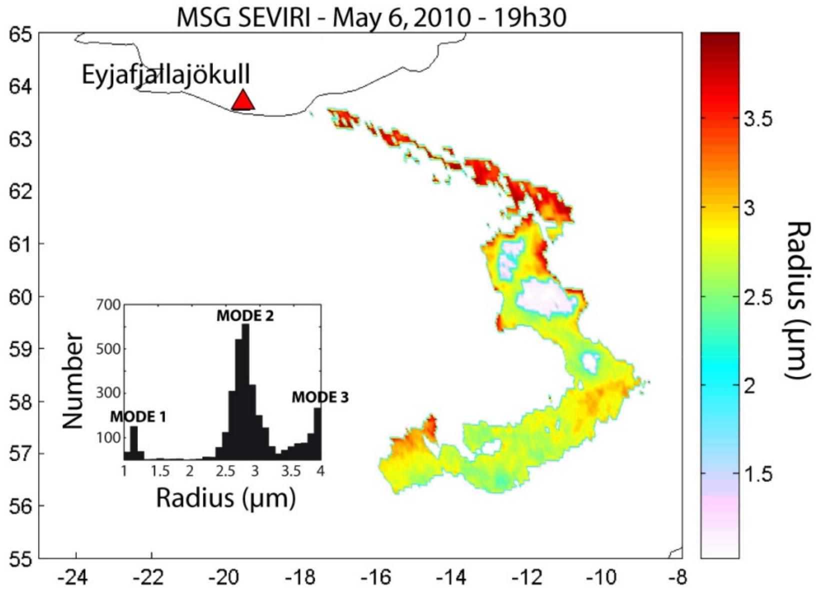


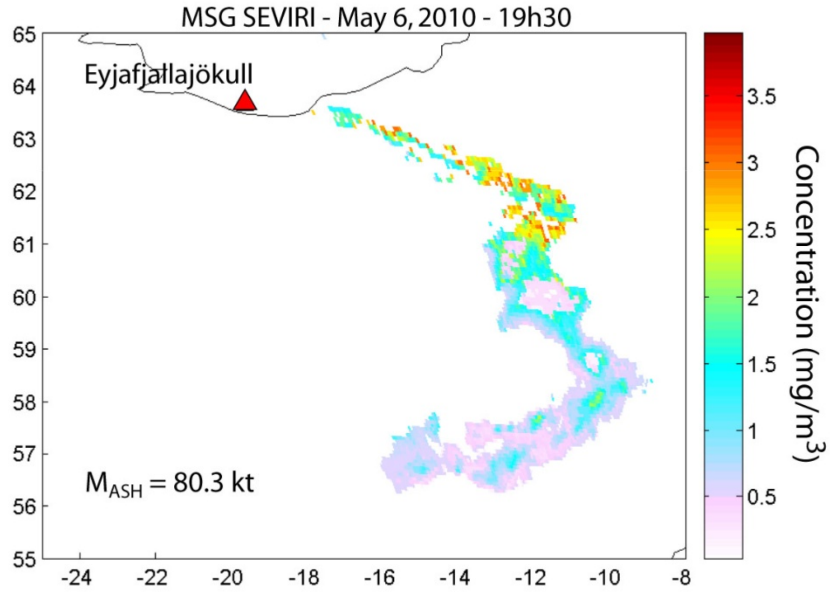


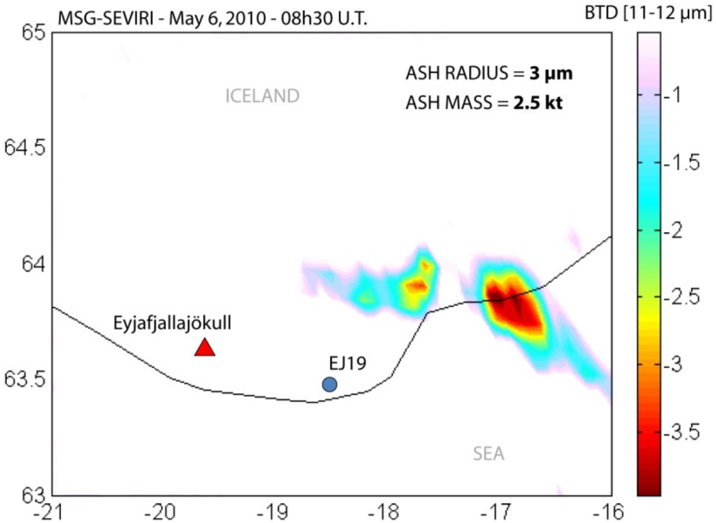


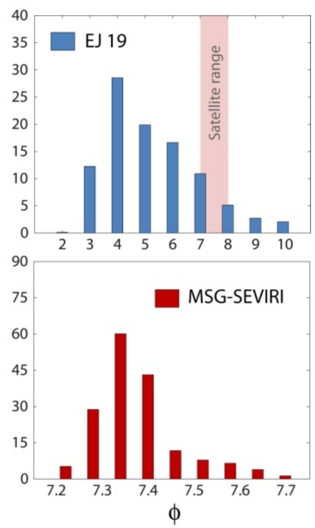
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

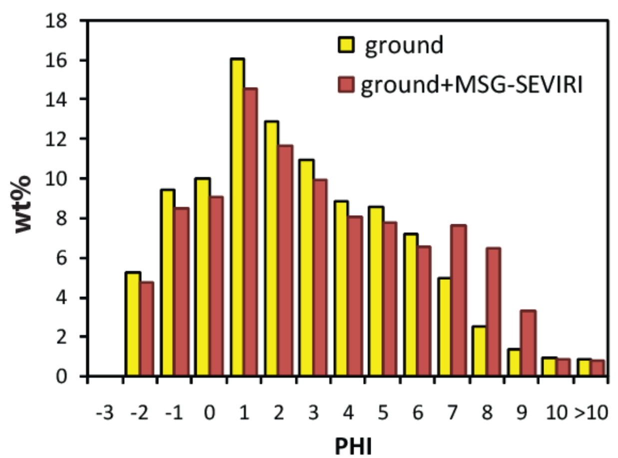
Sedimentation during the 2010 Eyjafjallajökull eruption











CONCLUSIONS

➢ Huge amounts of volcanic gas (mainly H_20, $C0_2$, $S0_2$), aerosol droplets, and ash are injected into the atmosphere depending on activity style, magma type and volume, latitude.

➢ Dynamics of volcanic plumes mainly depends on magma gas content, magma composition and interaction with the wind field.

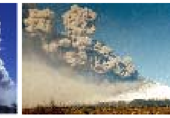
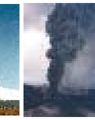
➢ Wide range of particle size in volcanic plumes (>1m to <1µm), but only particles <20mm (strong plumes) and <1mm (weak plumes) reach the horizontally spreading current.

➢ Residence time of small particles (<63 µm) in the horizontally spreading current is controlled by particle aggregation.

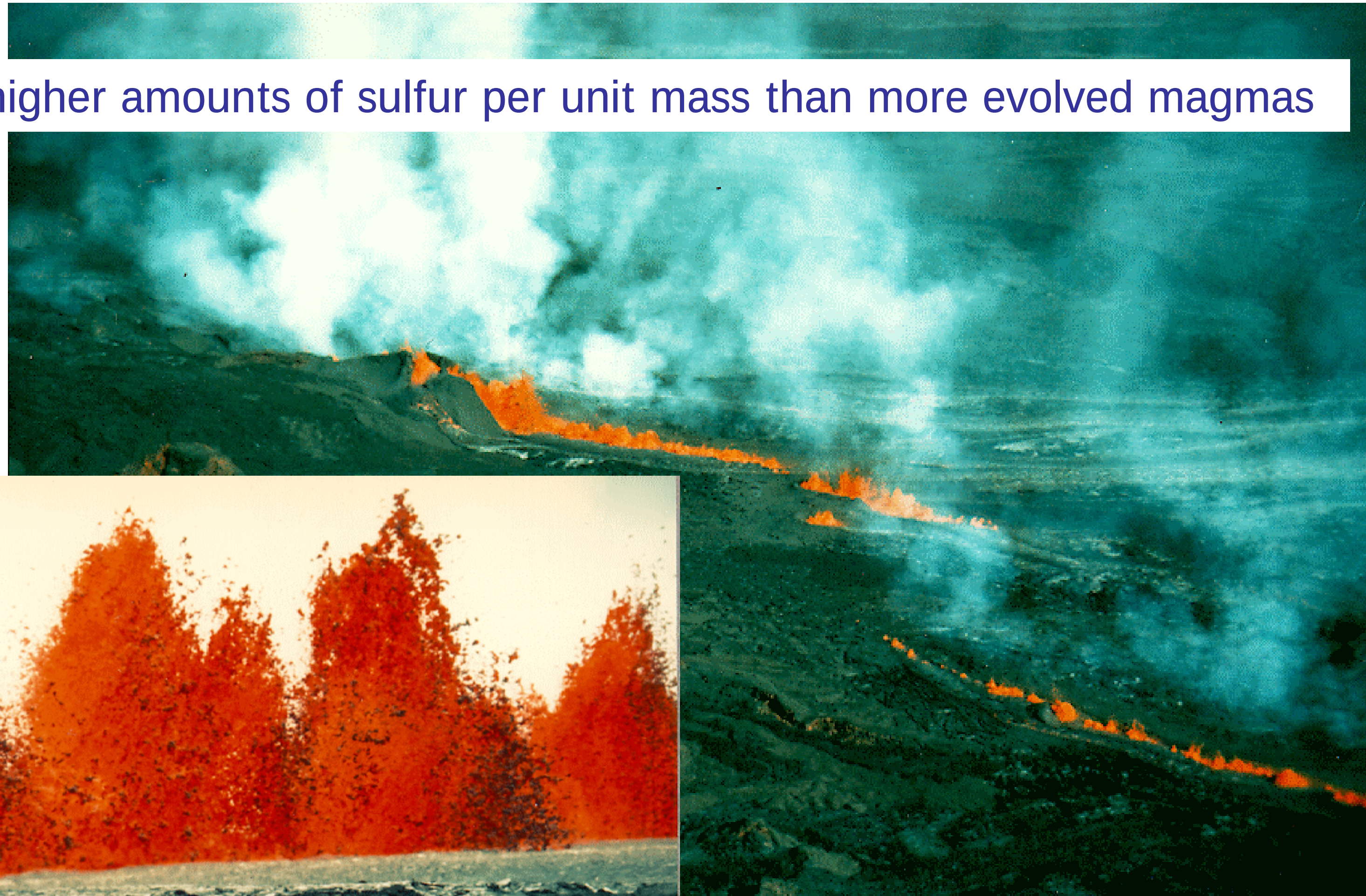
➢ Ground-based grainsize from the May 2010 Eyjafjallajökull eruption ranges between 8mm-0.1µm with a mode ~500 µm (between 2-56km). MSG-SEVIRI retrievals have revealed small particles (4-8 µm) in the Eyjafjallajökull cloud up to 1000 km.

➢ Ground-based grainsize distribution is time consuming. Space-based remote sensing retrievals provide real time grainsize information but for a limited size range.

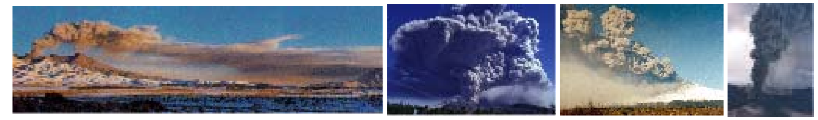


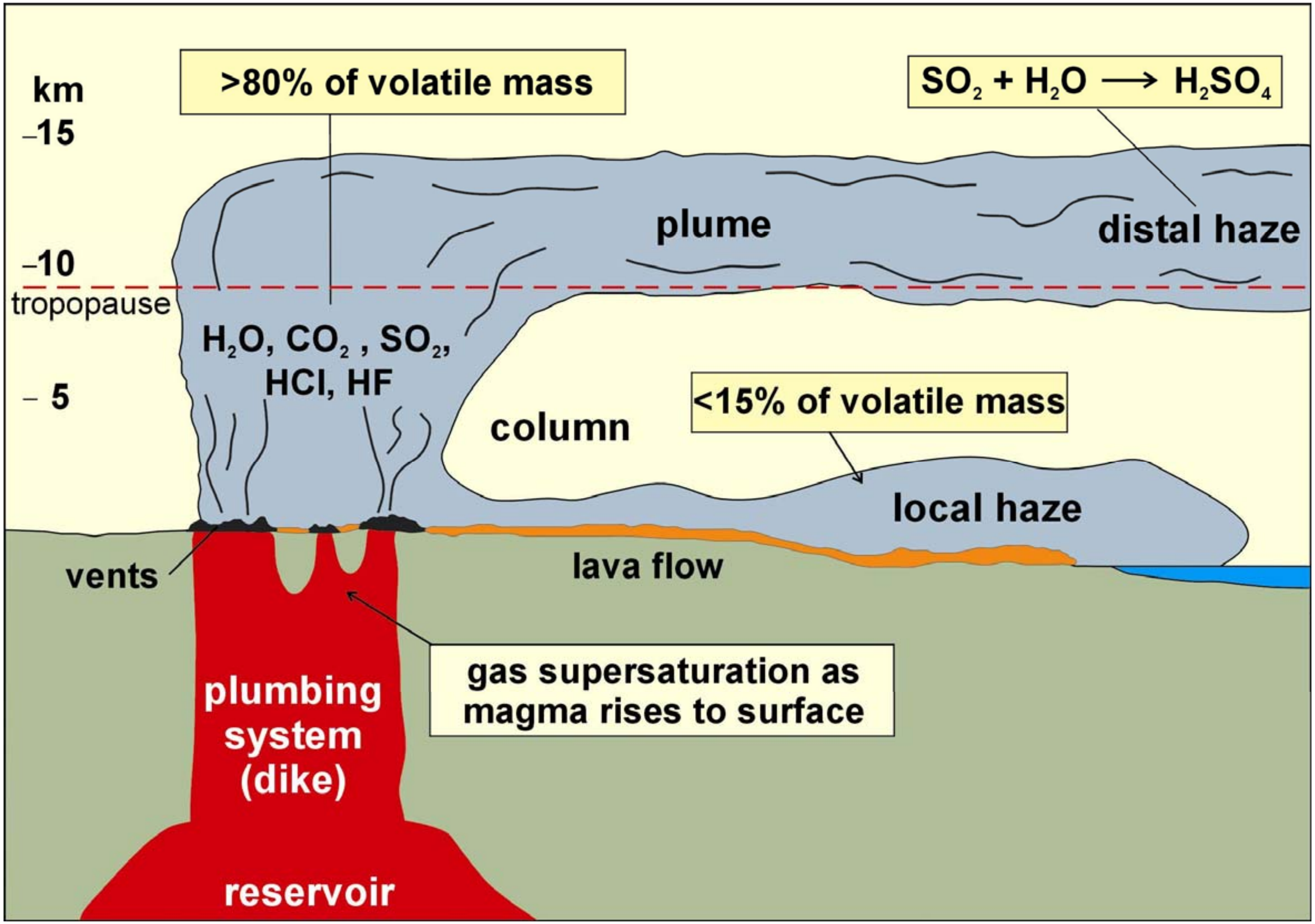



→ Basalts carry higher amounts of sulfur per unit mass than more evolved magmas



Fire fountains from Kilauea volcano in Hawaii



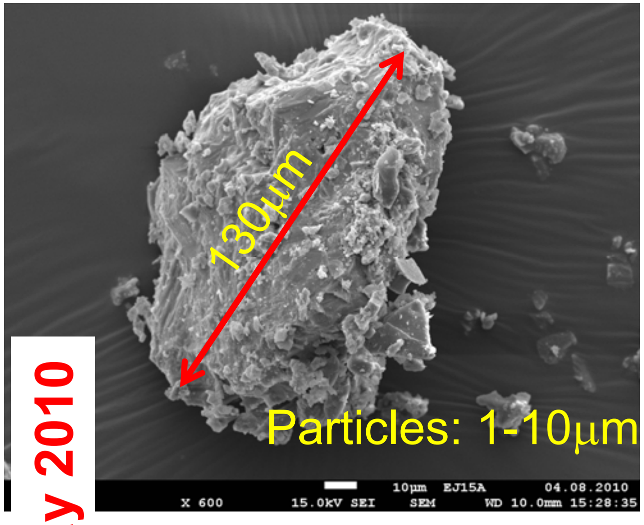


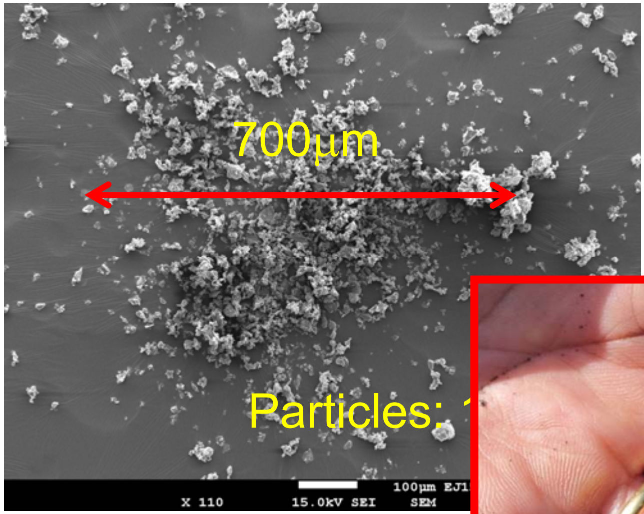
Laki (1873) eruption was both tropospheric and stratospheric.

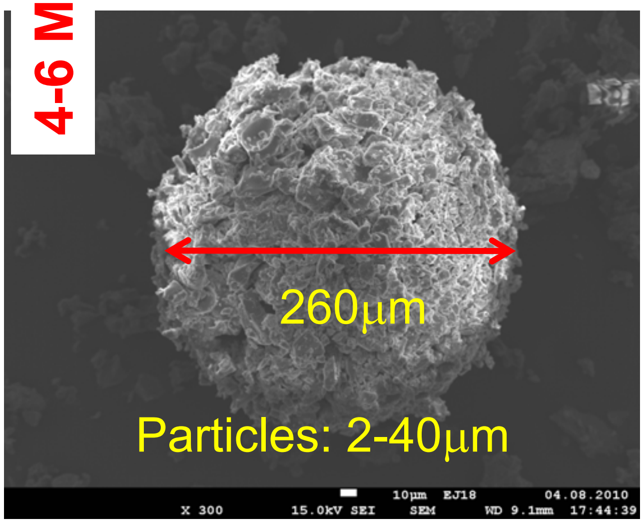
Thordarson and Self (2003)

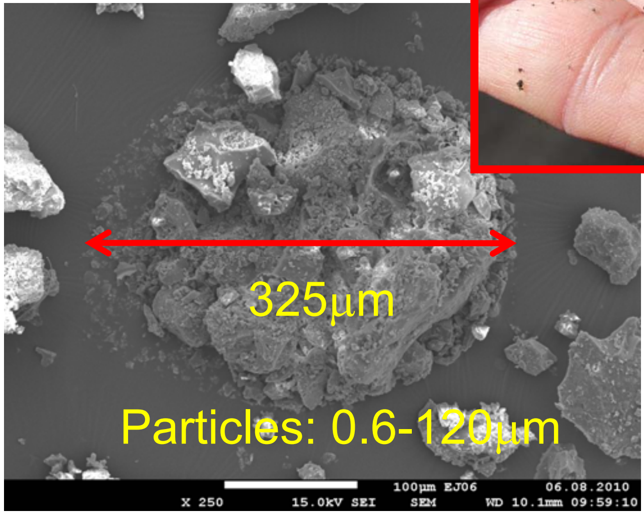
PARTICLE AGGREGATION

4-6 May 2010





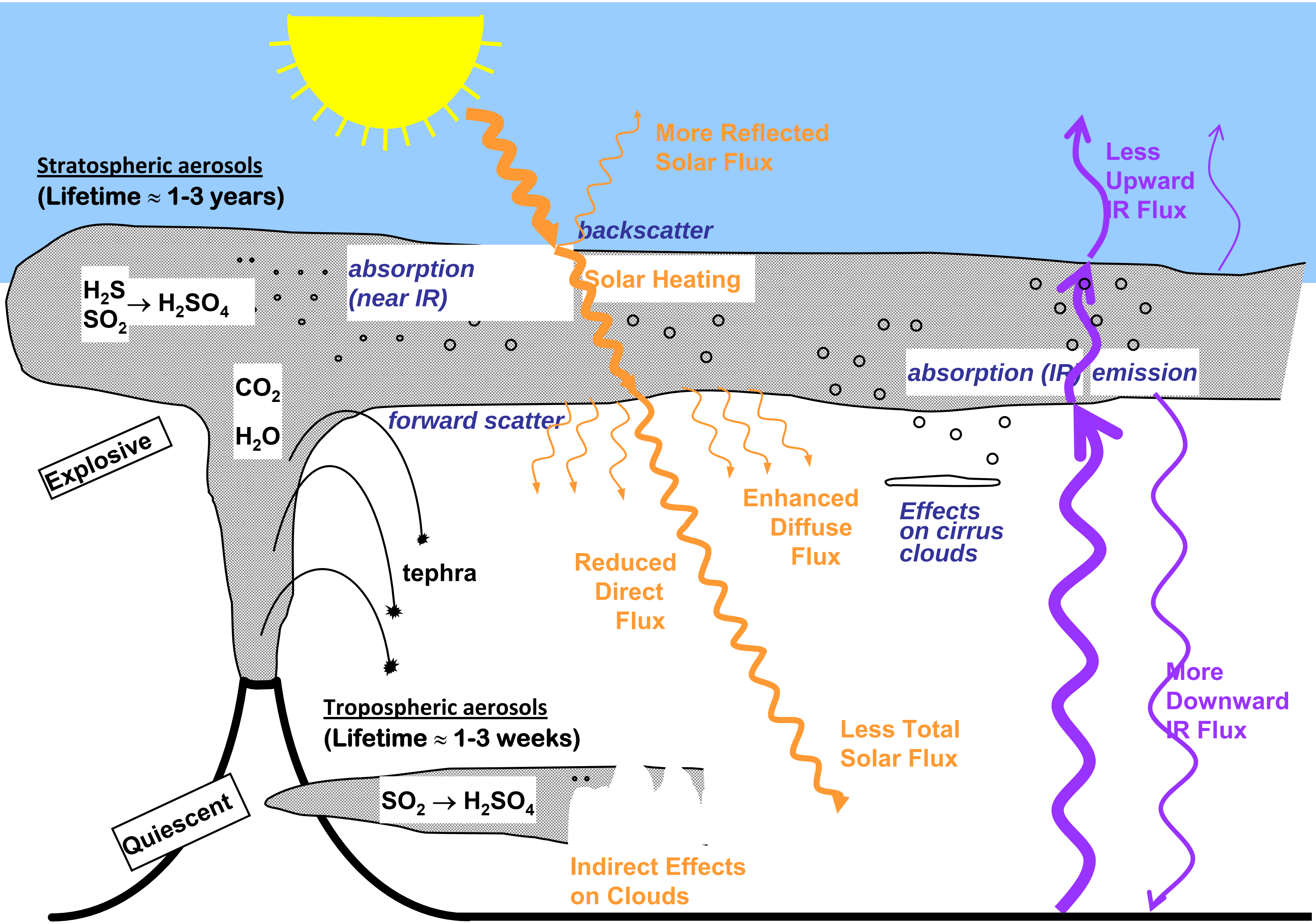




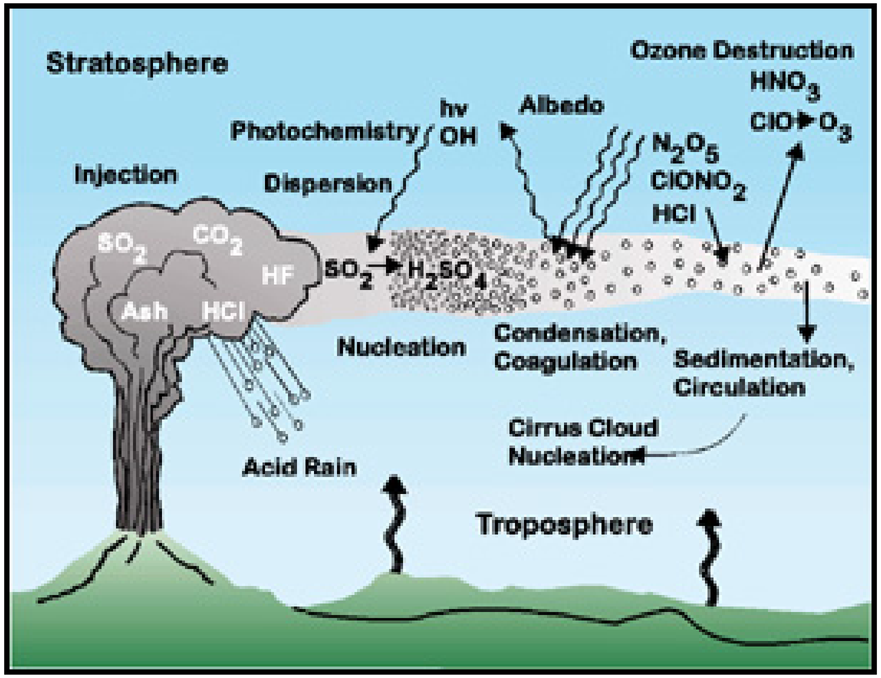
17 April 2010

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Explosive volcanism



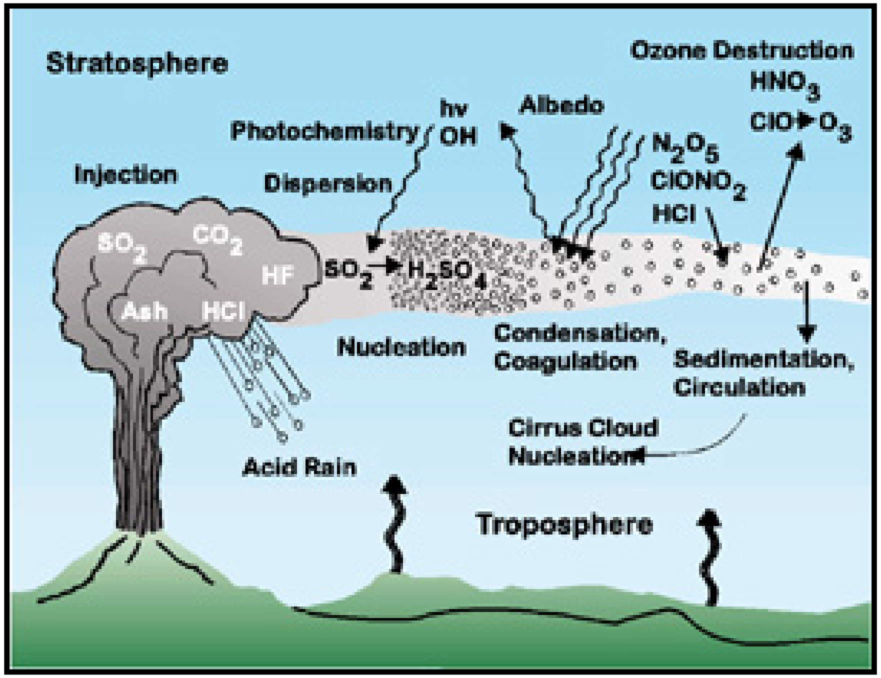
Explosive volcanism



Gas	Emission rate (Tg a^{-1})	Reference
H_2	0.24	Cadle (1980)
H_2O	~700	Stoiber (1995)
HF	0.7–8.6	Halmer *et al*. (2002)
	0.06–6	Symonds *et al*. (1988)
HBr	$2.6–43.2 \times 10^{-3}$	Halmer *et al*. (2002)
	3.3×10^{-3}	Stoiber *et al*. (1983)
HCl	1.2–170	Halmer *et al*. (2002)
	0.4–11	Stoiber *et al*. (1987)
H_2S	1.5–37.1	Halmer *et al*. (2002)
	0.21	Bandy *et al*. (1982)
	2.8	Andres and Kasgnoc (1998)
SO_2	7.5–10.5	Halmer *et al*. (2002)
	7.8	Cadle (1975)
	10.0	Stoiber and Jepsen (1973)
	13.0	Bluth *et al*. (1993)
	13.4	Andres and Kasgnoc (1998)
	15.2	Berresheim and Jaescke (1983)
	18.7	Stoiber *et al*. (1987)
	20.0	Graf *et al*. (1997)
OCS	$10^{-4}–0.3$	Halmer *et al*. (2002)
	0.022	Bandy et al. (1982)
	$6 \times 10^{-3}–0.09$	Belviso *et al*. (1986)
	0.3	Andres and Kasgnoc (1998)
CS_2	$10^{-5}–4 \times 10^{-2}$	Halmer *et al*. (2002)
	0.022	Bandy *et al*. (1982)
	0.3	Andres and Kasgnoc (1998)
CO_2	100–500	Gerlach (1991)
	65	Williams *et al*. (1992)
CO	0.02	Cadle (1980)
CH_4	0.34	Cadle (1980)
BrO	0.03 (Br)	Bobrowski *et al*. (2005)

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

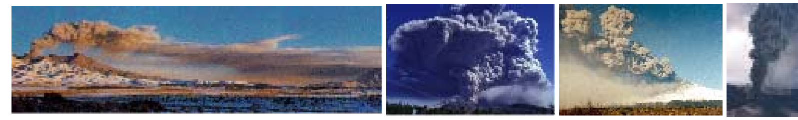
Explosive volcanism

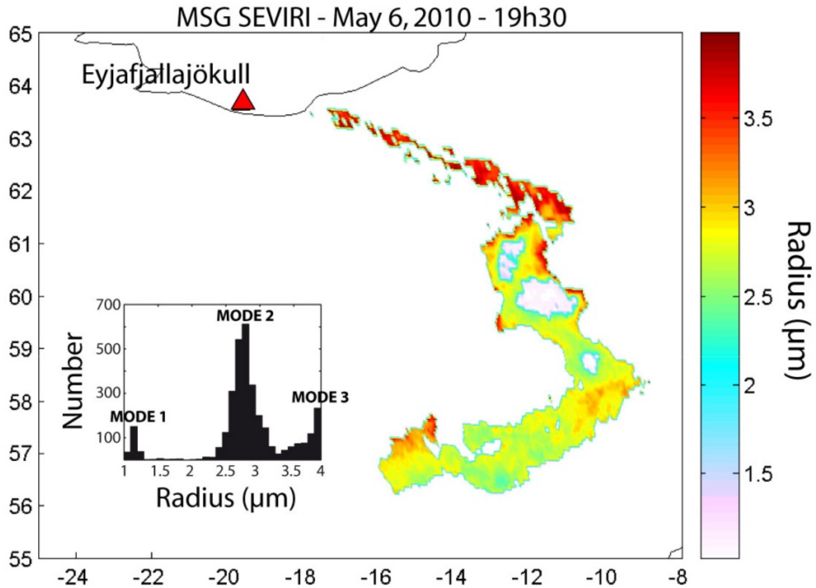


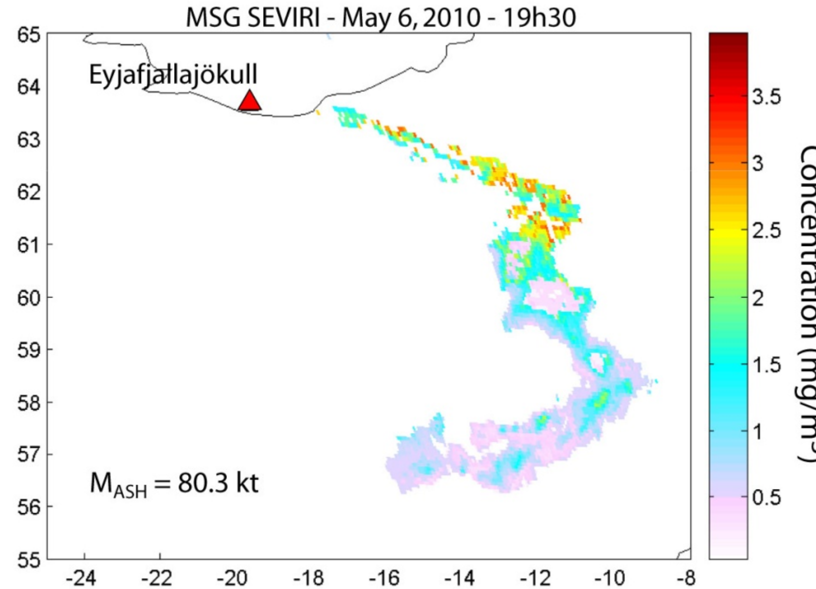
Gas	Emission rate (Tg a^{-1})	Reference
H_2	0.24	Cadle (1980)
H_2O	~700	Stoiber (1995)
HF	0.7–8.6	Halmer *et al*. (2002)
	0.06–6	Symonds *et al*. (1988)
HBr	$2.6–43.2x10^{-3}$	Halmer *et al*. (2002)
	$3.3x10^{-3}$	Stoiber *et al*. (1983)
HCl	1.2–170	Halmer *et al*. (2002)
	0.4–11	Stoiber *et al*. (1987)
H_2S	1.5–37.1	Halmer *et al*. (2002)
	0.21	Bandy *et al*. (1982)
	2.8	Andres and Kasgnoc (1998)
SO_2	7.5–10.5	Halmer *et al*. (2002)
	7.8	Cadle (1975)
	10.0	Stoiber and Jepsen (1973)
	13.0	Bluth *et al*. (1993)
	13.4	Andres and Kasgnoc (1998)
	15.2	Berresheim and Jaescke (1983)
	18.7	Stoiber *et al*. (1987)
	20.0	Graf *et al*. (1997)
OCS	$10^{-4}–0.3$	Halmer *et al*. (2002)
	0.022	Bandy et al. (1982)
	$6x10^{-3}–0.09$	Belviso *et al*. (1986)
	0.3	Andres and Kasgnoc (1998)
CS_2	$10^{-5}–4x10^{-2}$	Halmer *et al*. (2002)
	0.022	Bandy *et al*. (1982)
	0.3	Andres and Kasgnoc (1998)
CO_2	100–500	Gerlach (1991)
	65	Williams *et al*. (1992)
CO	0.02	Cadle (1980)
CH_4	0.34	Cadle (1980)
BrO	0.03 (Br)	Bobrowski *et al*. (2005)

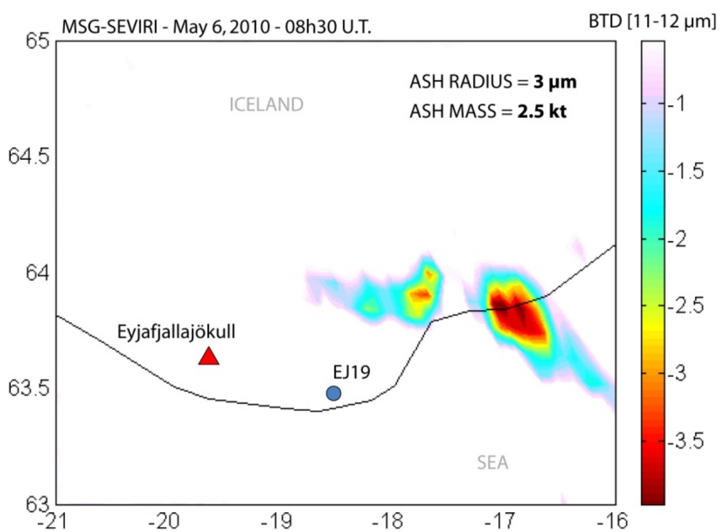
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

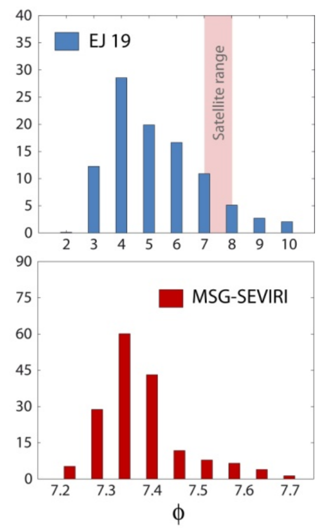
Sedimentation during the 2010 Eyjafjallajökull eruption

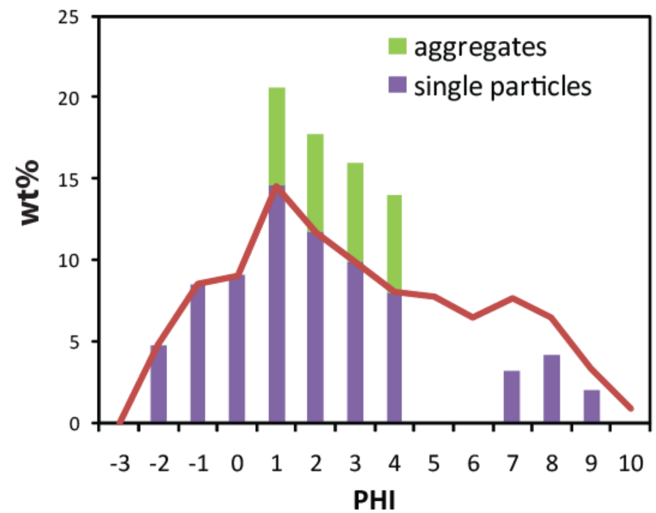


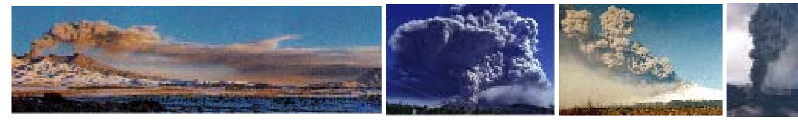










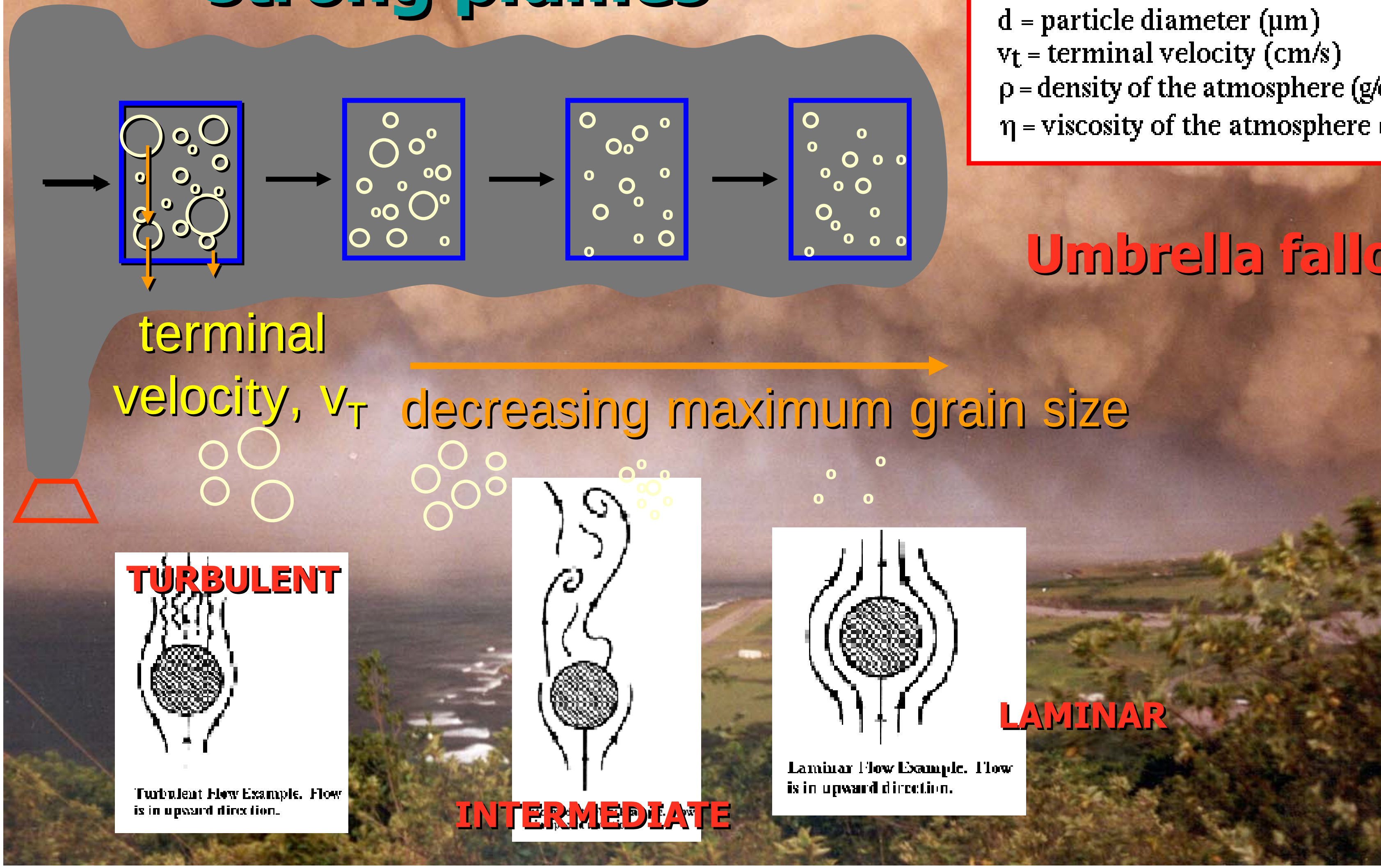


Sedimentation from strong plumes

Reynolds number (Re):

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

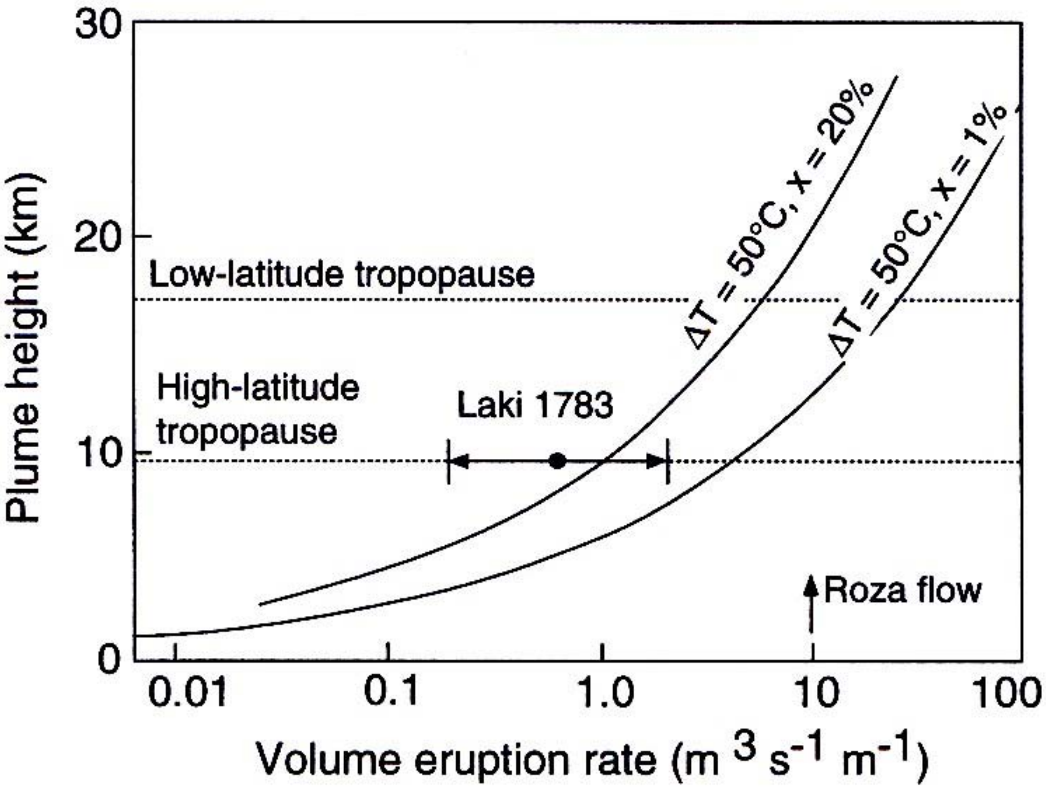
d = particle diameter (µm)
v_t = terminal velocity (cm/s)
ρ = density of the atmosphere (g/cm^3)
η = viscosity of the atmosphere (g/cm-s)



Large basaltic fissures

Potential climatic impact

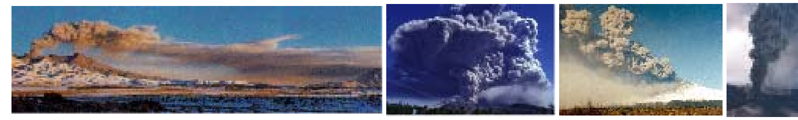
→ Basalts carry higher amounts of sulfur per unit mass than more evolved magmas



Potential climatic impact for Ht > 10-15 km

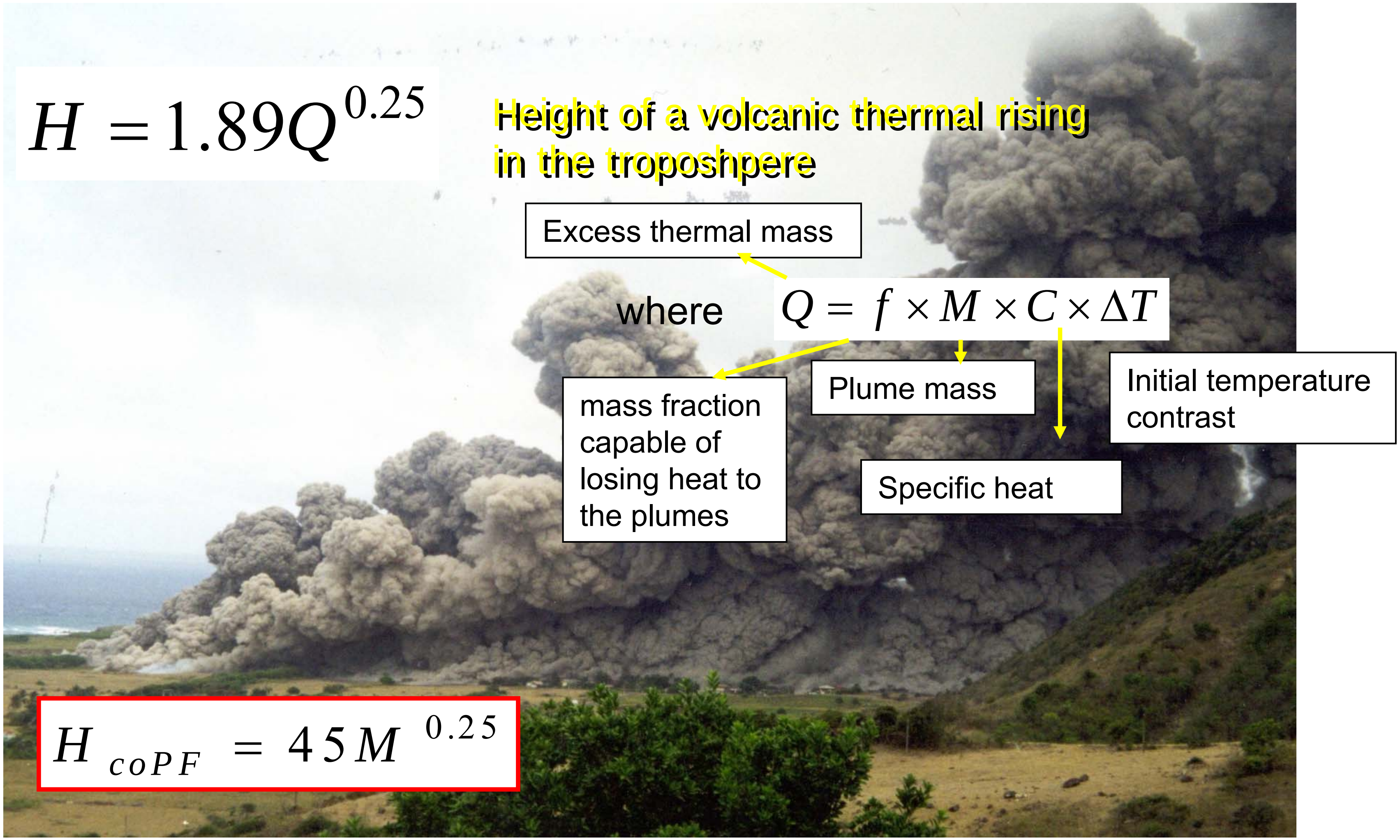
FF cooling of 50%

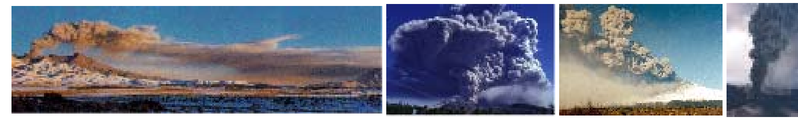
Use of 1 and 20% of the energy in fine ash



Co-pyroclastic flow plumes

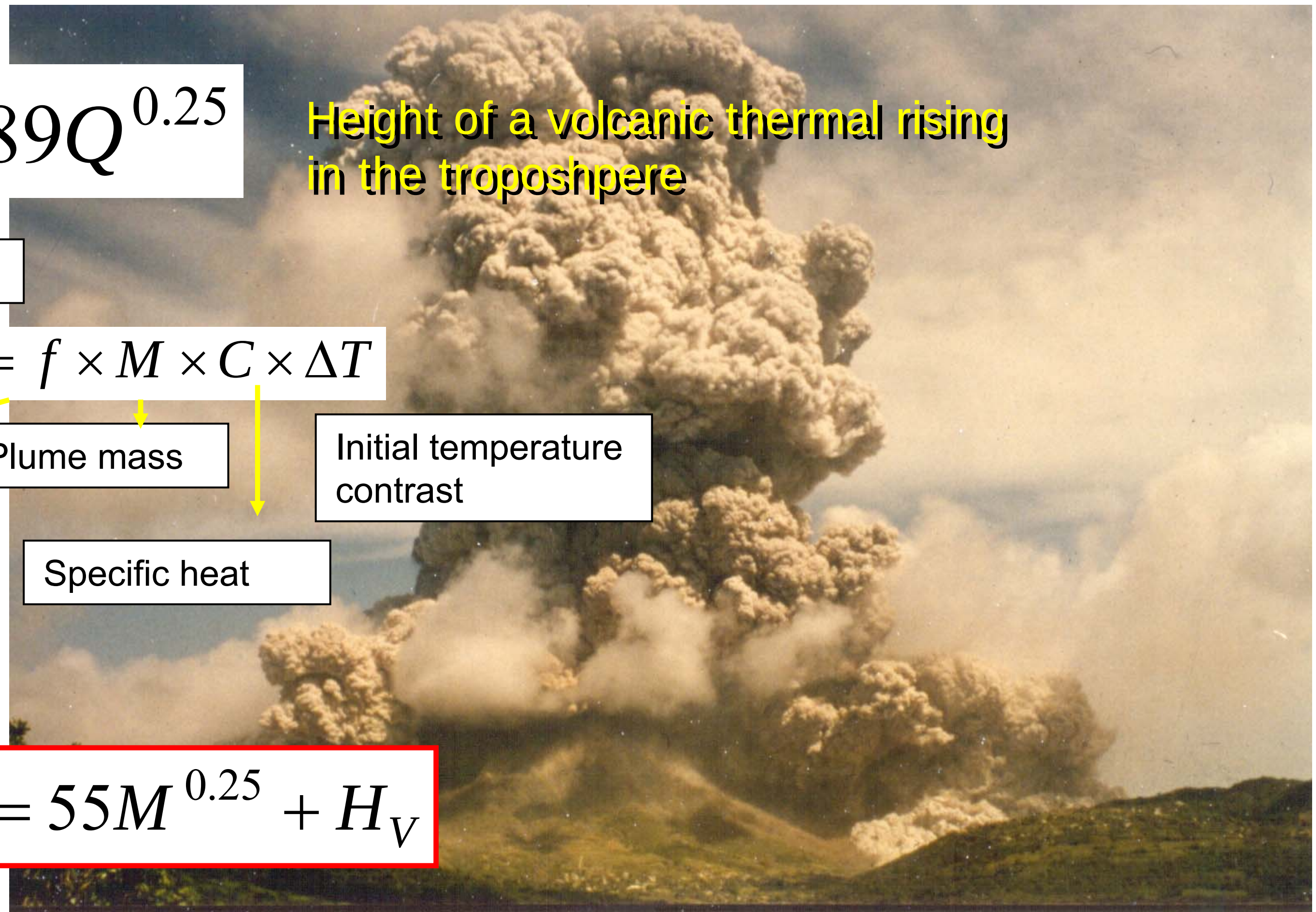
Example of Montserrat





Vulcanian plumes

Example of Montserrat



$$H = 1.89Q^{0.25}$$

where $Q = f \times M \times C \times \Delta T$

- Q: Excess thermal mass
- f: mass fraction capable of losing heat to the plumes
- M: Plume mass
- C: Specific heat
- ΔT: Initial temperature contrast

$$H_{VP} = 55M^{0.25} + H_V$$