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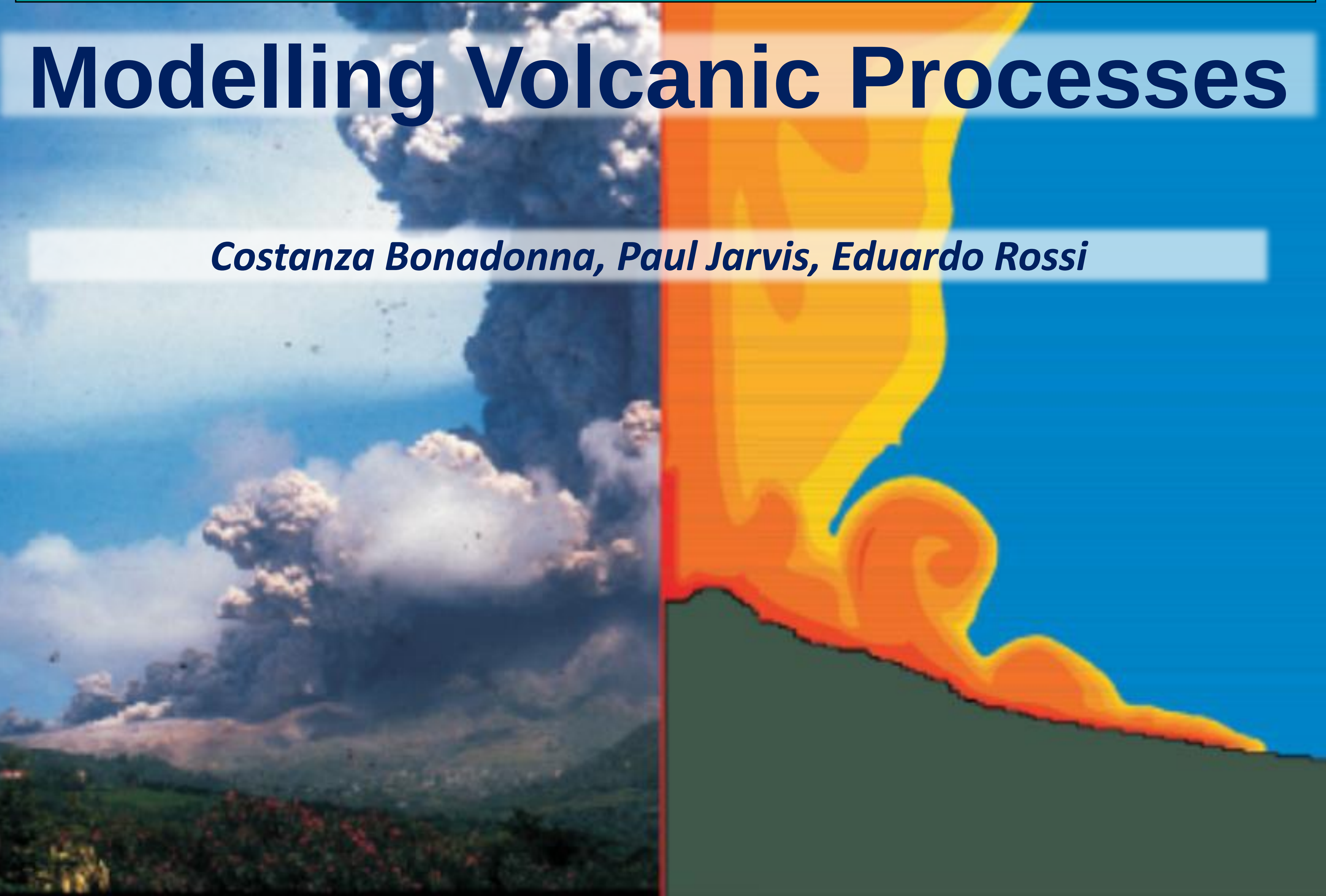
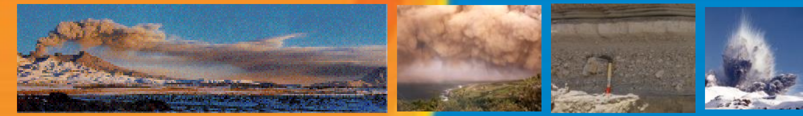
Department of Earth Sciences

Modelling Volcanic Processes

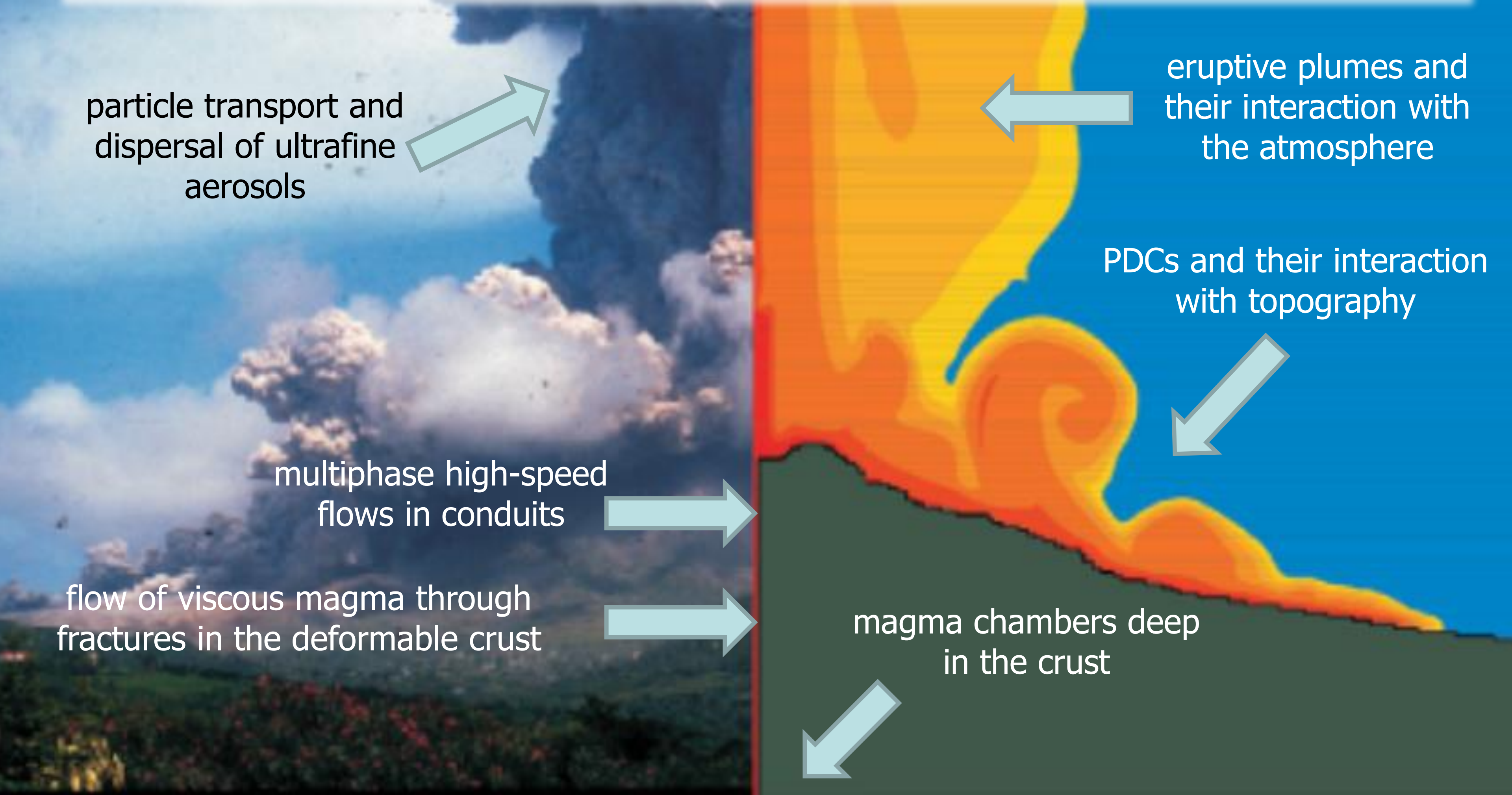
Costanza Bonadonna, Paul Jarvis, Eduardo Rossi





MOTIVATION

Volcanic system → range of scales, material property variations, and complex interacting physical and chemical processes






MOTIVATION

Volcanologists have the drive and the responsibility to progress their science to improve **understanding** and **mitigation** of the effects of volcanic eruptions

Many key volcanic processes cannot be observed and analysed directly

Hazardous processes are required to be analytically and numerically described for both real-time forecasting and long-term risk reduction strategies

A variety of dedicated models of different complexity needed to be developed at multiple scales that could address different purposes

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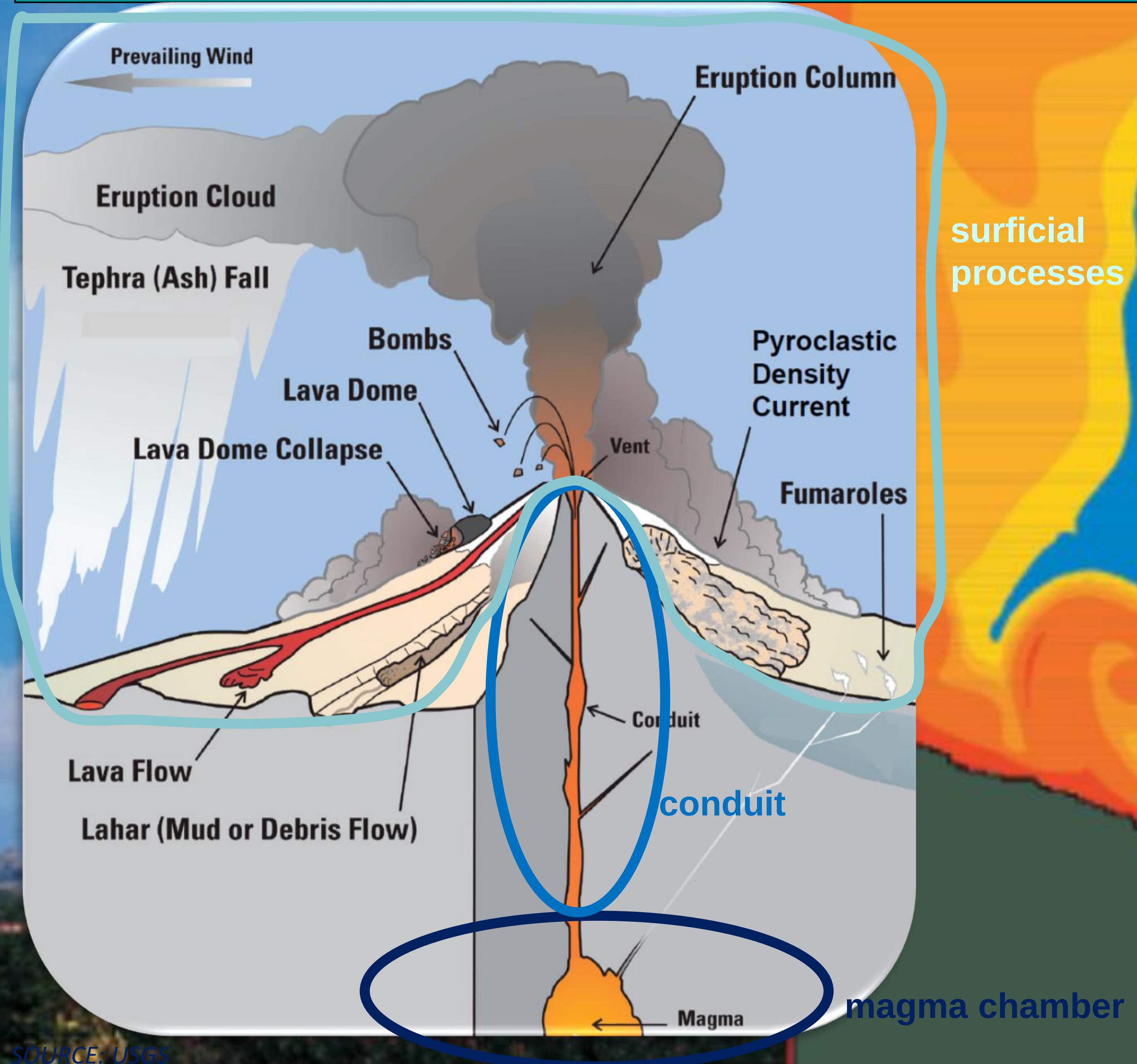

SOURCE: USGS

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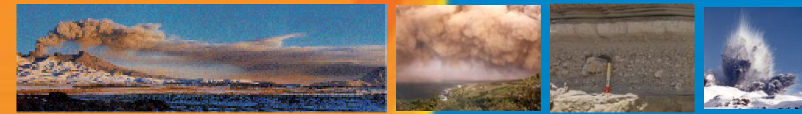
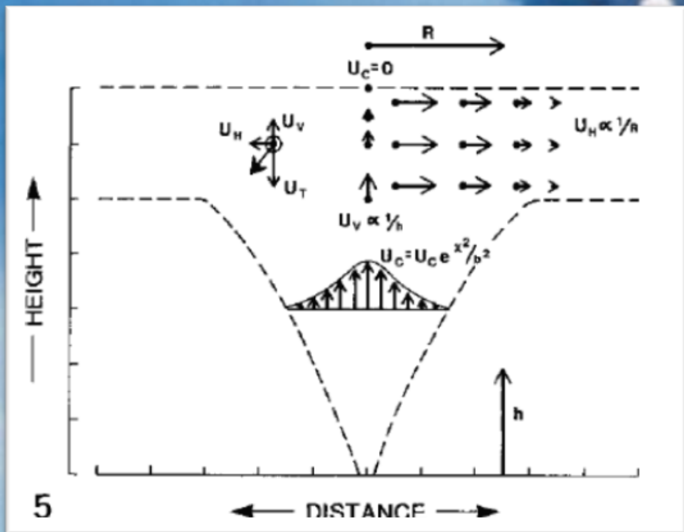
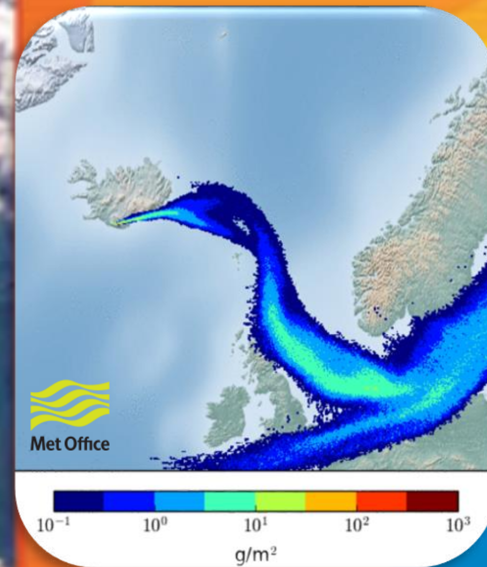
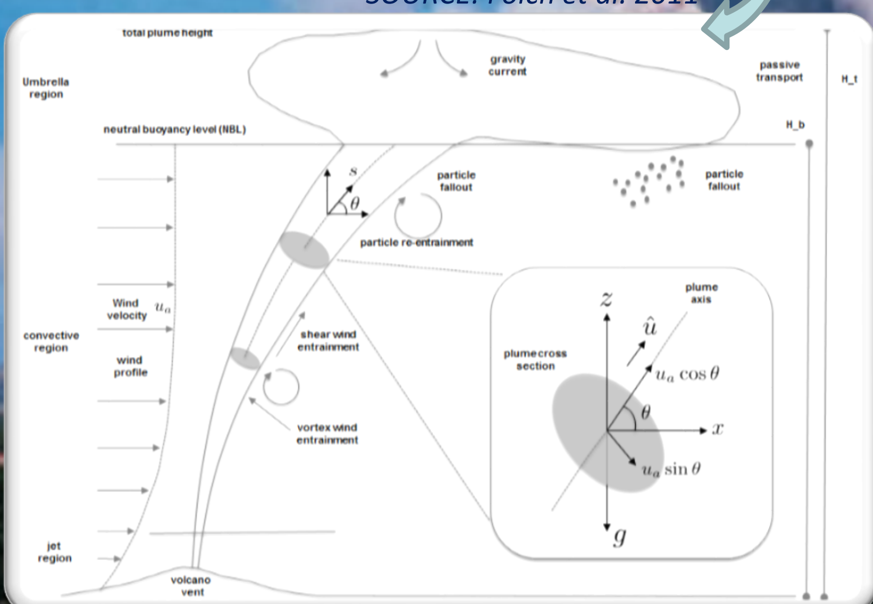


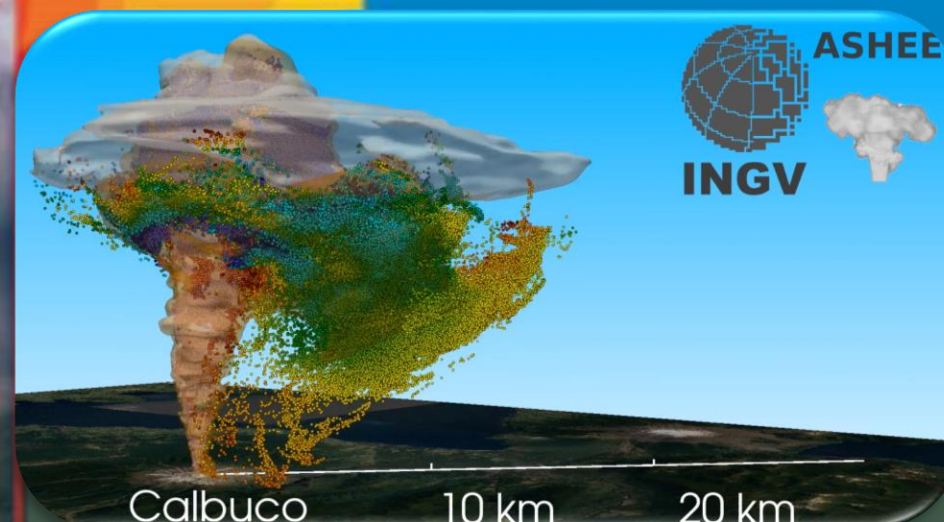


SOURCE: Carey and Spark 1986

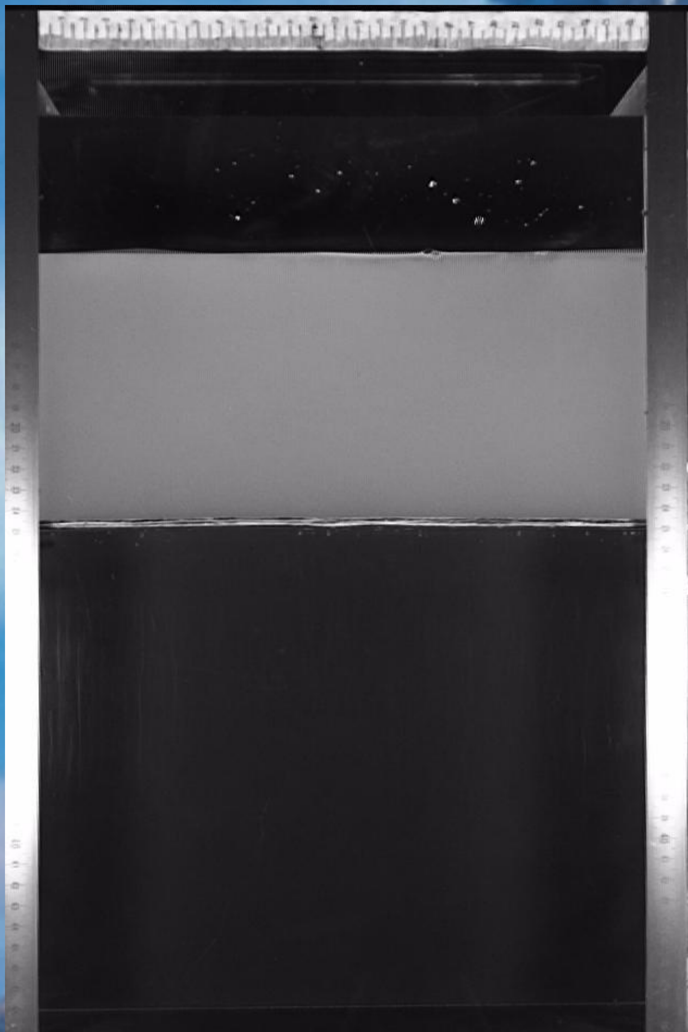


SOURCE: Folch et al. 2011

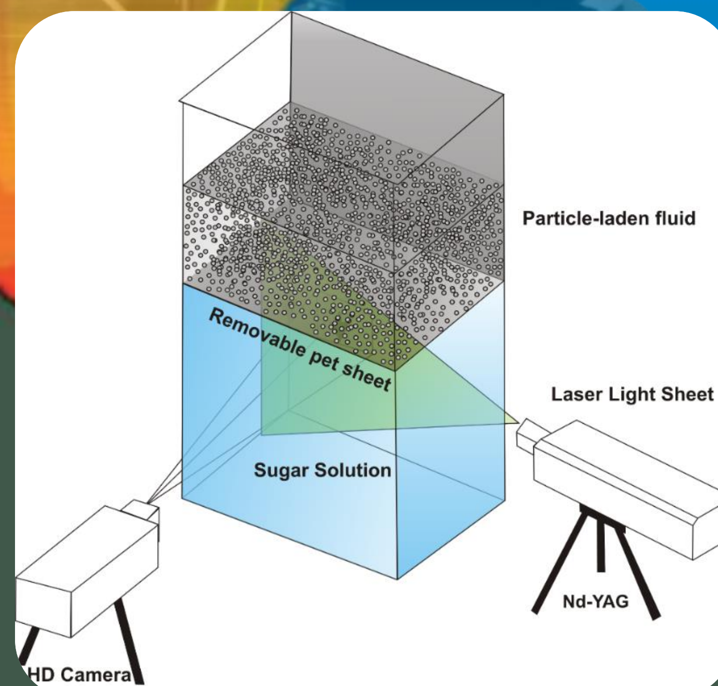




http://193.206.223.51:8081/software-list




Genesis CX STM


Particle-laden fluid
Removable pet sheet
Laser Light Sheet
Sugar Solution
Nd-YAG
HD Camera

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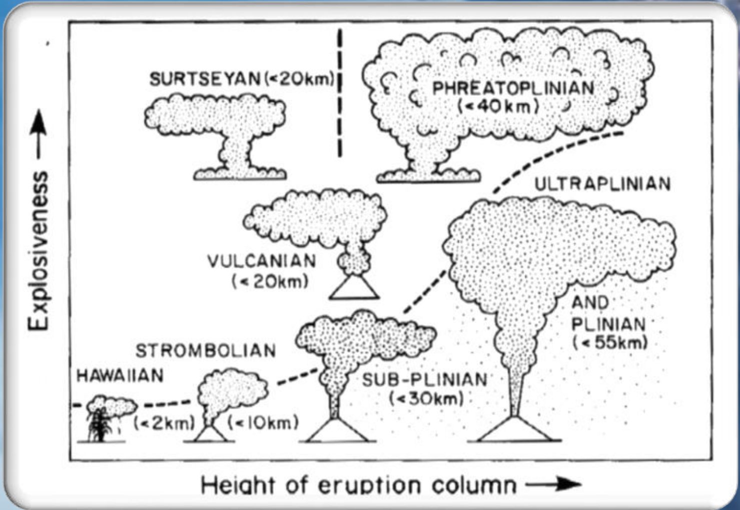
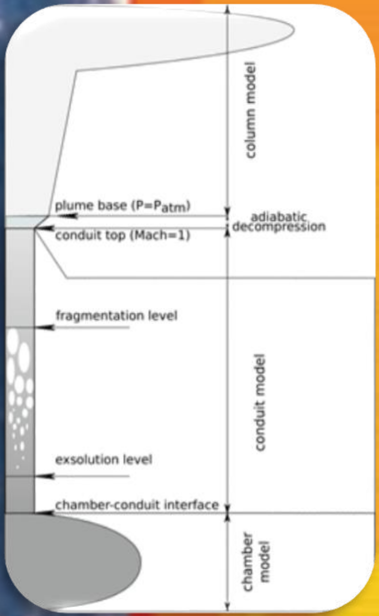
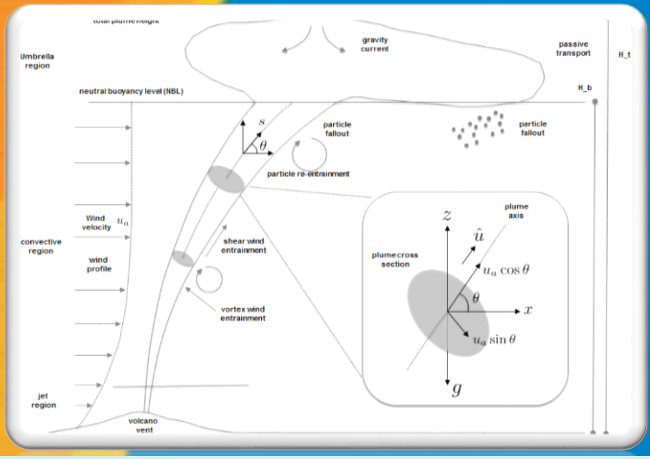


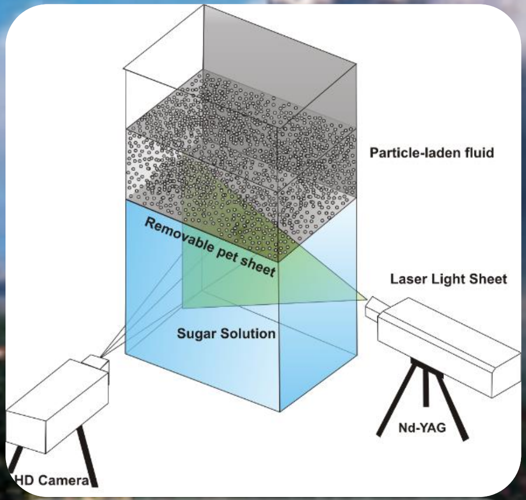
PART 1 – ERUPTION CHARACTERIZATION (Costanza BONADONNA)



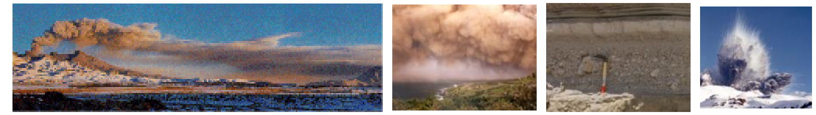
PART 2 – CONDUIT DYNAMICS (Paul JARVIS)



PART 3 – NUMERICAL MODELLING (Eduardo ROSSI)



PART 4 – EXPERIMENTAL MODELLING (Paul JARVIS)



PHYSICAL CHARACTERIZATION OF EXPLOSIVE ERUPTIONS

Costanza Bonadonna
Costanza.Bonadonna@unige.ch




MAIN QUESTION:

How well can we constrain explosive eruptions?

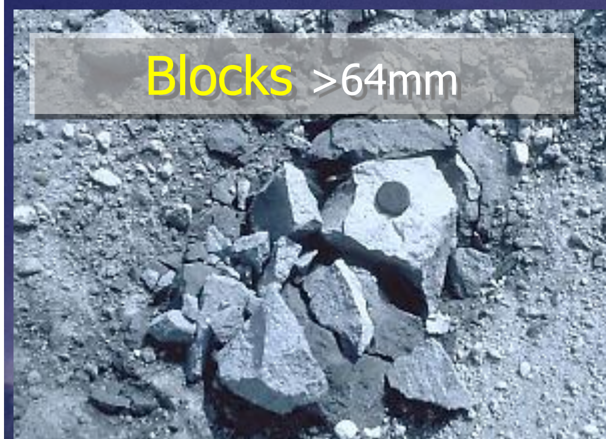
How well can we constrain Eruption Source Parameters (ESP)?

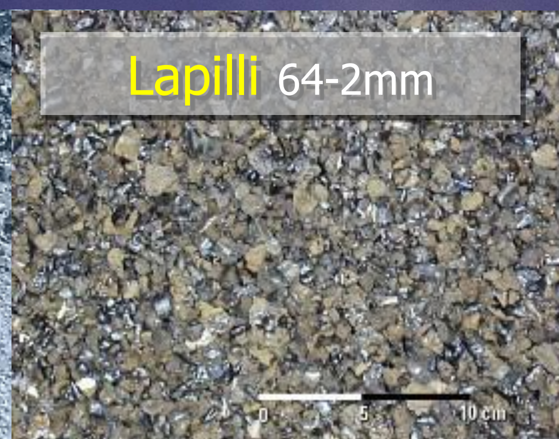
→ Erupted Volume/Mass, Plume Height,
Mass Eruption Rate (MER), Eruption Duration,
Total Grain-Size Distribution (TGSD)

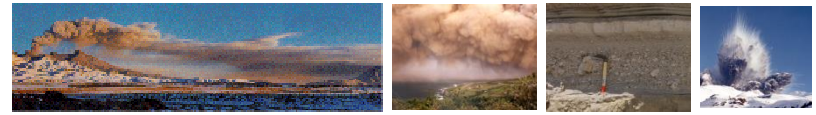



TEPHRA

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







TEPHRA

reticulite

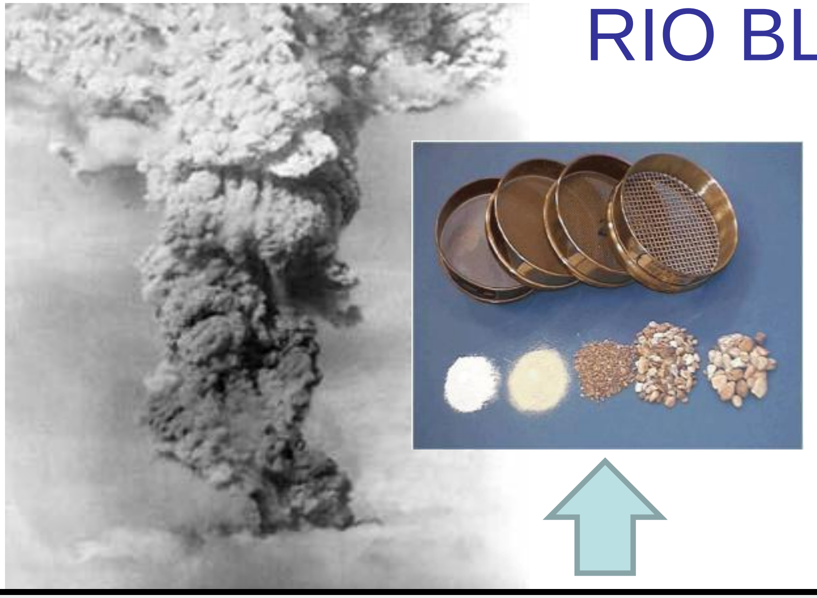
Pele's hair

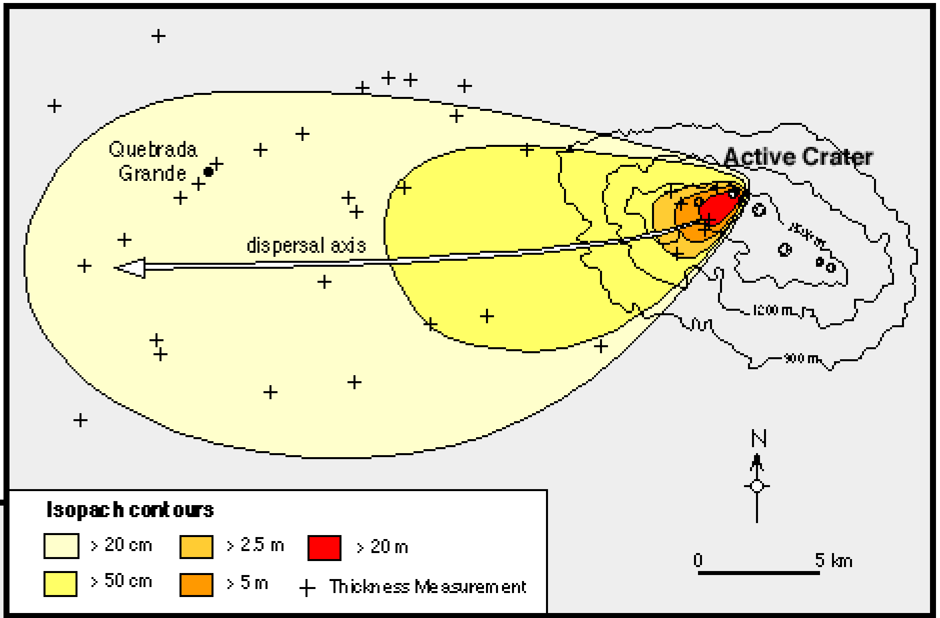
scoria

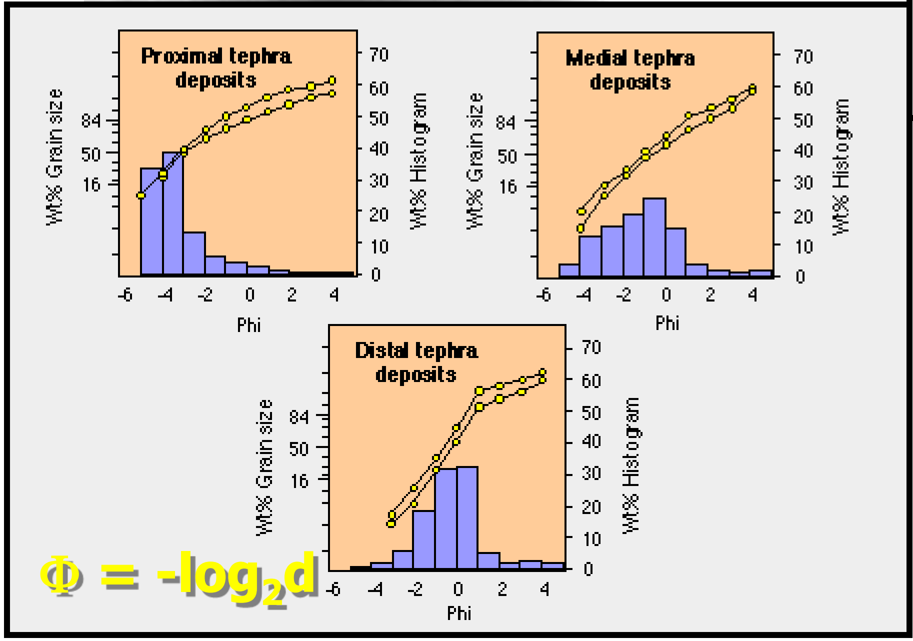
pumice

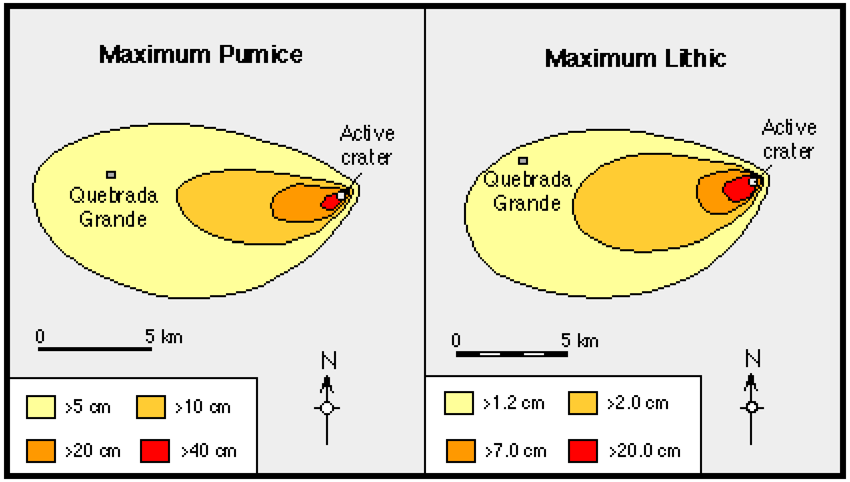



RIO BLANCO TEPHRA (3500 BP)



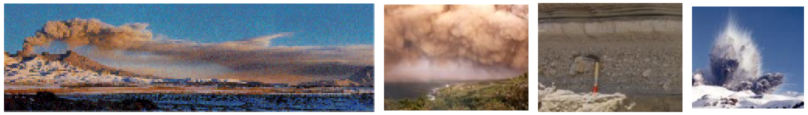


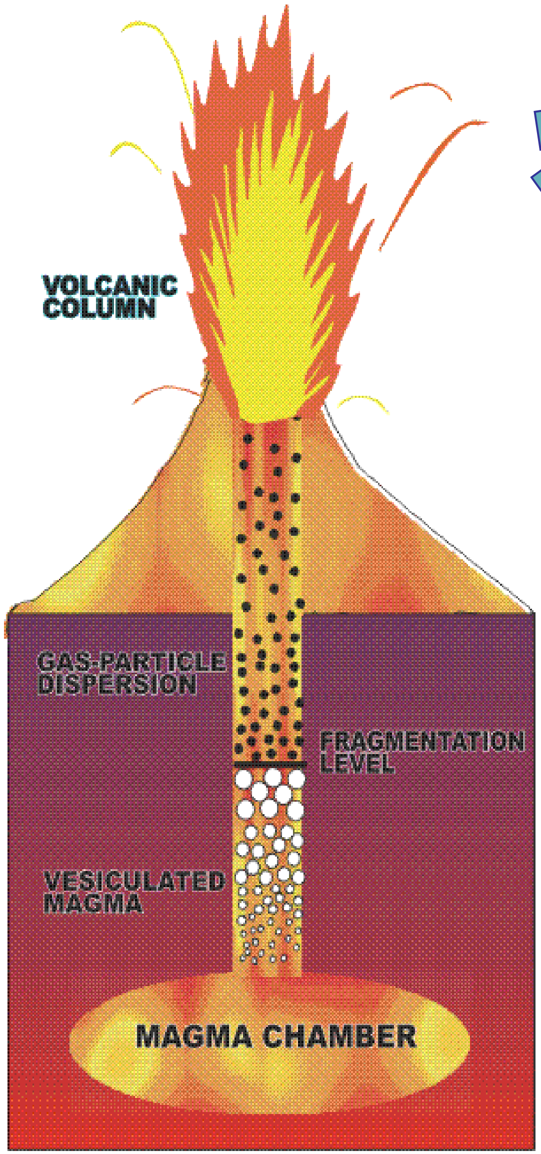


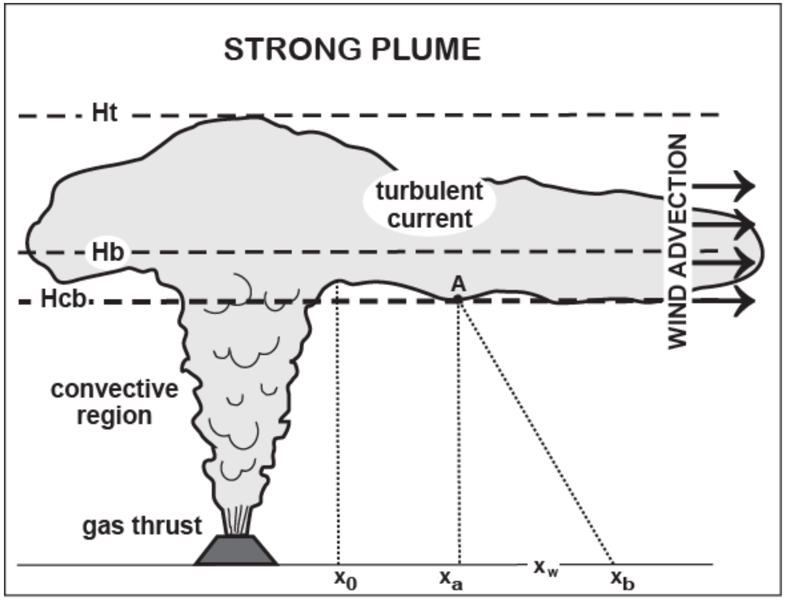


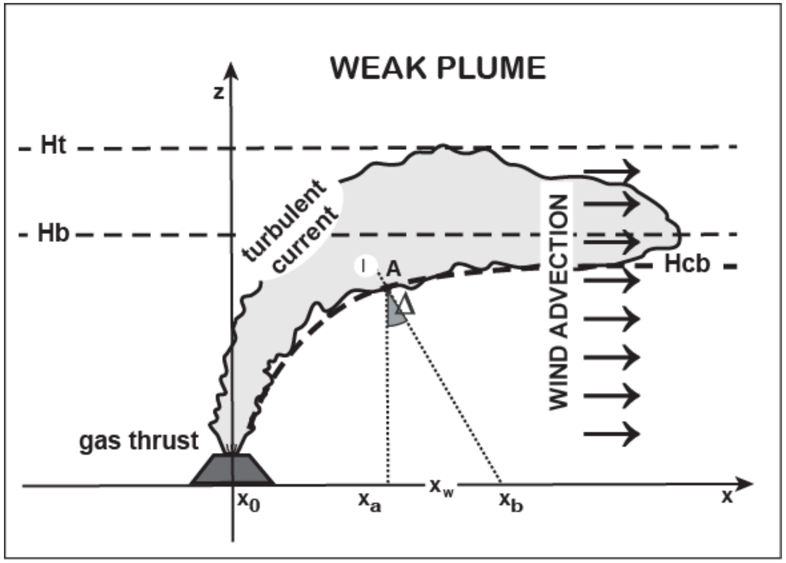
http://www.geo.utexas.edu/faculty/barker/kempter/rbtephra.html

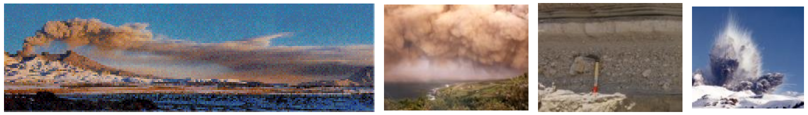
Characterization of tephra deposits: particle sedimentation



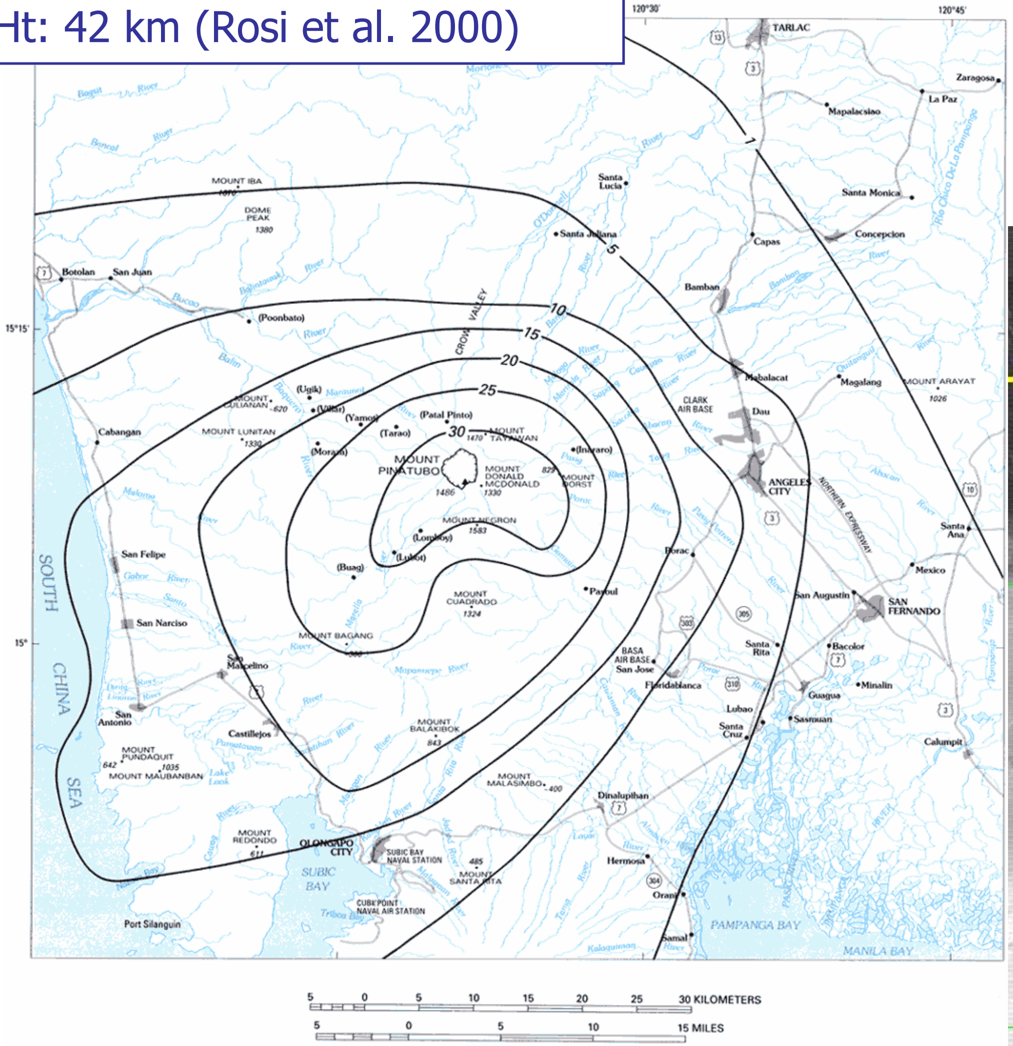


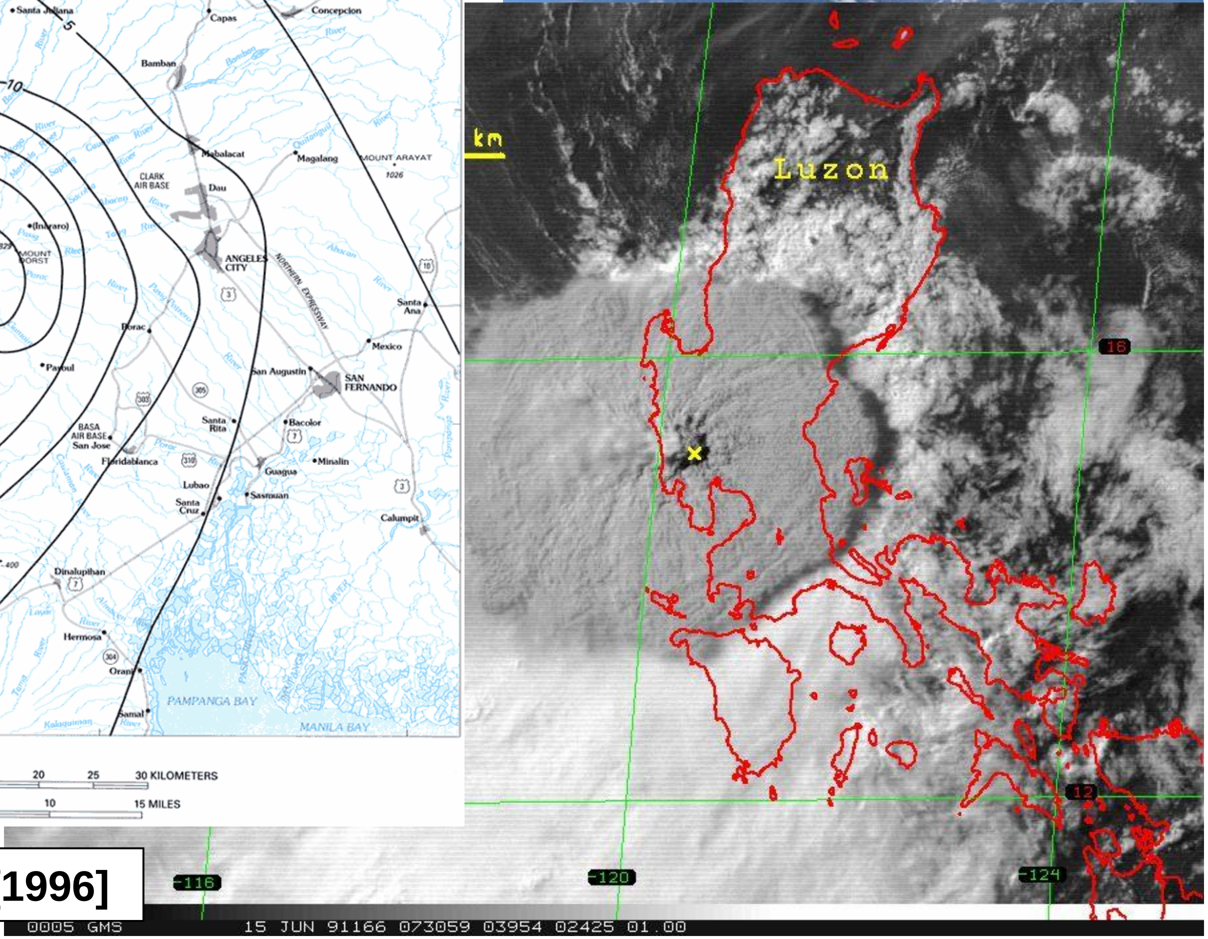




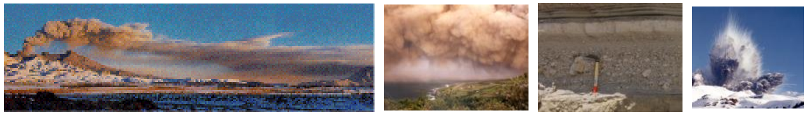


Pinatubo (Philippines) 1991
Ht: 42 km (Rosi et al. 2000)

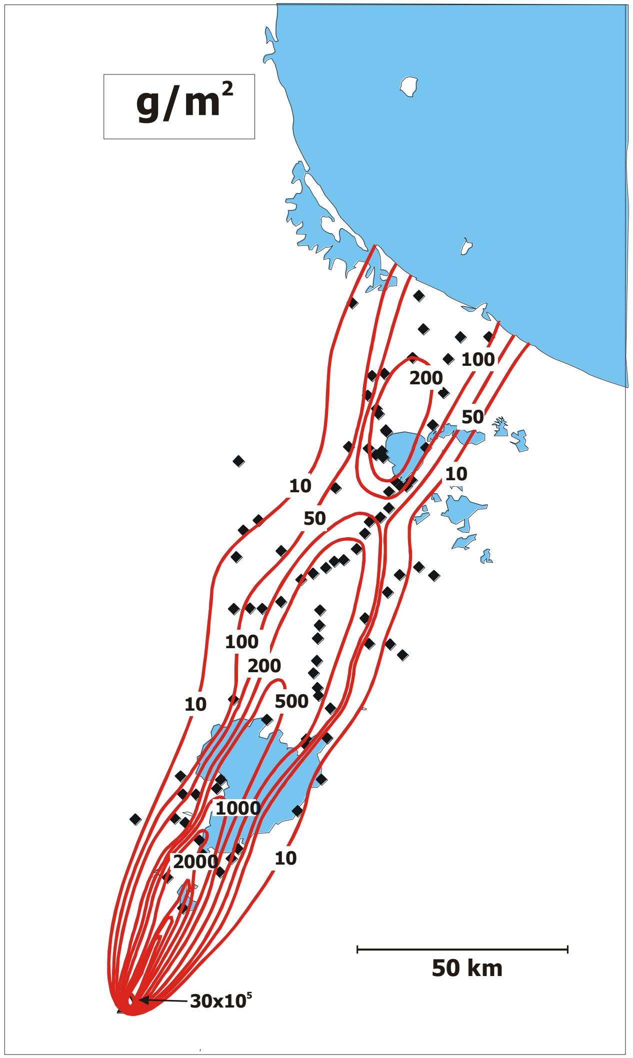




Paladio-Melosantos et al. [1996]



Ruapehu (NZ) 1996
Ht: 8.5 km
Wind speed: 24 m s^{-1}



- **no upwind sedimentation**
- **narrow deposit**
- **lapilli sedimentation from inclined sector**

MAIN QUESTION:

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→ **Erupted Volume/Mass, Plume Height,**
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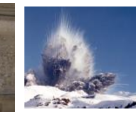
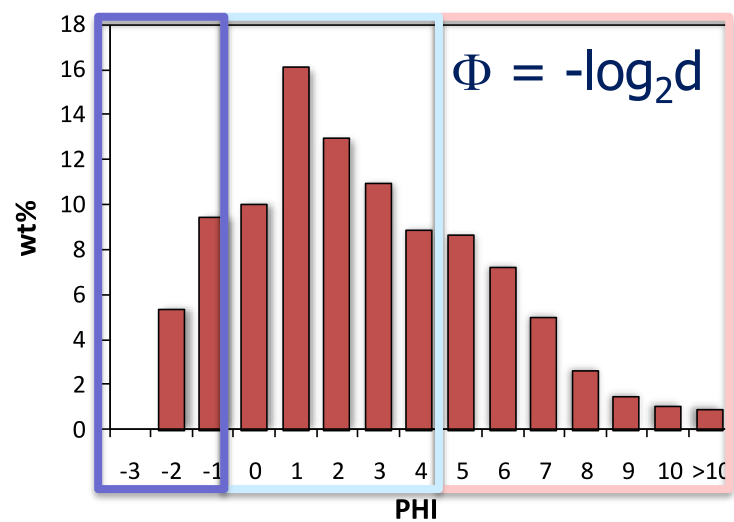
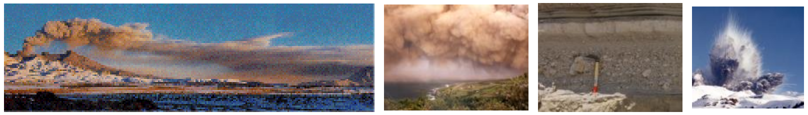


GRAIN SIZE PROPERTIES

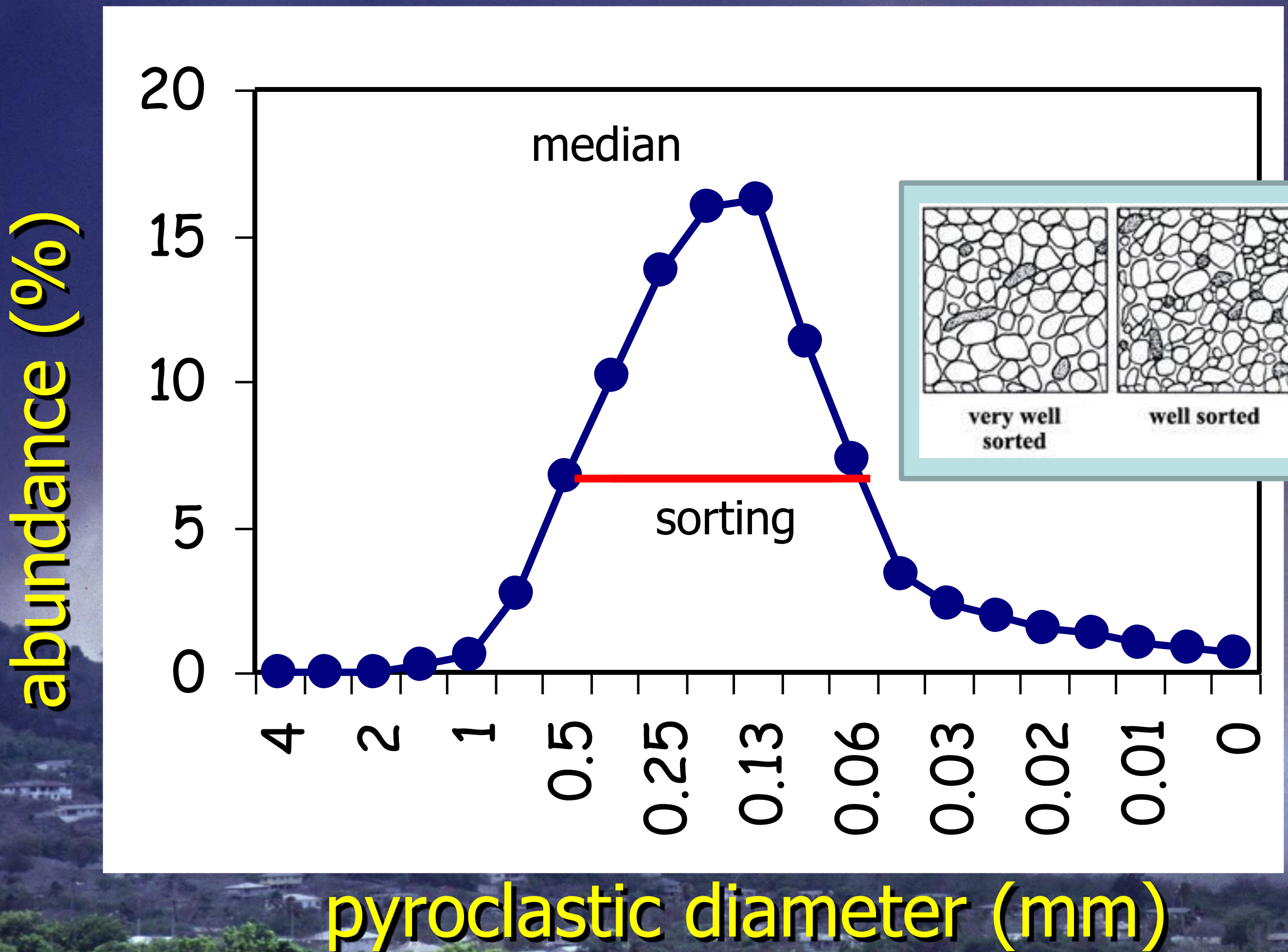
	bombs / blocks	lapilli	coarse ash	**fine ash**
Diameter	> 64 mm	(64 mm-2 mm)	(2 mm-63µm)	**(<63µm)**
Residence time	≈ sec	≈ min	≈ hours to few days	**several days**
Travel distance	proximal <10km	medial <50 km	distal <100 km	**very distal <1000 km**

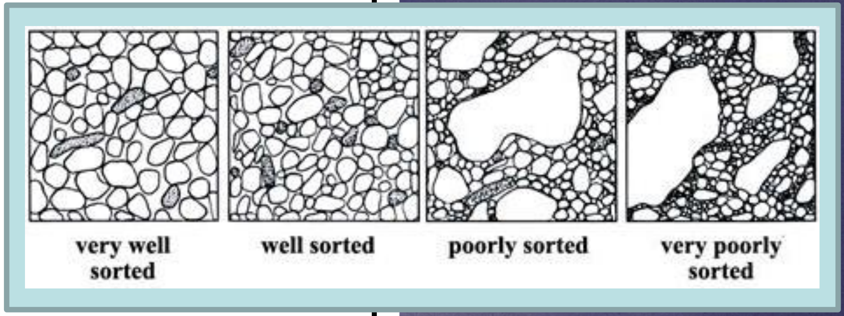


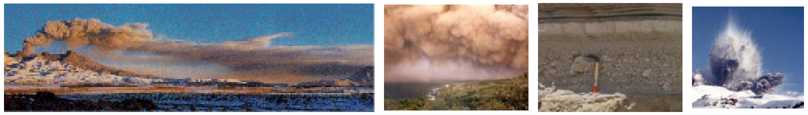


GRAIN SIZE PROPERTIES

absolute size = median   range of size = sorting







GRAIN SIZE PARAMETERS

percentiles ϕ 16, 50, 84

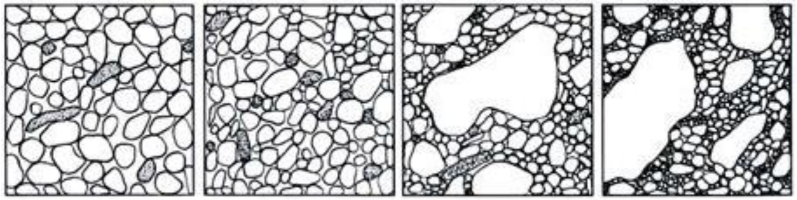
Log scale: bin data geometrically phi scale = $-\log_2 D$

Inman (1952)

ABSOLUTE SIZE: median (M_d) = $\phi 50$

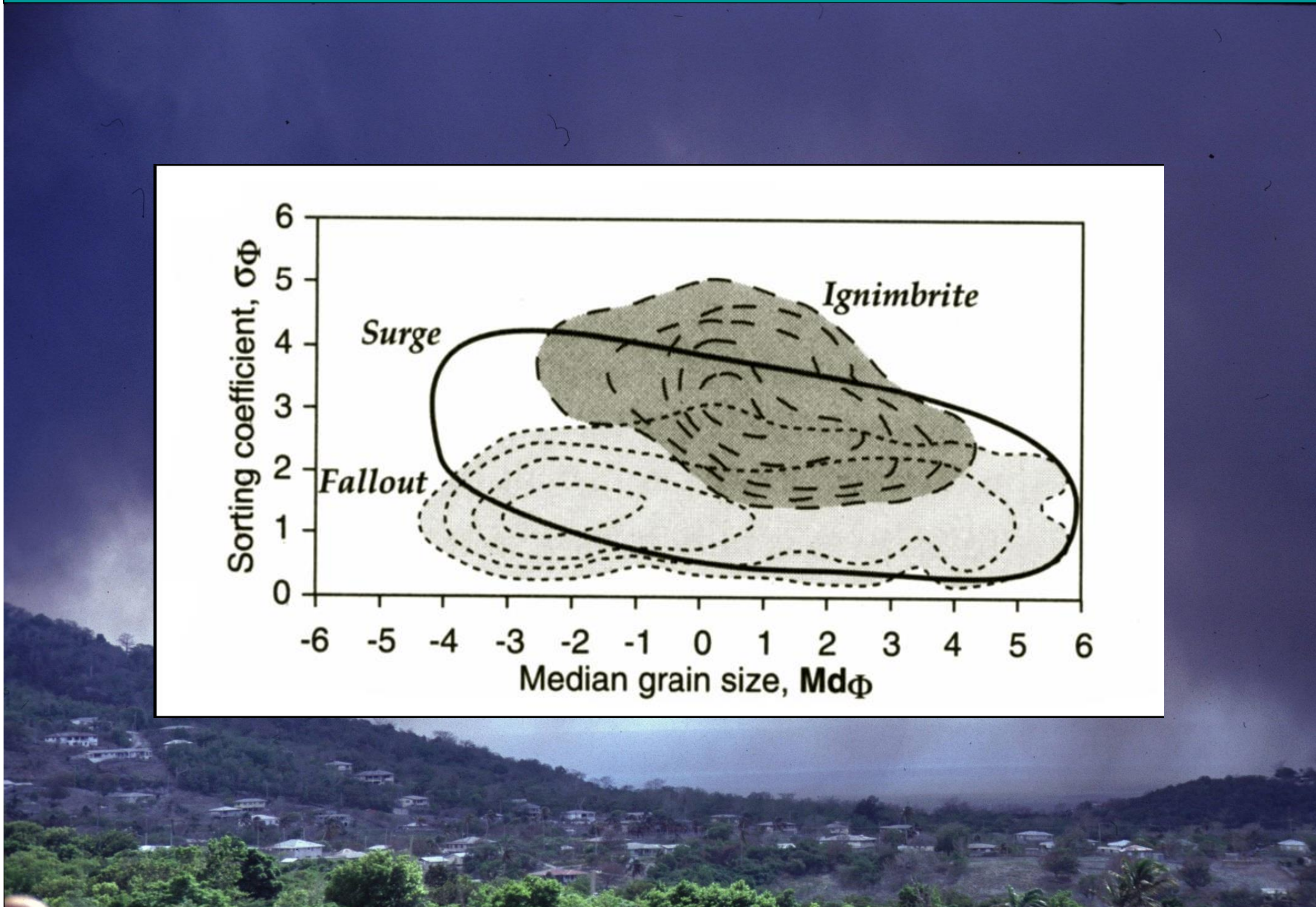
SORTING: graphic SD (s_G) = $(\phi 84 - \phi 16)/2$

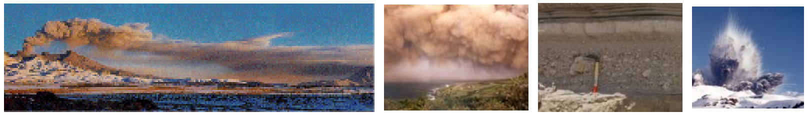
0-1 1-2 2-4 >4



very well sorted | well sorted | poorly sorted | very poorly sorted

Characterization of ESPs: grainsize distribution





Fall vs. Surge vs. Flow

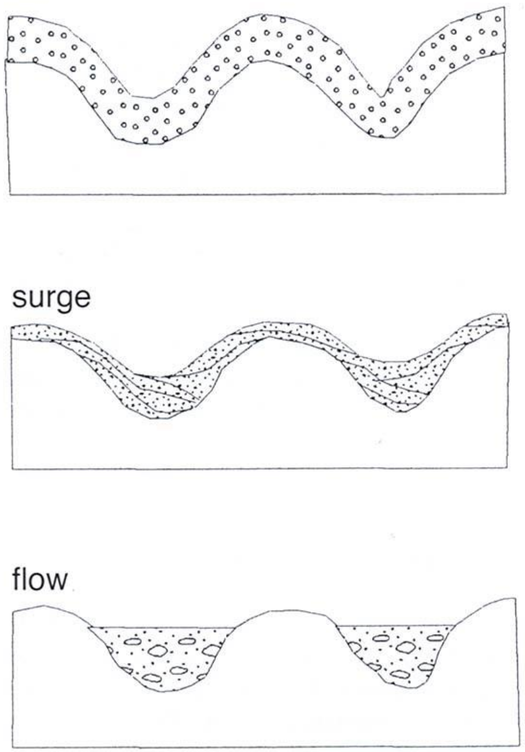


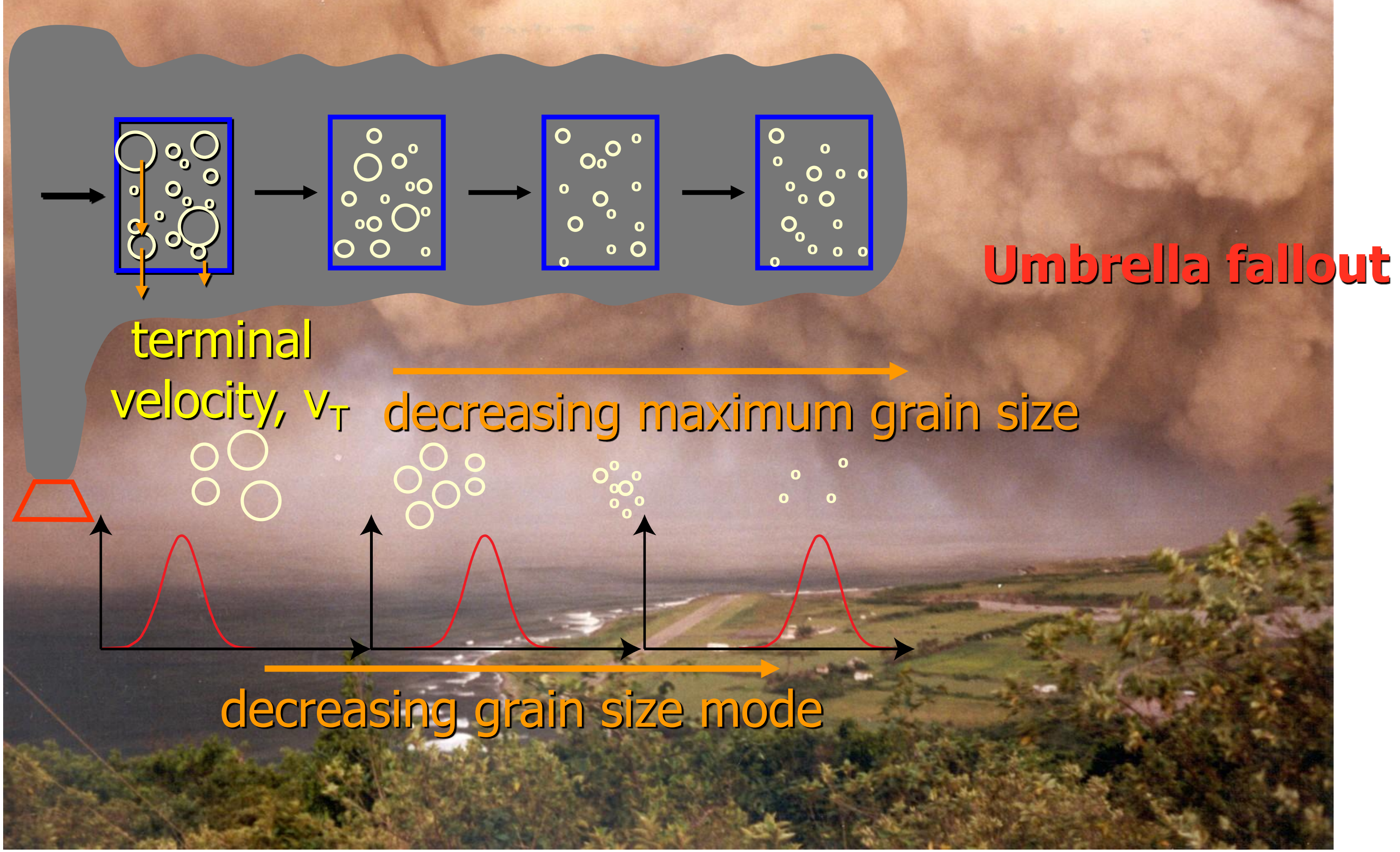
FIGURE 5 Schematic diagram of the archetypal characteristics of the three main pyroclastic deposit types. Fall—mantle bedding, with plane parallel beds and no internal erosion, good sorting (except where water is present; see Section III,E), juvenile clasts with angular to ragged shapes. Surge—nonmantling beds, thickening into low-lying areas, with cross-stratification, pinch-and-swell bedding and scoured contacts, moderate sorting, juvenile clasts with some degree of rounding. Flow—landscape-filling units, generally poorly bedded to nonbedded, poor sorting, rounded juvenile clasts.

Fall: drape landscape, no cross beds or wave bedforms, well sorted, bedded

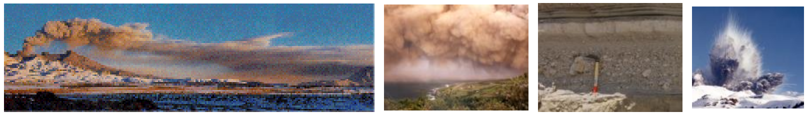
Surge: pinch and swell, basal scouring, cross bedding, (i.e., features that express lateral transport), good to poor sorting, sustained high temperatures rare.

Flow: thicken into or are confined in valleys because flow is gravity driven, show basal scouring but lack internal bedforms, poor sorting. Sustained high temperatures (welding) typical. High T indicative of efficient transport (little mixing with ambient air).

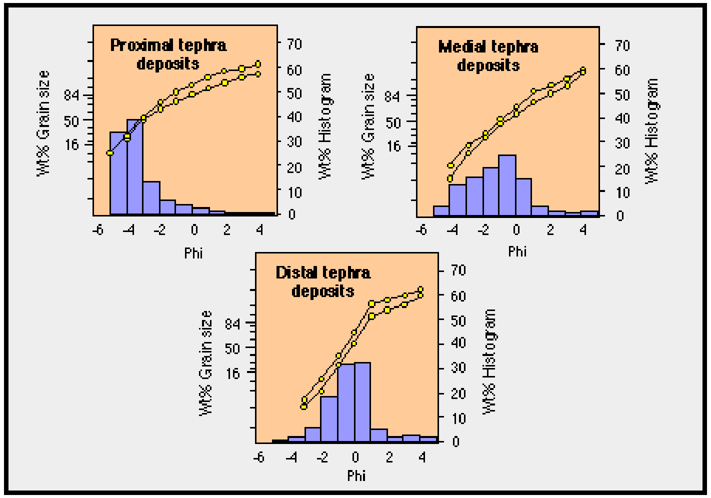
Sedimentation from volcanic plumes

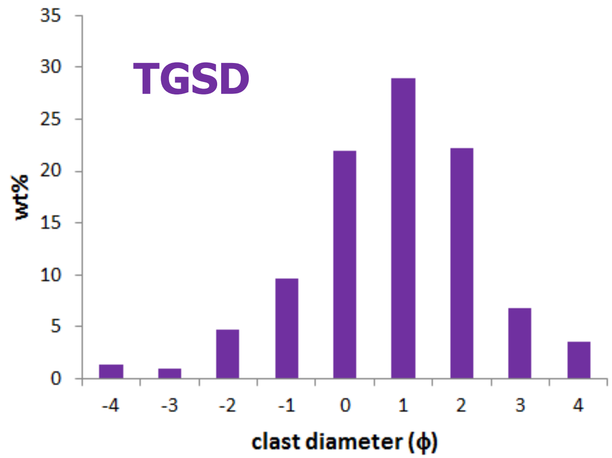


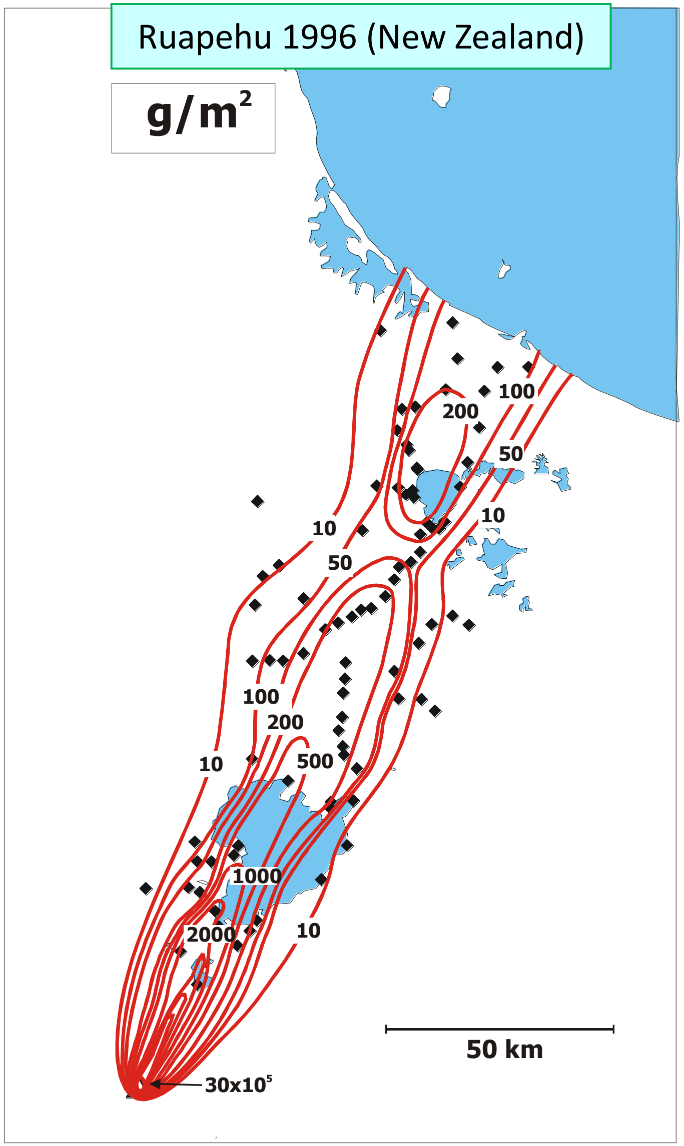
Characterization of ESPs: grainsize distribution

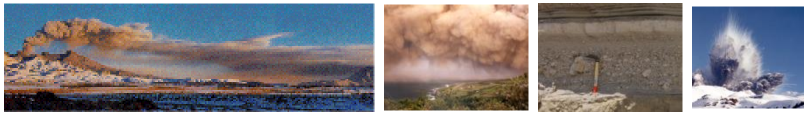


TOTAL GRAINSIZE DISTRIBUTION



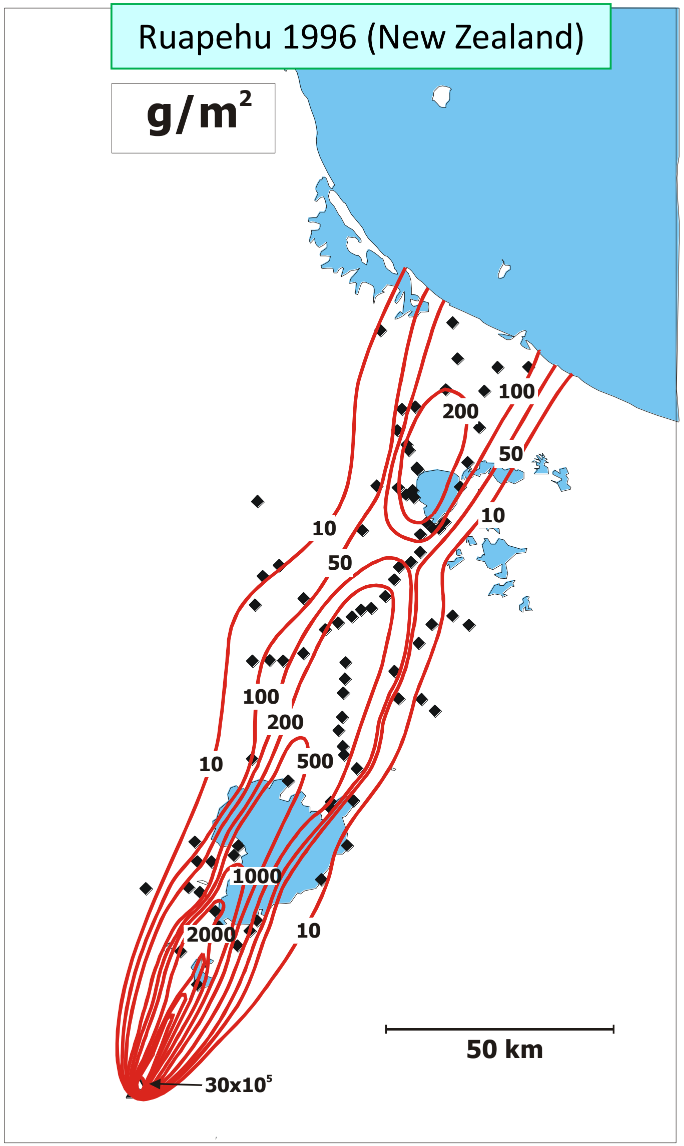






TOTAL GRAINSIZE DISTRIBUTION

The determination of the total grainsize distribution relies on the averaging technique used and on the exposure of the deposit



MOST COMMON TECHNIQUES:

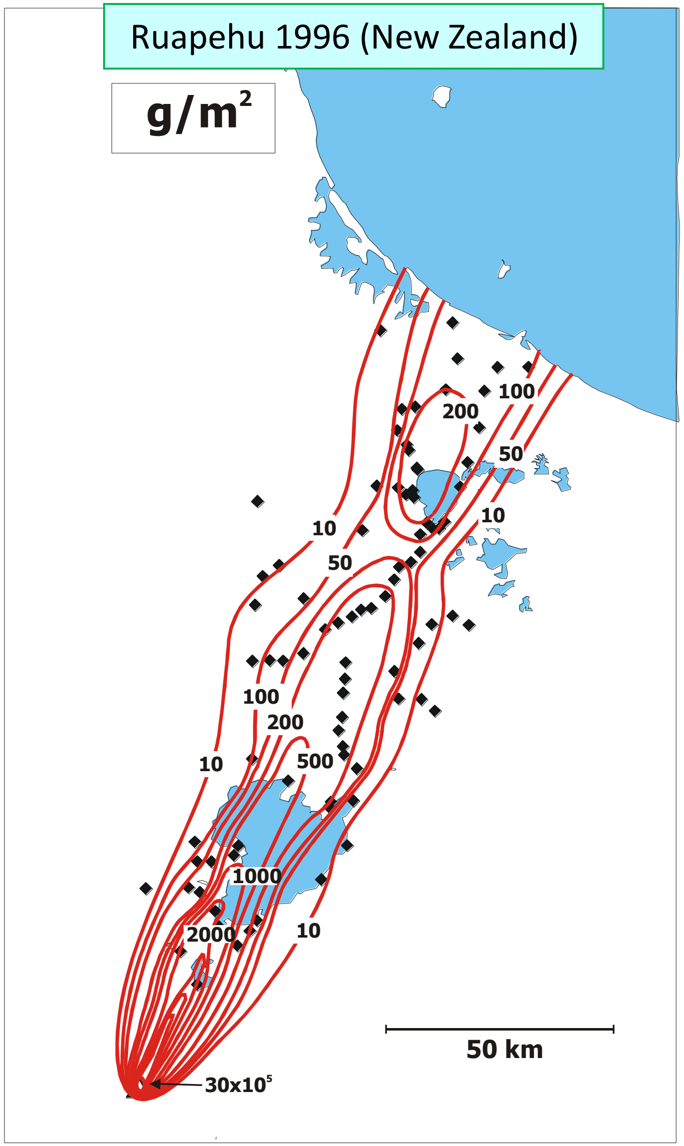
- <u>weighted average</u>

  does not deal well with deposits with non-uniform distributions of data

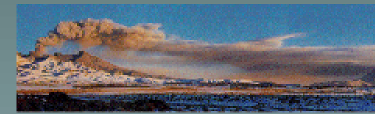
- <u>various types of sectorisation</u>

  biased due to the arbitrary choice of sectors

TOTAL GRAINSIZE DISTRIBUTION



Bonadonna and Houghton 2005




EXERCISE 1

DETERMINATION OF
TOTAL GRAIN-SIZE DISTRIBUTION

https://github.com/e5k/TOTGS




MAIN QUESTION:

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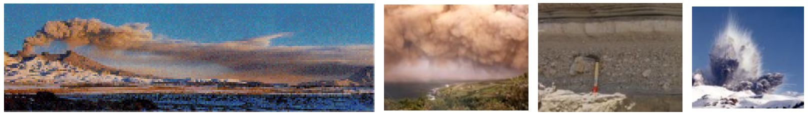
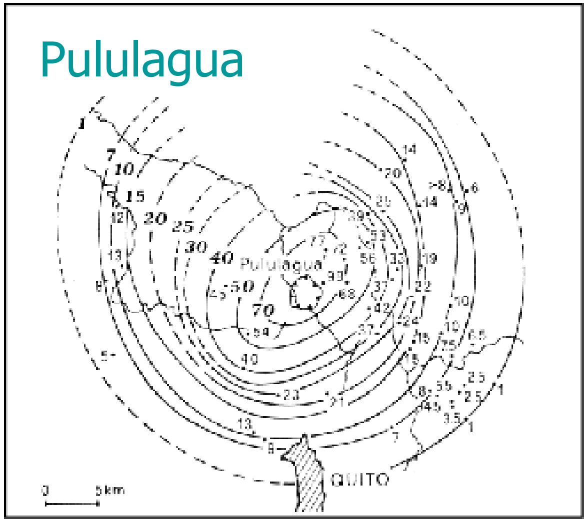
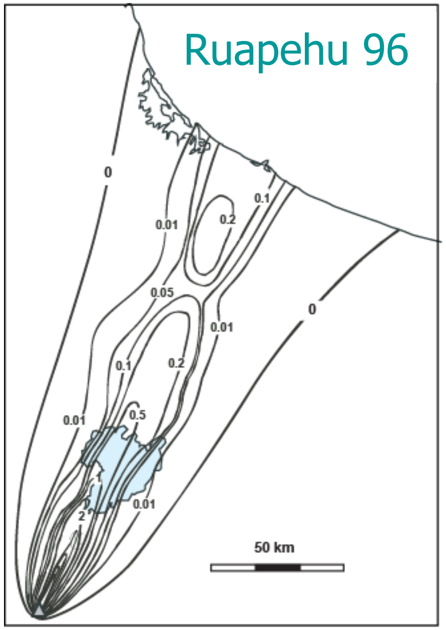


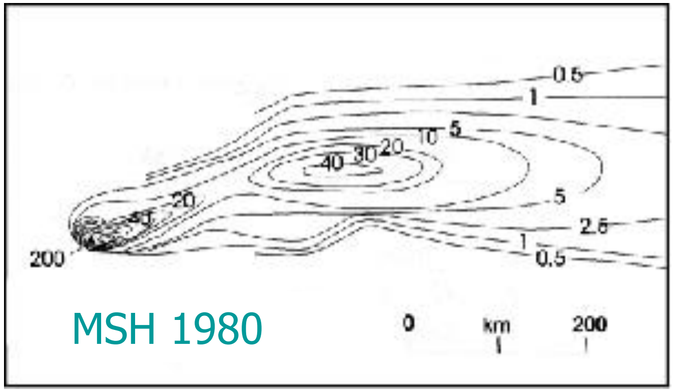
ERUPTED MASS/VOLUME

PROBLEMS:

- Non-linearity of the functions linking thickness and area
- General scarcity of data
- Lack of distal and very proximal data







Isopach/isomass maps



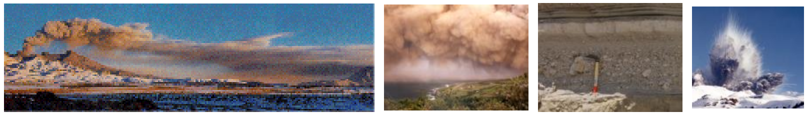

ERUPTED MASS/VOLUME

PROBLEMS:

- Non-linearity of the functions linking thickness and area
- General scarcity of data
- Lack of distal and very proximal data

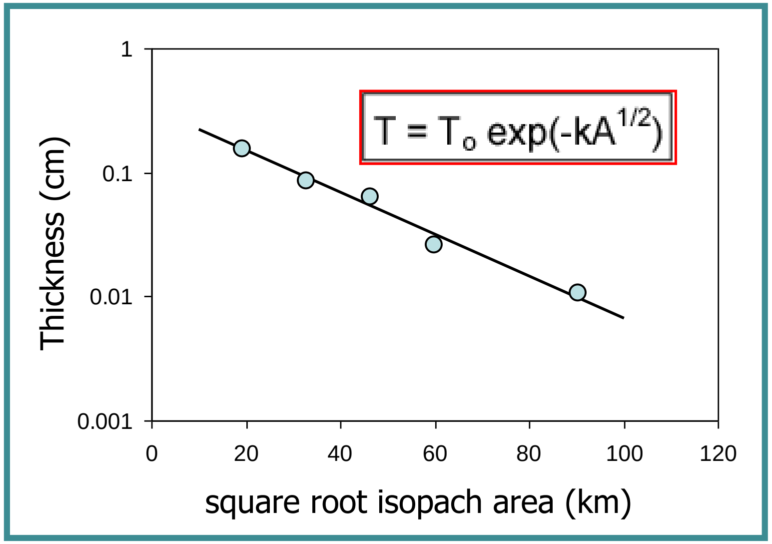
MOST COMMONLY USED MODEL:

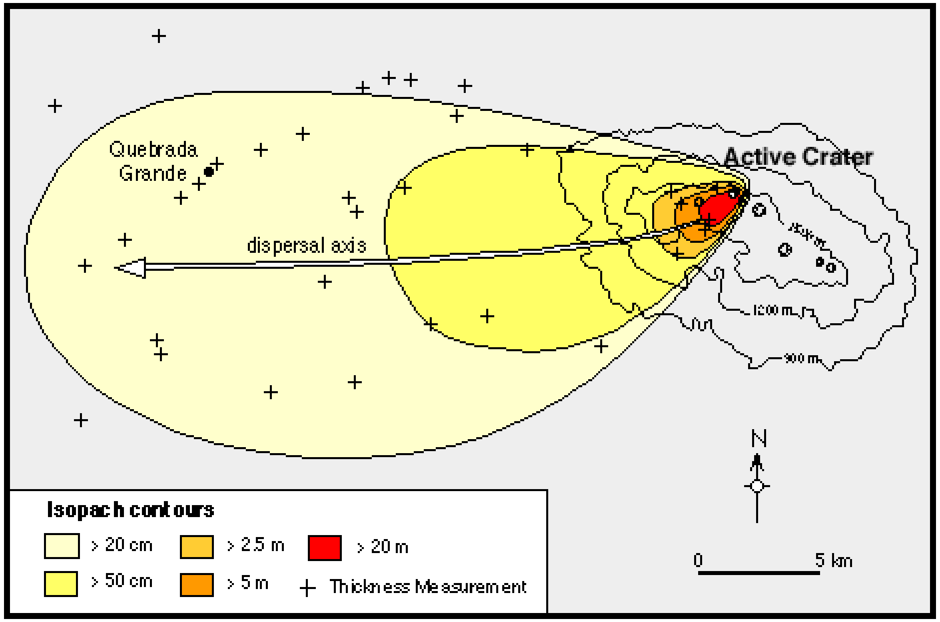
→ **EXPONENTIAL CURVE FITTING**



ERUPTED MASS/VOLUME

EXPONENTIAL FITTING

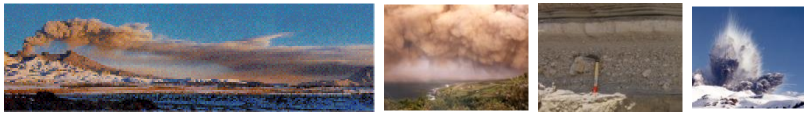




$$V = To\ 13.08\ bt^2$$

$$bt = \ln 2/(k\sqrt{\pi})$$

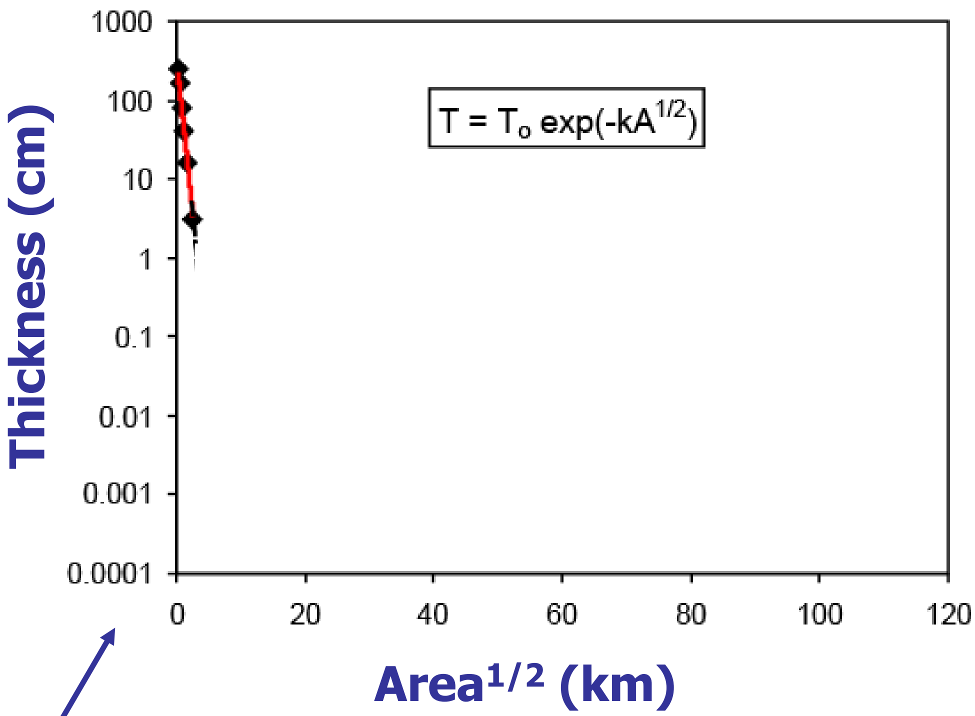
Pyle, 1989



ERUPTED MASS/VOLUME

EXPONENTIAL CURVE FITTING

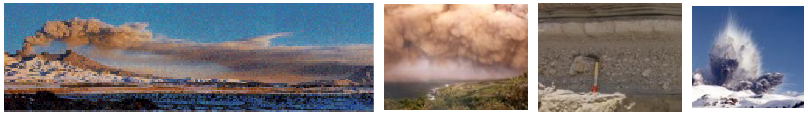
(1 exp. segment; Pyle 1989)



e.g. Ruapehu 1996 eruption

Empirical and theoretical support:

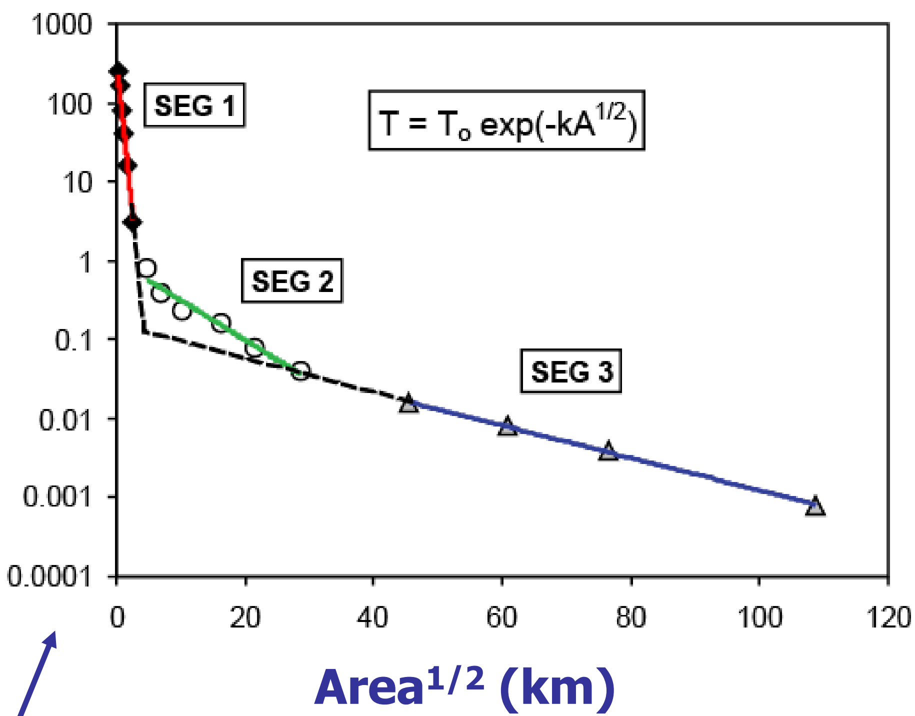
- Thorarinsson (1954)
- Bursik et al. (1992), Sparks et al. (1992)



ERUPTED MASS/VOLUME

EXPONENTIAL CURVE FITTING

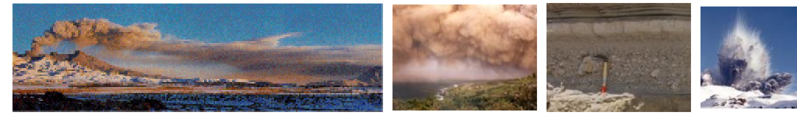
(multiple exp. segments: Fierstein and Nathenson 1992; Pyle 1995; Bonadonna and Houghton 2005)



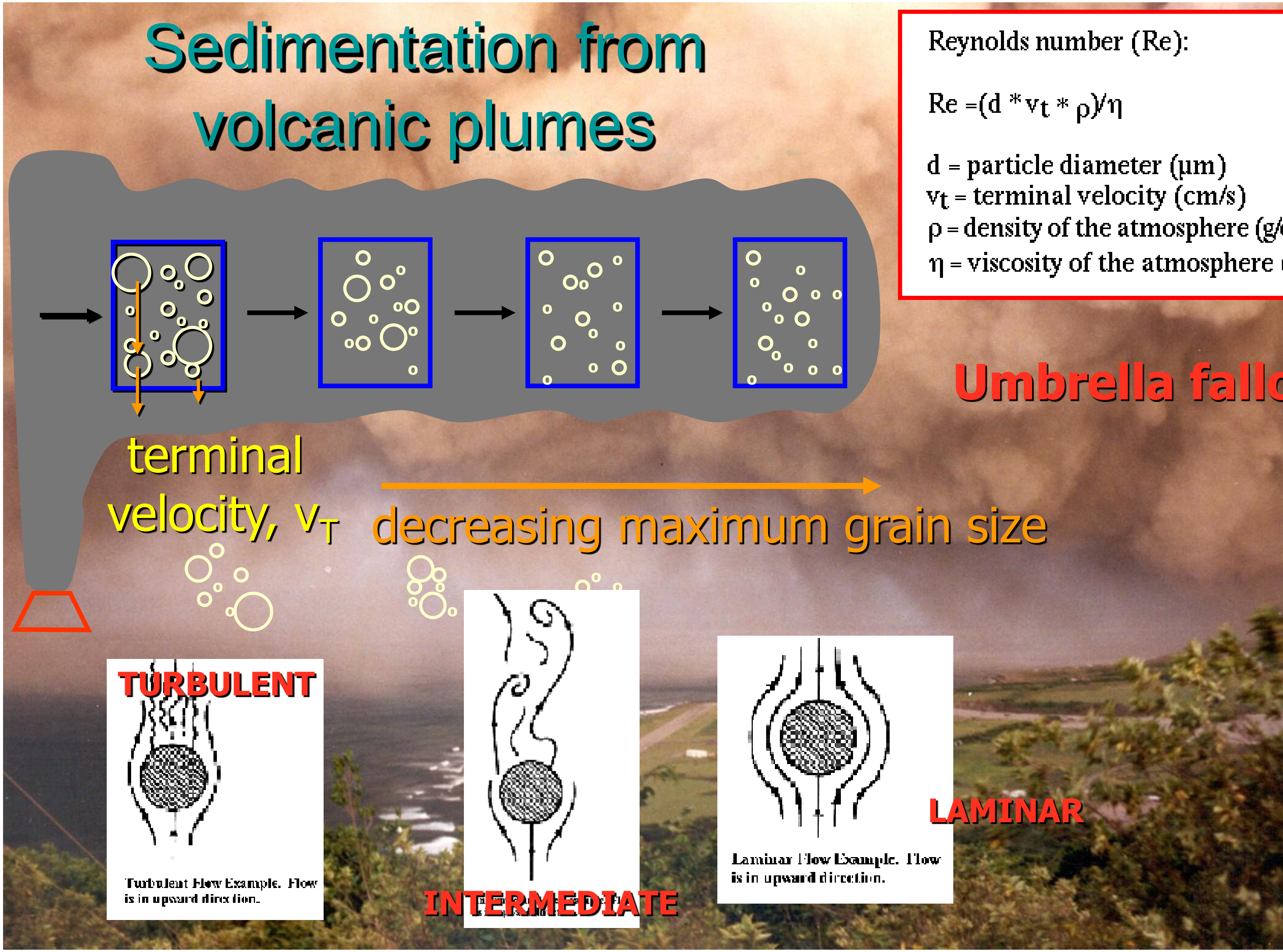
e.g. Ruapehu 1996 eruption

Empirical and theoretical support:

- **Thinning of well exposed deposits**
  e.g. Hildreth and Drake 1992 (Novarupta 1912); Fierstein and Hildreth 1992 (Quizapu 1932); Scasso et al. 1994 (Hudson 1991); Bonadonna and Houghton 2005 (Ruapehu 1996)
- **Rose 1993; Bonadonna et al. 1998**



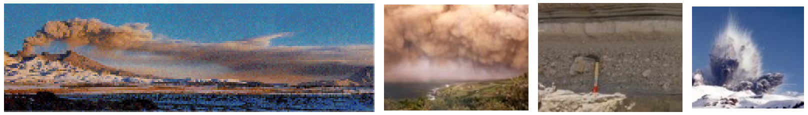
Sedimentation from volcanic plumes



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)



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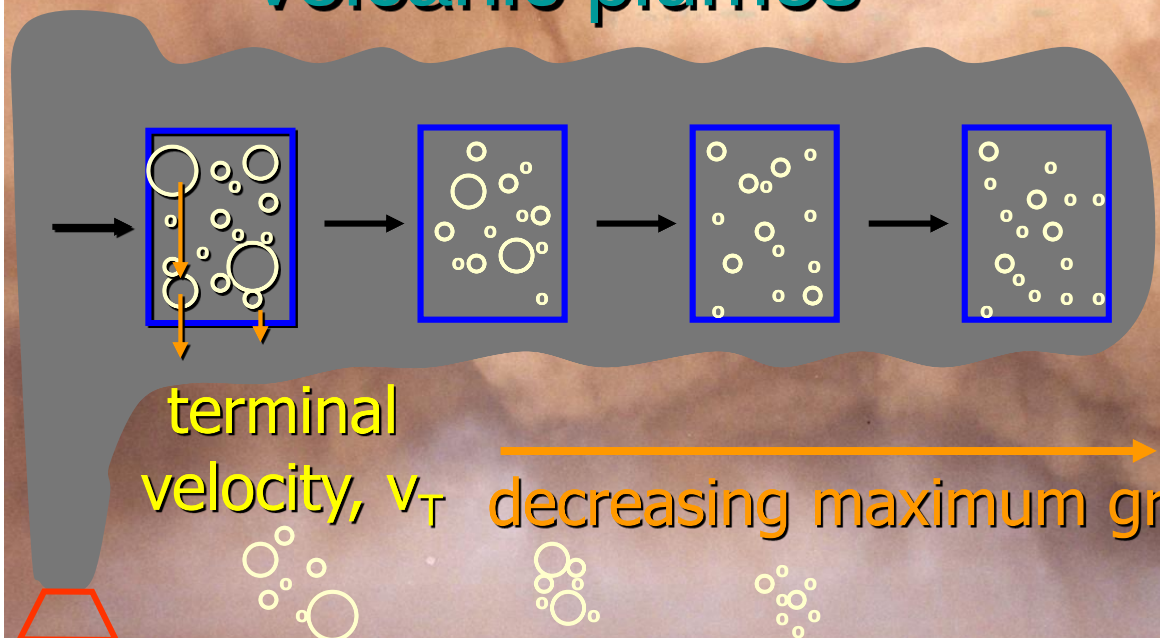


Umbrella fallout

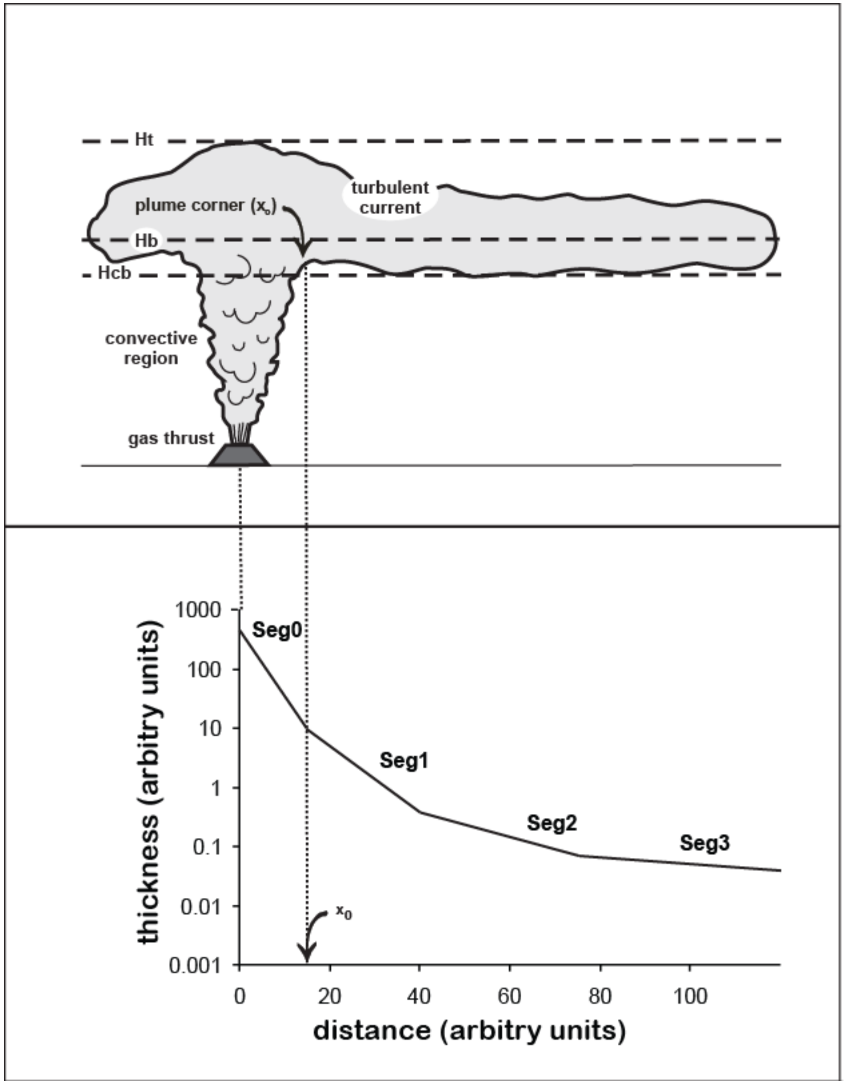
$V_t \approx (3.1\, g\rho d/\sigma)^{1/2}$ (for Reynolds numbers 500-200,000)

$V_t \approx d(4\rho^2 d^2/225\mu\sigma)^{1/3}$ (for Reynolds numbers 6-500)

$V_t \approx (g\rho d^2/18\mu)$ (for Reynolds numbers <6)




Sedimentation from strong plumes



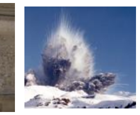
Segment 0: sedimentation from plume margins

Segment 1:
high-Re particle settling

Segment 2:
intermediate-Re particle

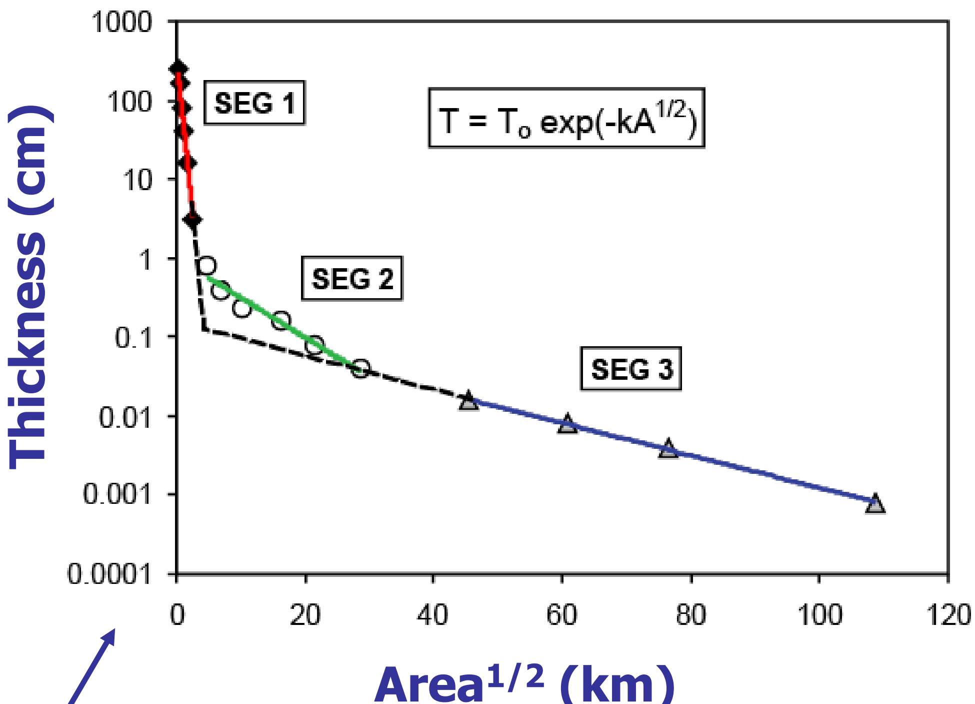
Segment 3:
low-Re particle settling



ERUPTED MASS/VOLUME

EXPONENTIAL CURVE FITTING



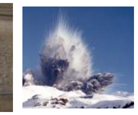
Variations:

- **1 exp. segment (Pyle 1989)**
- **2 exp. segments** (Fierstein and Nathenson 1992, Pyle 1995)
- **>2 exp. segments** (Bonadonna and Houghton 2005)
- **One proximal isopach line** (Legros 2000)
- **Missing distal data** (Sulpizio 2005)
- **Thickness measurements** (Burden et al. 2013)

PROBLEM: underestimation of volume in case of missing distal data

e.g. Ruapehu 1996 eruption

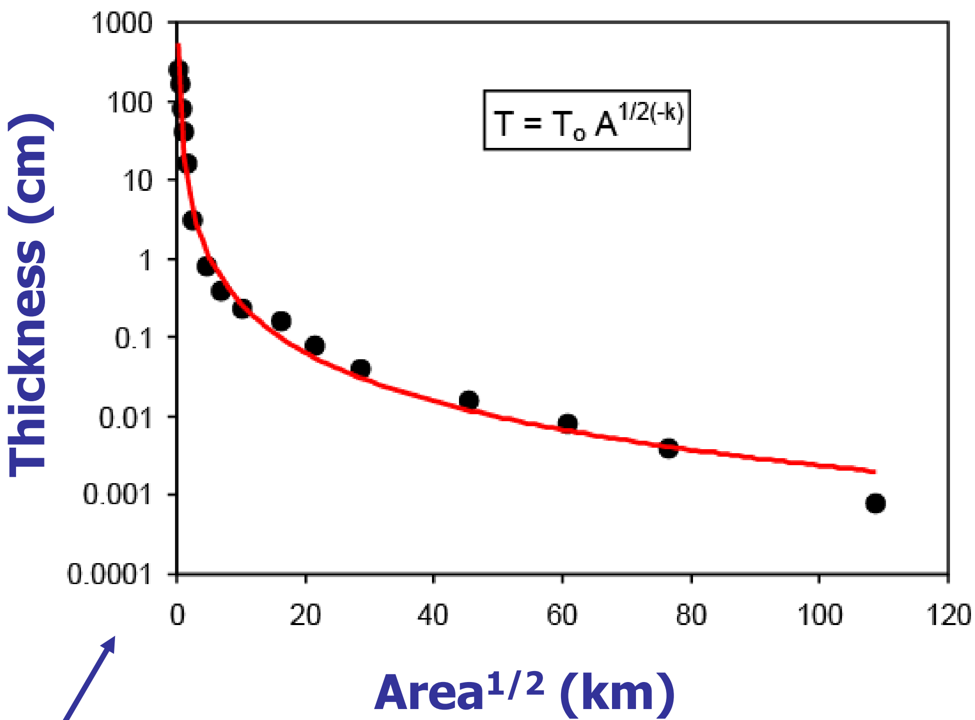


ERUPTED MASS/VOLUME

POWER-LAW CURVE FITTING

(Bonadonna and Houghton 2005)



e.g. Ruapehu 1996 eruption

Empirical and theoretical support:

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  e.g. Hildreth and Drake 1992 (Novarupta 1912); Fierstein and Hildreth 1992 (Quizapu 1932); Scasso et al. 1994 (Hudson 1991); Bonadonna and Houghton 2005 (Ruapehu 1996)

- **Rose 1993; Bonadonna et al. 1998**

PROBLEM: choice of integration limits




ERUPTED MASS/VOLUME

POWER-LAW CURVE FITTING

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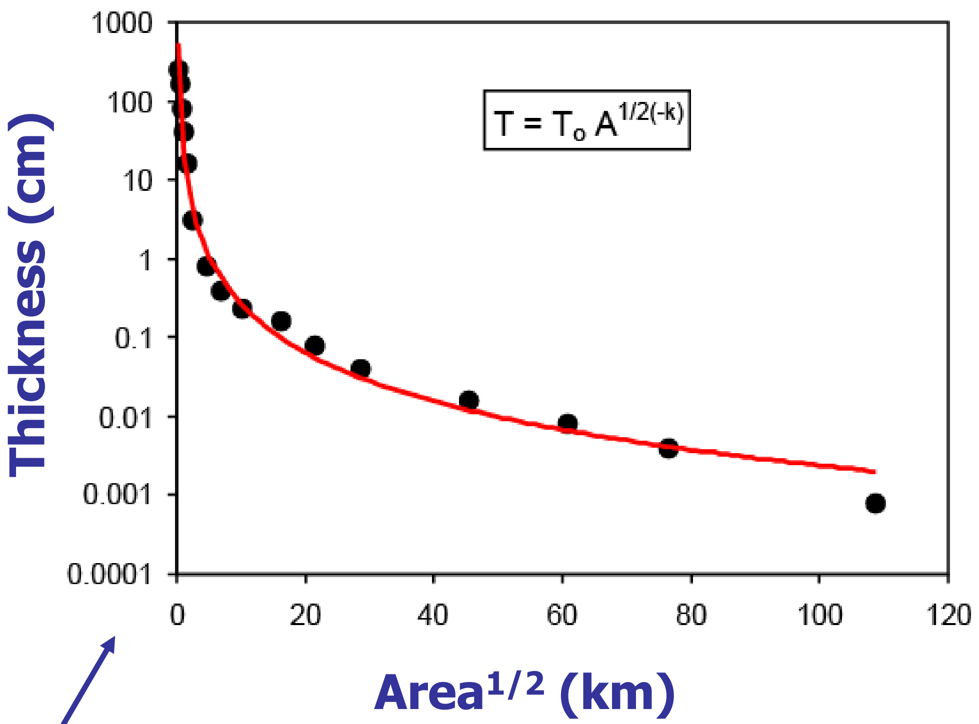


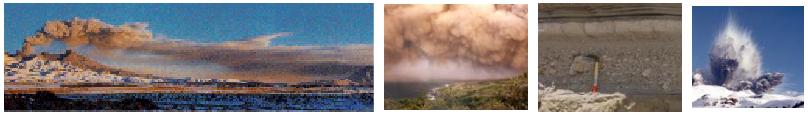
$$Volume = \frac{2T_{pl}}{2-k}\left(C^{(2-k)} - B^{(2-k)}\right)$$

k>2 → rapid thinning → small deposit → Volume sensitive to prox integration limit

k<2 → gradual thinning → large deposit → Volume sensitive to distal integration limit

e.g. Ruapehu 1996 eruption

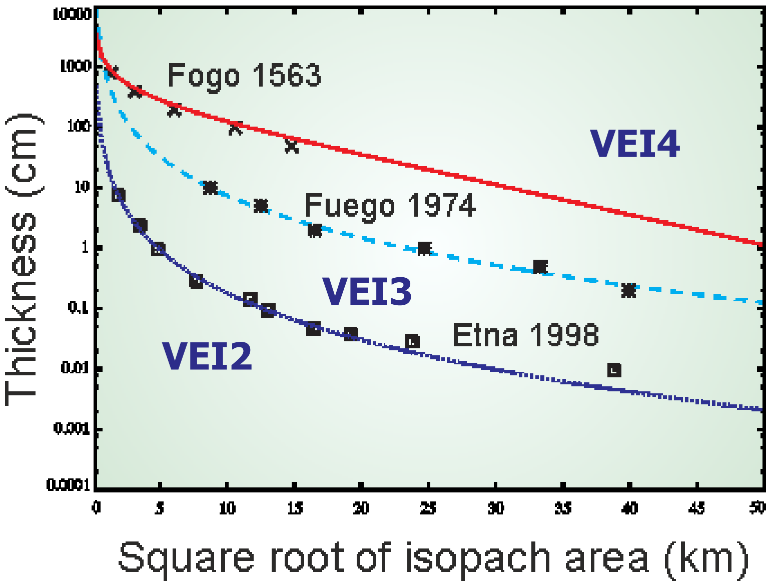
PROBLEM: choice of integration limits



ERUPTED MASS/VOLUME

WEIBULL CURVE FITTING

(Bonadonna and Costa 2012)

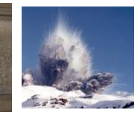


$$V = \int_0^\infty T \mathrm{d}A = 2\int_0^\infty T(x)\,x\,\mathrm{d}x = \frac{2\theta\lambda^2}{n}\left[1 - \mathrm{e}^{-\left(\frac{x}{\lambda}\right)^n}\right]_0^\infty = \boxed{\frac{2\theta\lambda^2}{n}}$$

λ: characteristic decay length scale of deposit thinning (km);

θ: thickness scale (cm)



ERUPTED MASS/VOLUME

PROS and CONS

Exponential fit:

☺ Easy to apply

☺ Can be integrated between 0 and ∞

☹ Underestimates the volume in case of missing distal and/or proximal data

☹ The choice of exponential segments can be arbitrary and biased by available data

Power-law fit:

☺ Easy to apply

☺ Can better describe the natural gradual deposit thinning with distance

☹ Cannot be integrated between 0 and ∞ (→ difficult choice of extremes of integration)

Weibull fit:

☺ Can better describe the natural gradual deposit thinning with distance

☺ Can be integrated between 0 and ∞

☹ Is of more complex application and needs > 3 data points (because it has 3 free par.)

UNIVERSITÉ DE GENÈVE
FACULTY OF SCIENCE
Department of Earth Sciences



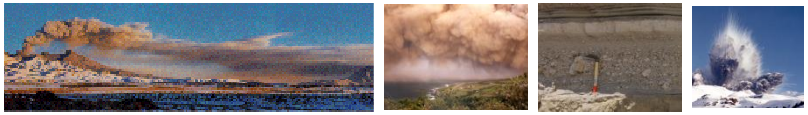

Volcanic Explosivity Index (VEI)

Volume of ejecta: both tephra and igmbrite if present

Criteria VEI:	0	1	2	3	4	5	6	7	8
DESCRIPTION	non-explosive	small	moderate	mod-large	large	very large------------------------------------			
VOLUME OF EJECTA (M^3)	$<10^4$	10^4-10^6	10^6-10^7	10^7-10^8	10^8-10^9	10^9-10^{10}	10^{10}-10^{11}	10^{11}-10^{12}	$>10^{12}$
(TSUYA CLASSIFICATION)+	(I)	(II-III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX) ---------	
COLUMN HEIGHT (KM)*	<0.1	0.1-1	1-5	3-15	10-25	>25--			
QUALITATIVE DESCRIPTION	---"gentle, effusive"--		-----"explosive"-------		-----"cataclysmic, paroxysmal, colossal"----------------------				
				"severe, violent, terrific"--					
CLASSIFICATION		----------"Strombolian"-			-------"Plinian"--				
	-------"Hawaiian"------		-------------"Vulcanian"-------------			--------"Ultraplinian"---------------------------			
DURATION (hours)	------------------------<1--------------				------------>12--				
of continuous blast			-----------------1-6----------------						
				--------------------6-12---------------					
CAVW MAX EXPLOSIVITY**	--lava flows-	---------------explosion or nuée ardente--							
		------phreatic---------......................................							
	-----dome or mudflow---								
TROPOSPHERIC INJECTION	negligible	minor	moderate	substantial--					
STRATOSPHERIC INJECTION	none	none	none	possible	definite	significant------------------------------------			

+If all eruptive products were pyroclastic ejecta
*For VEI's 0-2, uses km above crater; for VEI's 3-8, uses km above sea level.
**The most explosive activity indicated for the eruption in the Catalogue of Active Volcanoes

Newhall and Self 1982



Dense Rock Equivalent (km^3)

Mass deposit = Mass magma

$$\rho_{deposit} \times V_{deposit} = \rho_{magma} \times V_{magma}$$

$$V_{magma}\,(DRE) = \rho_{dep} \times V_{dep} \,/\, \rho_{magma}$$




MAIN QUESTION:

How well can we constrain explosive eruptions?

→ Erupted Volume/Mass, **Plume Height**, Mass Eruption Rate (MER), Eruption Duration, Total Grain-Size Distribution (TGSD)

PLUME HEIGHT

- Direct observations
- Satellite images (thermal infrared data; cloud shadow clinometry; cloud stereoscopy)
- Empirical methods (Rossi et al. 2018)
- Analytical methods (inversion on grainsize)

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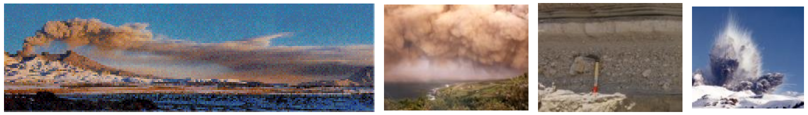
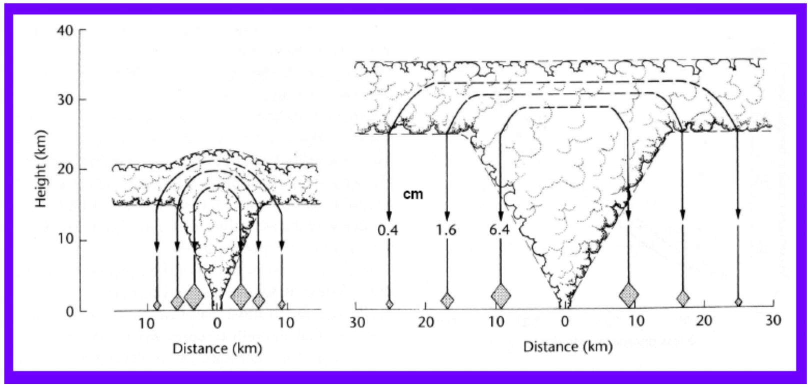


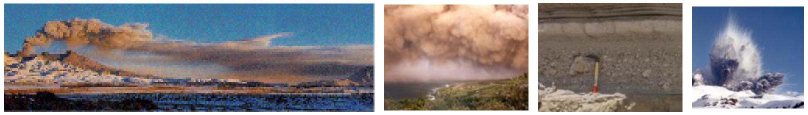
COLUMN HEIGHT

Method of Carey and Sparks (1986)



a more intense plume carries a clast higher:

- **it takes longer to fall**
- **the wind carries it further away**
- **it falls further from the vent**



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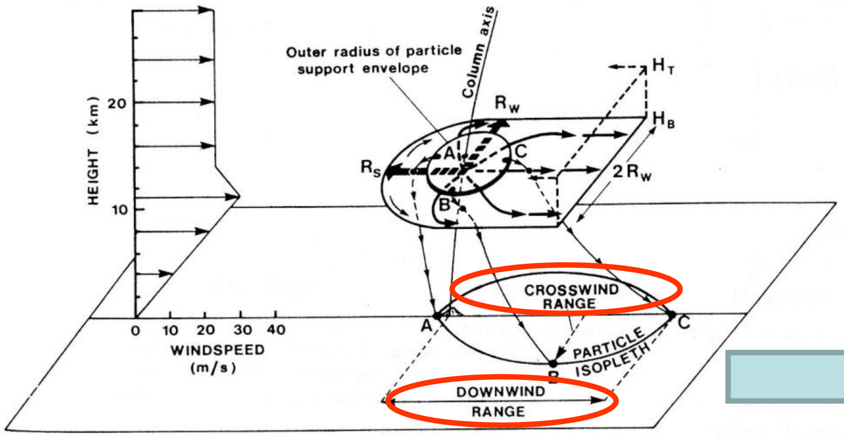

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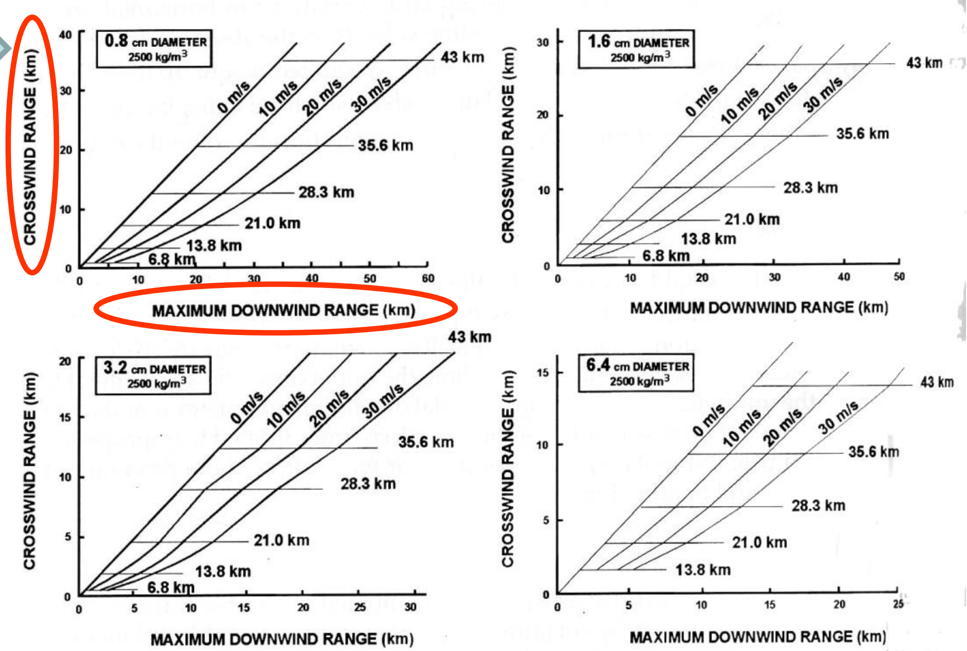
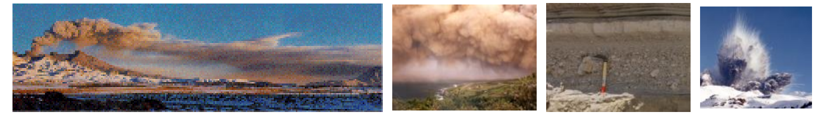


Main assumptions:

- Sustained strong plumes
- Monotone plume vertical velocity
- Fixed wind profile → trop.=11km



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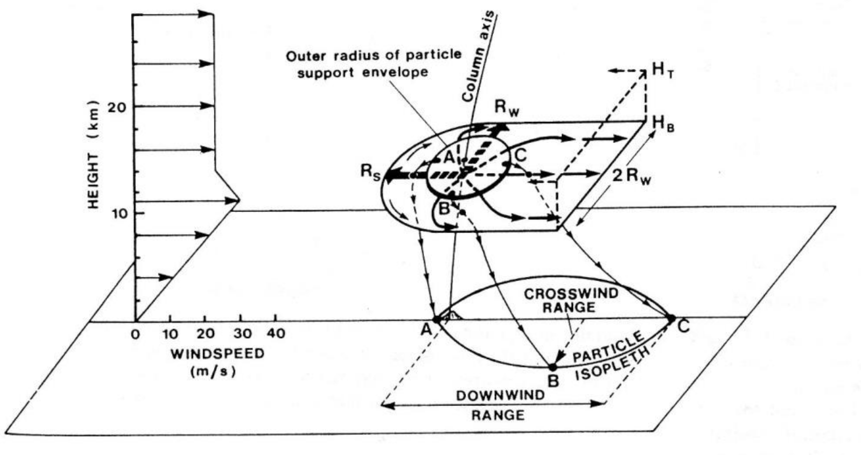
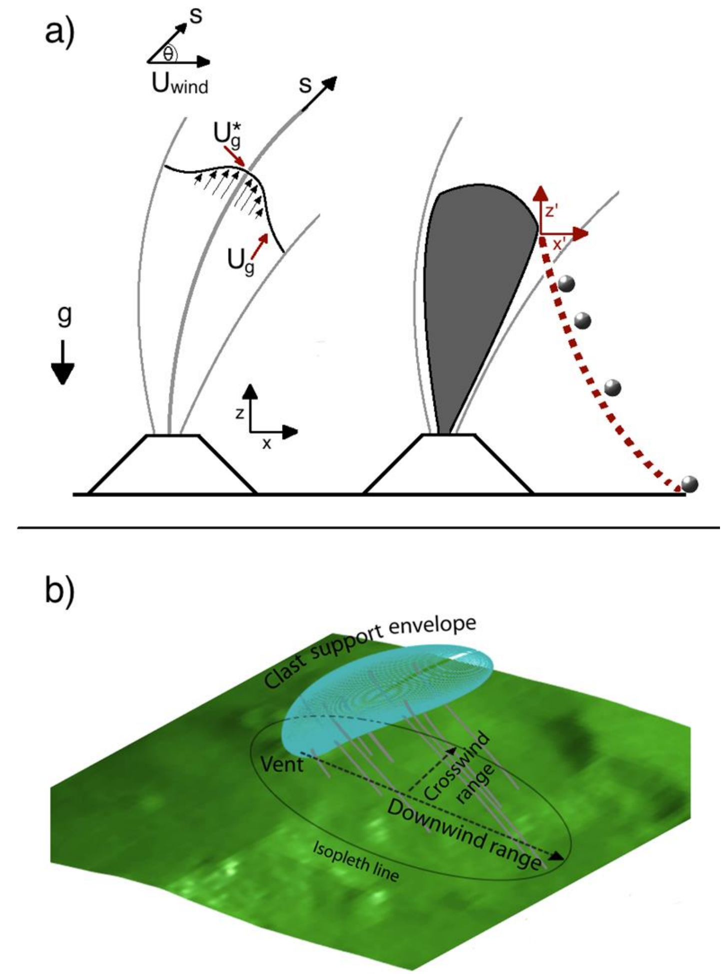
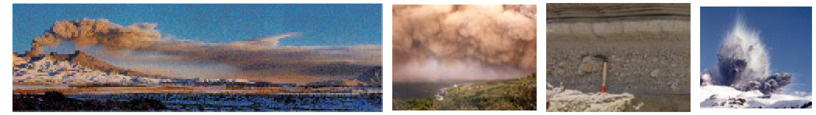




Implementations:

- Better description of plume dynamics (e.g. better description of gravitational spreading) and of the effect of wind on plume rise
- Wind profiles used to construct the nomograms are the same as for C&S86 but real 3D wind profiles can also be considered
- Effect of particle shape on settling velocity



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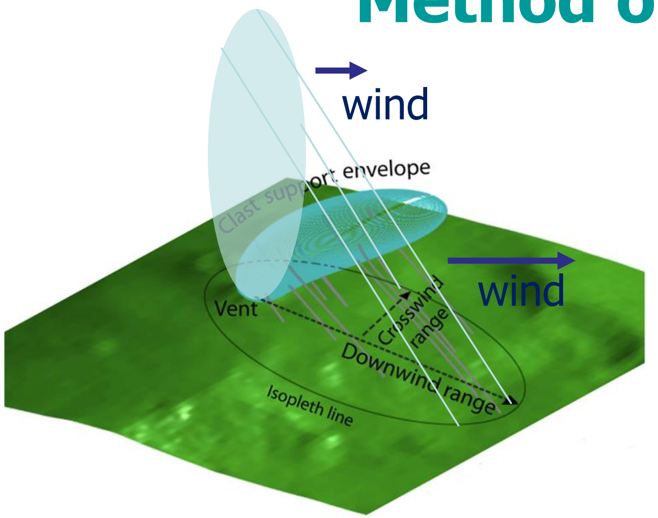

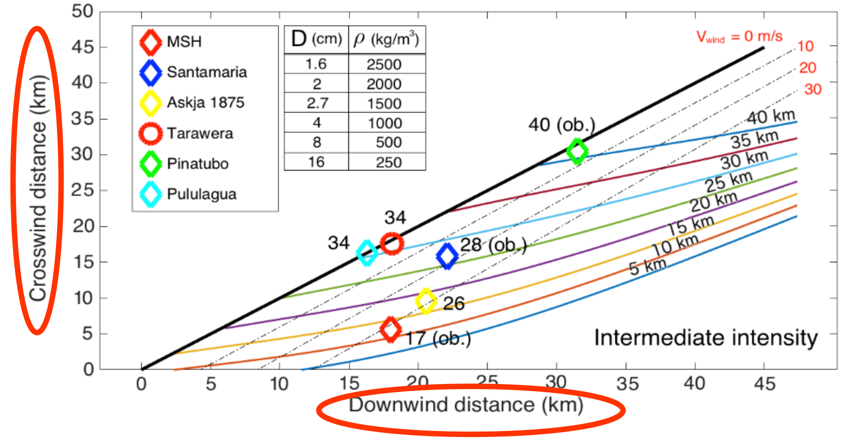

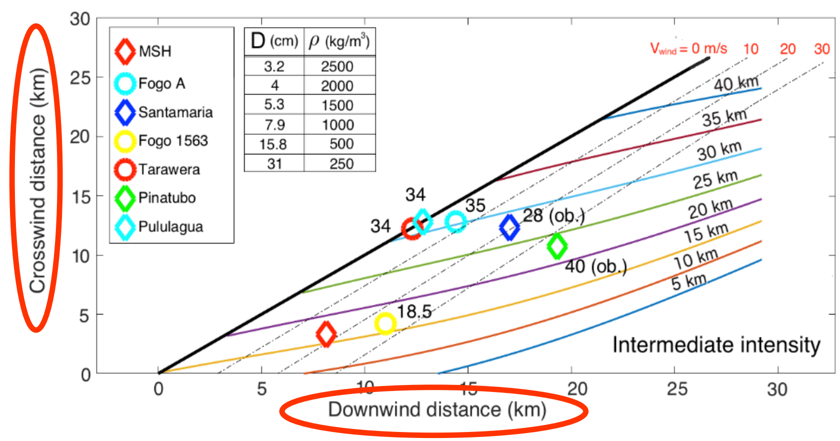

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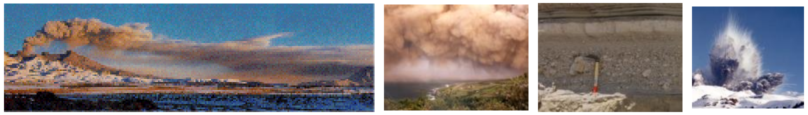
Relation between height and CW range is not longer univocal for a given DW range (effect of wind)



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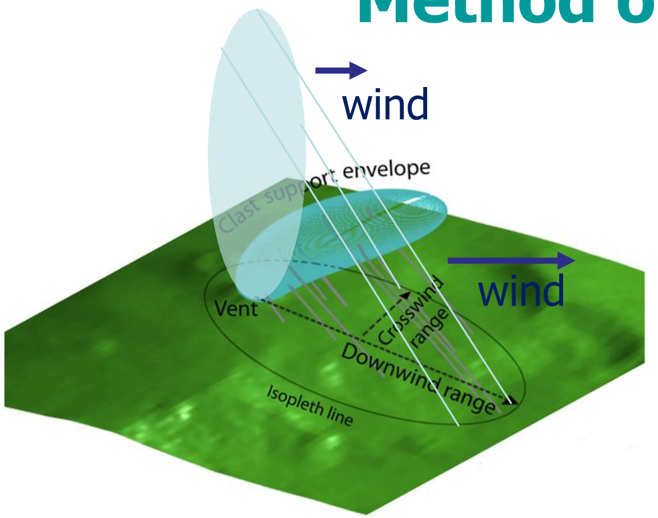

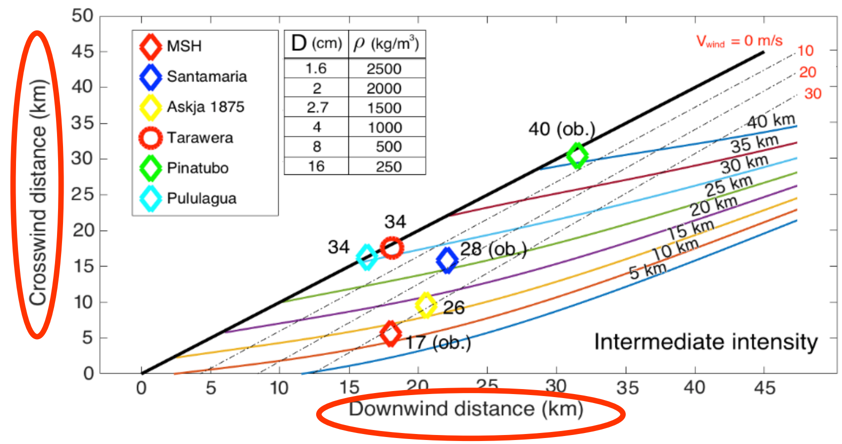

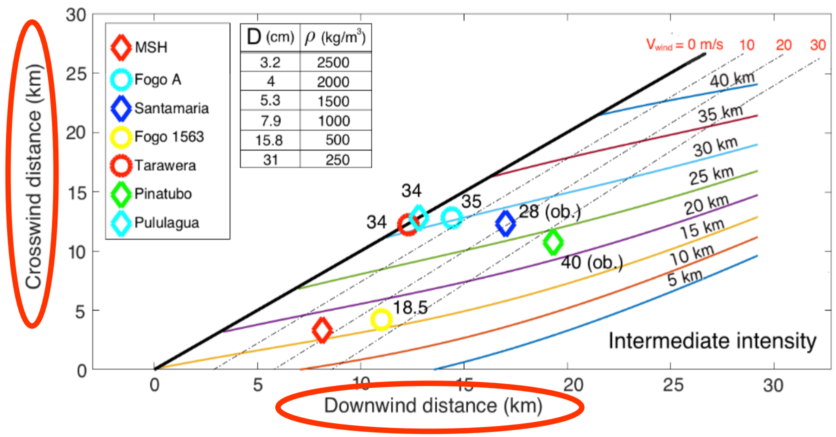

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Resulting heights are generally lower than those predicted by C&S86 because also the wind is accounted for




MAIN QUESTION:

How well can we constrain explosive eruptions?

How well can we constrain Eruption Source Parameters (ESP)?

→ **Erupted Volume/Mass, Plume Height,**

Mass Eruption Rate (MER), Eruption Duration,

Total Grain-Size Distribution (TGSD)




MASS ERUPTION RATE

$$\mathbf{Ht}\ (\mathrm{km}) = \mathbf{K}\ [\mathbf{MER}(\mathrm{Kg/s})]^{1/4}$$

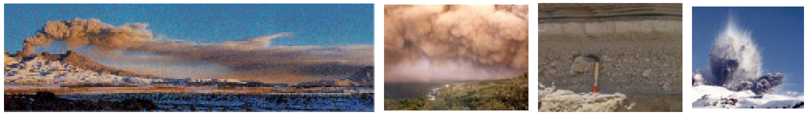
Wilson and Walker 1987

K= 0.236

- Central vent
- Silicic eruptions
- No wind
- Dry atmosphere

K= 0.295
K= 0.247
K= 0.244

Fontana Lapilli (Masaya, Nicaragua); Etna 2001, 2002 (Italy)
Wehrmann et al. 2006, Scollo et al. 2007, Andronico et al. 2008



MASS ERUPTION RATE

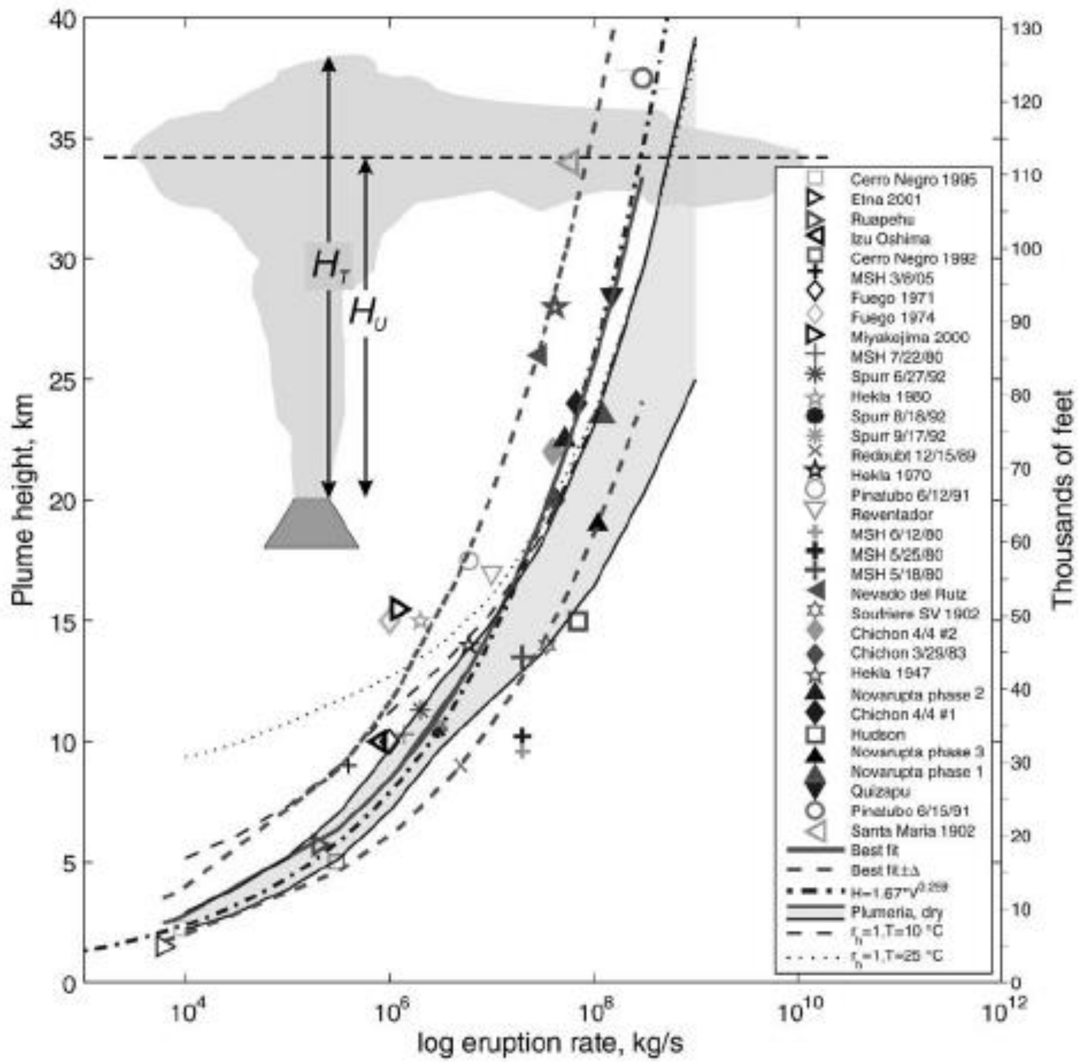
Ht (km)= **K [MER**(Kg/s)**]$^{1/4}$**

Wilson and Walker 1987

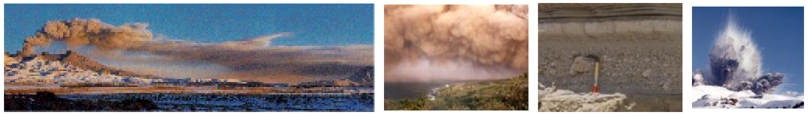
➢ Mass eruption rate from empirical equations can only be constrained within a factor of 10

Ht = 2.00 Q$^{0.241}$

Mastin et al. 2009

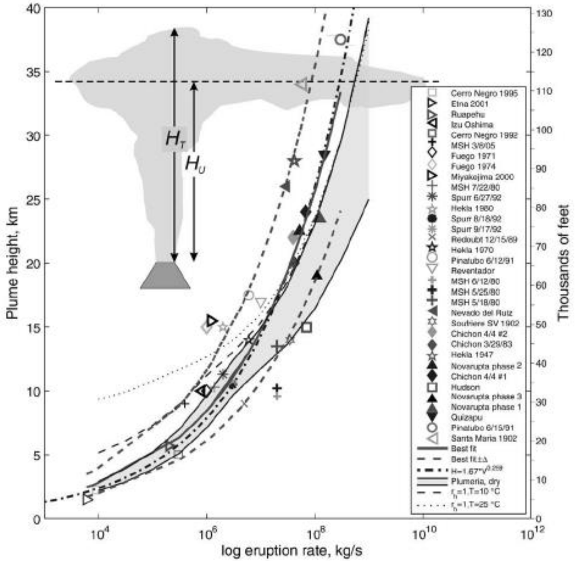


Q=volumetric flow rate (m^3/s)
MER=Q x magma density
= Q x 2500 kg m^{-3}



MASS ERUPTION RATE

$$MER = \pi \frac{\rho_{a0}}{g'} \left(\frac{\alpha^2 \overline{N}^3}{10.9} H^4 + \frac{\beta^2 \overline{N}^2 \overline{v}}{6} H^3 \right)$$



H	Plume height
$\overline{N}$	Average buoyancy frequency across the plume height
$\overline{v}$	Average wind velocity across the plume height
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 ERUPTION RATE

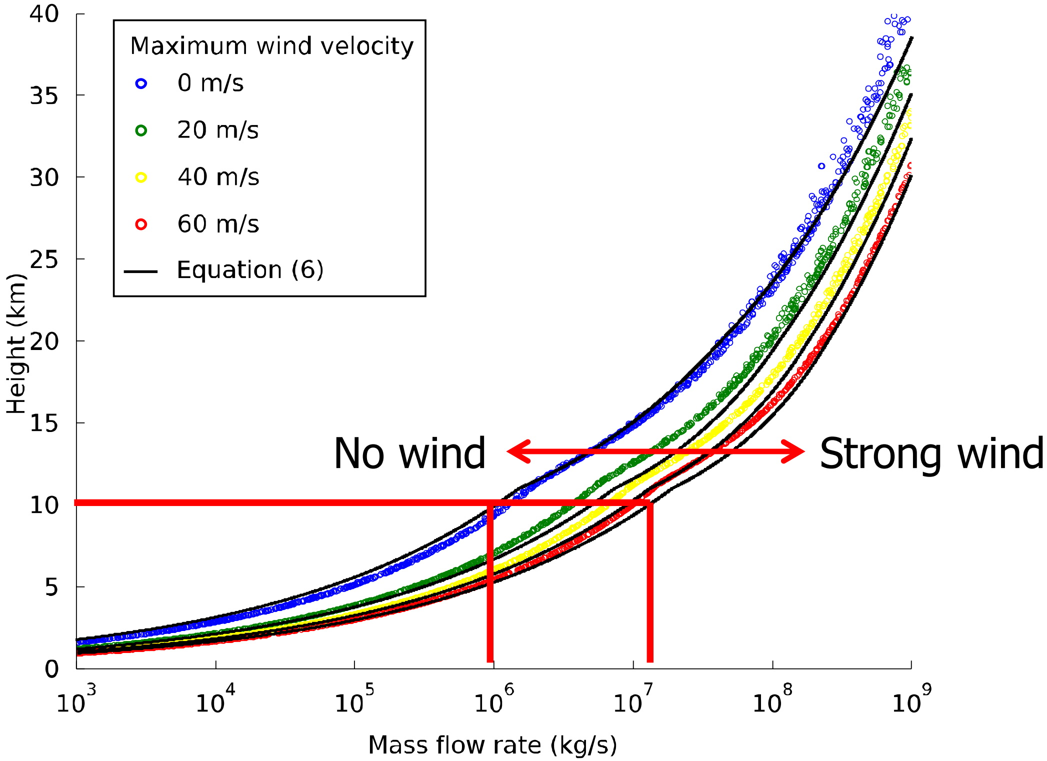
$$MER = \pi \frac{\rho_{a0}}{g'} \left(\frac{\alpha^2 \overline{N}^3}{10.9} H^4 + \frac{\beta^2 \overline{N}^2 \overline{v}}{6} H^3 \right)$$

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

$$\Pi = \frac{\overline{N} H}{1.8 \overline{v}} \left(\frac{\alpha}{\beta} \right)^2$$

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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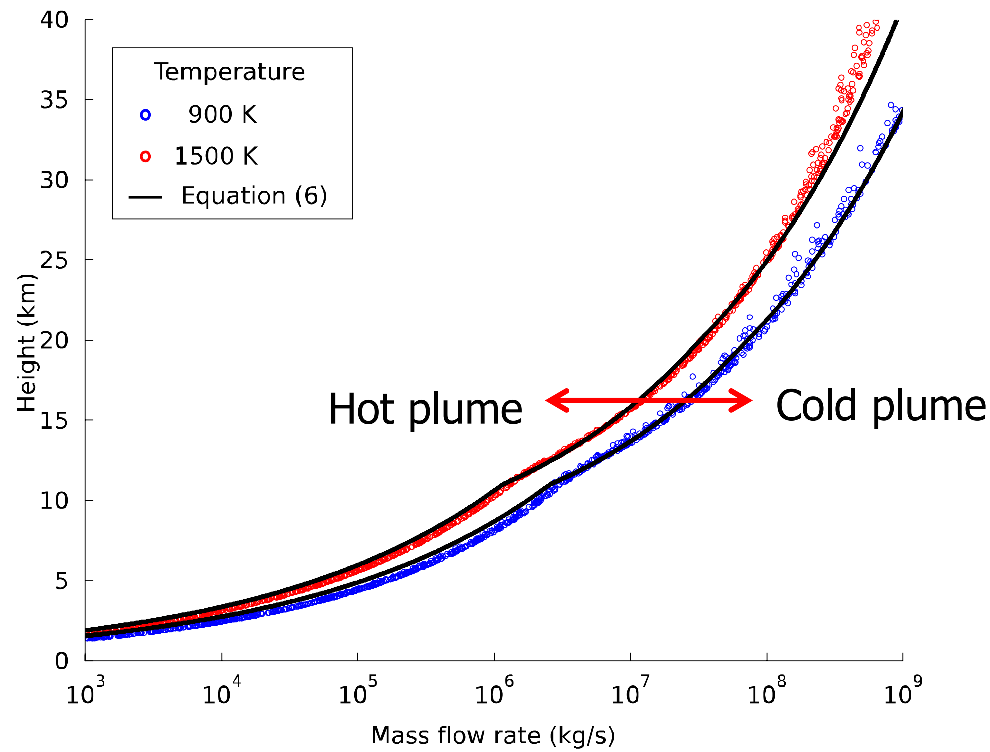


Degruyter and Bonadonna (2012)




MASS ERUPTION RATE AND DURATION

$$Ht = K\ MER^{1/4}$$

Wilson and Walker 1987

$$Ht = 2.00\ Q^{0.241} \quad \rightarrow MER = Q \times 2500\ kg\ m^{-3}$$

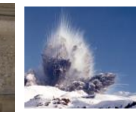
Mastin et al. 2009

$$MER = \pi \frac{\rho_{a0}}{g'} \left(\frac{\alpha^2 \overline{N}^3}{10.9} H^4 + \frac{\beta^2 \overline{N}^2 \overline{v}}{6} H^3 \right)$$

Degruyter and Bonadonna (2012)

Eruption duration (s) = Erupted Mass (kg) /MER (kg/s)

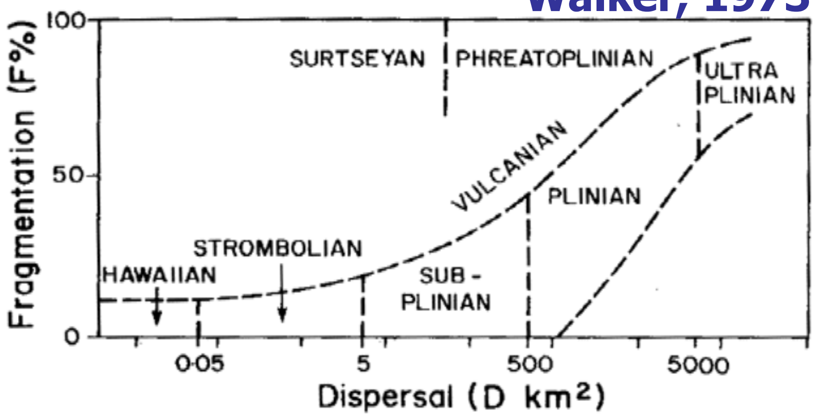


CLASSIFICATION

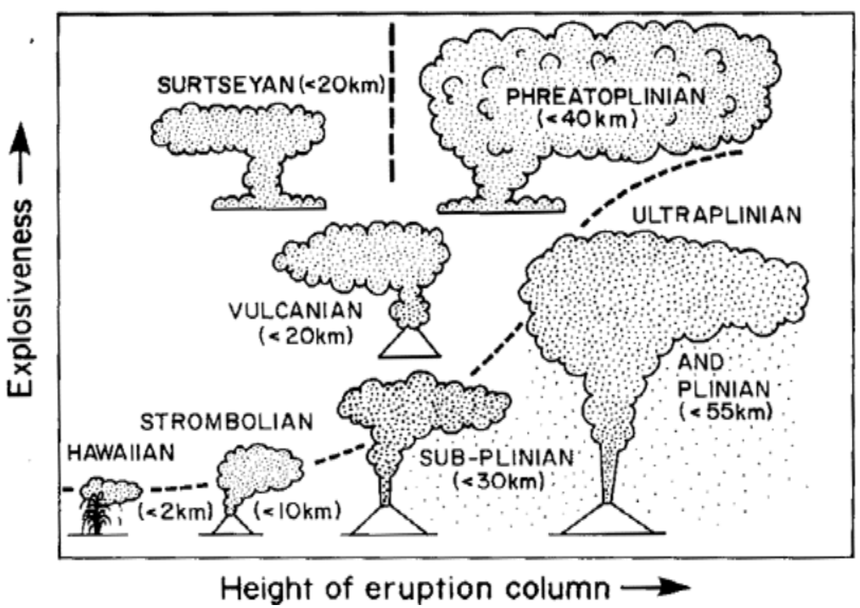
(a)

Walker, 1973



(b)

Cas et al. 1988

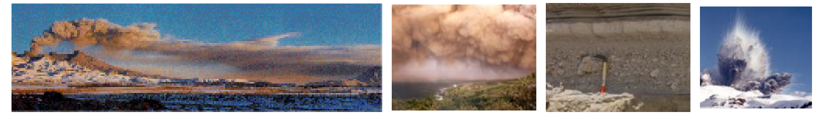


D (area of pyroclastic dispersal) → indicator of the column height.

Area enclosed by an isopach contour representing 1% of the maximum thickness (0.01 Tmax).

F (fragmentation) → indicator of the explosiveness of the eruption.

Percent of tephra <1mm, measured along an axis of dispersal where the isopach is 10% of Tmax (0.1 Tmax).

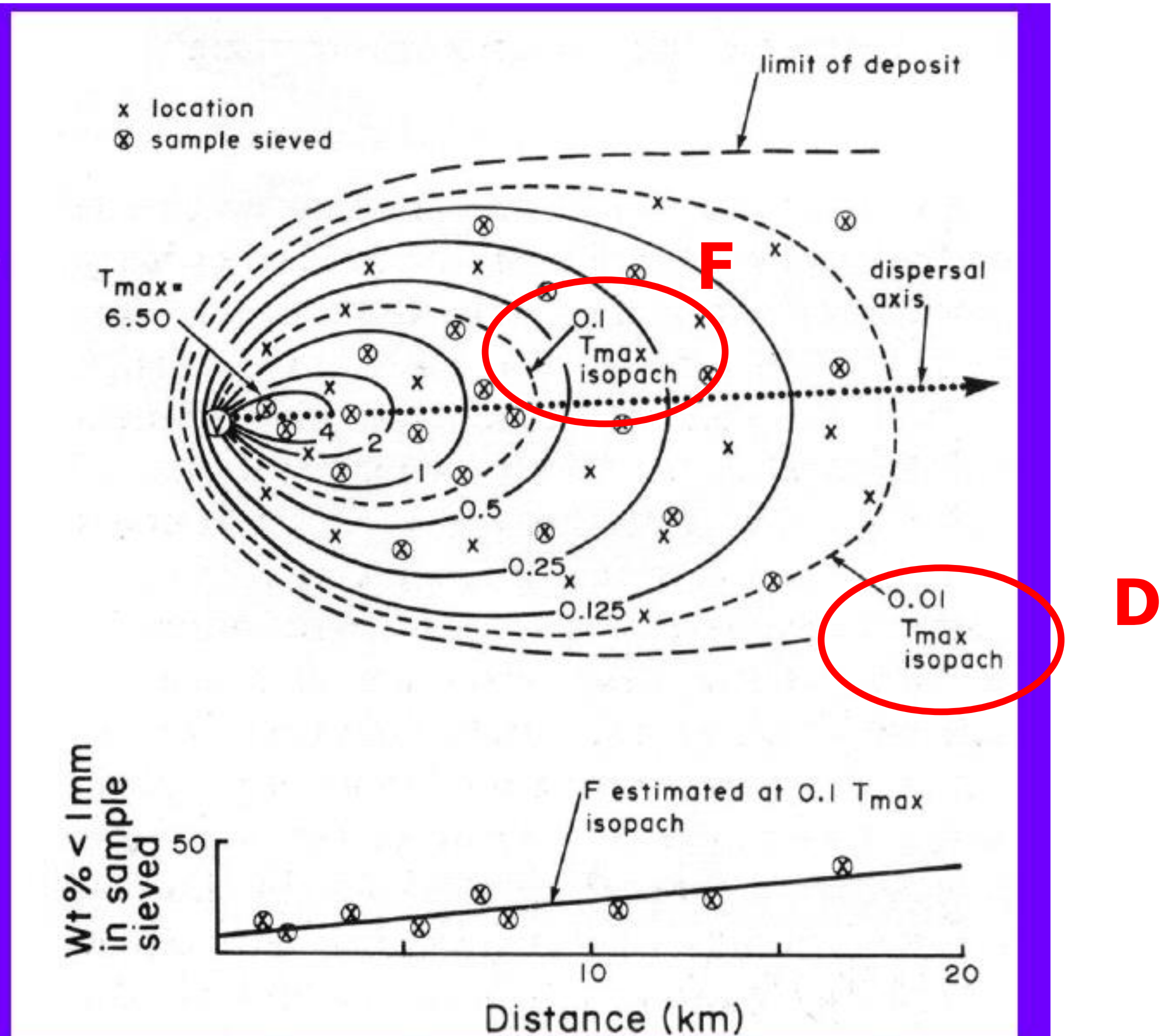


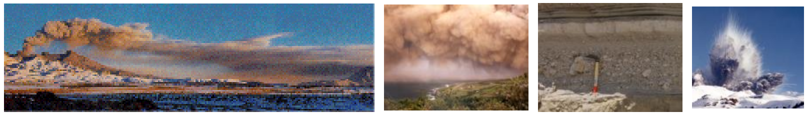
CLASSIFICATION

Fragmentation (F), a measure of how thoroughly the magma is blown apart.

It's one measure of the intensity of an explosion.

Walker, 1973

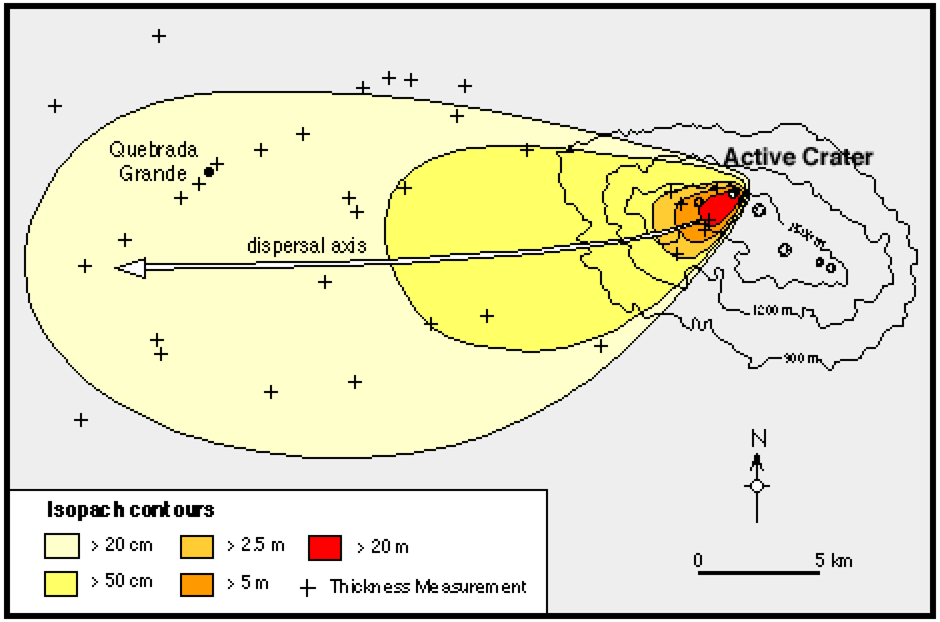


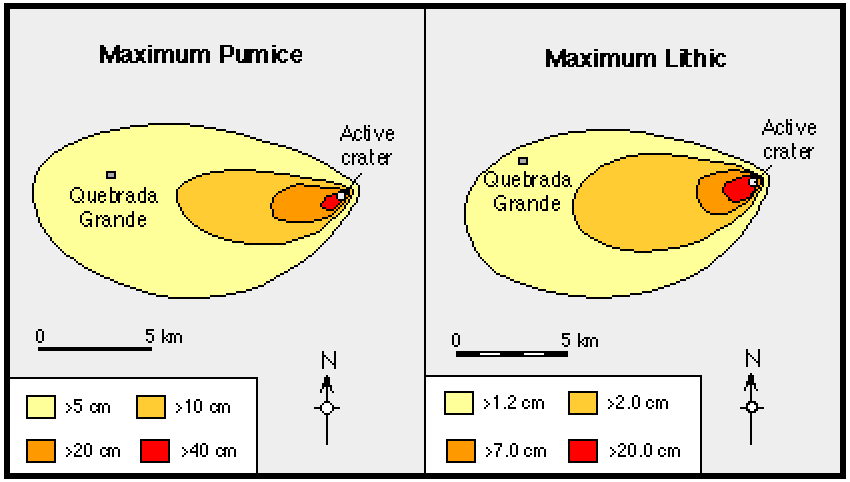


CLASSIFICATION

Pyle 1989

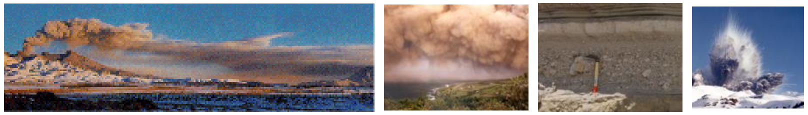
Classification based on the distribution of
largest clasts (bc) and on deposit thinning (bt)





Isopach maps

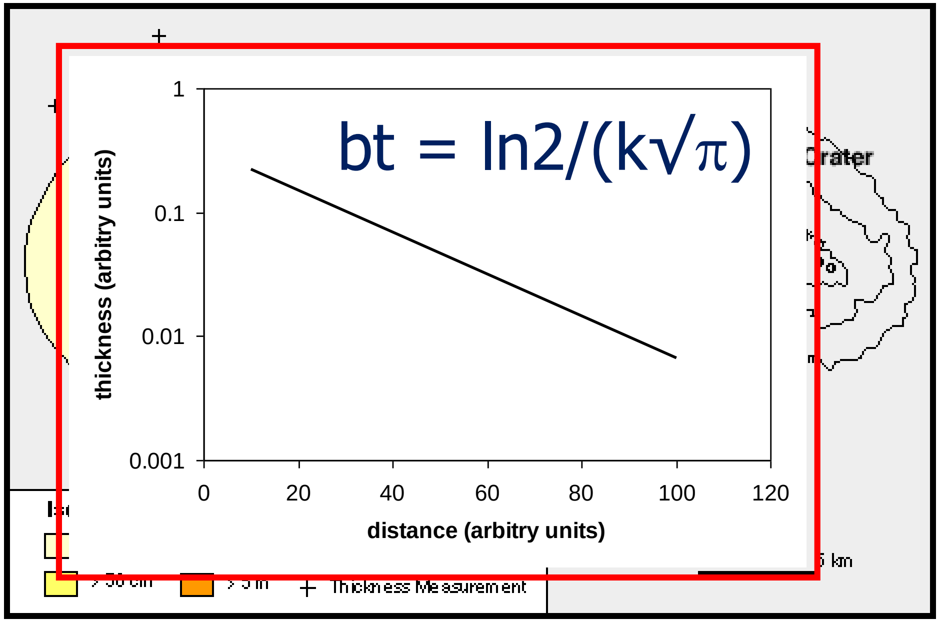
Isopleth maps

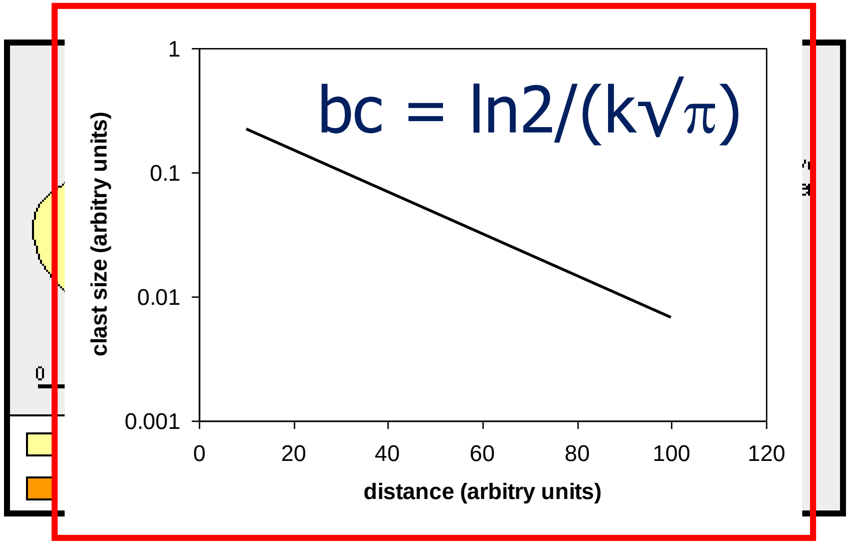


CLASSIFICATION

Pyle 1989

Classification based on the distribution of largest clasts (bc) and on deposit thinning (bt)





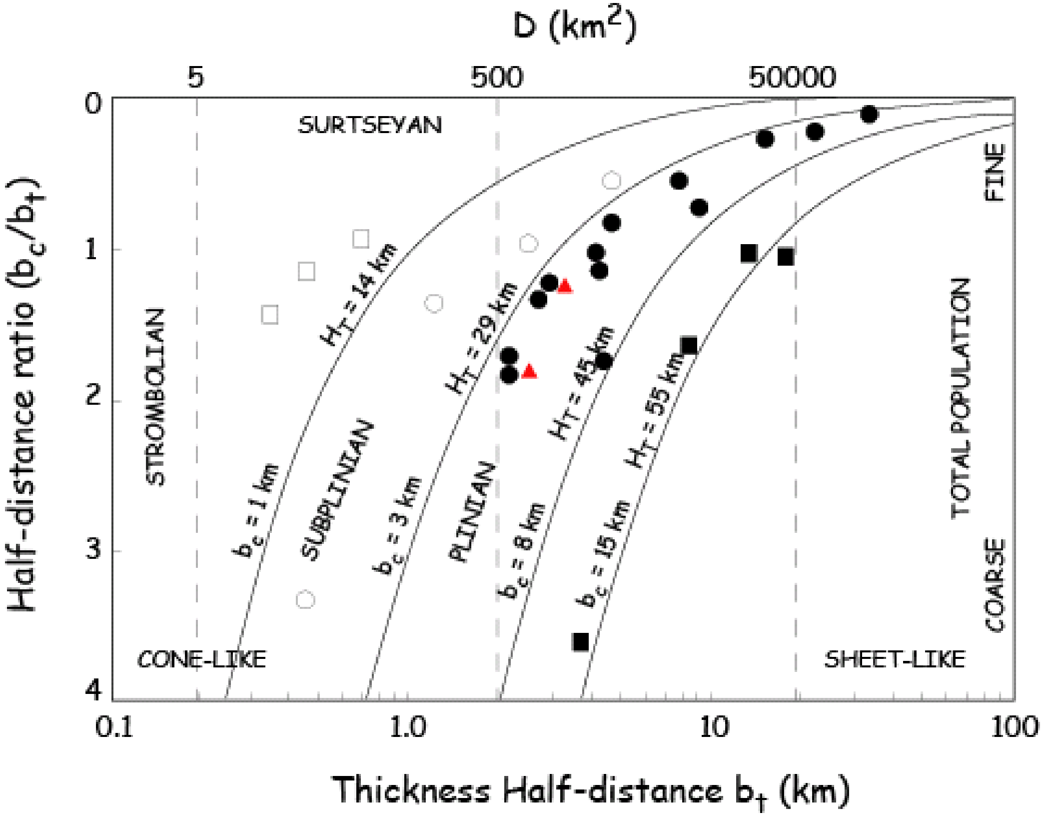
Isopach maps

Isopleth maps

CLASSIFICATION

Pyle 1989

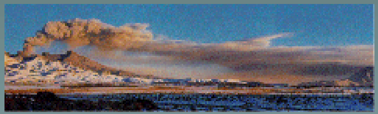
Classification based on the distribution of largest clasts (bc) and on deposit thinning (bt)






Physical characterization of explosive eruptions

- **Isopach maps/Isomass maps** → erupted volume/mass (+VEI and DRE) + wind direction
- **Isopleth maps** → Plume height → Mass Eruption Rate → Eruption duration (when combined with erupted mass)
- **Isopleth maps** → Wind speed
- **Individual grainsize distributions** → Total grainsize distribution → Infos on eruptive style and fragmentation efficiency
- **Thickness vs grainsize data** → eruption classification




FURTHER READING

DETERMINATION OF ERUPTED VOLUME:

https://vhub.org/resources/531/download/Eruption_Magnitude_and_Deposit_Volume.pdf

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