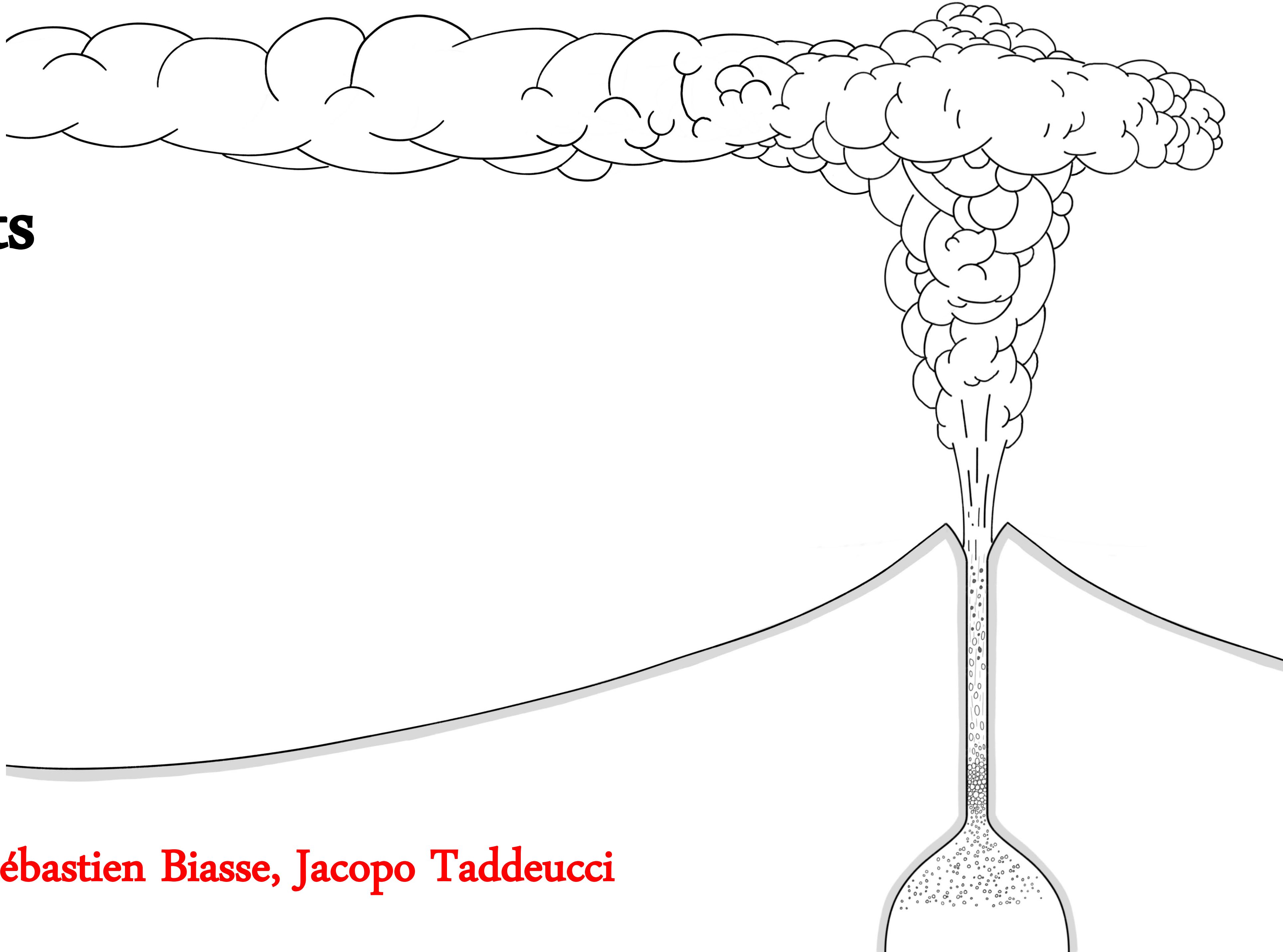
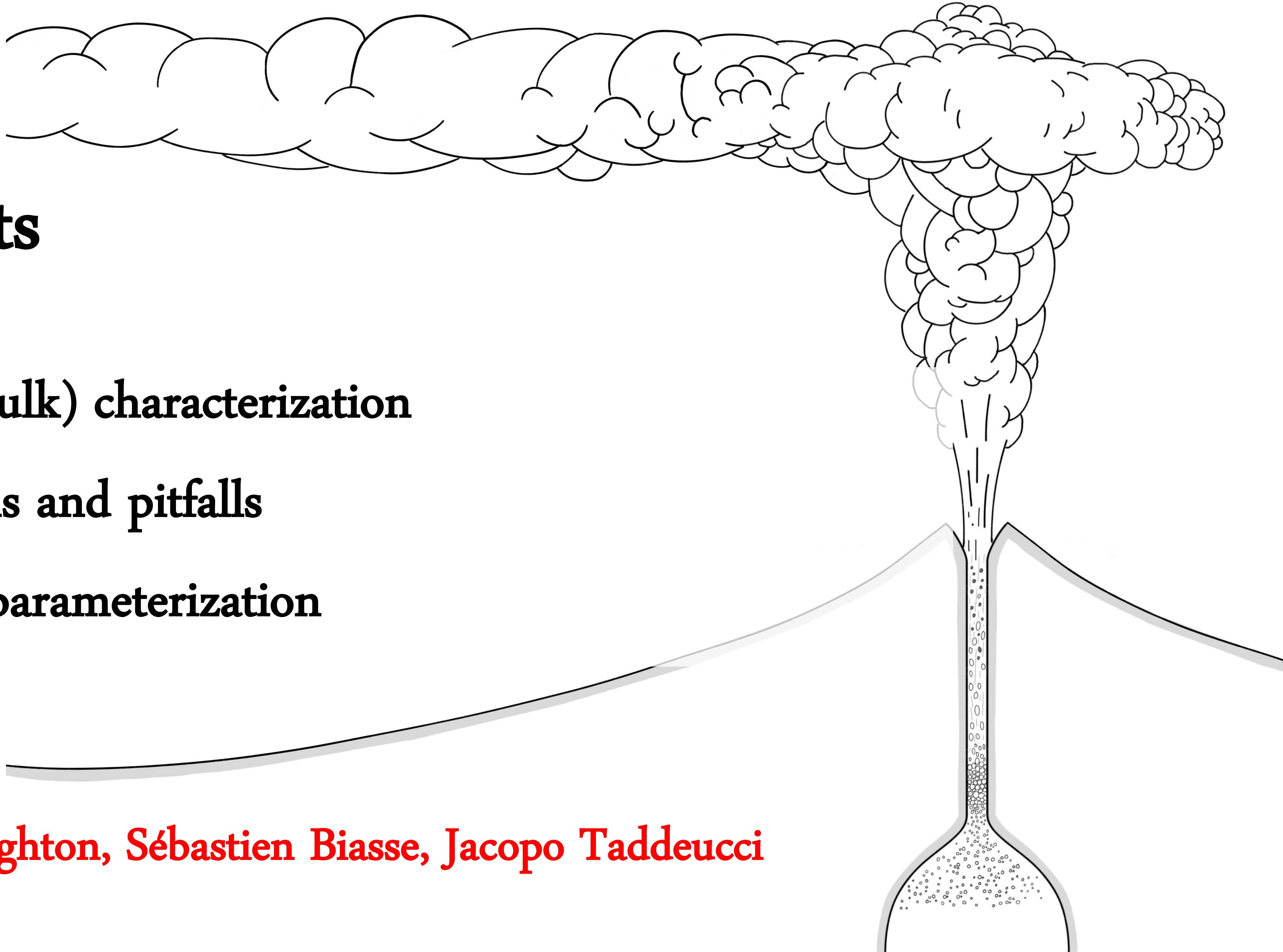
Fall deposits



Bruce Houghton, Sébastien Biasse, Jacopo Taddeucci

Fall deposits

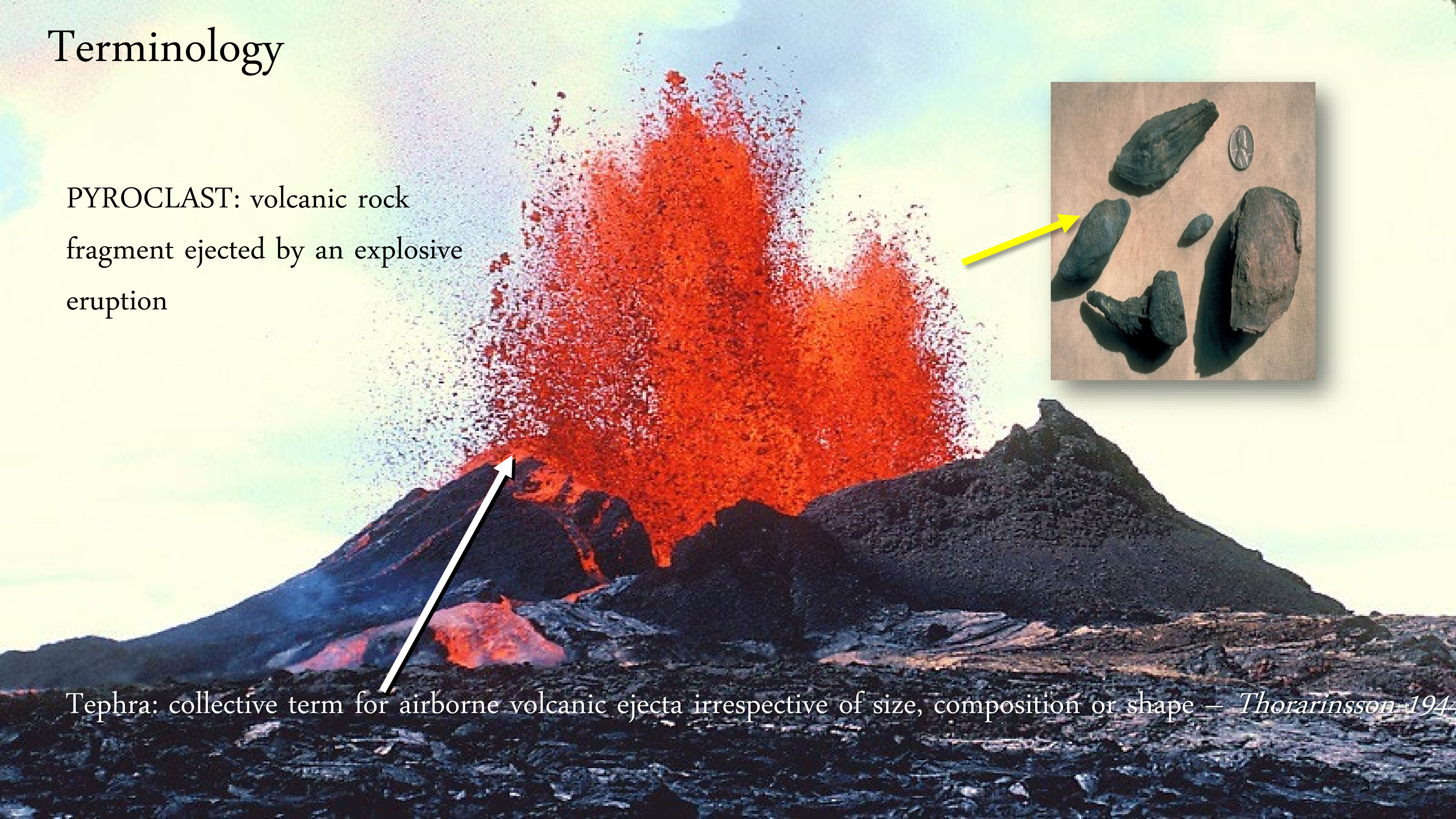
1) in situ (bulk) characterization
2) limitations and pitfalls
3) in-flight parameterization



Bruce Houghton, Sébastien Biasse, Jacopo Taddeucci

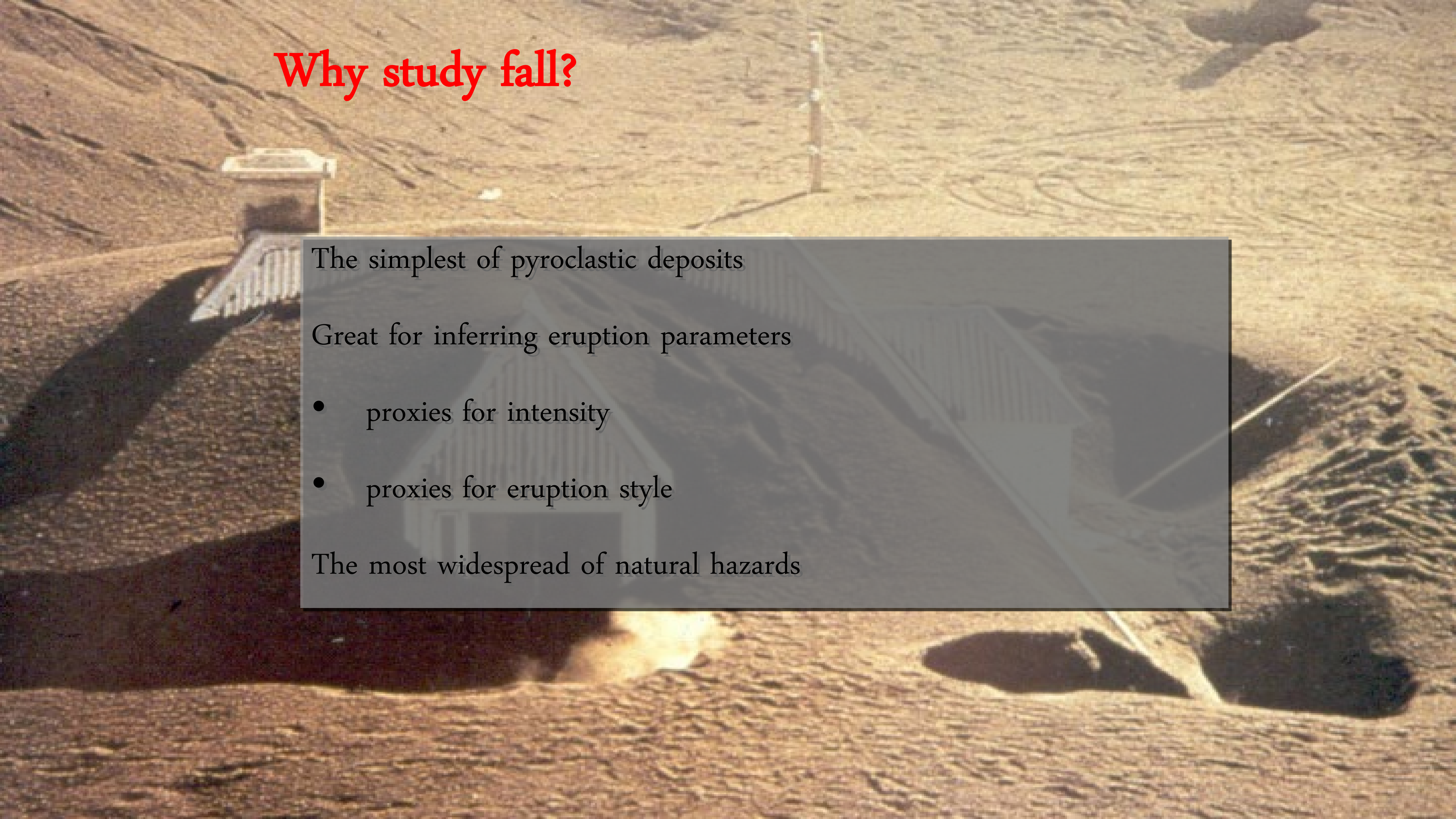
Terminology

PYROCLAST: volcanic rock fragment ejected by an explosive eruption



Tephra: collective term for airborne volcanic ejecta irrespective of size, composition or shape – *Thorarinsson 194*

Why study fall?



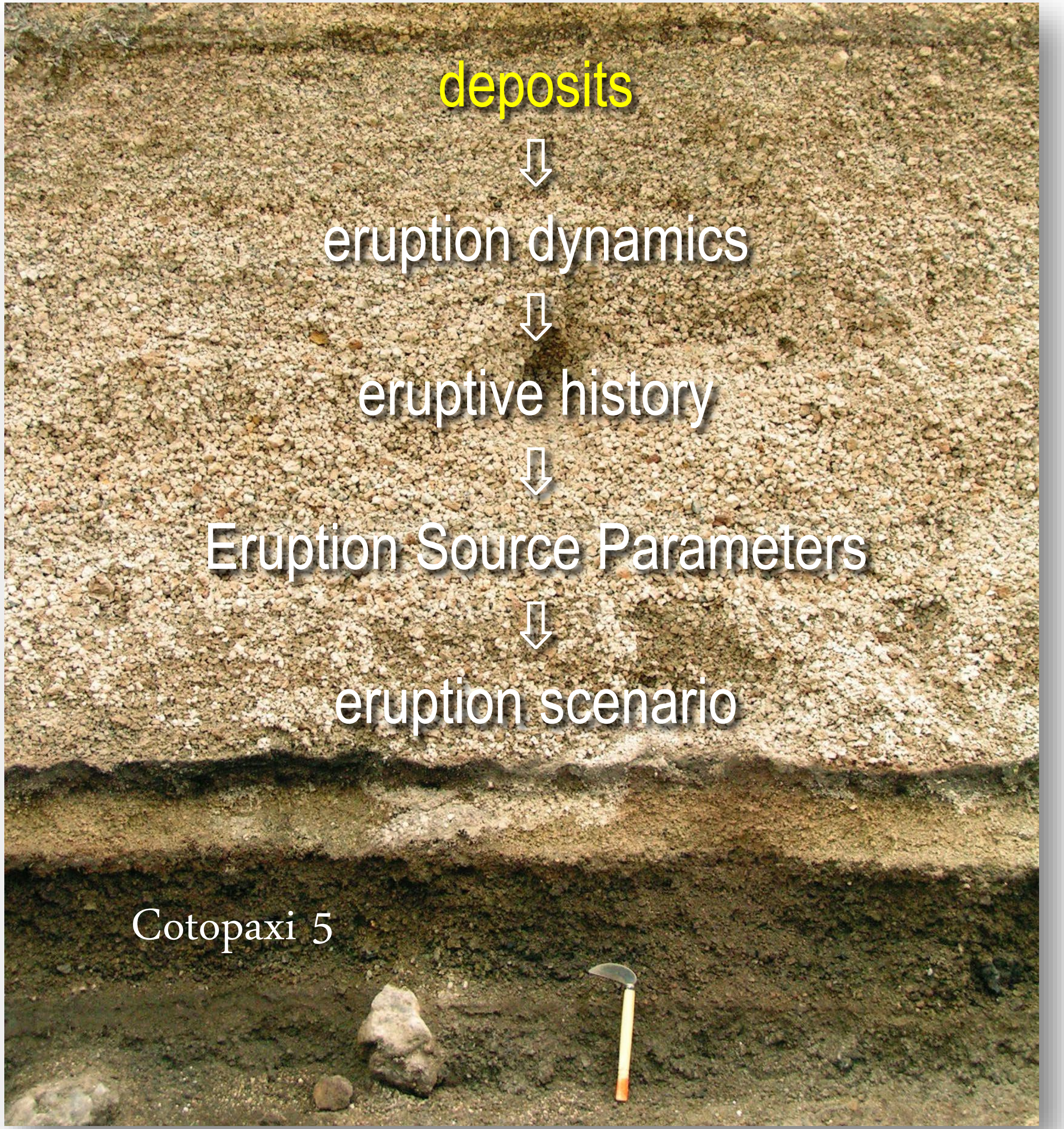
The simplest of pyroclastic deposits

Great for inferring eruption parameters

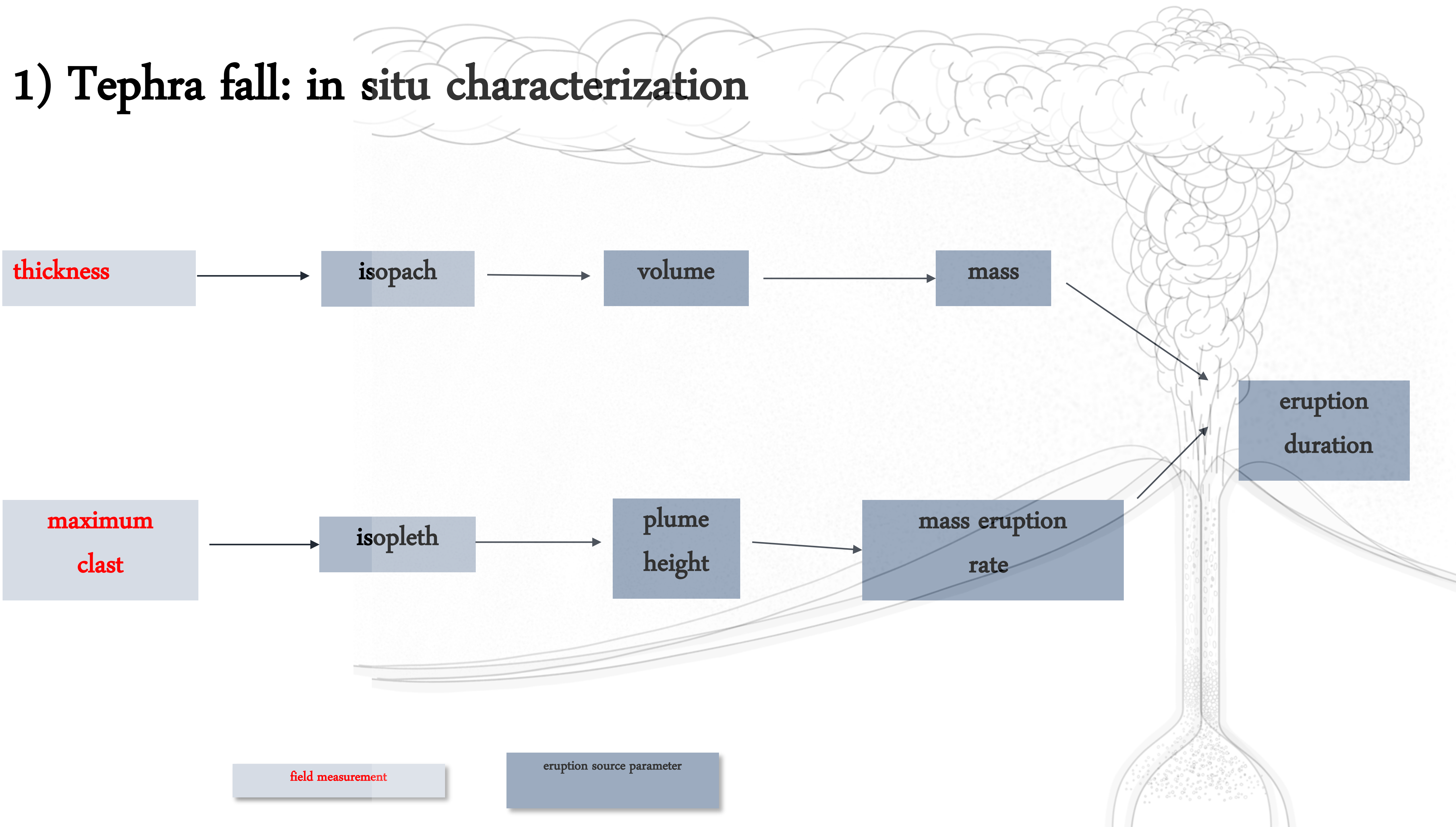
- proxies for intensity
- proxies for eruption style

The most widespread of natural hazards

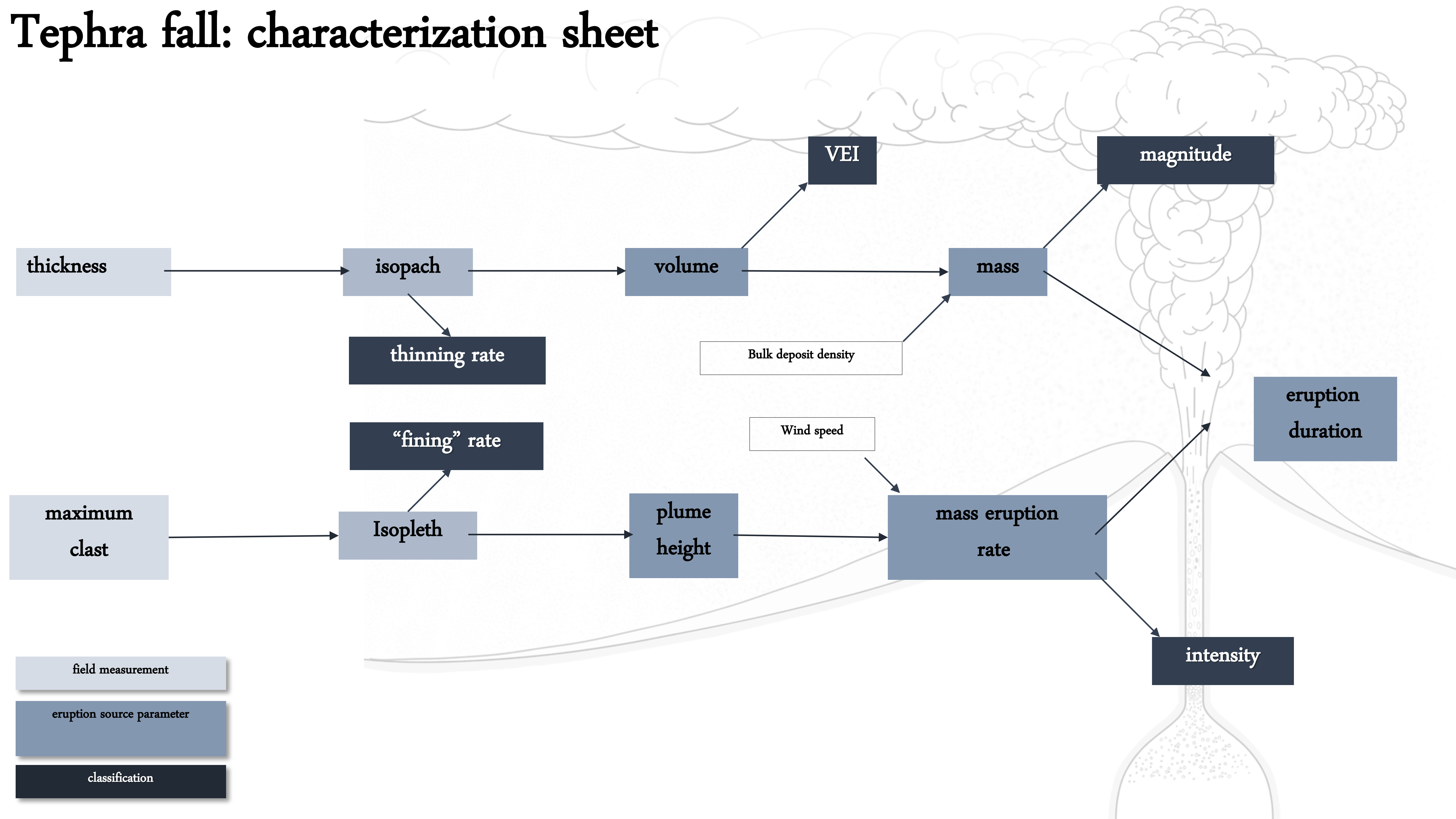

What do falls record ?


deposits
⇩
eruption dynamics
⇩
eruptive history
⇩
Eruption Source Parameters
⇩
eruption scenario
Cotopaxi 5

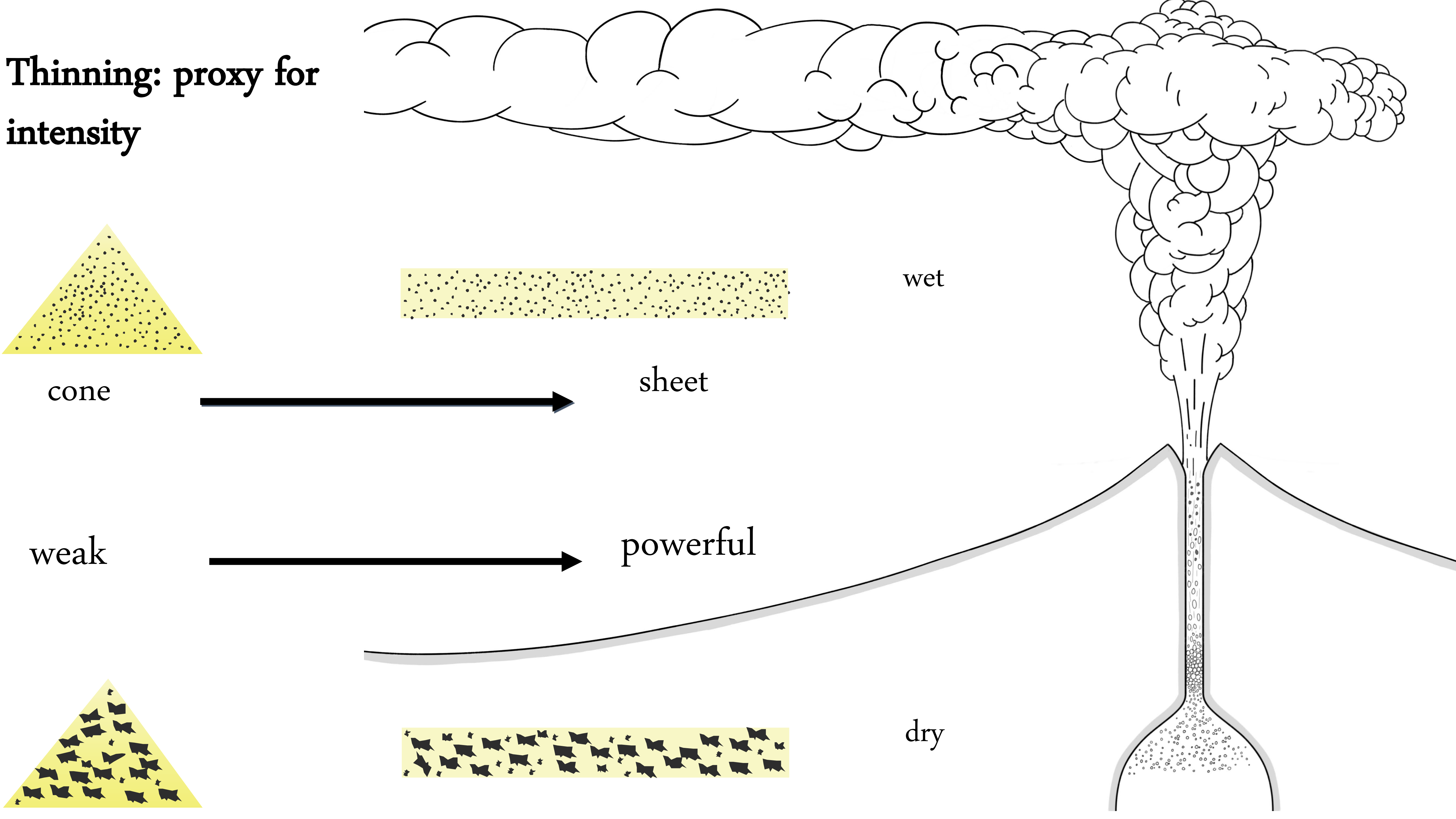
1) Tephra fall: in situ characterization



Tephra fall: characterization sheet

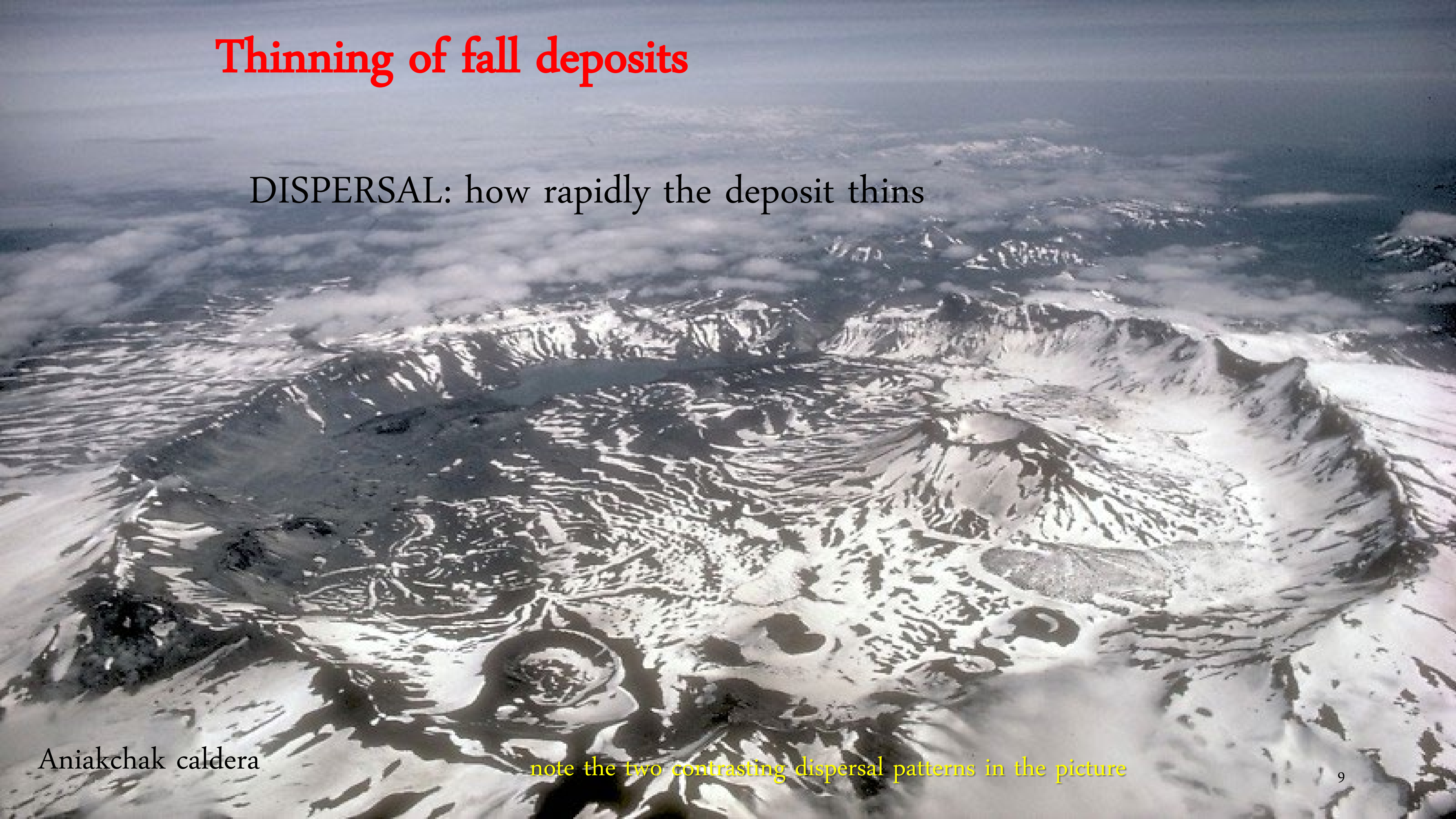


Thinning: proxy for intensity



Thinning of fall deposits

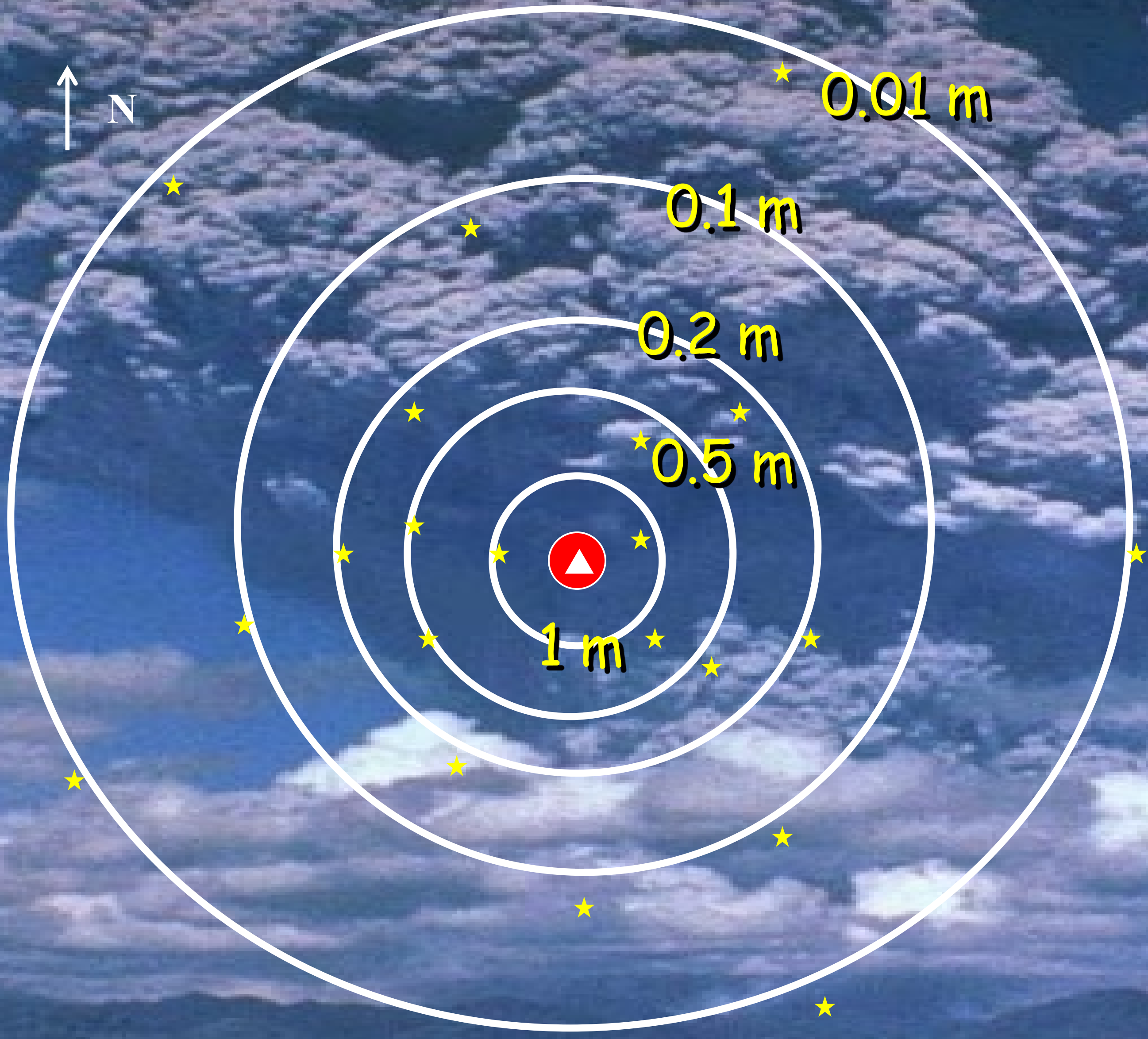
DISPERSAL: how rapidly the deposit thins



Aniakchak caldera

note the two contrasting dispersal patterns in the picture

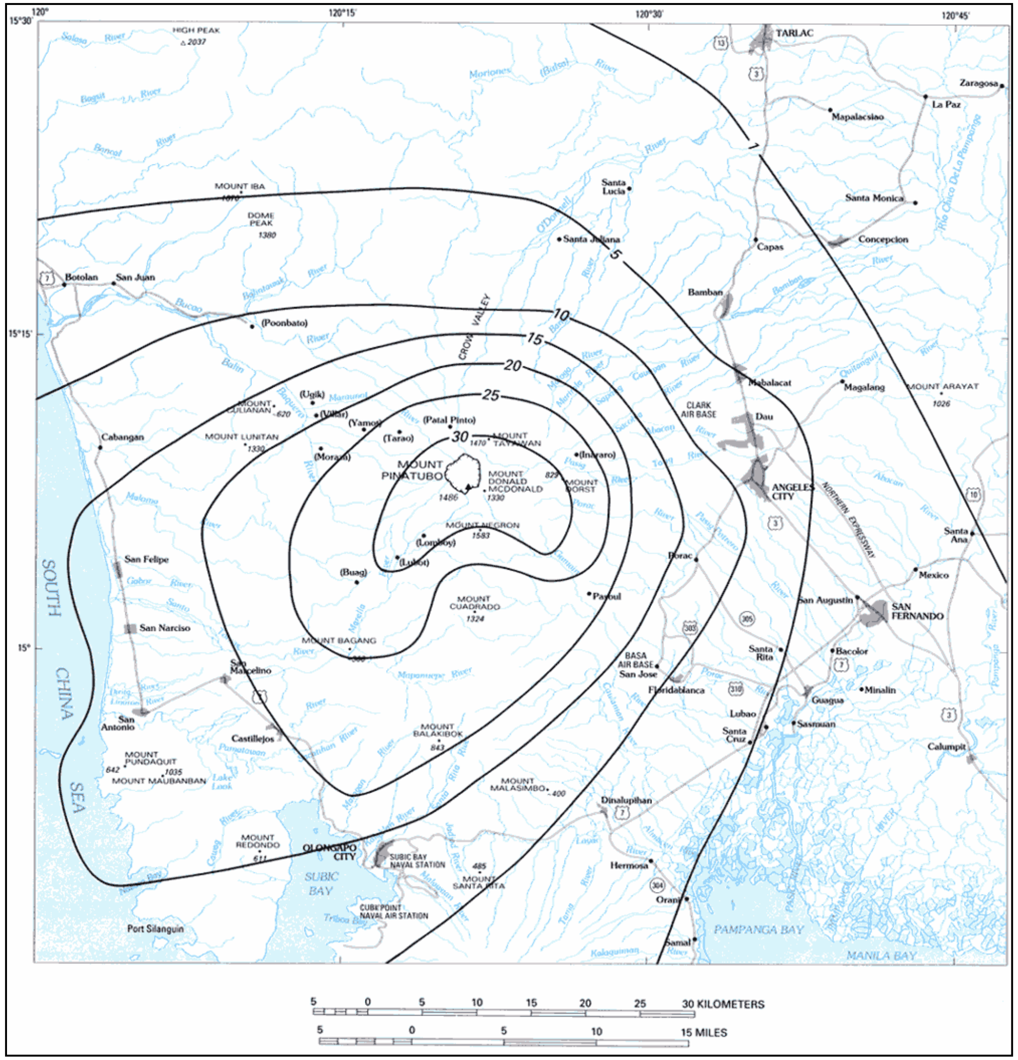
ISOPACHS: lines of equal thickness



ISOPACHS of contrasting intensity

ISOPACHS: strong wind

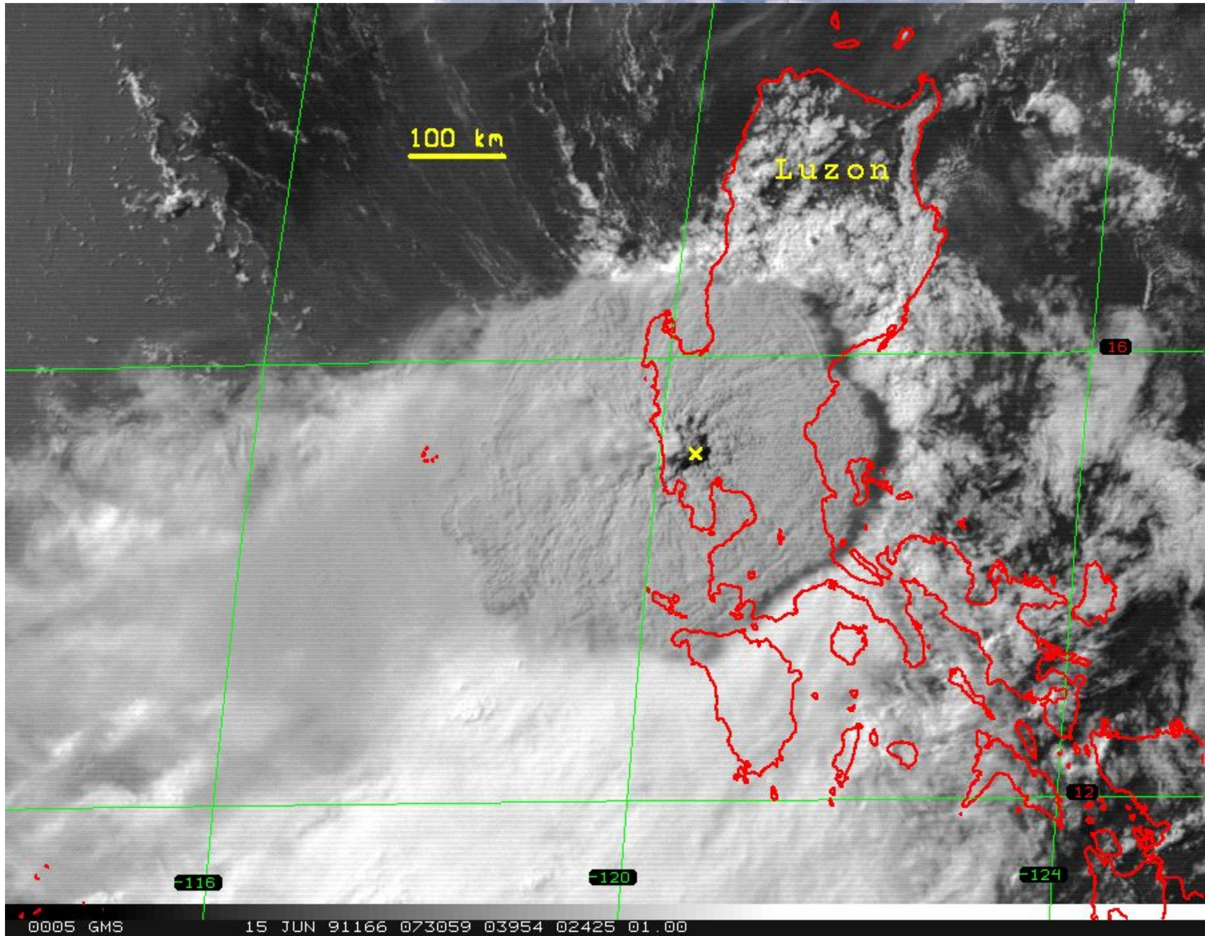
Deposit geometry



Paladio-Melosantos et al. [1996]

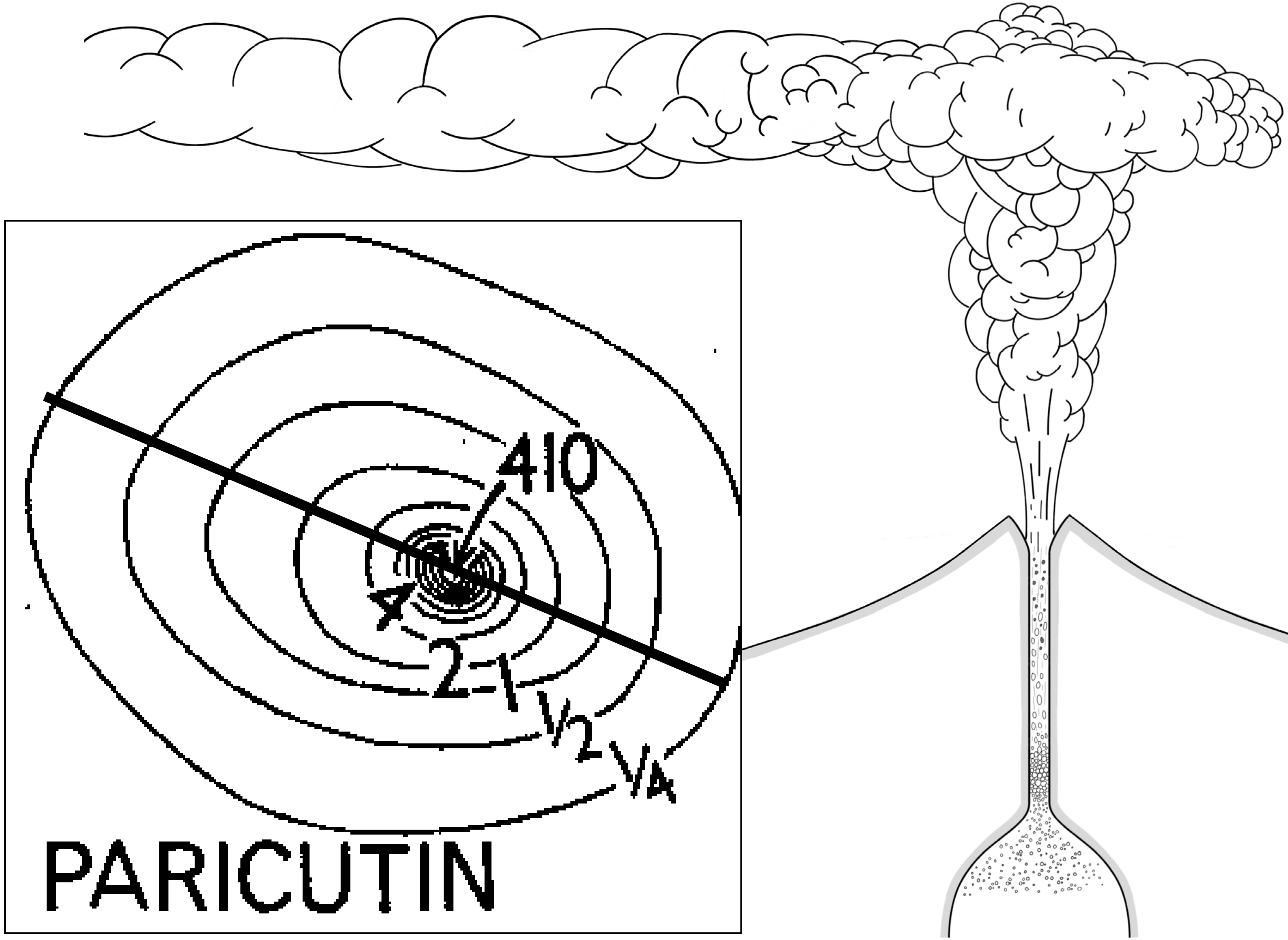
Pinatubo (Philippines) 1991

Ht: 42 km (Rosi et al. 2000)



Quantitative analysis

1. thickness vs
2. distance from vent, or
3. area contained within an isopach



Isopachs & volume calculation

1. Recognize and correlate layers
2. Measure thickness
3. Constrain deposit geometry

Layer 5 of Cotopaxi volcano in Ecuador

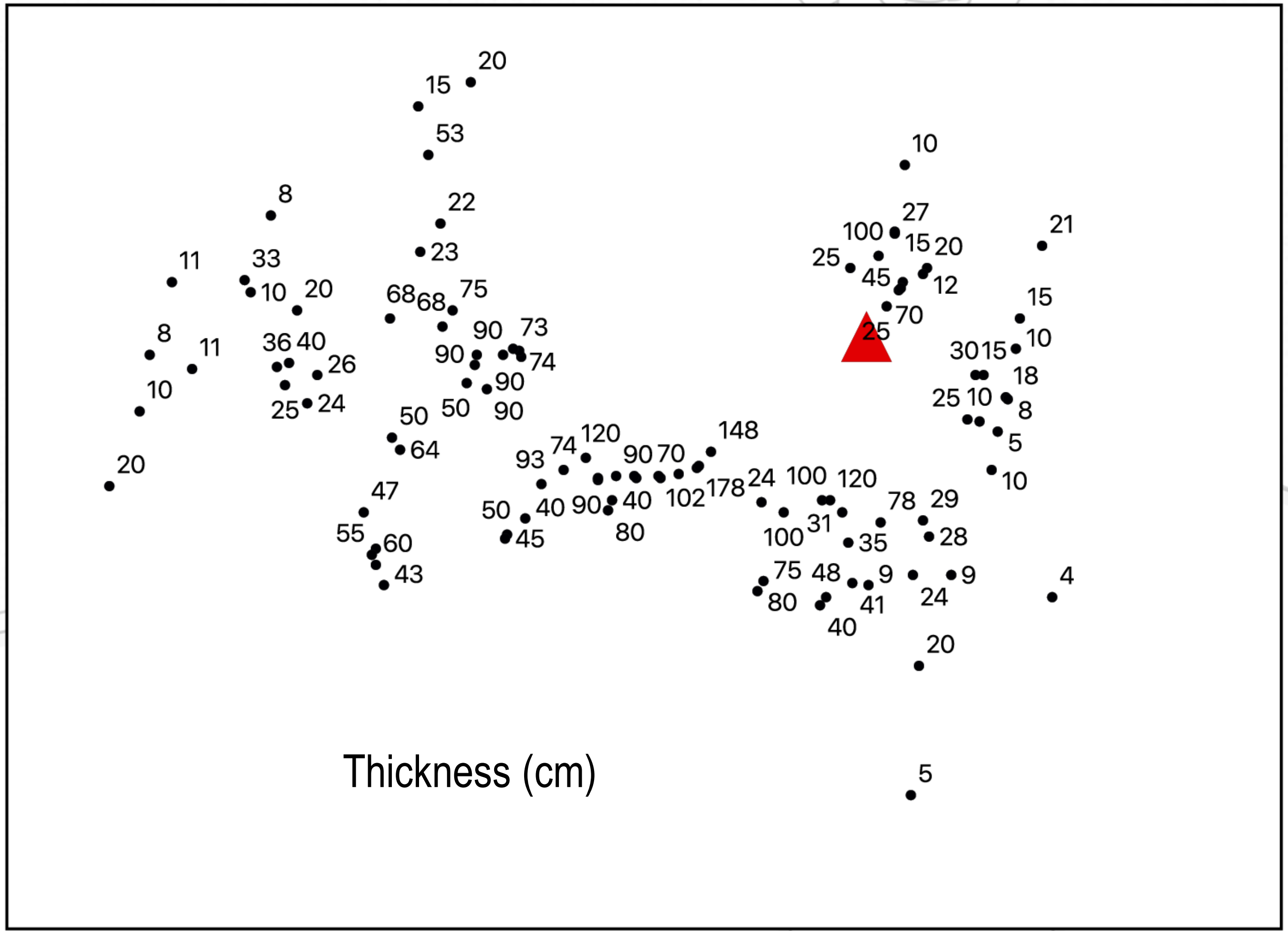
Barberi et al, 1995; Biass and Bonadonna, 2011

1180 yr

c 26 km

0.5 km^3

10^{12} kg

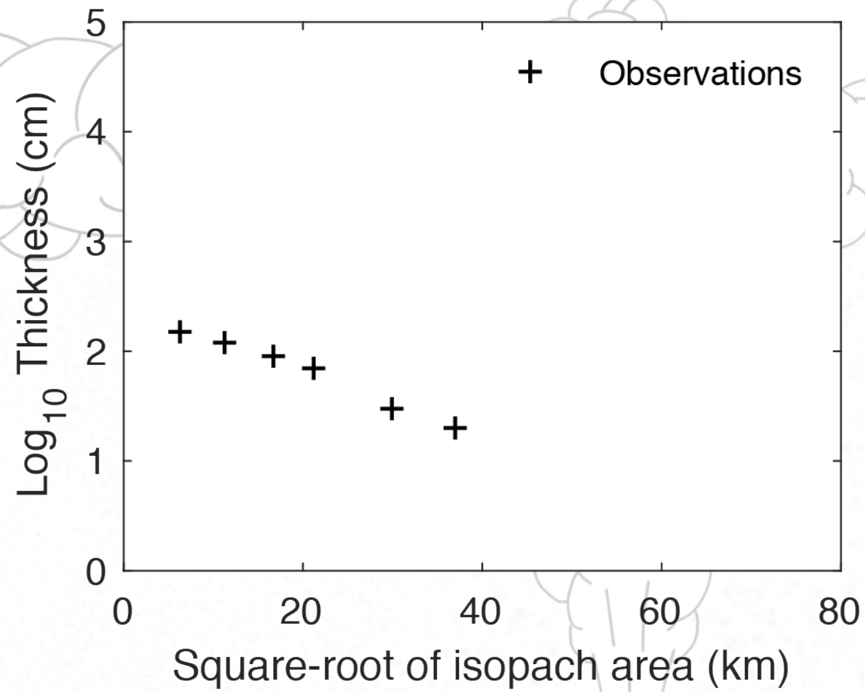


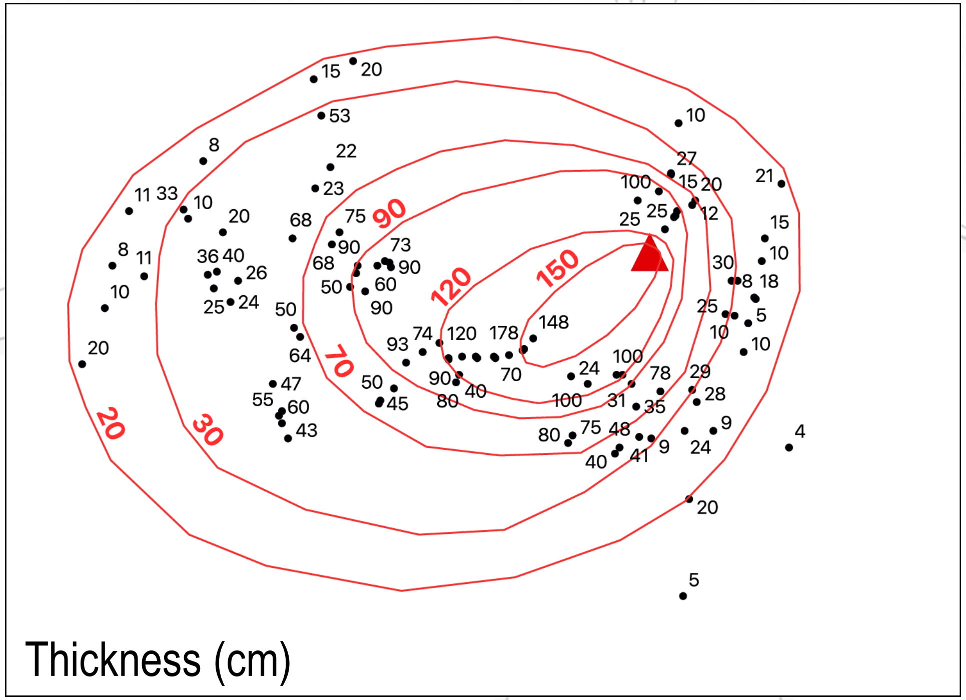
Isopach & volume calculation

4. Contour **isopach**

   = contours of equal thickness

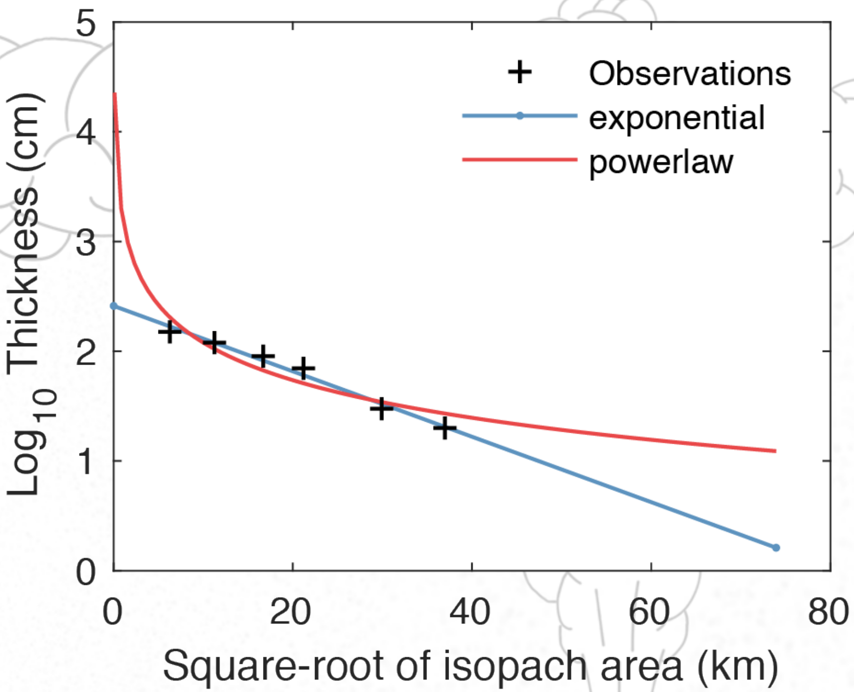
5. Plot log(thickness) vs sqrt(area)
   - Early recognition that fallout thins exponentially
   - Square-root of area is a normalized distance that reduces effect of isopach distortion due to wind
   - Makes comparison of deposits possible

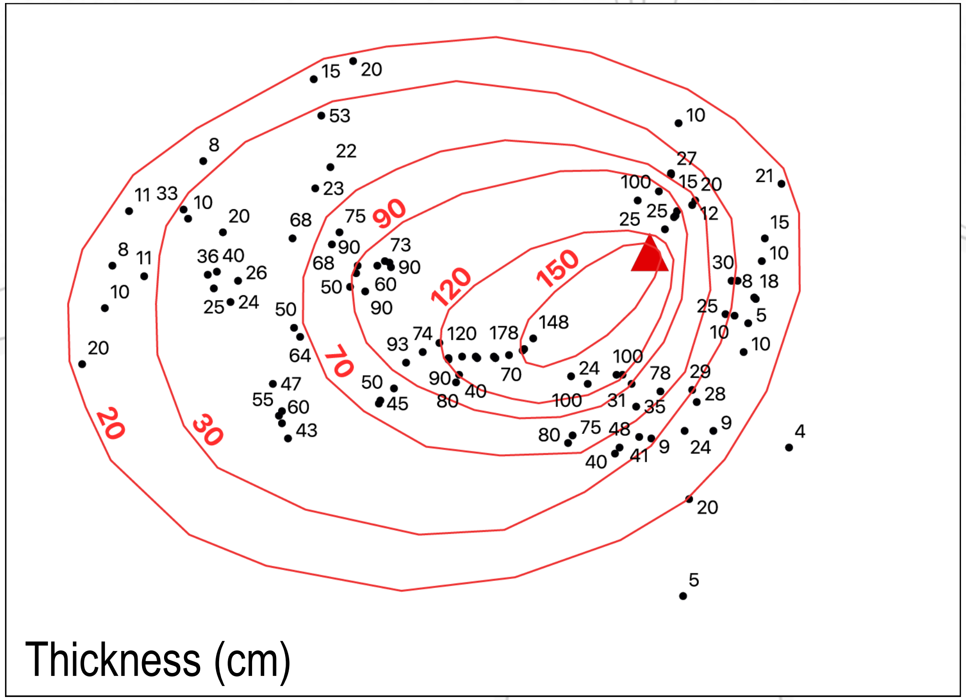




Isopach & volume calculation

6. Fit:
   - One or multiple **exponential** segments
     - Deposit exposure rarely allows identification of multiple segments
     - One segment underestimates max thickness
     - $y = T_0 e^{kx}$
     - T_0: Thickness at intercept
     - k: Thinning rate
   - **Power-law**
     - Extrapolates thickness in proximal and distal regions
     - Sometimes unconstrained





Isopach & volume calculation

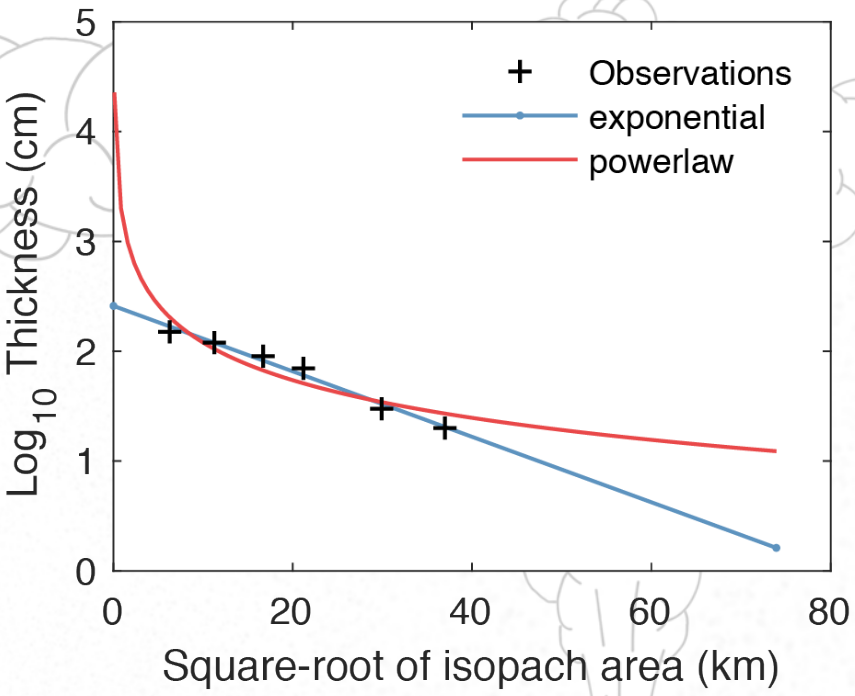
7. Calculate volume by integrating area below curve. For 1 exponential segment:

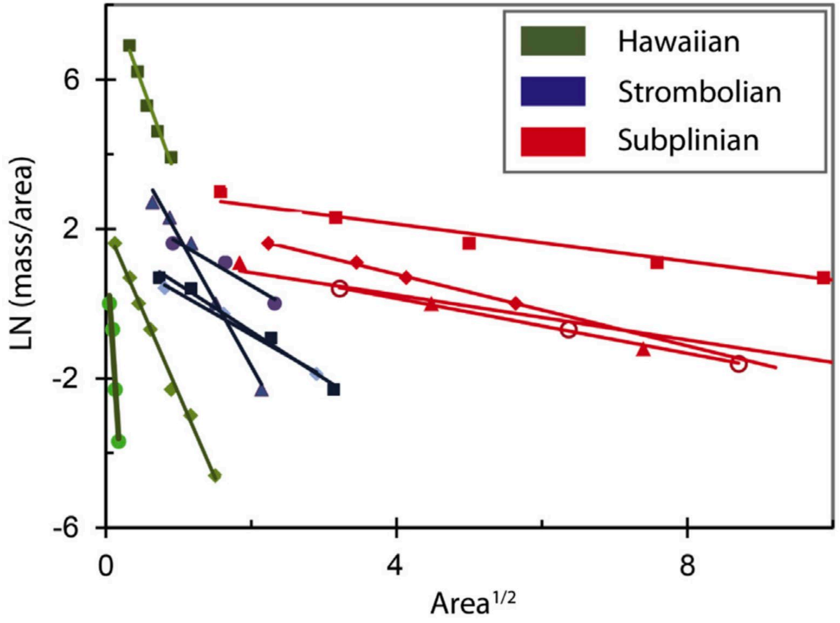
$$V = \frac{2T_0}{k^2}$$

- $\mathbf{T_0}$ = intercept, **k** = thinning rate, **V** = volume (m^3)

8. Calculate thickness half distance $\mathbf{b_T}$ as: $\frac{\log(2)}{k\sqrt{\pi}}$

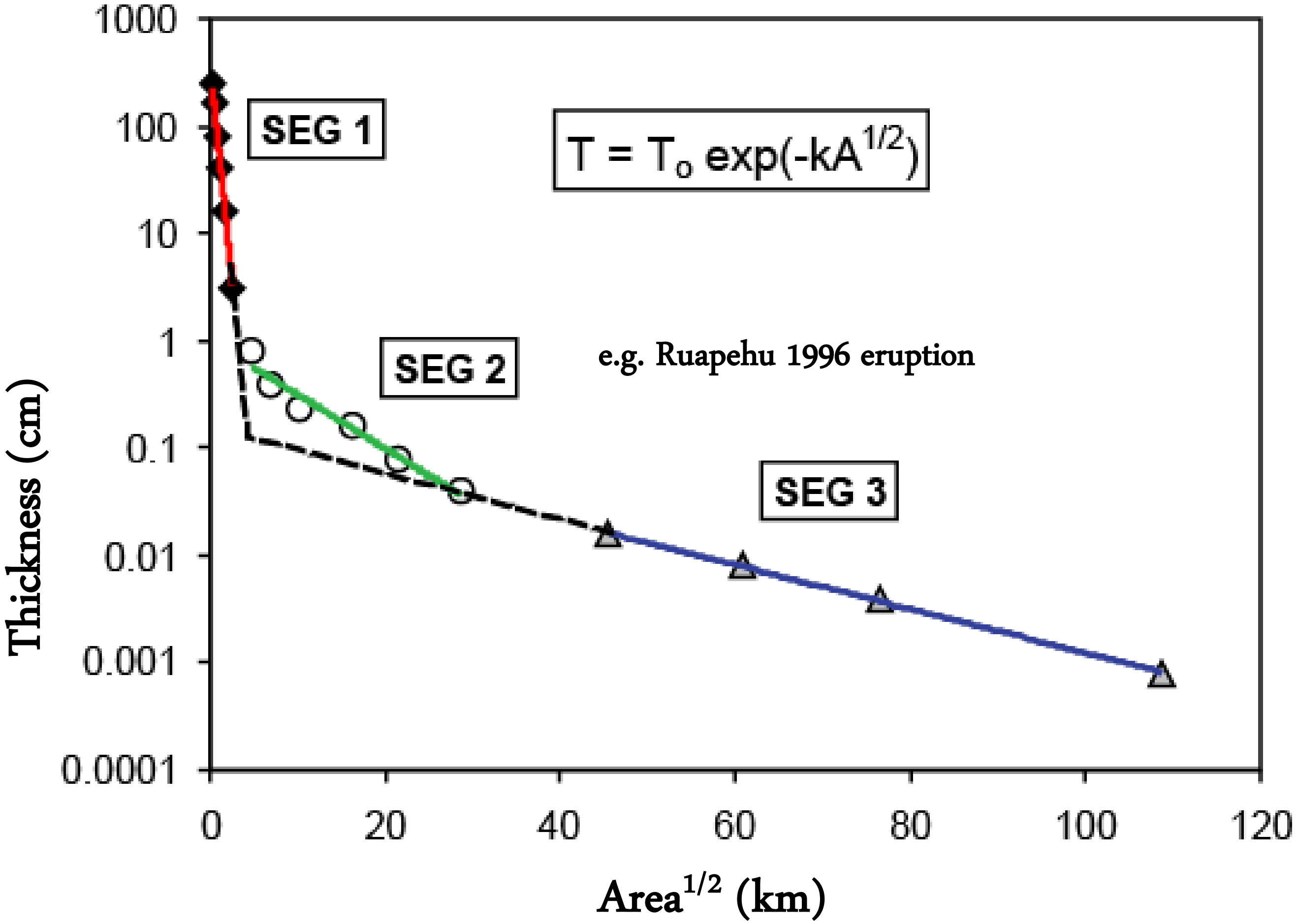
9. Convert to mass → *bulk deposit density*
   - Typically assumed between 500-1500 kg/m^3





Exponential treatments:

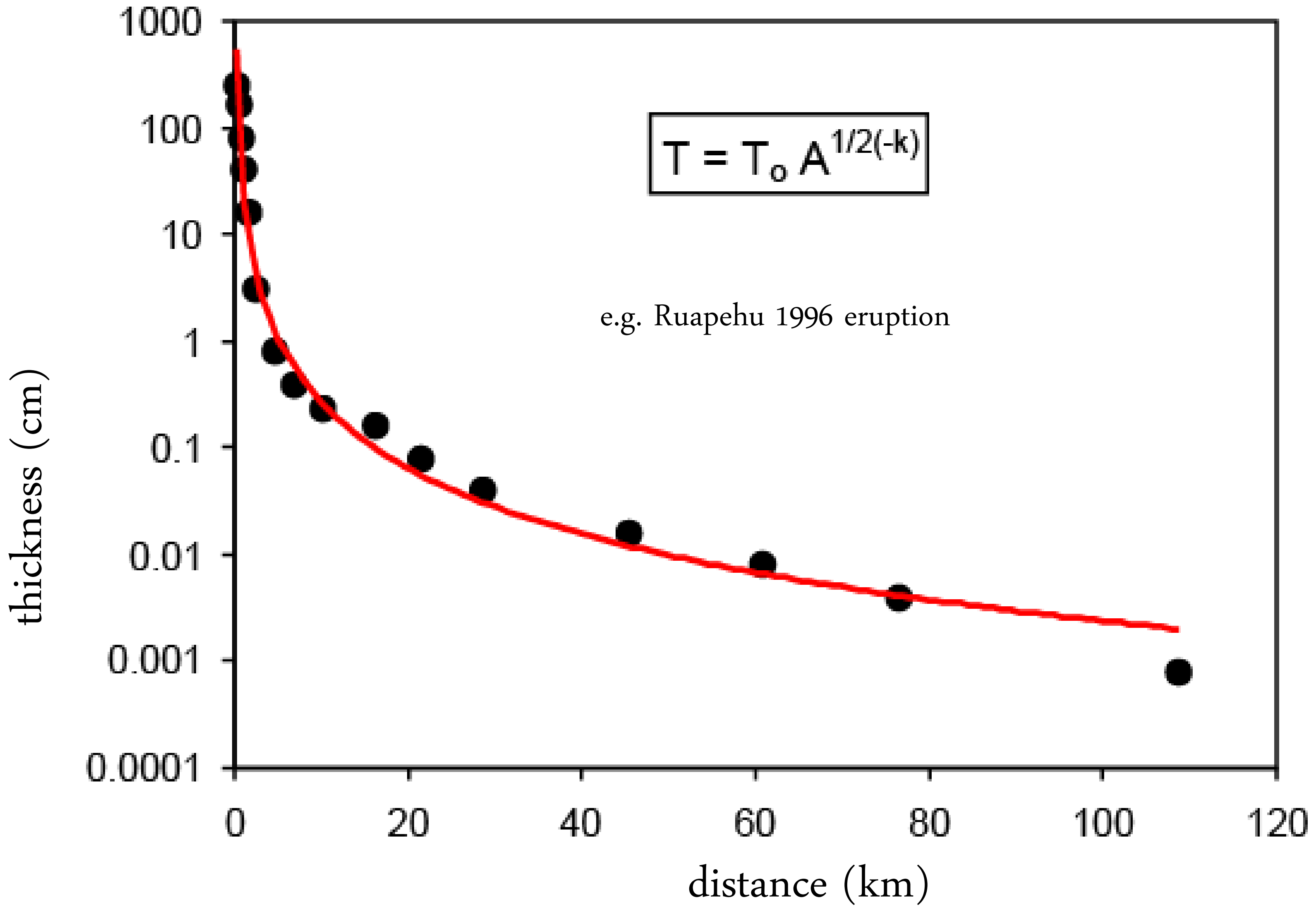
- **1 exp. segment** (Pyle 1989)
- **2 exp. segments** (Fierstein and Nathenson 1992, Pyle 1995)
- **>2 exp. segments** (Bonadonna and Houghton 2005)
- **One proximal isopach line** (Legros 2000)
- **Thickness measurements** (Burden et al. 2013)



PROBLEM: underestimation of volume in case of missing distal data

Power law relationships

- Extrapolates thickness in proximal and distal regions
- Sometimes unconstrained



PROBLEM: choice of integration limits

(Bonadonna and Houghton 2005)

Isopach & volume calculation

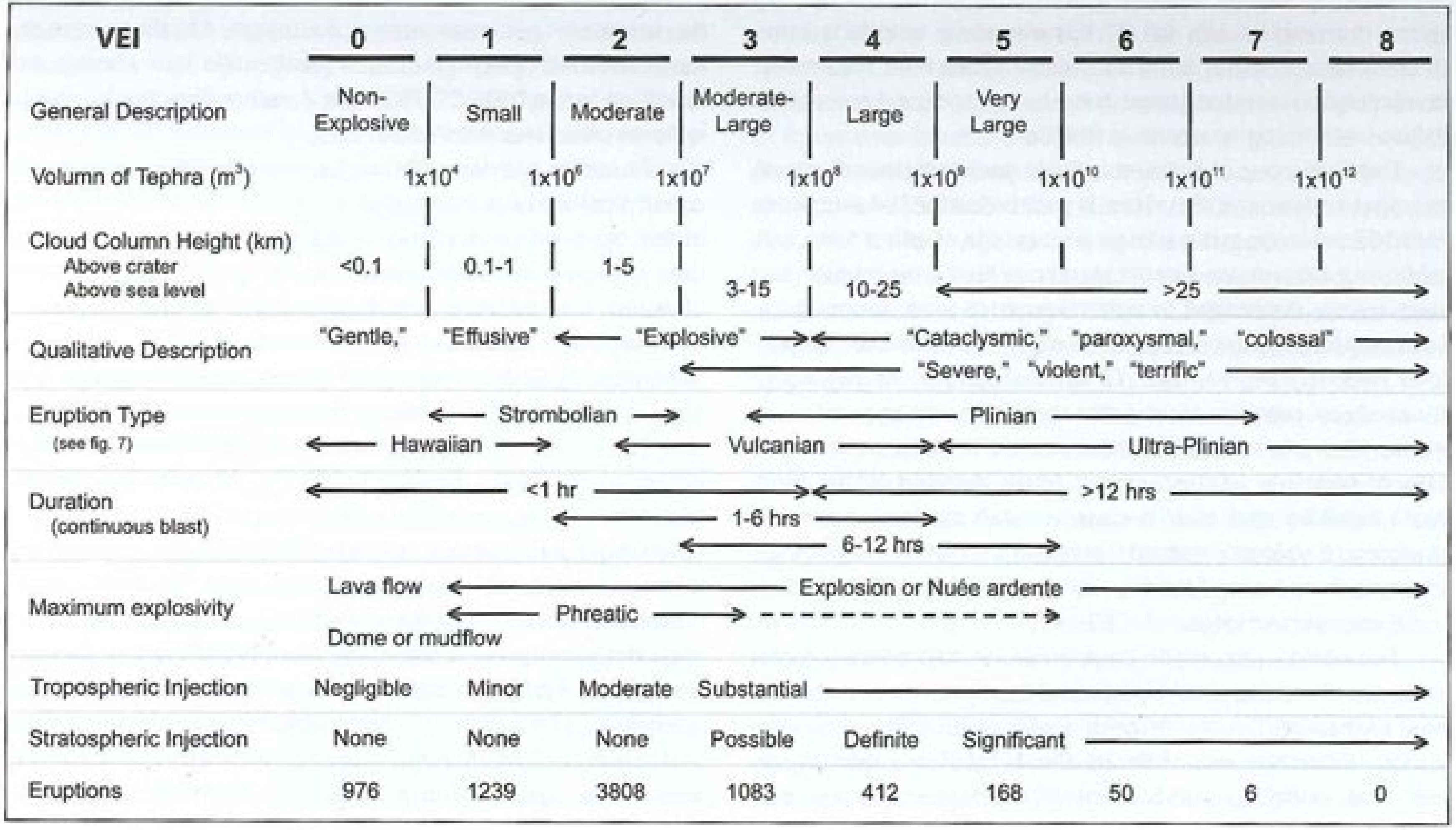
- Volume → **VEI**
  - Log volume of tephra
  - Designed for communication

VEI	0	1	2	3	4	5	6	7	8
General Description	Non-Explosive	Small	Moderate	Moderate-Large	Large	Very Large			
Volumn of Tephra (m^3)		1×10^4	1×10^6	1×10^7	1×10^8	1×10^9	1×10^{10}	1×10^{11}	1×10^{12}
Cloud Column Height (km) Above crater	<0.1	0.1-1	1-5						
Cloud Column Height (km) Above sea level				3-15	10-25	←	>25		→
Qualitative Description	"Gentle,"	"Effusive"	← "Explosive"	→	← "Cataclysmic,"	"paroxysmal,"	"colossal"	→	
				← "Severe,"	"violent,"	"terrific"	→		
Eruption Type (see fig. 7)		← Strombolian →		← Plinian		→			
	← Hawaiian →		← Vulcanian	→		← Ultra-Plinian			→
Duration (continuous blast)	← <1 hr		→		← >12 hrs				→
			← 1-6 hrs	→					
				← 6-12 hrs		→			
Maximum explosivity	Lava flow	← Explosion or Nuée ardente							→
		← Phreatic →		- - - - - - - - →					
	Dome or mudflow								
Tropospheric Injection	Negligible	Minor	Moderate	Substantial	→				
Stratospheric Injection	None	None	None	Possible	Definite	Significant	→		
Eruptions	976	1239	3808	1083	412	168	50	6	0

Isopach & volume calculation

- Volume ➞ **VEI**
  - Log volume of tephra
  - Designed for communication

- **Problem 1:**
  - Only explosive



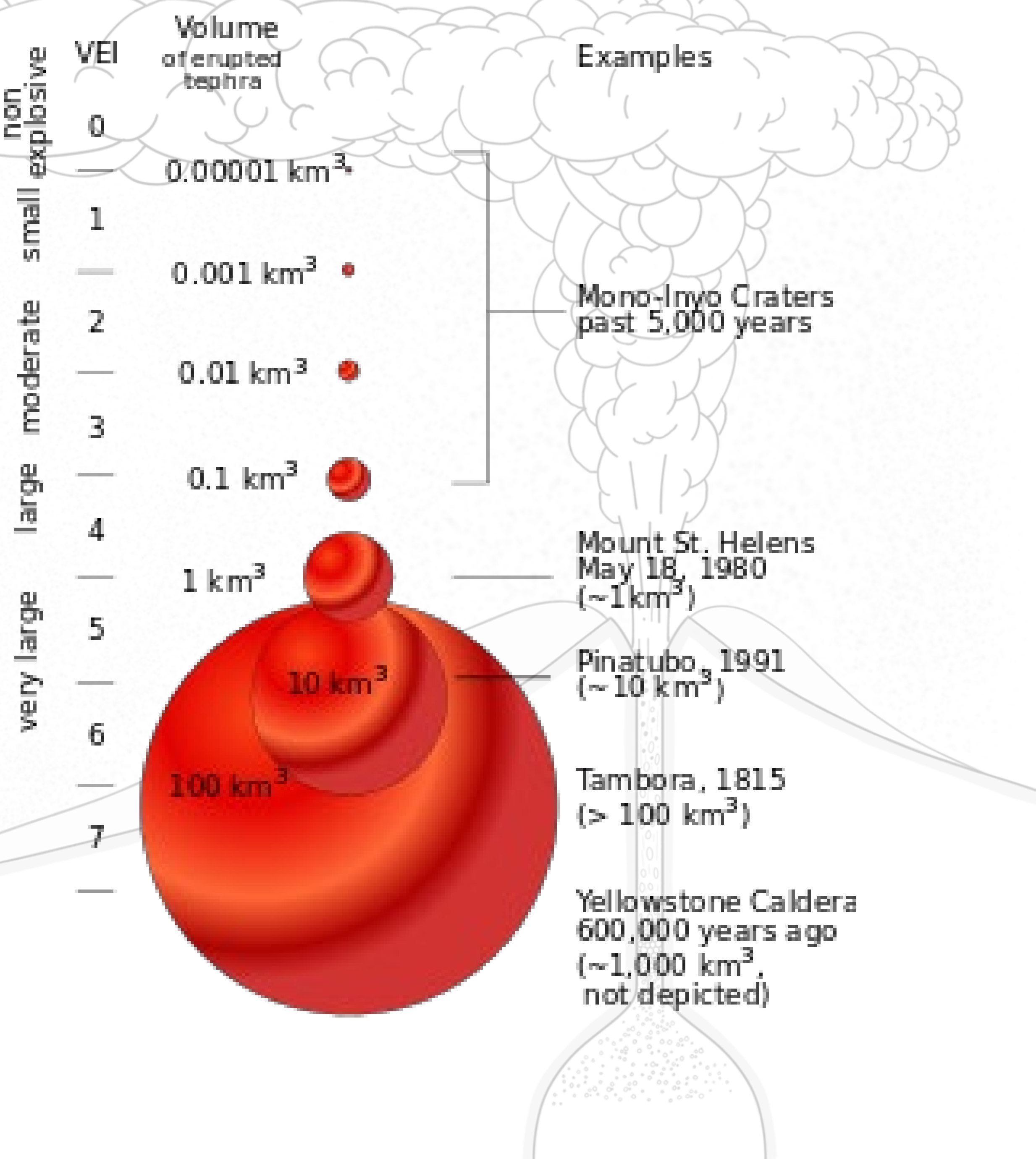
VEI	0	1	2	3	4	5	6	7	8
General Description	Non-Explosive	Small	Moderate	Moderate-Large	Large	Very Large			
Volumn of Tephra (m^3)		$1x10^4$	$1x10^6$	$1x10^7$	$1x10^8$	$1x10^9$	$1x10^{10}$	$1x10^{11}$	$1x10^{12}$
Cloud Column Height (km) Above crater	<0.1	0.1-1	1-5						
Above sea level				3-15	10-25	←	>25		→
Qualitative Description	"Gentle,"	"Effusive"	← "Explosive"	→	← "Cataclysmic,"	"paroxysmal,"	"colossal"		→
				←	"Severe,"	"violent,"	"terrific"		→
Eruption Type (see fig. 7)	← Hawaiian →	← Strombolian →	← Vulcanian	→		← Plinian		→	
						← Ultra-Plinian			→
Duration (continuous blast)	← <1 hr			→	← >12 hrs				→
			← 1-6 hrs		→				
				← 6-12 hrs		→			
Maximum explosivity	Lava flow	← Explosion or Nuée ardente							→
		← Phreatic		→	- - - -	- - →			
	Dome or mudflow								
Tropospheric Injection	Negligible	Minor	Moderate	Substantial →					
Stratospheric Injection	None	None	None	Possible	Definite	Significant →			
Eruptions	976	1239	3808	1083	412	168	50	6	0

Isopach & volume calculation

- Volume → **VEI**
  - Log volume of tephra
  - Designed for communication

- **Problem 1:**
  - Only explosive

- **Problem 2:**
  - Integer (Stepwise) function
  - **Magnitude**: $\log_{10}$(mass [kg]) - 7



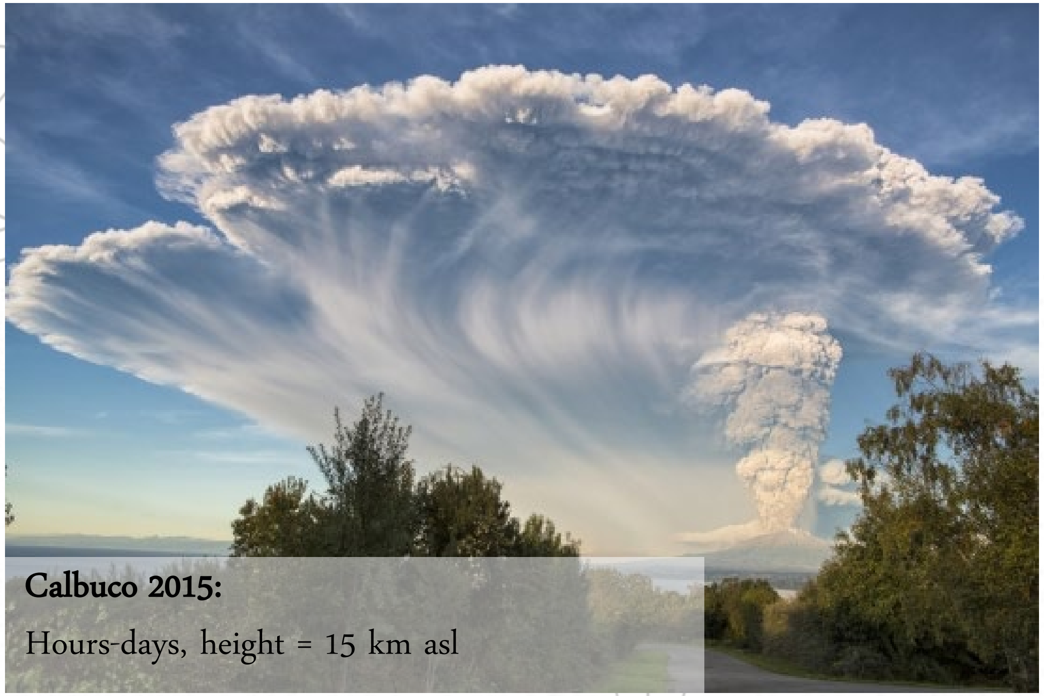
Isopach & volume calculation

- Volume ➞ **VEI**
  - Log volume of tephra
  - Designed for communication

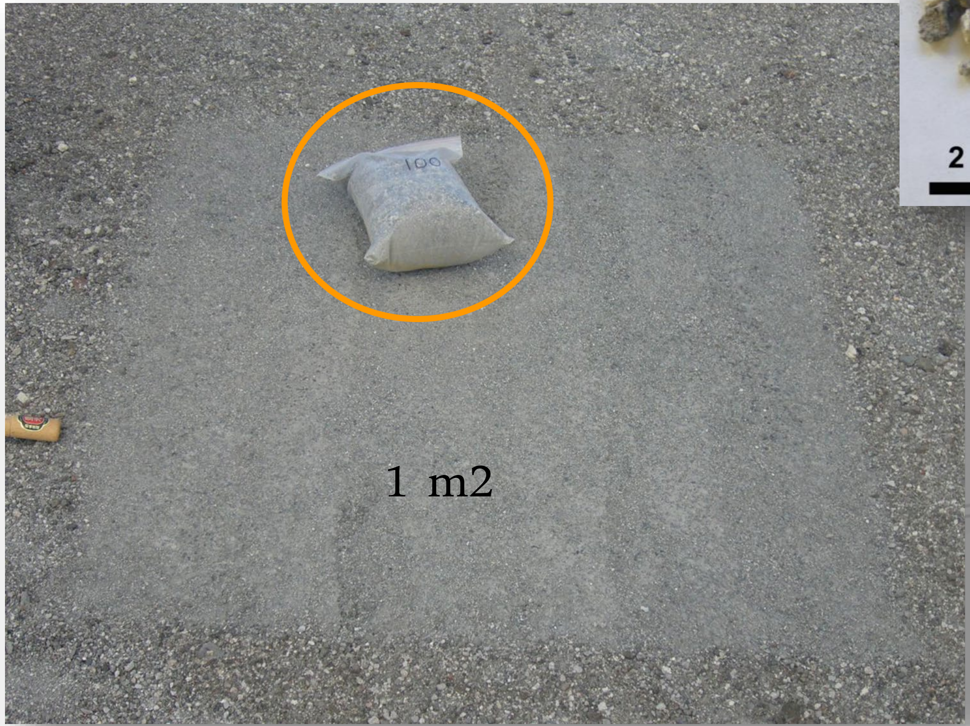
- **Problem 1:**
  - Only explosive

- **Problem 2:**
  - Stepwise function
  - **Magnitude**: $\log_{10}$(mass [kg]) + 7

- **Problem 3:**
  - Something missing?



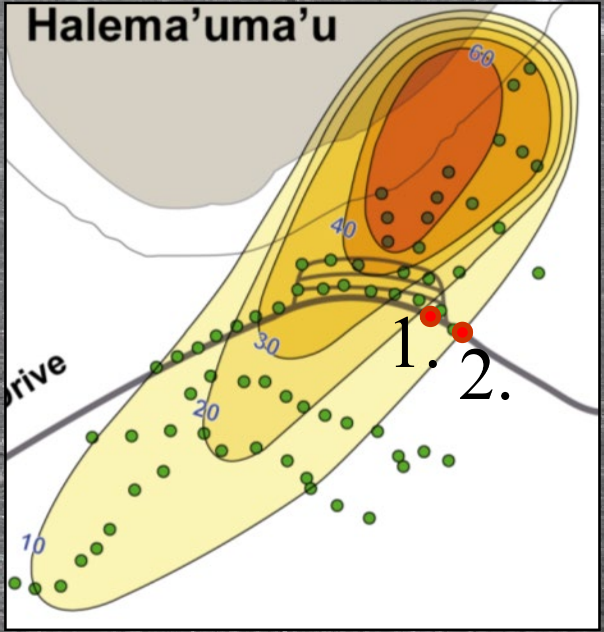
Isomass: alternative for thin or distal deposits



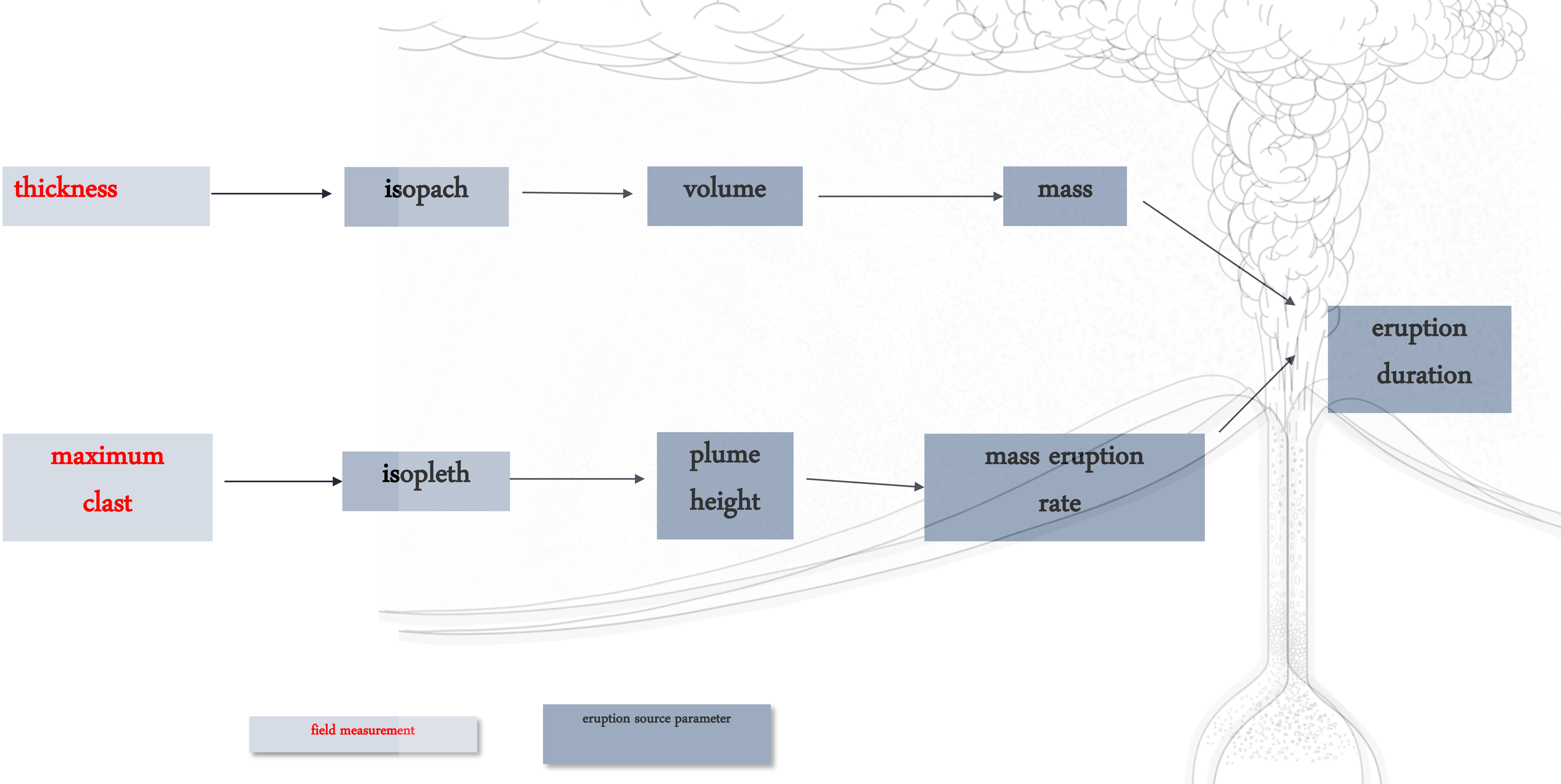
Isomass: lateral margins

1. eastern margin: 22 g m^{-2}

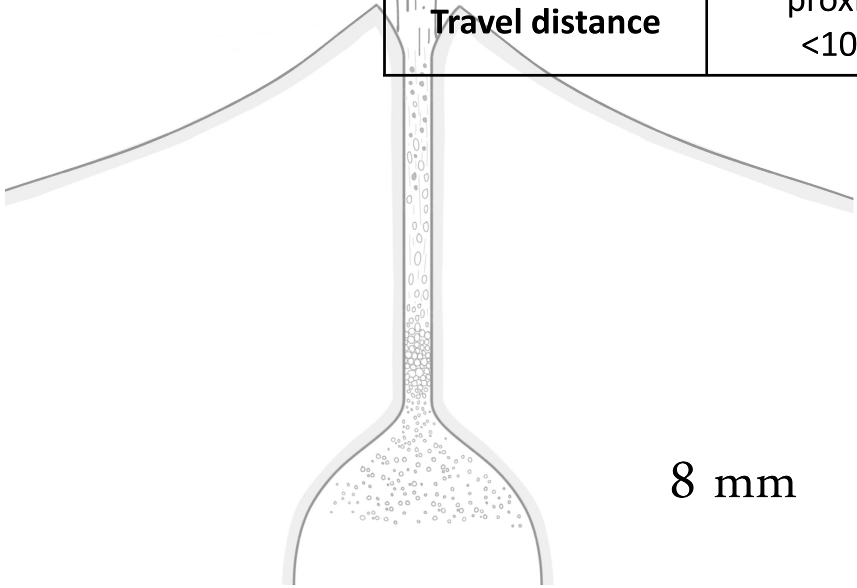
2. far east margin: 1 g m^{-2}



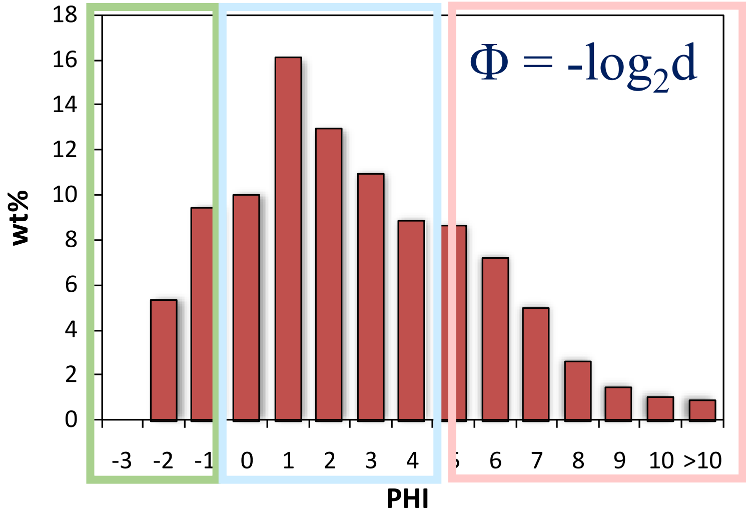
Tephra fall: characterization sheet



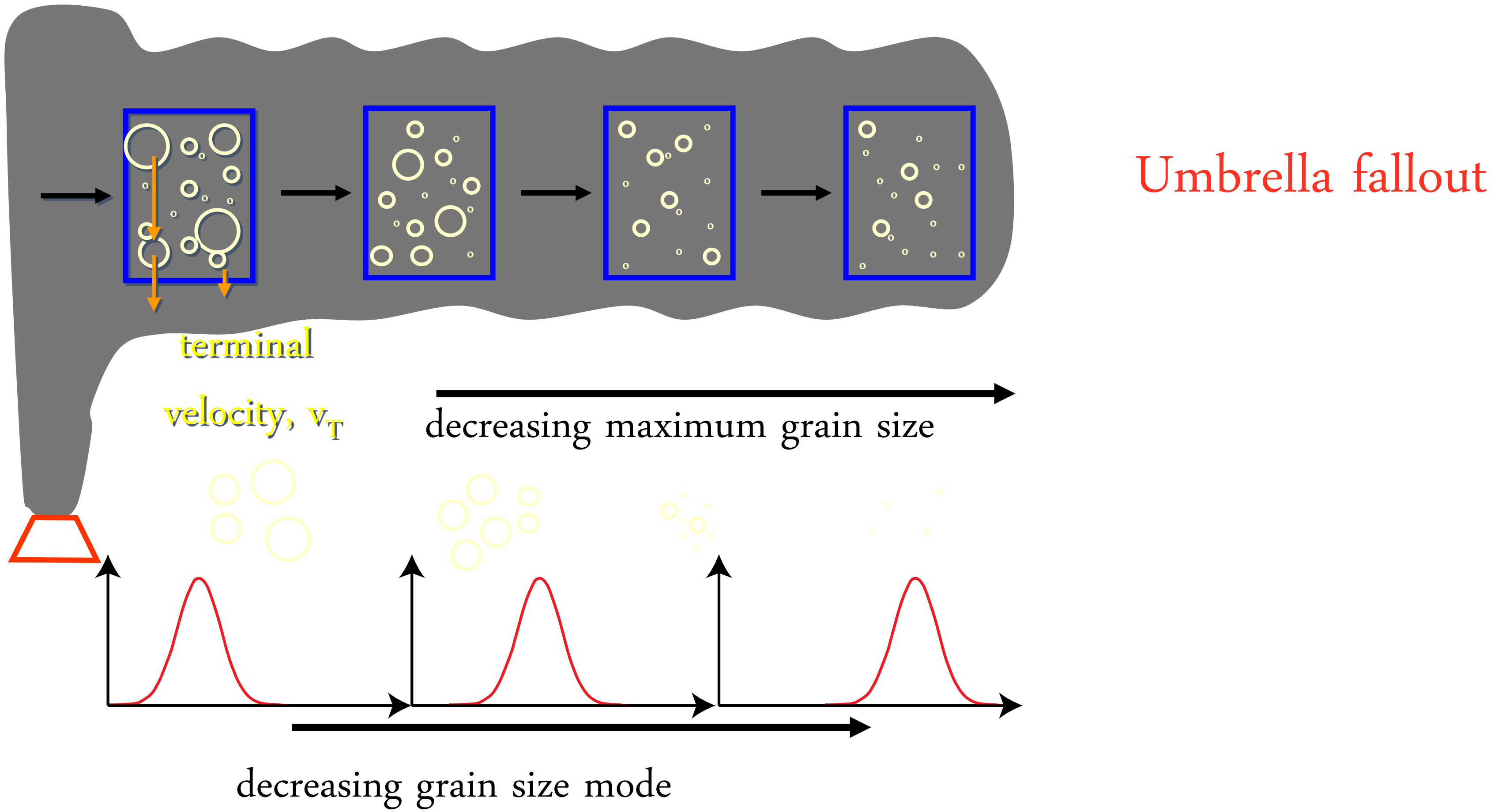
Grain size



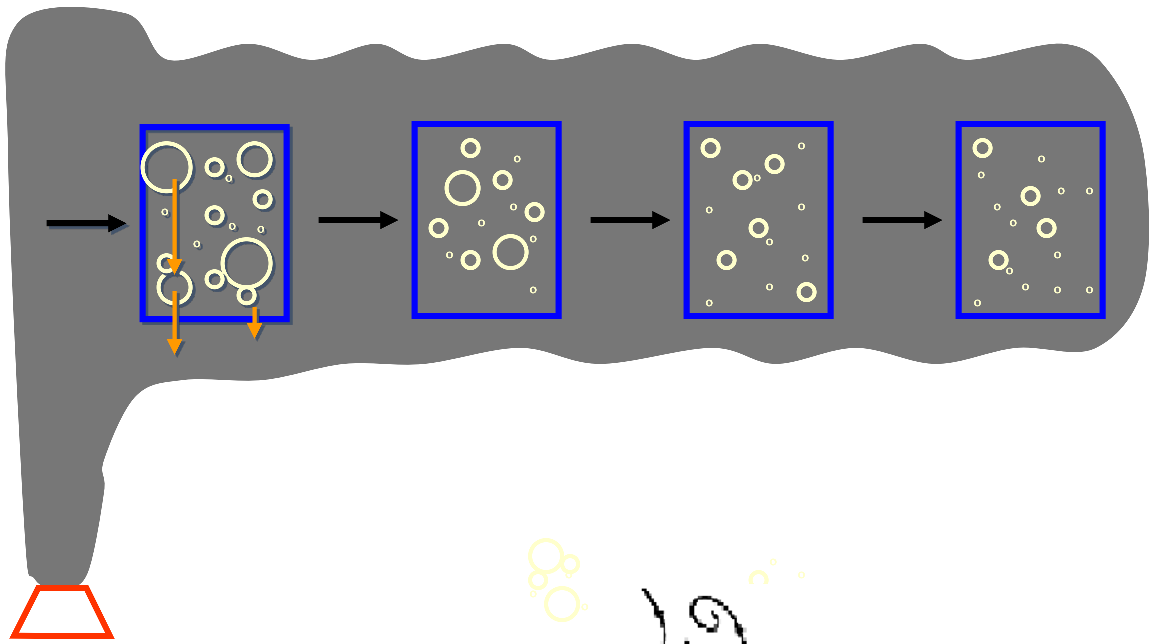
	bombs / blocks	lapilli	coarse ash	**fine ash**
Diameter	> 64 mm	(64 mm-2 mm)	(2 mm-63µm)	**(<63µm)**
Residence time	≈ sec	≈ min	≈ hours to few days	**several days**
Travel distance	proximal <10km	medial <50 km	distal <100 km	**very distal <1000 km**



Fining of fall deposits



Sedimentation from volcanic plumes

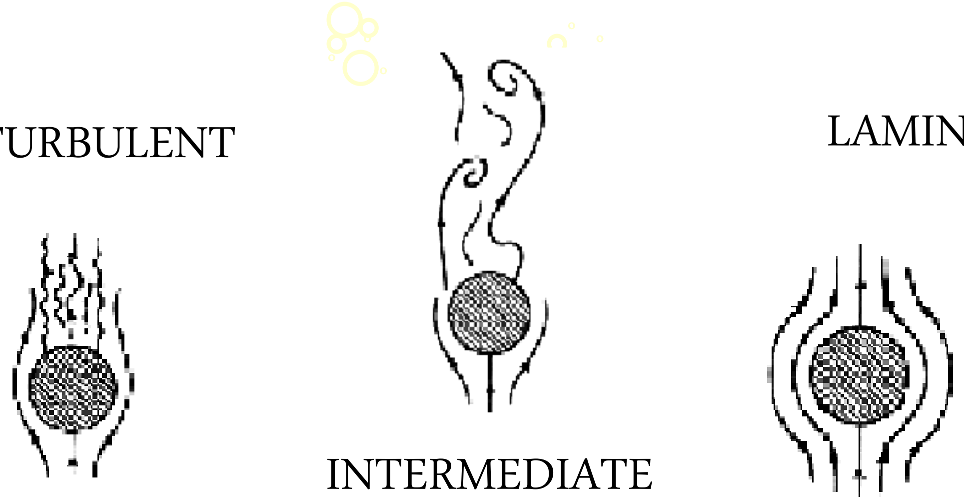


Umbrella fallout

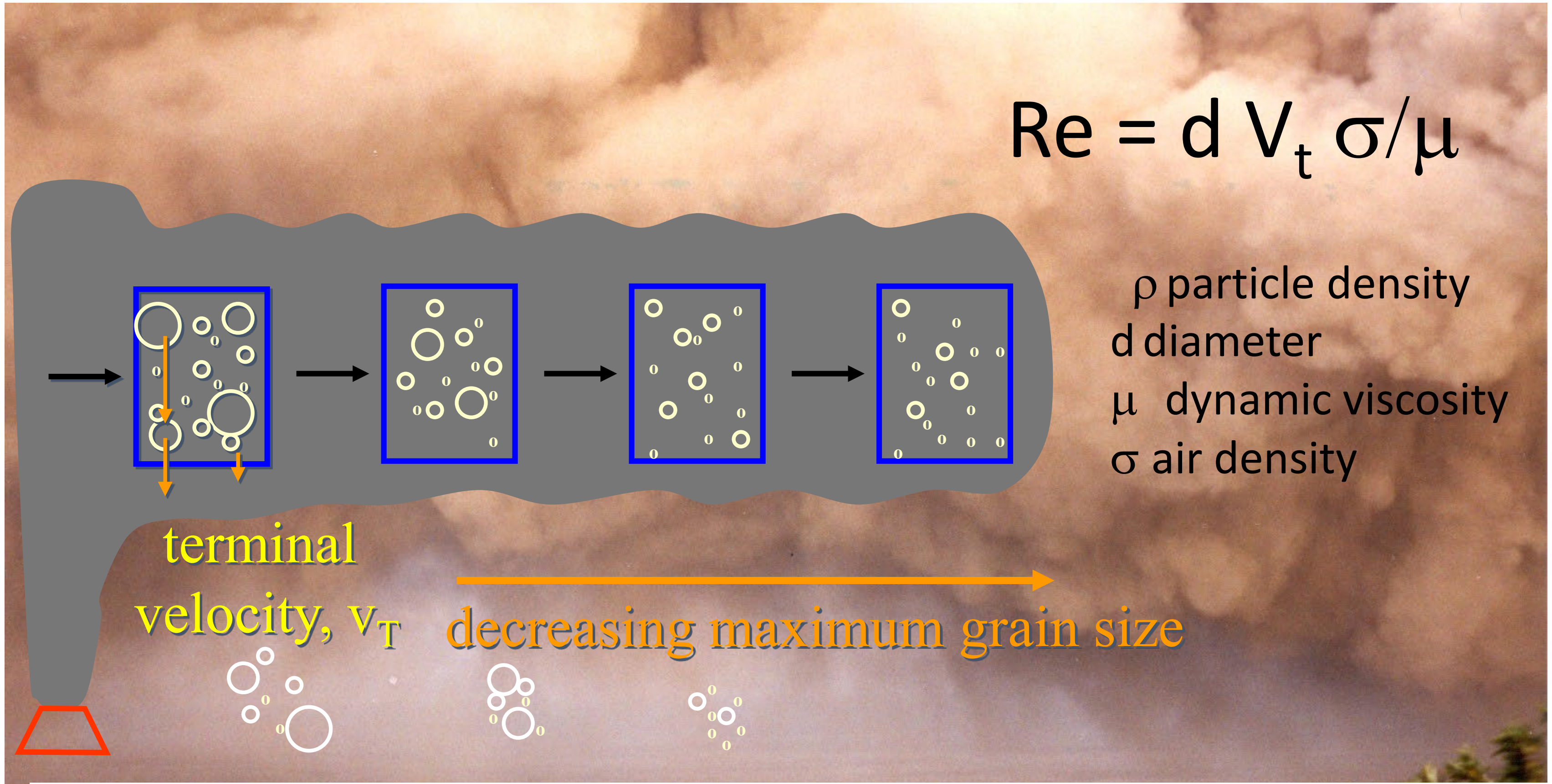
TURBULENT

INTERMEDIATE

LAMINAR



Settling laws for volcanic plumes

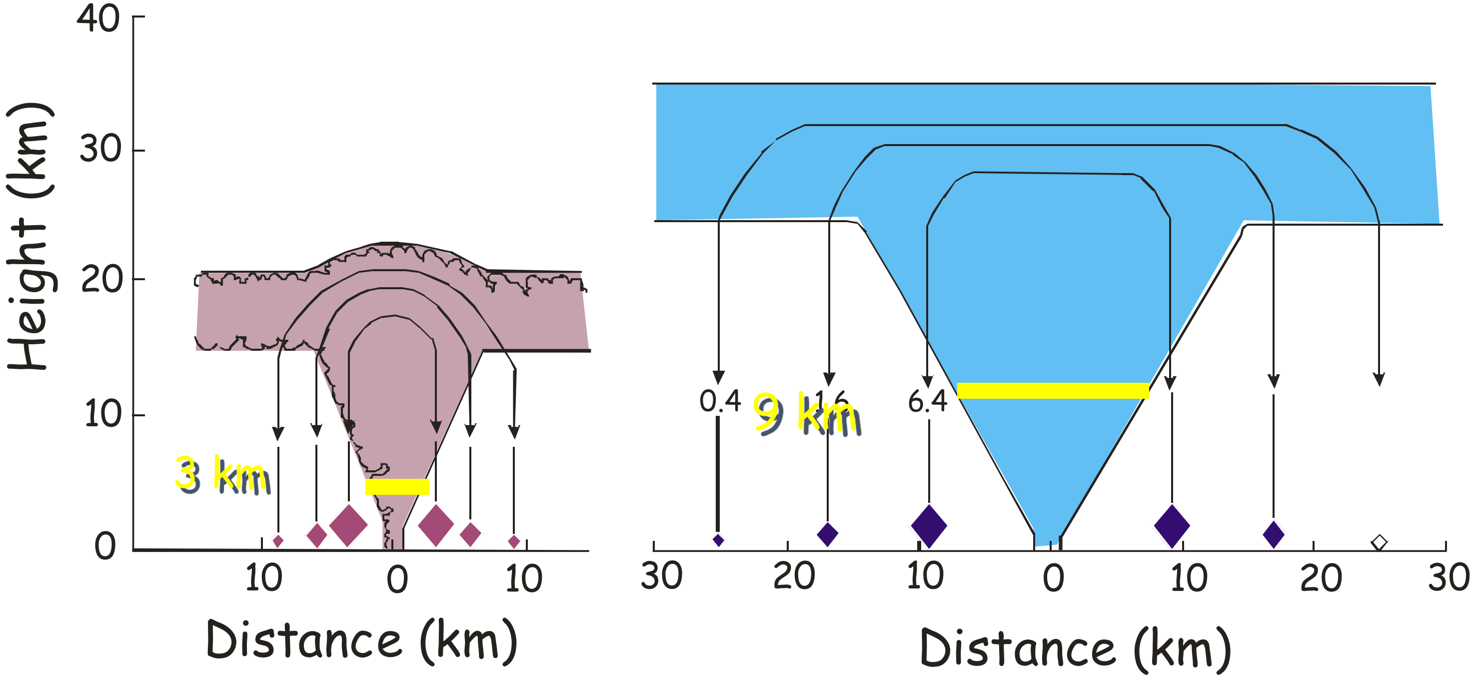


$V_t \approx (3.1\, g\rho d/\sigma)^{1/2}$ (for Reynolds numbers 500-200,000)

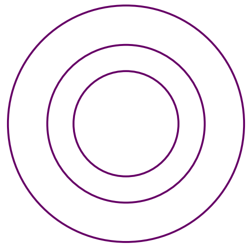
$V_t \approx d(4\rho^2 d^2/225\mu\sigma)^{1/3}$ (for Reynolds numbers 6-500)

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

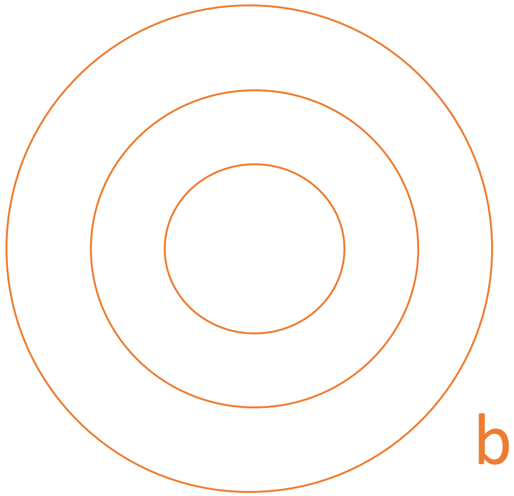
GRAIN SIZE: eruption height



Carey & Sparks 1986

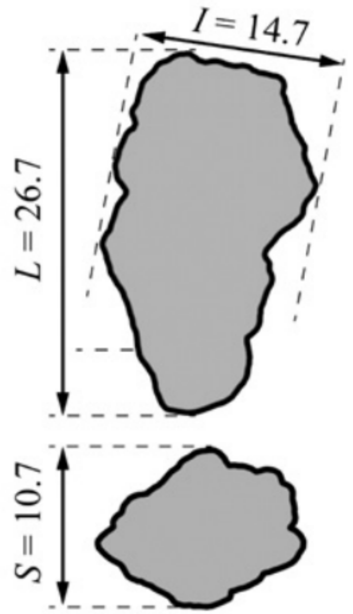


b_c = 1.0 km



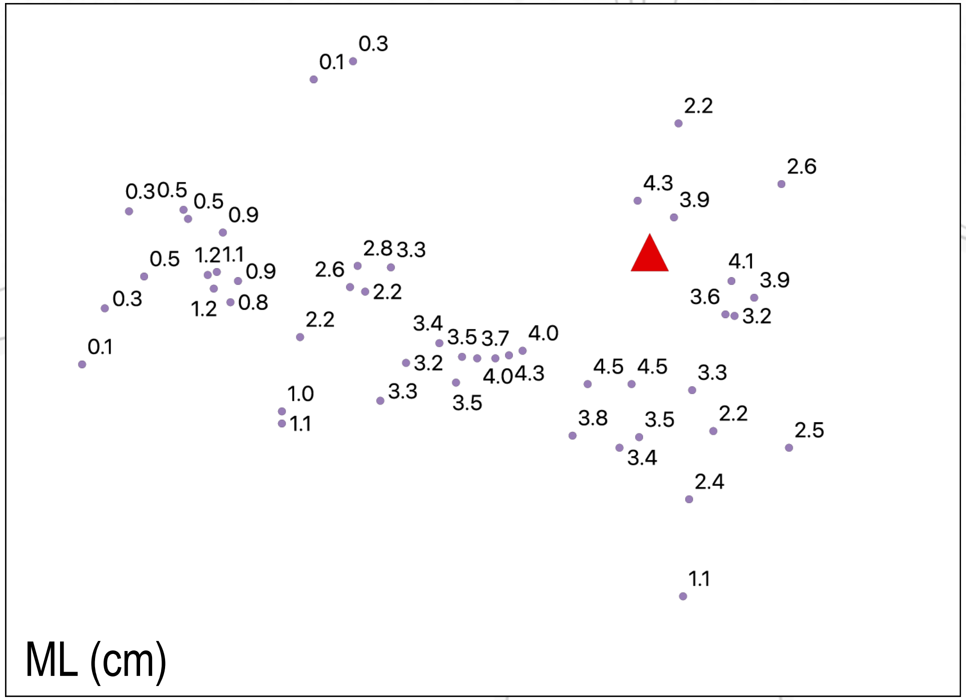
b_c = 4.5 km

Isopleth & plume height calculation



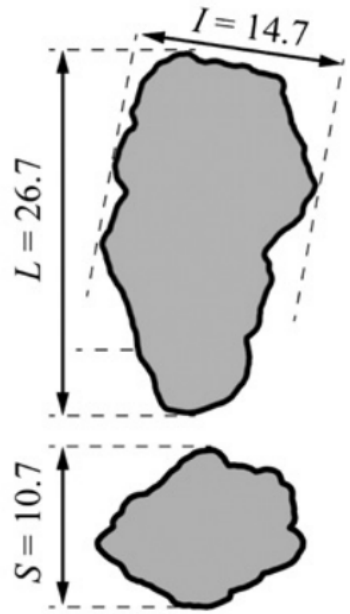
1. Measure the maximum clasts at an outcrop

    - MP: Maximum pumice
    - ML: Maximum lithics
    - Geometric mean of 3 axes
    - Mean of the 5 largest clasts



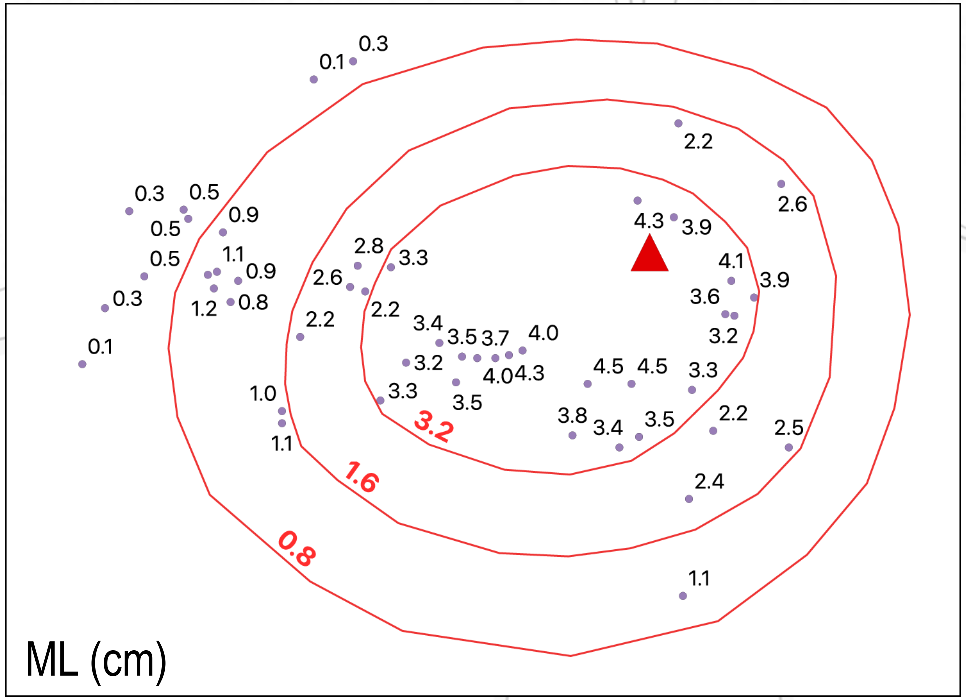
Isopleth & plume height calculation

1. Measure the maximum clast at an outcrop
    - MP: Maximum pumice
    - ML: Maximum lithics
    - Geometric mean of 3 axes
    - Mean of the 5 largest clasts



2. Contour **isopleth**

= contours of equal diameter



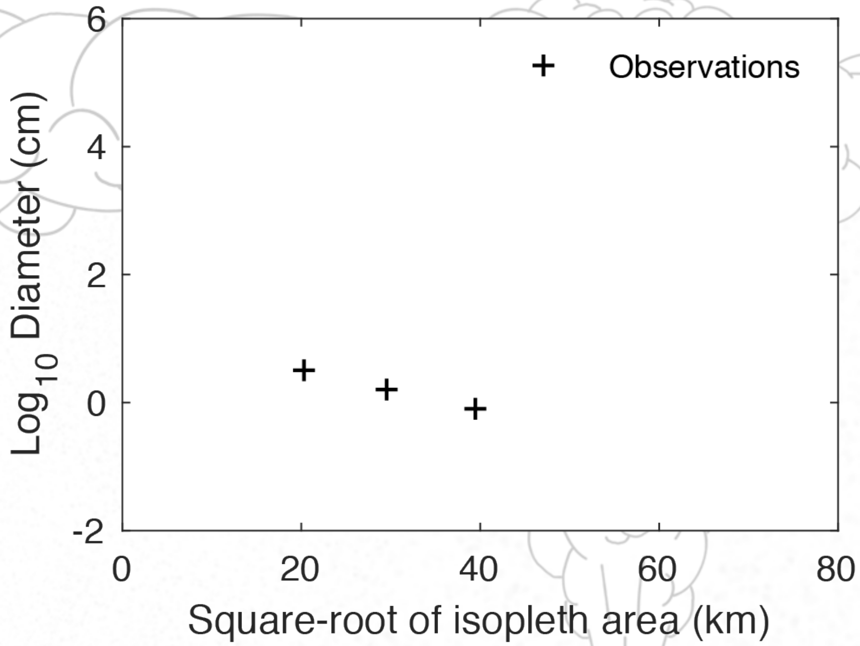
Isopleth & plume height calculation

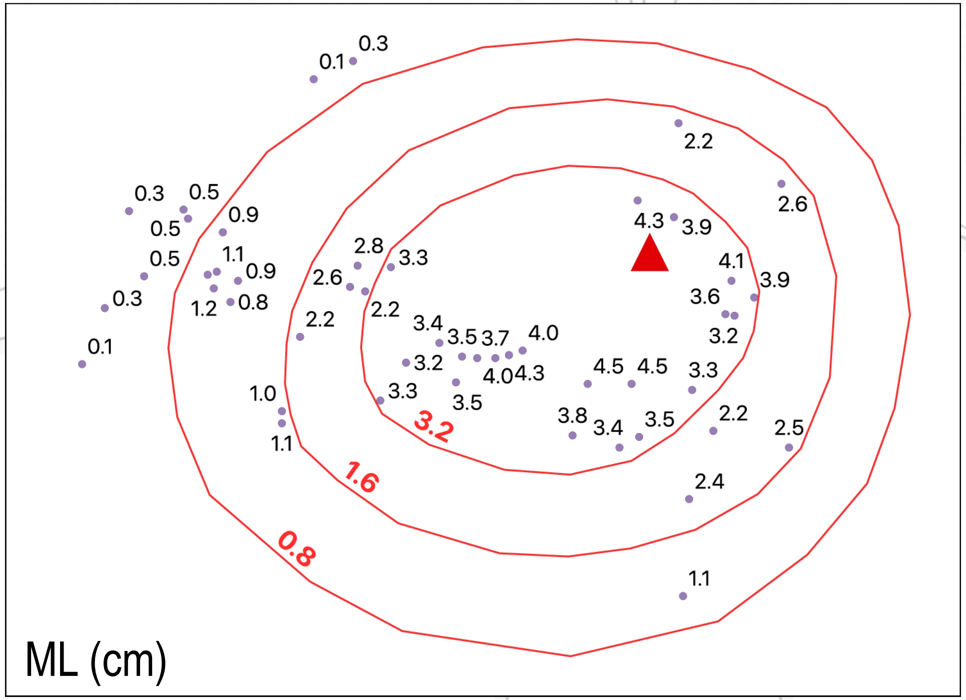
1. Measure the maximum clast at an outcrop
   - MP: Maximum pumice
   - ML: Maximum lithics
   - Geometric mean of 3 axes
   - Mean of the 5 largest clasts

2. Contour **isopleth**

   = contours of equal diameter

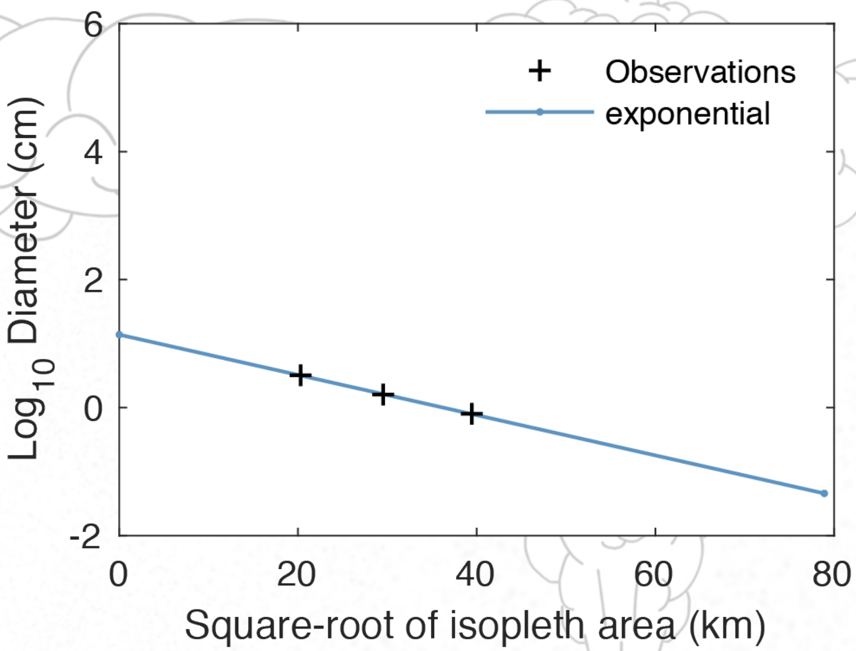
3. Plot log(diameter) vs sqrt(area)





Isopleth & plume height calculation

1. Measure the maximum clasts at an outcrop
   - MP: Maximum pumice
   - ML: Maximum lithics
   - Geometric mean of 3 axes
   - Mean of the 5 largest clasts



2. Contour **isopleth**

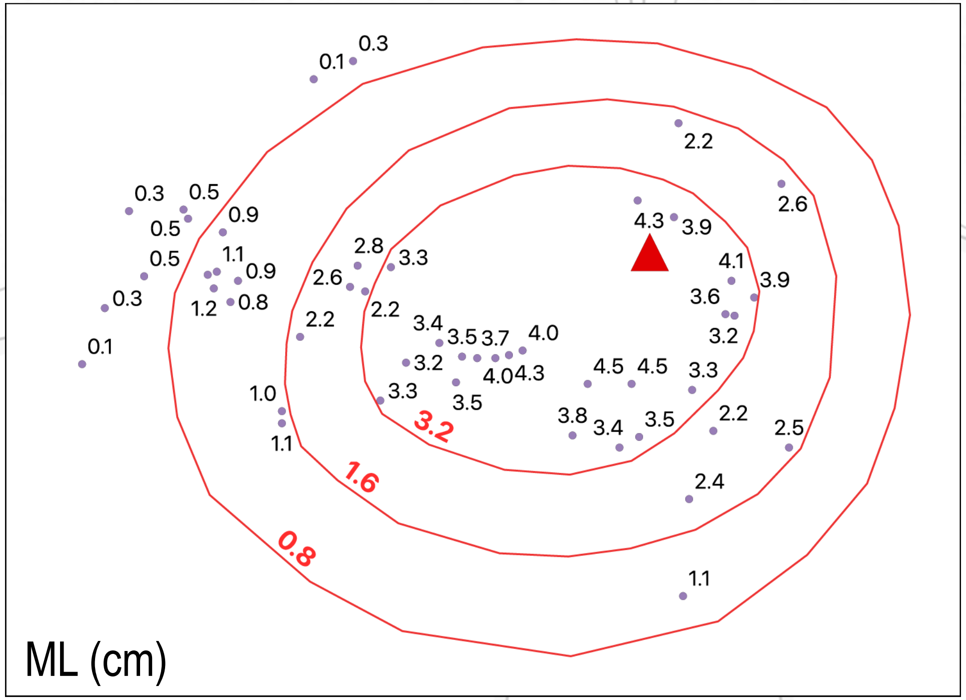
   = contours of equal diameter

3. Plot log(diameter) vs sqrt(area)

4. Fit exponential segment
   - D_0: Diameter at intercept, k: Fining rate

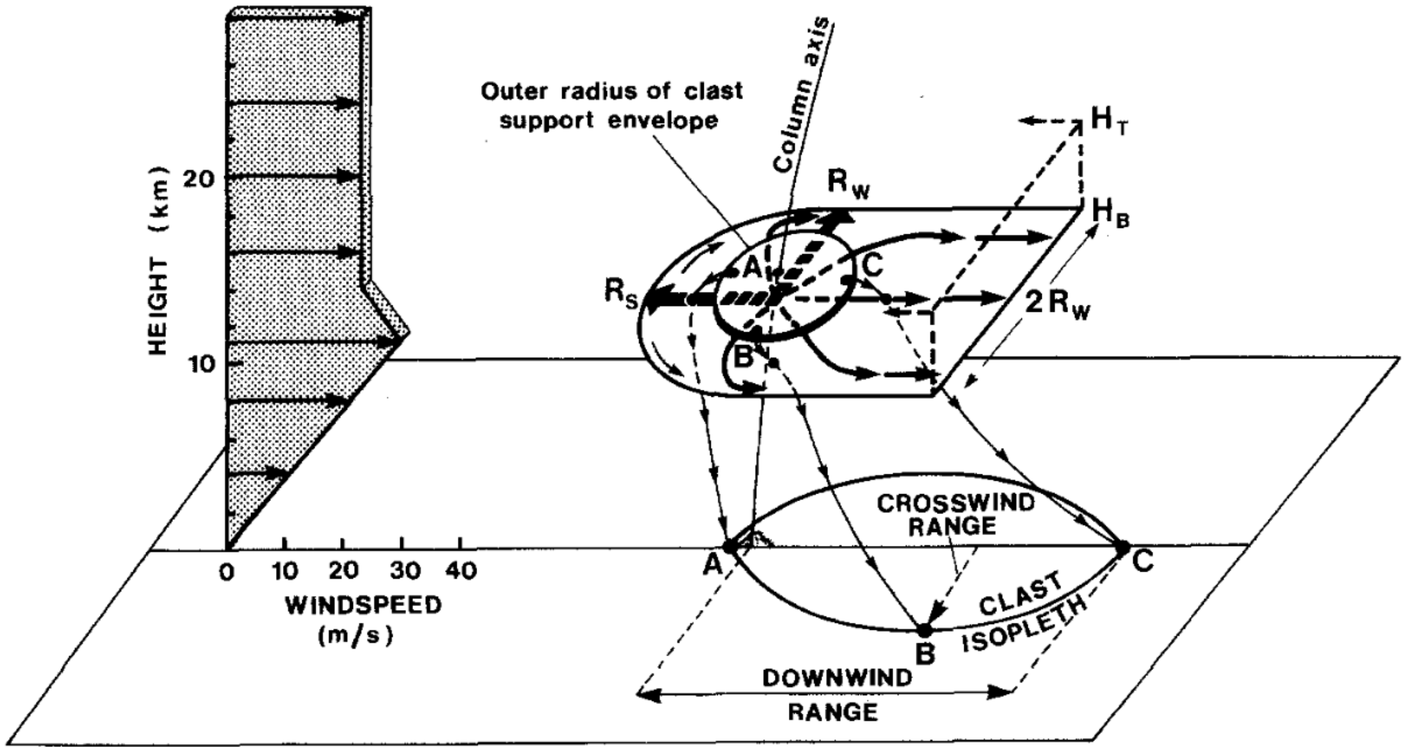
5. Calculate diameter half-distance $\mathbf{b_C}$ as:

$$\frac{\log(2)}{k\sqrt{\pi}}$$

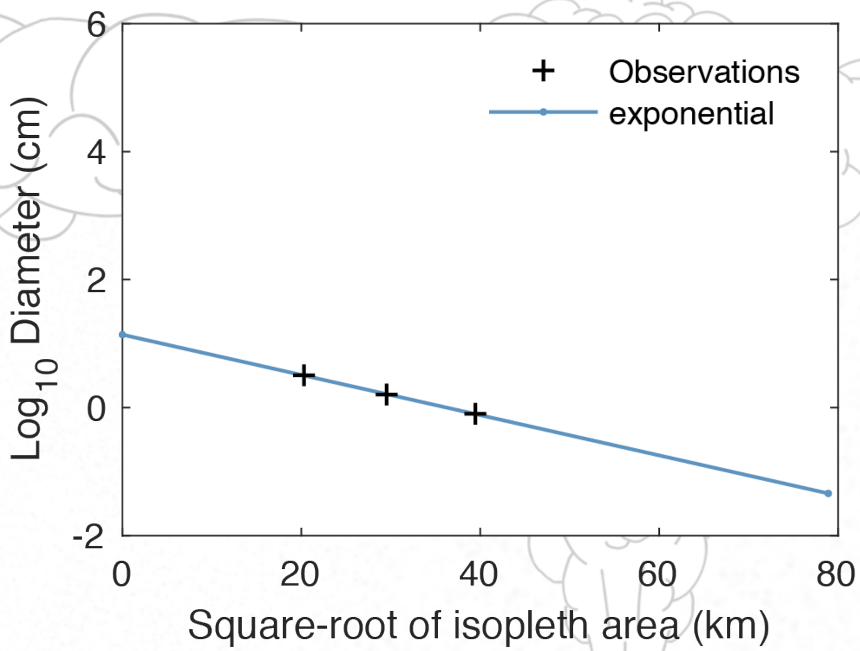


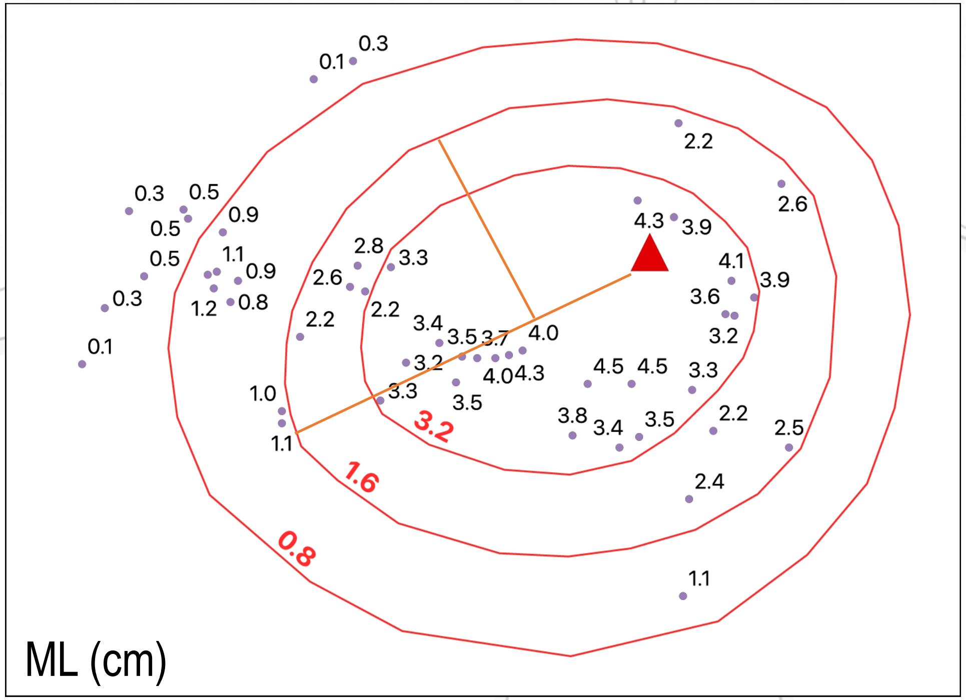
Isopleth & plume height calculation

6. Measure downwind and half crosswind distances



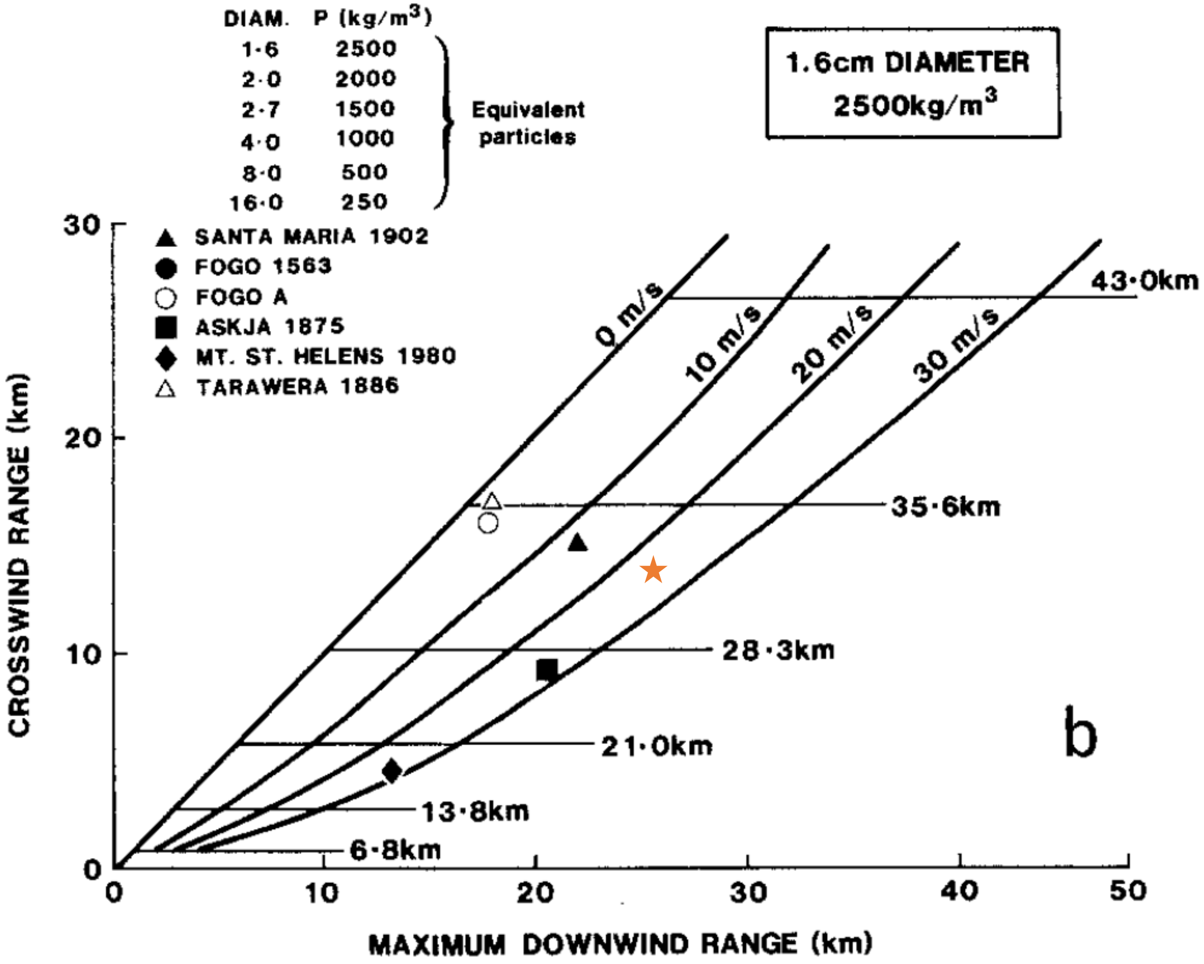
Carey and Sparks 1986

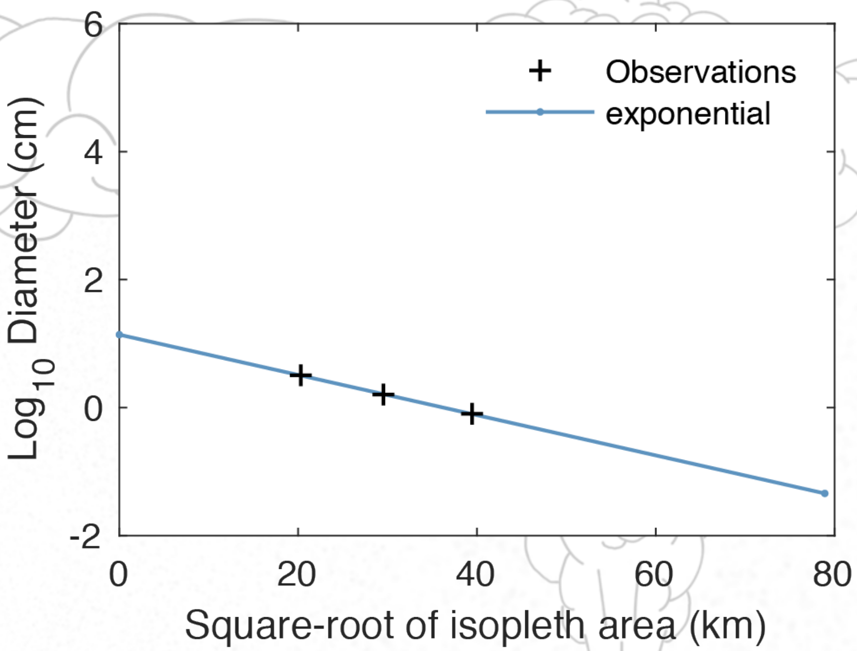


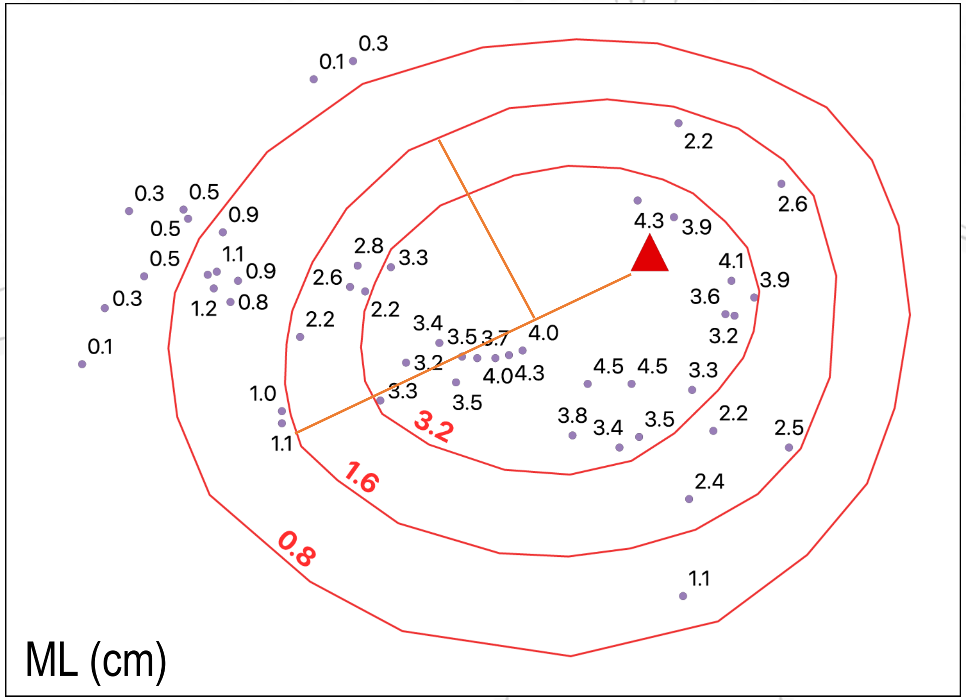


Isopleth & plume height calculation

7. Estimate plume height (H_b) and wind speed using the plots of Carey and Sparks (1986)



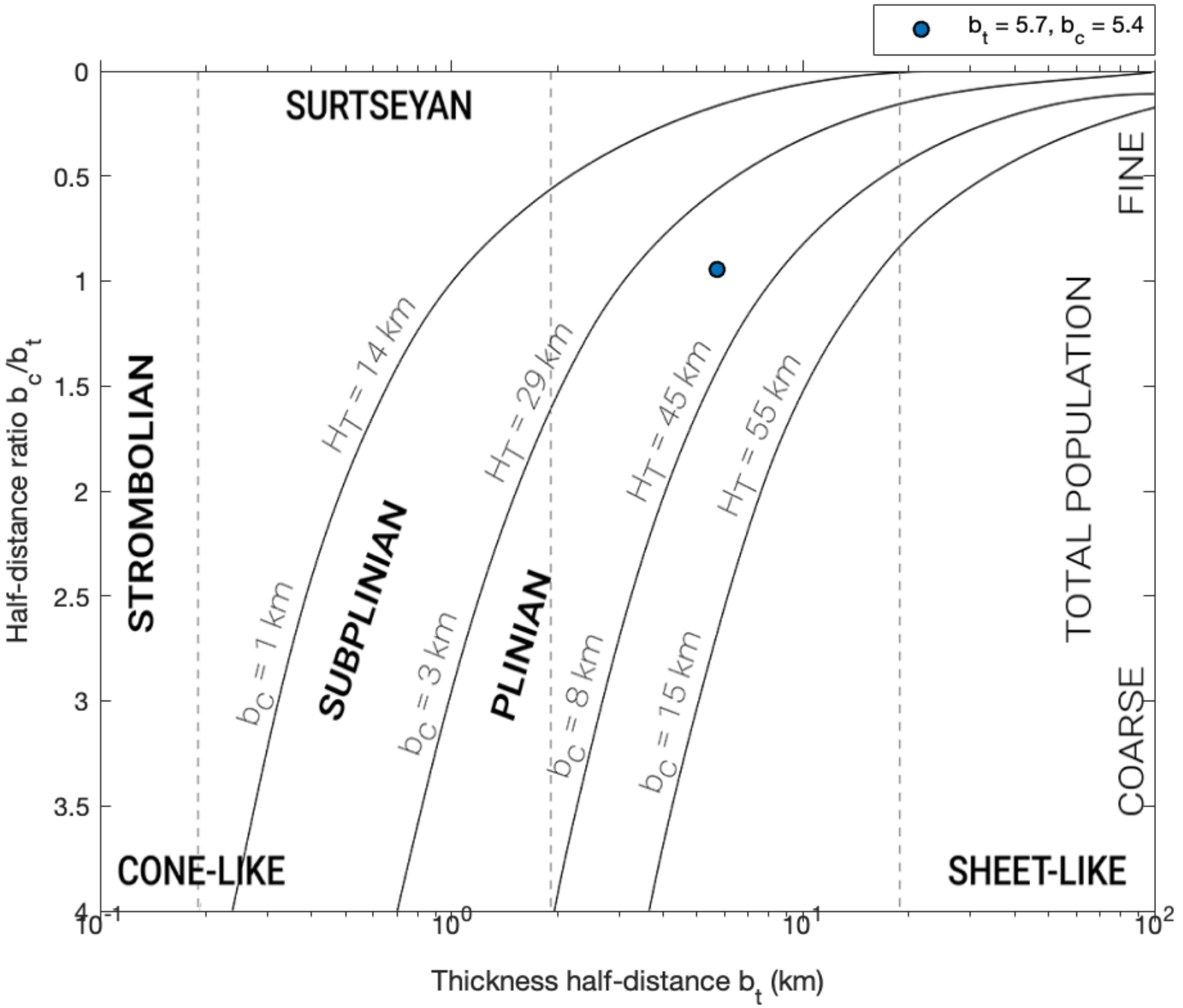




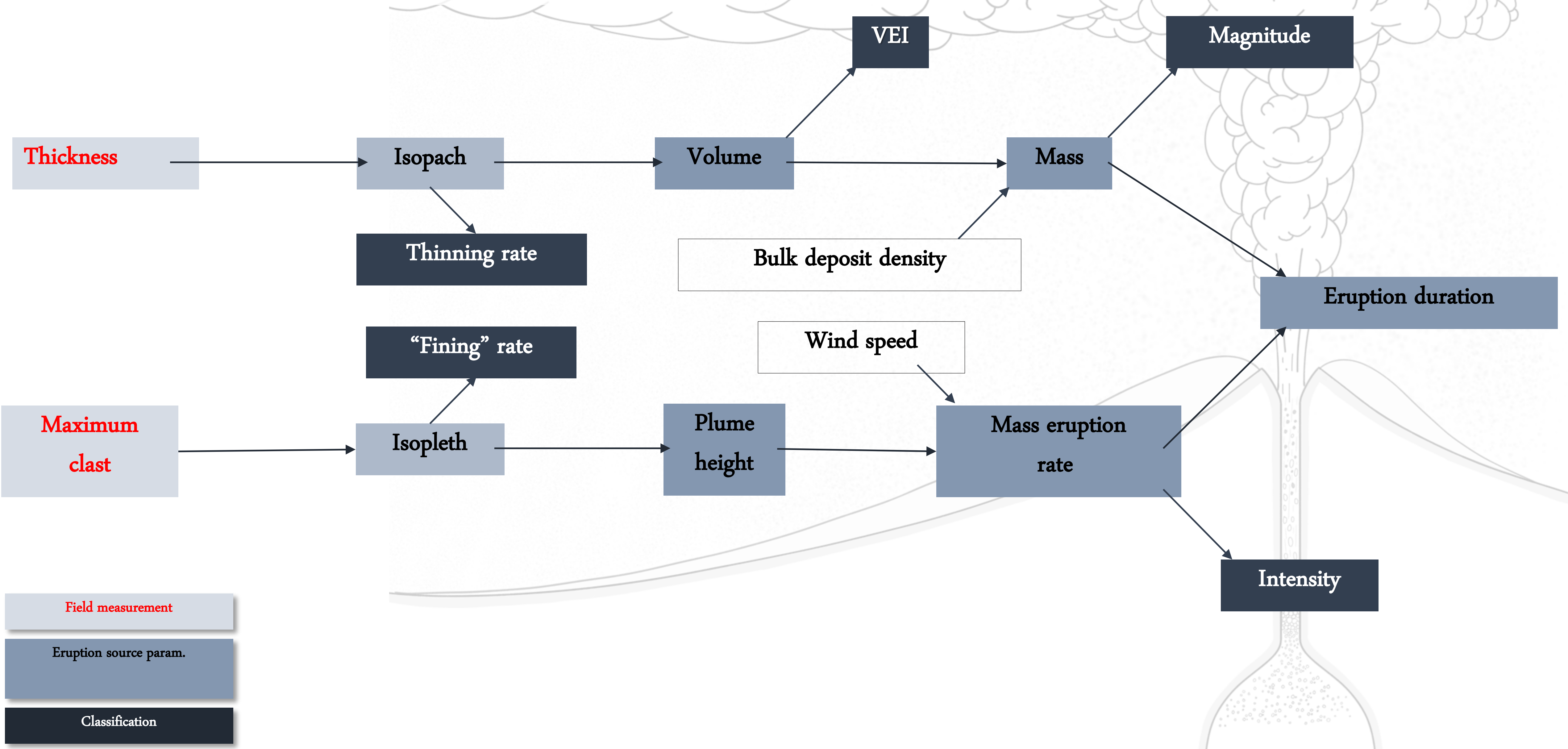
Classifications

- **b_t**: Half-thickness distance → *Thinning*
- **b_C**: Half-diameter distance → *Fining*

- **Basis of field-based classification**



Tephra fall summary



2) limitations and pitfalls

- In situ characterization is averaged over at least episodes and often eruptions
- Abrupt and gradual temporal sifts are neglected and glossed-over

Componentry

Juvenile

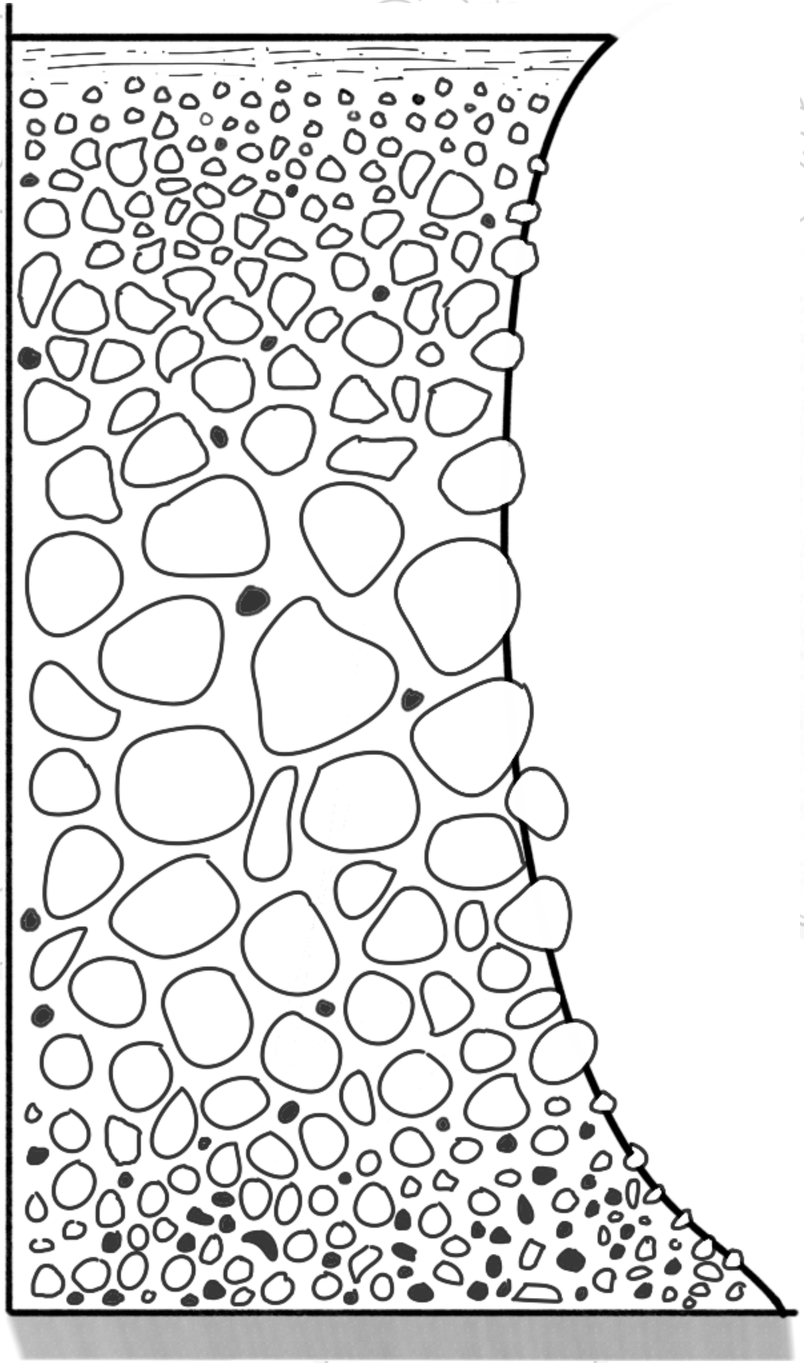
Wall rock

Size

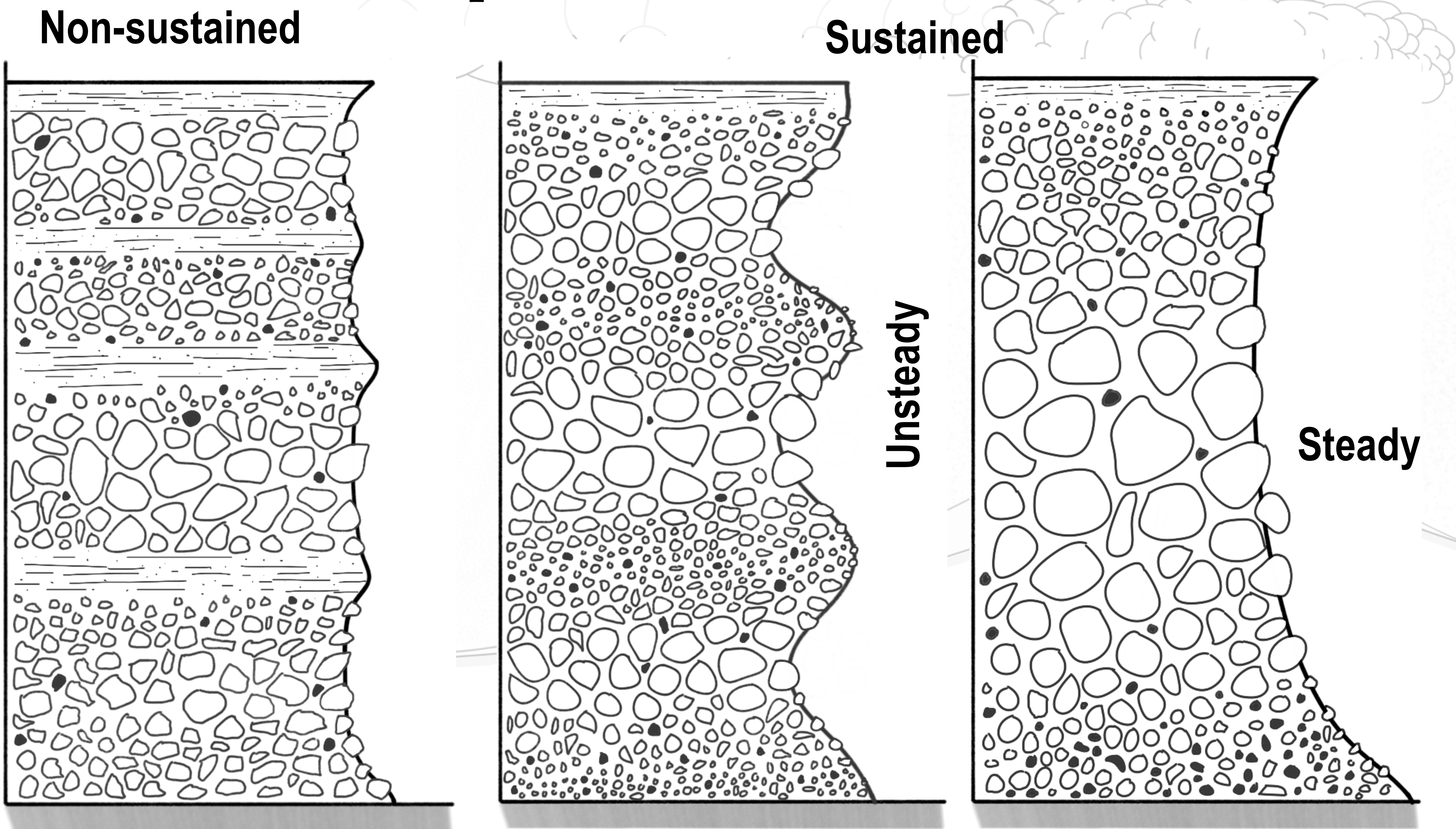
Lapilli

Ash

→ **Sorting? Grading? Layering?**

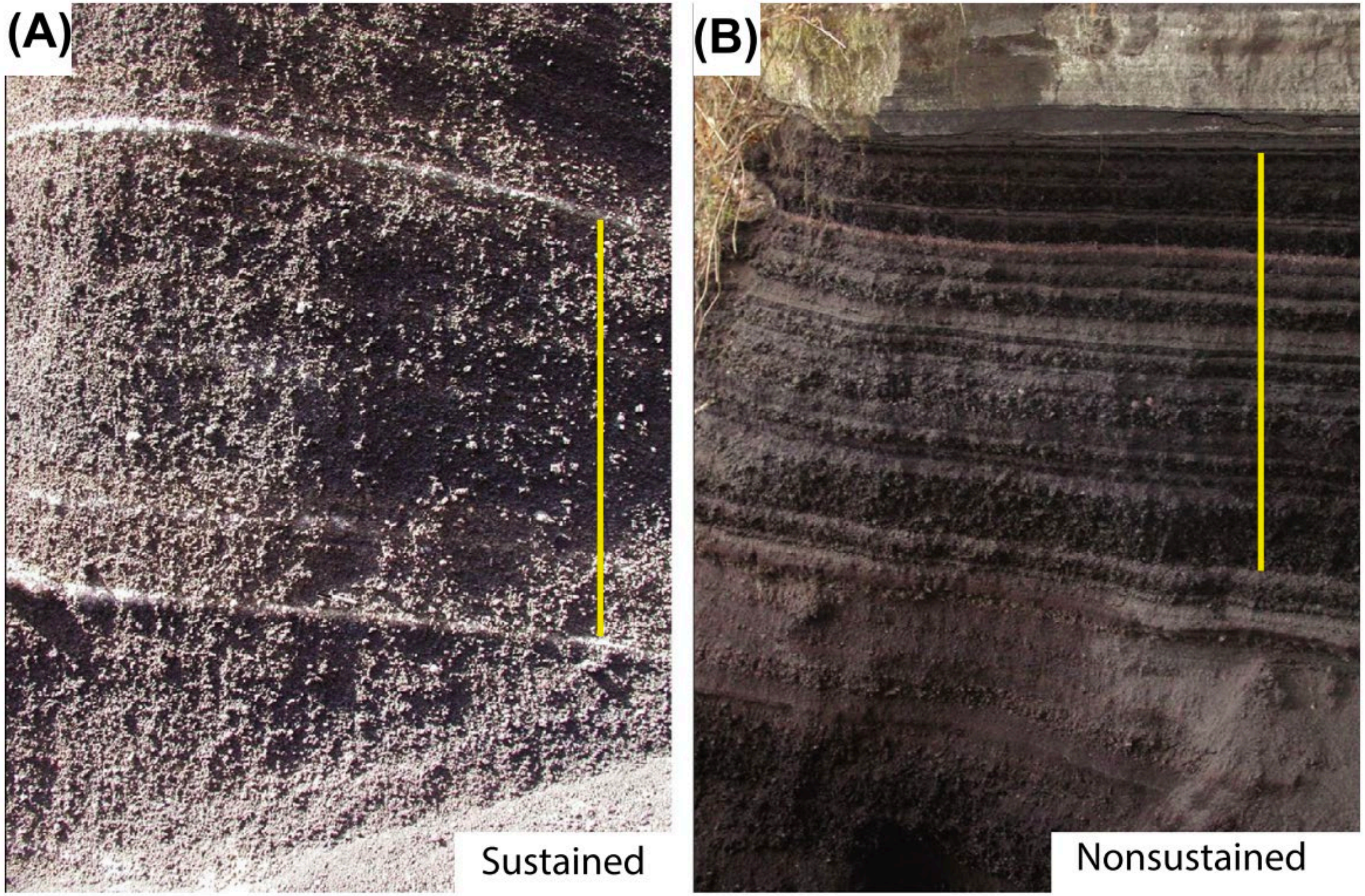


Limitations: temporal variations in MER



Eruption dynamics

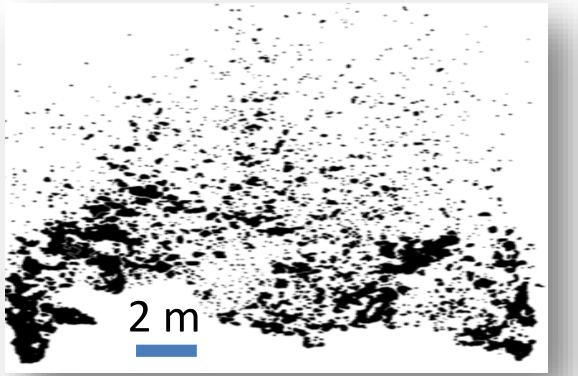
- In situ characterization is averaged over at least episodes and often entire eruptions
- Abrupt and gradual temporal sifts are neglected and glossed-over



A new approach: particle characterization using high resolution videos

Key inputs to plume and fountain models include: **exit velocity,** plume/ or fountain **height**, the **total erupted mass**, **mass eruption rate** and **size distribution of ejected particles**. All are hard to constrain by conventional means due to poor temporal resolution and the effects of down-transport size an density fractionation.

3. in-flight characterization



velocimetry

in-flight grain size

in-flight total mass

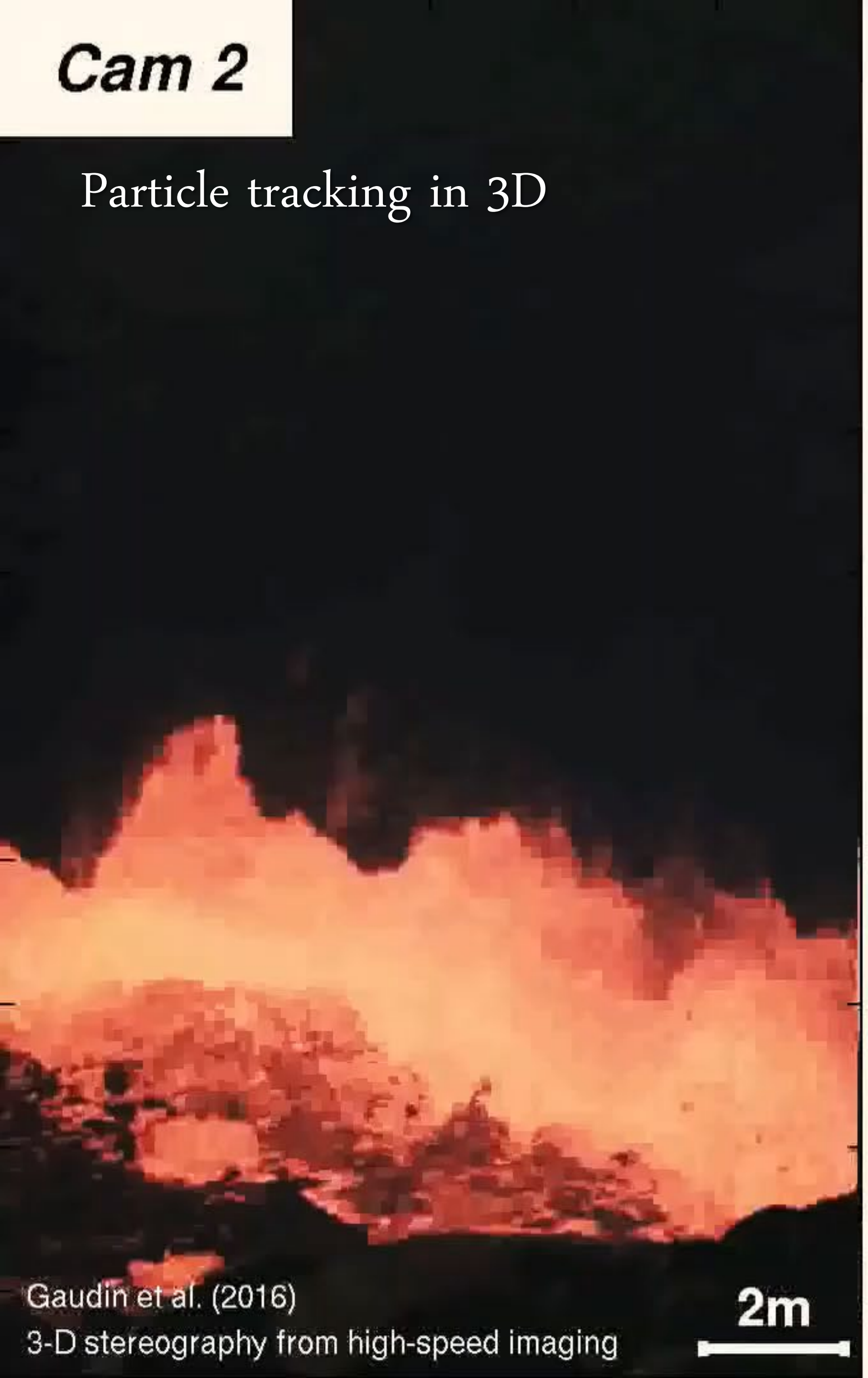
In-flight mass discharge rate

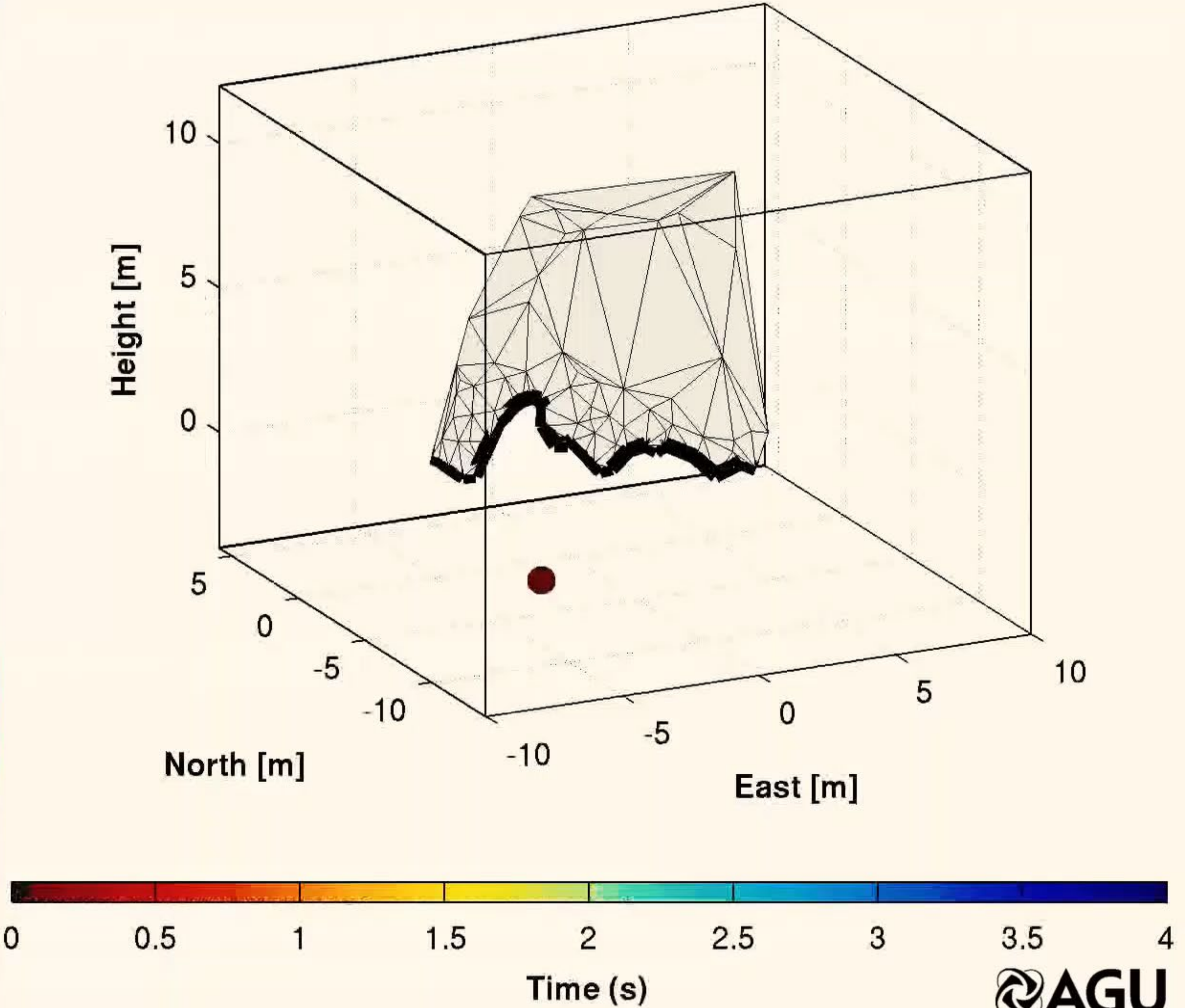
- processed using Photoshop/ImageJ (MTrackJ)
- pixel size via laser range-finder

- volume assumed = (area) x (minor axis)

- duration ImageJ/matlab

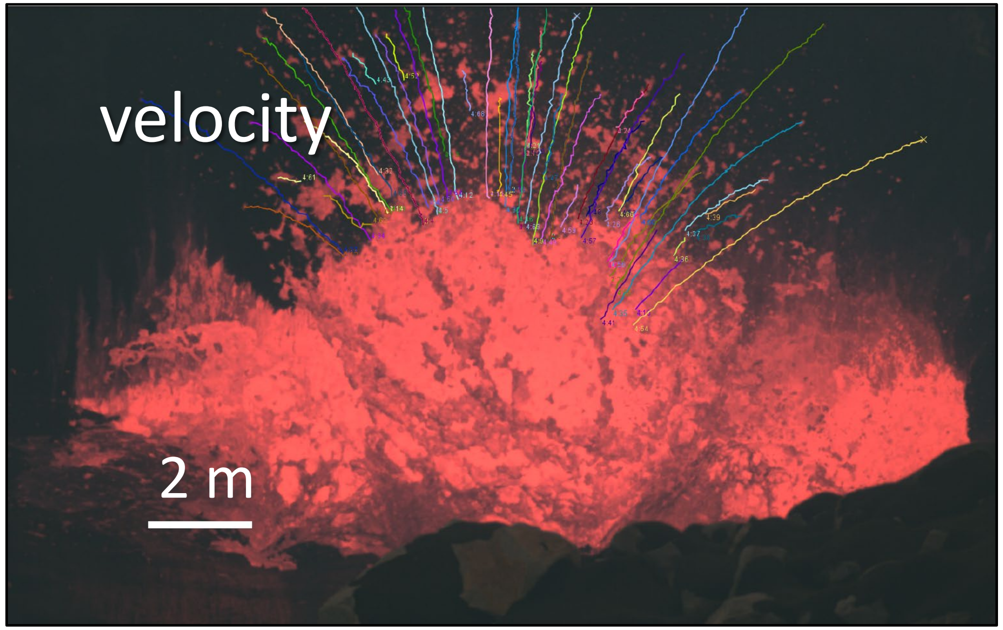
Quantifying complex changes on fine spatial and temporal scales

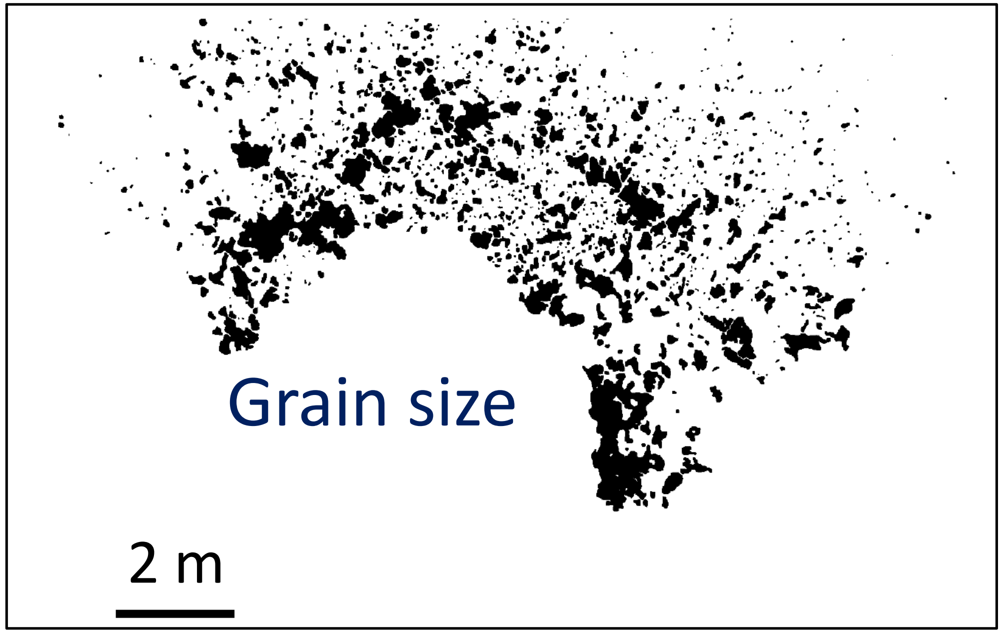

Cam 2
Particle tracking in 3D
Gaudin et al. (2016)
3-D stereography from high-speed imaging
2m

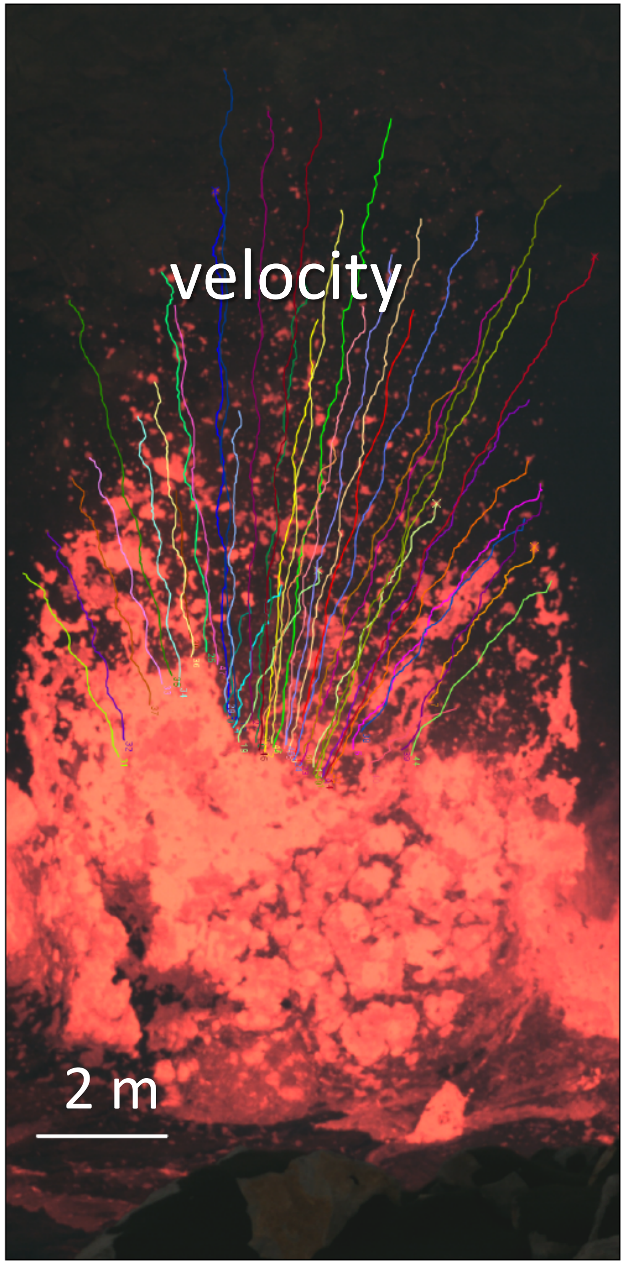

Height [m]
10
5
0
North [m]
5
0
-5
-10
East [m]
-10
-5
0
5
10
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (s)

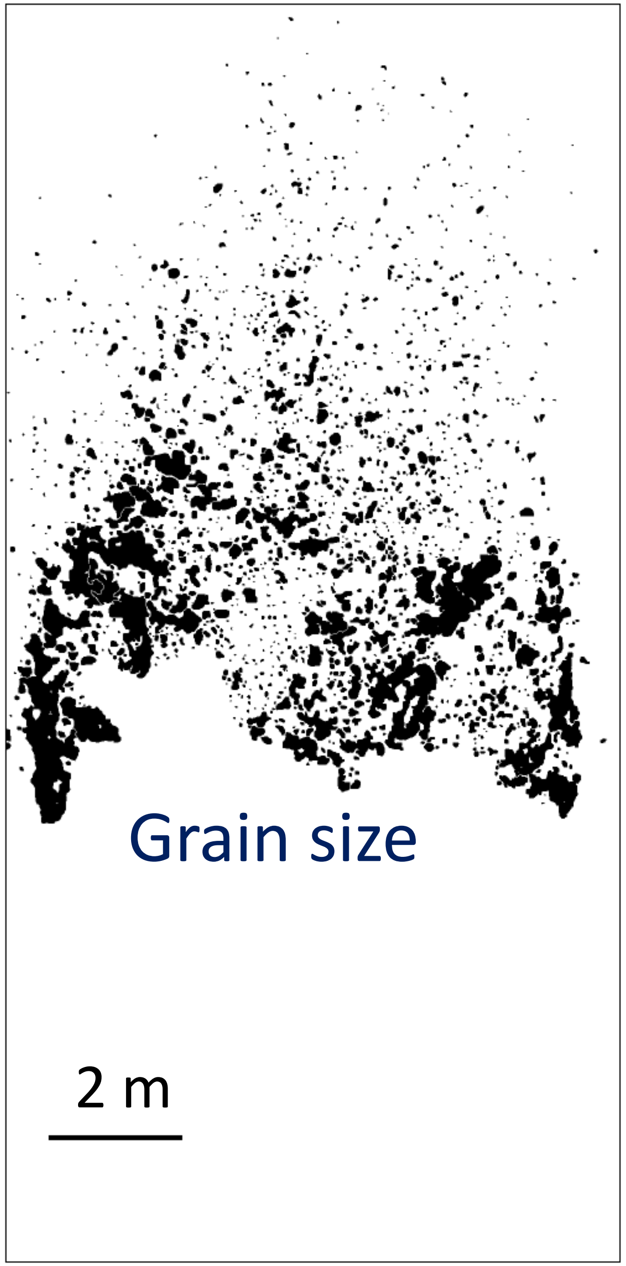
AGU

Pyroclast tracking and manual grain size

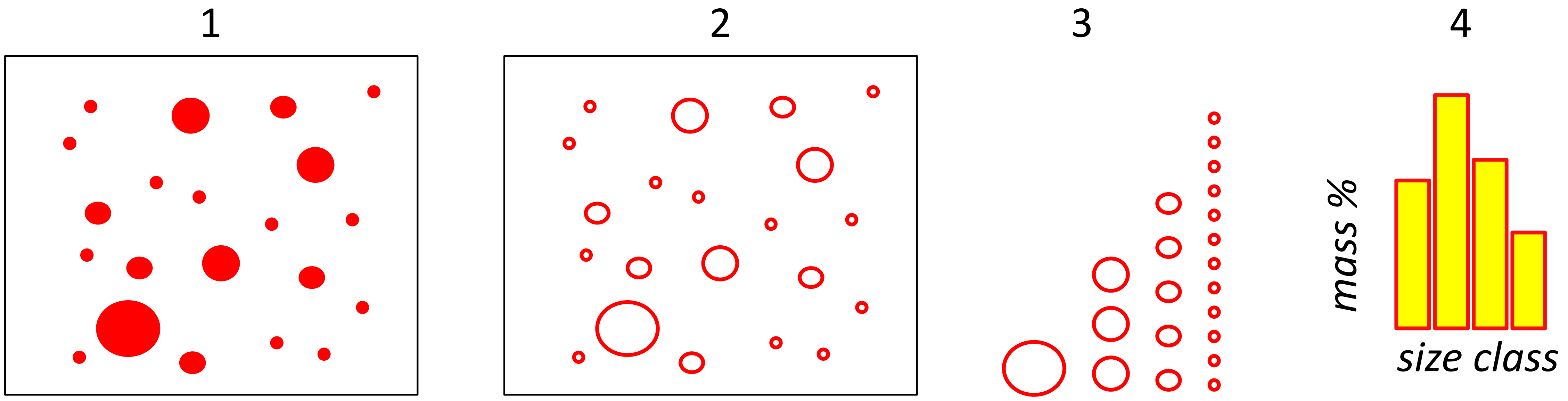








Automated grain size distributions



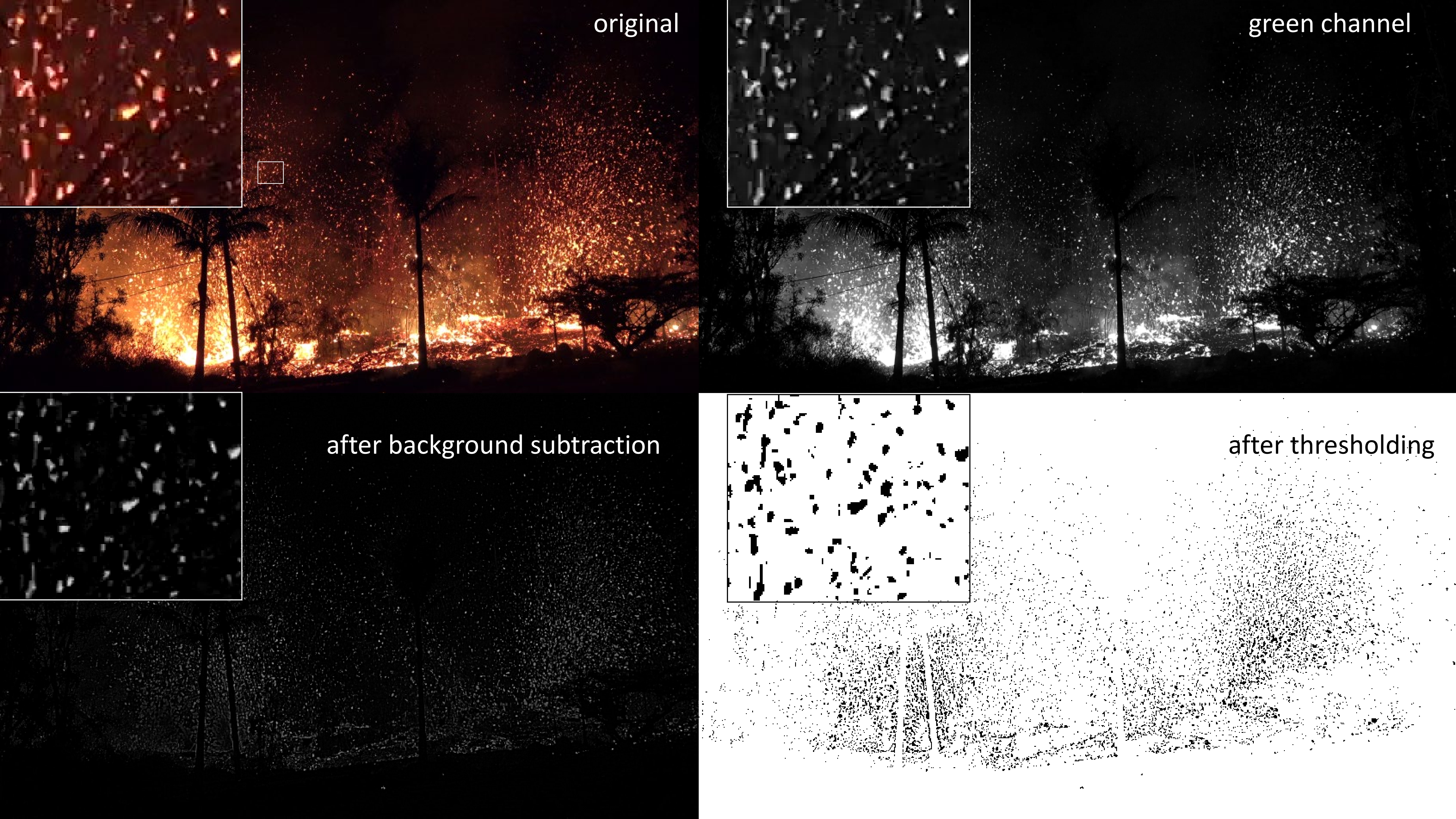
1) **image preprocessing: Matlab** wavelength/background removal

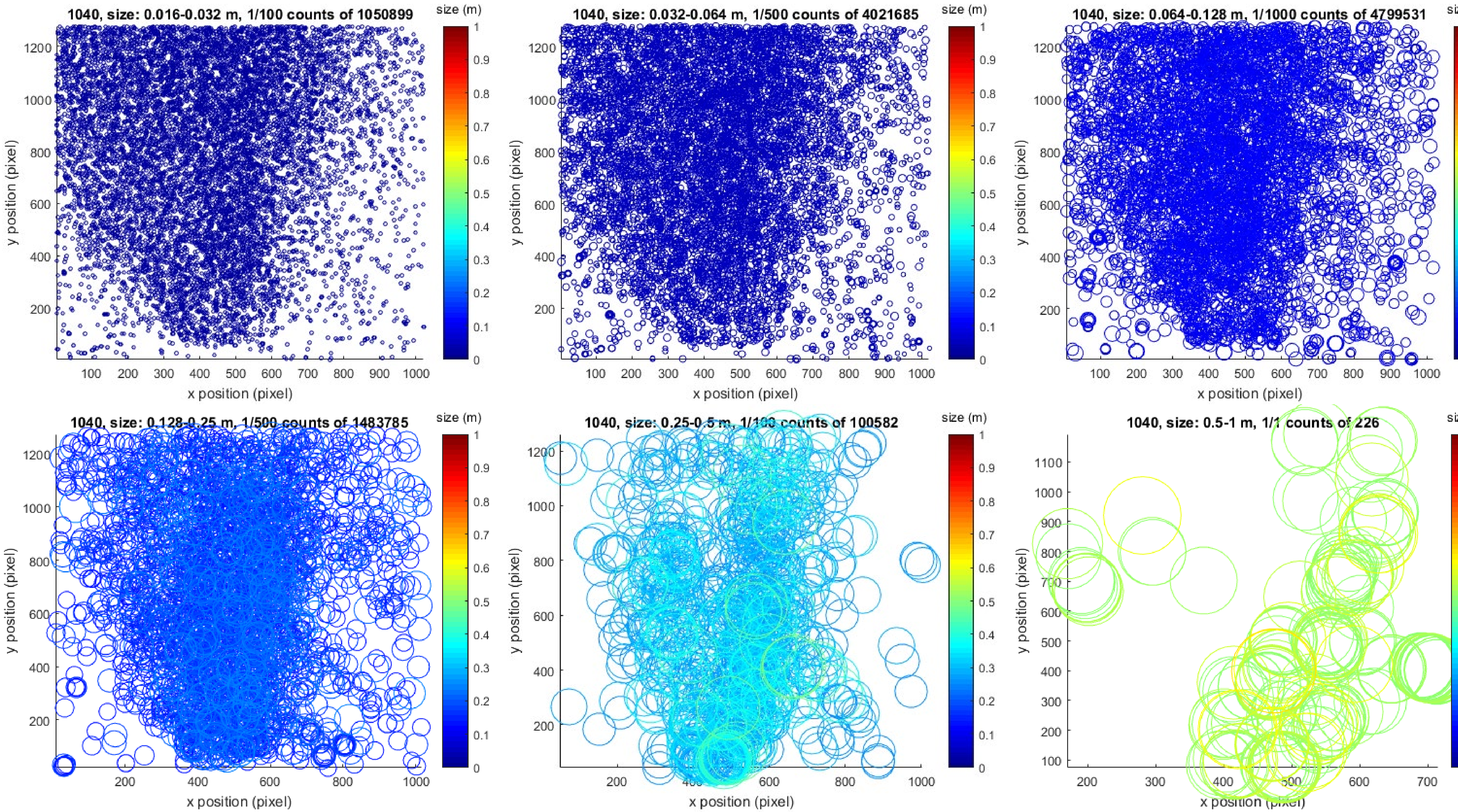
2) **image thresholding: ImageJ** grey scale intensity

3) **particle analysis Matlab/Image J**

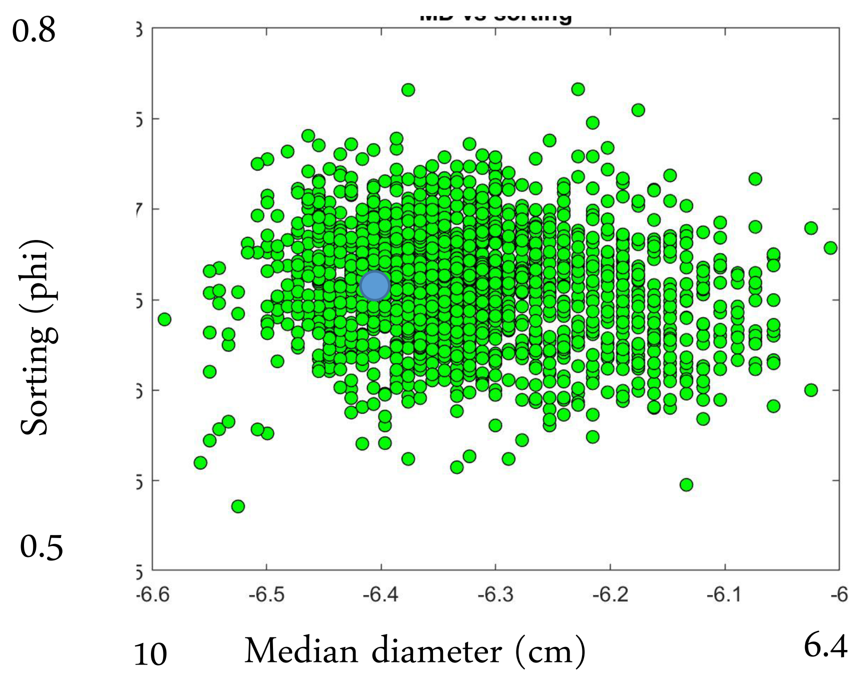
4) **data postprocessing Matlab**

5) **data analysis**


original
green channel
after background subtraction
after thresholding

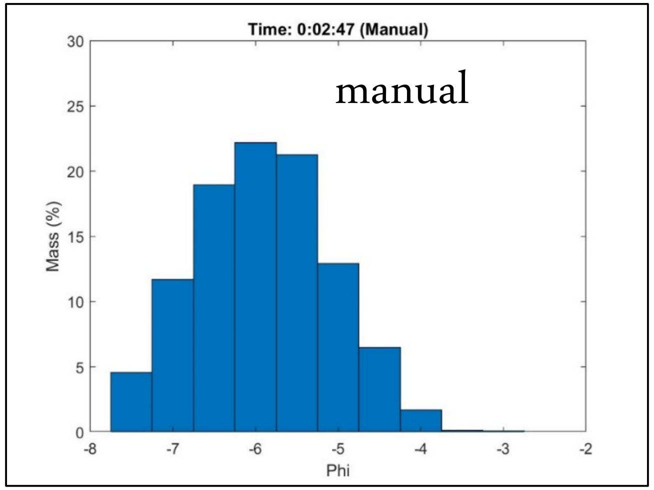

1040, size: 0.016-0.032 m, 1/100 counts of 1050899
1040, size: 0.032-0.064 m, 1/500 counts of 4021685
1040, size: 0.064-0.128 m, 1/1000 counts of 4799531
1040, size: 0.128-0.25 m, 1/500 counts of 1483785
1040, size: 0.25-0.5 m, 1/100 counts of 100582
1040, size: 0.5-1 m, 1/1 counts of 226
size (m)
x position (pixel)
y position (pixel)

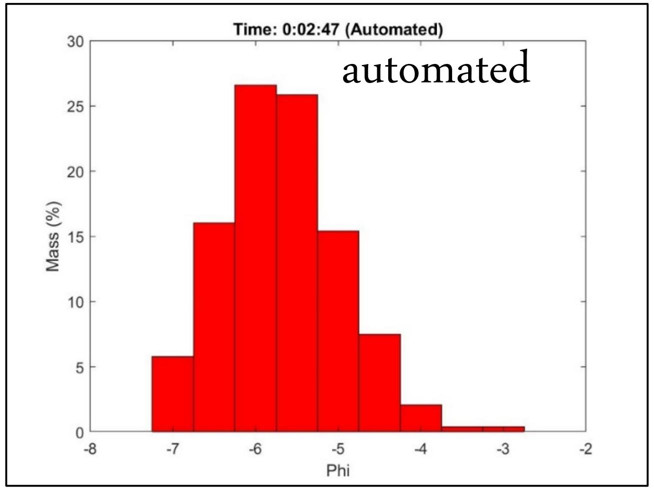
In-flight grain size distribution for a single frame (frame rate 0.033 sec) using two different methods



Side-by-side comparison

Sorting coefficient (phi)





Bin size (phi)

- processed using Photoshop/ImageJ
- clasts are outlined in photoshop and parameters are calculated in ImageJ

- processed using ImageJ/Matlab
- image background is subtracted in Matlab and threshold is applied in ImageJ to detect pyroclasts

2 m natural duration: 0.5 s

Stromboli,
Sept. 2018

Optronis CR600X2,
1280x1024
500 fps
1 pixel=0.010 m

Kilauea,
spring 2018

Sony AX100,
3840x2160
30 fps
1 pixel=0.009 m

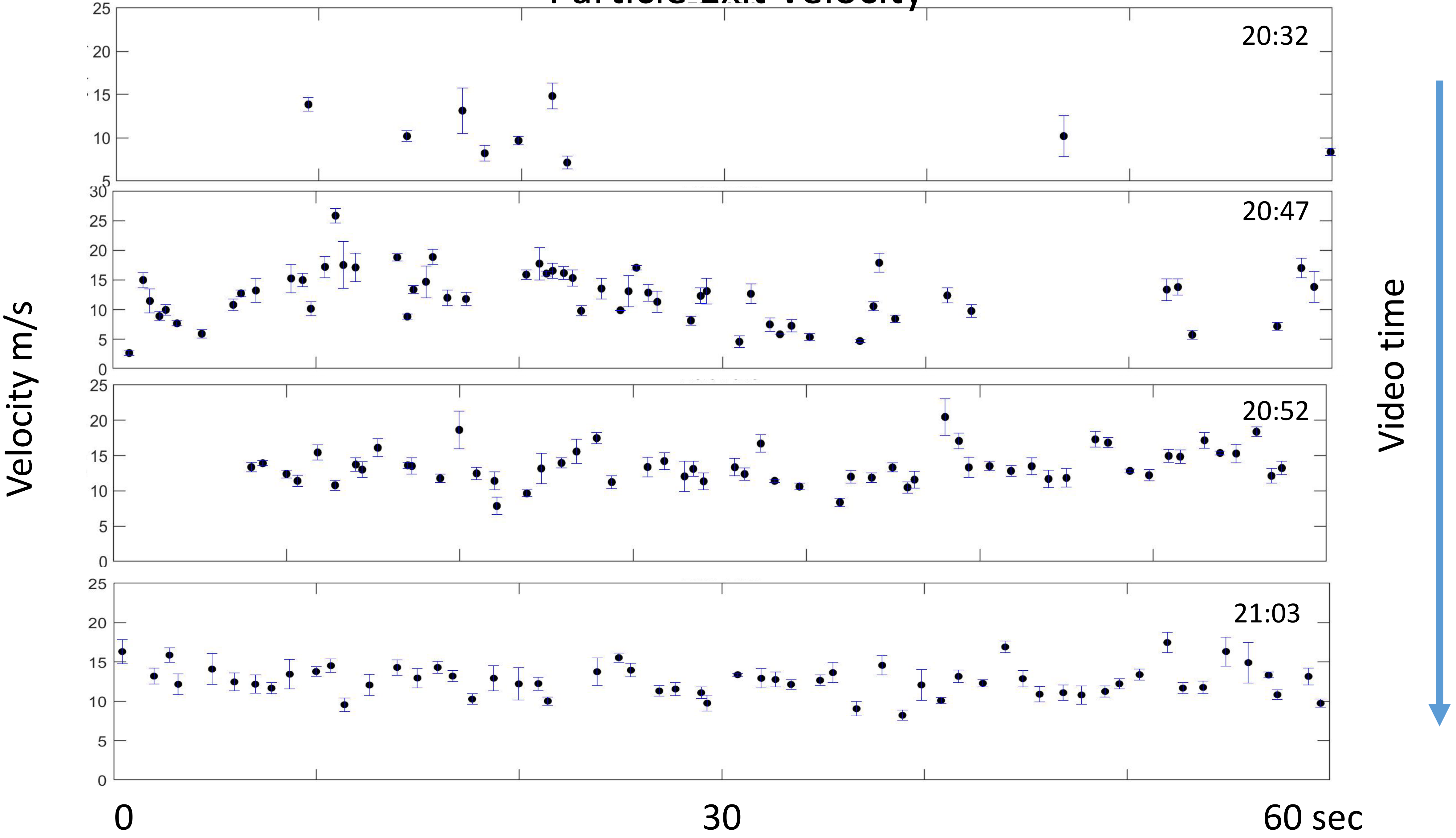
10 m natural duration: 5 s

1 m natural duration: 5 s

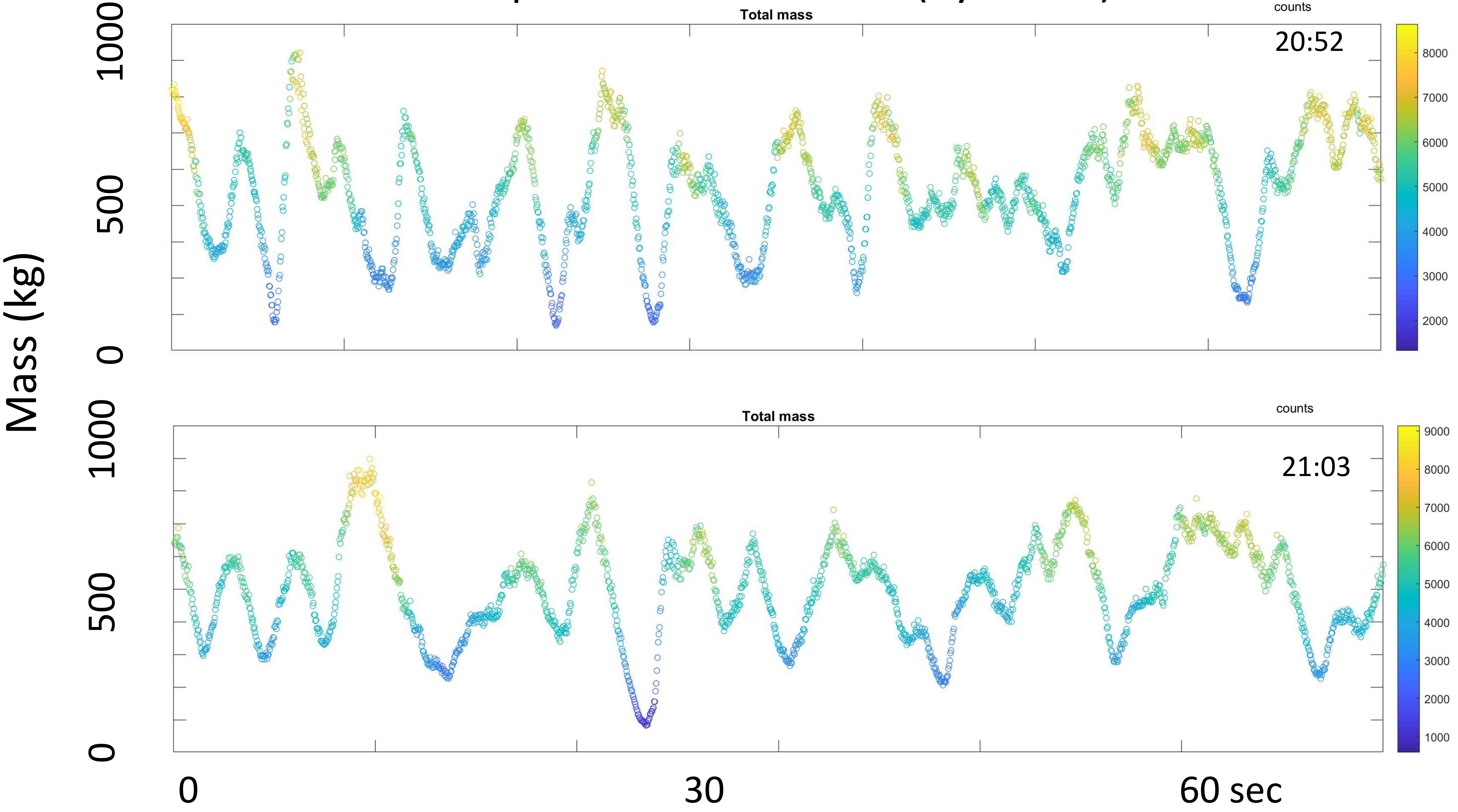
Etna,
July 2014

Optronis CR600X2,
1280x1024
500 fps
1 pixel=0.008 m

Particle Exit Velocity



Erupted mass with time (by frame)

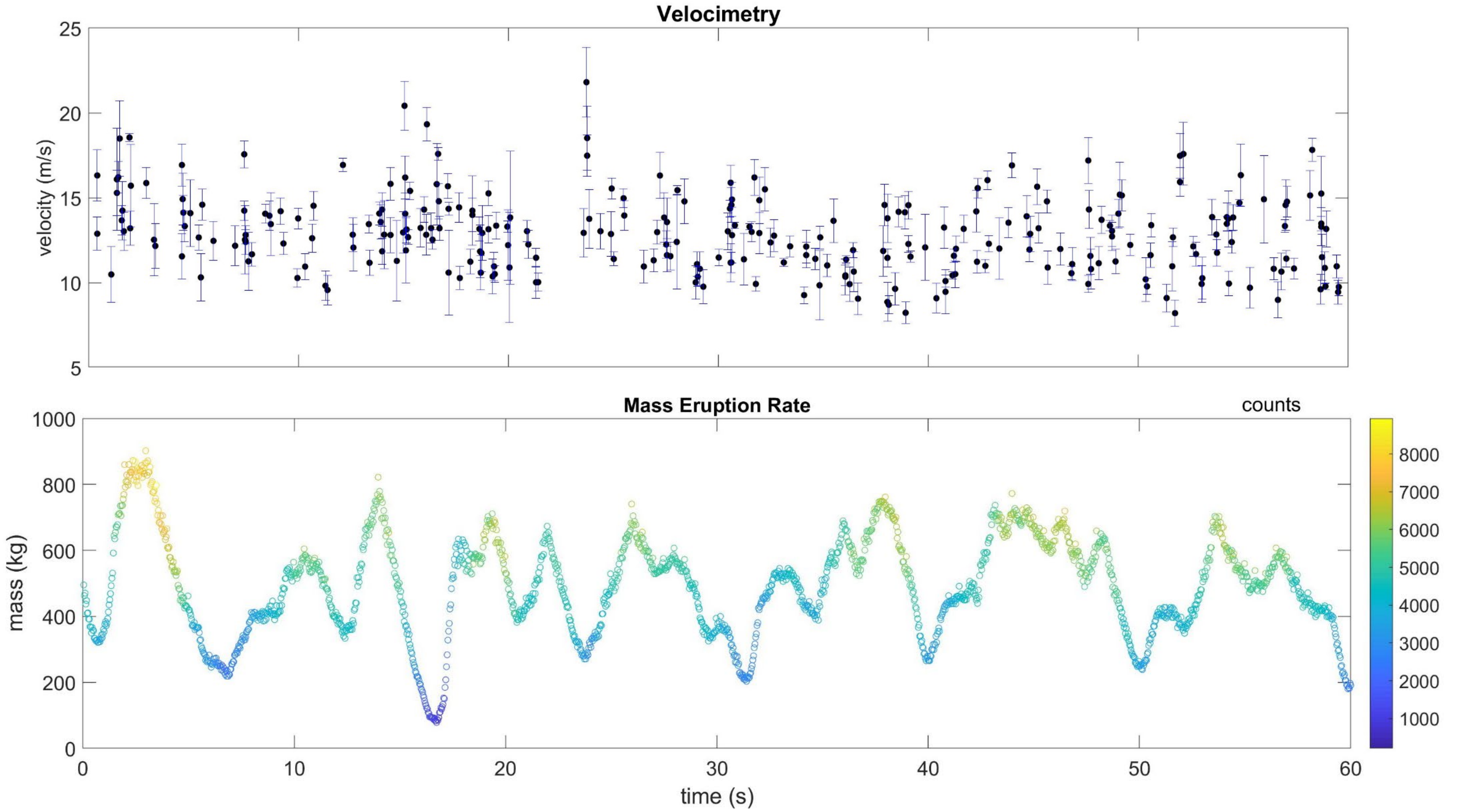


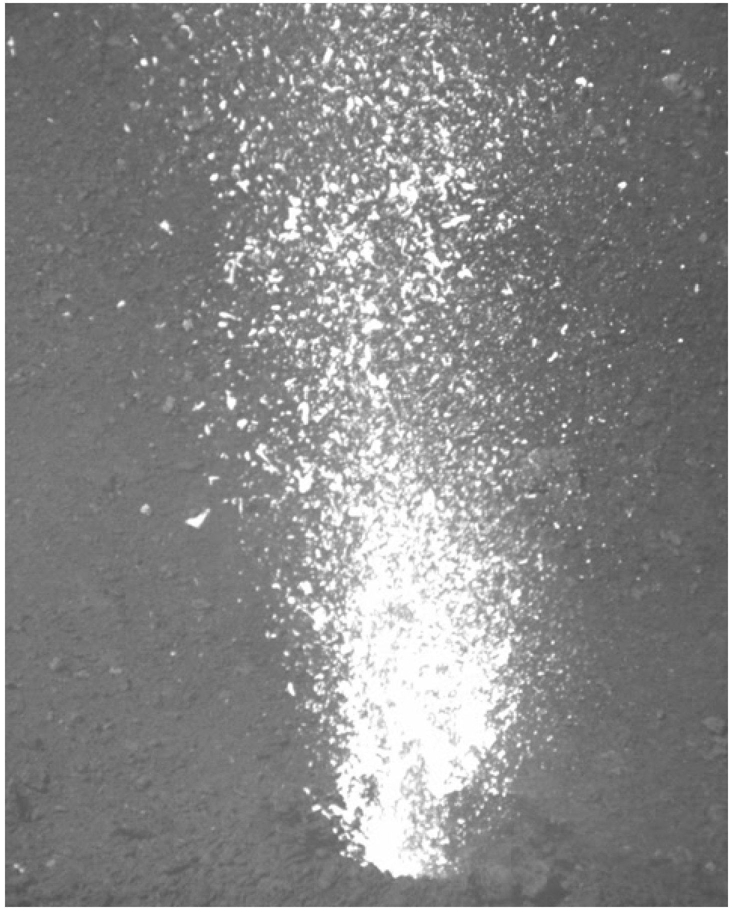
In-flight velocimetry and mass eruption rate measurements over a 60 second clip

ejection velocity

- processed using ImageJ (MTrackJ)

in-flight mass eruption rate





2 m natural duration: 0.5 s

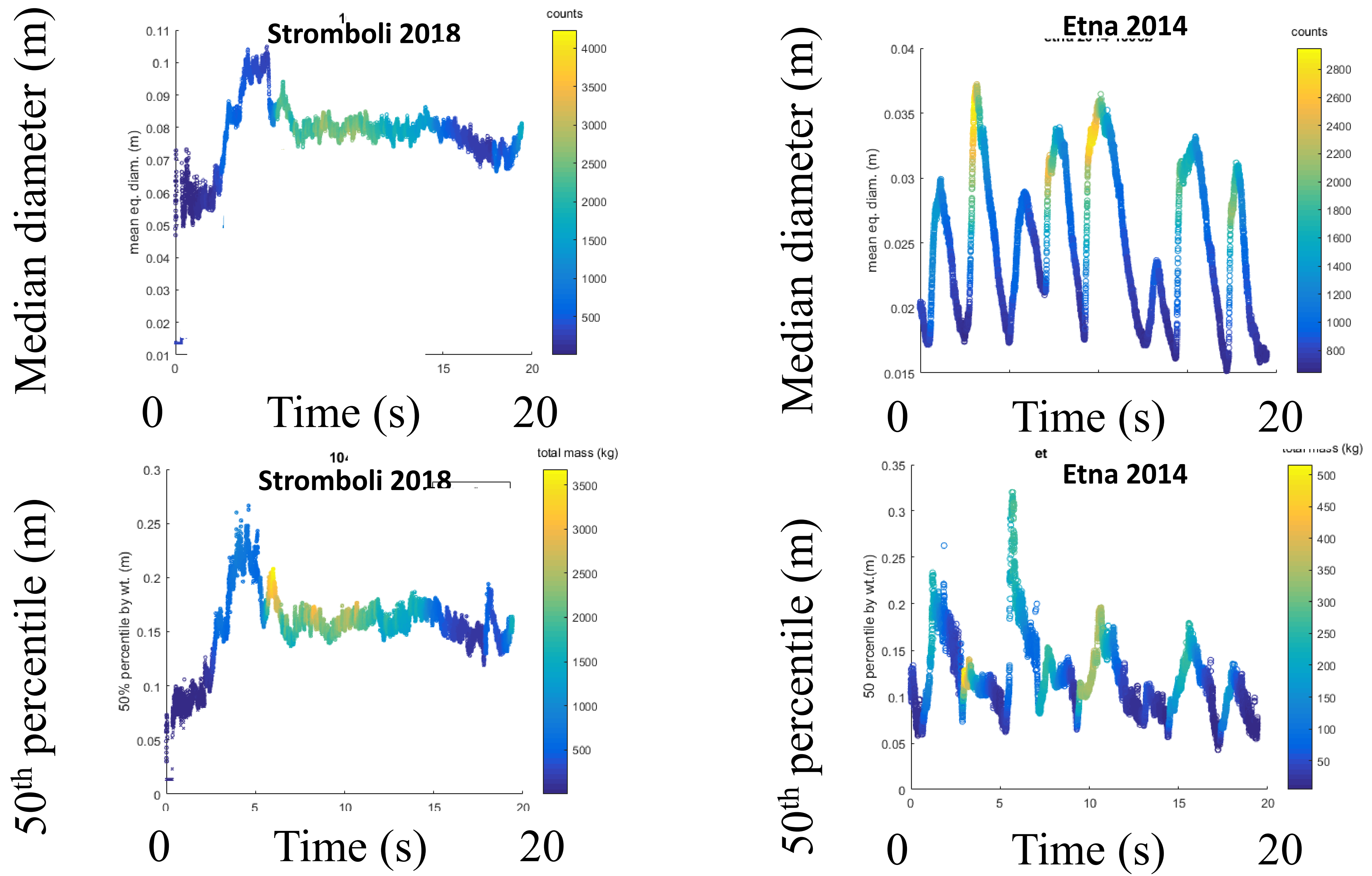
Stromboli,
Sept. 2018

Optronis CR600X2,
1280x1024
500 fps
1 pixel=0.010 m

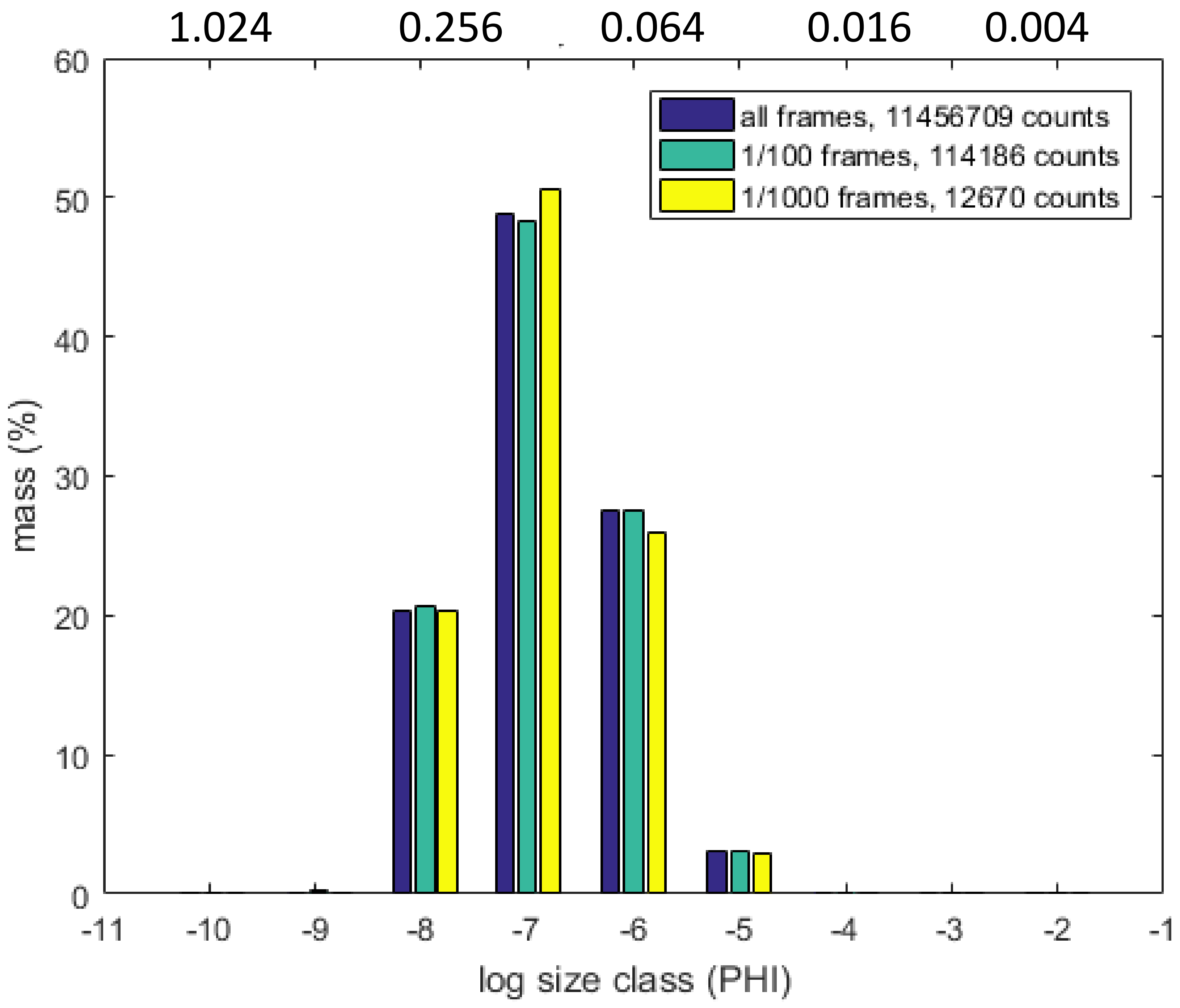
1 m natural duration: 5 s

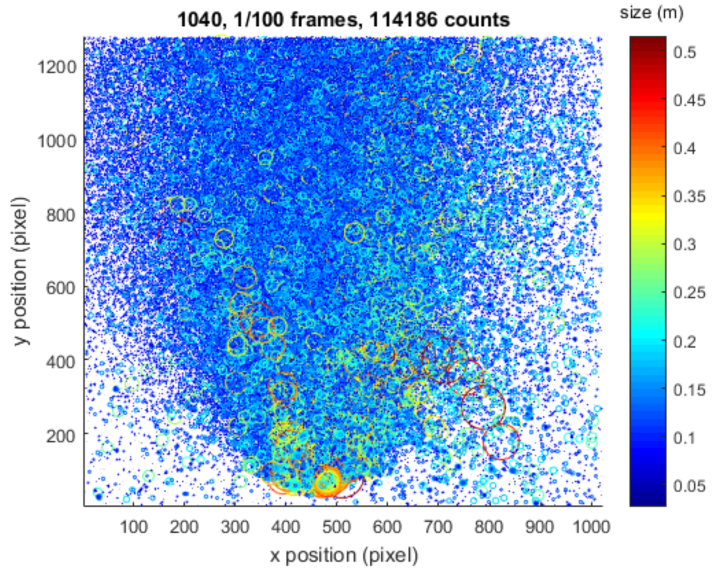
Etna,
July 2014

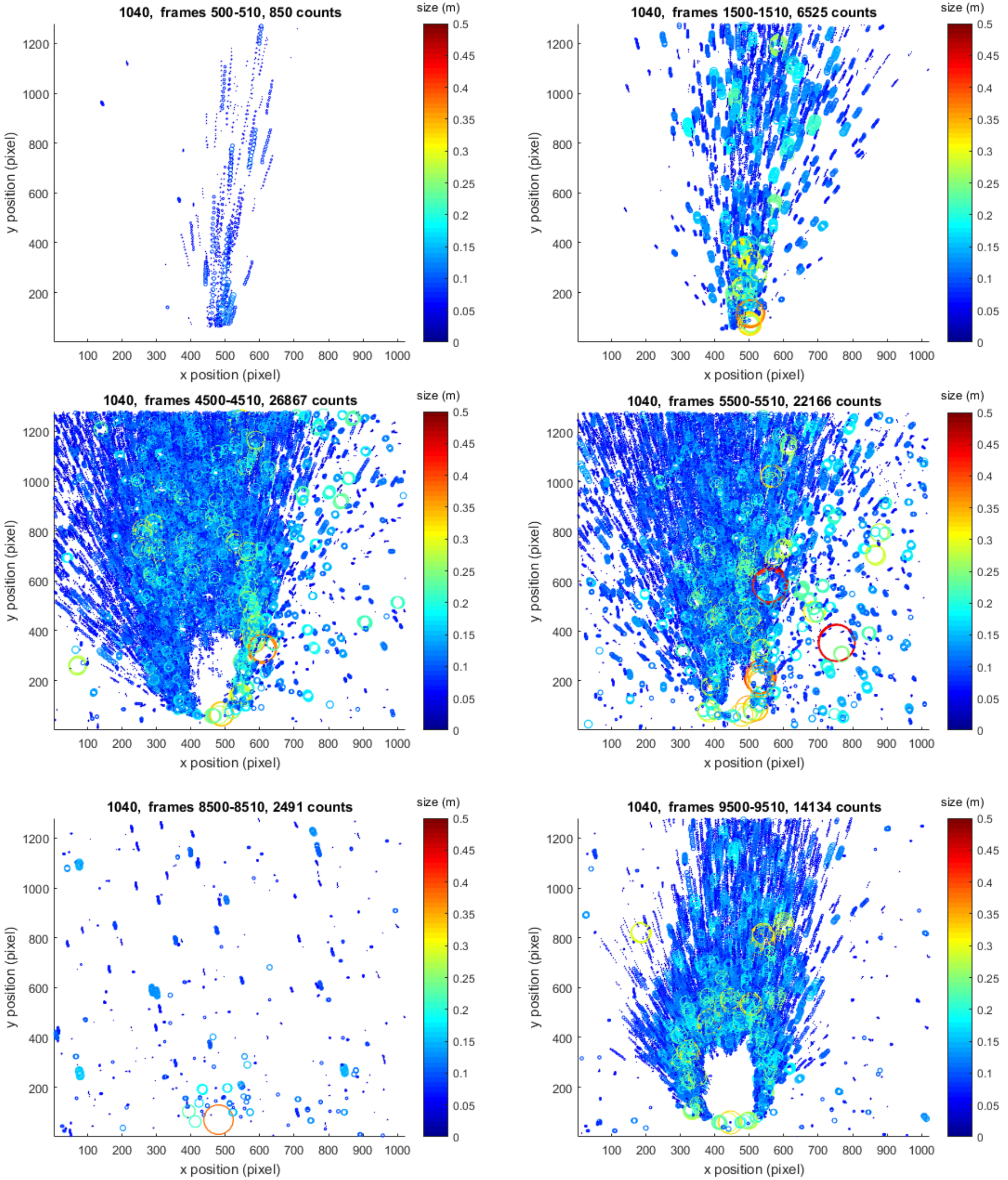
Optronis CR600X2,
1280x1024
500 fps
1 pixel=0.008 m



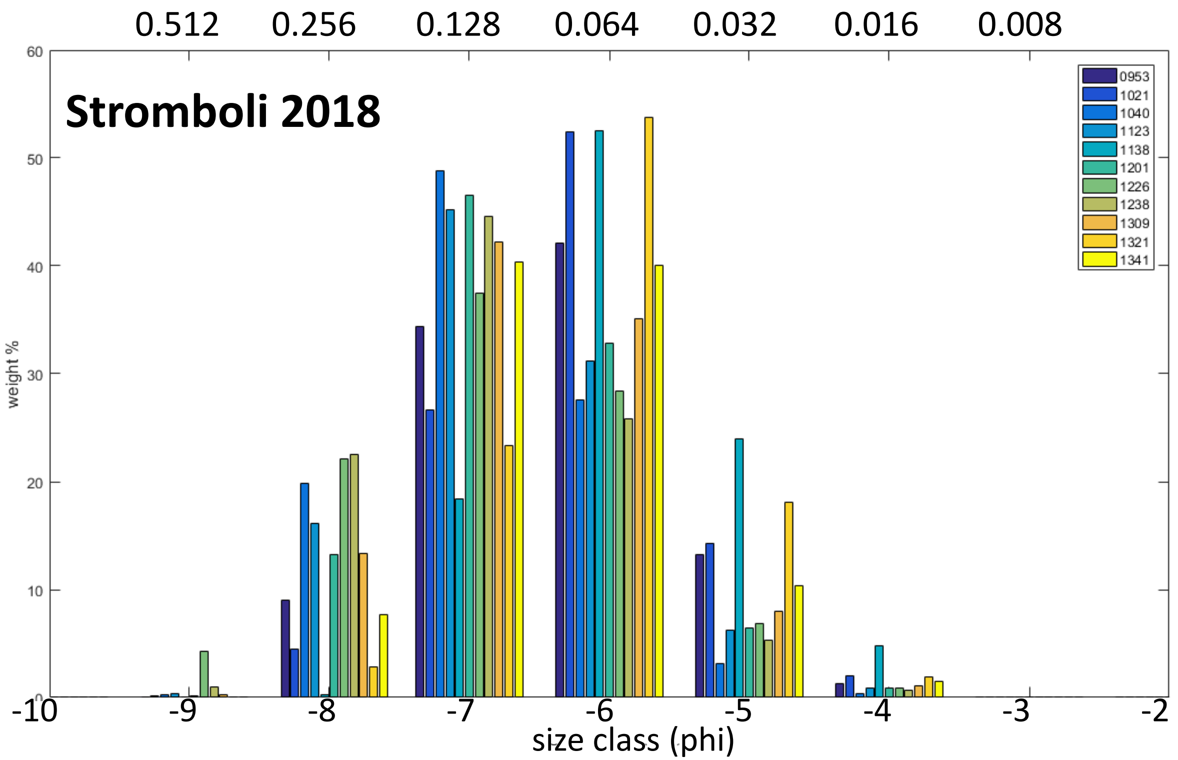
Stromboli 2018
Median diameter (m)
mean eq. diam. (m)
counts
Time (s)
Etna 2014
Median diameter (m)
mean eq. diam. (m)
counts
Time (s)
Stromboli 2018
50th percentile (m)
50% percentile by wt. (m)
total mass (kg)
Time (s)
Etna 2014
50th percentile (m)
50 percentile by wt.(m)
Time (s)

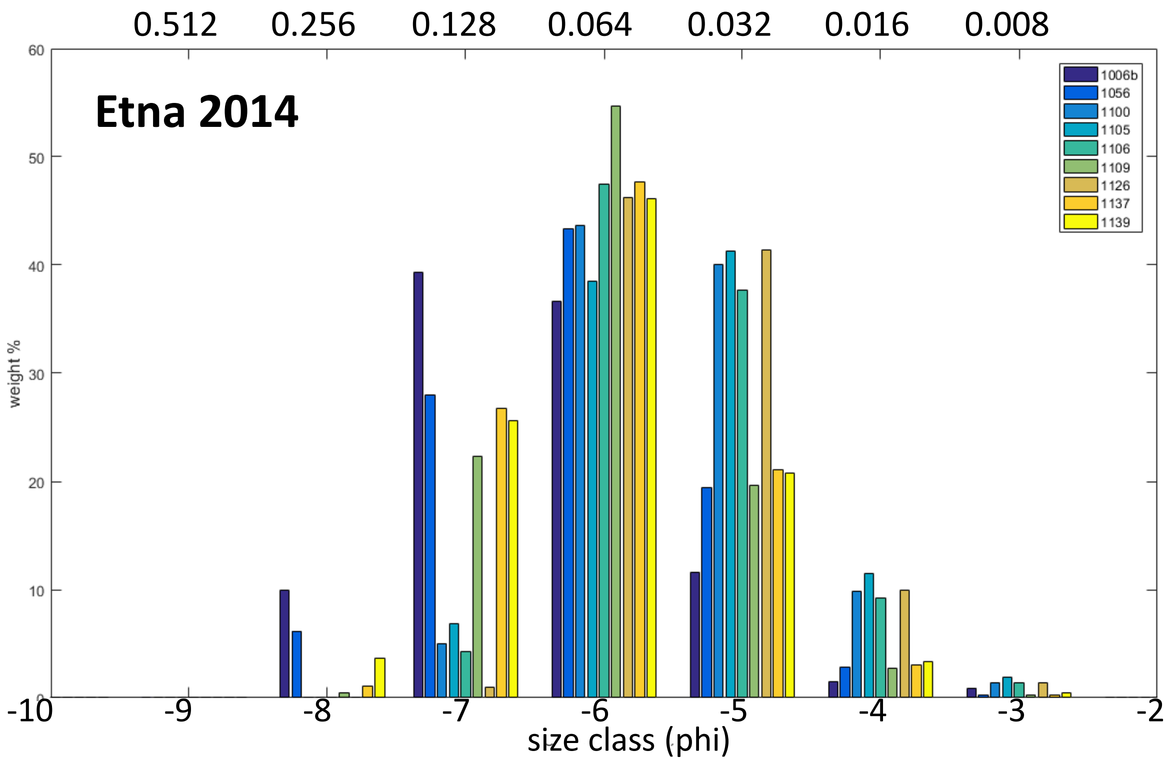

1.024
0.256
0.064
0.016
0.004
all frames, 11456709 counts
1/100 frames, 114186 counts
1/1000 frames, 12670 counts
mass (%)
log size class (PHI)


1040, 1/100 frames, 114186 counts
size (m)
y position (pixel)
x position (pixel)

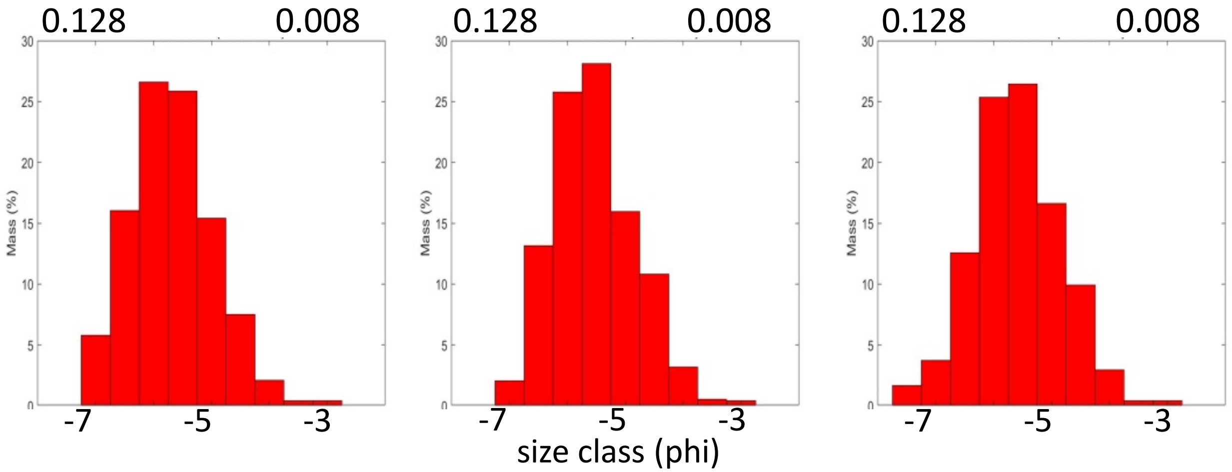


20 second-long clip: 10 frames sampled every 1000 frames (2 sec)

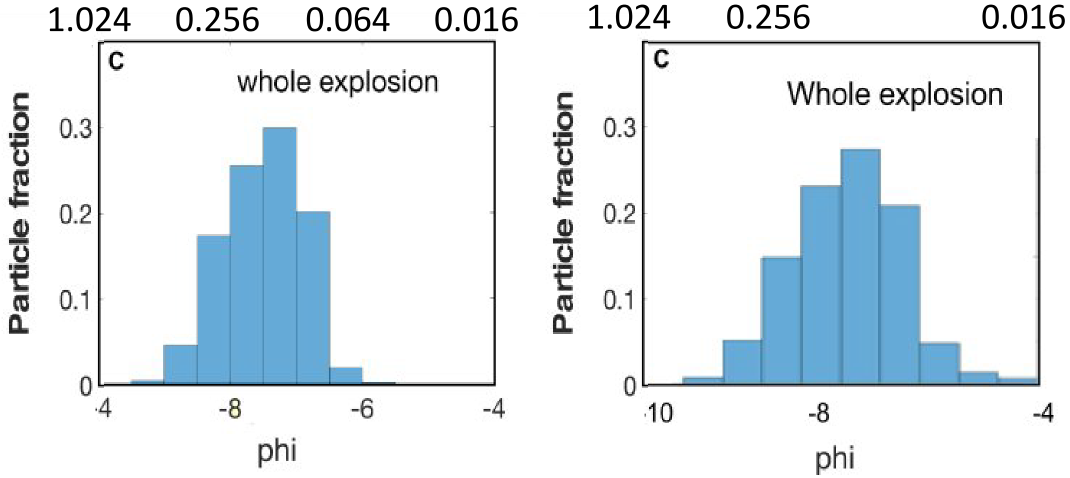




Kilauea 2018



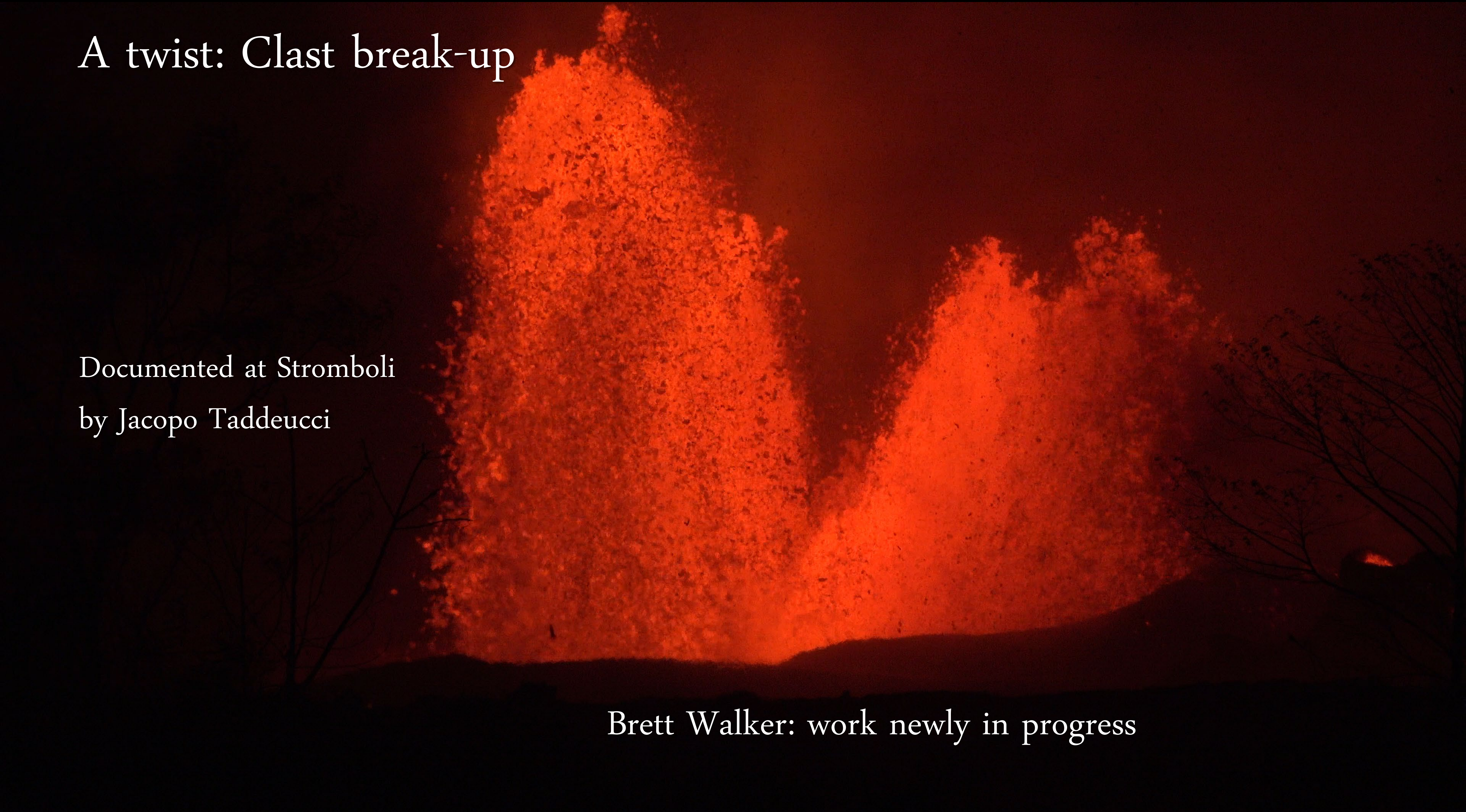
Stromboli 2012 *Pioli and Harris (2019) Front. Earth Sci. 7:52.*



Some caveats

- Currently (generally) limited to small/ weak eruptions
- Issues with thermally or visually opaque fountains/plumes

A twist: Clast break-up



Documented at Stromboli
by Jacopo Taddeucci

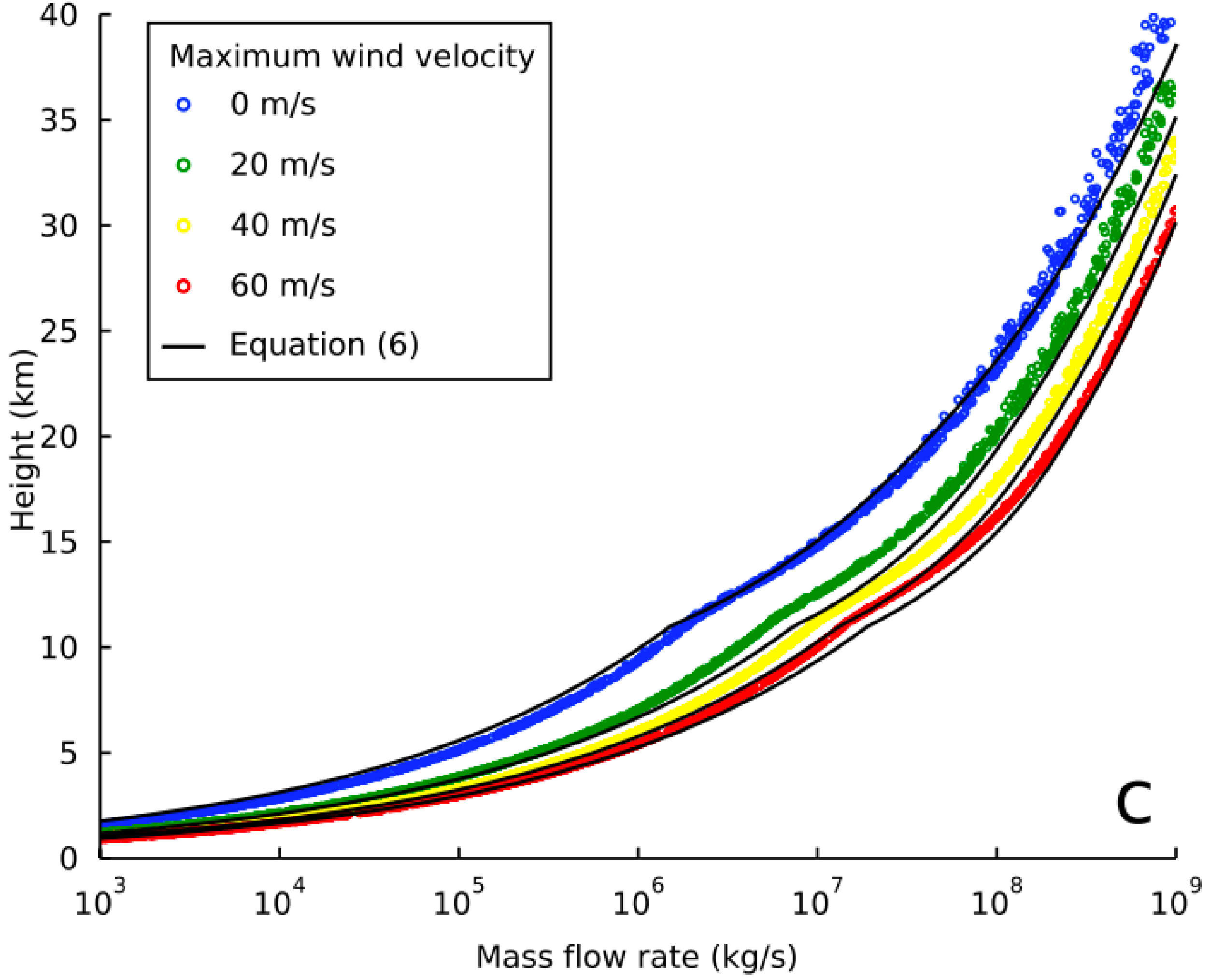
Brett Walker: work newly in progress

Thank you

Plume height & flux

1. Plume theory predicts that the **mass eruption rate** (MER; kg $^{s-1}$) is related to the 4th power of the plume height

2. Wind influences MER



Plume height & flux

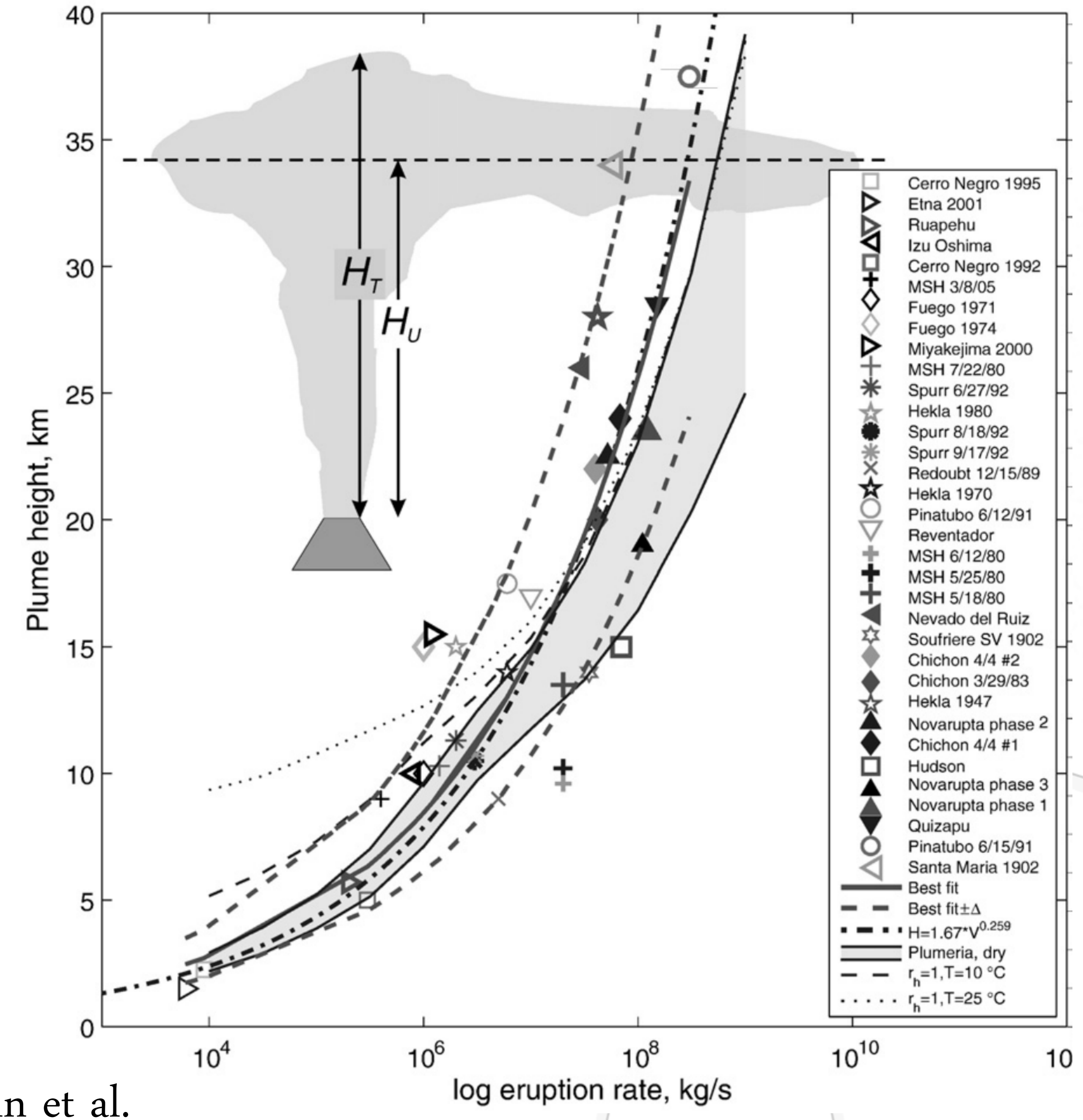
1. Plume theory predicts that the **mass eruption rate** (MER; kg s-1) is related to the 4th power of the plume height

2. Wind influences MER

3. Empirical relationship:

$$H = 2.00\,\dot{V}^{0.241}$$

- **H** Height of the umbrella cloud (km asl)
- **V** Volumetric flow rate (m^3 DRE s^{-1})
- **DRE** Dense rock equivalent

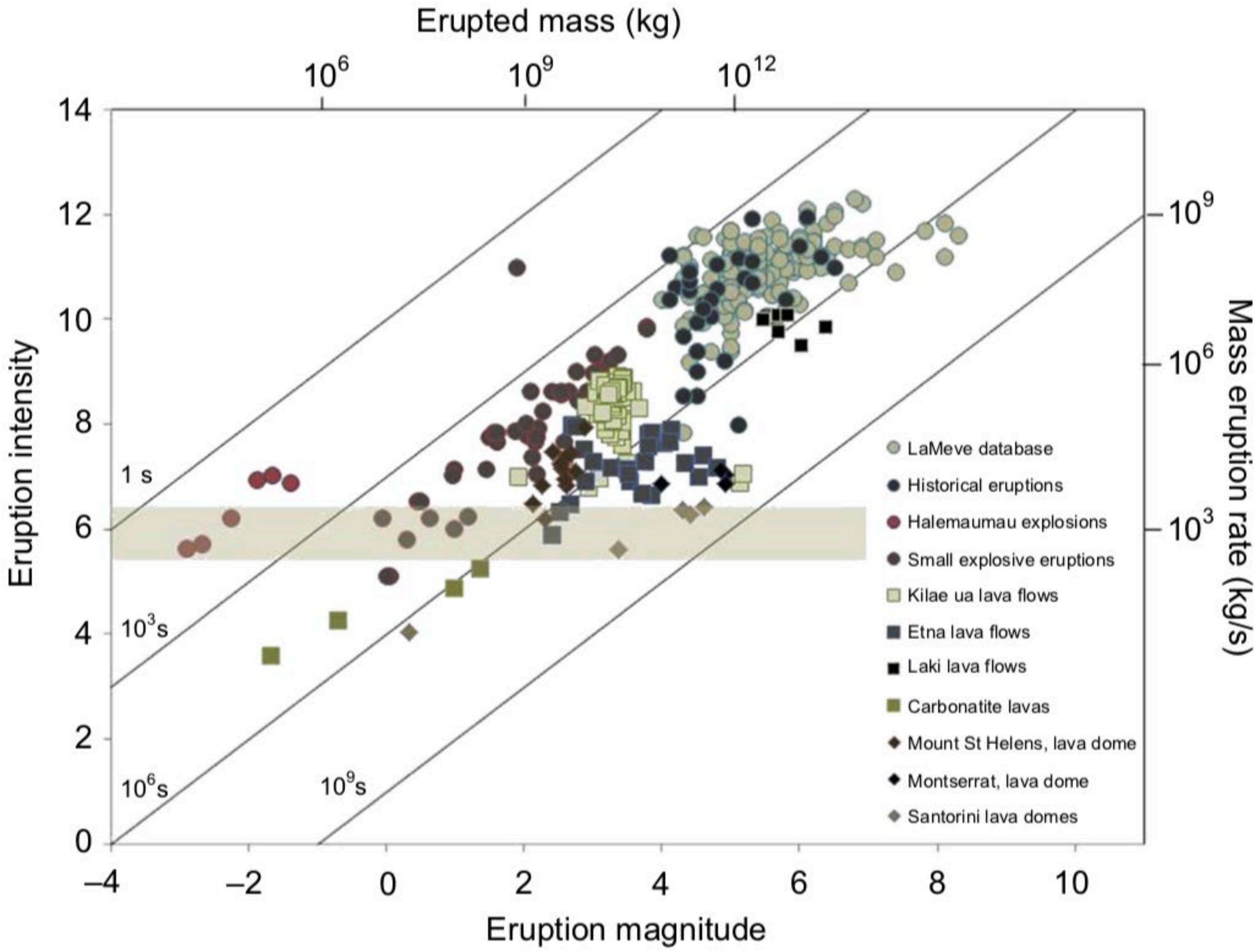


Mastin et al.

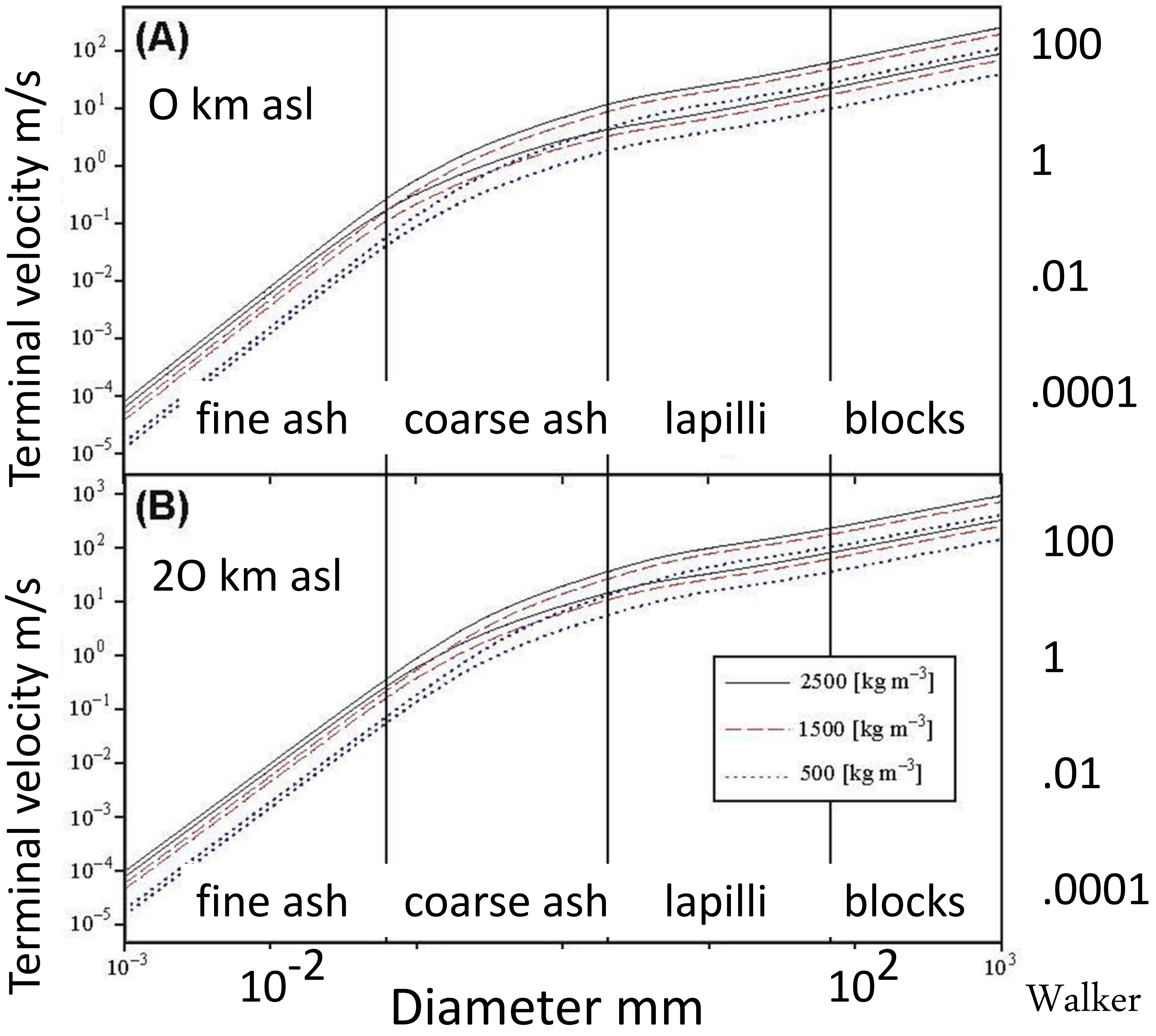
Plume height & flux

- MER ➞ **Intensity**

  = log10(MER [kg s^{-1}]) + 3



Sedimentation from volcanic plumes



Walker et al. 1971