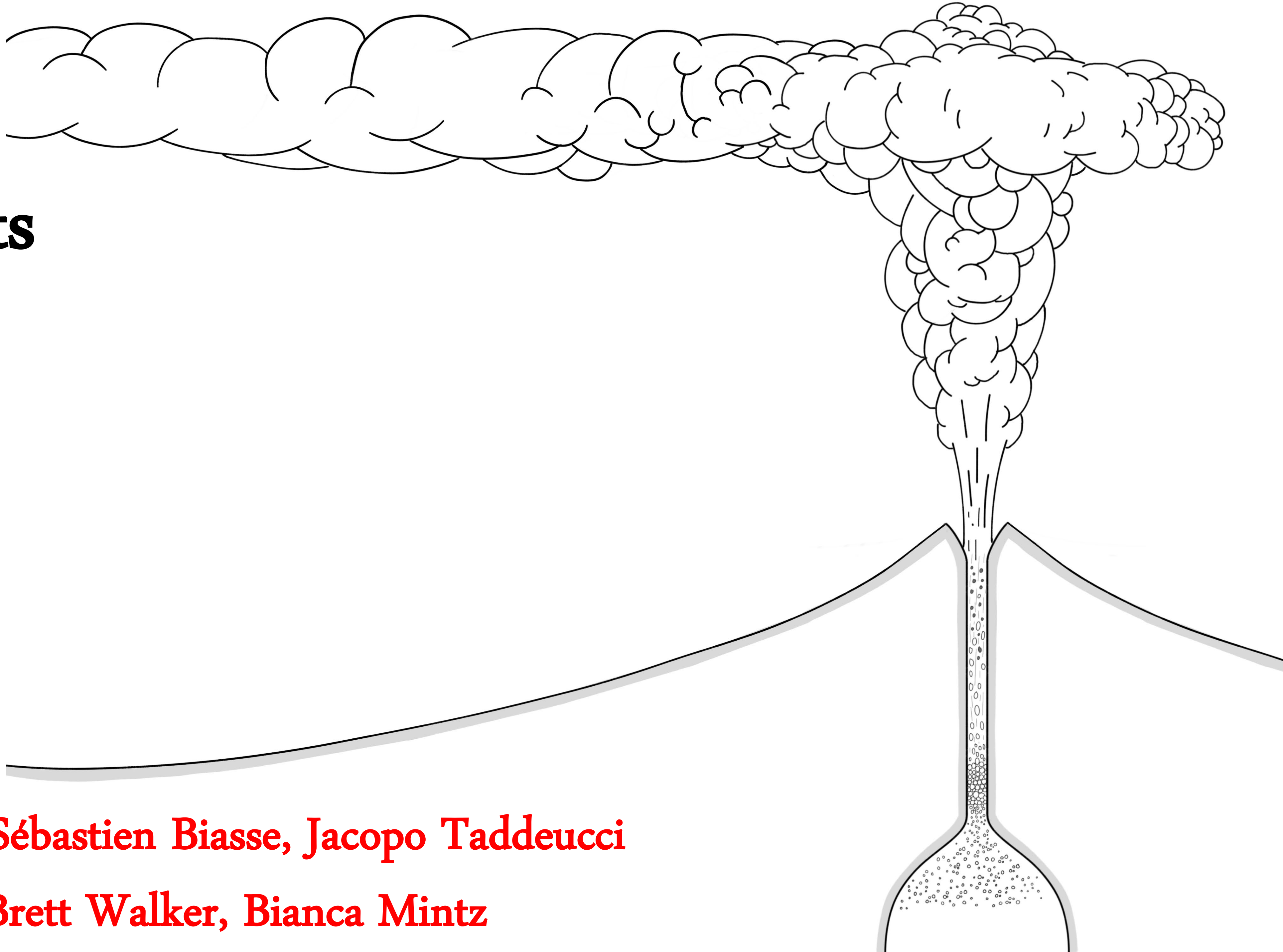
Fall deposits

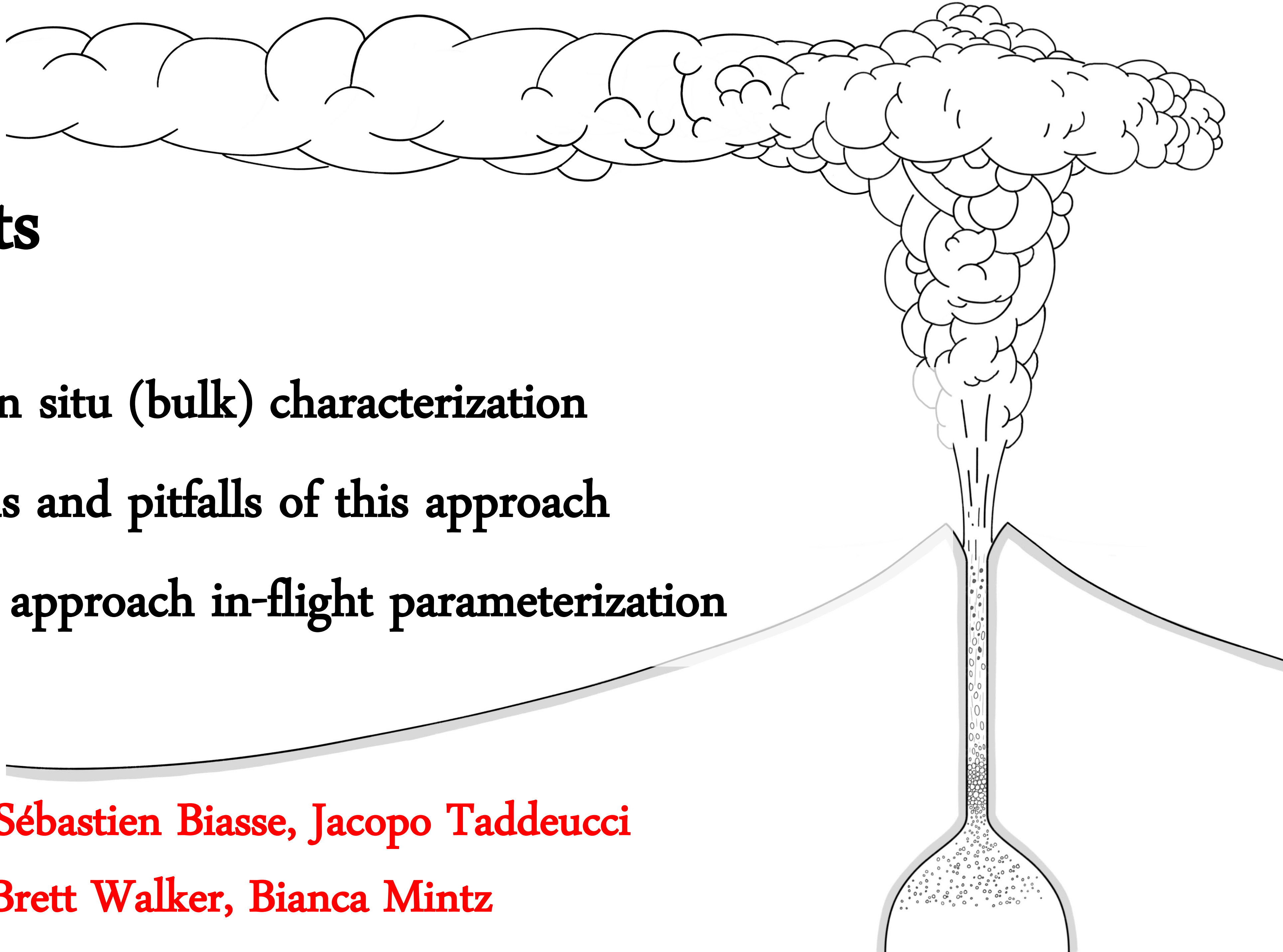


Bruce Houghton, Sébastien Biasse, Jacopo Taddeucci

Caroline Tisdale, Brett Walker, Bianca Mintz

Fall deposits

1) classical in situ (bulk) characterization
2) limitations and pitfalls of this approach
3) emerging approach in-flight parameterization



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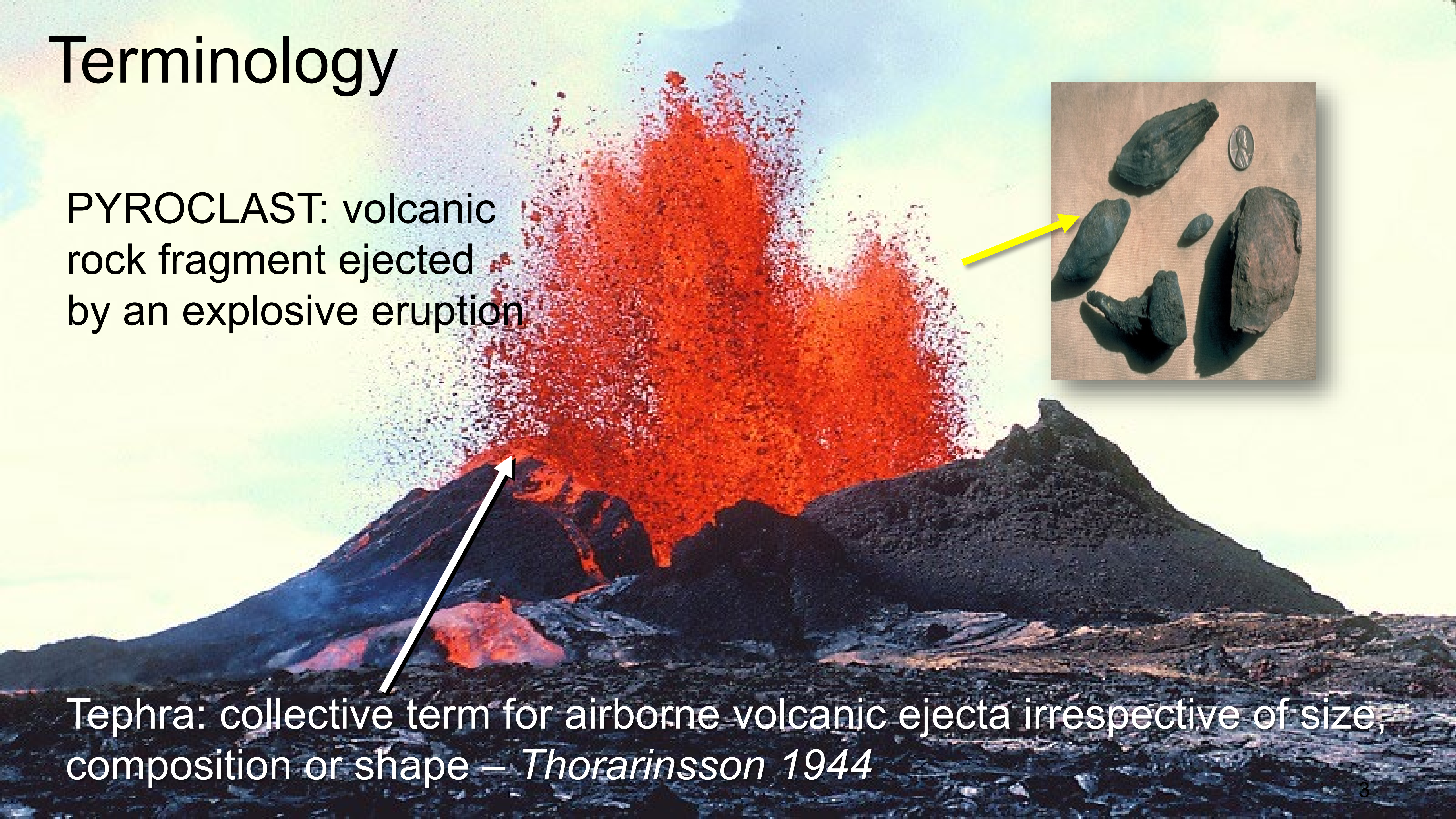
Terminology



PYROCLAST: volcanic rock fragment ejected by an explosive eruption

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

Why study fall?

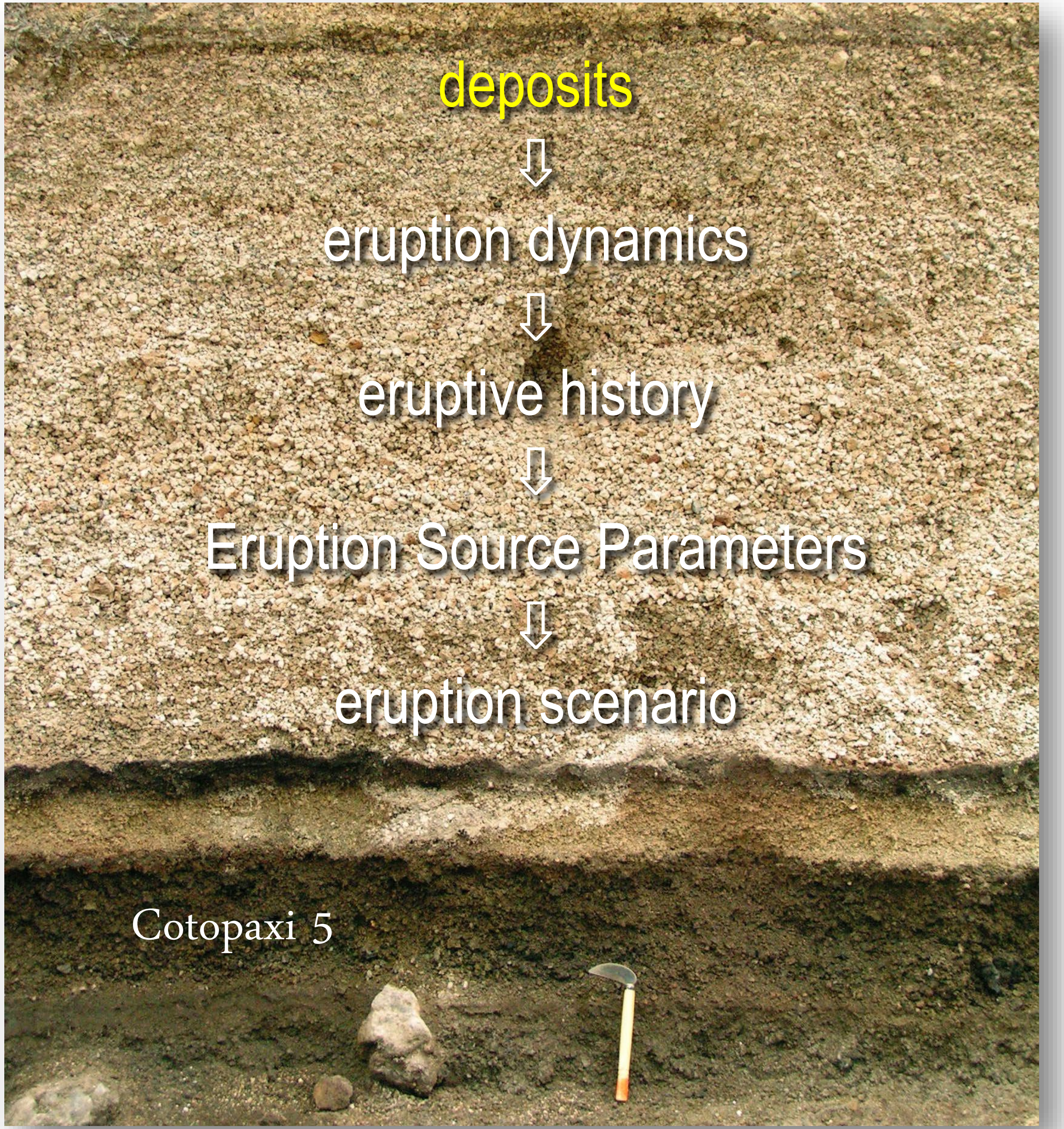
The simplest of pyroclastic deposits

Unrivalled for inferring eruption source parameters

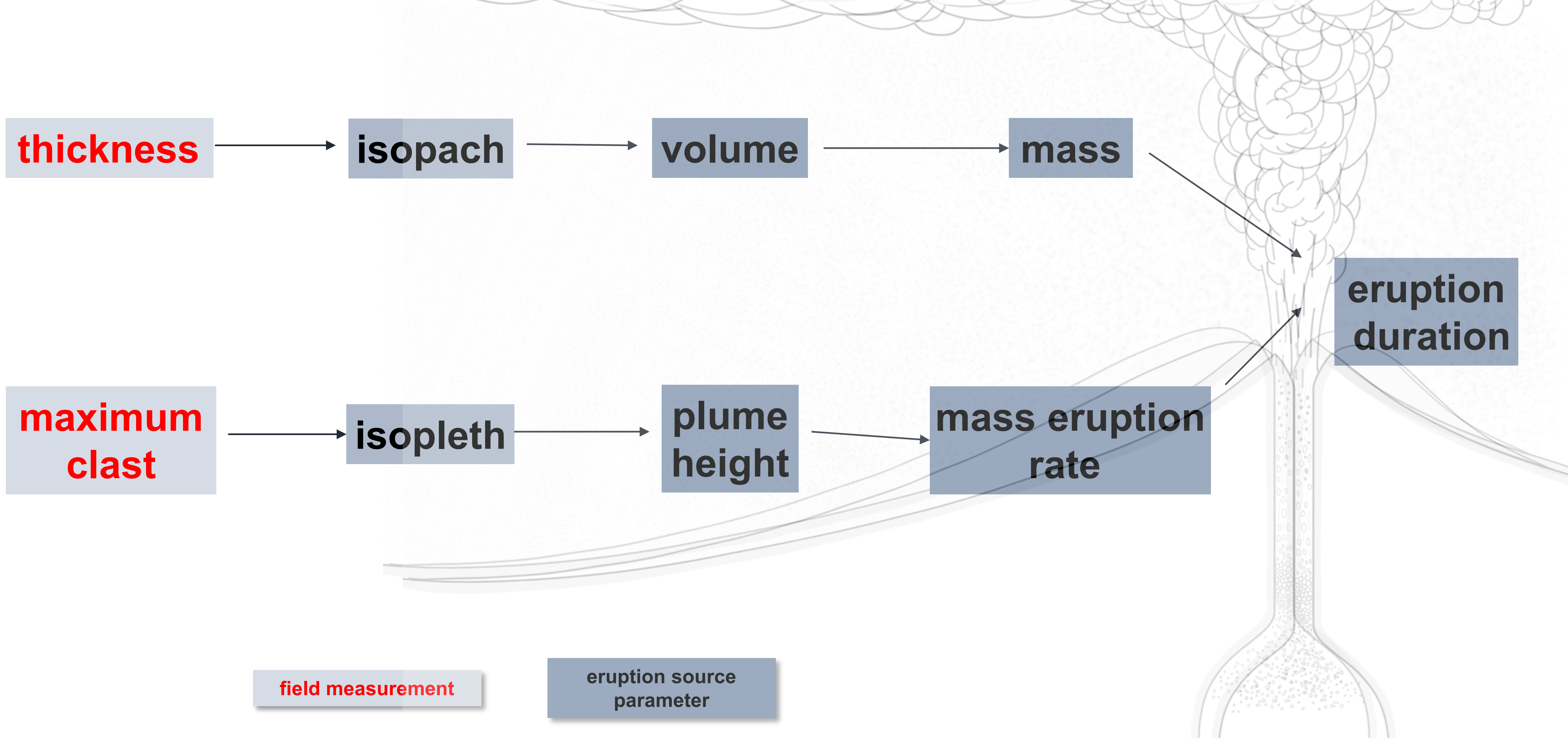
- proxies for magnitude, intensity
- proxies for eruption style

The most widespread of natural hazards

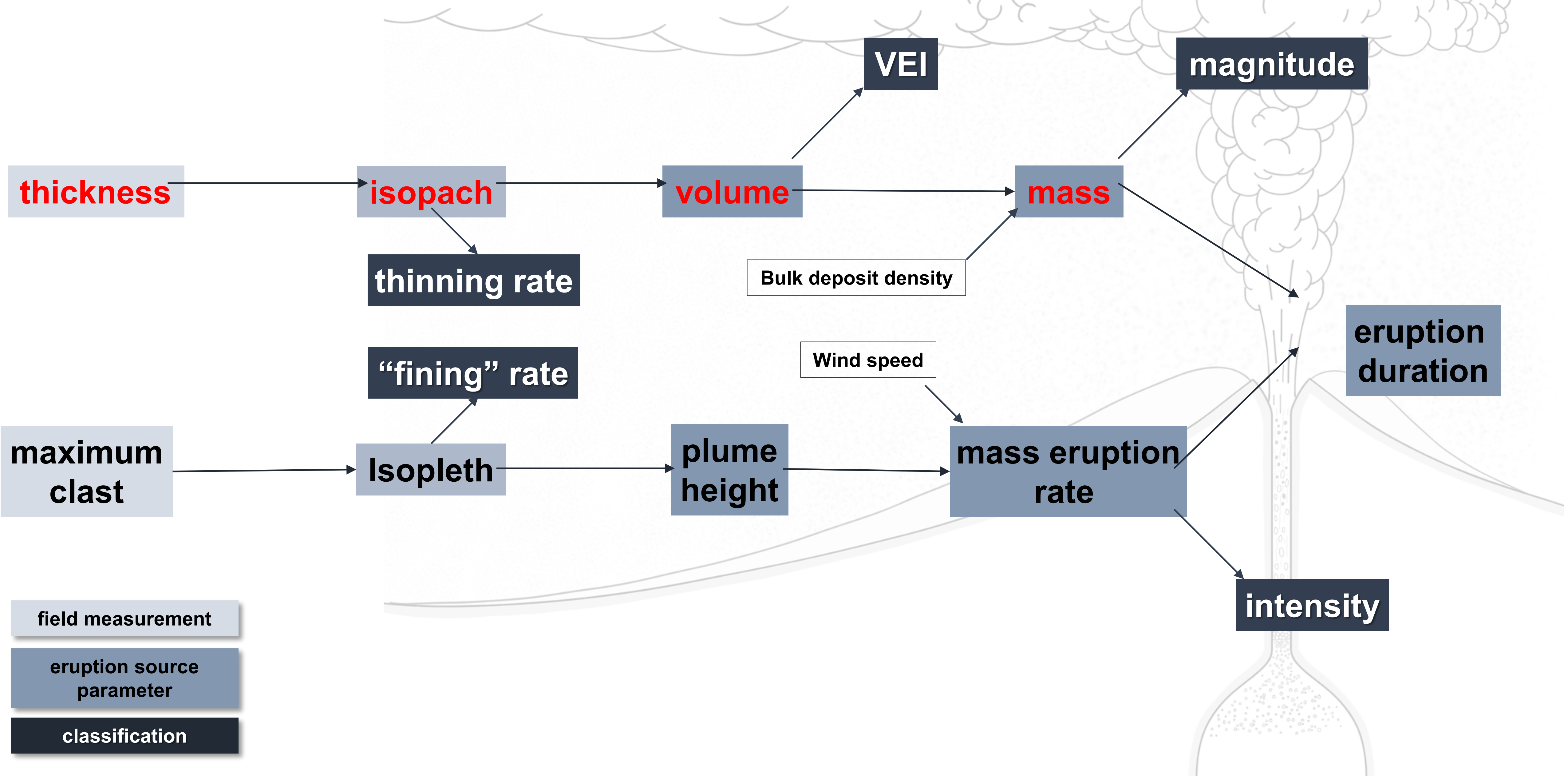

What do falls record ?


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

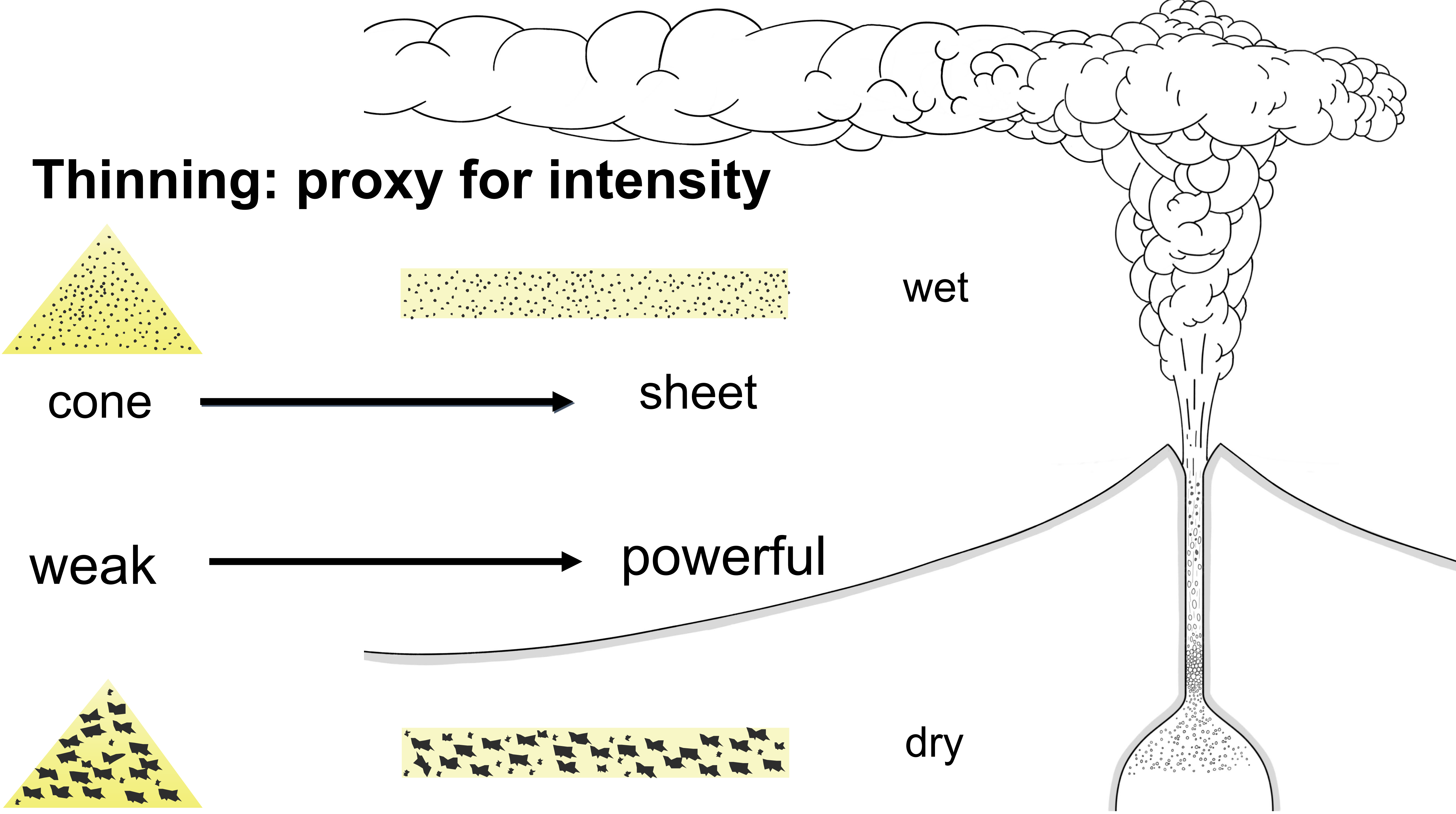
1) Tephra fall: in situ characterization



Tephra fall: characterization sheet

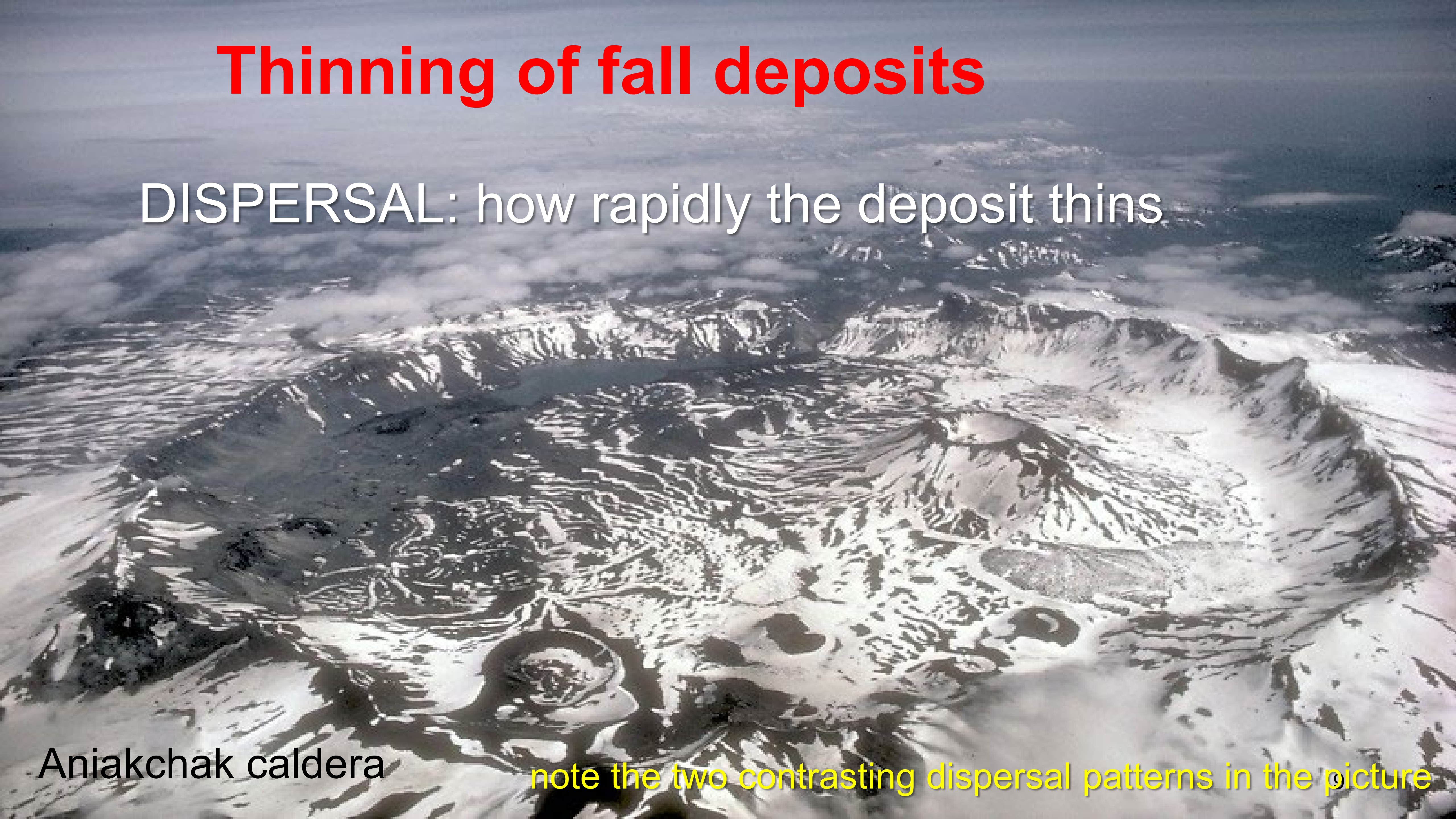


Thinning: proxy for intensity



Thinning of fall deposits

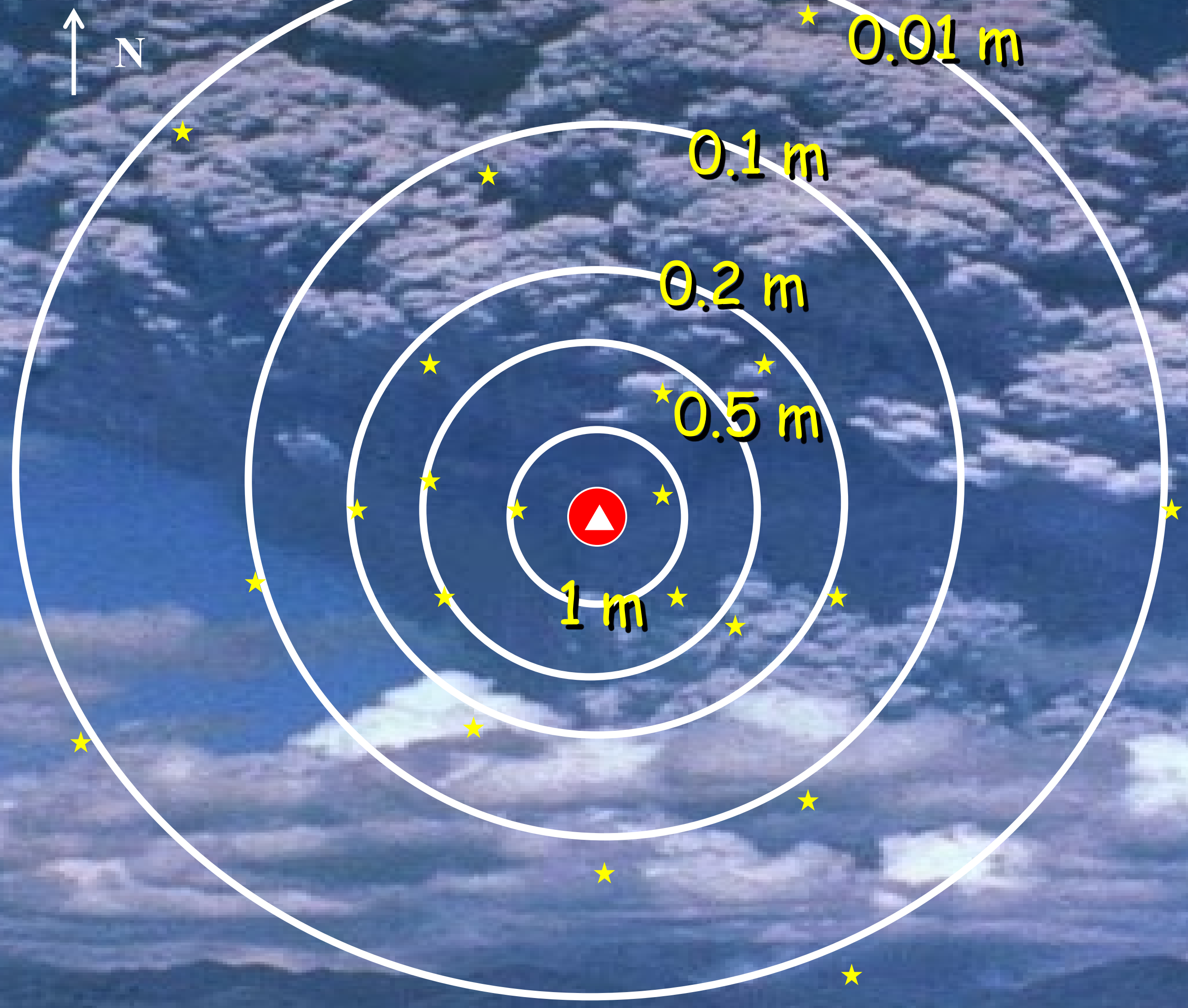
DISPERSAL: how rapidly the deposit thins



Aniakchak caldera

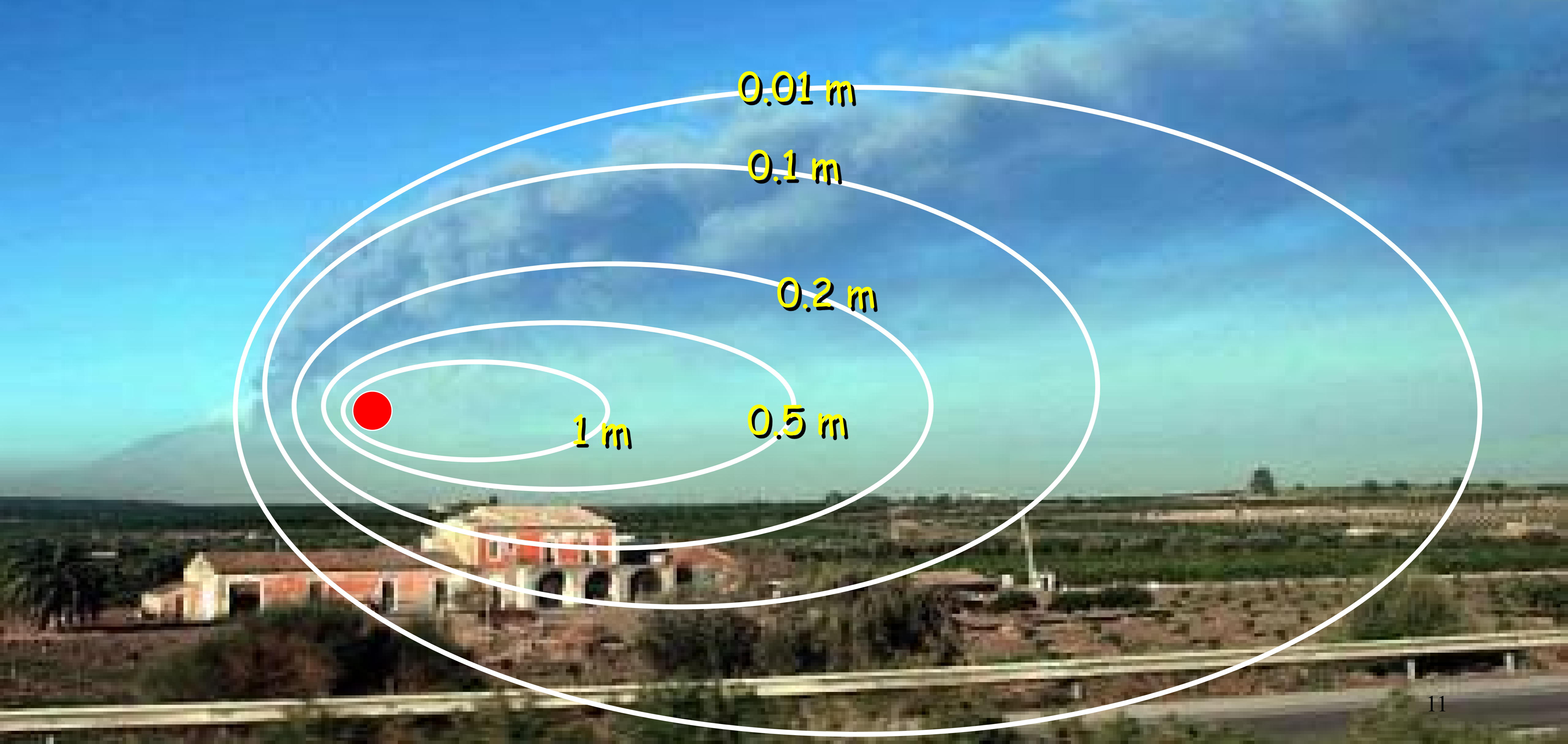
note the two contrasting dispersal patterns in the picture

ISOPACHS: lines of equal thickness

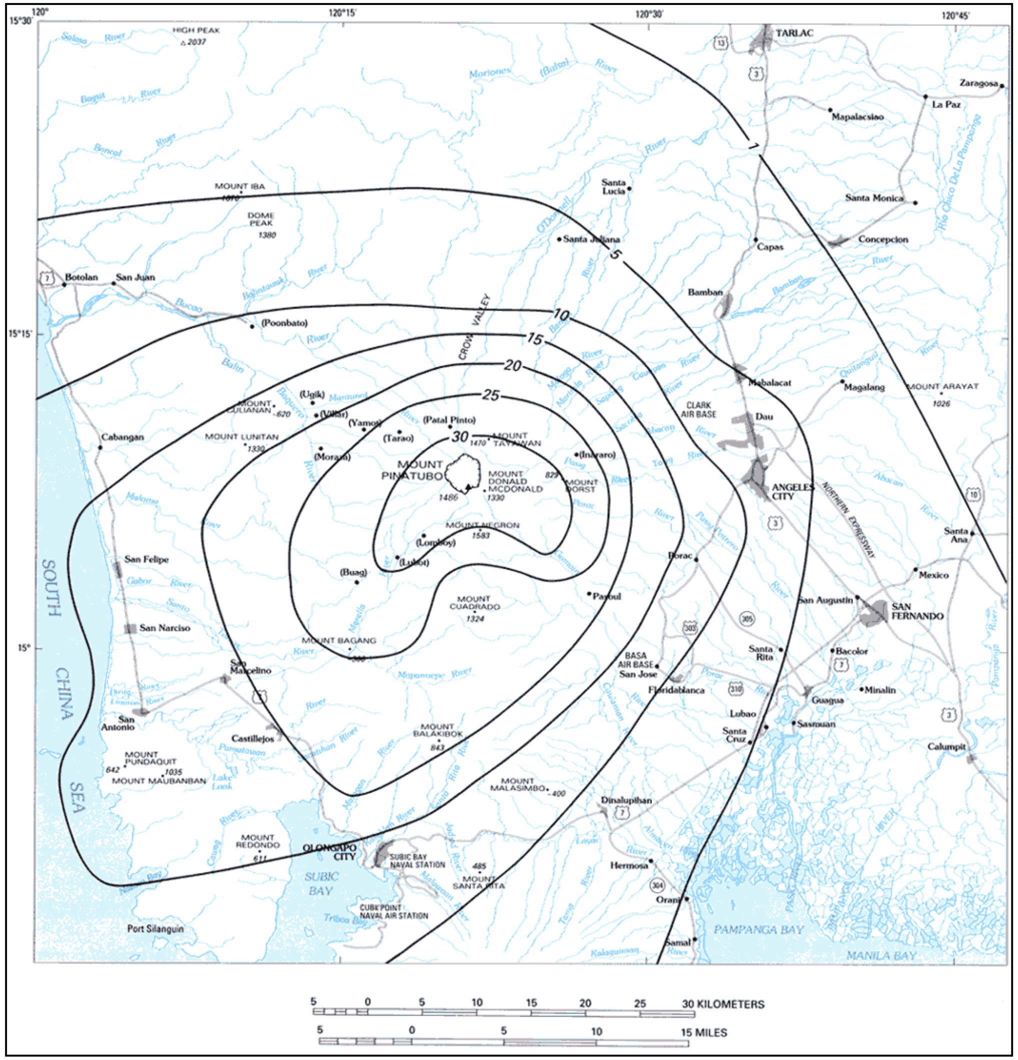


ISOPACHS of contrasting intensity

ISOPACHS: strong wind



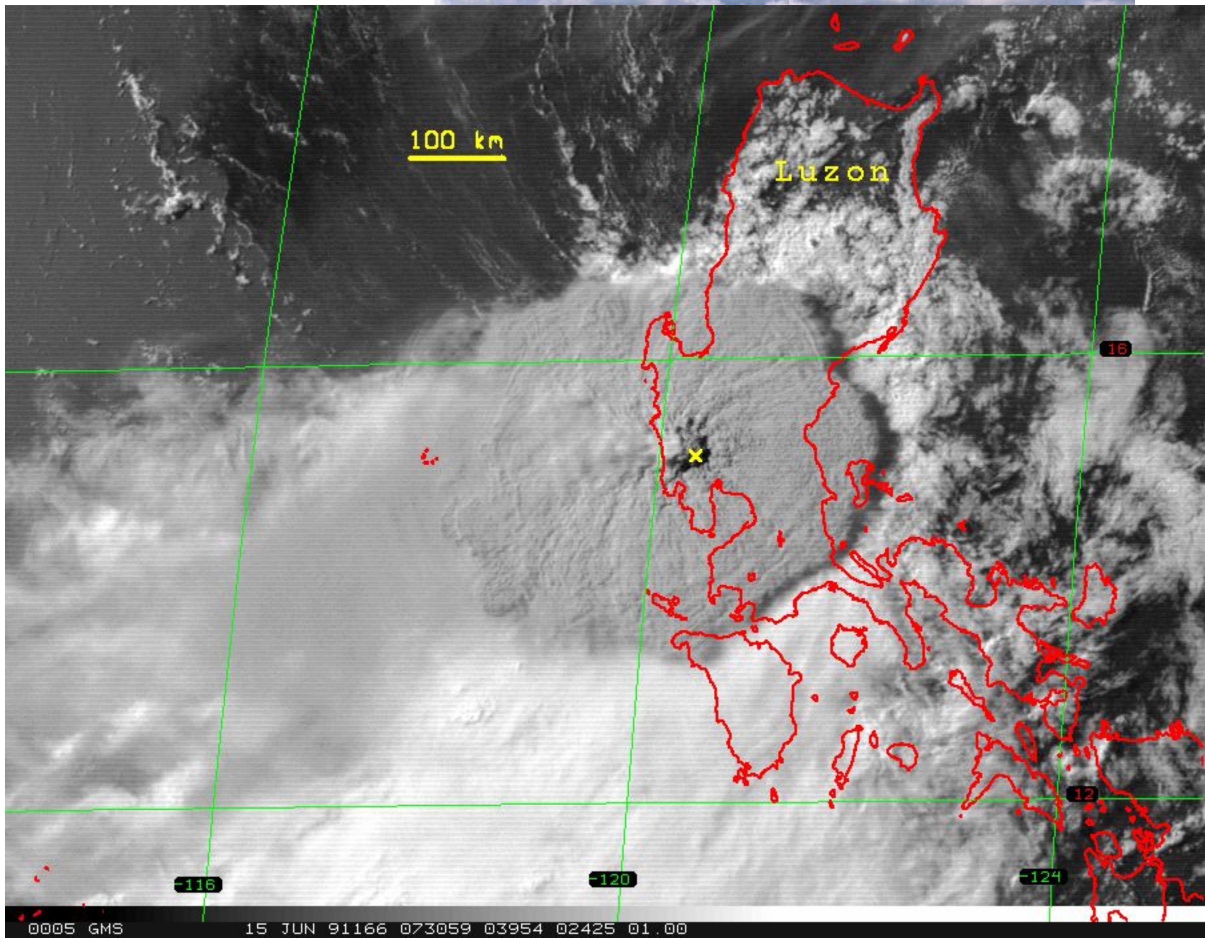
Deposits in nature



Paladio-Melosantos et al. [1996]

Pinatubo (Philippines) 1991

Ht: 42 km (Rosi et al. 2000)

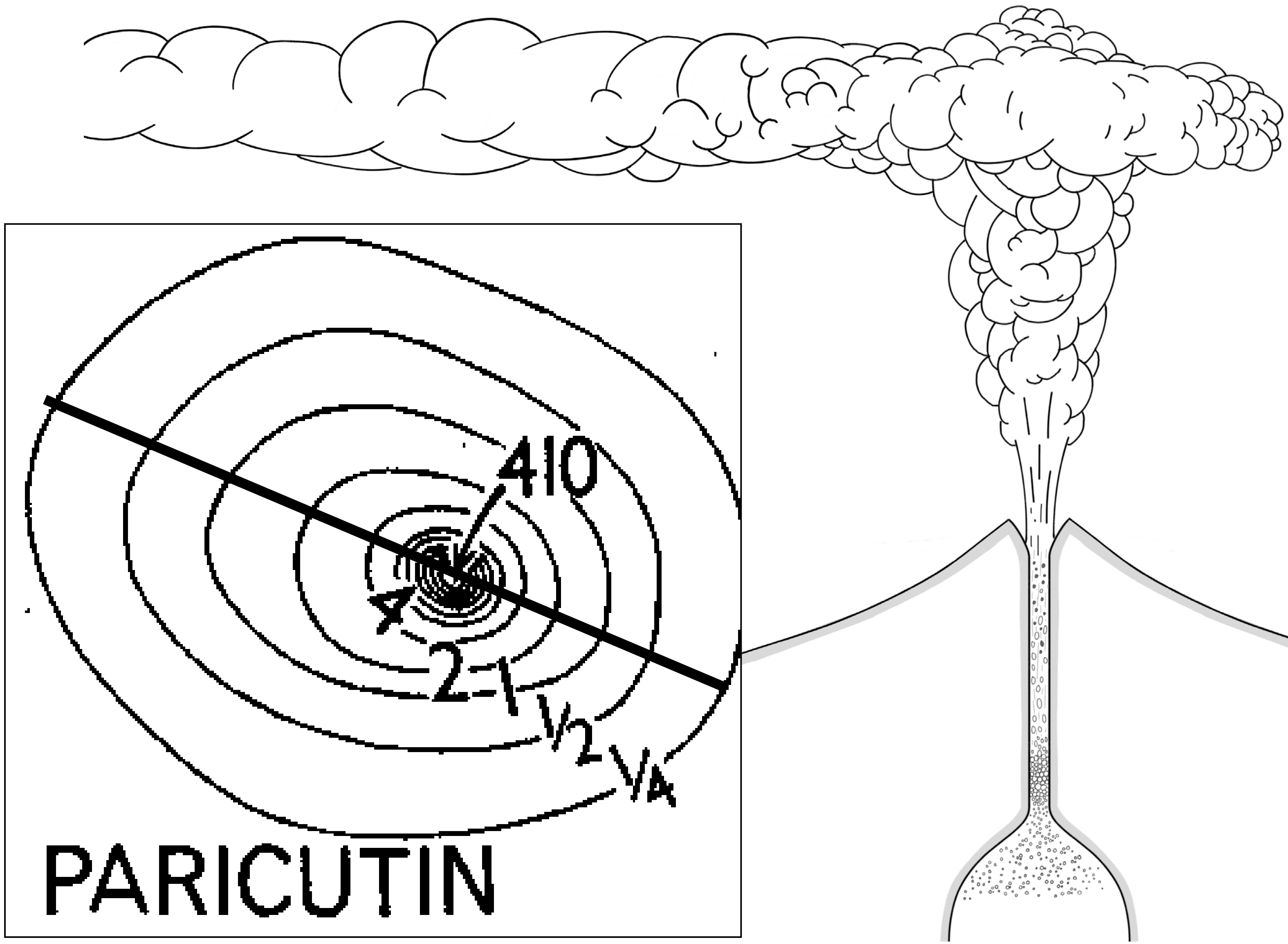


Quantitative analysis

thickness vs

1) distance from vent, or

2) area within an isopach



Walker 1971

Isopachs & volume calculation

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

Layer 5 of Cotopaxi volcano in Ecuador

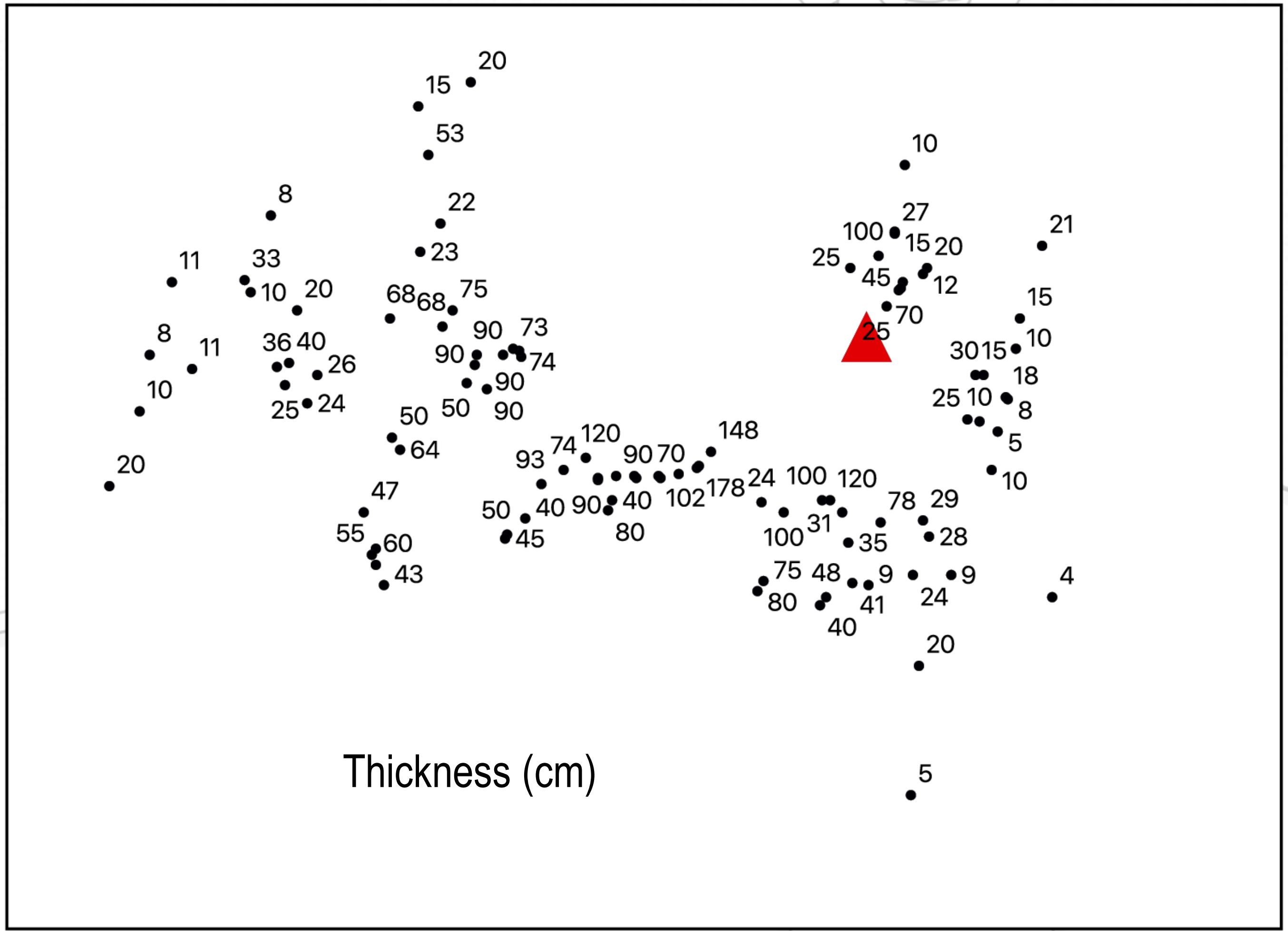
Barberi et al, 1995; Biass and Bonadonna, 2011

1180 yr

c 26 km

0.5 km^3

10^{12} kg

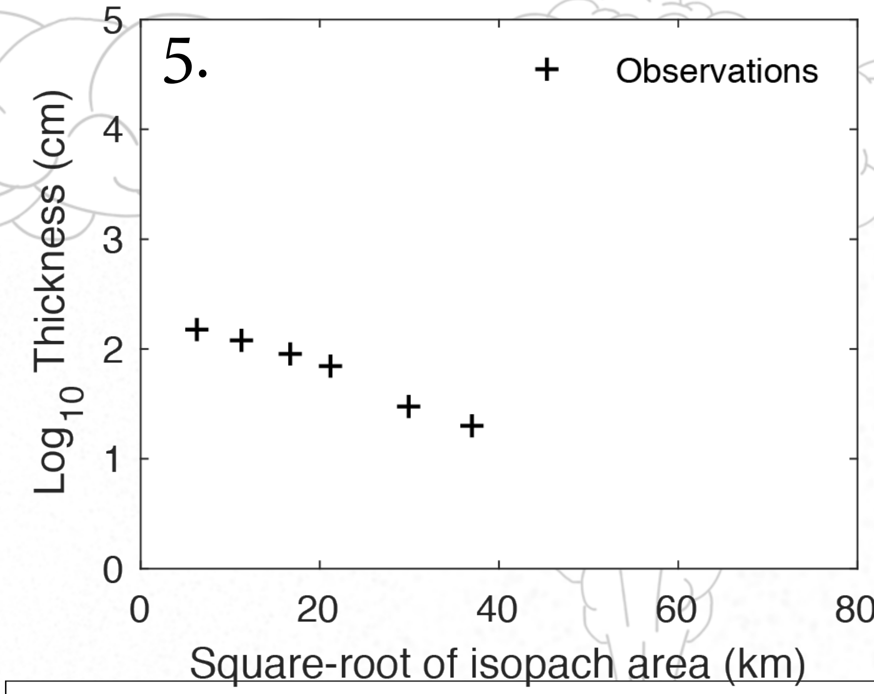


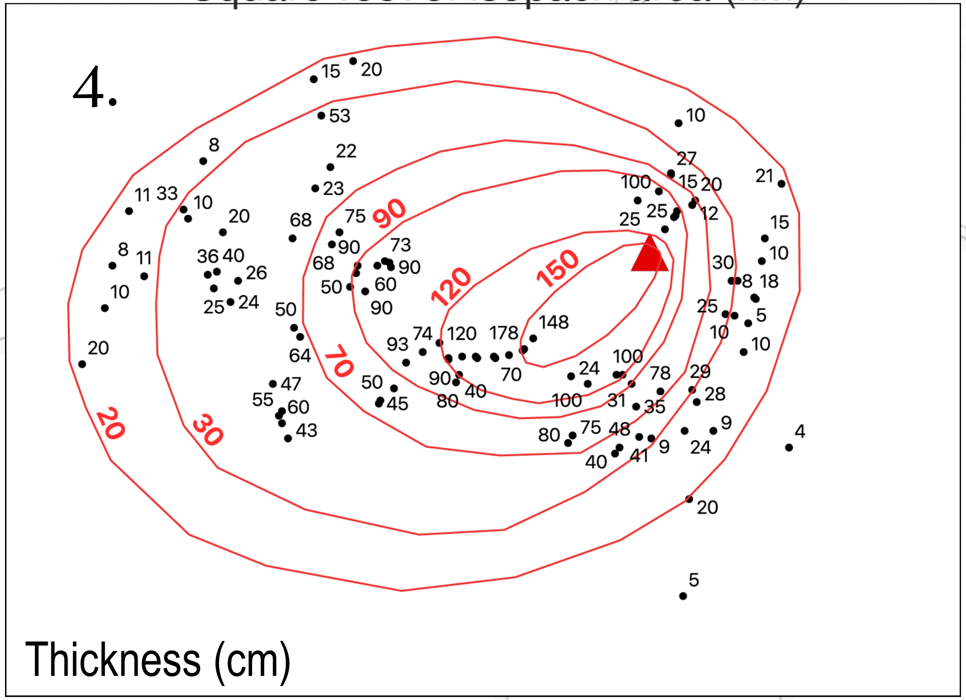
Isopach & volume calculation

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





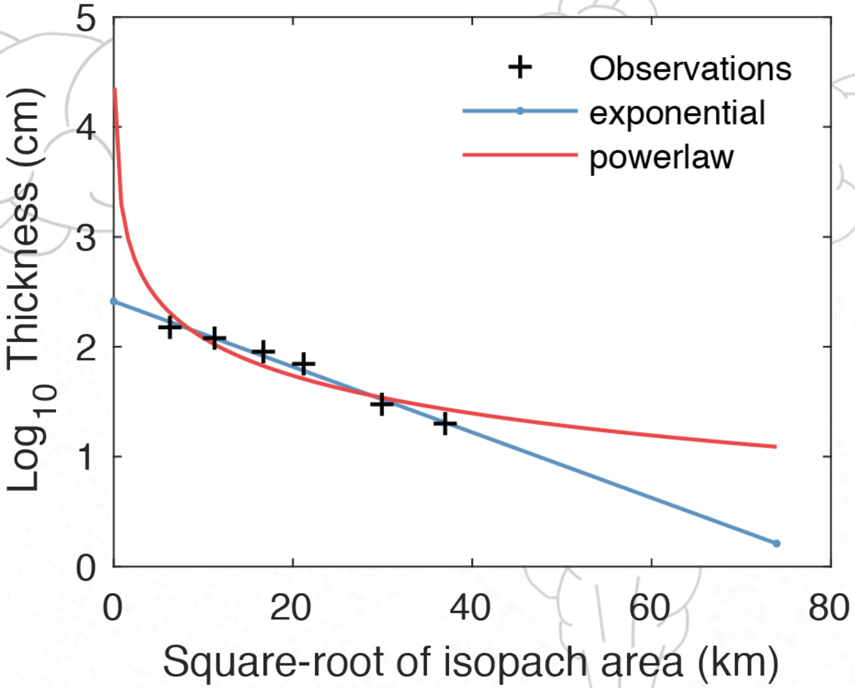
Note changing wind direction with elevation

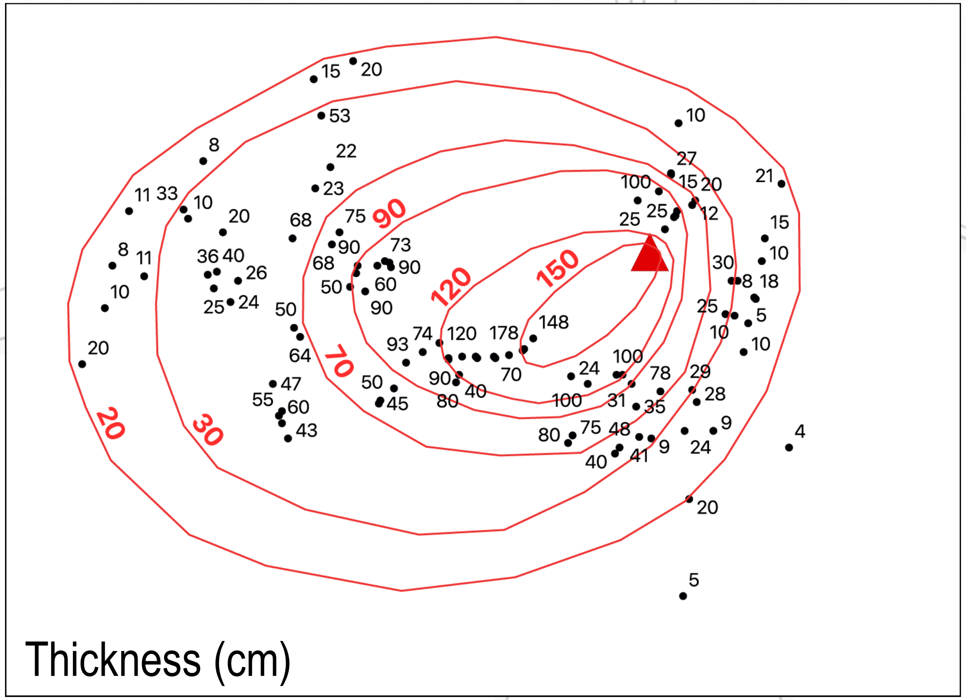
Isopach & volume calculation

6. Fit:

- One or multiple **exponential** segments
  - Deposit exposure may obscure 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



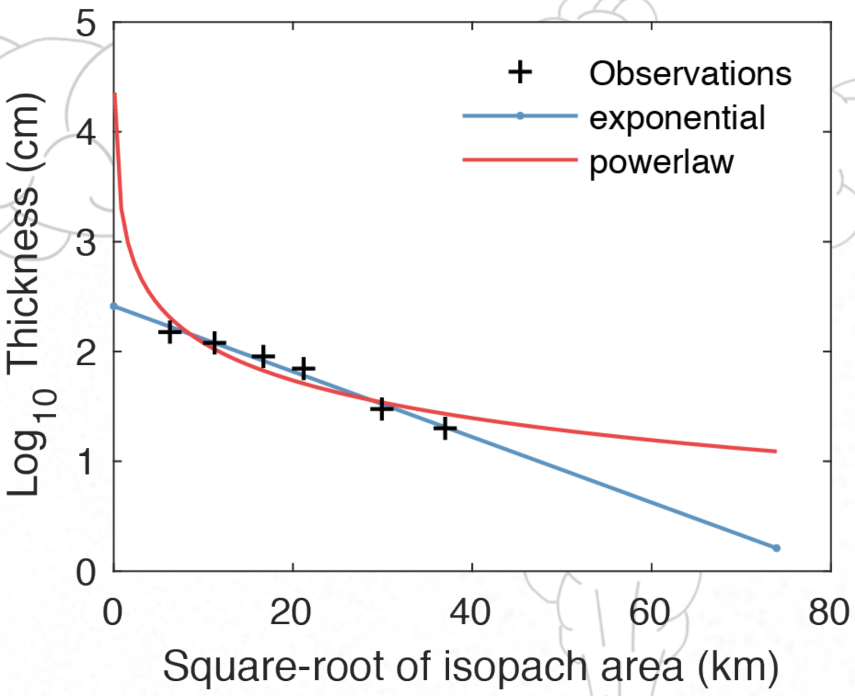


Isopach & volume calculation

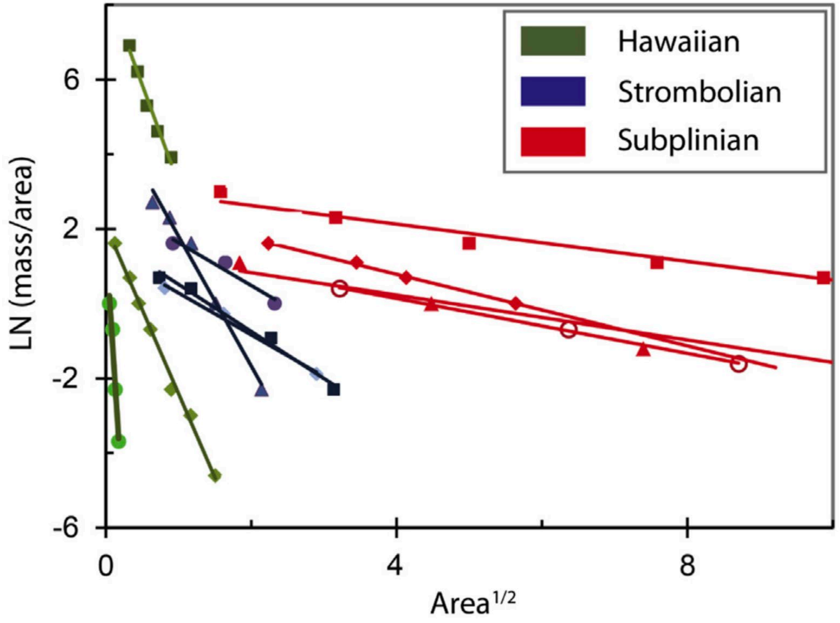
7. Calculate volume by integrating area below curve. For 1 exponential segment:

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

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



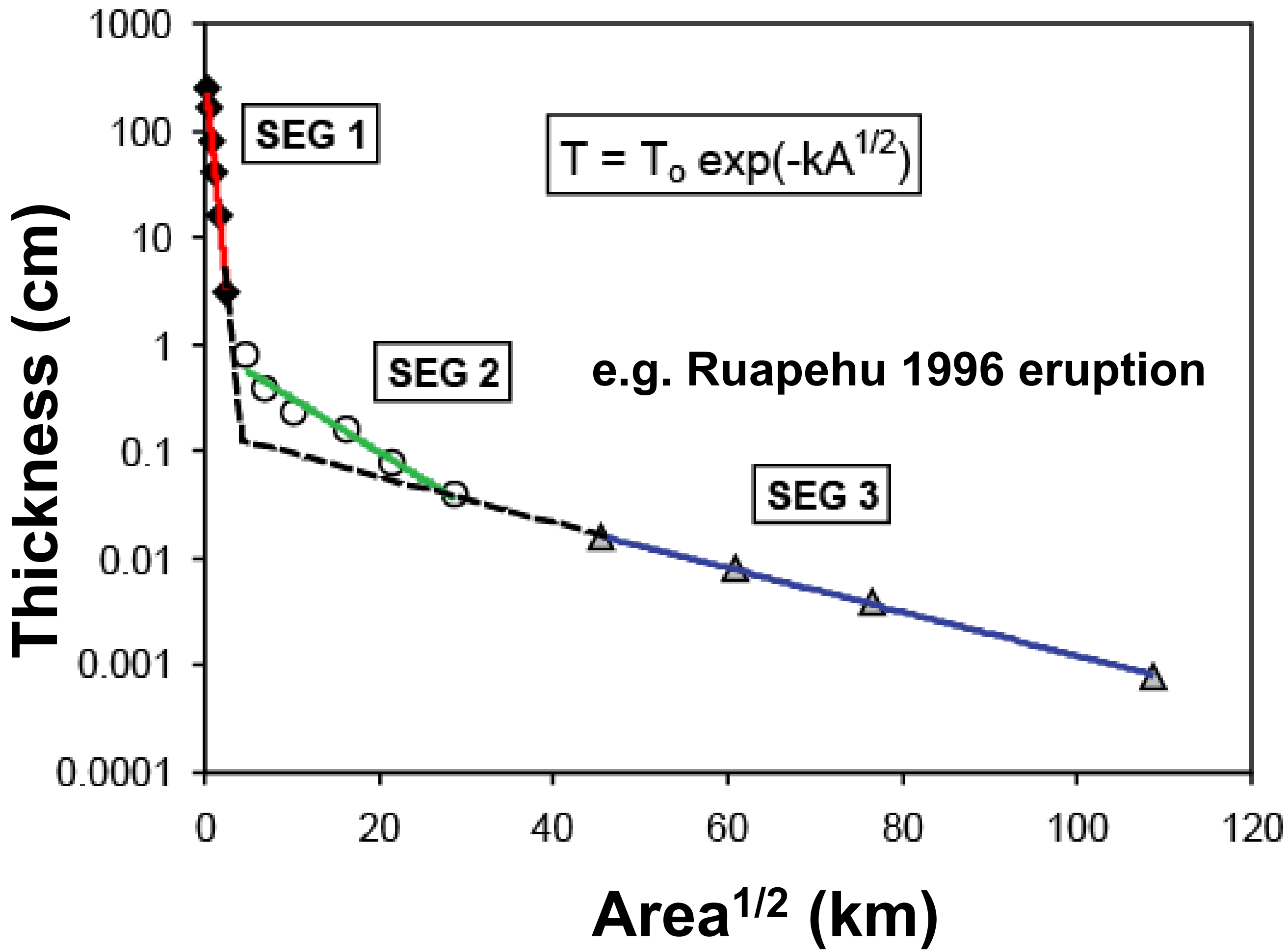
8. Calculate thickness half distance $\mathbf{b_T}$ as: $\frac{\log(2)}{k\sqrt{\pi}}$



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

Exponential treatments:

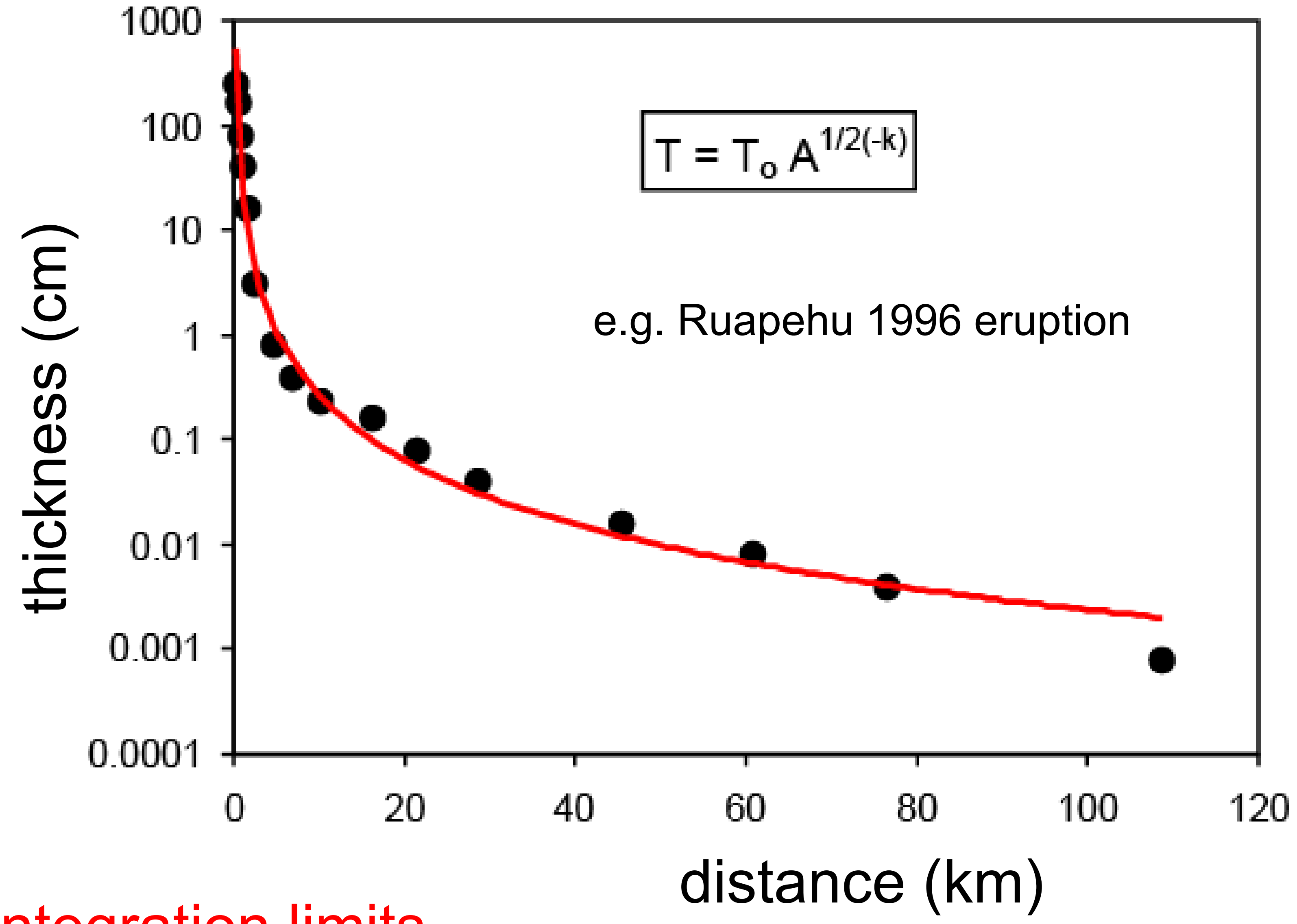
- **1 exp. segment** (Pyle 1989)
- **2 exp. segments** (Fierstein and Nathenson 1992, Pyle 1995)
- **>2 exp. segments** (Bonadonna and Houghton 2005)
- **One proximal isopach line** (Legros 2000)
- **Thickness measurements** (Burden et al. 2013)



PROBLEM: underestimation of volume in case of missing distal segment(s)

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)		$1x10^4$	$1x10^6$	$1x10^7$	$1x10^8$	$1x10^9$	$1x10^{10}$	$1x10^{11}$	$1x10^{12}$
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	→	←	Plinian		→		
			← 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)		$1x10^4$	$1x10^6$	$1x10^7$	$1x10^8$	$1x10^9$	$1x10^{10}$	$1x10^{11}$	$1x10^{12}$
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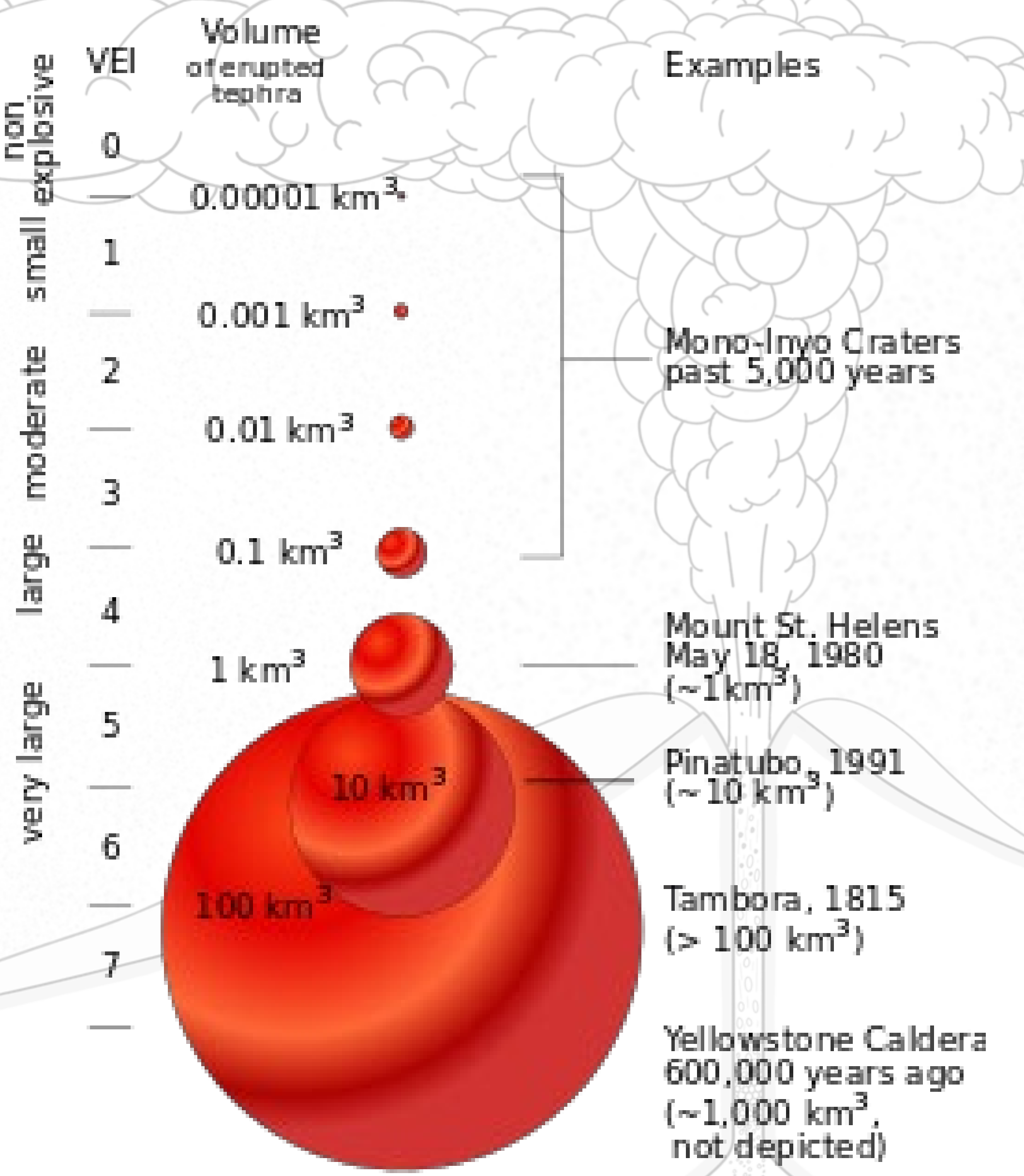
Isopach & volume calculation

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

- **Problem 1:**
  - Only explosive

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



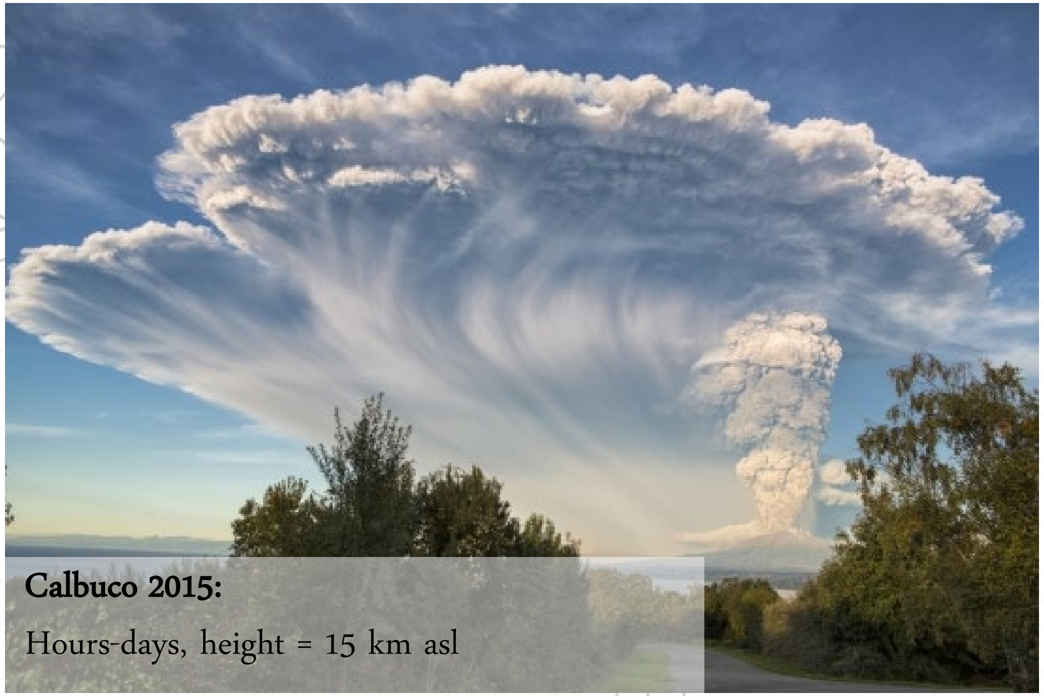
Isopach & volume calculation

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

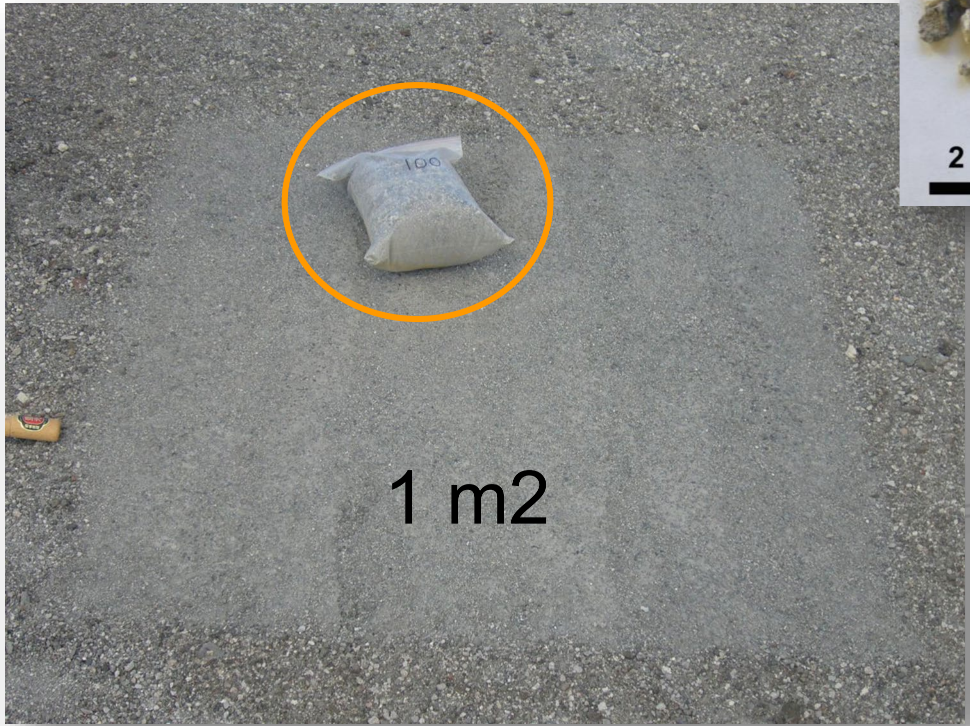
- **Problem 1:**
  - Only explosive

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

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



Isomass: alternative for thin or distal deposits



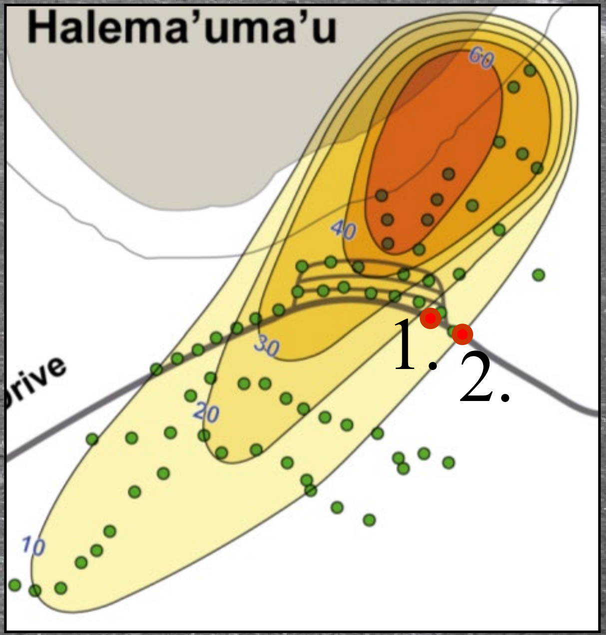
Measure mass over a known surface area

Isomass: lateral margins

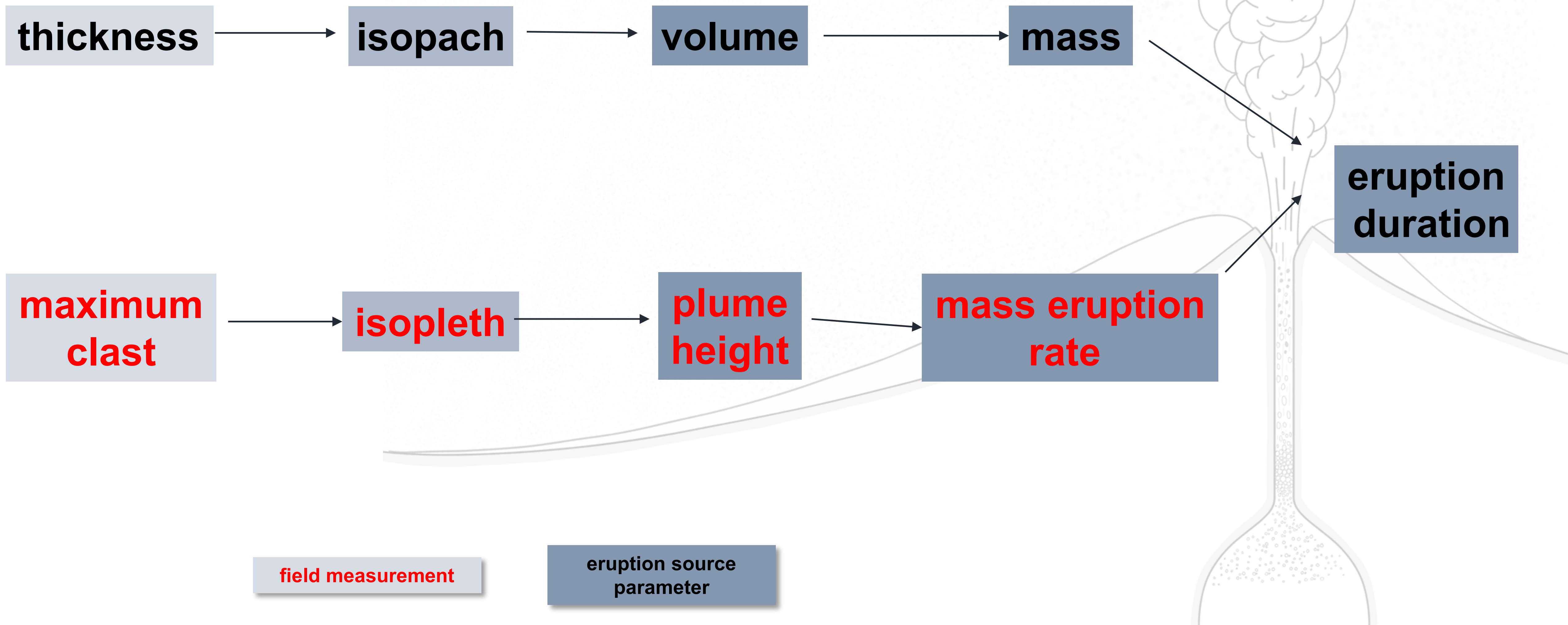
1. eastern margin: 22 g m^{-2}

mm thick. equivalent

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



Tephra fall: characterization sheet



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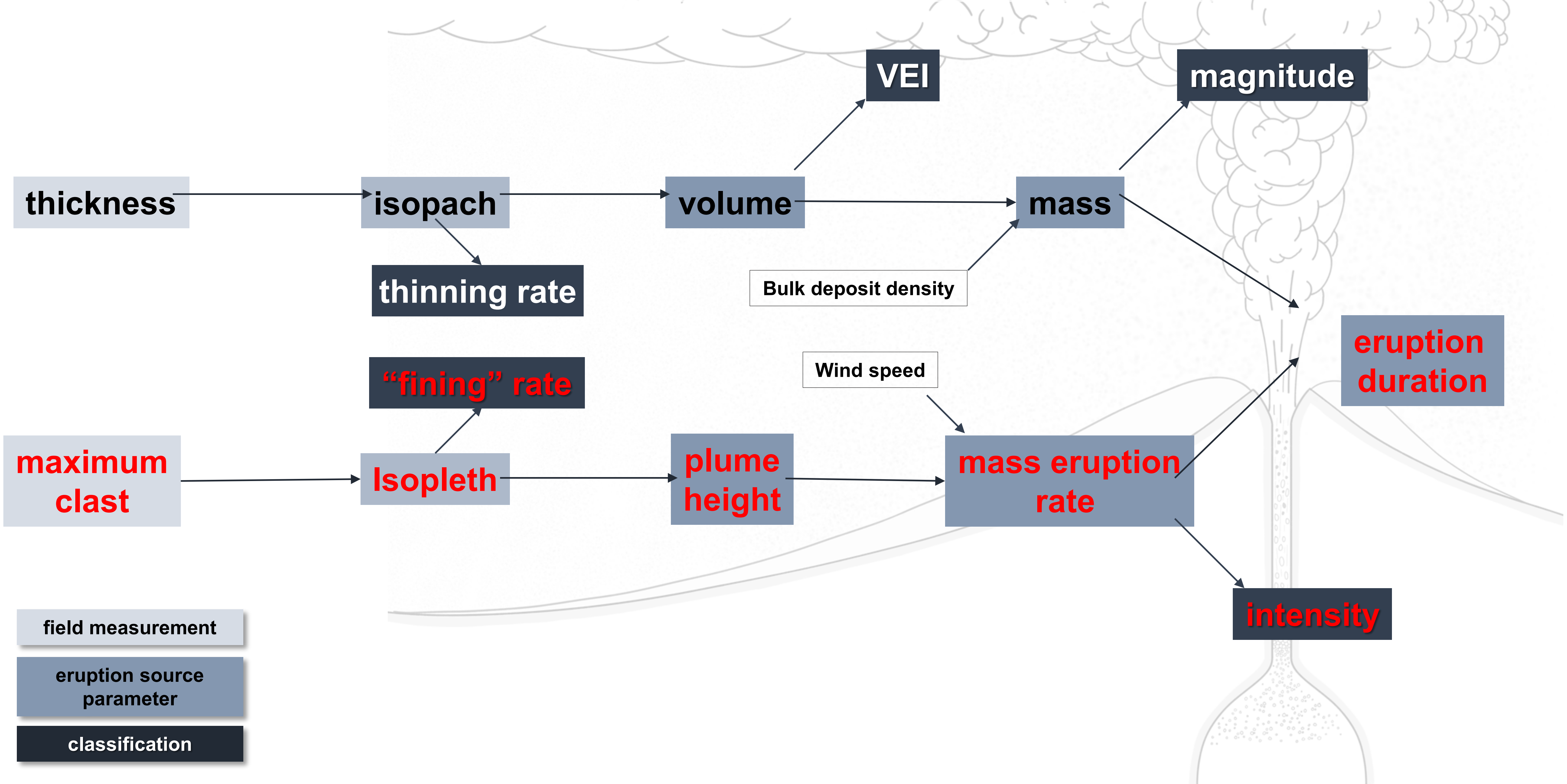
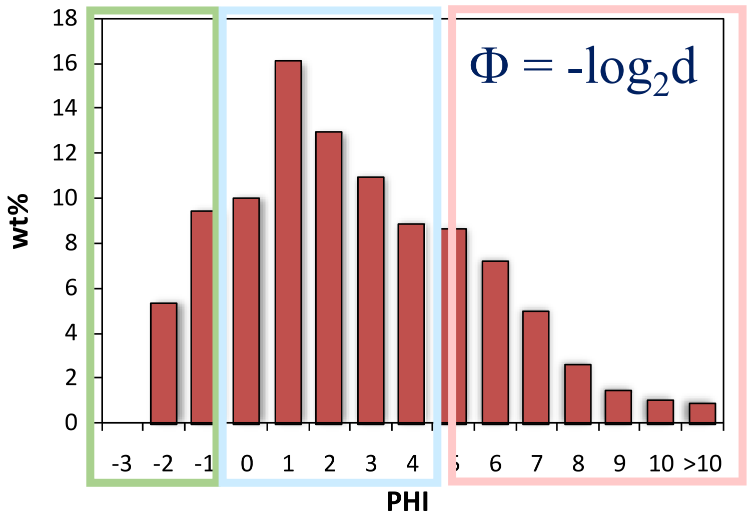


Grain size

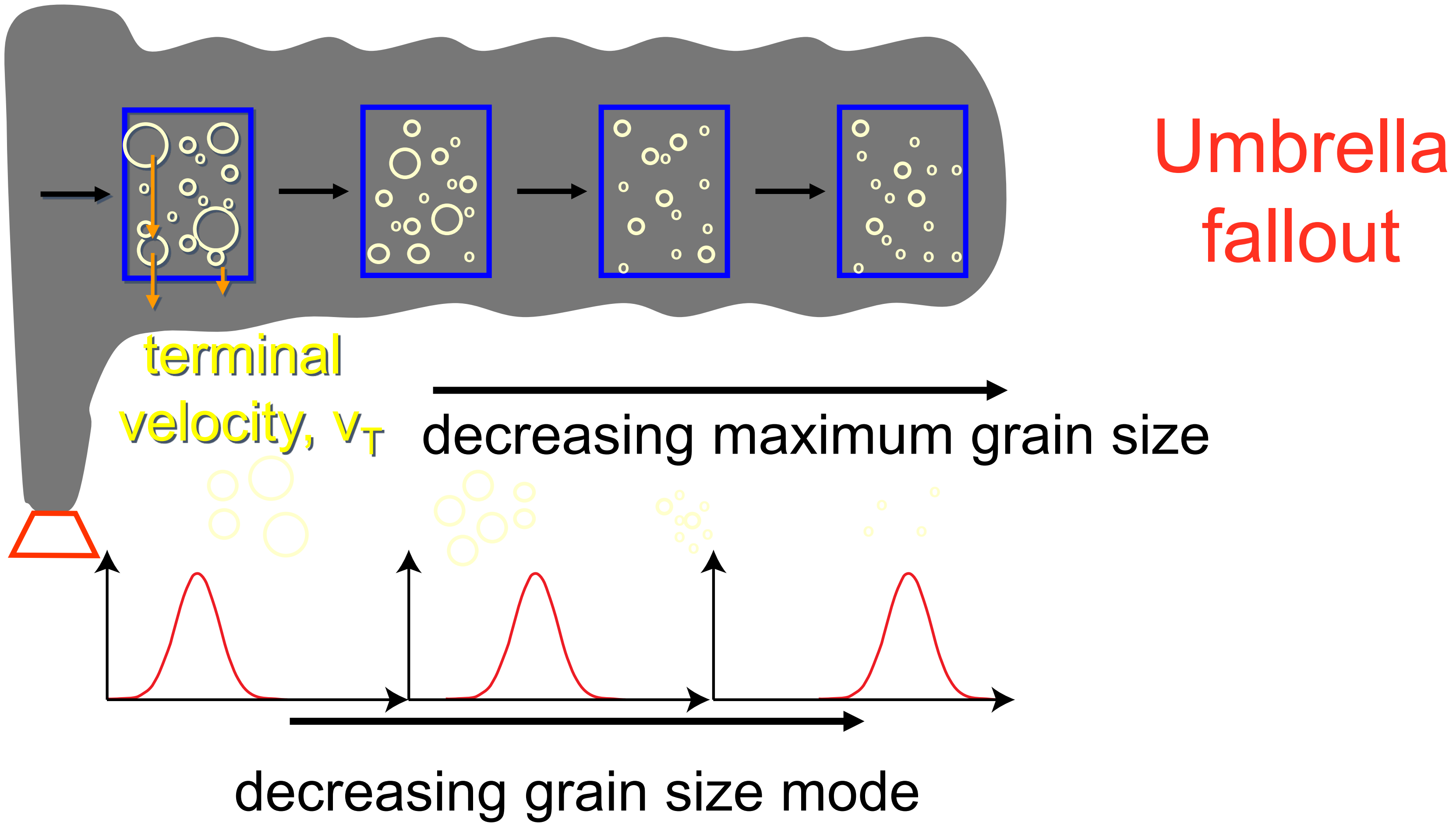
	bombs / blocks	lapilli	coarse ash	**fine ash**
Diameter	> 64 mm	(64 mm-2 mm)	(2 mm-63μm)	**(<63μm)**
Residence time	≈ sec	≈ min	≈ hours to few days	**several days**
Travel distance	proximal <10km	medial <50 km	distal <100 km	**very distal** **<1000 km**

8 mm

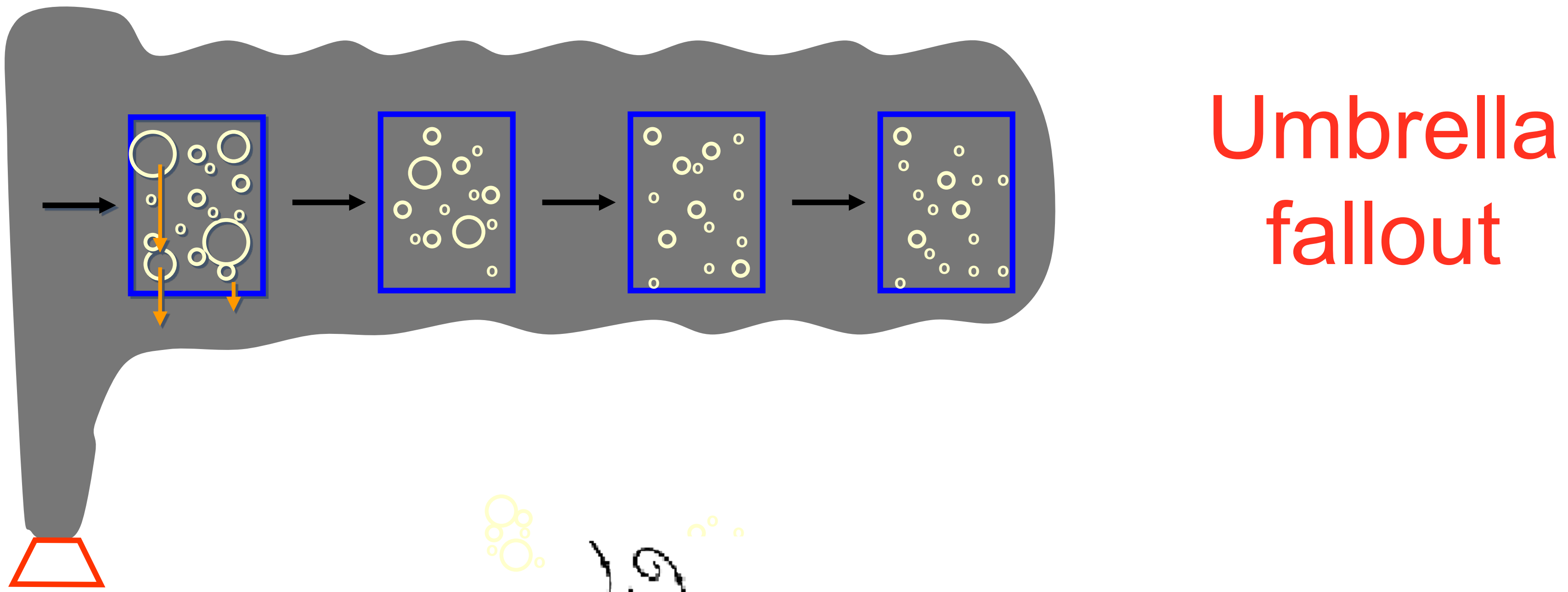


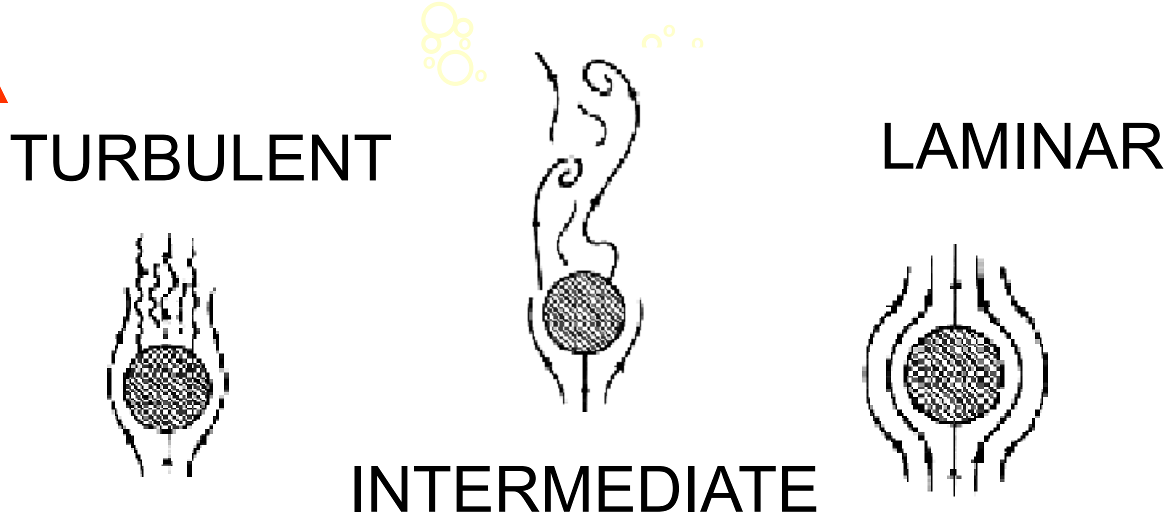
4 μm

Fining of fall deposits

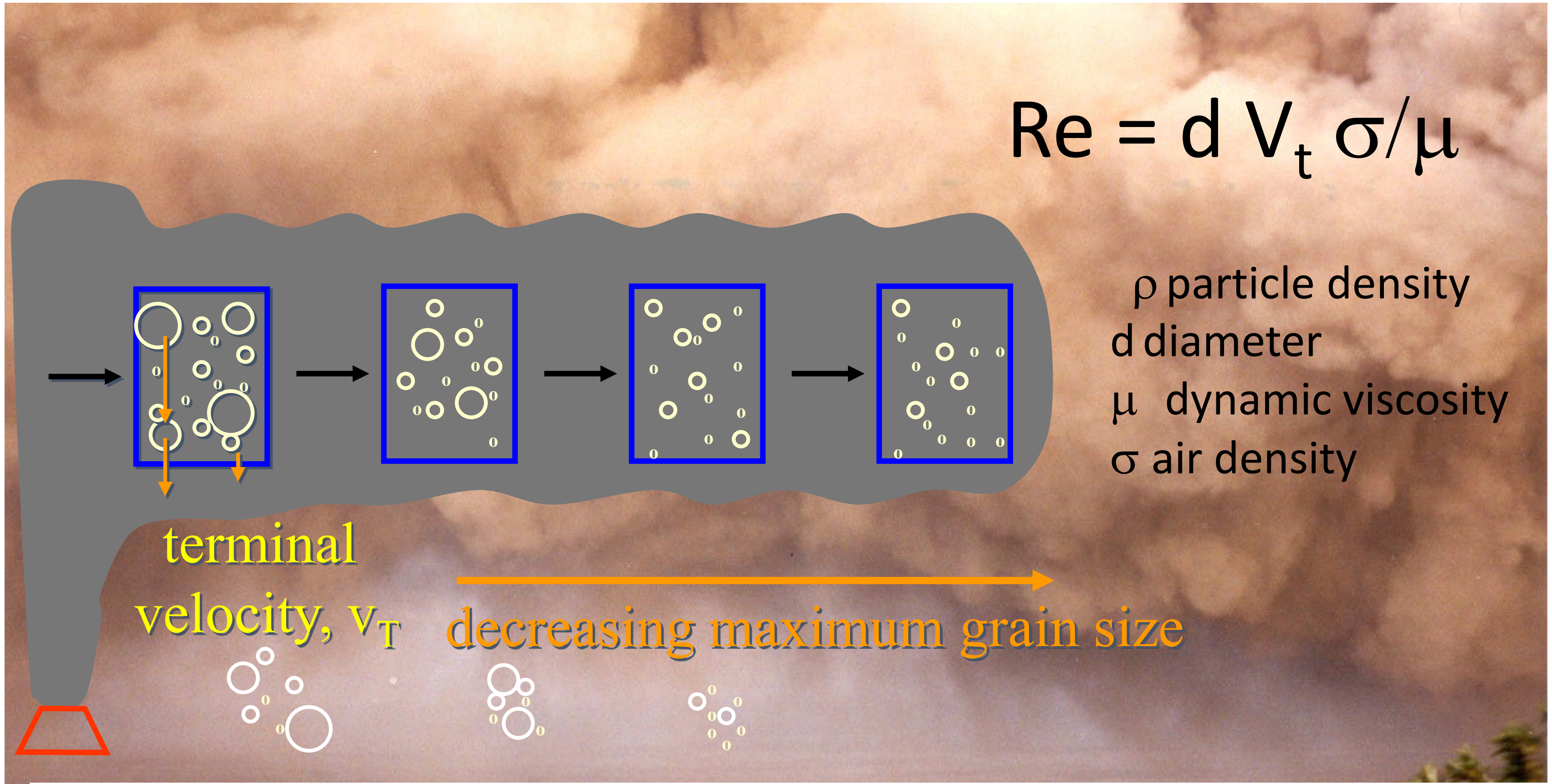


Sedimentation from volcanic plumes





Settling laws for volcanic plumes

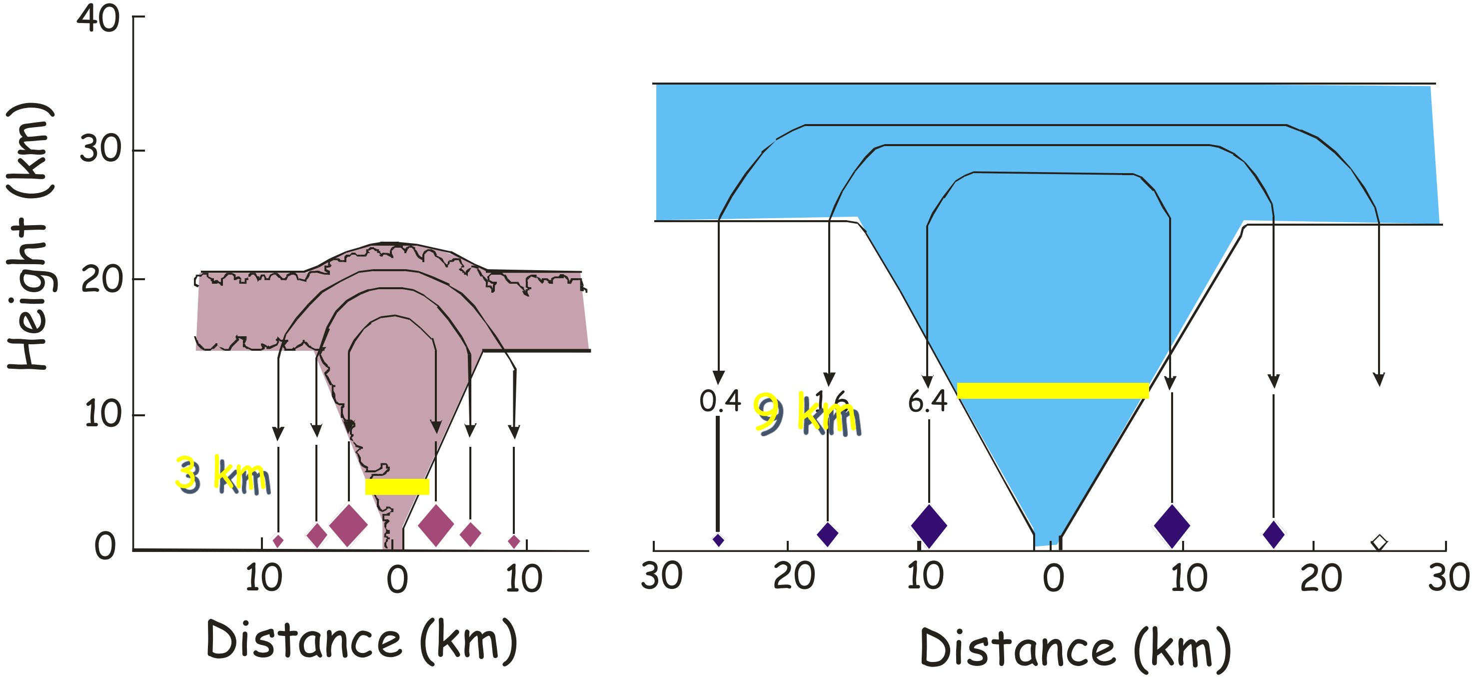


$V_t \approx (3.1\,g\rho d/\sigma)^{1/2}$ (for Reynolds numbers 500-200,000)

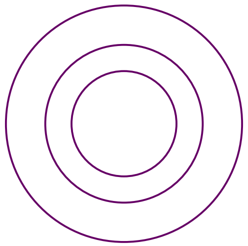
$V_t \approx d(4\rho^2 d^2/225\mu\sigma)^{1/3}$ (for Reynolds numbers 6-500)

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

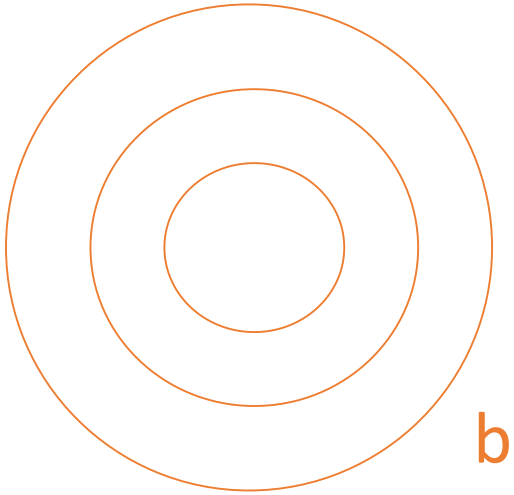
GRAIN SIZE: eruption height



Carey & Sparks 1986



b_c = 1.0 km

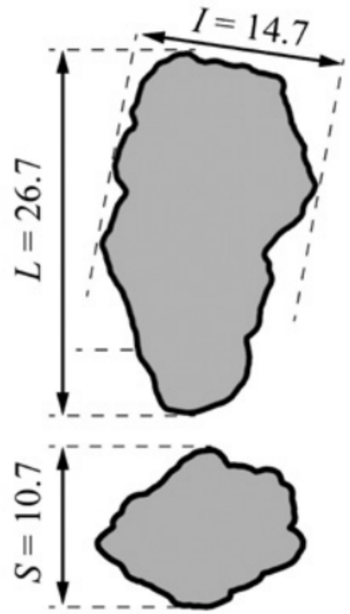


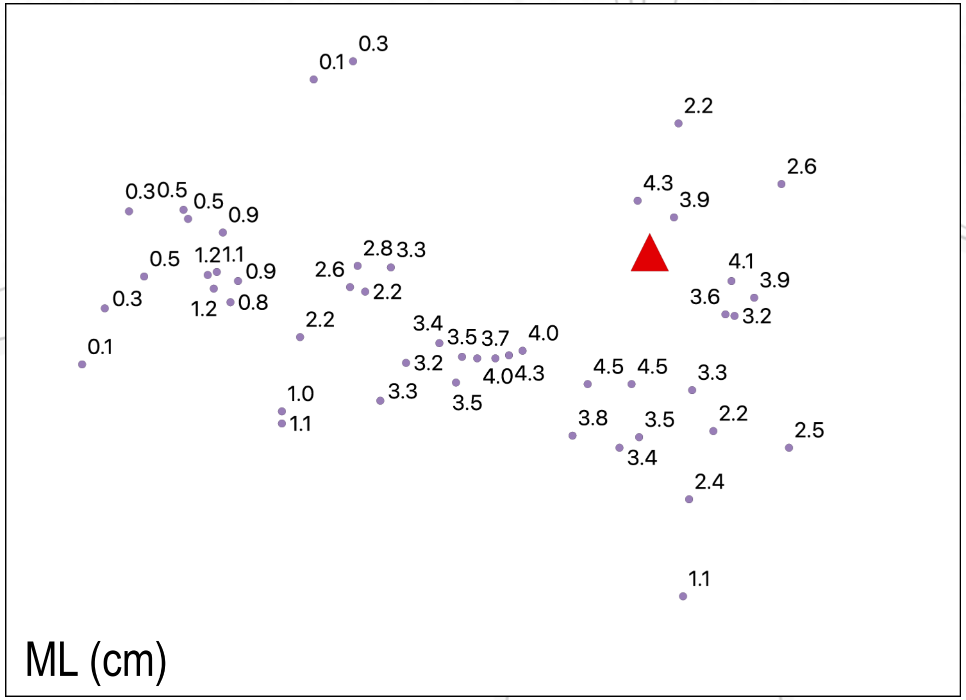
b_c = 4.5 km

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

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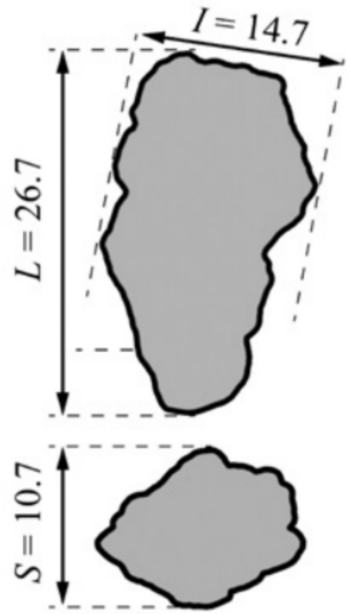
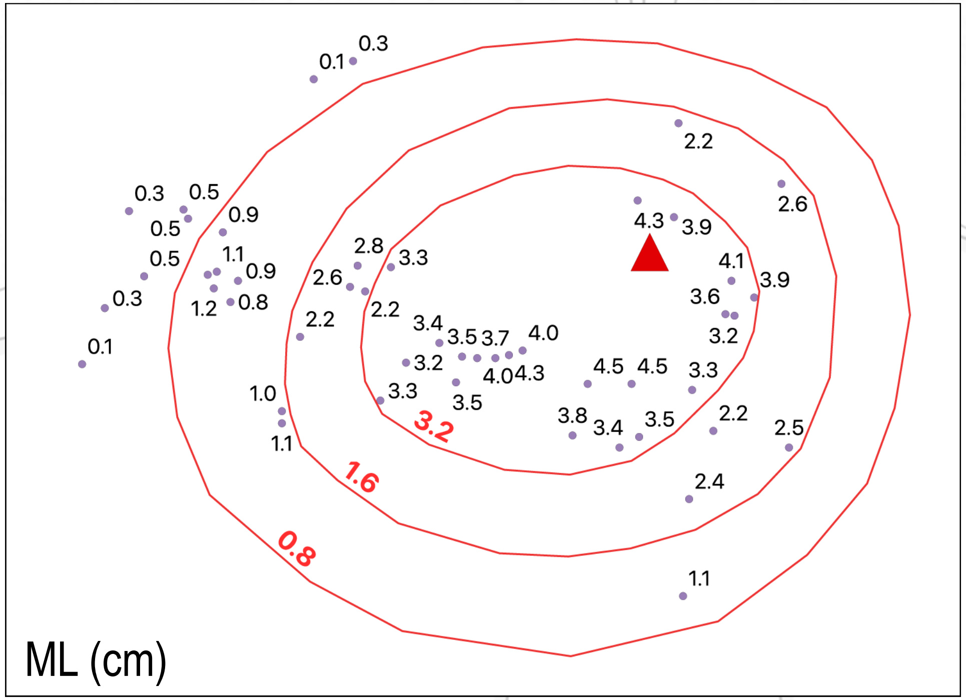


2. Contour **isopleth**

   = contours of equal diameter



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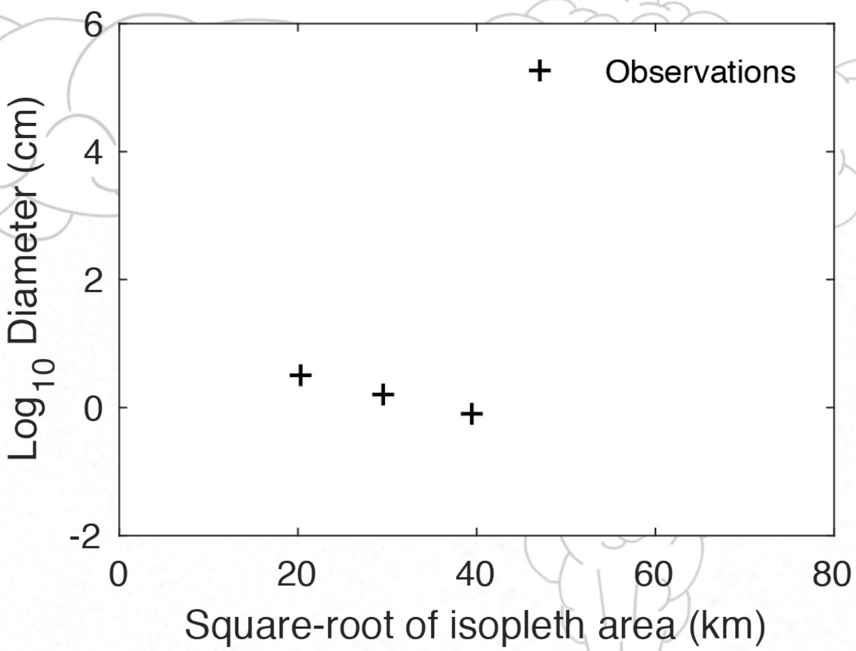
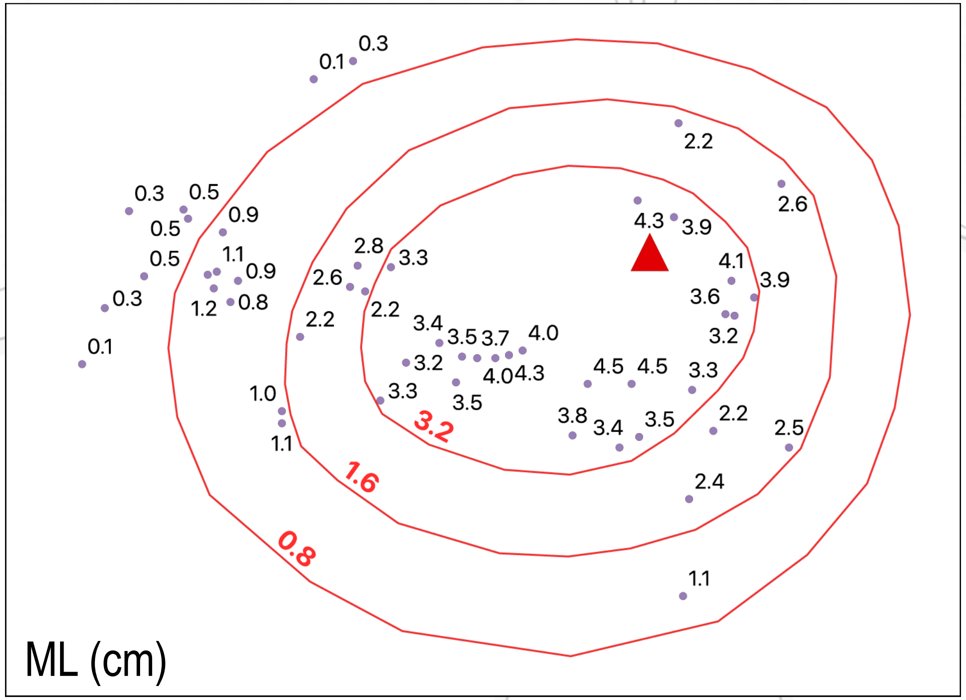
3. Plot log(diameter) vs sqrt(area)





Isopleth & plume height calculation

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2. Contour **isopleth**

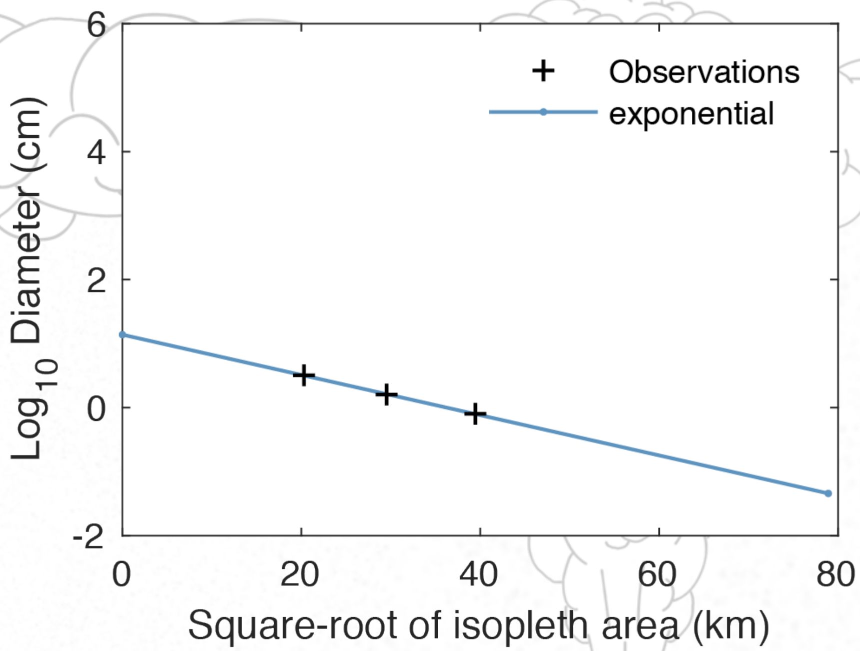
   = contours of equal diameter

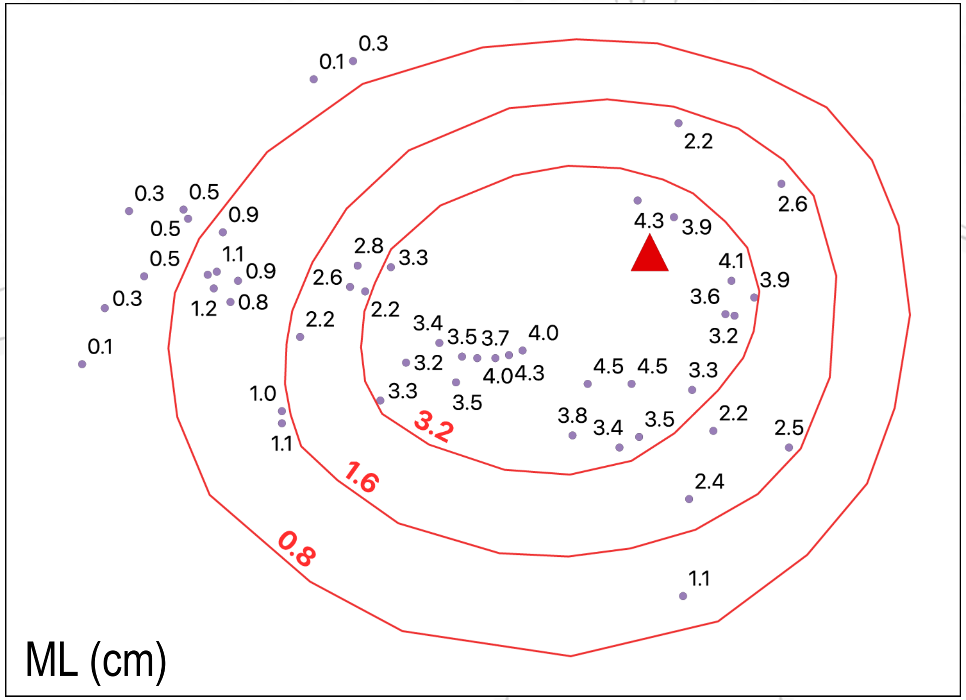
3. Plot log(diameter) vs sqrt(area)

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

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

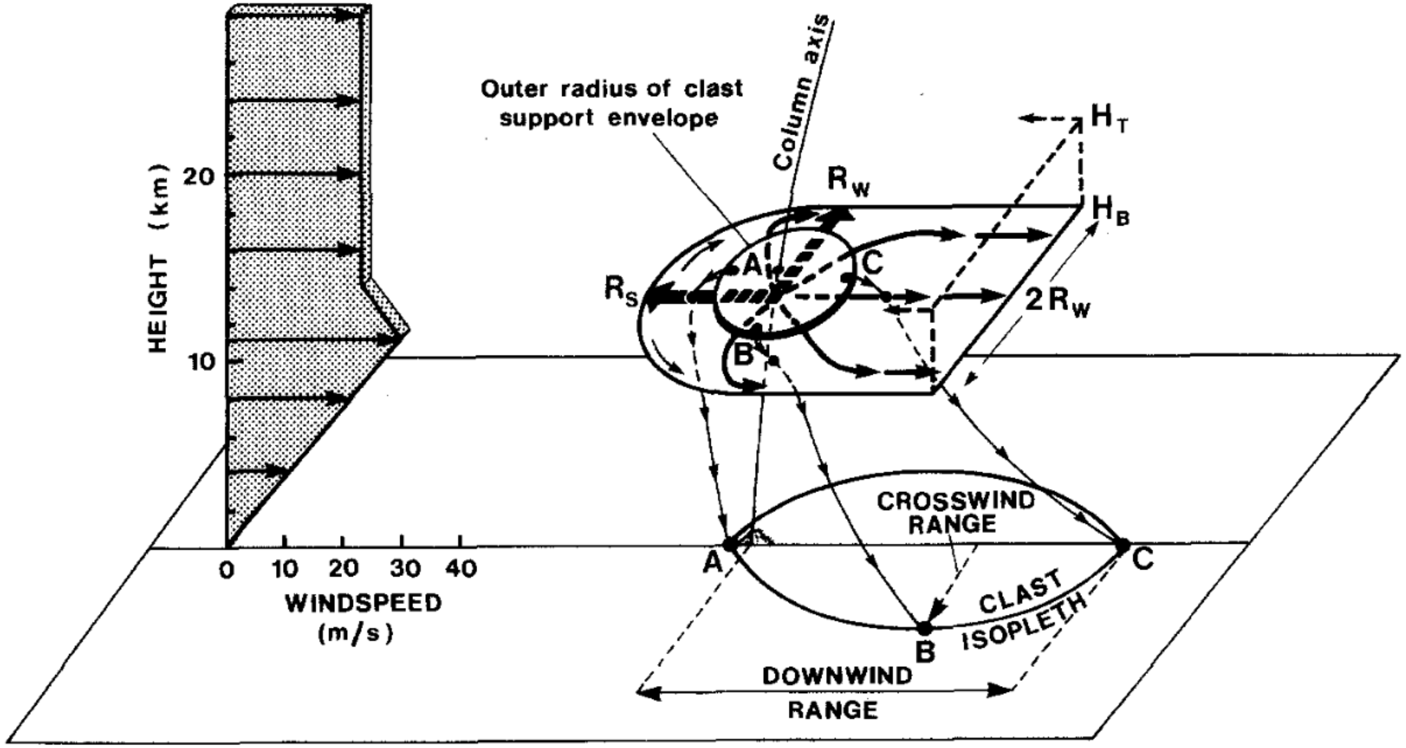
$$\frac{\log(2)}{k\sqrt{\pi}}$$



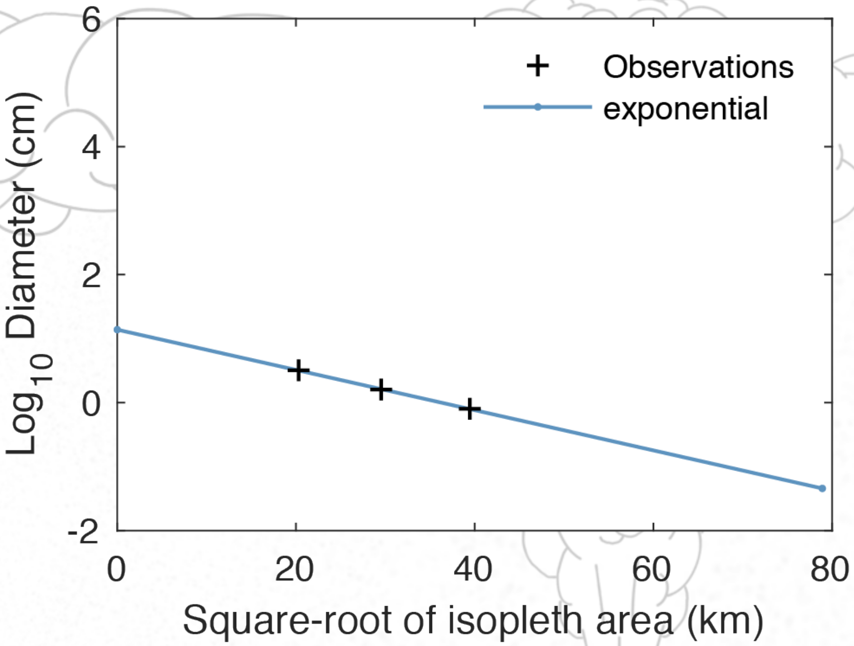


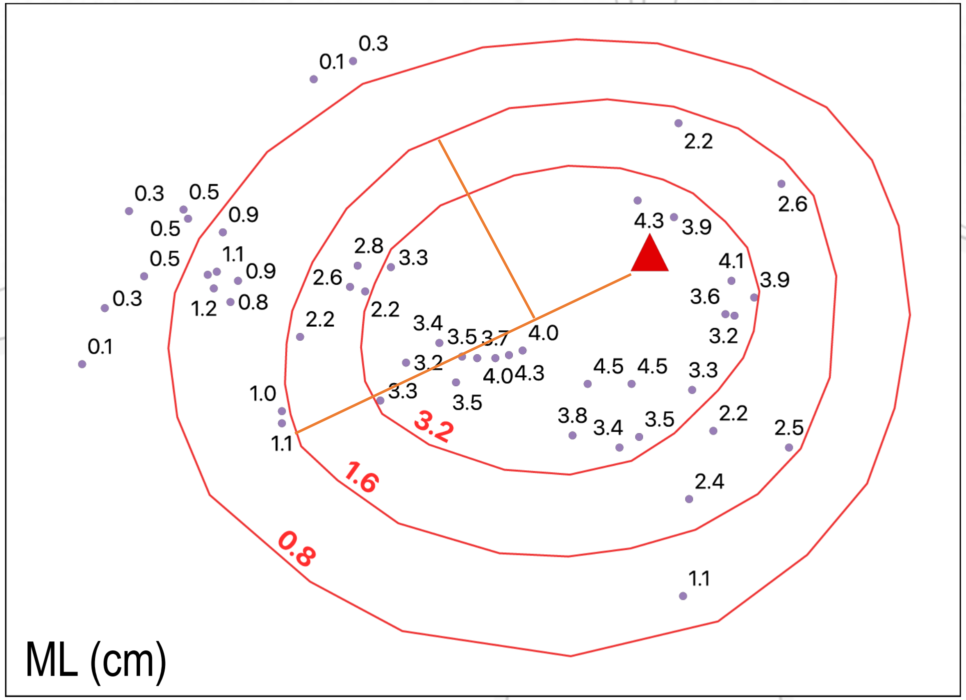
Isopleth & plume height calculation

6. Measure downwind and half-crosswind half distances



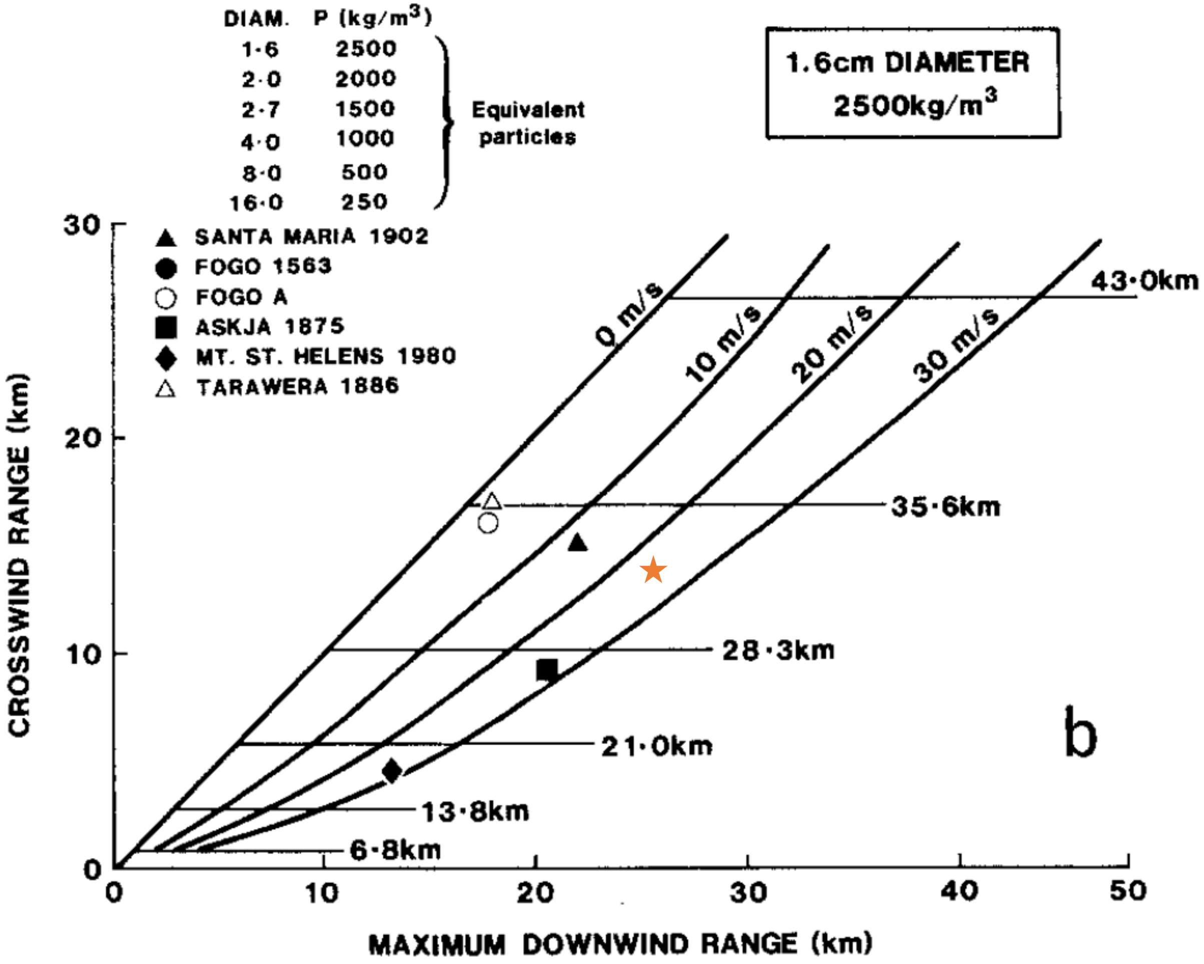
Carey and Sparks 1986

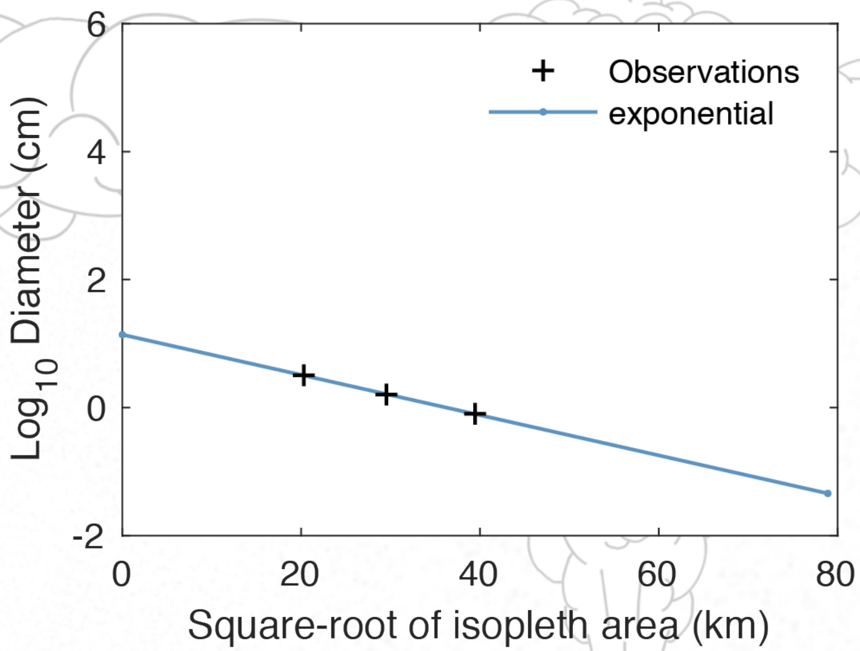


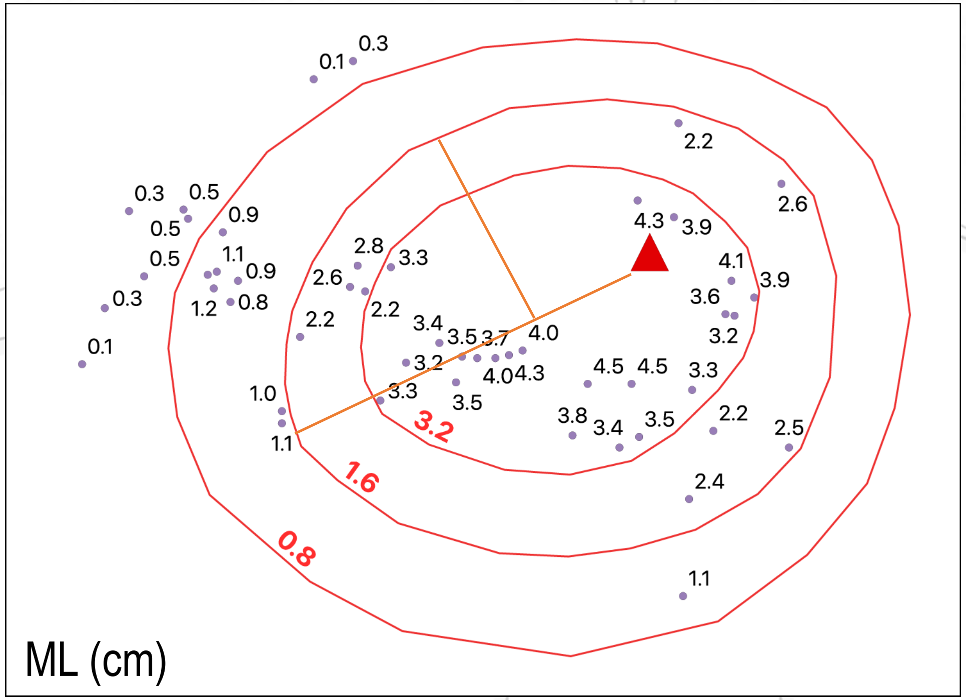


Isopleth & plume height calculation

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



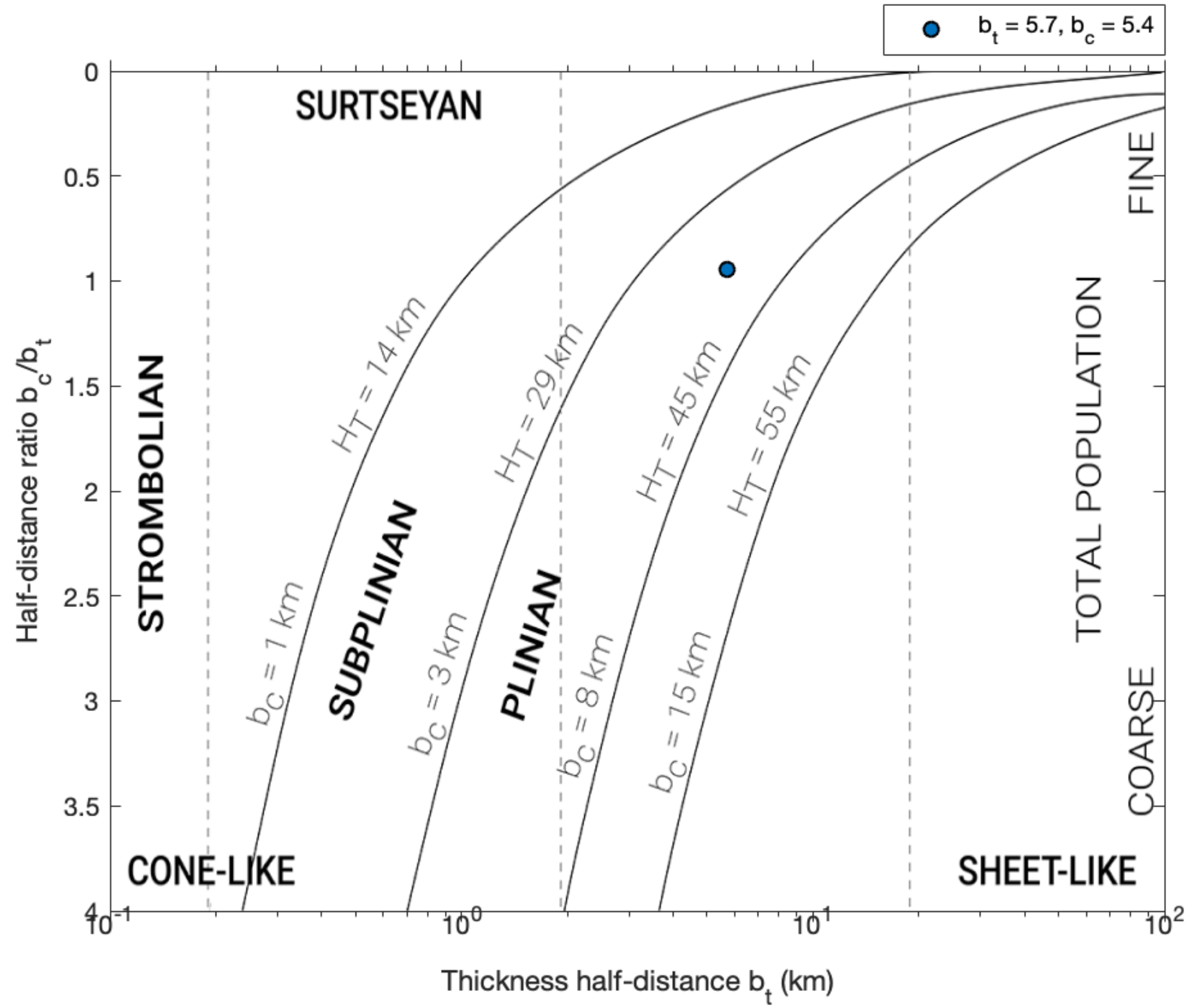




Classifications

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

- **Basis of field-based classification**



2) limitations and pitfalls

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

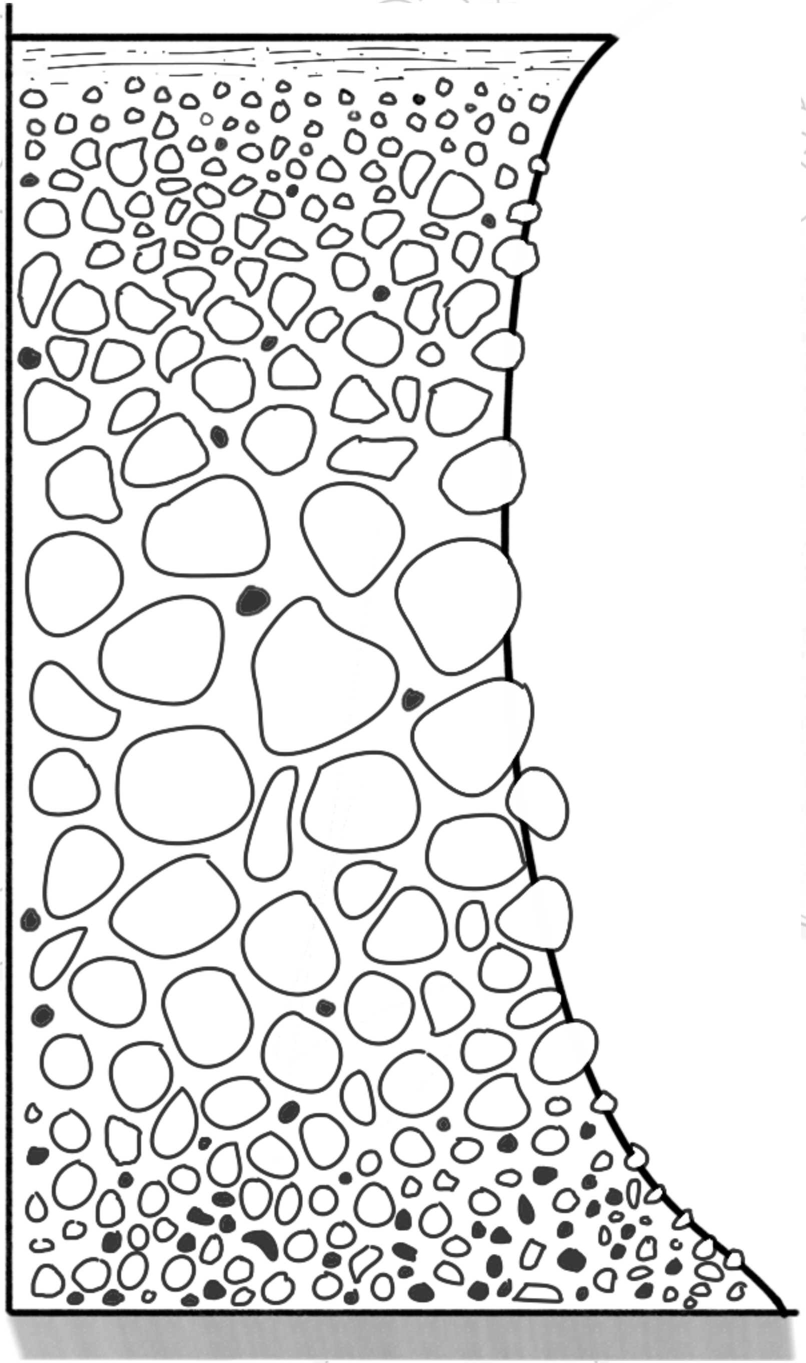
Componentry

Juvenile
Wall rock (lithic)

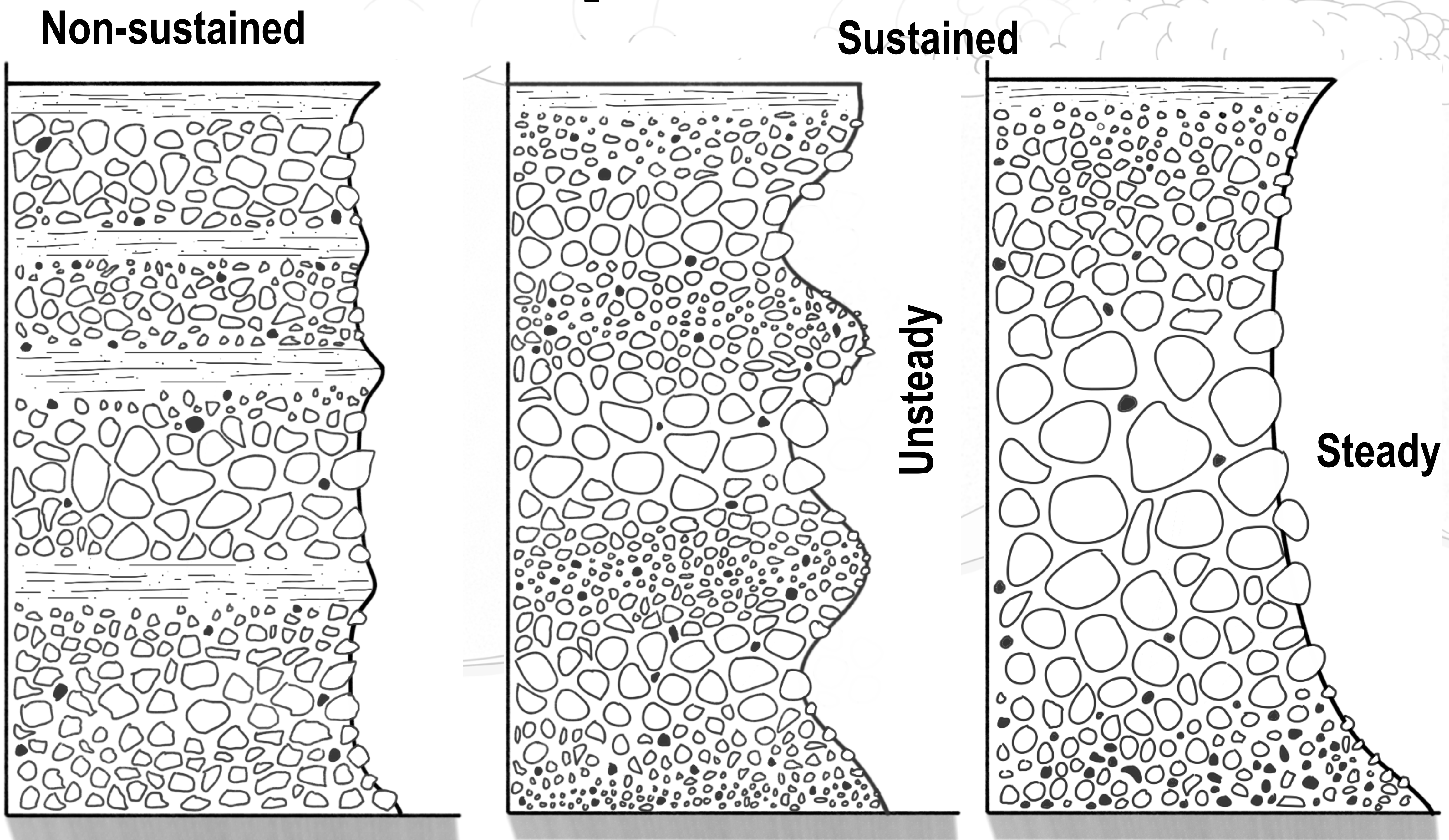
Size

Lapilli
Ash

→ **Sorting? Grading? Layering?**

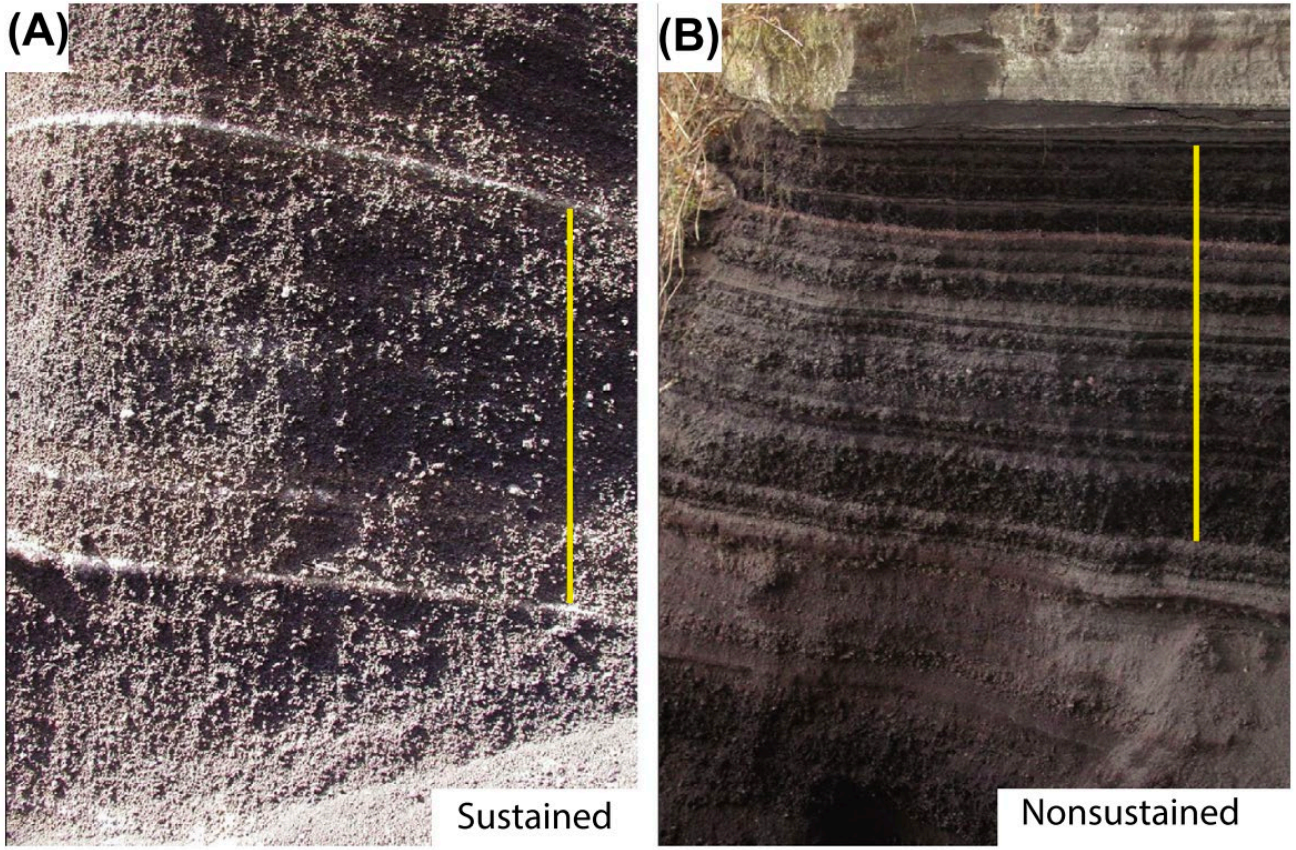


Limitations: Fine temporal variations in MER



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

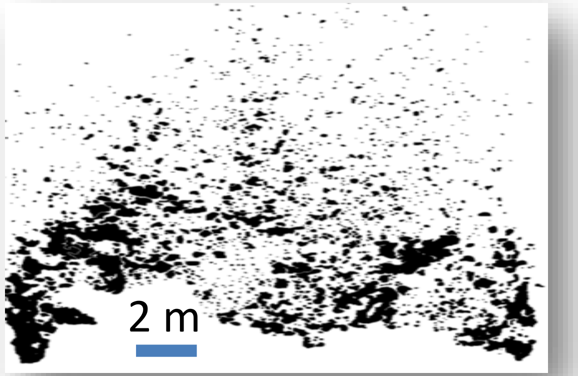


A new approach: particle characterization in-flight using high resolution videos

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.

Quantifying complex changes on fine spatial and temporal scales

3. in-flight characterization



velocimetry

in-flight grain size

in-flight total mass

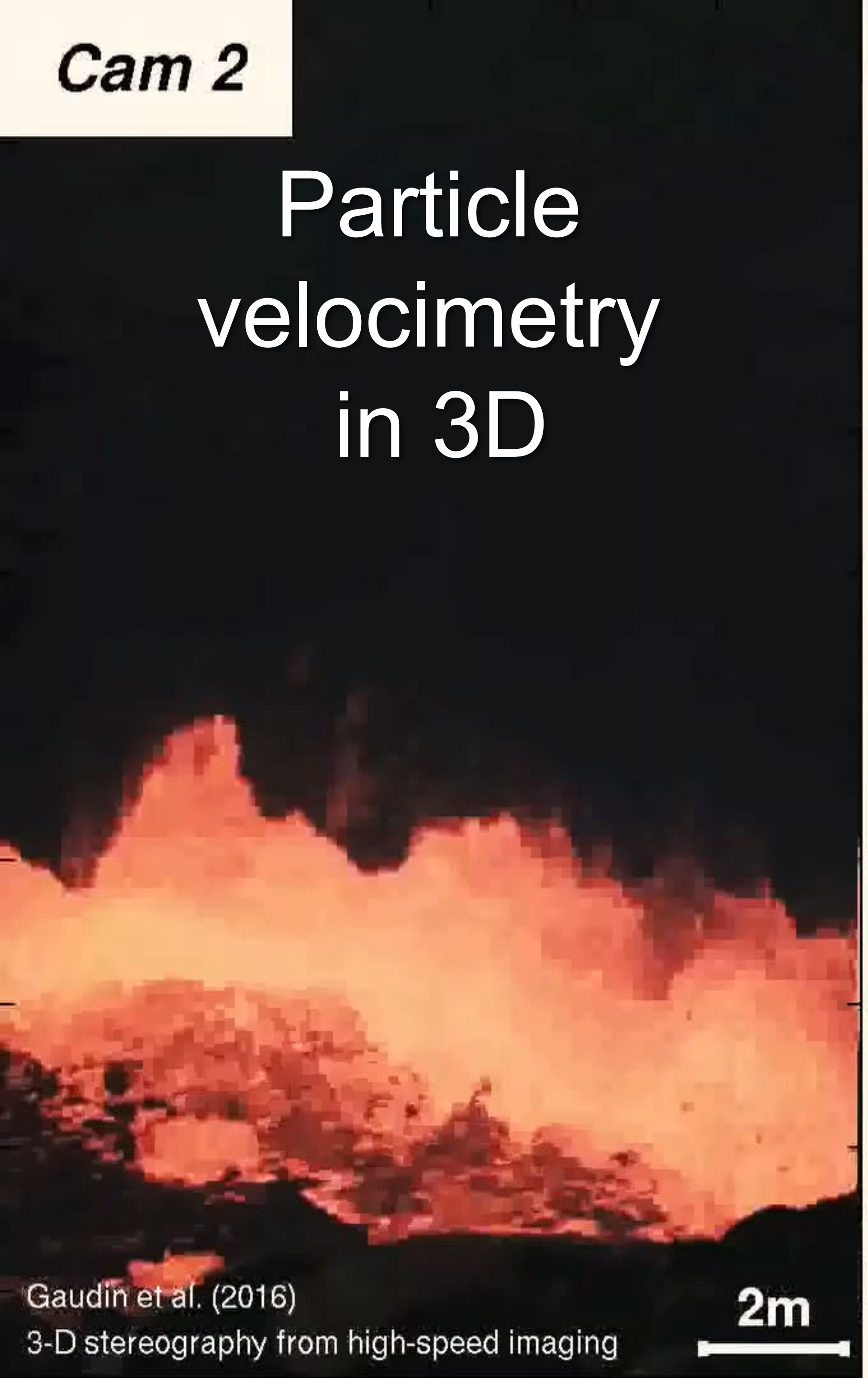
In-flight mass discharge rate

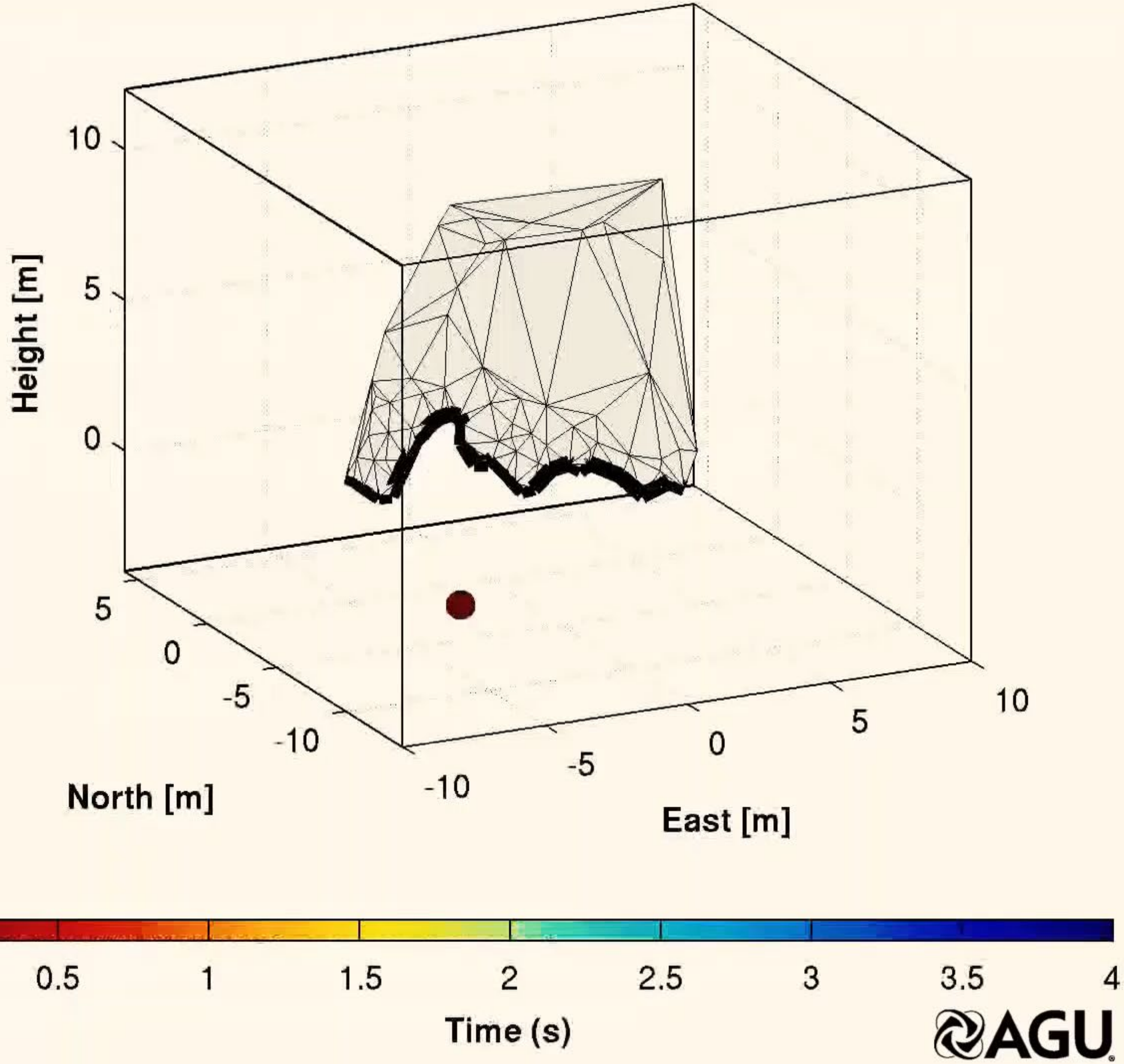
- processed using Photoshop/ImageJ (MTrackJ)
- pixel size via laser range-finder

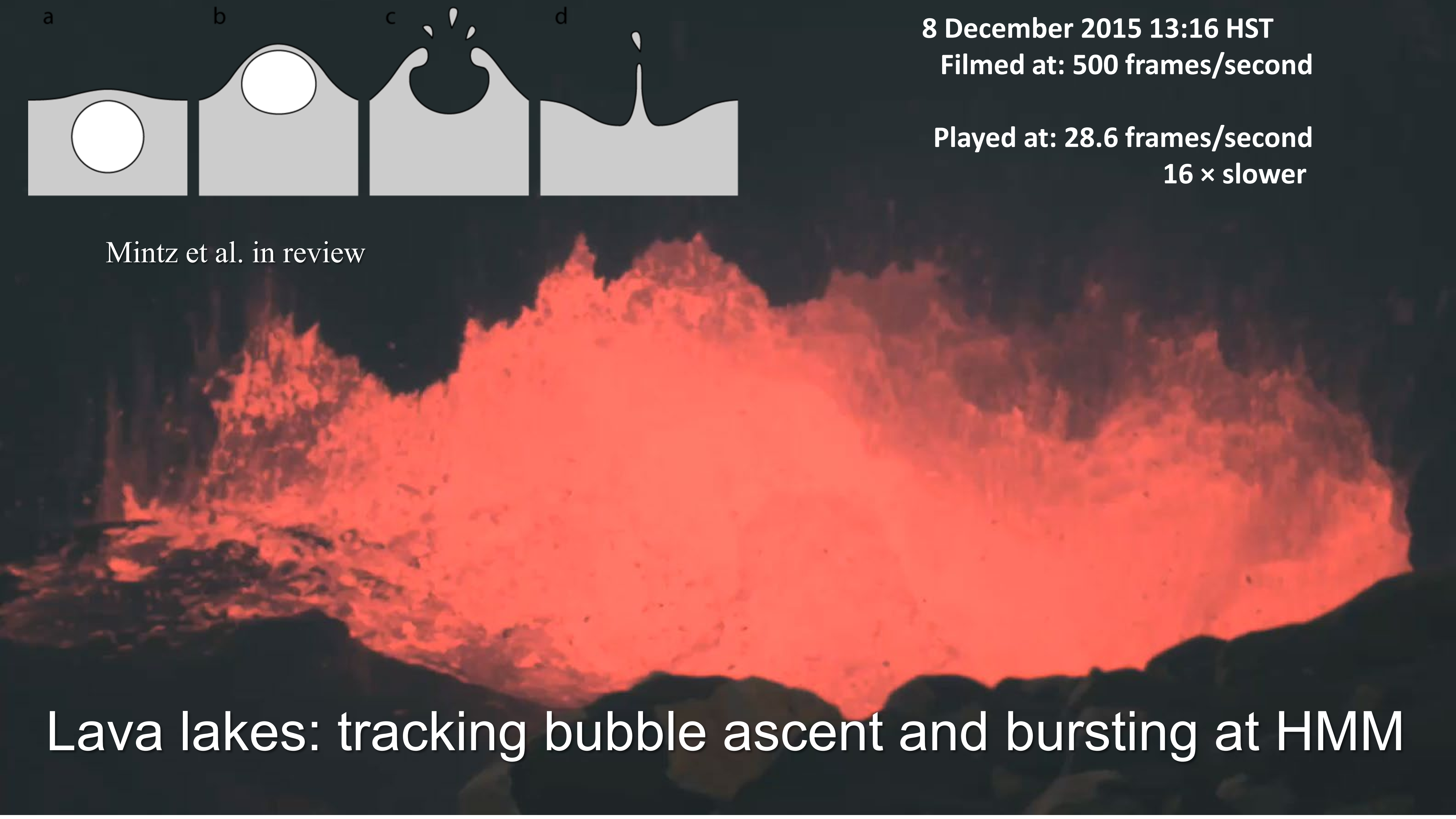
- volume assumed = (area) x (minor axis)

- duration ImageJ/matlab

Particle velocimetry in 3D



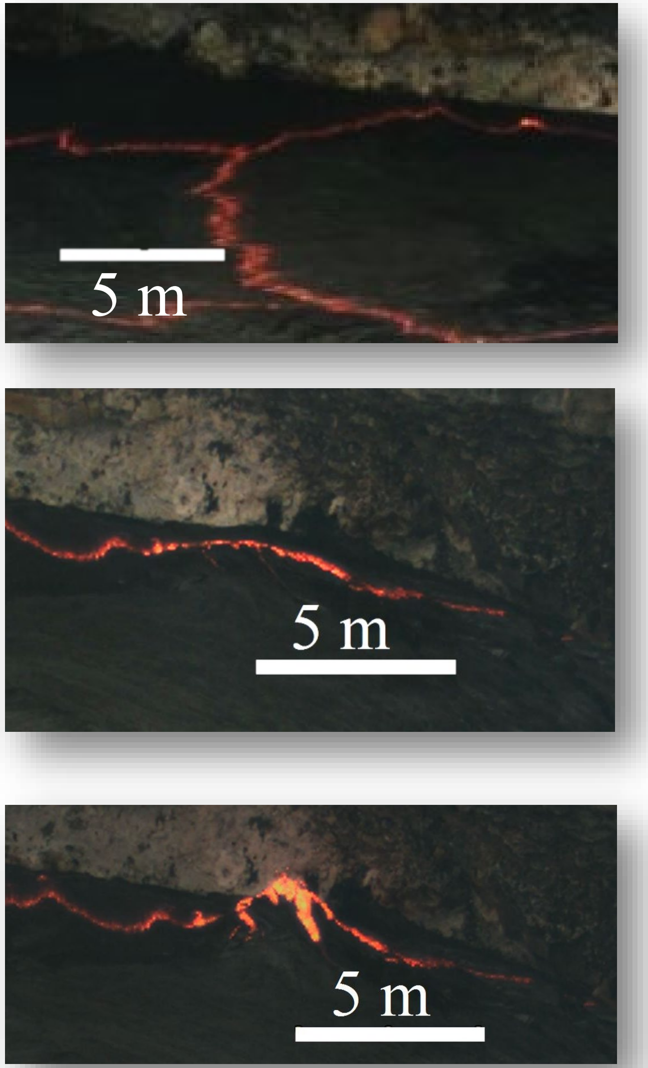


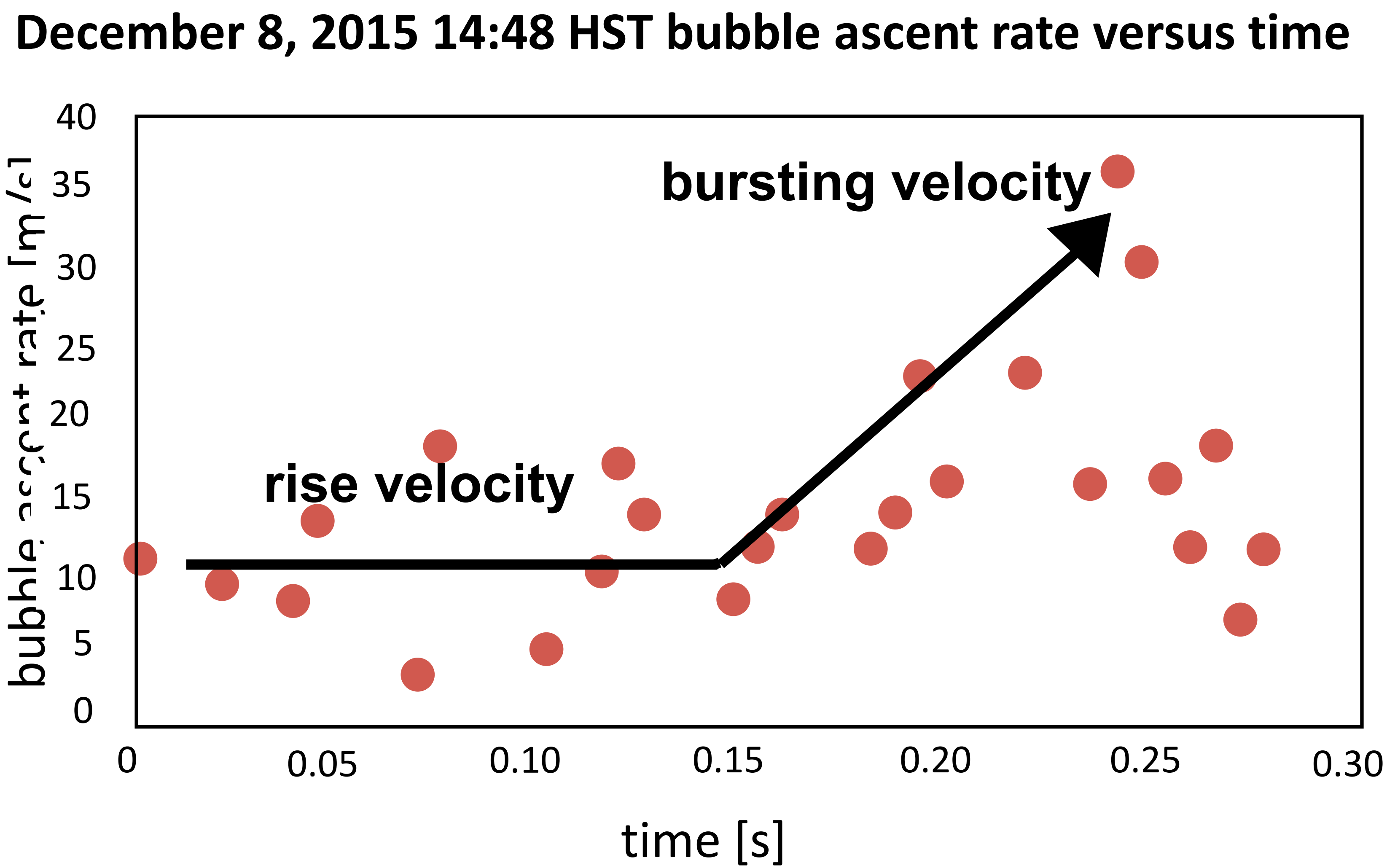


a
b
c
d
Mintz et al. in review
8 December 2015 13:16 HST
Filmed at: 500 frames/second
Played at: 28.6 frames/second
16 × slower
Lava lakes: tracking bubble ascent and bursting at HMM

Pre-bursting bubble ascent

Mintz et al. in review





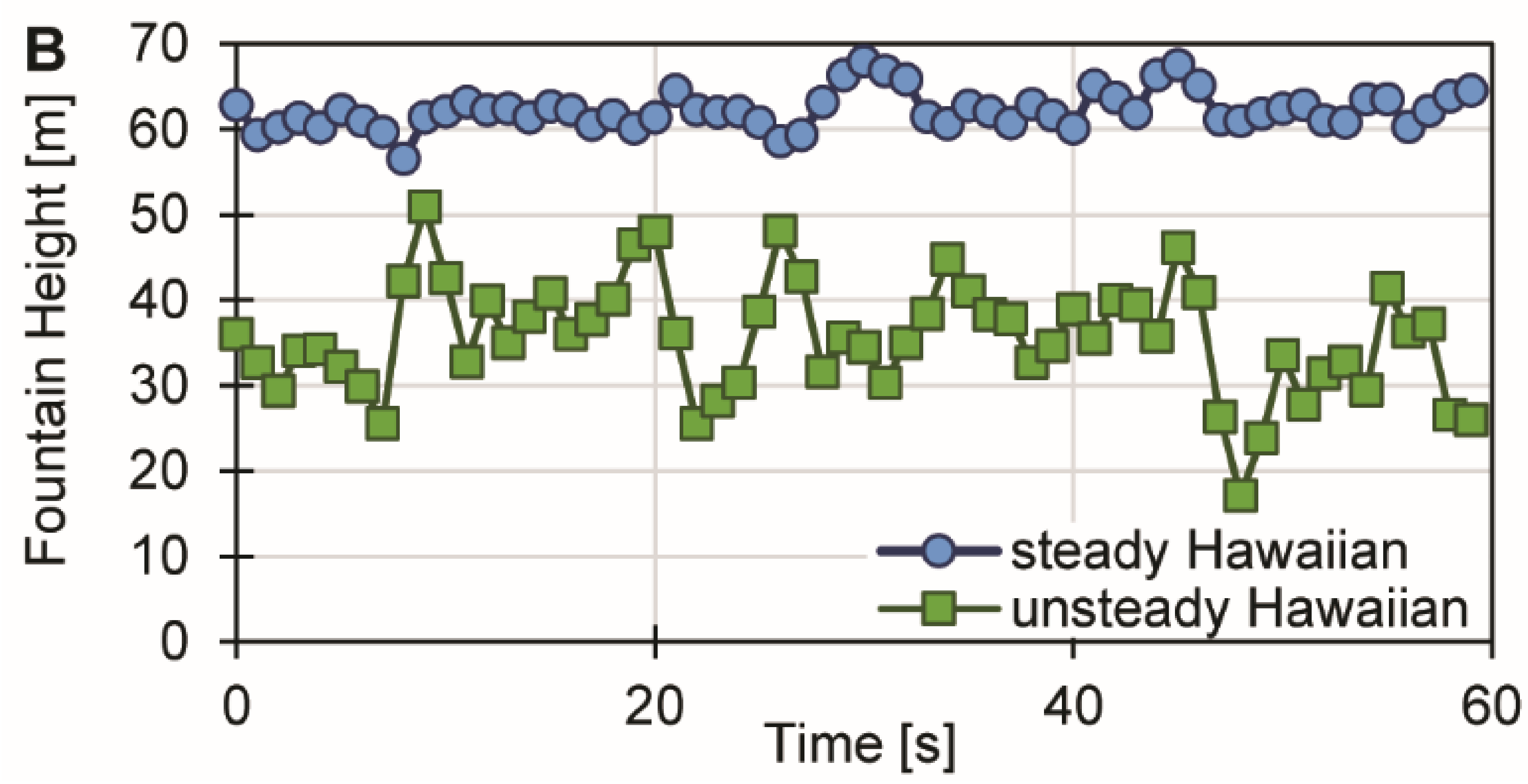
Fountain/jet heights: steady vs unsteady Hawaiian

- STEADY: Height deviates from average height by only ~5%
  - increased role of coupled bubbles

Note contrasting styles →

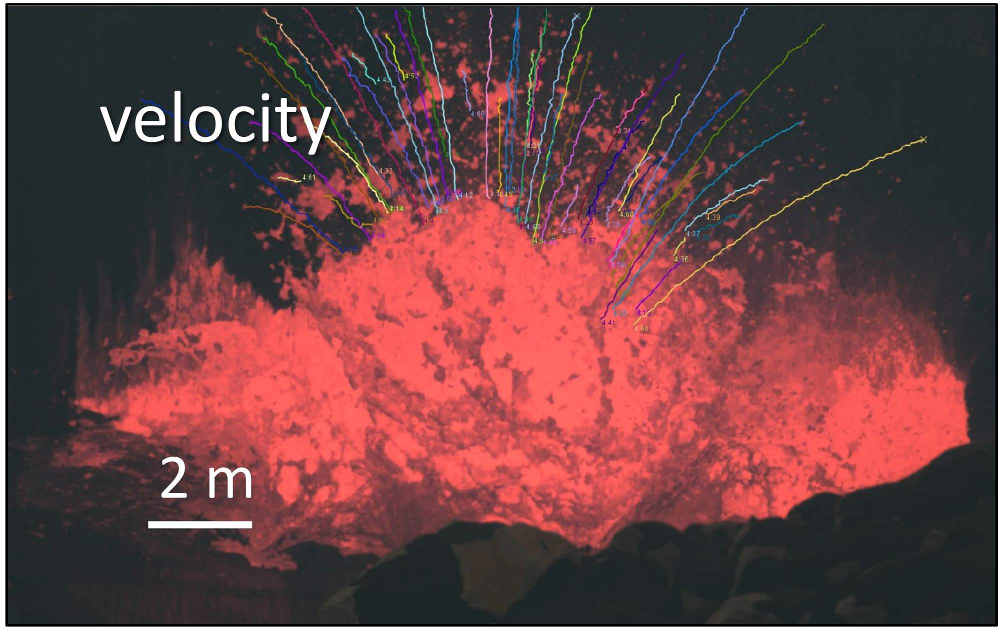
LERZ Fissure 8 (29 May, 2018)

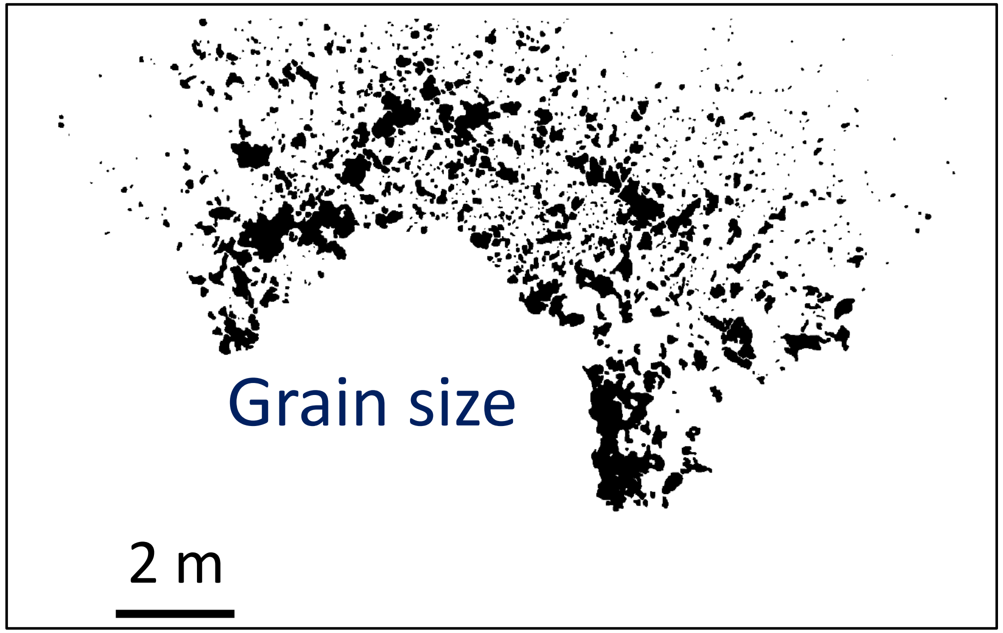
Walker & Houghton submitted to Geology

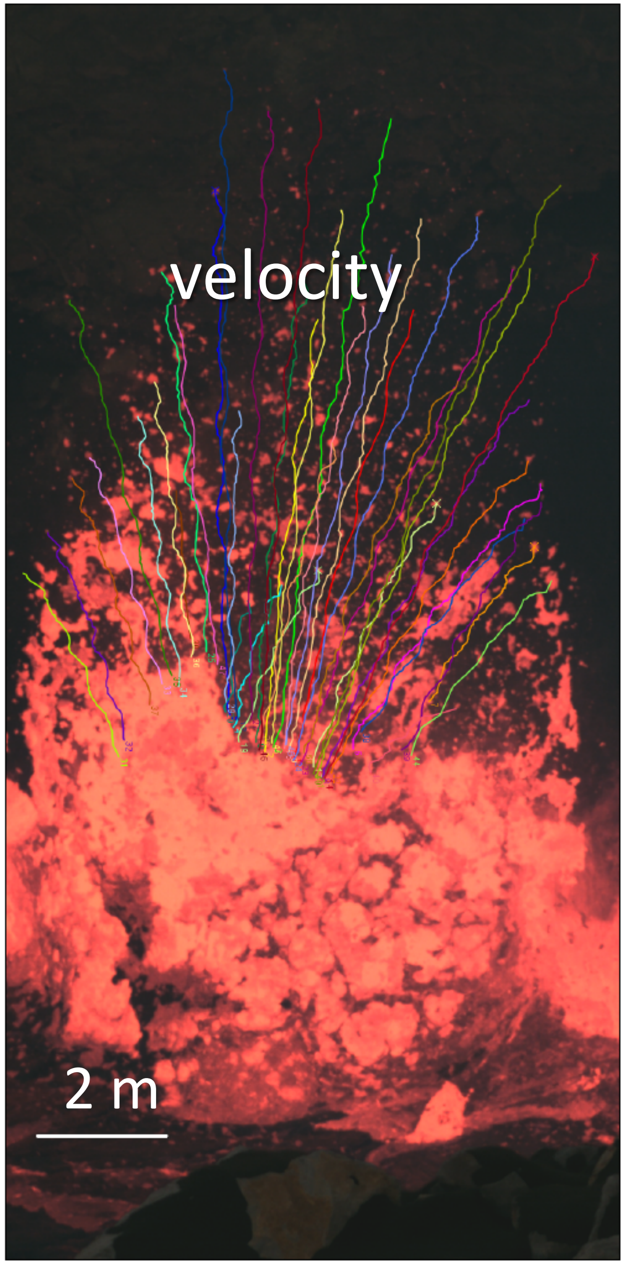


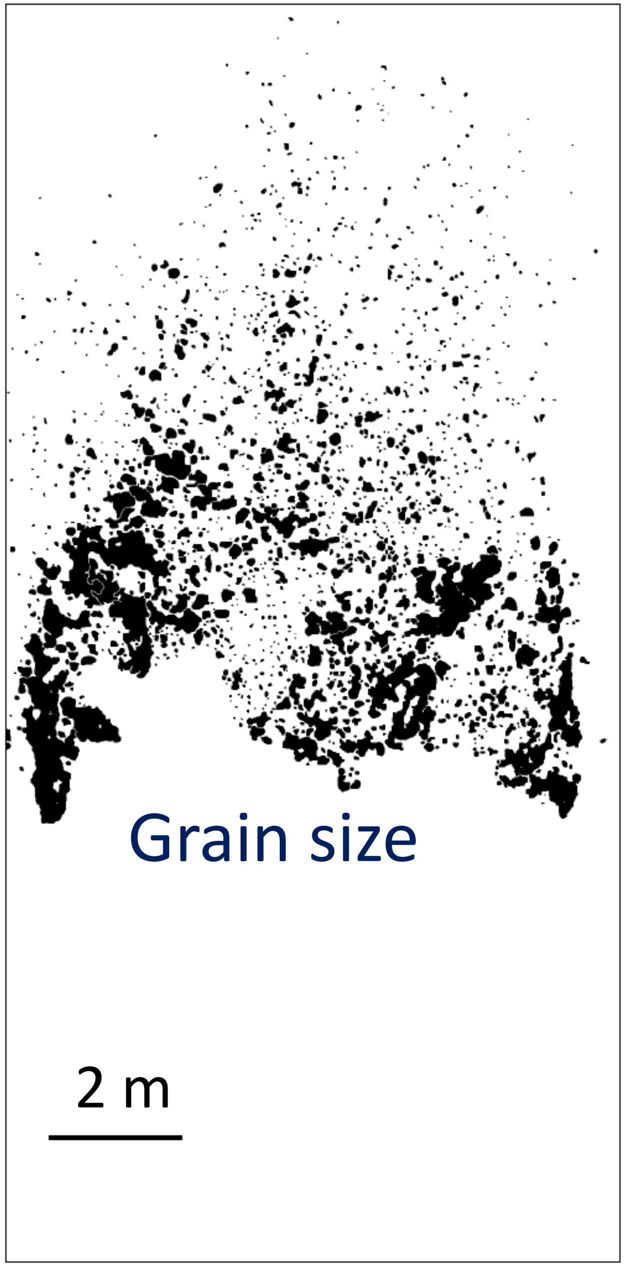
Walker & Houghton submitted to Geology

Pyroclast tracking and manual grain size

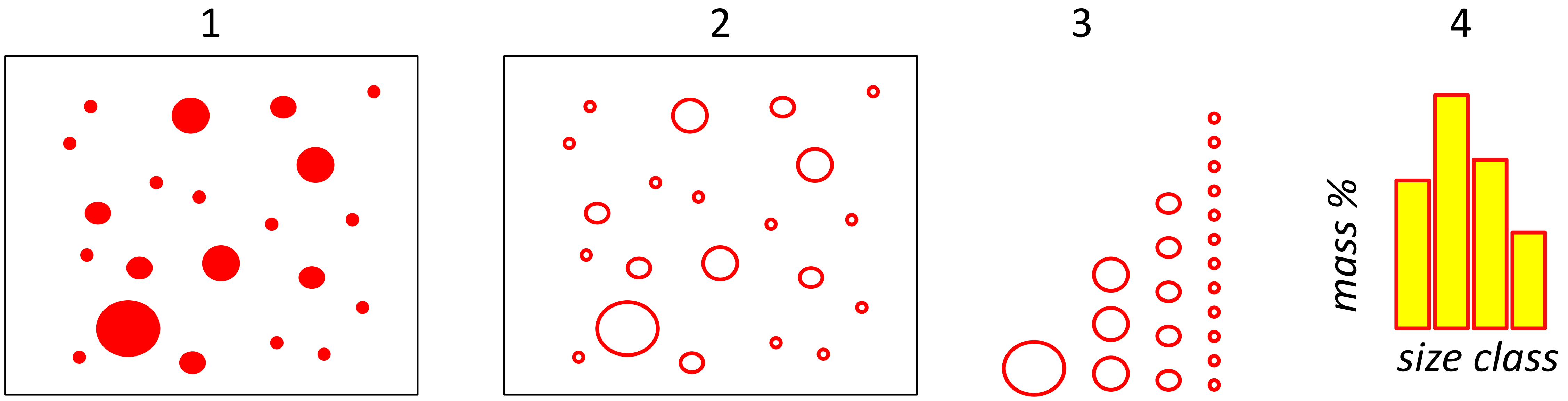




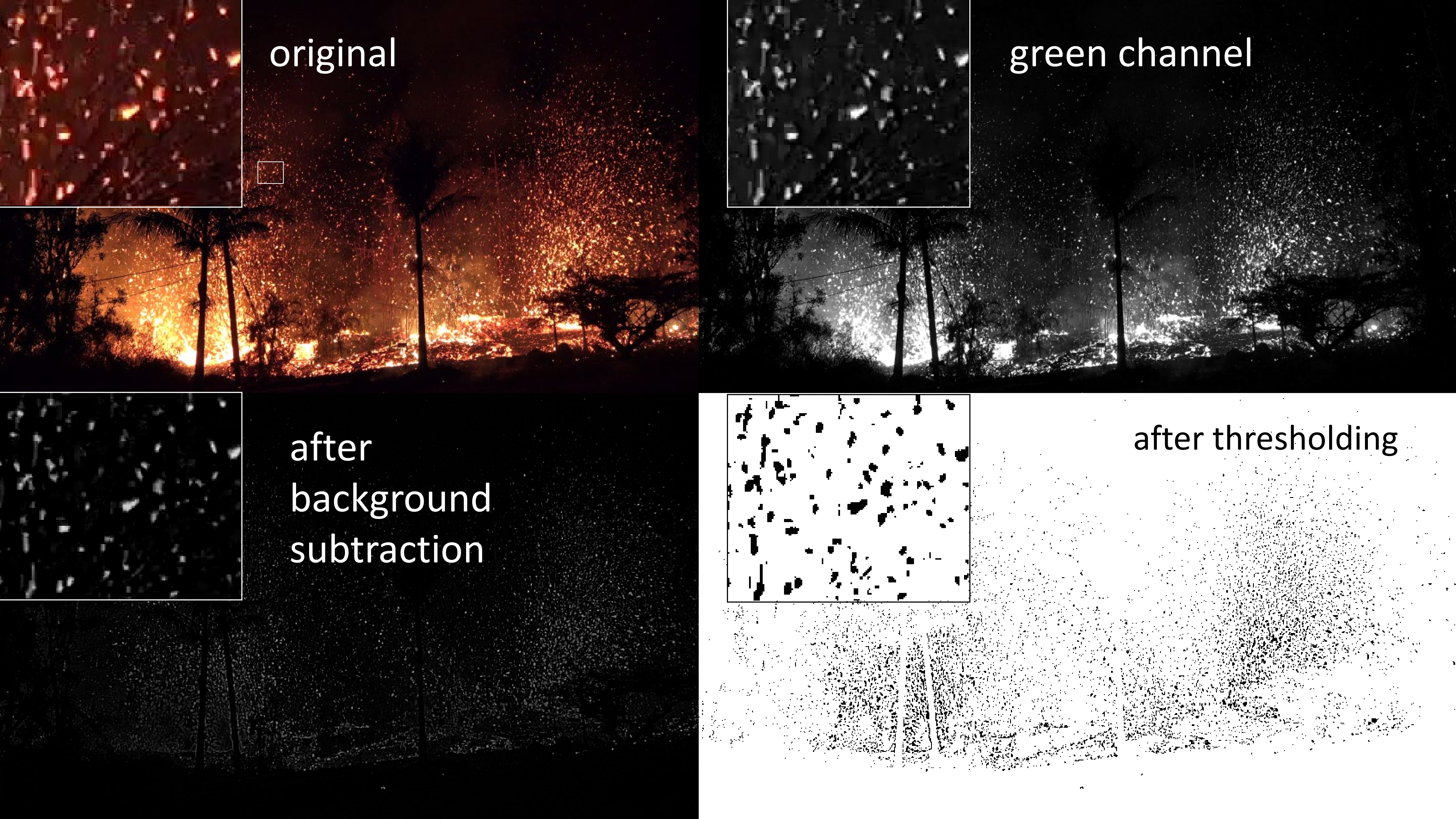


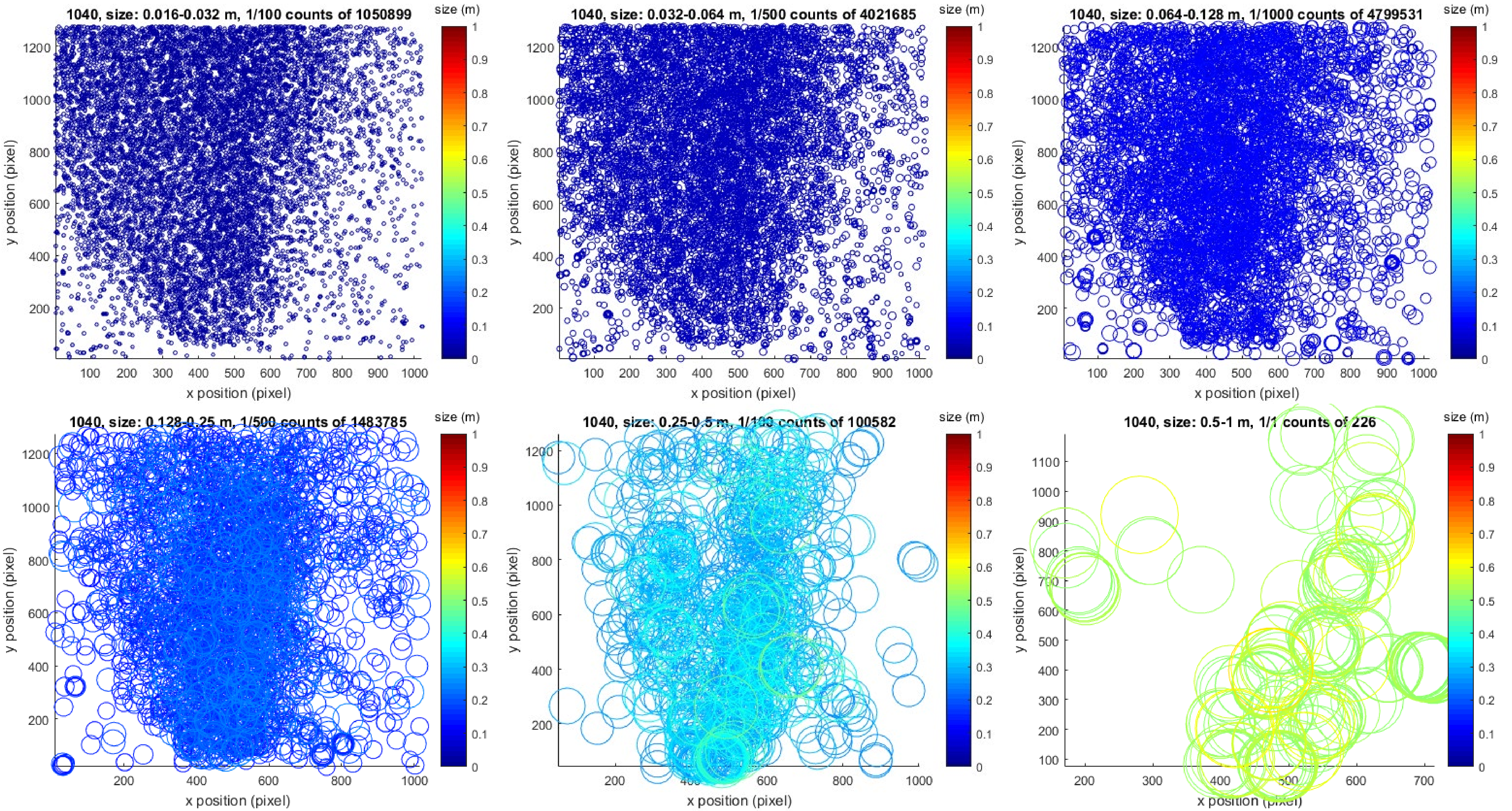


Automated grain size distributions

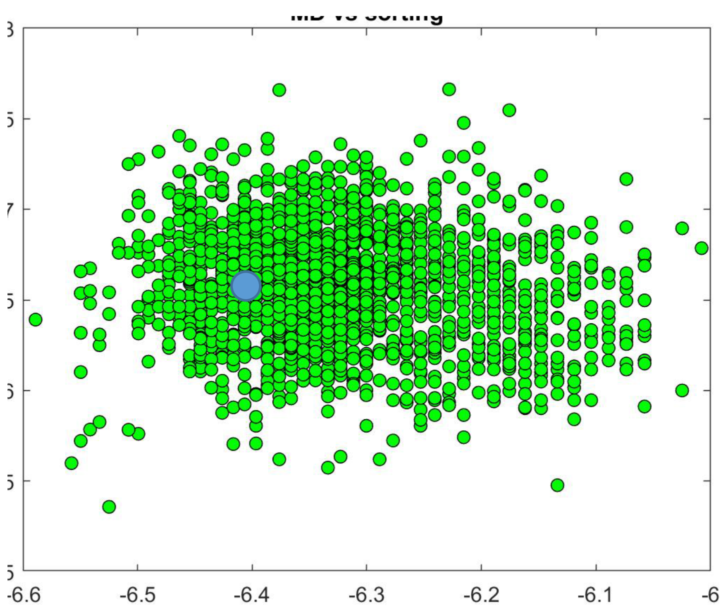


1) **image preprocessing: Matlab** wavelength/background removal
2) **image thresholding: ImageJ** grey scale intensity
3) **particle analysis Matlab/Image J**
4) **data postprocessing Matlab**
5) **data analysis**


original
green channel
after background subtraction
after thresholding

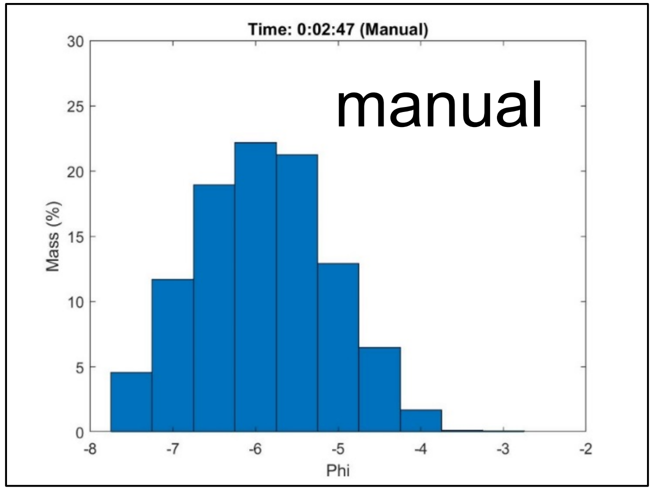

1040, size: 0.016-0.032 m, 1/100 counts of 1050899
1040, size: 0.032-0.064 m, 1/500 counts of 4021685
1040, size: 0.064-0.128 m, 1/1000 counts of 4799531
1040, size: 0.128-0.25 m, 1/500 counts of 1483785
1040, size: 0.25-0.5 m, 1/100 counts of 100582
1040, size: 0.5-1 m, 1/1 counts of 226
size (m)
x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

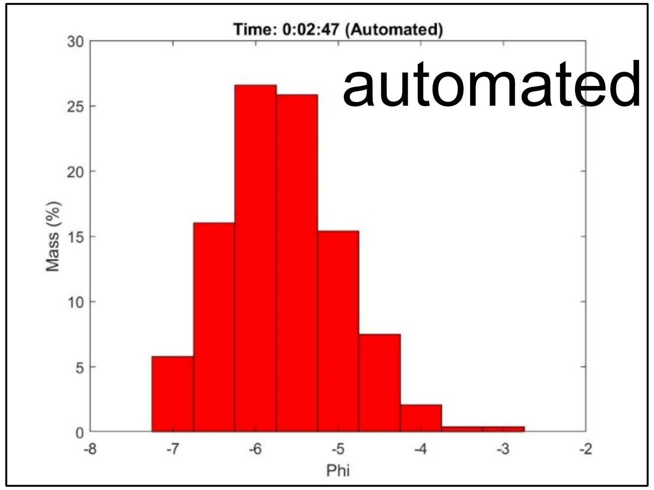
In-flight grain size distribution for a single frame (frame rate 0.033 sec) using two different methods



Side-by-side comparison

Sorting coefficient (phi)

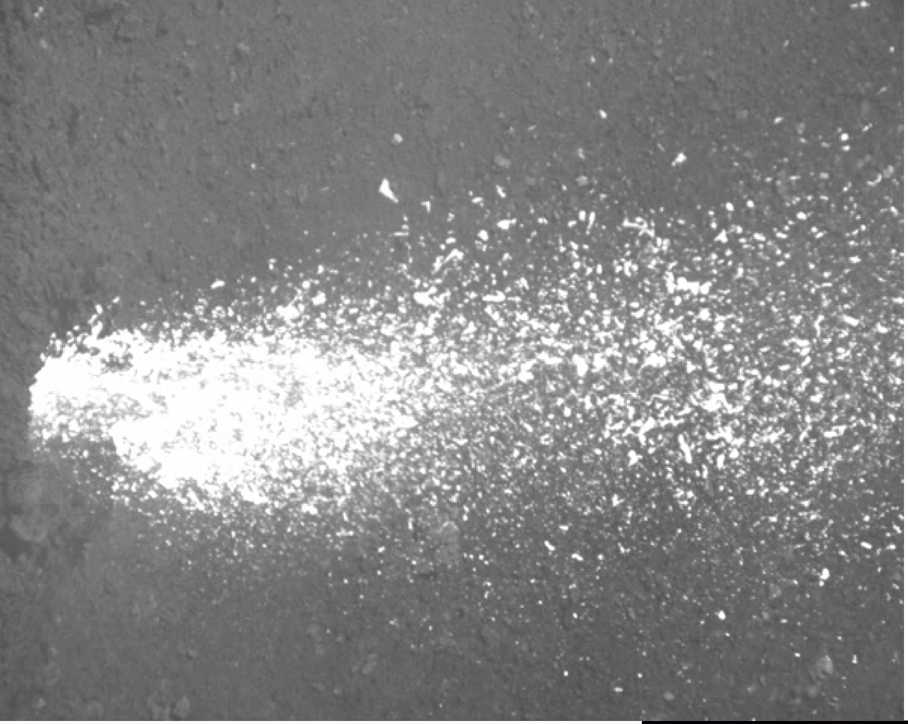




Bin size (phi)

- 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

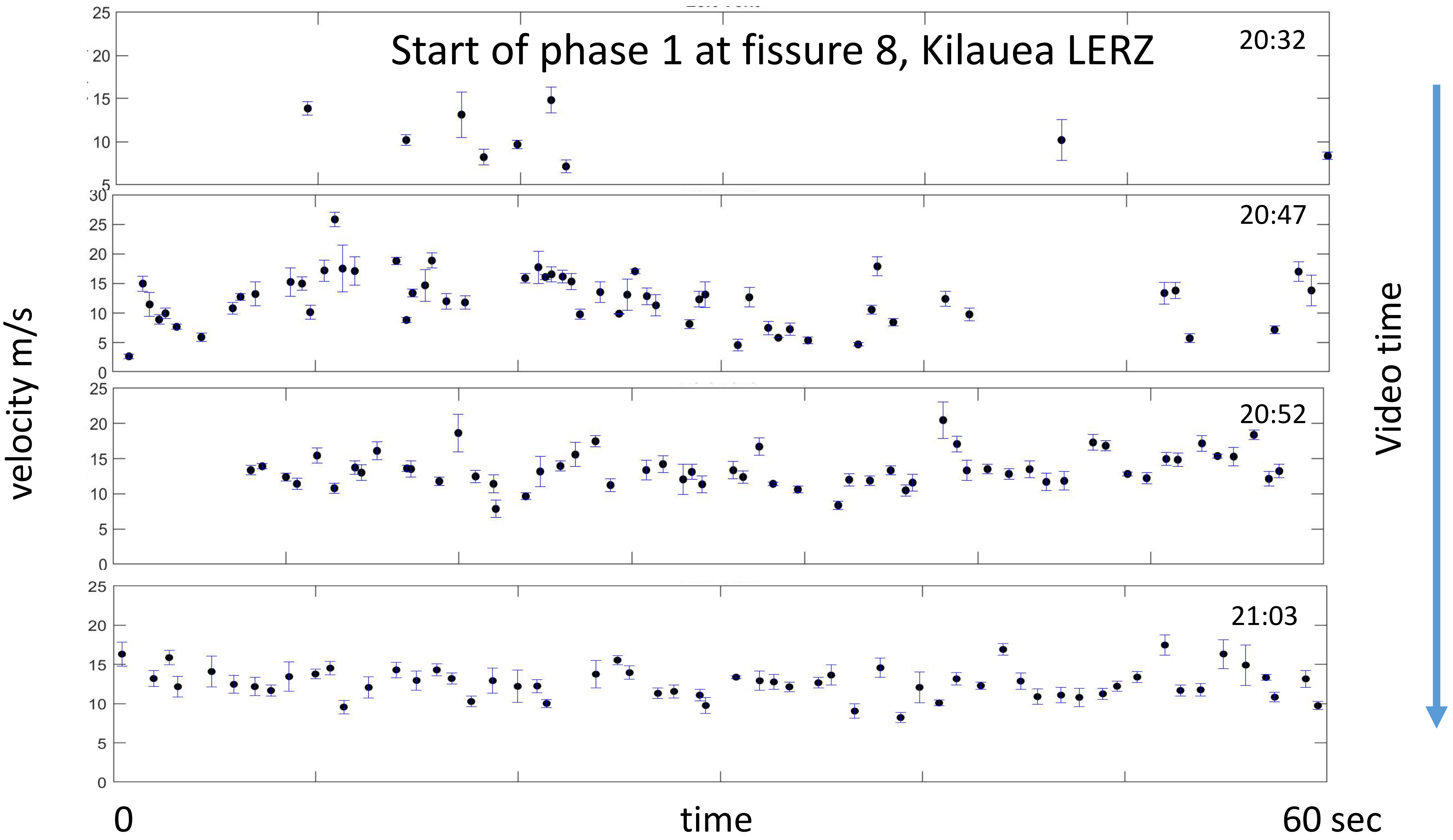
Sony AX100,
3840x2160
30 fps
1 pixel=0.009 m

10 m natural duration: 5 s

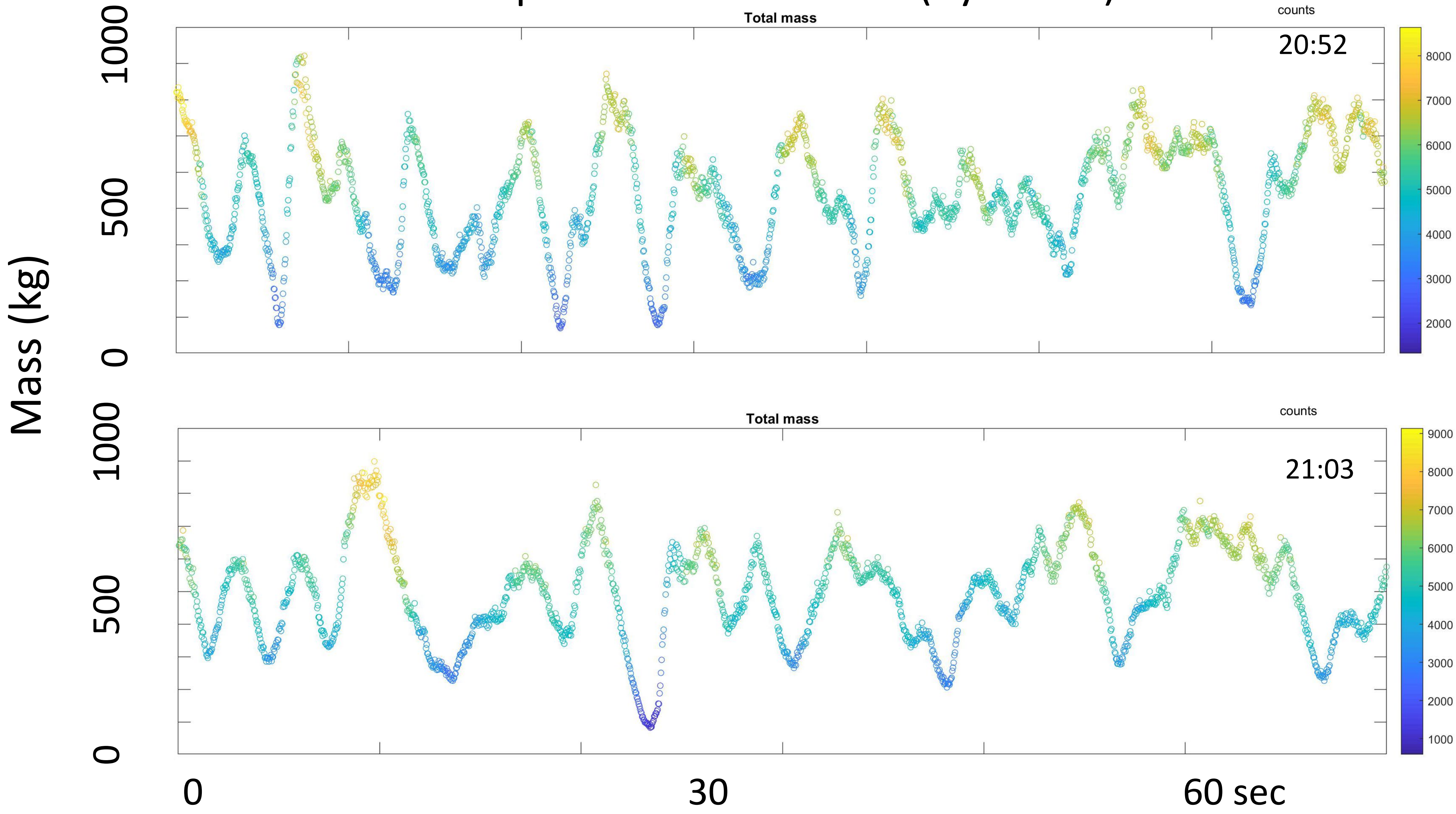
1 m natural duration: 5 s

Etna,
July 2014

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


Start of phase 1 at fissure 8, Kilauea LERZ
20:32
20:47
20:52
21:03
velocity m/s
Video time
0
time
60 sec
25
20
15
10
5
30
0

Erupted mass with time (by frame)

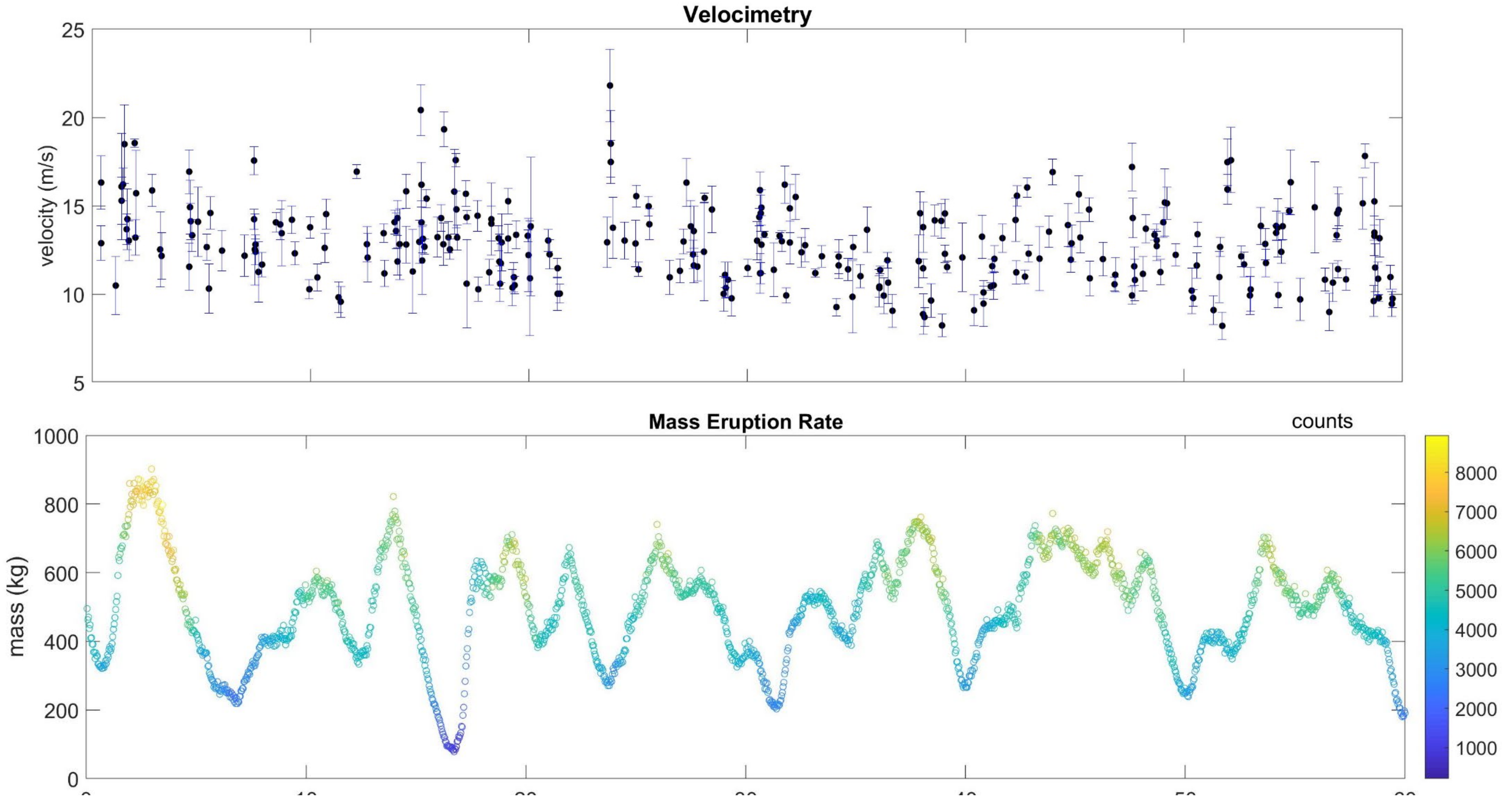


In-flight velocimetry and mass eruption rate measurements over a 60 second clip

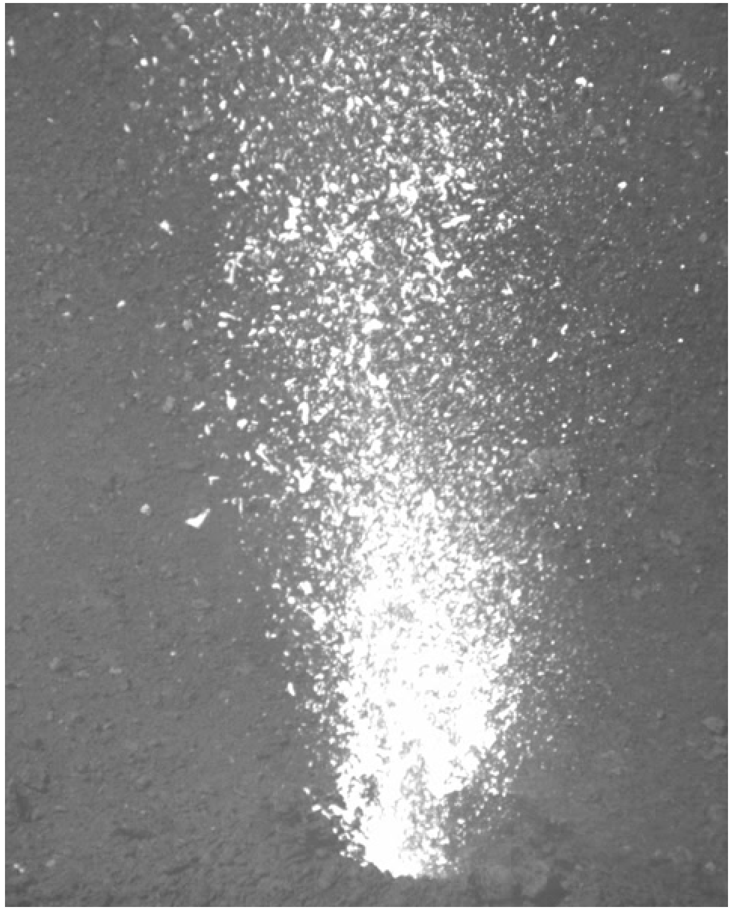
ejection velocity

- processed using ImageJ (MTrackJ)

in-flight mass



0 time 60 sec



2 m natural duration: 0.5 s

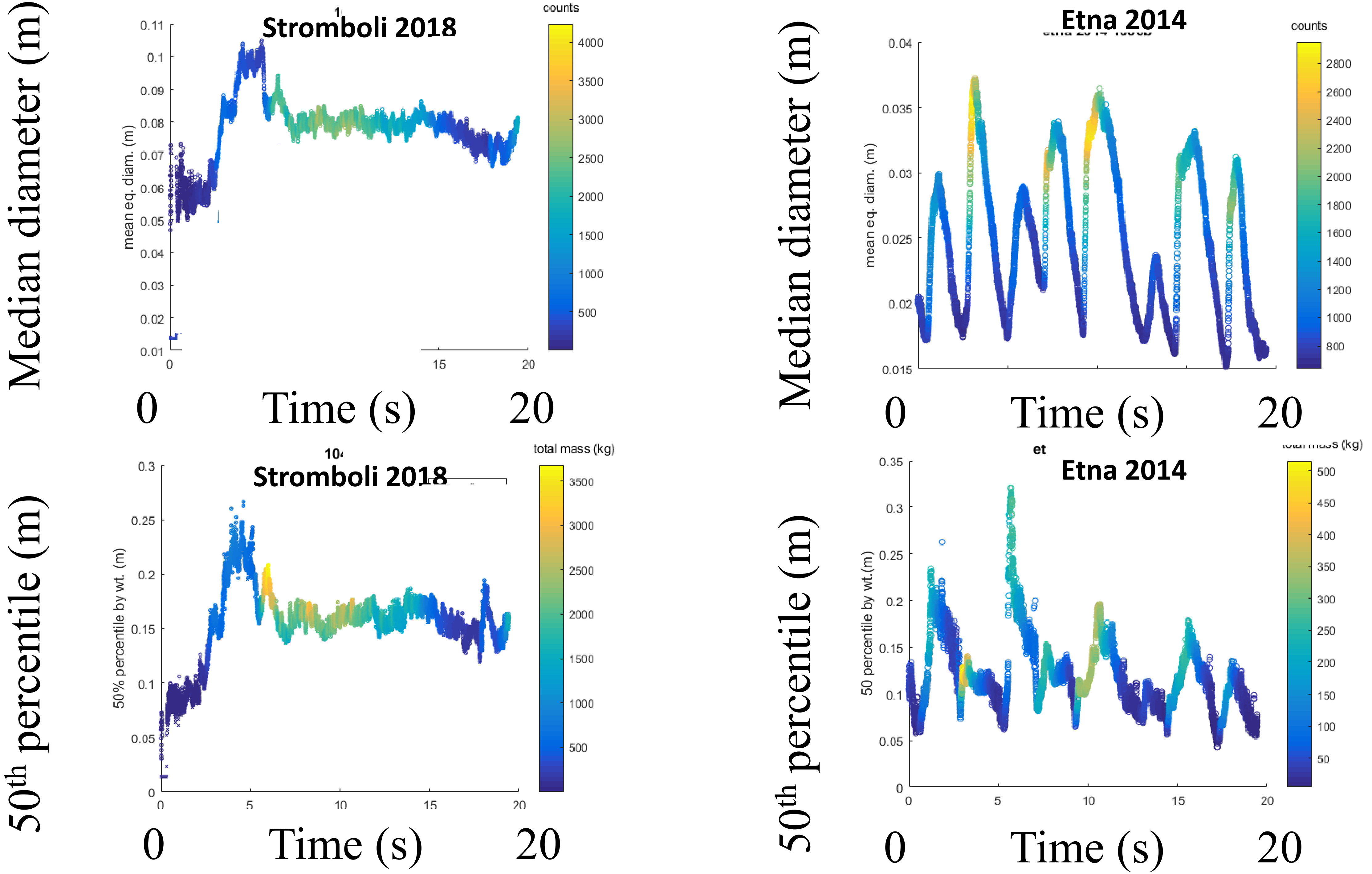
Stromboli,
Sept. 2018

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

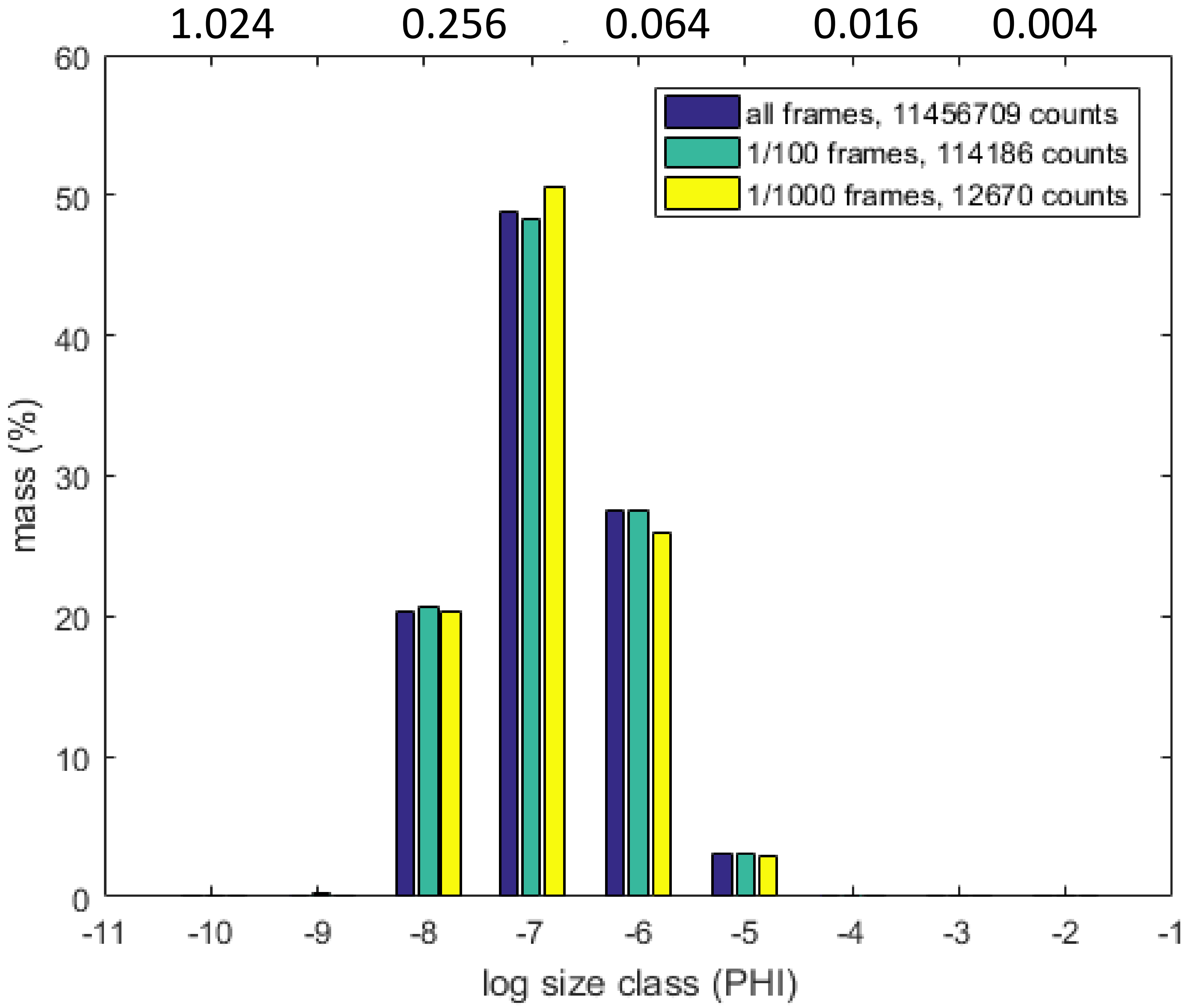
1 m natural duration: 5 s

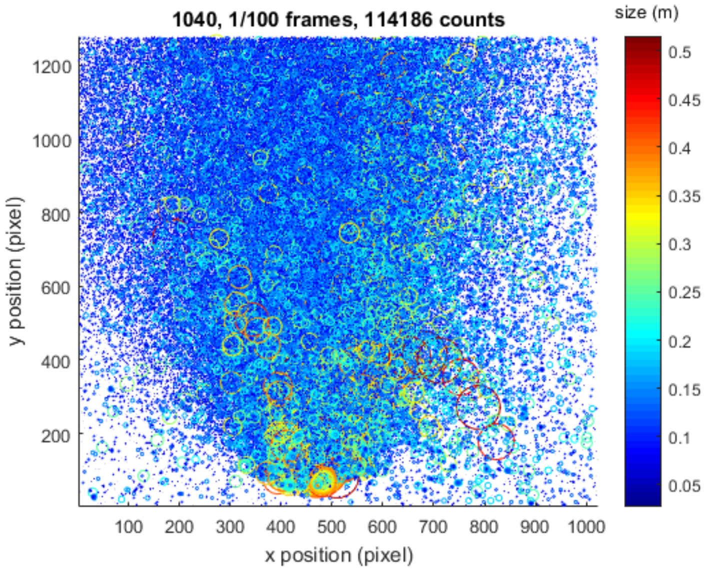
Etna,
July 2014

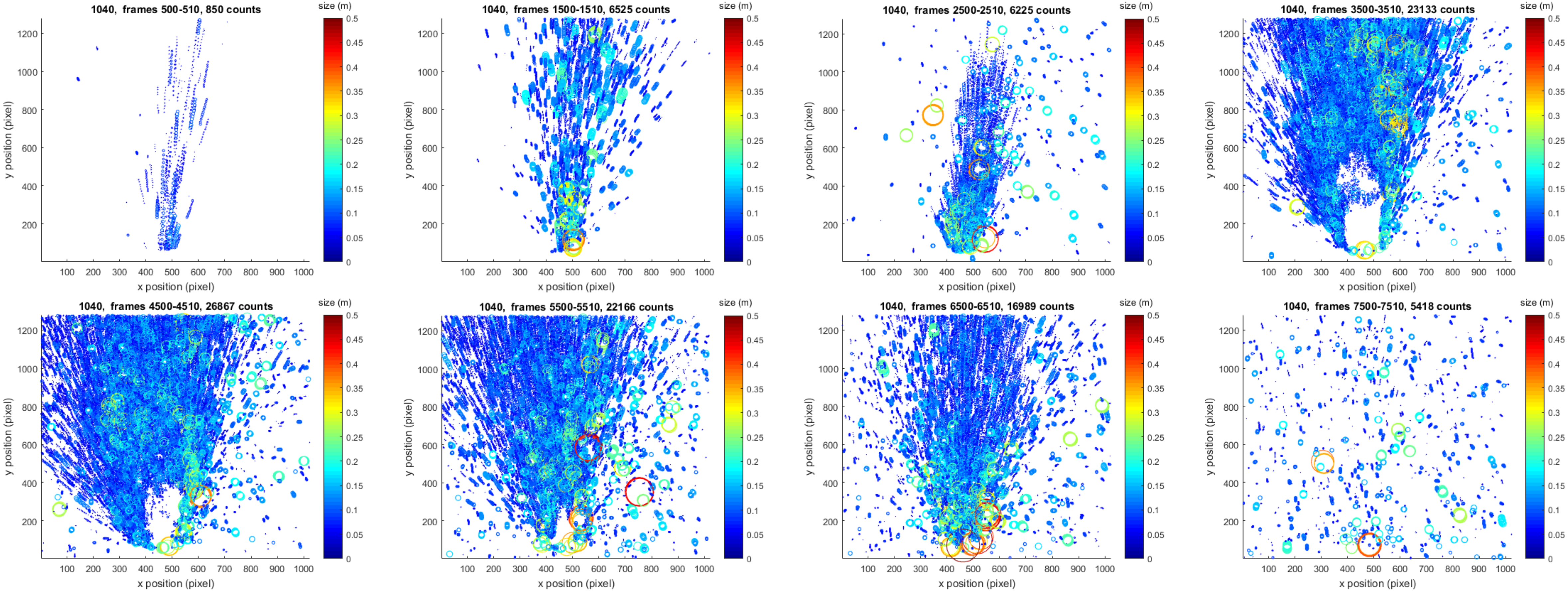
Optronis CR600X2,
1280x1024
500 fps
1 pixel=0.008 m

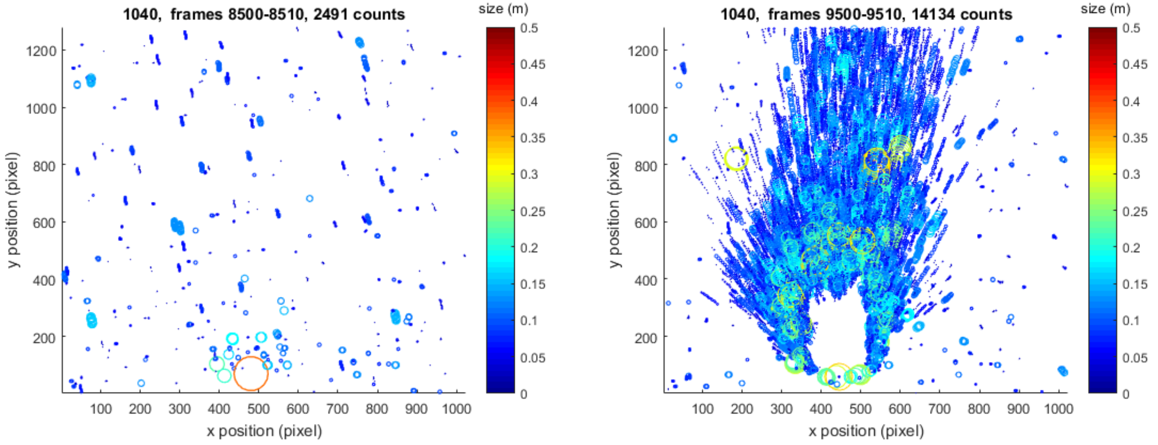


Stromboli 2018
Median diameter (m)
mean eq. diam. (m)
counts
Time (s)
Etna 2014
Median diameter (m)
mean eq. diam. (m)
counts
Time (s)
Stromboli 2018
50th percentile (m)
50% percentile by wt. (m)
total mass (kg)
Time (s)
Etna 2014
50th percentile (m)
50 percentile by wt.(m)
Time (s)

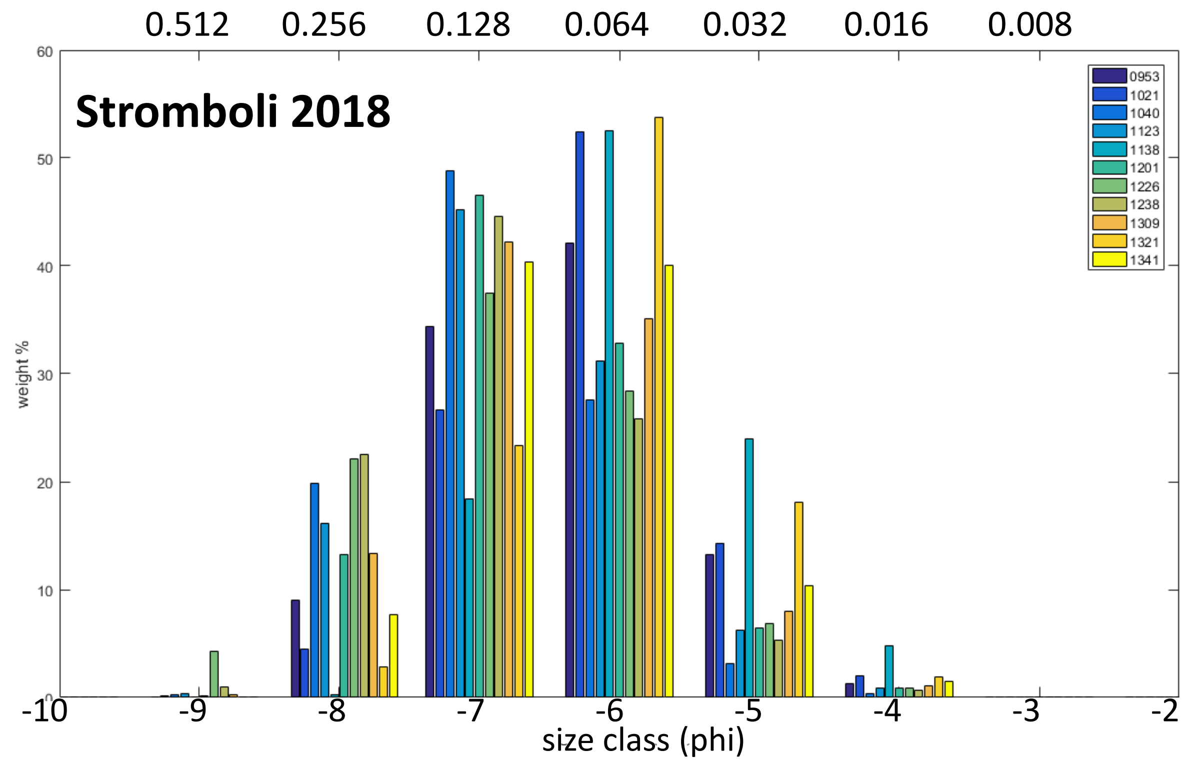

1.024
0.256
0.064
0.016
0.004
all frames, 11456709 counts
1/100 frames, 114186 counts
1/1000 frames, 12670 counts
mass (%)
log size class (PHI)

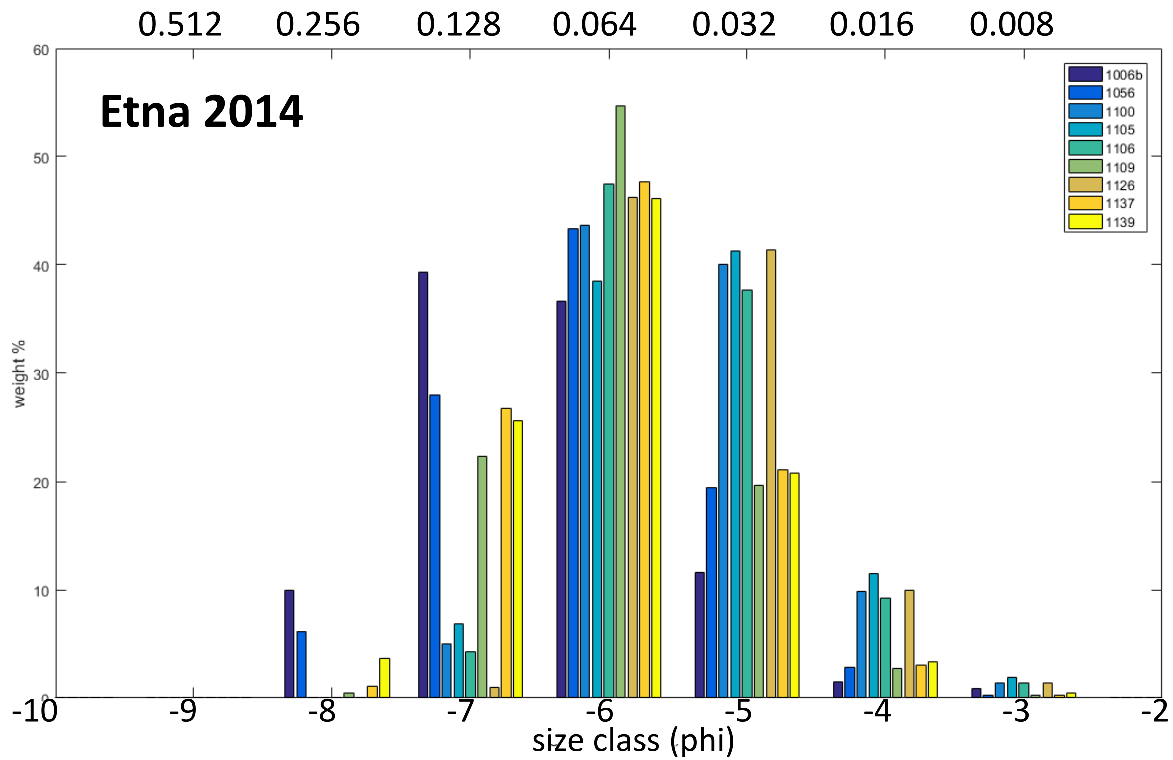

1040, 1/100 frames, 114186 counts
size (m)
y position (pixel)
x position (pixel)





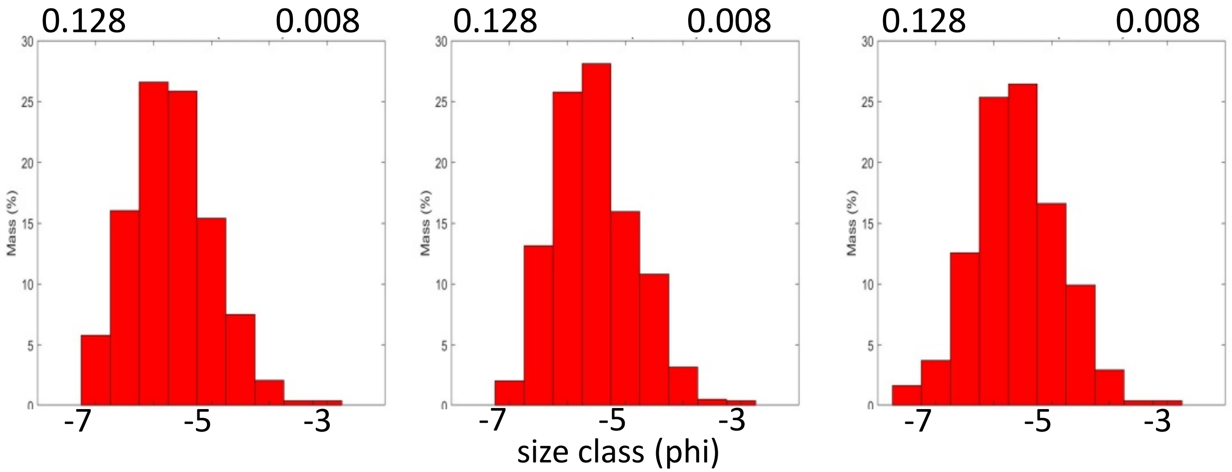
20 second-long clip: 10 frames sampled every 1000 frames (2 sec)

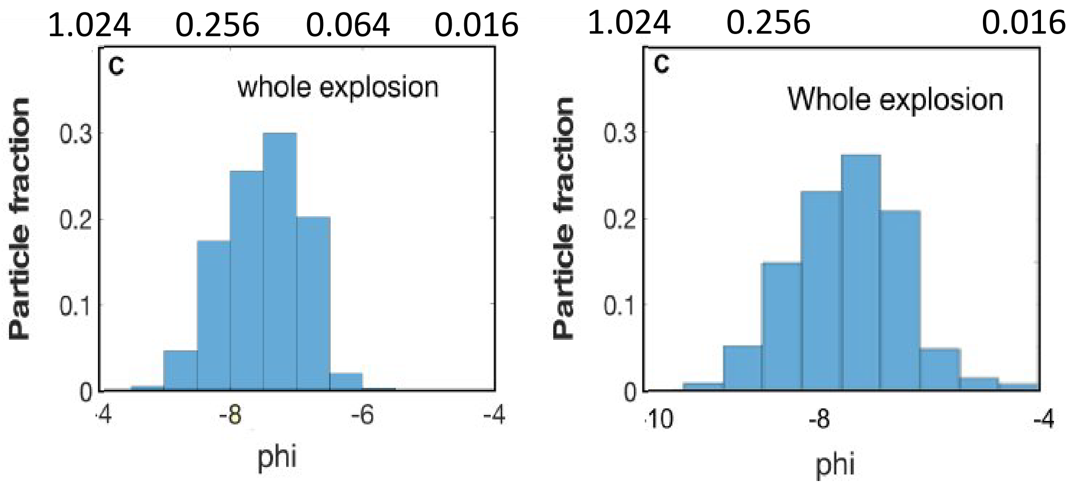




Kilauea 2018

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





Some caveats

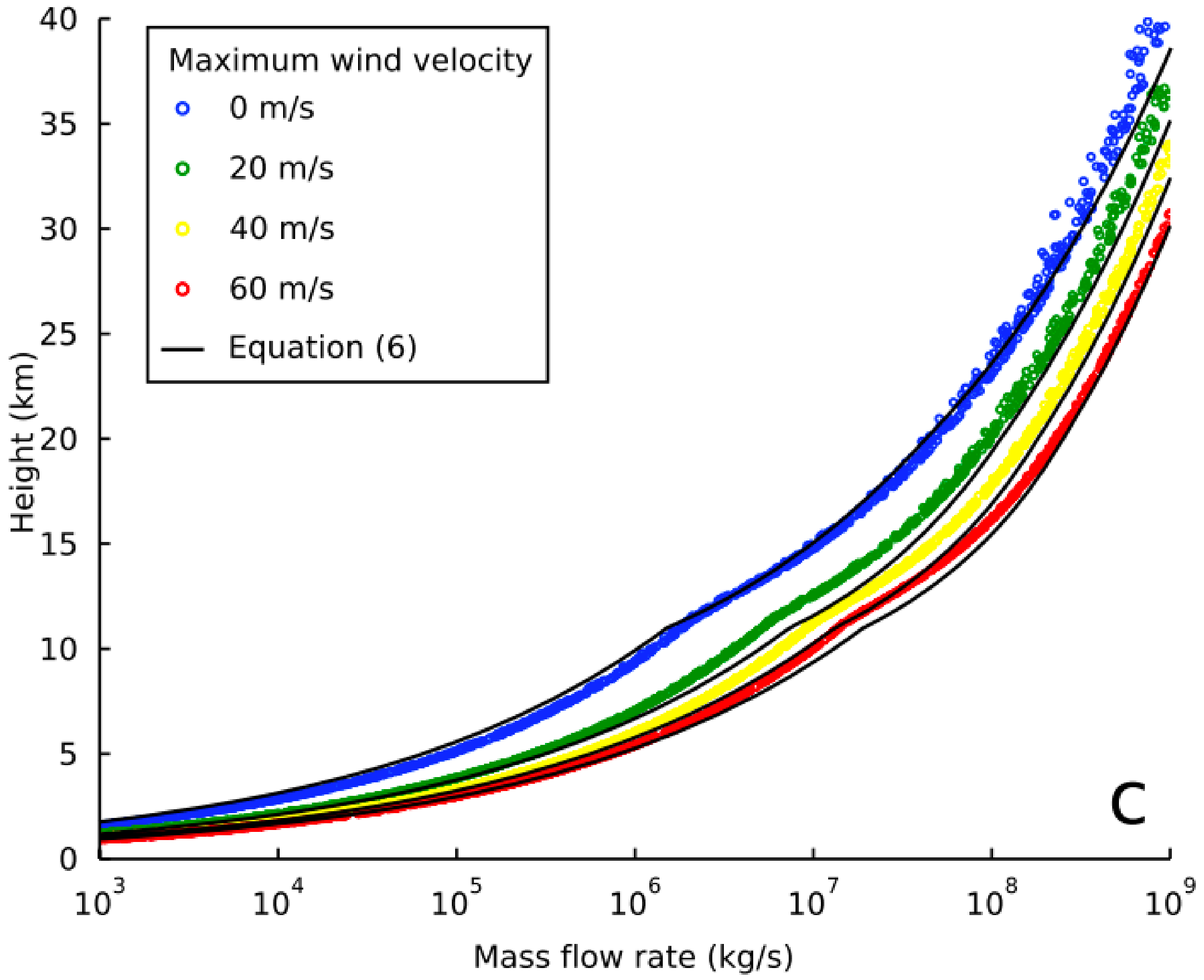
- Currently (generally) limited to small/ weak eruptions
- Issues with thermally or optically opaque fountains/plumes

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

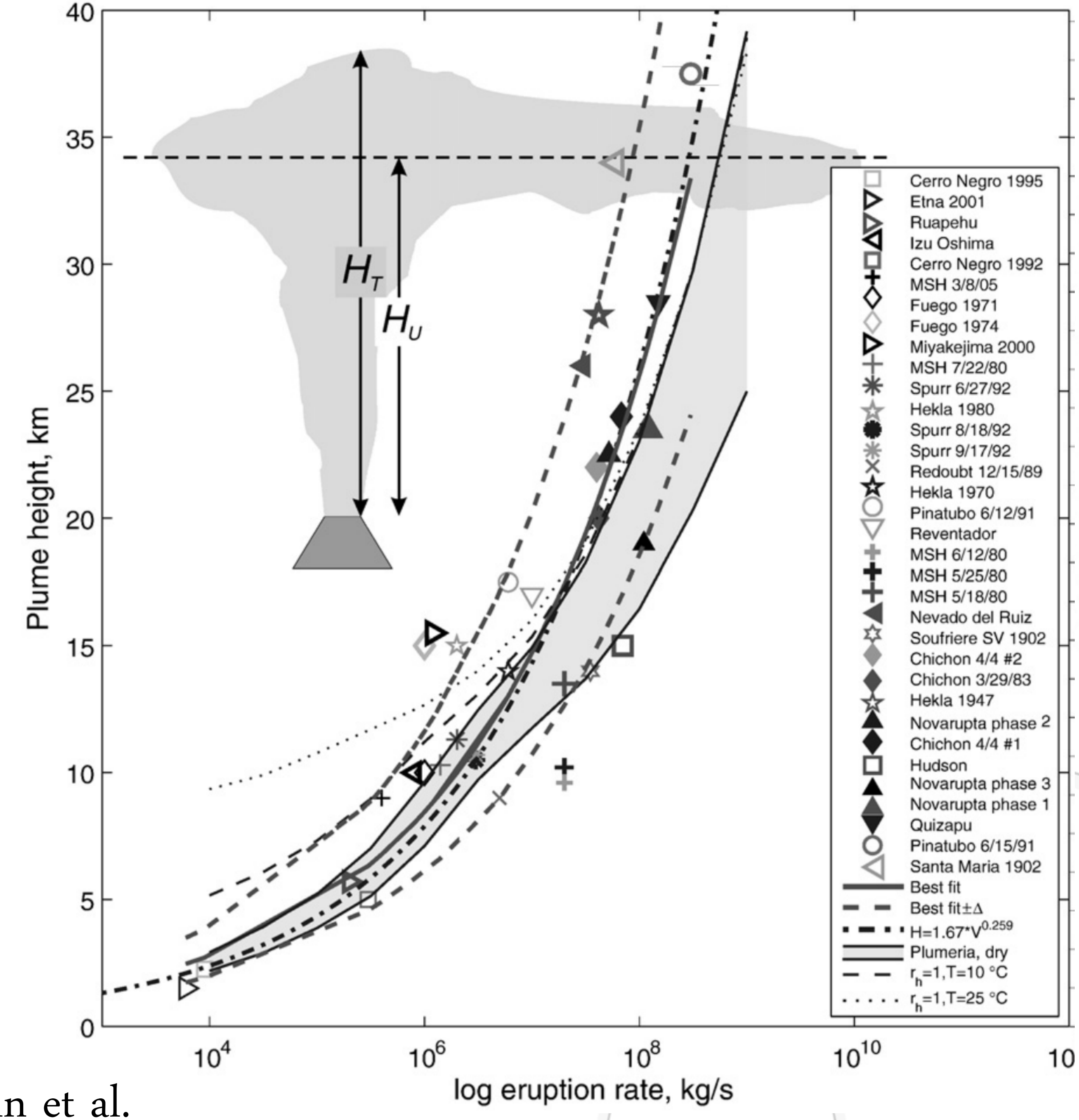
1. Plume theory predicts that the **mass eruption rate** (MER; kg s^{-1}) is related to the 4^{th} power of the plume height

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

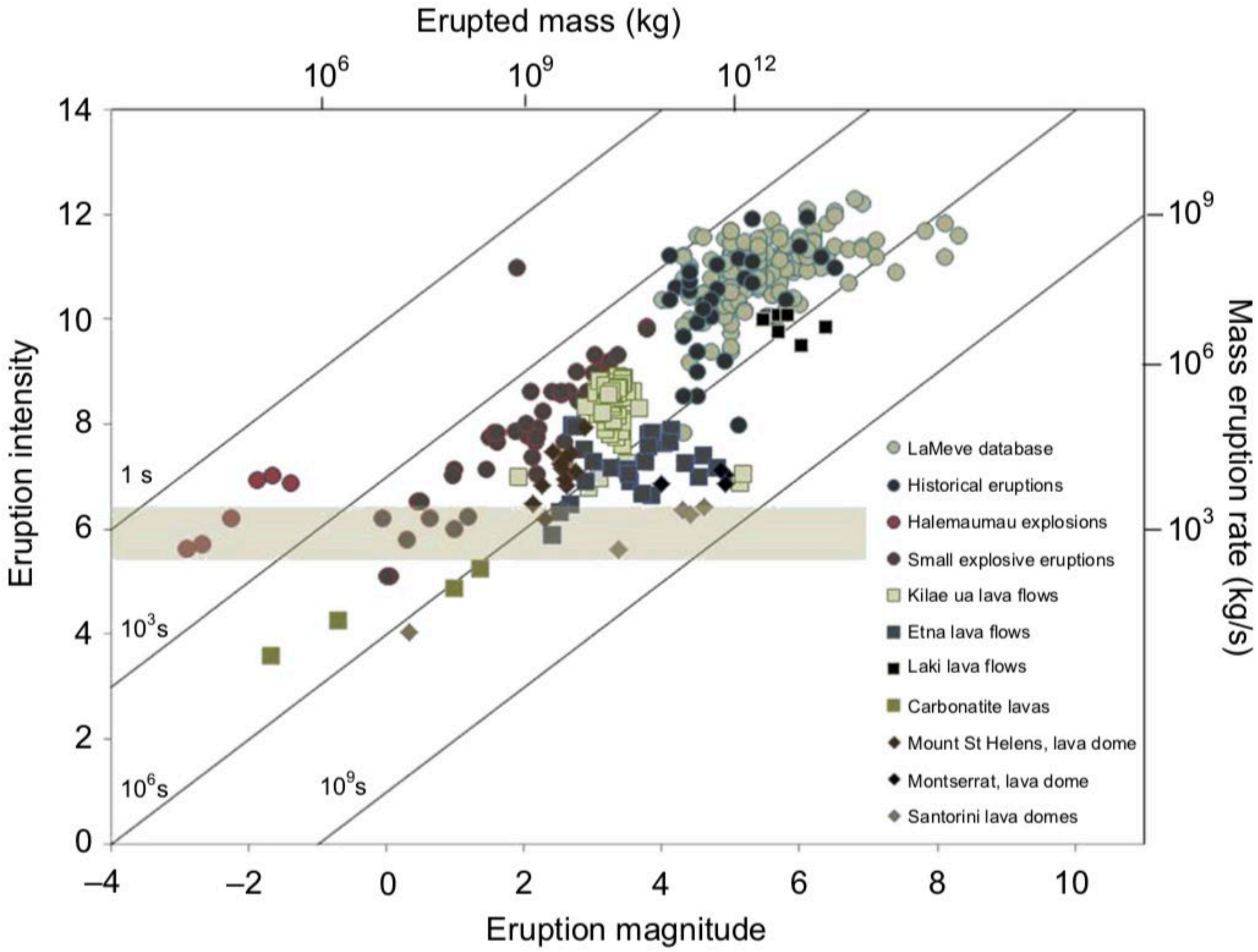


Mastin et al.

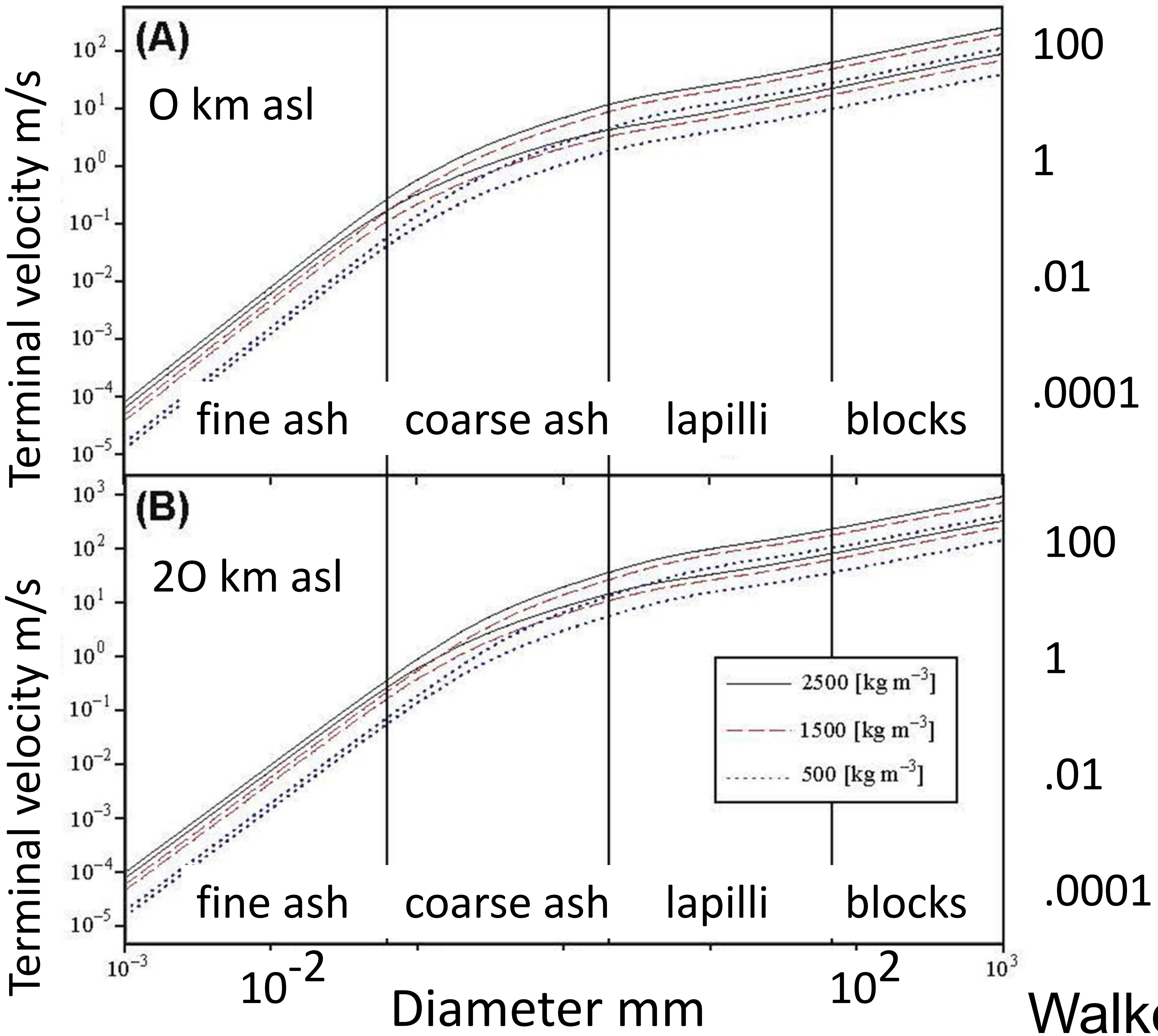
Plume height & flux

- MER → **Intensity**

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



Sedimentation from volcanic plumes



Walker et al. 1971