What if the **power-law** model did not apply for the prediction of **very large rockfall** events?

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Large landslides / rockfalls

= extreme → **appears rarely**

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Power-law model – definition

N number of events (landslides) with size ≥ v (volume, area, etc.)

$$\boxed{N \propto v^{-\theta}, v > v_{\min}}$$

θ decay exponent = measure of « tail heaviness »

« the higher θ, the lower Prob(V>v) »

Power-law model – definition

N number of events (landslides) with size ≥ v (volume, area, etc.)

$$\boxed{N \propto v^{-\theta}, v > v_{\min}}$$

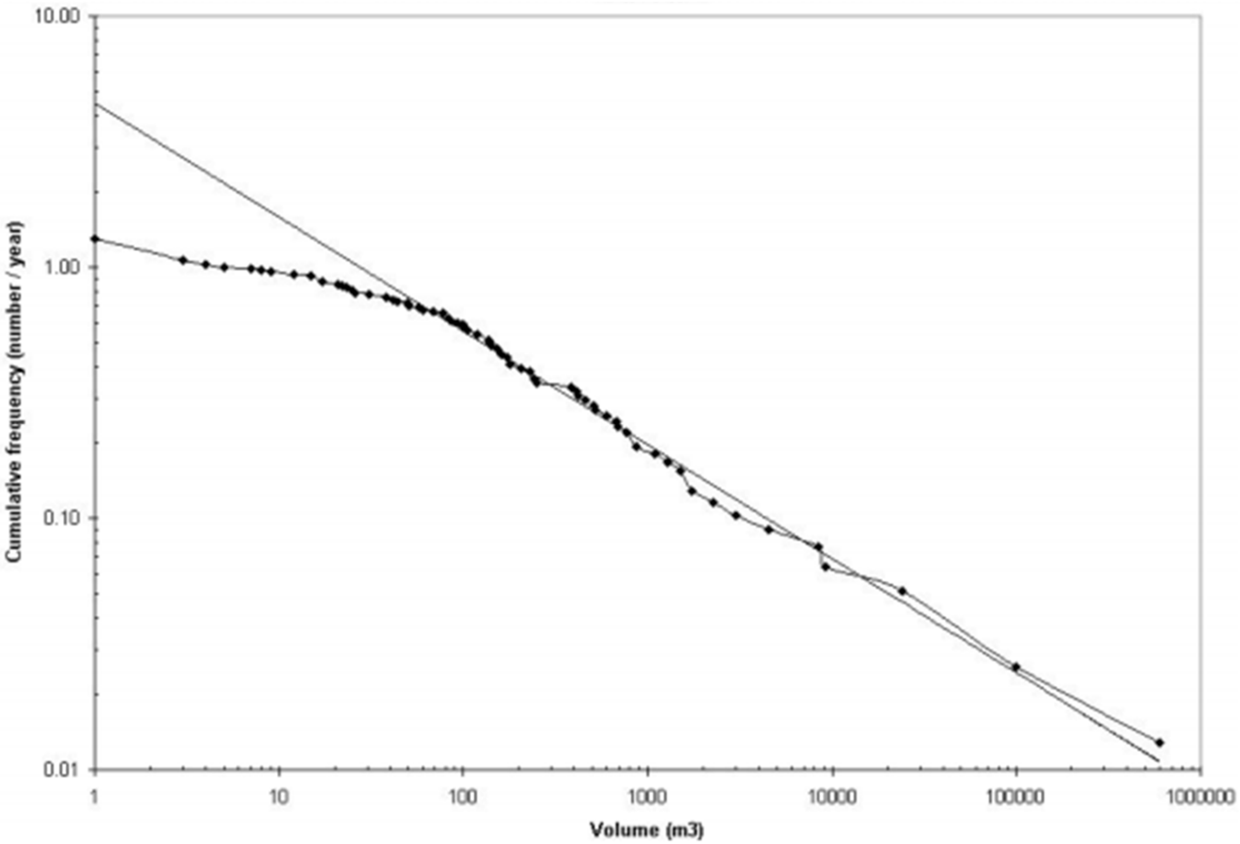
n number of events with size = v

$$\boxed{n \propto v^{-(\theta+1)}, v > v_{\min}}$$

θ decay exponent = measure of « tail heaviness »
« the higher θ, the lower Prob(V>v) »

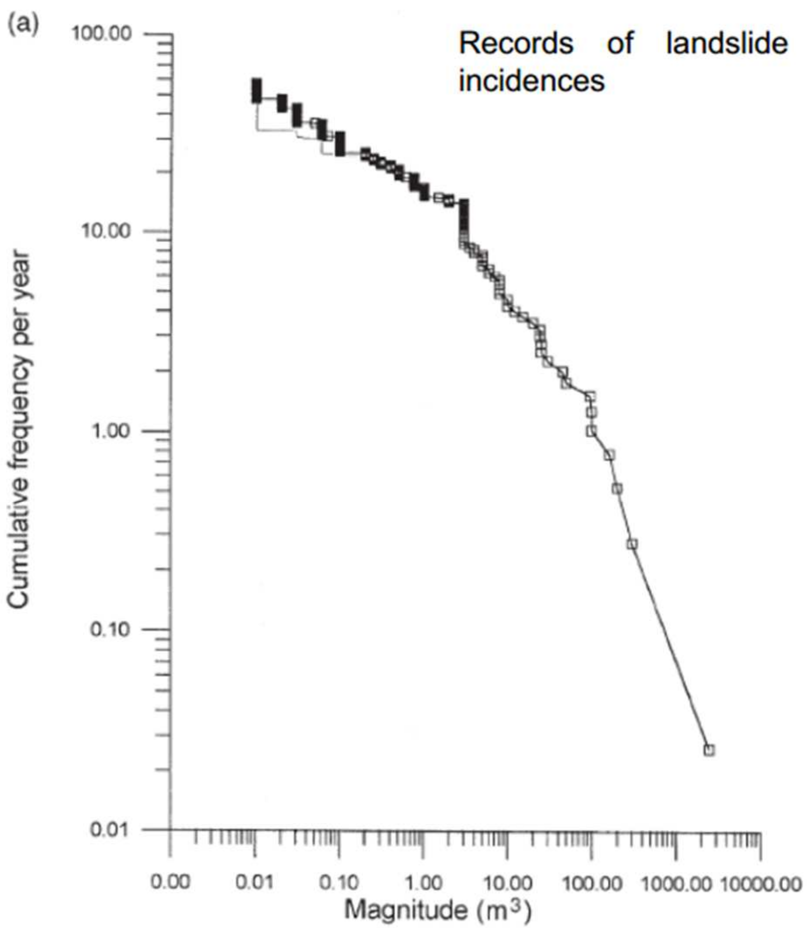
Power-law model for rockfalls

$$\log(N) = -\theta \cdot \log(v) + Cste \,, v > v_{\min}$$



Dussauge-Peisser et al., NHESS, 2002

Power-law model for rockfalls



Hungr et al., 1999

Power-law model for rockfalls

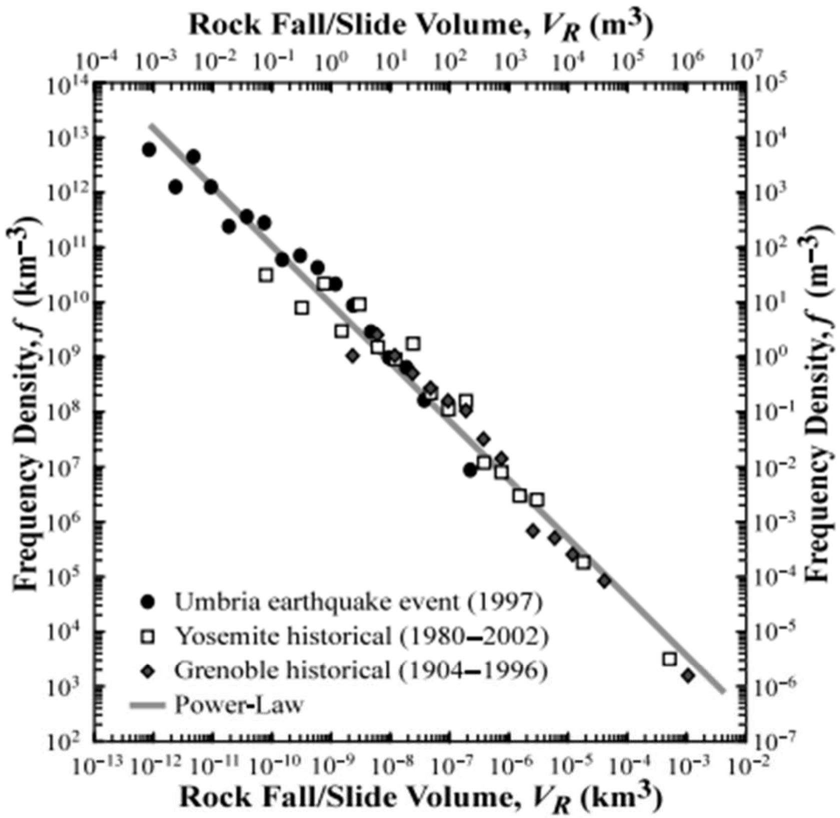


Figure 7. Dependence of the frequency density f on volume V_R for rockfall and rock-slide inventories, both on logarithmic axes. Three inventories are given: 157 rockfalls/slides triggered by the Umbria–Marche earthquakes of September and October, 1997 (closed circles); 135 rockfalls/slides in the Yosemite region, California, USA, for the period 1980–2002 (open squares) (Wieczorek *et al.*, 1998); 89 historical rock falls in the Grenoble region of France, for the period 1904–1996 (closed diamonds) (RTM, 1997). The straight line is the power-law correlation given by $\log f = -1{\cdot}07 \log V_R + 0{\cdot}37$.

Malamud et al., ESPL, 2004

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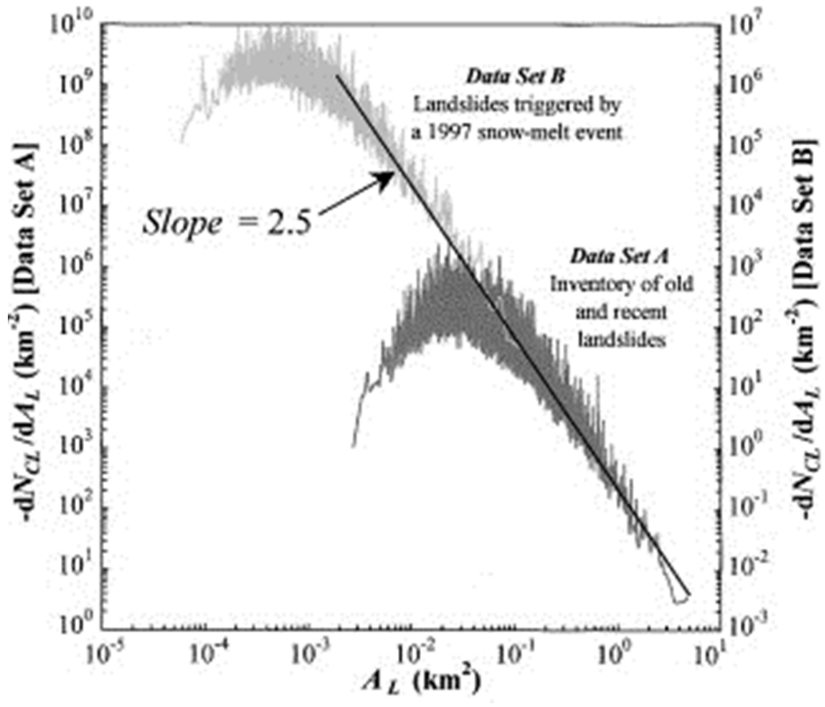
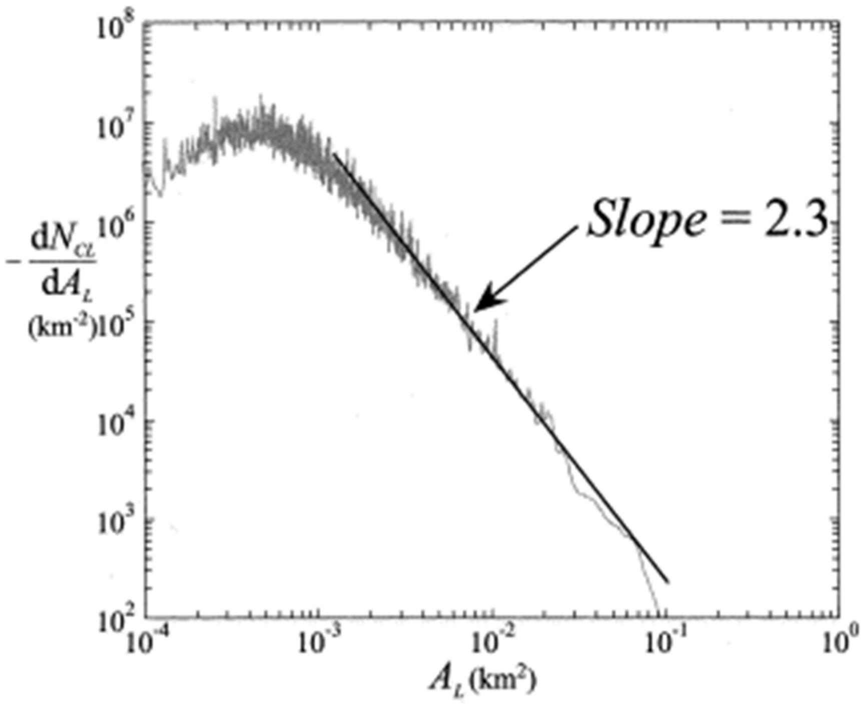
Power-law model for landslides





Guzzetti et al., EPSL, 2002

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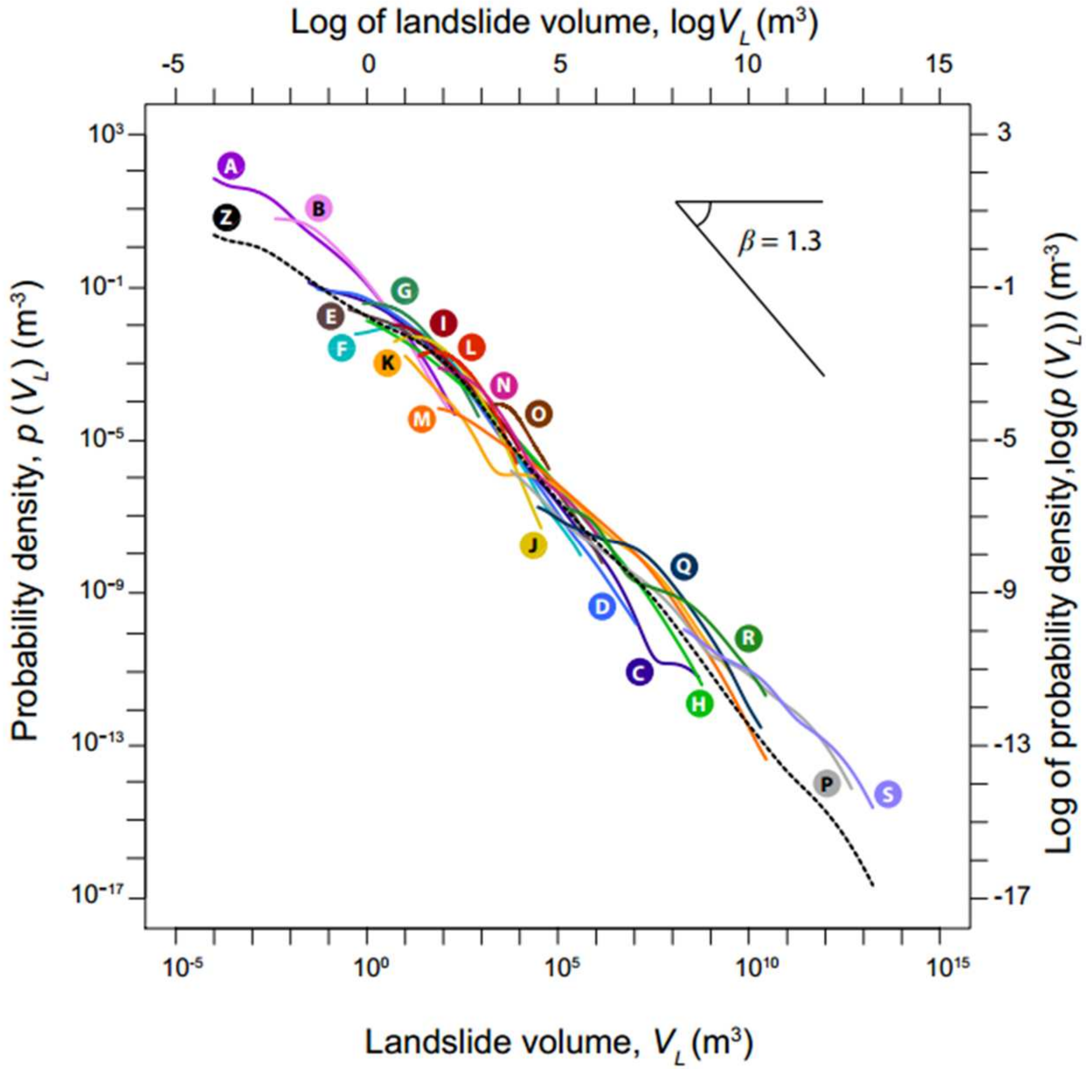
Power-law model for landslides



Brunetti et al., NPG, 2009

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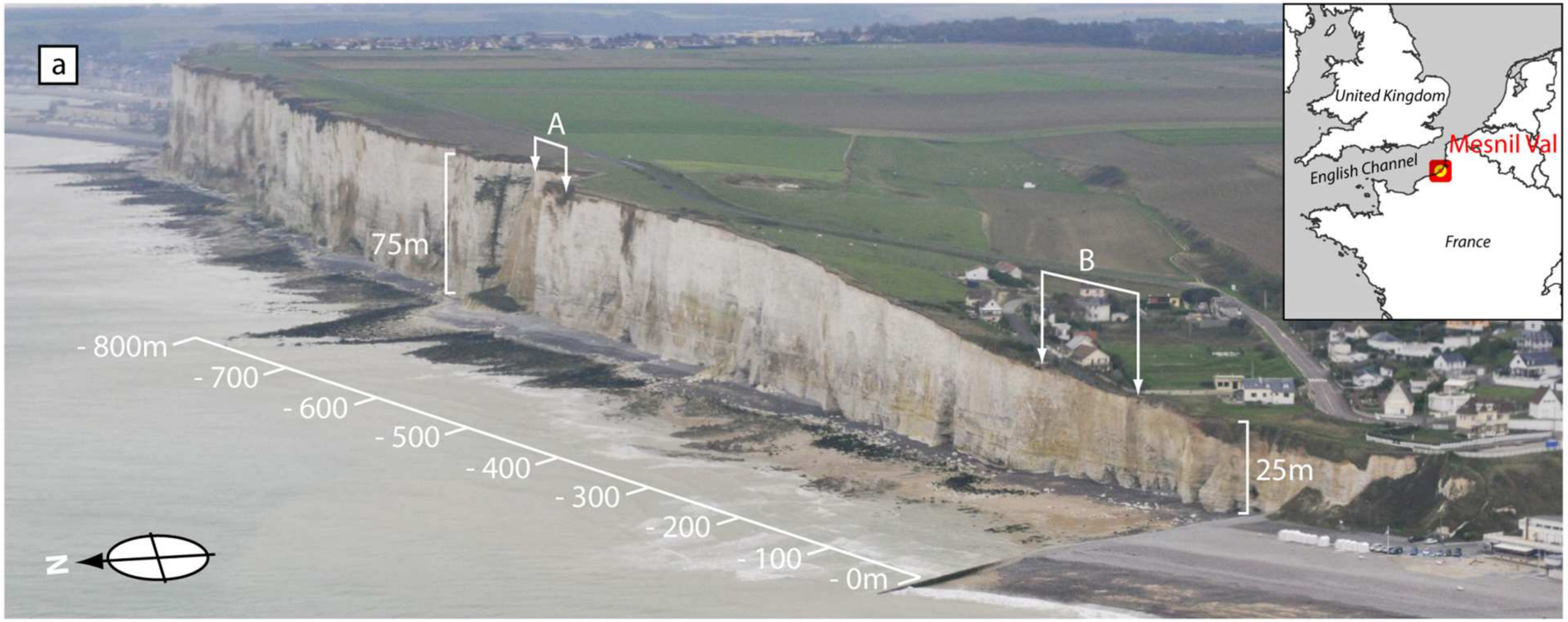
Coastal chalk cliff of Mesnil-Val, France



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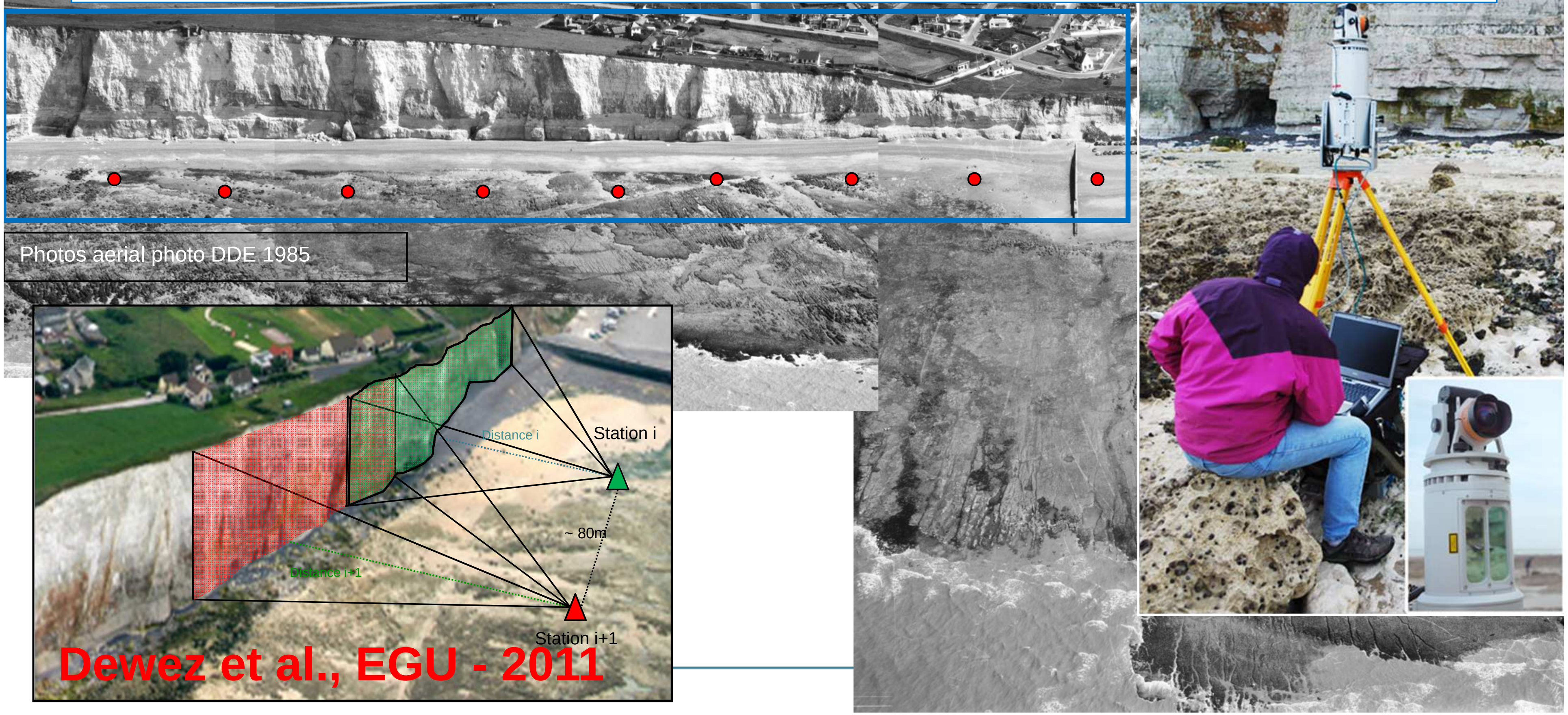
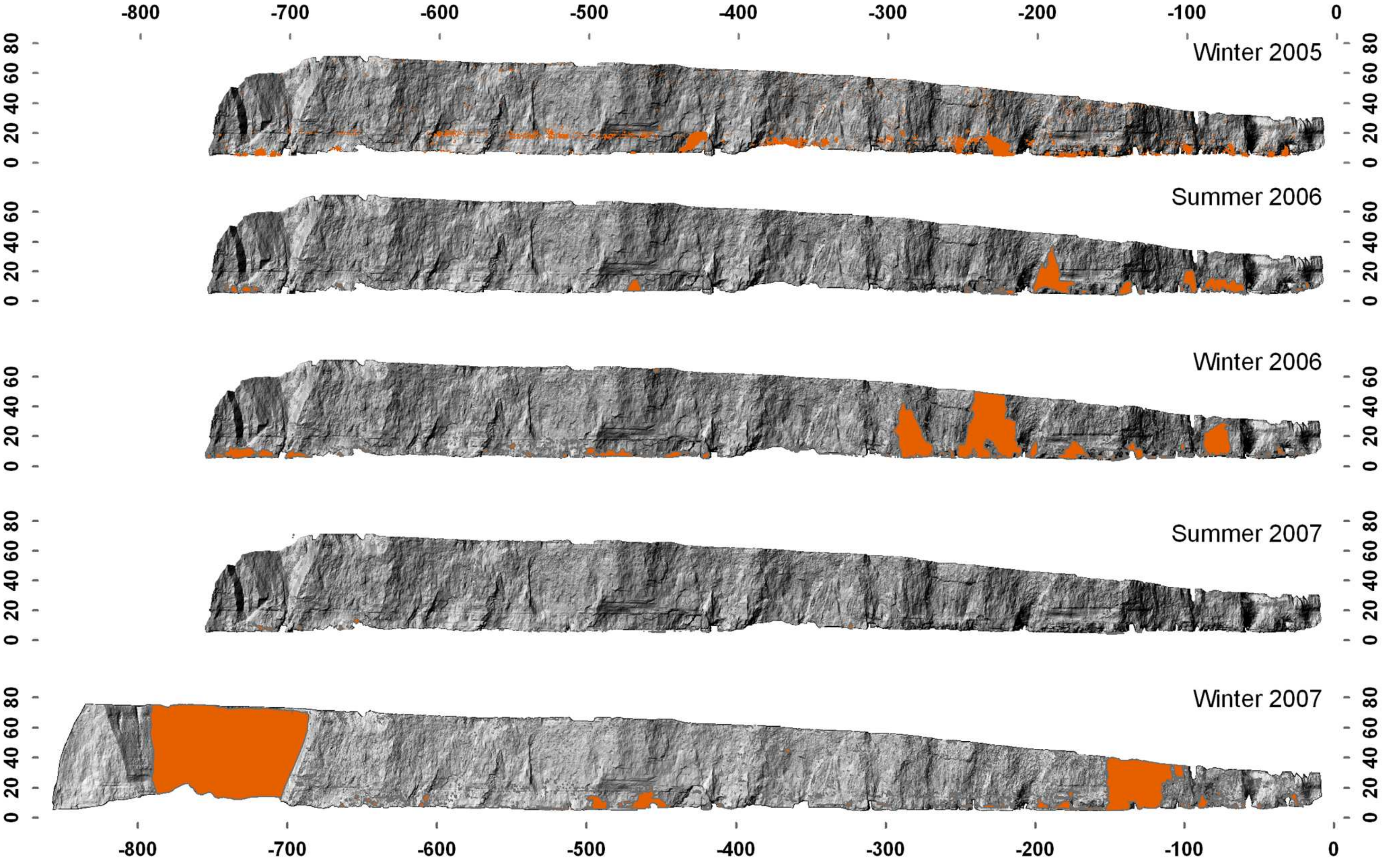
Terrestrial Laser Scanning surveys

- **6 epochs of measurement** at equinoxes from December 2005
  - December 2005, March 2006, August 2006, March 2007, September 2007, April 2008, (+March 2009 – helicopter-borne lidar)
- 8 scanning stations (re-occupied to within +/-1m)
- Scanning resolution (0.05° x 0.05°) – Digital Surface Mo dels 5x5cm
- Each scan contains ca. 11 million points (pt precision 2σ<1.5 cm)

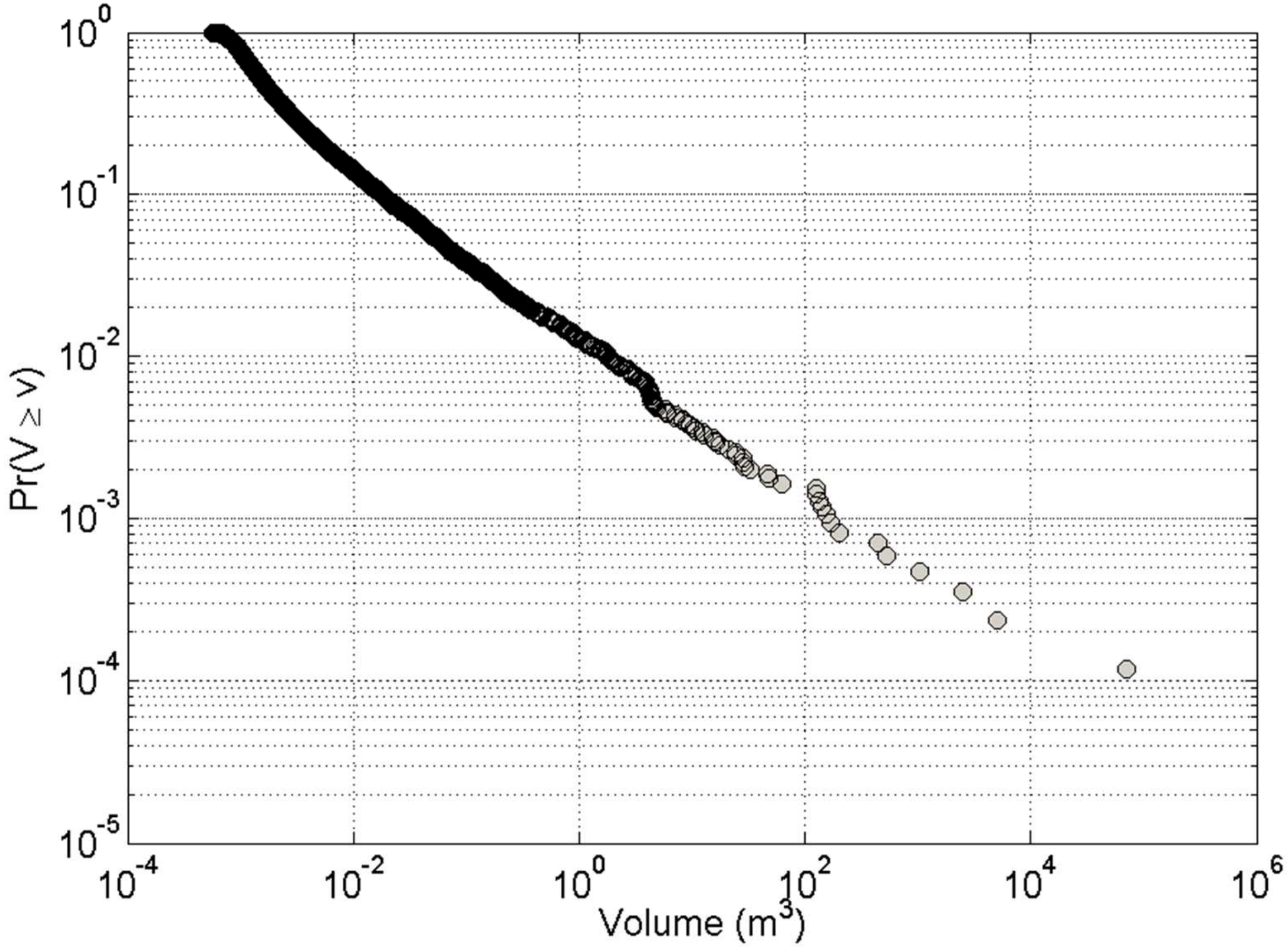


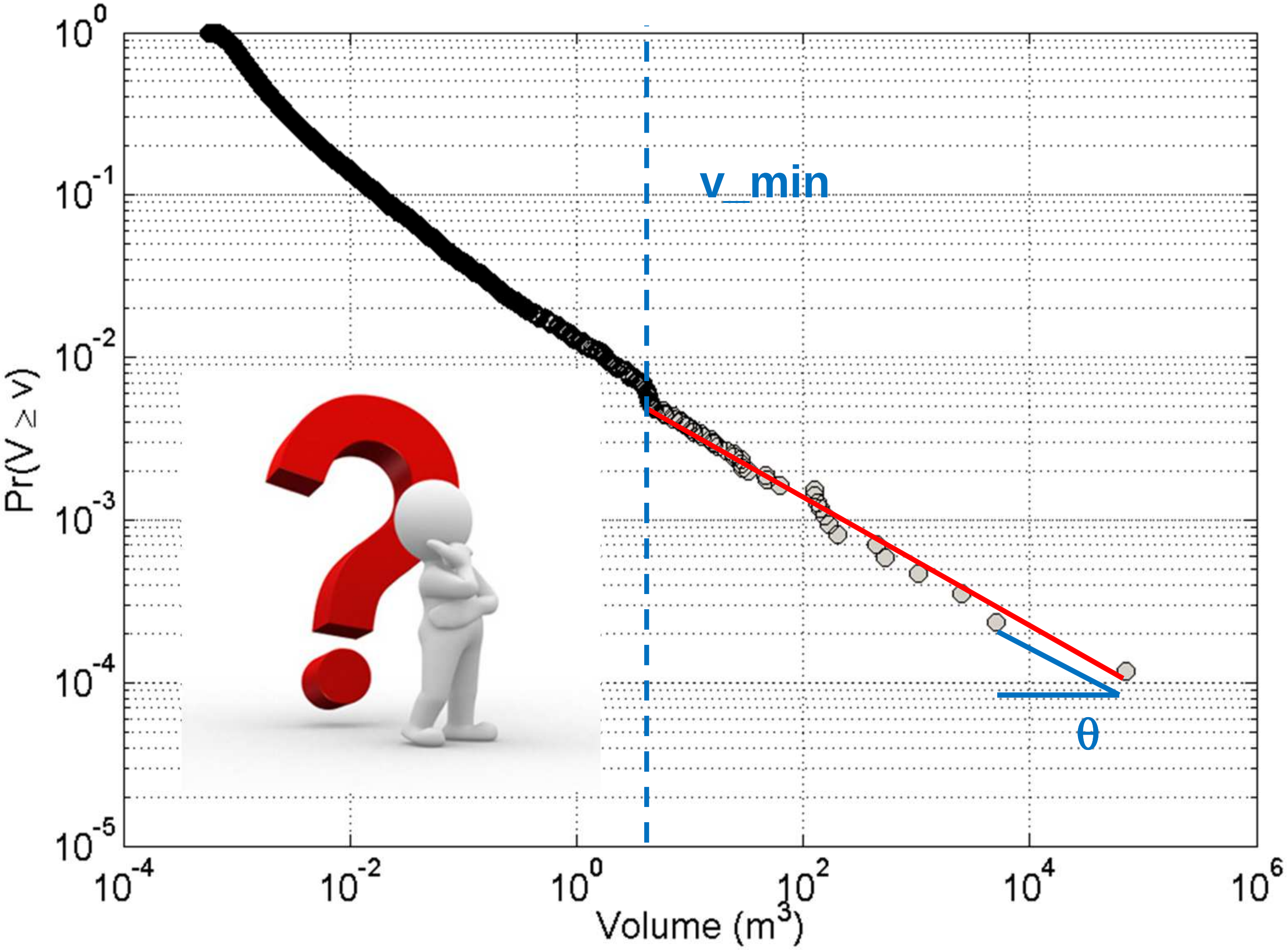
Digital Surface Model differences → Rockfall inventory



Empirical Frequency-size relationship,

>8000 events



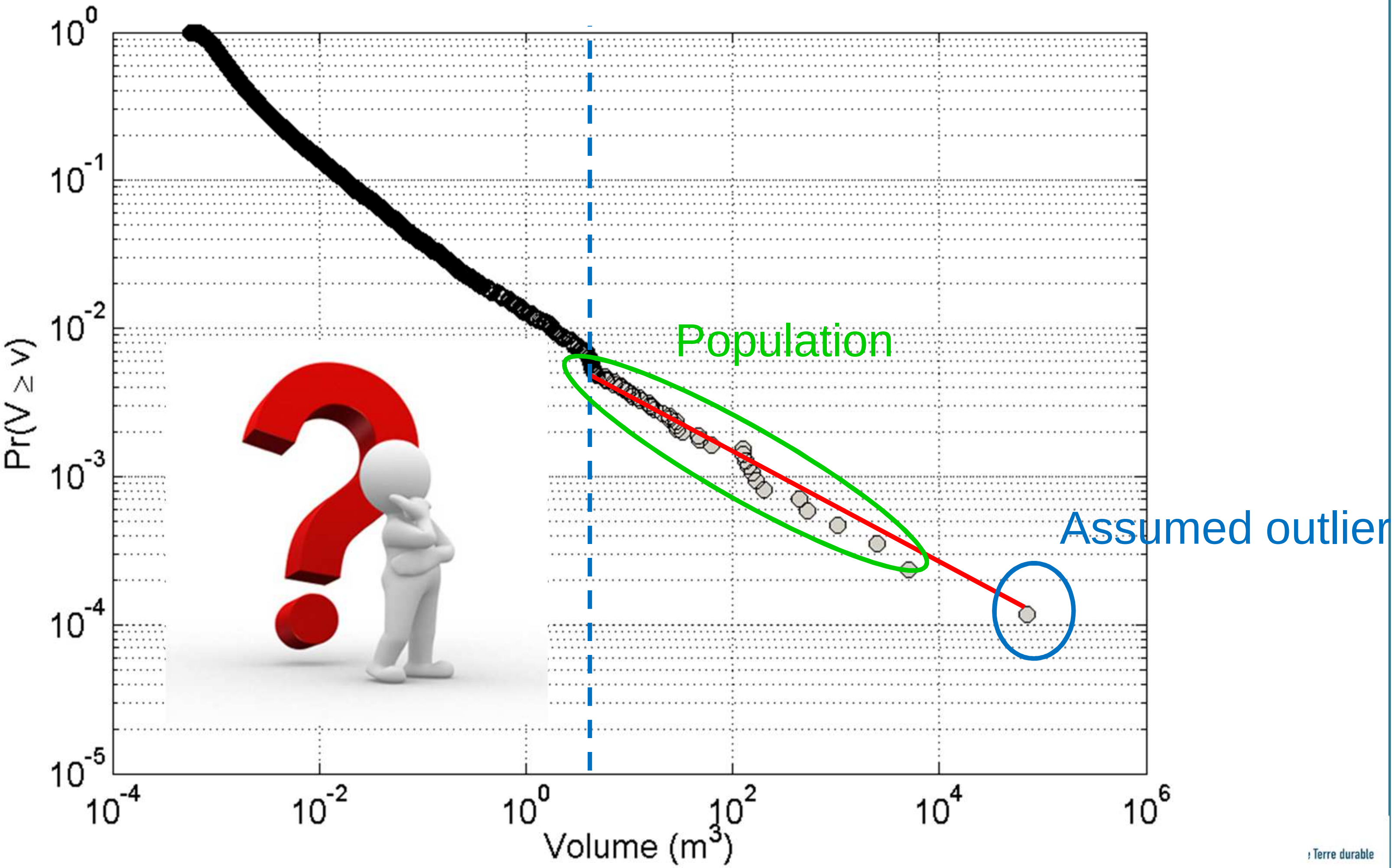


v_min
θ
Pr(V ≥ v)
Volume (m3)

“An outlier is an observation that lies an ***abnormal distance*** *from other values in a random sample from a population.”*

Engineering Statistical Handbook, National Institute of Standards and Technology (2007) See http://www.itl.nist.gov/div898/handbook/prc/section1/prc16.htm

Sensitivity to the presence of outlier



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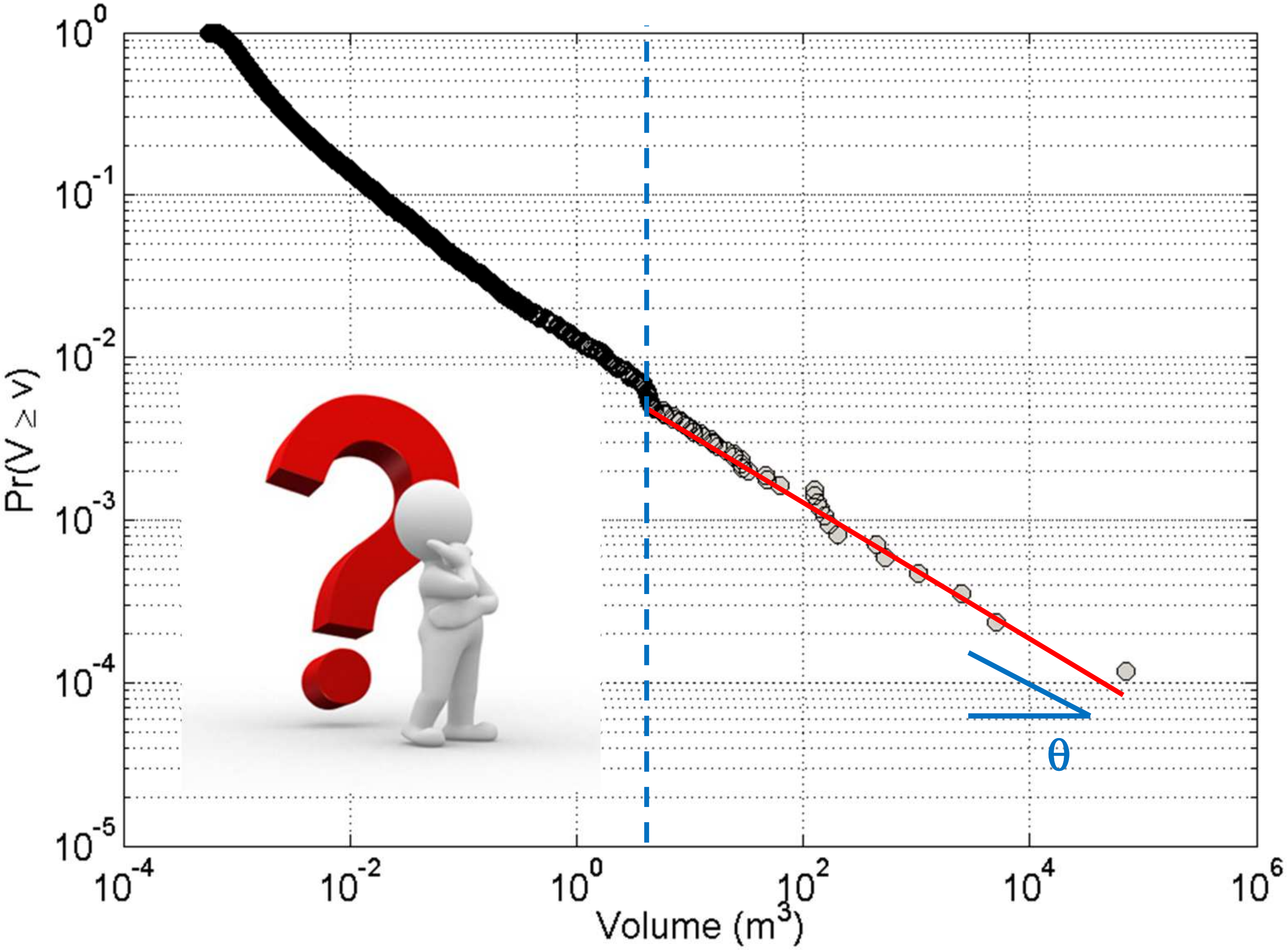

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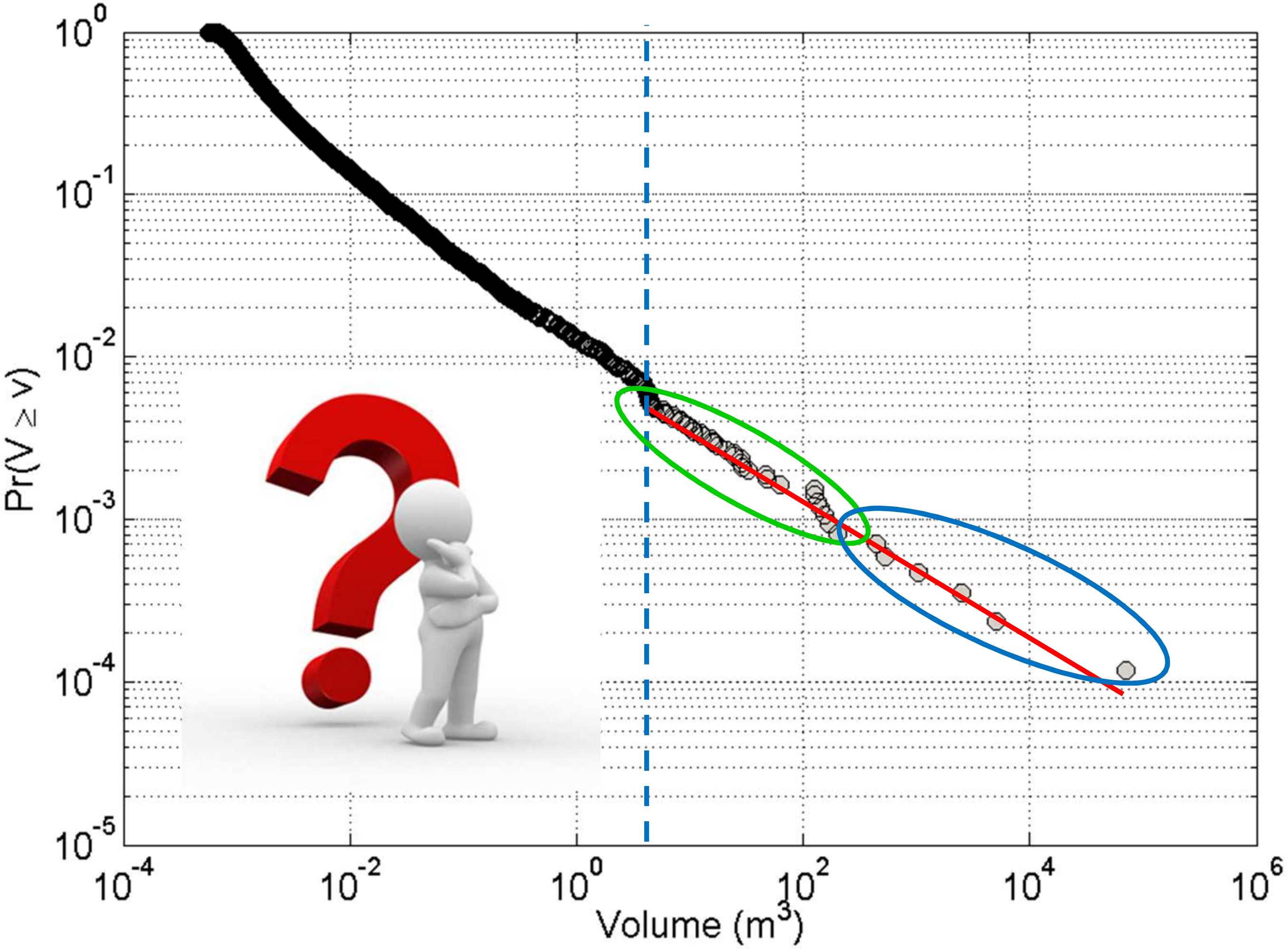

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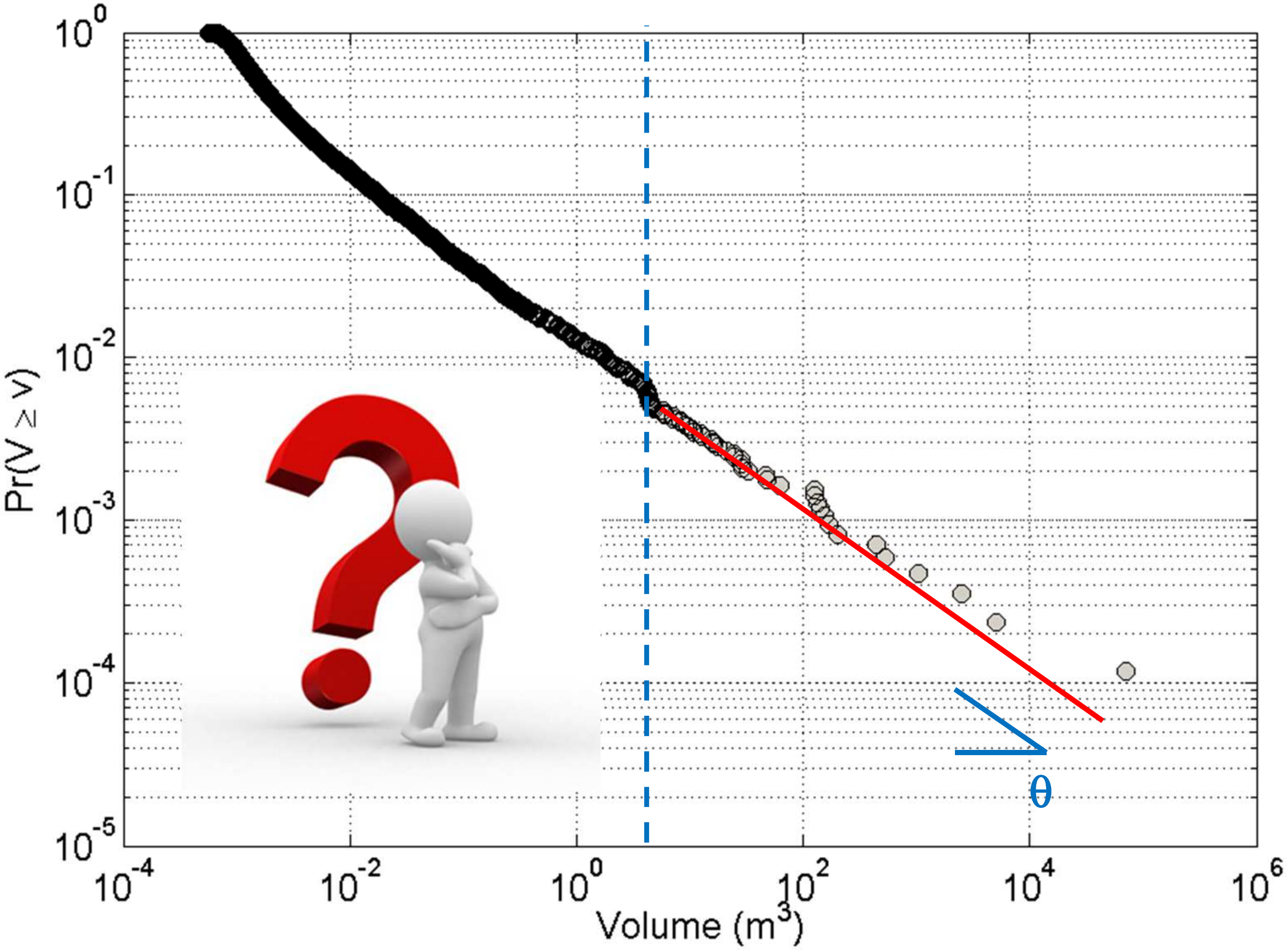
Sensitivity to the presence of outlier



Robust estimation of θ

Use of Weighed Maximum likelihood estimation MLE (Dupuis and Victoria-Feser, 2006)

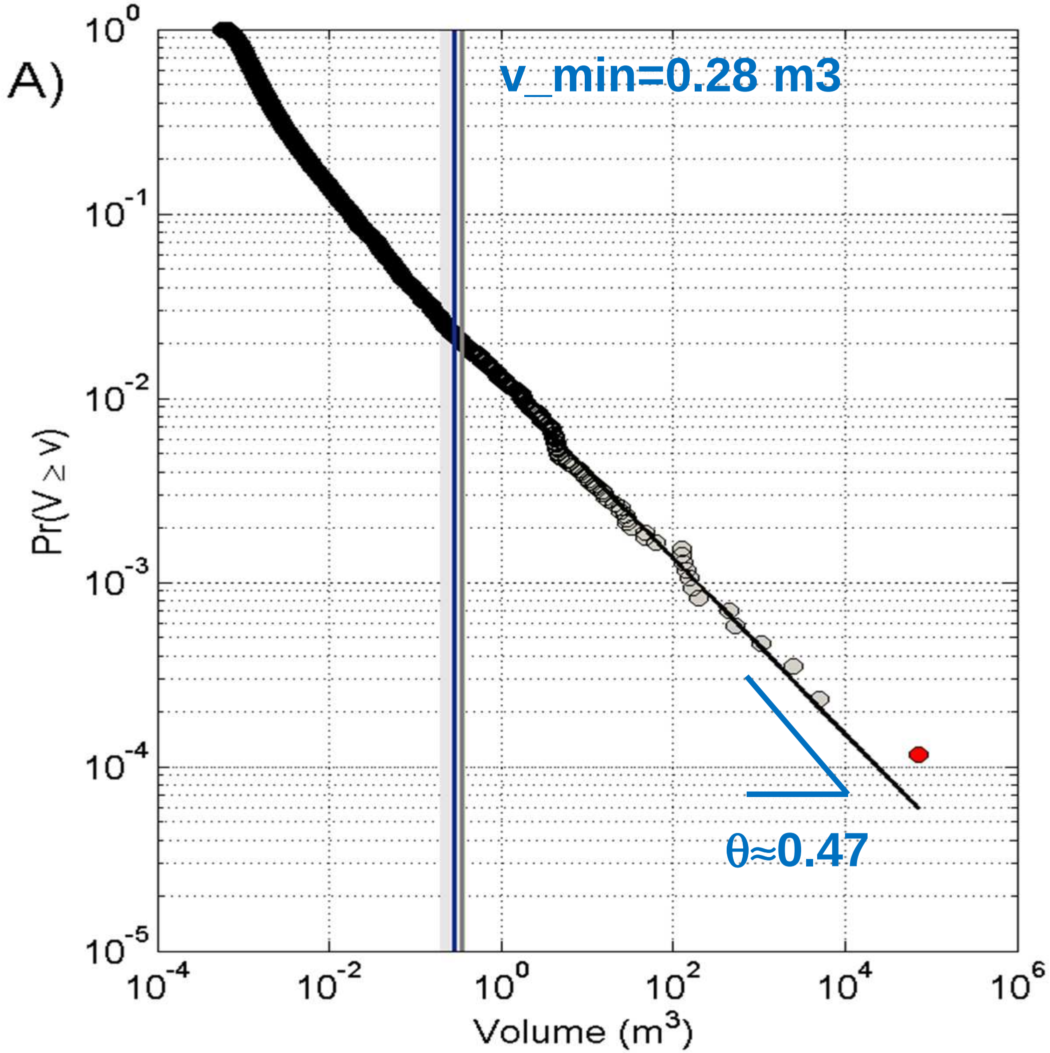
Basic idea:

Assign to each observation a weight w depending on

- Rank order
- Representativeness

$$w(x;\theta) = \begin{cases} F_\theta(x)/p_1, & \text{if } F_\theta(x) < p_1, \\ 1, & \text{if } p_1 < F_\theta(x) < 1 - p_2, \\ \{1 - F_\theta(x)\}/p_2, & \text{if } F_\theta(x) > 1 - p_2, \end{cases}$$

Any points which do not lie in the central p_1 and 1-p_2 part of the distribution F (p_1=p_2=0.005), ➔ smoothly down-weighted **(weight <1)**



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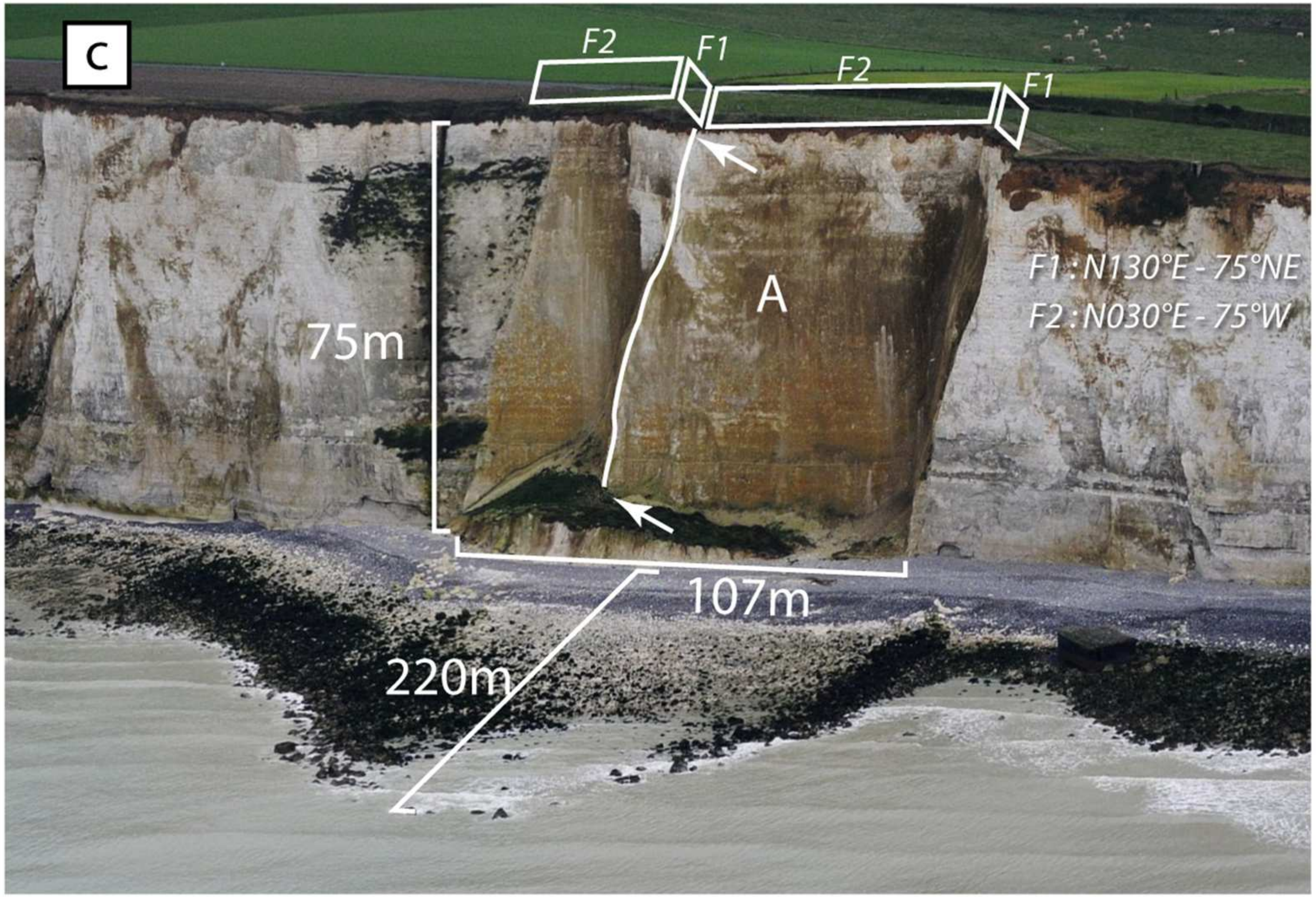
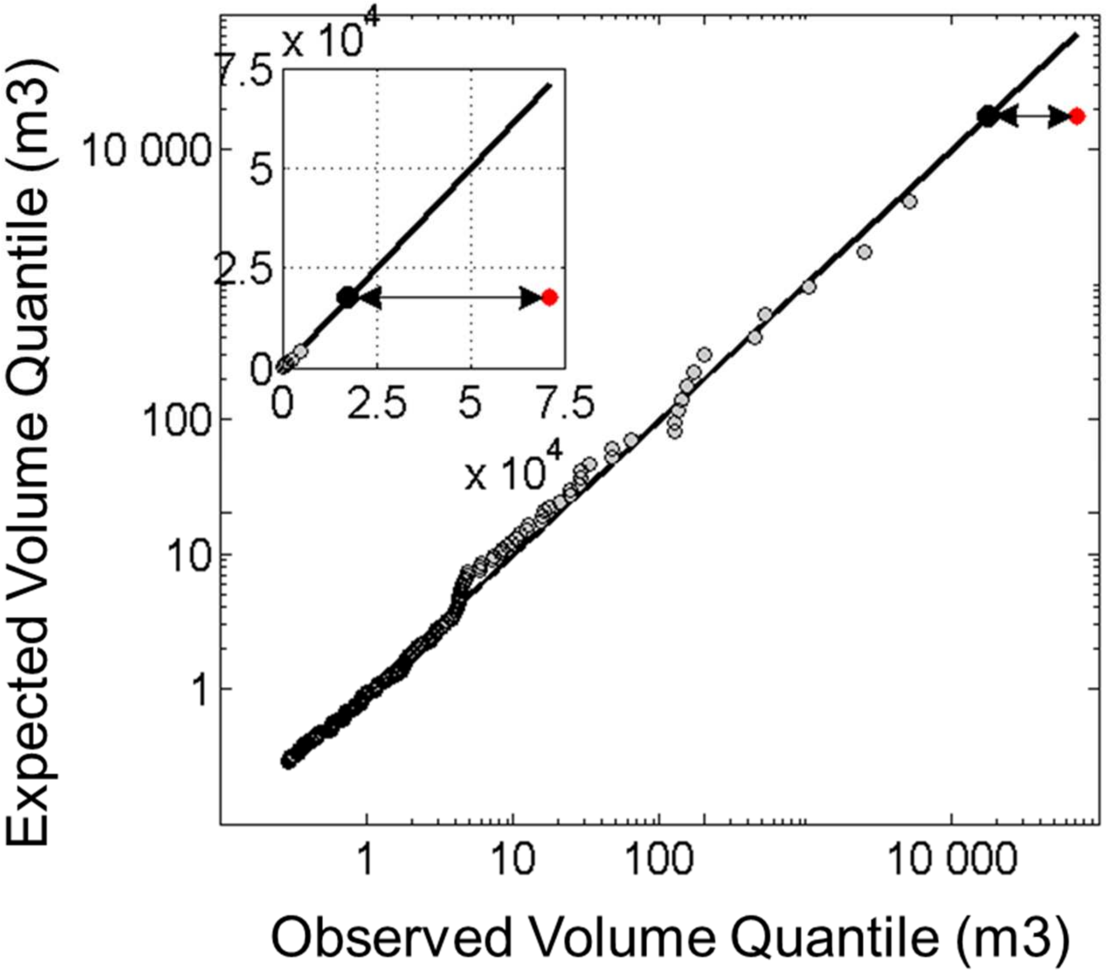
Largest event: >70 000 m3



Quantile – Quantile plot



Test for « outlyingness »

Use of the **weight** of the WMLE (Dupuis et al. 2004)

Here : 0.53

Statistical significance ?

➔ what is the probability of finding a weight ≤ 0.53 if the empirical distribution followed a power-law model ?

Test for « outlyingness »

➔ **Hypothesis Ho:** “the largest event follows a power-law model”

➔ **Use of a bootstrap approach:**

➔ Generate 10,000 times a sample of same size as the observations from a power law (θ=0.47 & v_min=0.28 m3) ;

➔ Calculate the weight of the largest event;

➔ Calculate the ratio of largest events with weight $\leq$ 0.53;

➔ **p-value < 1 %**

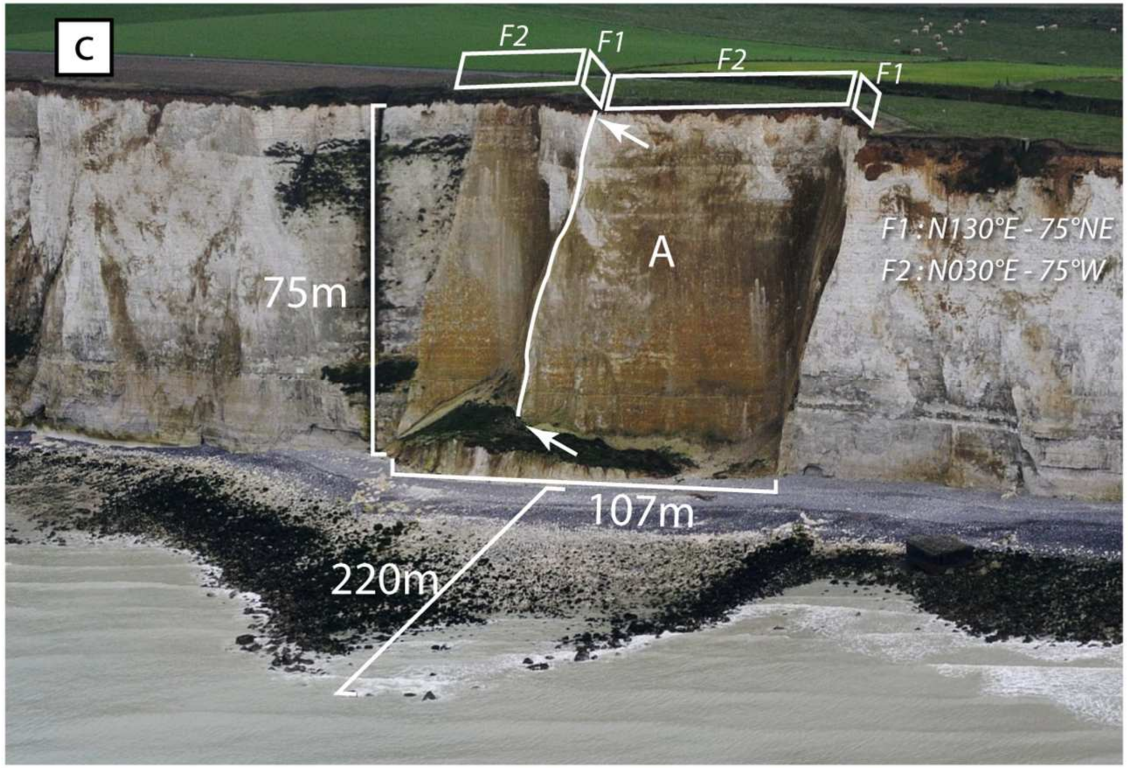
= probability of Type-I error: to reject Ho when it is true

Origin n°1: error measurement ?

Point precision 2σ<1.5 cm

Scar depth precision 2σ~1.8 cm

➔ Uncertainty on volume ~0.12 %



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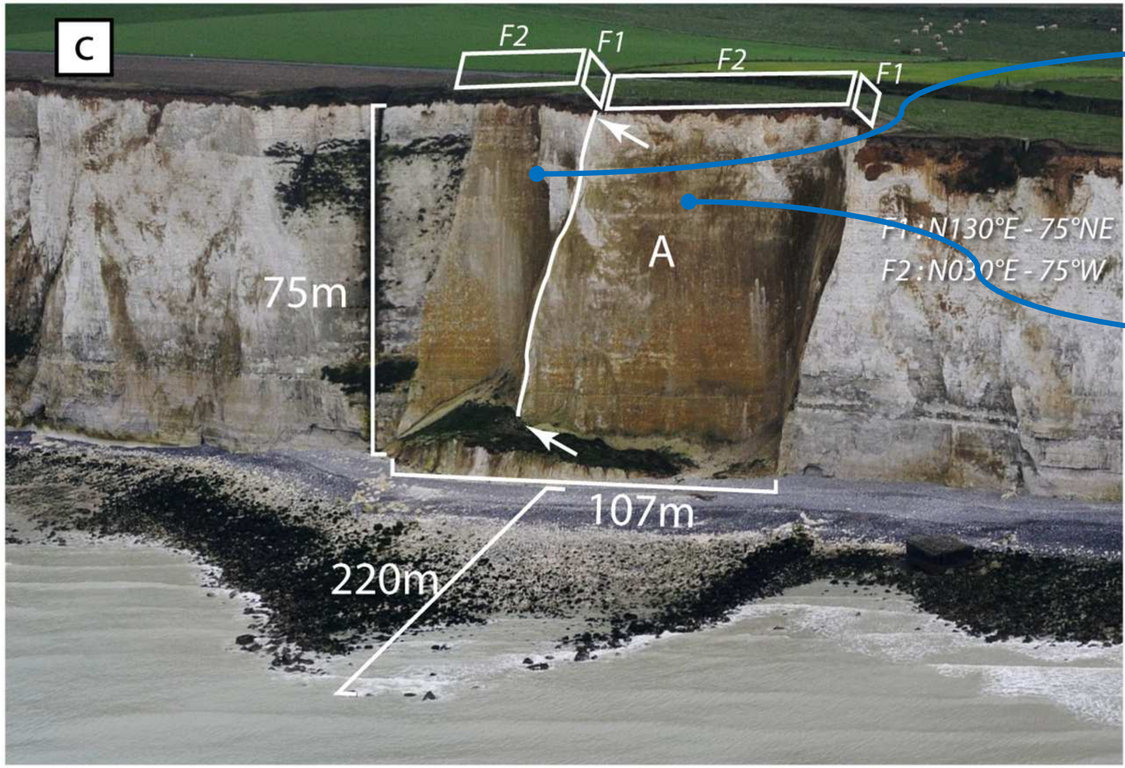
Origin n°2: temporal resolution ?

TLS survey every ~6 months

➔ **Does not allow capturing multiple failure processes**
➔ **Large rockfall = two "smaller" events ?**



Event A1
~22,700 m3

Event A2
~48,240 m3

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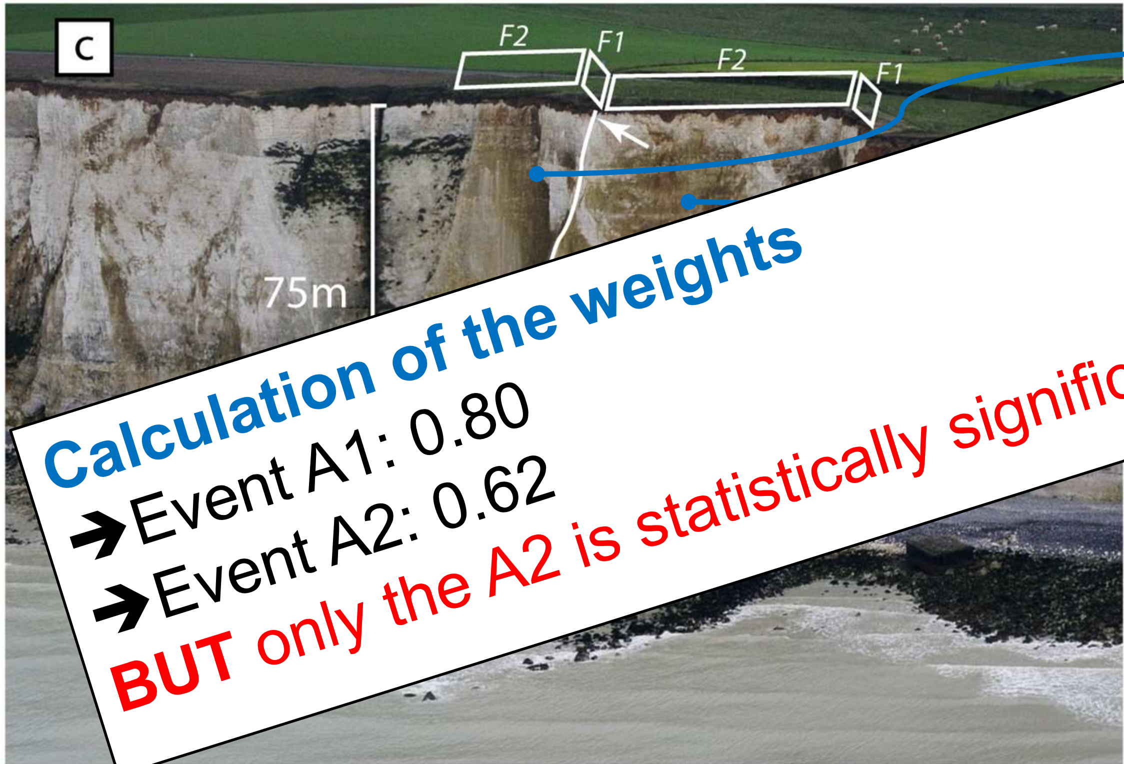

48,240 m3

Calculation of the weights
➔Event A1: 0.80
➔Event A2: 0.62
BUT only the A2 is statistically significant (p-value ~1 %)

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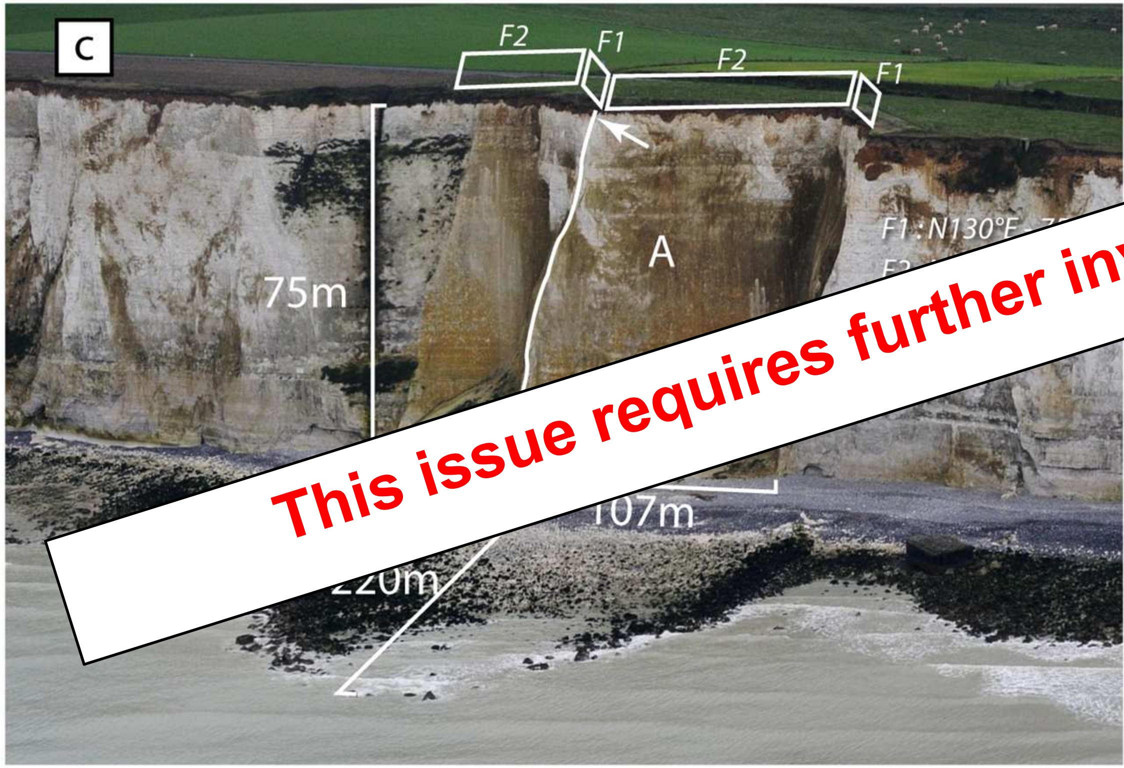

This issue requires further investigation …

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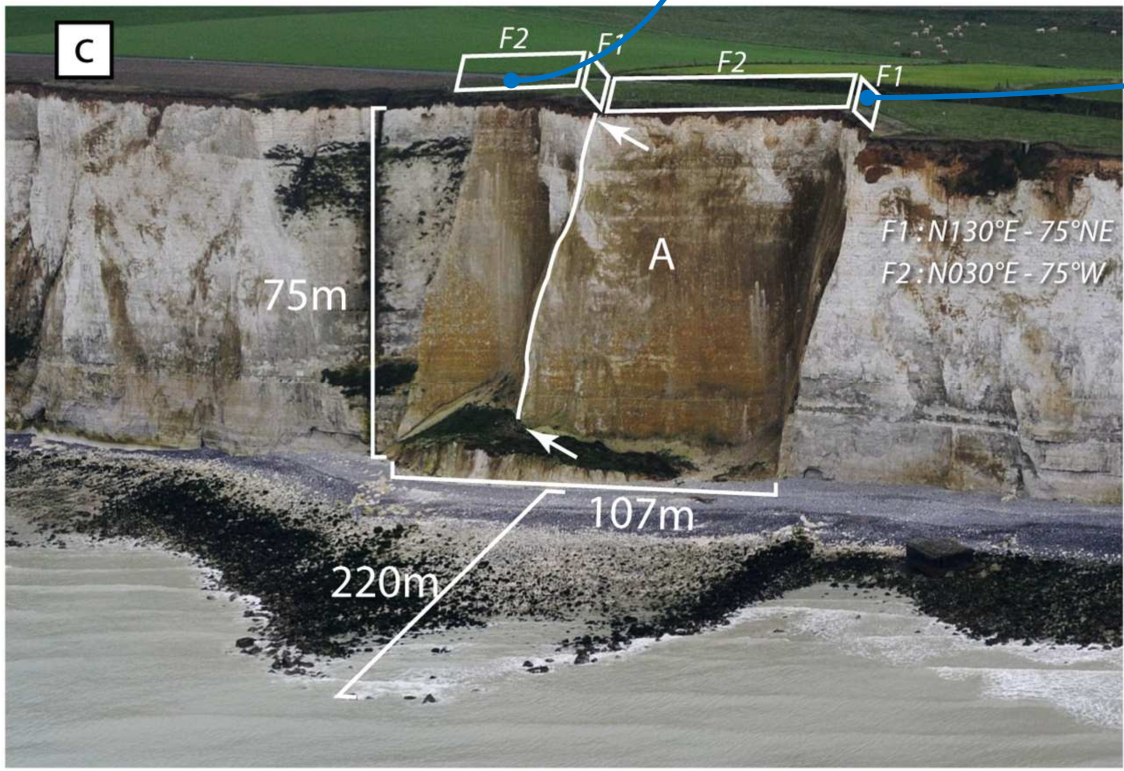
Origin n°3: physical mechanism ?

Role of pre- existing structural faults ?



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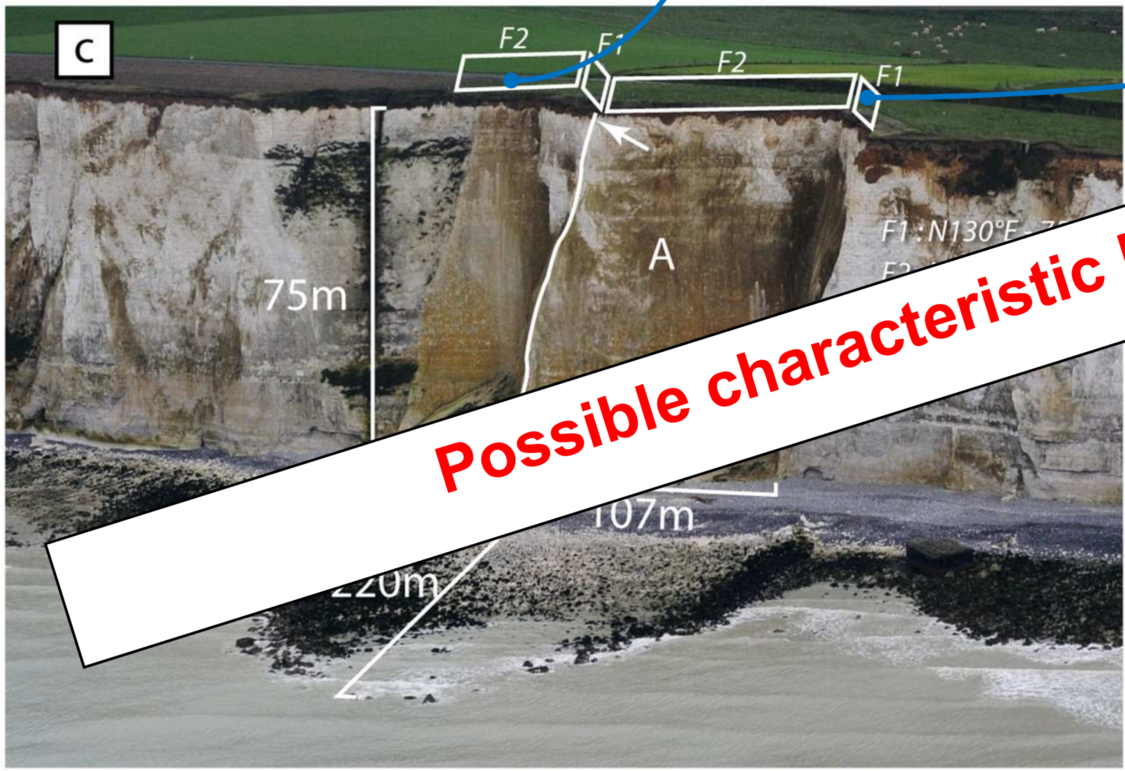

Possible characteristic length ?

EARTHQUAKES AND FAULTING: SELF-ORGANIZED CRITICAL PHENOMENA WITH A CHARACTERISTIC DIMENSION

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Palisades, New York, 10964, U.S.A.

ABSTRACT. Earthquakes are among the most frequently cited natural phenomena that exhibit the behavior called self-organized criticality that is found in models of spacially extended dissipative systems. In this article the relevant phenomenological aspects of earthquakes, and of faults, the objects upon which earthquakes occur, are reviewed in terms of this concept. Both earthquakes and faults have fractal (power law) size distributions, a prime characteristic of SOC systems. Earthquake statistics do not vary in space except for a factor that defines the overall rate of activity, and observations of artificially induced seismicity suggests that the continental crust is virtually everywhere in a state close to seismic failure. These observations lead to the conclusion that the continental crust is in a self-organized critical state everywhere, but with geographically varying rates of loading. However, the earthquake system contains a characteristic dimension, the width of the brittle zone, or schizosphere, within which earthquakes can occur, and this has a profound effect on the behavior. Earthquakes of size on either side of this crossover dimension have very different characteristics. The seismic moments of small earthquakes, which are unconstrained to propagate in two dimensions, scale with dimension cubed. For large earthquakes, that may only propagate in one dimension, moment scales with rupture dimension squared. On a given fault, the large earthquakes do not belong to the same fractal set as the small earthquakes. Globally, both small and large earthquakes have power law size distributions but with different exponents, being somewhat less than 2/3 for small earthquakes and 1 for large earthquakes. The morphology of faults also exhibits profound changes at the crossover dimension.

T. Riste and D. Sherrington (eds.), Spontaneous Formation of Space-Time Structures and Criticality, 41–56.

In summary…

Large event = extrapolation of power law model ?

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More complicated story:

Data → statistical reality of the deviation

In summary…

Large event = extrapolation of power law model ?

More complicated story:

Data → statistical reality of the deviation

Physical reality ?

→ Geometry and structural pre-existing pattern

→ Heterogeneity;

→ Driving forces …

In summary…

Large event = extrapolation of power law model ?

More complicate

→ **Hetero**

g forces

→ **Geometry and structural pre-existing pattern**

→ **…**

➔improve technique for cliff monitoring

Thank you for your attention !

Acknowledgements
We would like to thank ATM3D for acquiring laser data, point-clouds pre-processing and fruitful discussions to optimize survey protocols. This work is part of the project EVOLGEOM and ESCARP funded by BRGM's Directorate of Research.

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