SOC in Natural Hazards

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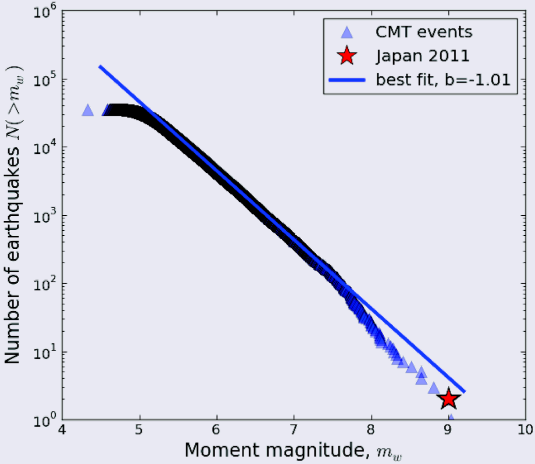
Earthquakes

Gutenberg-Richter law



Sachs et al. (Self-organized criticality systems, 2012)

Earthquakes

Gutenberg-Richter law

Number of earthquakes with magnitude m or greater:

$$\log_{10} N(m) \;=\; a - bm$$

with $b \approx 1$ ($b \in [0.8, 1.2]$)
Magnitude m is a logarithmic measure of the seismic moment.

$$\Downarrow$$

Power-law distribution of the seismic moments (or energies, rupture areas etc.).

Earthquakes

Temporal correlations

Characteristic earthquakes: large earthquakes occurring almost periodically

Foreshocks and aftershocks according to Omori's law:

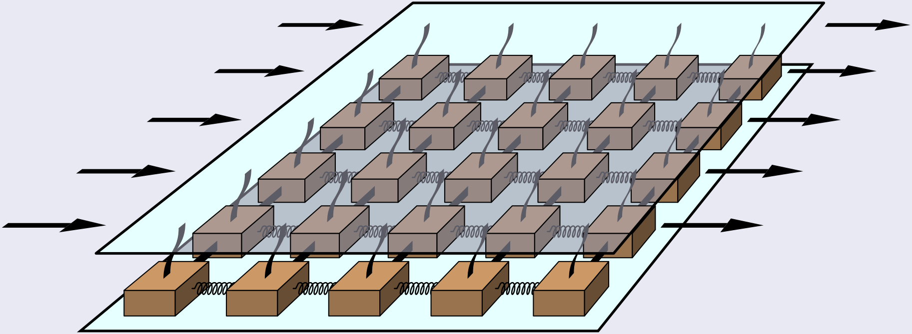
$$N(t) \propto |t - t_m|^{-p}$$

where

$$\begin{aligned} N(t) &= \text{number of earthquakes per time} \\ t_m &= \text{time of mainshock occurrence} \\ p &\approx 1 \end{aligned}$$

Earthquakes

Olami-Feder-Christensen model



Earthquakes

Relaxation rule

$$
\begin{aligned}
F_{nn(i)} &:= F_{nn(i)} + \alpha F_i \quad (nn = \text{nearest neighbors}) \\
F_i &:= 0
\end{aligned}
$$

Conservative for $\alpha = \frac{1}{4}$, nonconservative for $\alpha < \frac{1}{4}$

Earthquakes

Arguments for the nonconservative version

- Scaling exponent of the event-size distribution (Gutenberg-Richter law)
- Characteristic earthquakes
- Foreshocks and aftershocks according to Omori's law

Arguments for the conservative version

- Elastic driver plate or three-dimensional realization: conservative with long-range interactions (Jansen & Hergarten, PRE, 2006)
- Relation between seismic moment M and rupture area A:

$$M \propto A^{\gamma}, \quad \gamma > 1$$

How does the nonconservative OFC model work?

- (Apparent) criticality arises from long-term synchronization of almost periodic events (Middleton & Tang, PRL, 1995).
- Universal scaling exponent $\tau = 1.775$ was derived from the scaling properties of the accessible perimeter of the rupture areas (Hergarten & Krenn, NPG, 2011).

$$\Downarrow$$

$$b = \tfrac{3}{2}\,(\tau - 1) = 1.16$$

Not too bad compared to $b \in [0.8, 1.2]$ in nature

Earthquakes

How does the nonconservative OFC model work?

- Foreshocks and aftershocks originate from desynchronization of characteristic earthquakes (Hergarten & Krenn, NPG, 2011).

$$\Downarrow$$

- Explains why some large earthquakes are not accompanied by any foreshocks or aftershocks.
- Sizes of characteristic earthquakes decrease during a sequence, while the number of foreshocks and aftershocks increases.
- Omori exponent $p < 1$ in contradiction to $p > 1$ for many real earthquake series

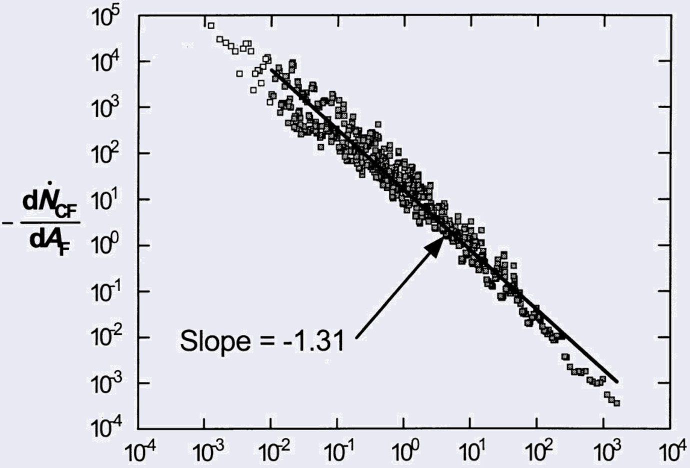
Earthquakes

Summary

- Overwhelming evidence for power-law distributions in earthquakes suggests a relationship to SOC.
- Nonconservative OFC model predicts several statistical properties of earthquakes more or less well.
- But also several arguments why the OFC model is unrealistic, e. g.,
    - relation between seismic moment and rupture area,
    - Omori exponent.

Wildfires

Power-law distribution



Malamud et al. (Science, 1998)

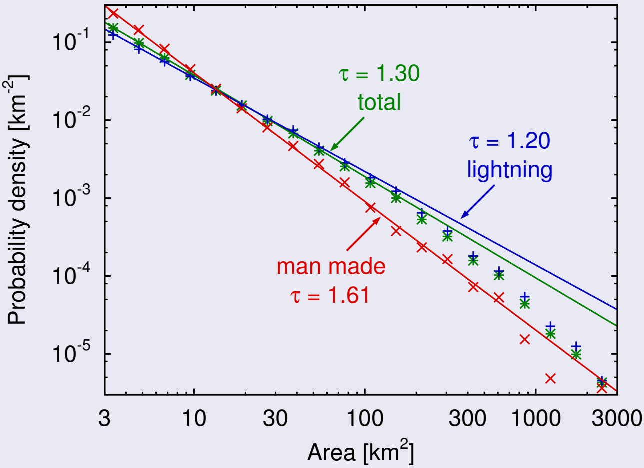
Wildfires

Power-law distribution

- Strong variation in the scaling exponents,
  majority in the interval $\tau \in [1.1, 2.0]$.
- Presumably not just an artefact of data sampling

Wildfires

Natural and man-made fires in Canada



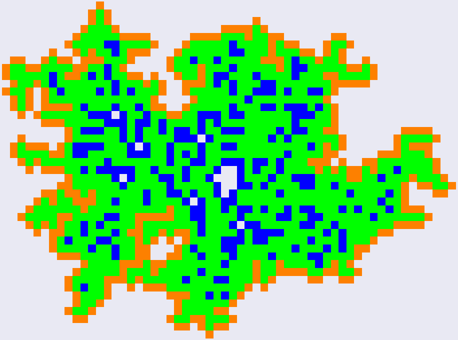
Krenn & Hergarten (NHESS, 2009)

Drossel-Schwabl forest-fire model

- Older than knowledge on power-law distribution of wildfires
- Scaling exponent $\tau = 1.19$ at the lower edge of the range $\tau \in [1.1, 2.0]$.
- Not widely accepted in forest ecology
- Main criticism: simplicity, random growth of trees
- Apparently even reproduces some geometric properties of real wildfires

Extension of the forest-fire model towards man-made fires

Ignition only at the accessible perimeter of a cluster of trees (Krenn & Hergarten, NHESS, 2009)

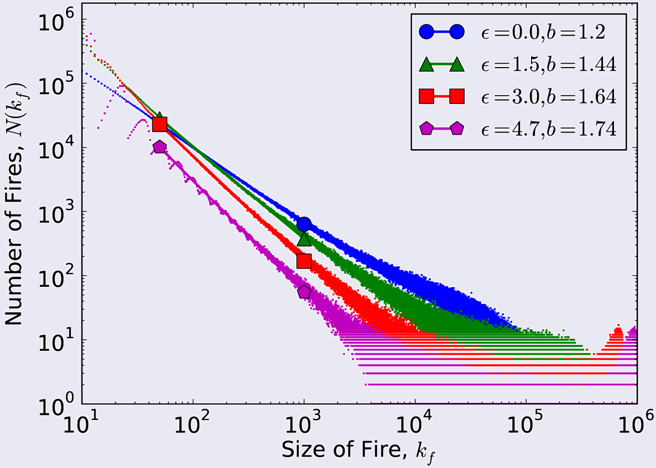


Scaling exponents:

	Model	Data
Lightning	1.19	1.20
Man made	1.51	1.61

Wildfires

Extension of the forest-fire model by fire suppression



Yoder et al. (PRE, 2011)

Wildfires

Summary

- Strong evidence for power-law distributions in wildfire sizes suggests a relationship to SOC.
- Drossel-Schwabl forest-fire model has great potential with respect to real wildfire dynamics.

Landslides

Different materials

- (Fractured) rock
- Regolith cover (soil)

Types of movement

- Sliding
- Falling
- Rolling
- Avalanching
- Toppling

Landslides

Example of a regolith landslide

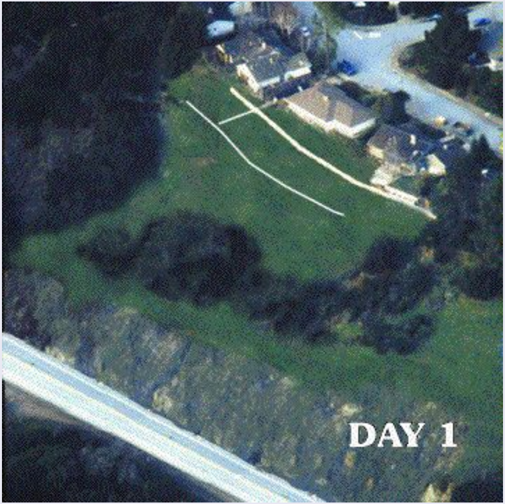


Photo: USGS

Landslides

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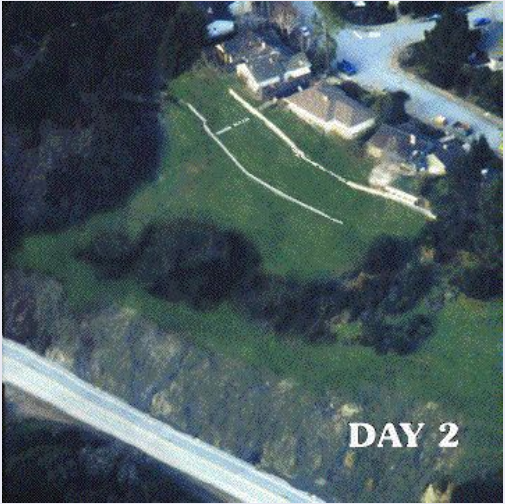


Photo: USGS

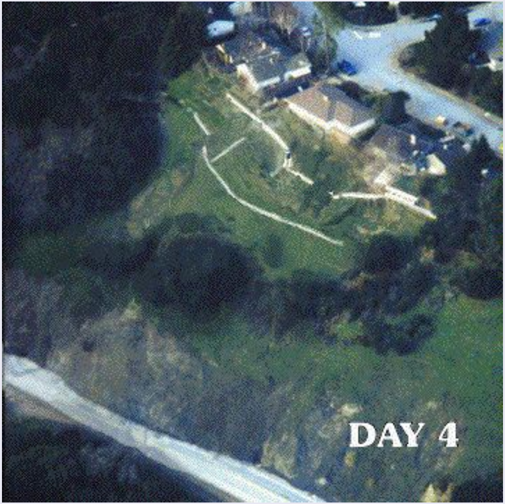
Landslides

Example of a regolith landslide

Photo: USGS

Landslides

Example of a regolith landslide



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Landslides

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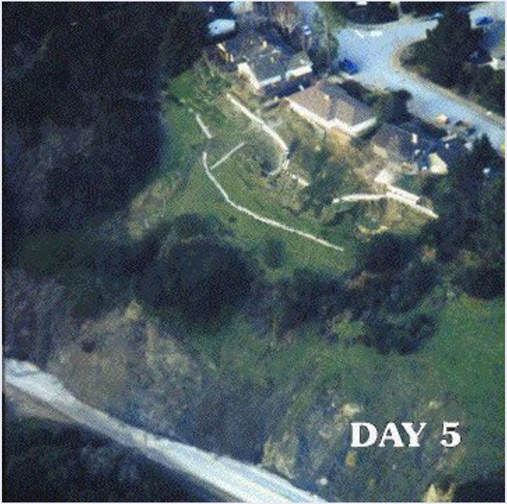

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Landslides

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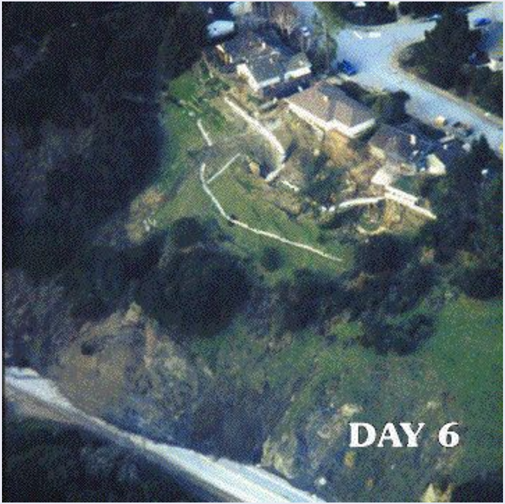


Photo: USGS

Landslides

Example of a regolith landslide

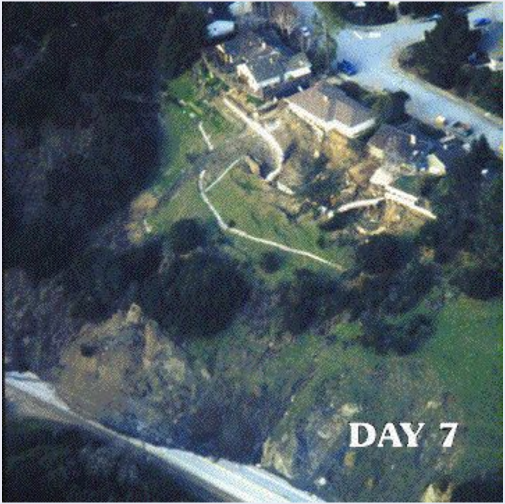
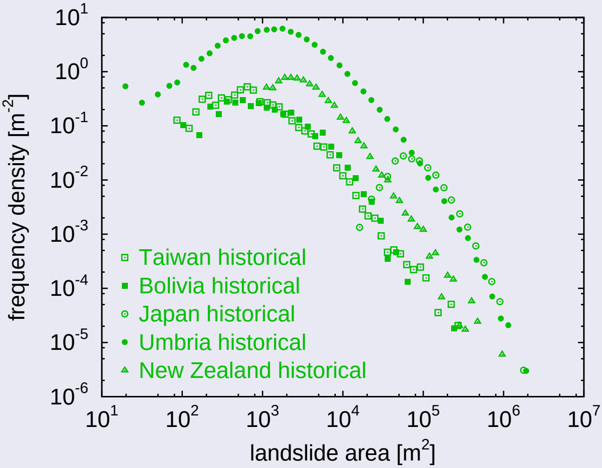


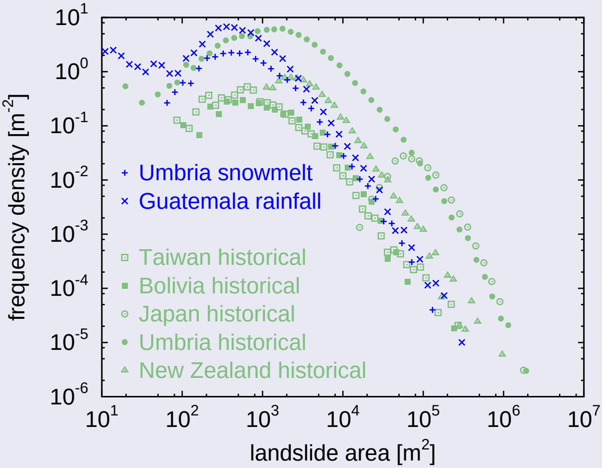
Photo: USGS

Power-law distribution of regolith landslides



Data: Hovius et al. (Geology, 1997), Malamud et al. (ESPL, 2004)

Power-law distribution of regolith landslides



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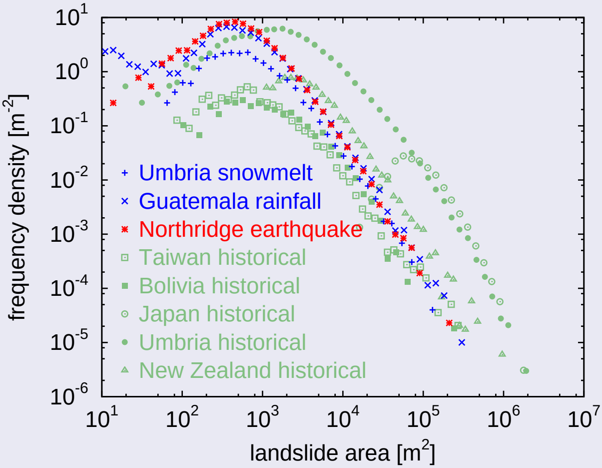
Power-law distribution of regolith landslides



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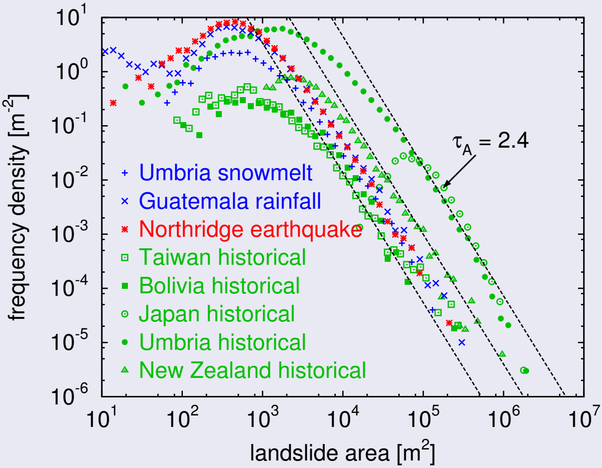
Landslides

Power-law distribution of regolith landslides



Data: Hovius et al. (Geology, 1997), Malamud et al. (ESPL, 2004)

Example of a large rockslide: Randa (1991, 30 mil. m^3)

Photo: S. Hergarten

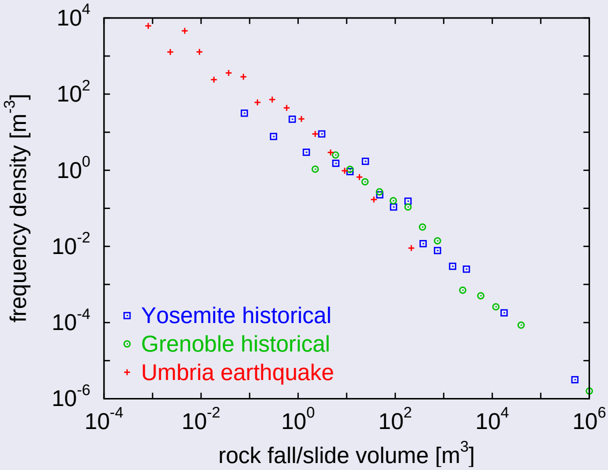
Landslides

Flims rockslide (10,000 years b.p., 10 km^3)

Photo: K. Stüwe & R. Homberger (www.alpengeologie.org)

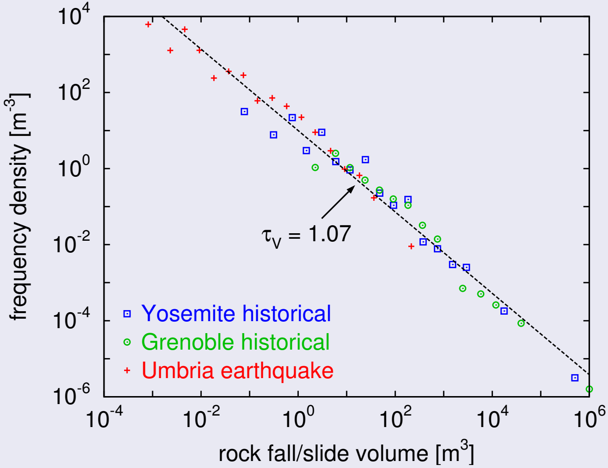
Landslides

Power-law distribution of rockfalls and rockslides



Data: Dussauge et al. (NHESS, 2002), Malamud et al. (ESPL, 2004)

Power-law distribution of rockfalls and rockslides



Data: Dussauge et al. (NHESS, 2002), Malamud et al. (ESPL, 2004)

Landslides

Rockfalls and rockslides vs. regolith landslides

	τ_V	τ_A
Rockfalls and rockslides	$1.07 \ldots 1.52$	
Regolith landslides		2.4

Landslides

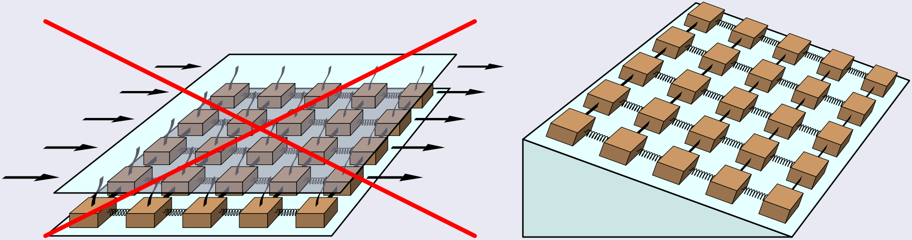
Rockfalls and rockslides vs. regolith landslides

	τ_V	τ_A
Rockfalls and rockslides	$1.07 \ldots 1.52$	
Regolith landslides	2.0	2.4

Landslides

Mechanical models

Regolith landslide on a given slip plane



Realistic scaling exponents:

Non-conservative: Piegari et al. (GRL, 2006)

Conservative with time-dependent weakening:

Hergarten & Neugebauer (PRE, 2000)

Landslides

Geomorphic models

- Regolith landslides: Densmore et al. (JGR, 1998), Hergarten & Neugebauer (GRL, 1998)
  - Power-law distribution over a very small range of scales
  - No serious parameter studies
- Rockfalls and rockslides:
  - BTW model

    Realistic scaling exponent, but relationship to topography questionable
  - New "sandpile model" (Hergarten, GRL, 2012)

Landslides

New "sandpile model"

- Based on local slope s in direction of steepest descent among the 8 nearest and diagonal neighbors
- Random triggering

$s \leq s_{\text{min}}$:	stable
$s \geq s_{\text{max}}$:	unstable
$s_{\text{min}} < s < s_{\text{max}}$:	probability of instability

$$p = \frac{s - s_{\text{min}}}{s_{\text{max}} - s_{\text{min}}}$$

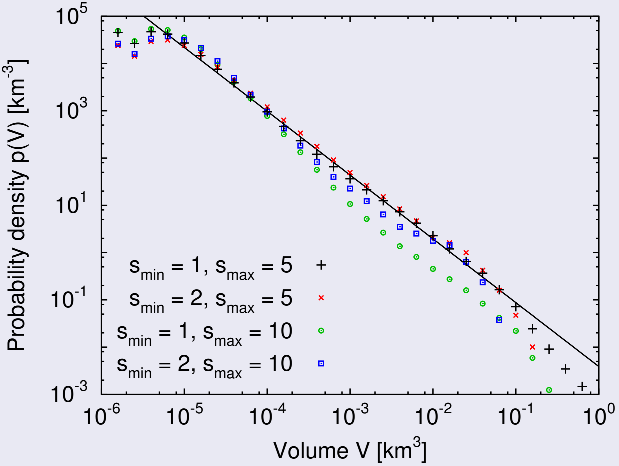
- In case of instability:
    - Remove material until $s = s_{\text{min}}$
    - Trigger all neighbors

New "sandpile model"

- Various ways of long-term driving

  or
- Direct application to a real topography

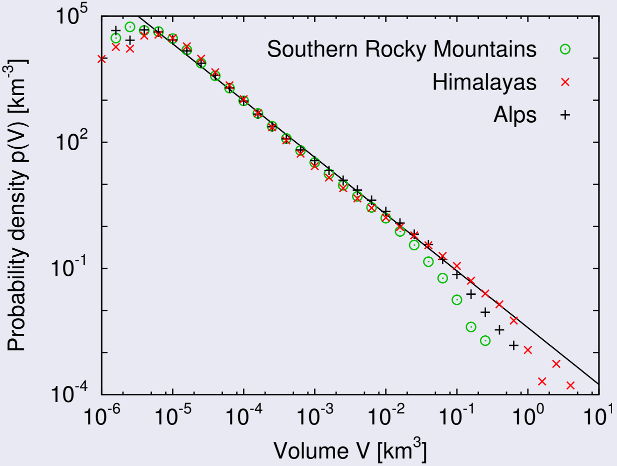
Application to the European Alps



Hergarten (GRL, 2012)

Landslides

Application to other mountain belts



Hergarten (GRL, 2012)

New "sandpile model"

Scaling exponent $\tau_V = 1.35$

- $\in [1.07, 1.52]$
- almost independent on s_{min} and s_{max}
- almost the same for the three mountain belts

Regional differences only reflected in the cutoff at large sizes

$$\Downarrow$$

Different levels of (sub)criticality

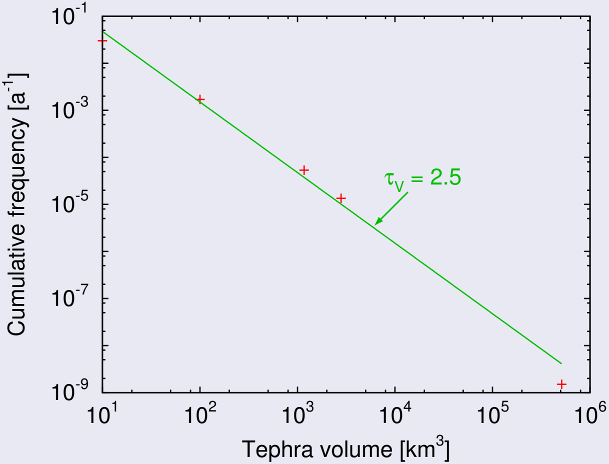
Landslides

Summary

- Strong evidence for power-law distributions in rockfalls and rockslides suggests a relationship to SOC.
- Power-law distribution of regolith landslides only within a narrow range of scales
- Geomorphic models seem to capture the phenomena better than mechanical models.
- Still no clear explanation of the difference in the statistics of the two types of landslides

Volcanic eruptions

Statistics of large eruptions



Data: Wikipedia

Volcanic eruptions

Spatio-temporal patterns

- Worldwide distribution may be a power law.
- Individual volcanoes seem to behave more regularly over long times (constant volume per time, eruptions of similar sizes).
- Relationship to SOC is unclear.