# Understanding landscape mass-wasting in response to geophysical forcings to constrain long-term erosional budgets

Odin MARC

Coseismic landslides in the Bhote Koshi, Nepal, June 2015

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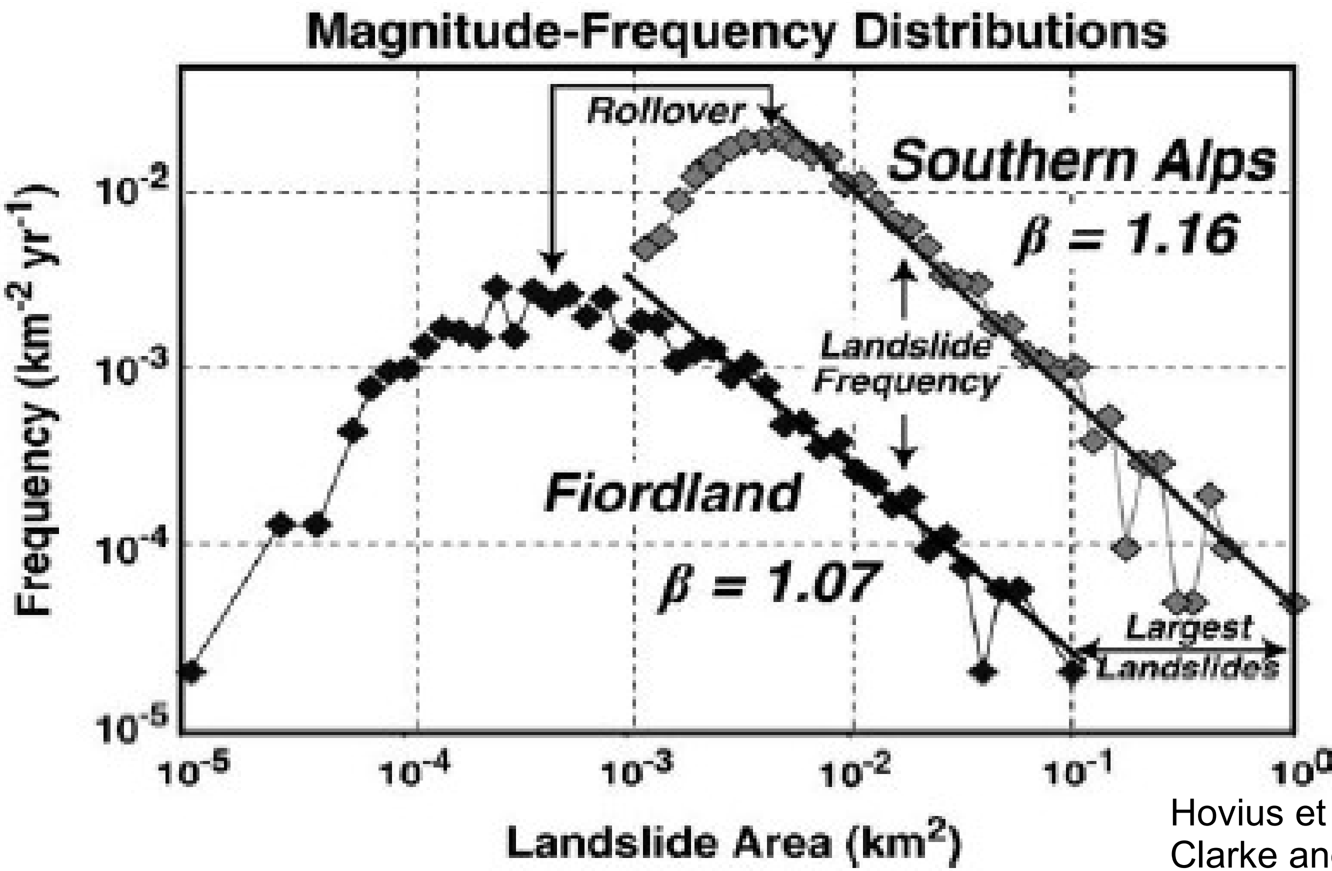
# Deriving long-term 'landslide' erosion rates

**Standard Method: Estimate and integrate Frequency Area Distributions (FAD).**
**– With a comprehensive landslide inventory, over large area and time period.**
**– Knowing the largest landslide size.**

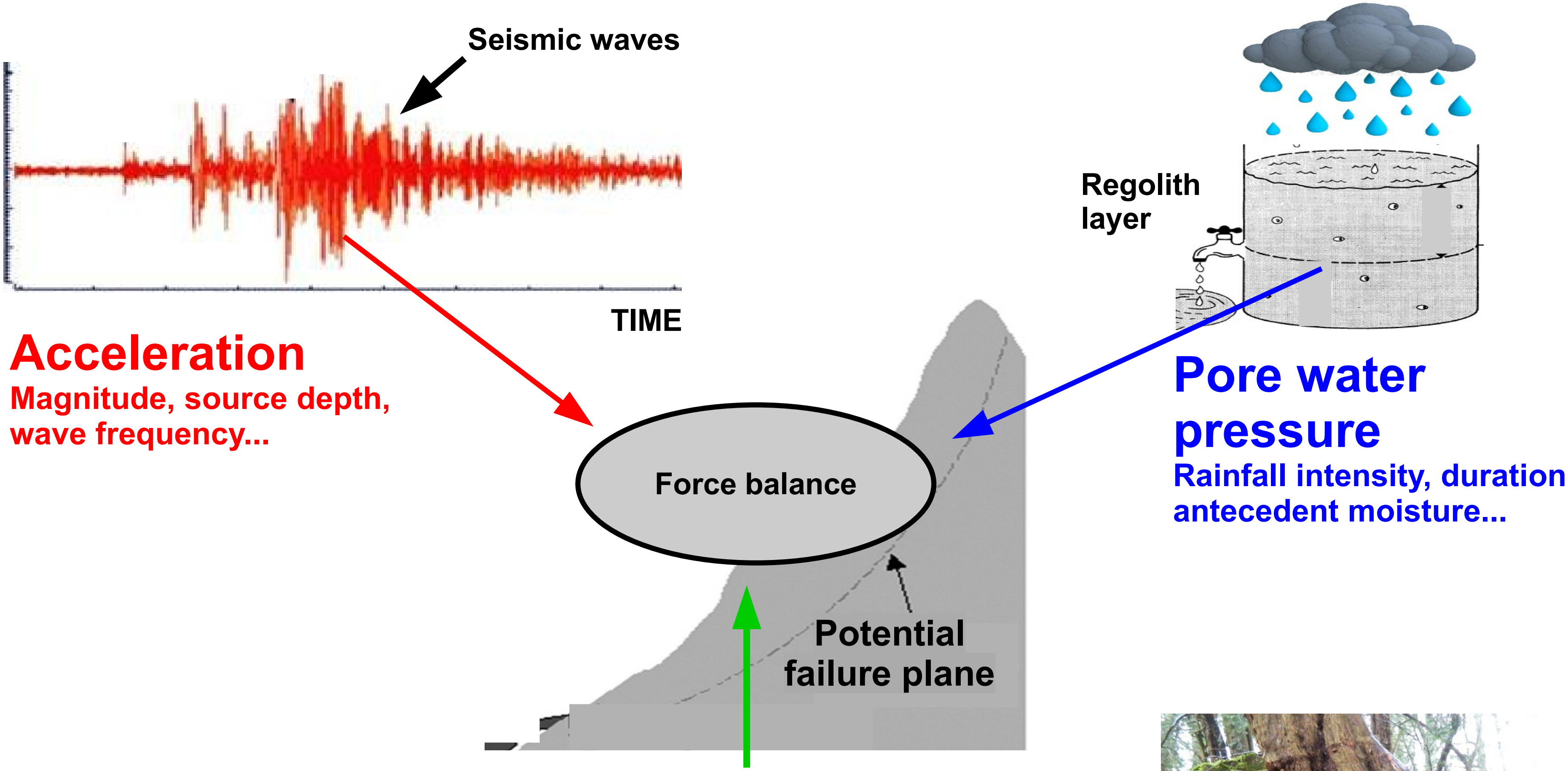
**However, the Frequency Area Distributions (FAD) varies with the triggering process as well as the landscape properties !→ How to account for that ?**

**→ quantify the frequency of the various trigger and their impact on landsliding.**




Hovius et al., 1997
Clarke and Burbank, 2011

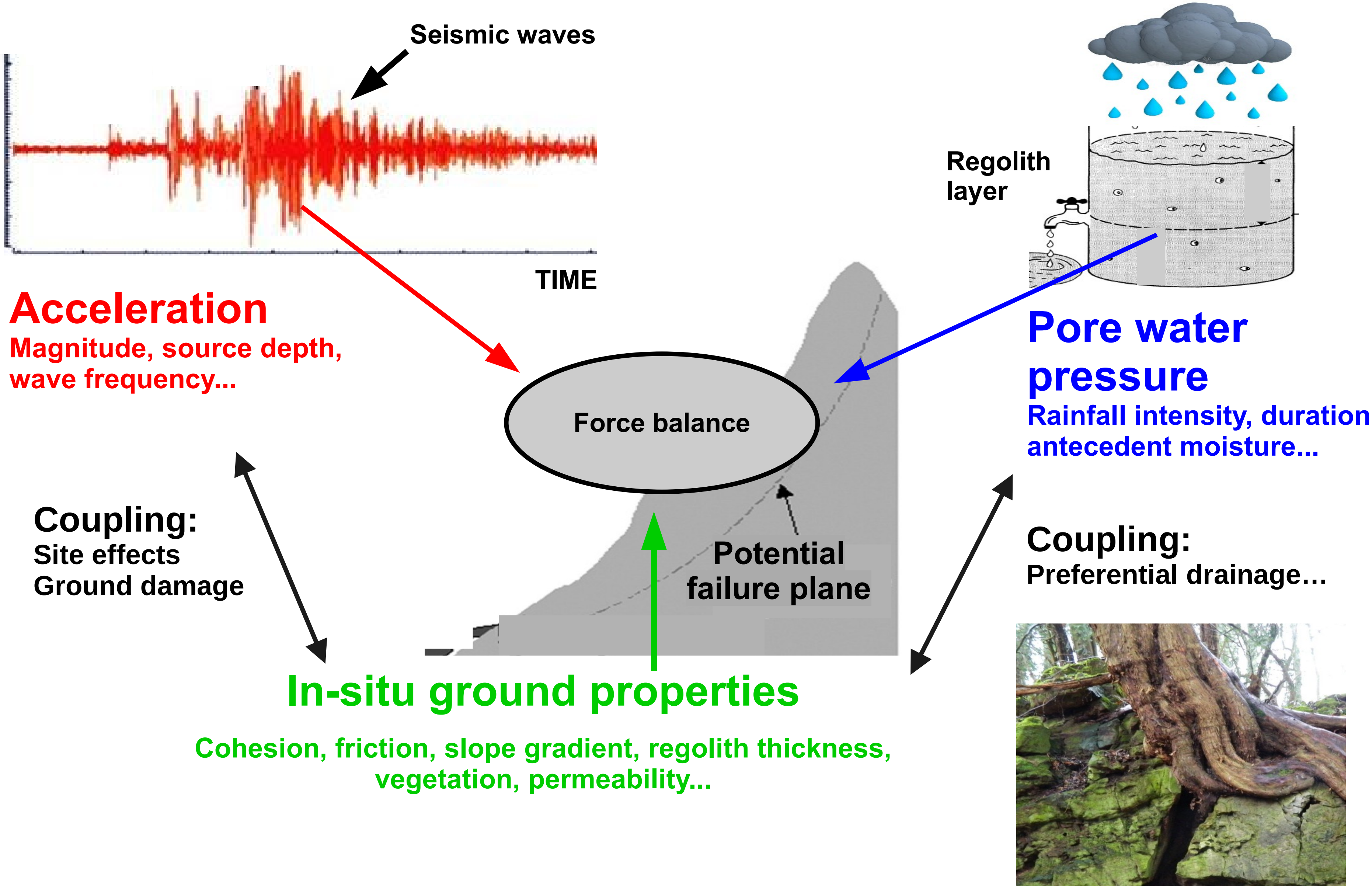
# Relating landsliding to triggering conditions




**In-situ ground properties**

Cohesion, friction, slope gradient, regolith thickness, vegetation, permeability...

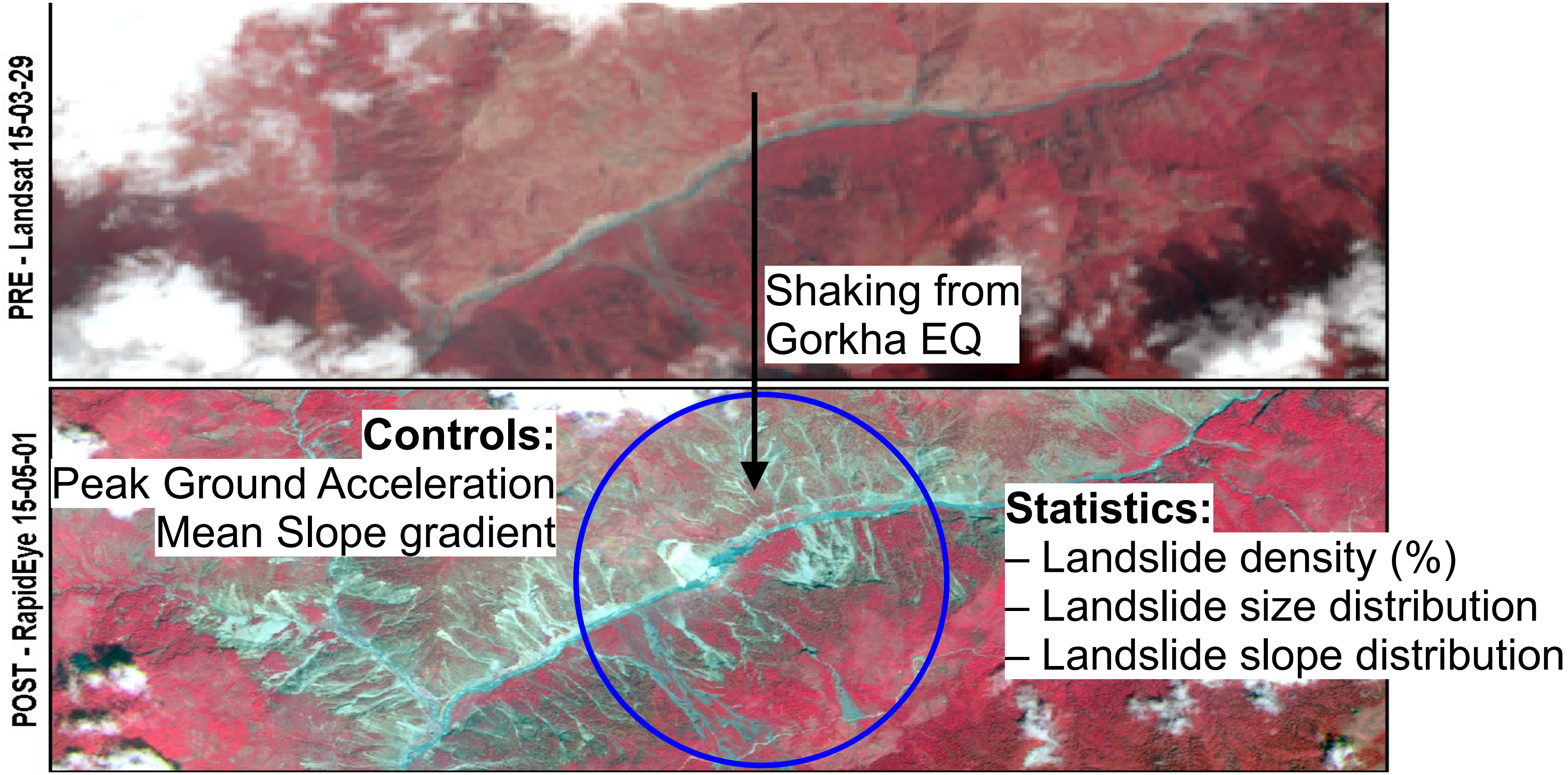
# How to get rid of the in-situ variability ?



# Averaging out landslide properties over spatial units

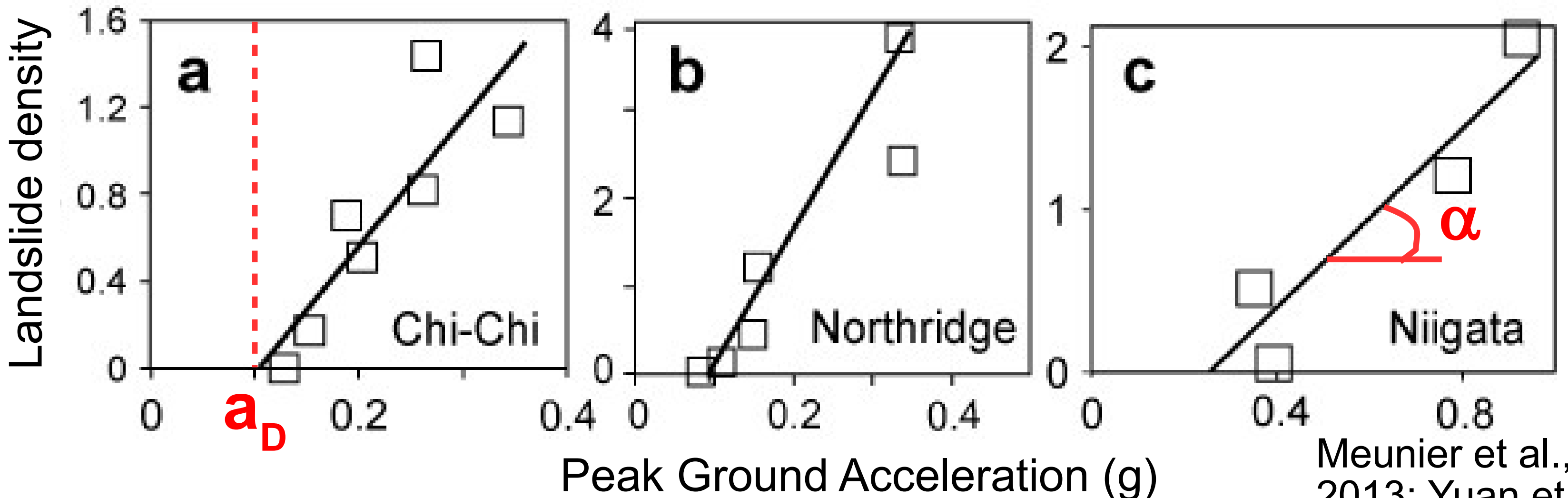
**We combine a comprehensive landslide polygon inventory, with information about its triggerring event !**

**Extract statistics over spatial cluster of landslide, within which trigger characteristics are known.**



# Landslide density scales with shaking

**Landslide density is proportional to the ground shaking above a threshold.**




Meunier et al., 2007, 2013; Yuan et al 2013.

$a_D$= Threshold acceleration for damage. Assumed constant at 0.15g

$\alpha$ = Landscape sensitivity modulated by slope, cohesion and pore pressure

**→ Combining prediction about fault dimension and shaking level (from seismology), with such scaling and adjusting with landscape topographic characteristics (from geomorphometry) we can predict total landsliding by EQ and total affected area.**

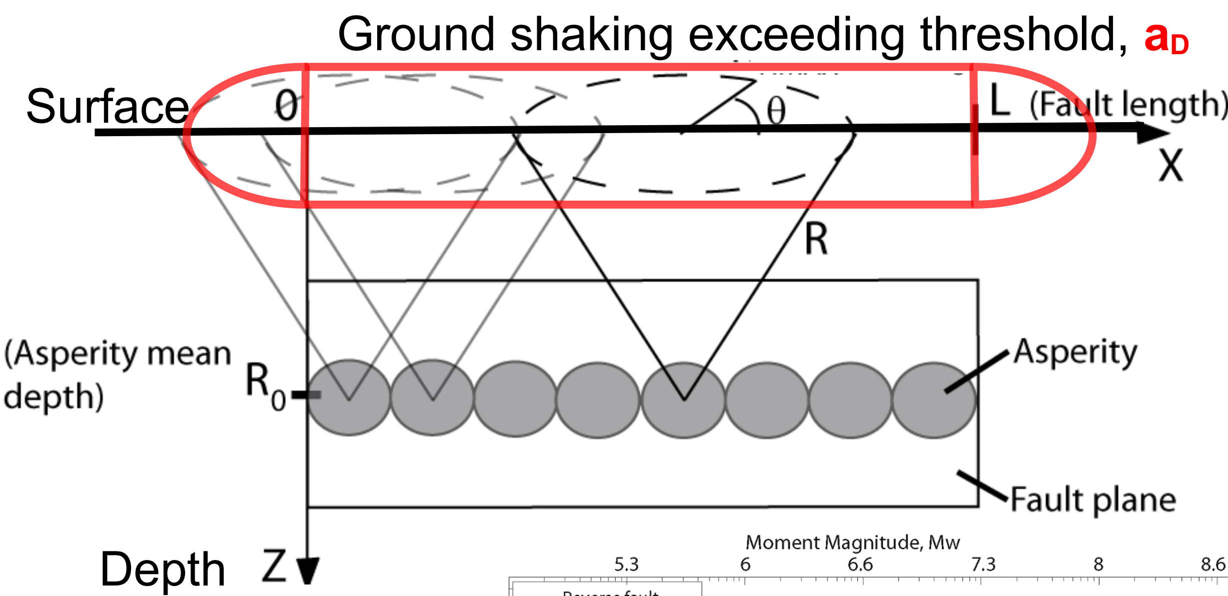
# Applications to model landslide response to earthquake

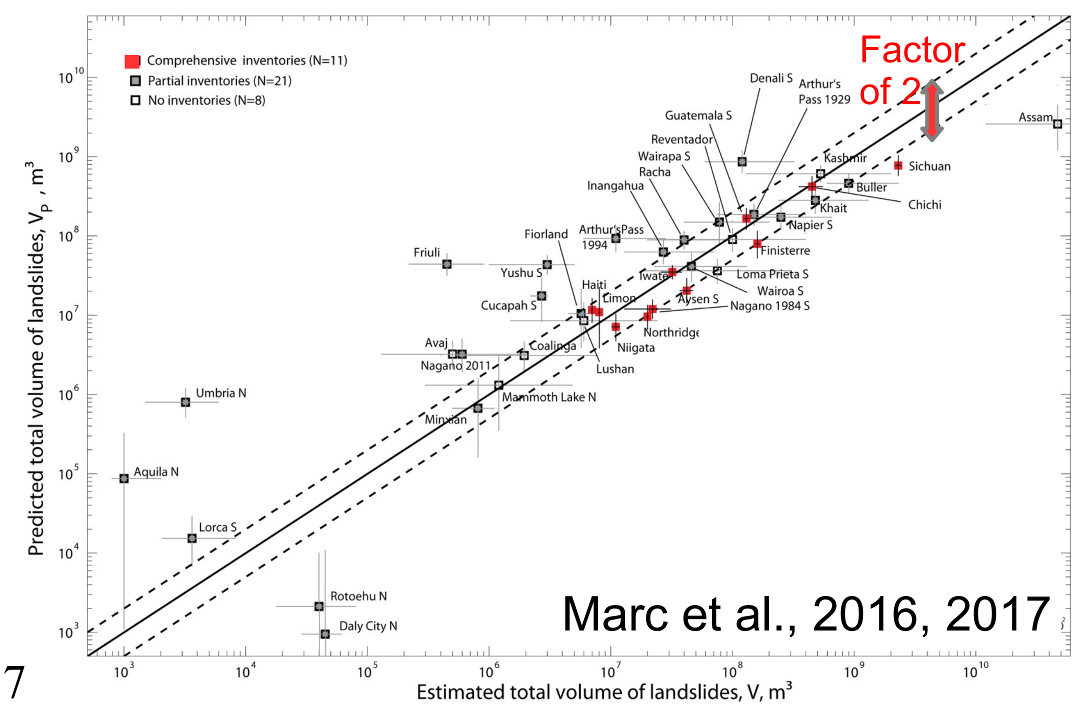
**Analytical prediction of:**

1) Landscape area affected

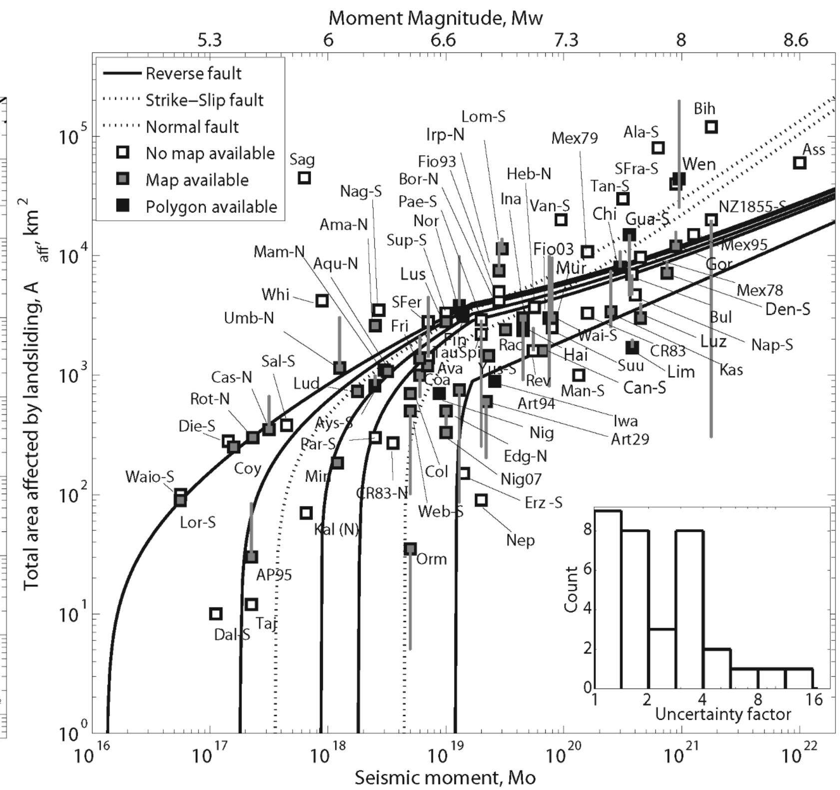
2) Total landslide volume, and area, within it.

More details in online materials



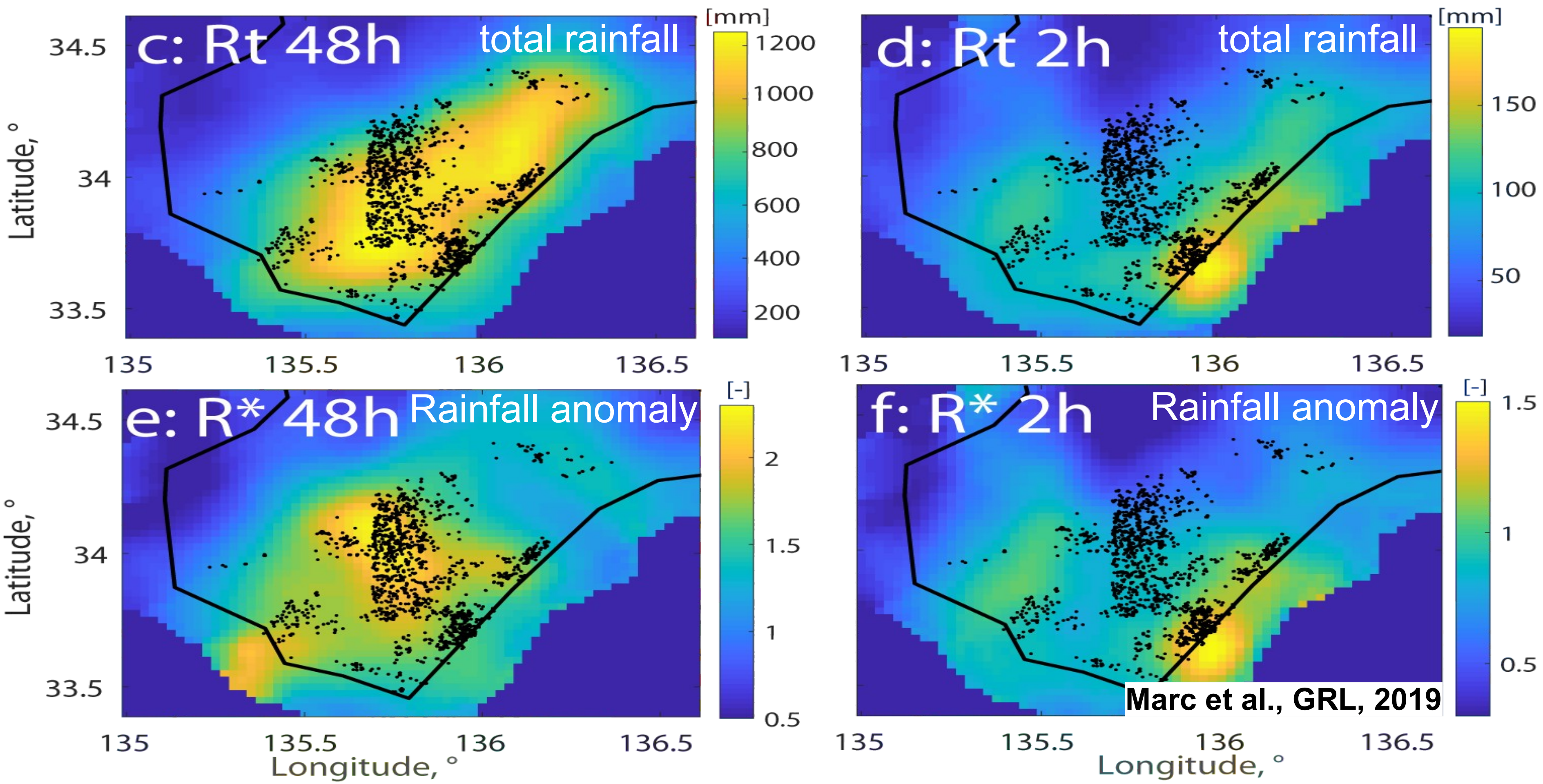




Marc et al., 2016, 2017



# Landsliding matches rainfall anomaly: $R^*=Rt/R_{10}$

We hyptohesize that regolith properties have evolved witht he local extreme frequency, here quantified by the 10 year- return rainfall.




**More on Tuesday at 11H40 in session NH 3.6:**

**Global assessment of the skills of satellite precipitation products to retrieve extreme rainfall events**

# Application to co-seismic and non-seismic landsliding in Nepal

# Multi-temporal landslide inventories

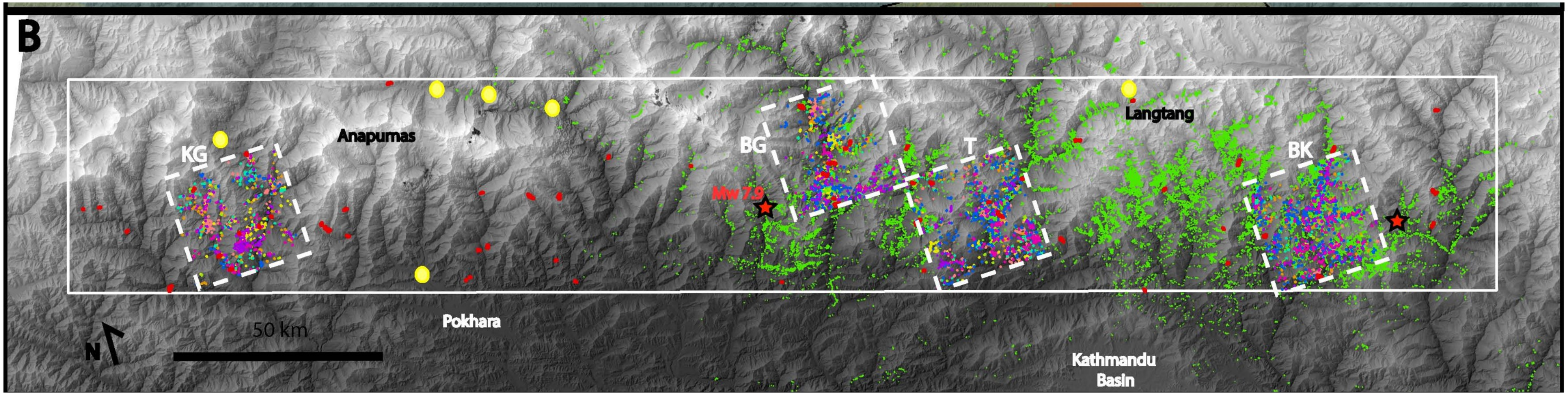
6 giant landslides (>1km$^3$) deposits for the last 50 kyr compiled from the literature.

80 large landslides (> 0.1km$^2$) mapped with Landsat between 1972-2014 (46 years).

>4000 monsoon-induced landslides from mapping in 4 catchments from 2010-2017.

>20,000 earthquake-induced landslide (Mw 7.8 Gorkha 2015; Roback et al., 2018)

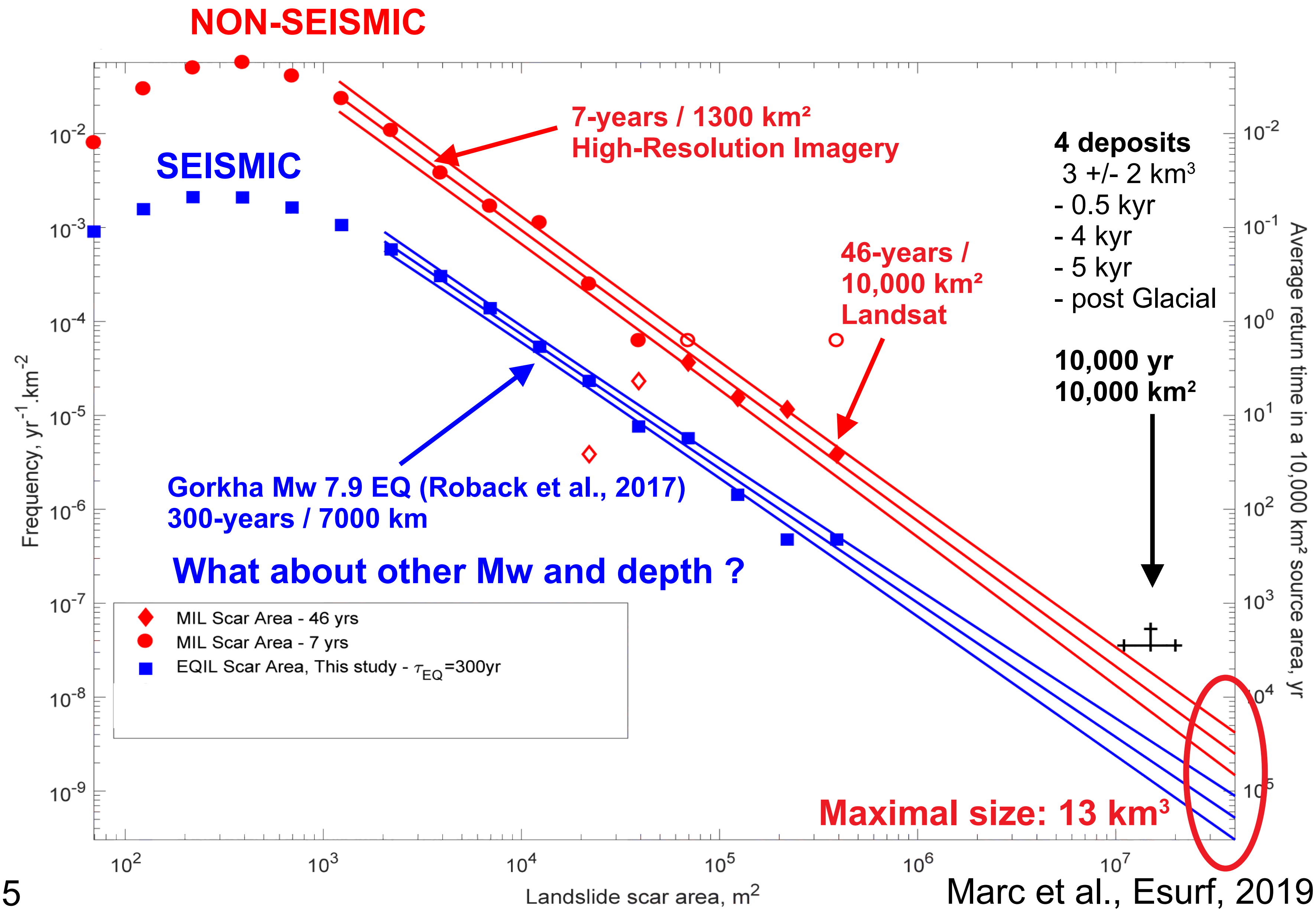
**We can constrain the relative frequency and erosion of different seismic and aseismic landslide sizes.**






Marc et al., Esurf, 2019

# Landslide FAD for distinct triggers

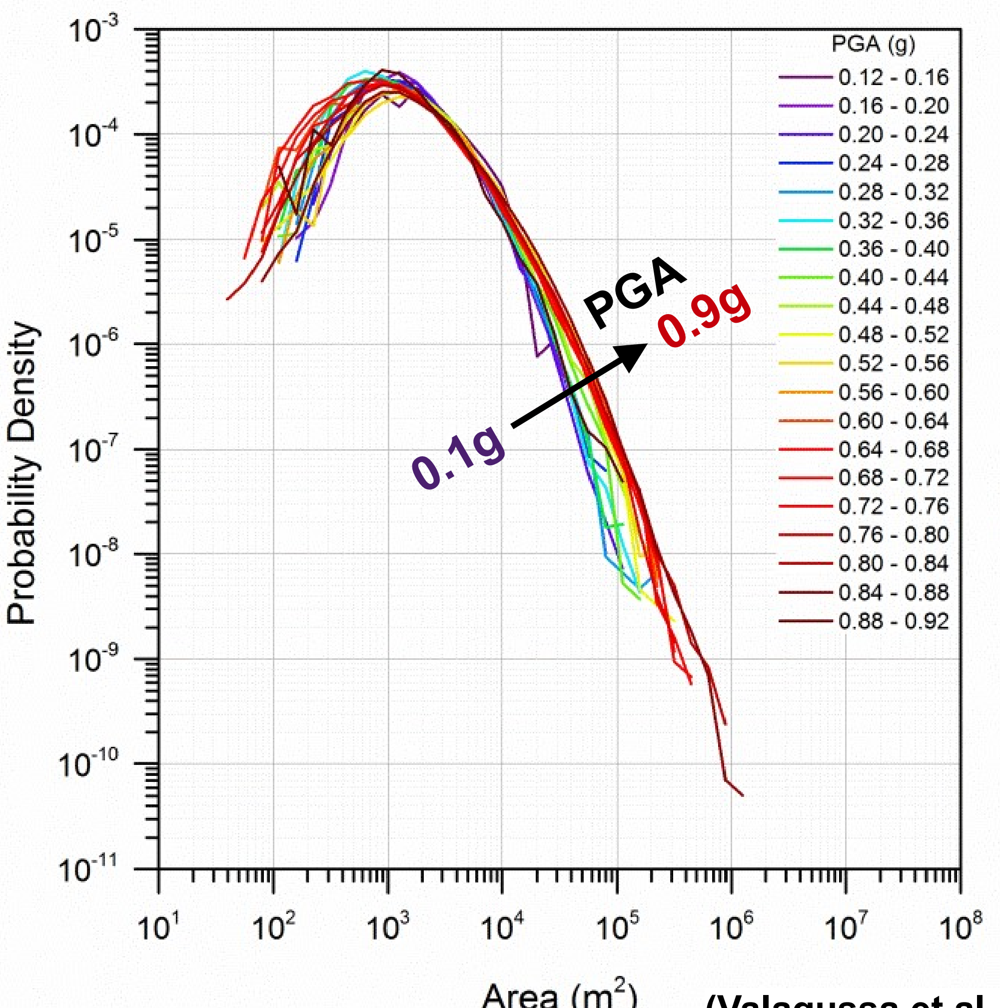



Marc et al., Esurf, 2019

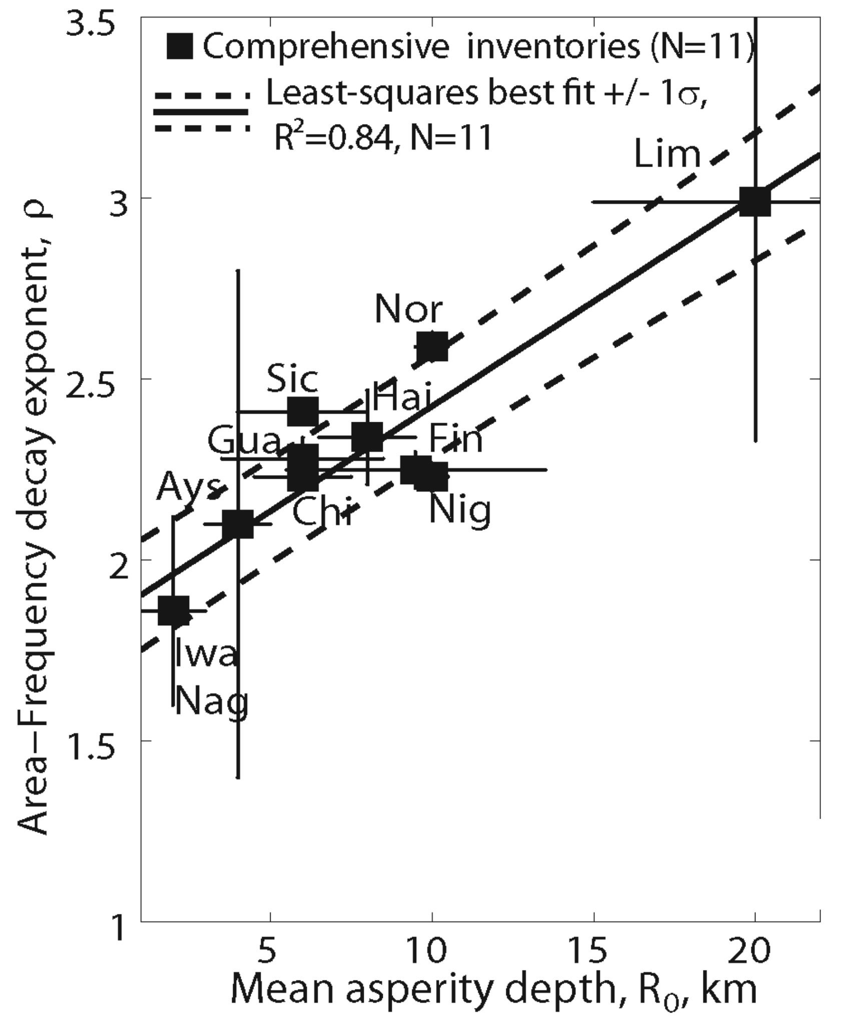
# Earthquakes cause landslides with variable FAD !

→ **Landslide size distribution varies with ground shaking !**

– Within the epicentral zone : more larger landslide for strong shaking.
– Between EQ, deeper earthquake have less large landslides.



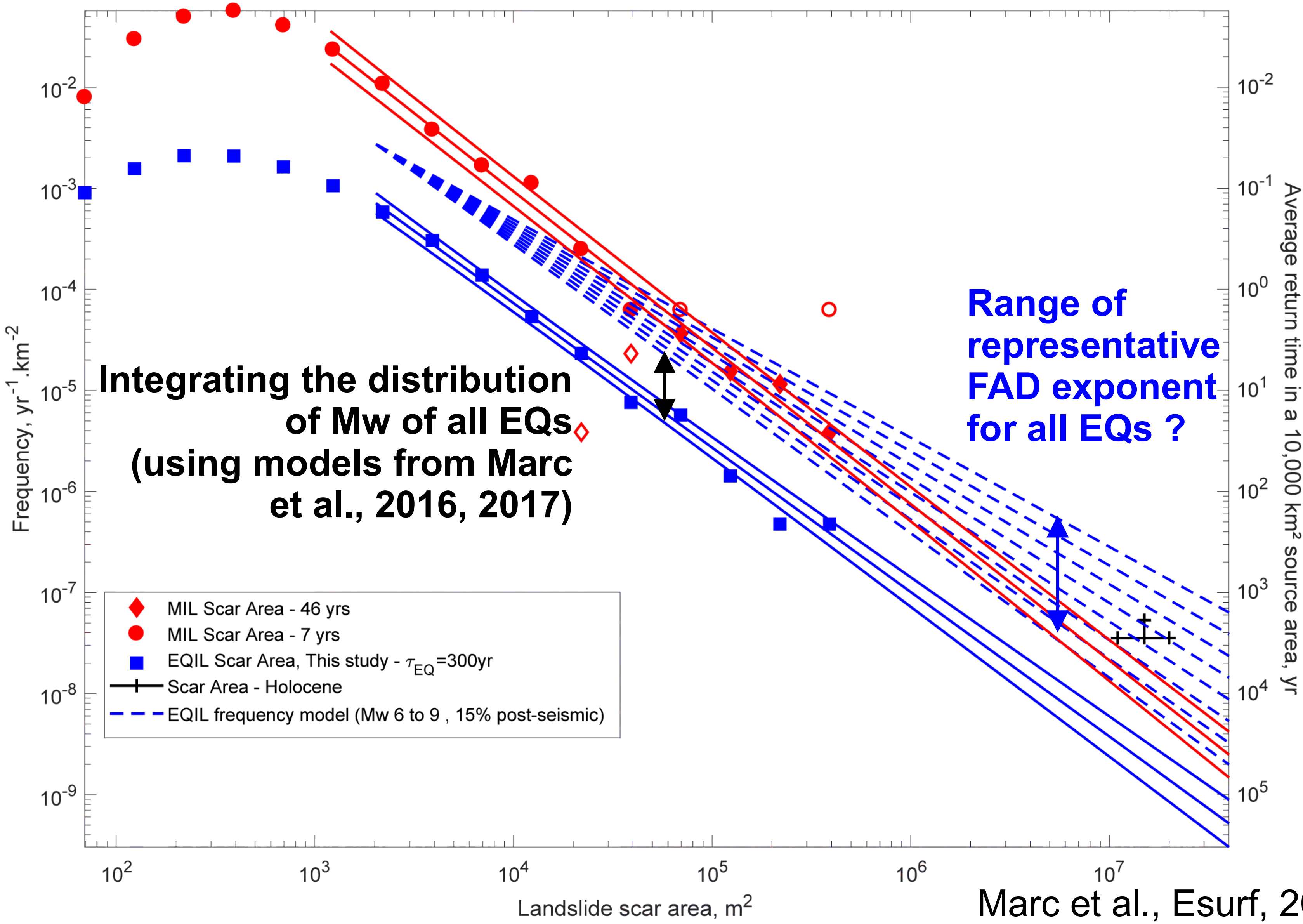

**(Valagussa et al., EPSL, 2019)**




**(Marc et al., JGR, 2016)**

# Model-assisted Landslide Freq. Area Distrib.

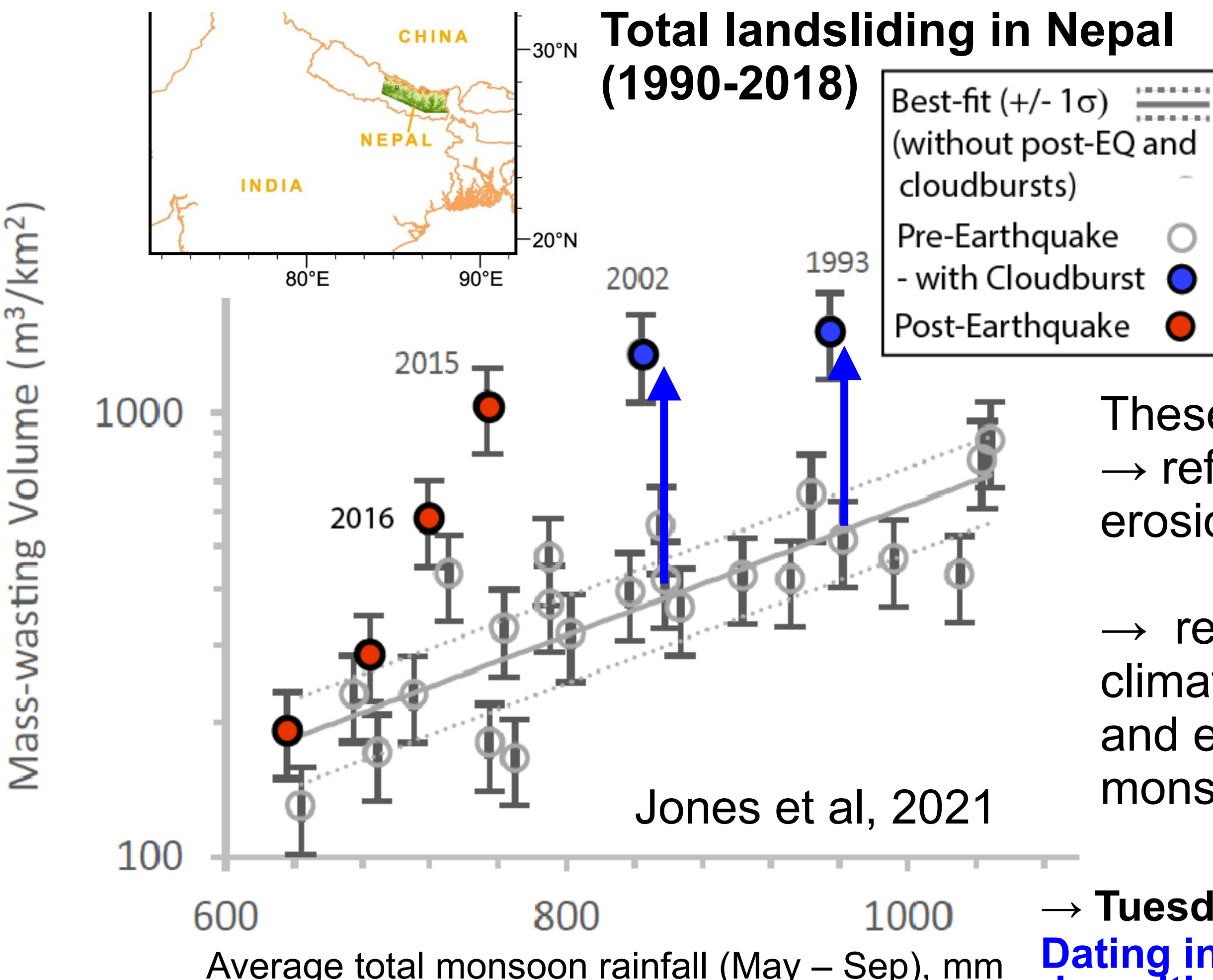
**→ integrating these mixture of FAD allows to retrieve long-term erosion rate in Nepal, with monsoon and EQ contributing half of the total erosion.**




Marc et al., Esurf, 2019

# Landslide FAD varies with the triggers

**New results from 30 years of landslide mapping in Nepal !**




These new findings may allow to
→ refine the long-term landslide erosion estimate

→ relate paleo-erosion rate to climatic variability affecting the mean and extreme rainfall during the monsoon.

→ **Tuesday at 14H20 in session NH 9.8:**
**Dating individual rainfall-triggered landslides with Sentinel-1 SAR time series: Application to the Nepal monsoon**

# CONCLUSIONS*

**Landslide Frequency Area distribution is considered the main tool to retrieve landslide erosion rate, but it varies with both landscapes and triggers.**

**So how to find the representative FAD, over long periods ?**

**Characterizing landscape response to trigger events allows to:**
**→ ground physically the shift from an empirical FAD, based on a limited sample of trigger event, to the representative FAD.**
**In Nepal, with this approach we retrieve a landslide erosion rate similar to the long-term exhumation rate, and half come from earthquake triggering.**

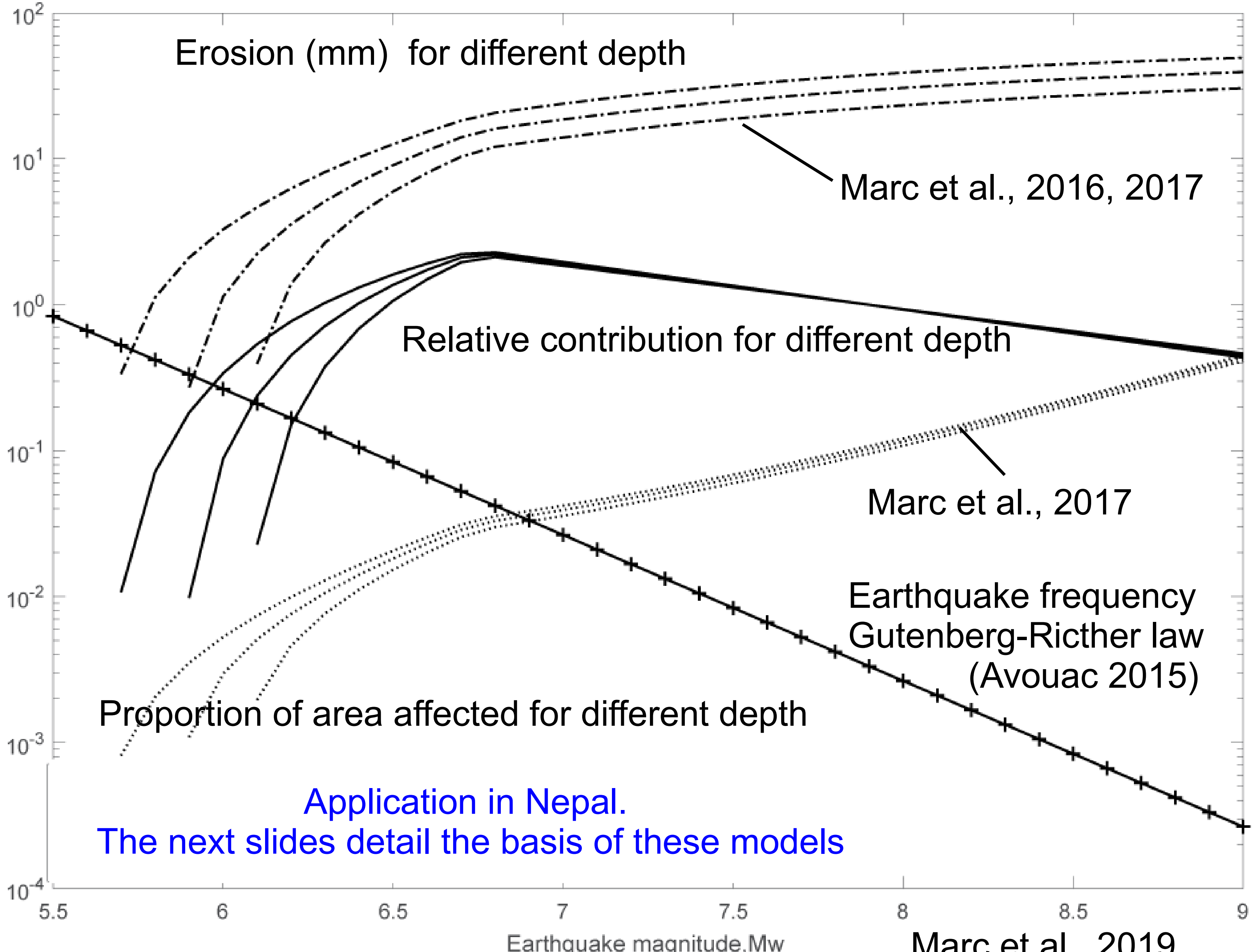
**→ At finer scale it may also allow to understand or predict spatial or temporal variations in erosion rate.**
**Future goal: understand the impact of the frequency of extreme rainfall during the monsoon and its variation.**

**→ check other presentation by Marc et al NH 3.6 and Burrows et al., NH 9.8**

**→ To safely integrate until very large landslide sizes we must also improve our understanding of the necessary and sufficient causes for deep-seated landsliding .**

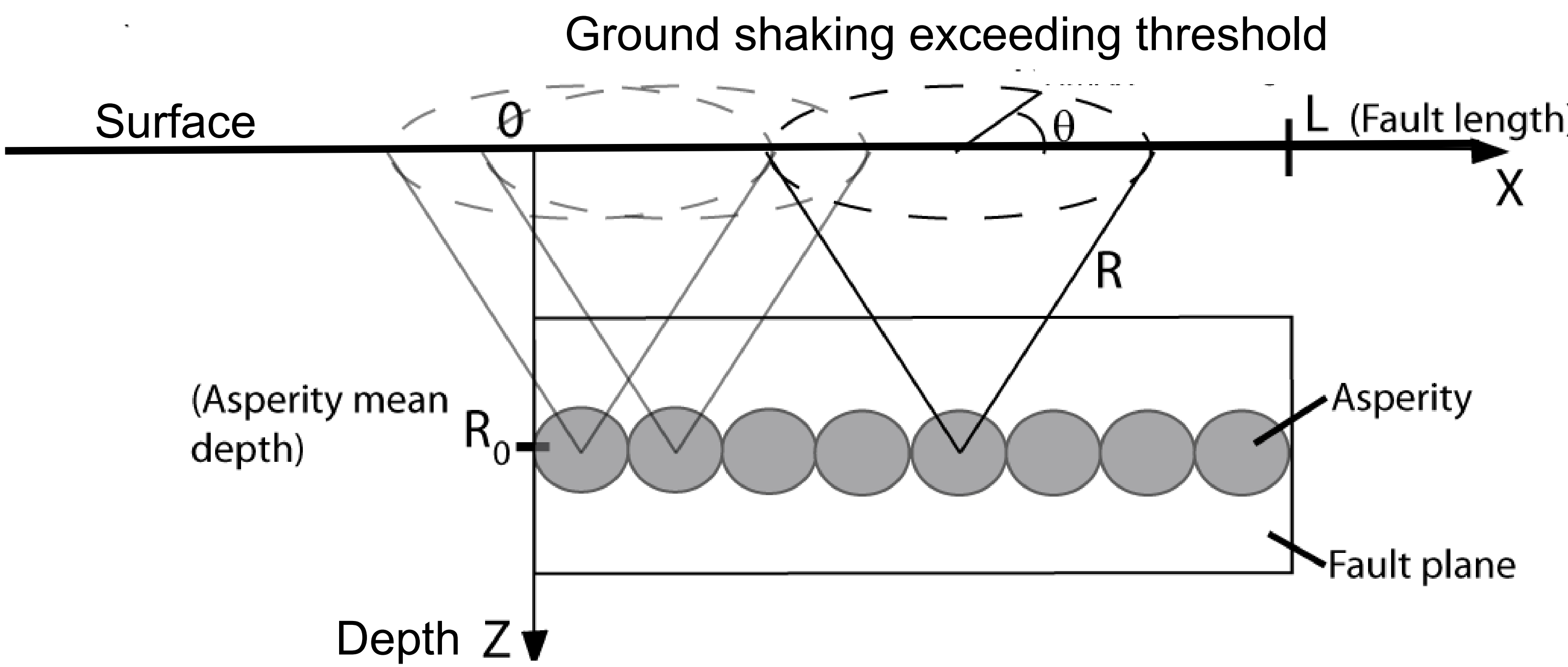
*** Check the extra slides online if you want to see more details !**

# Impact of earthquakes: modelling All Mw




Marc et al., 2019

# Details on the coseismic landslide model (all following slides until the bibliography)




**Ground-motion modeling:**

Wave emitted at the source.

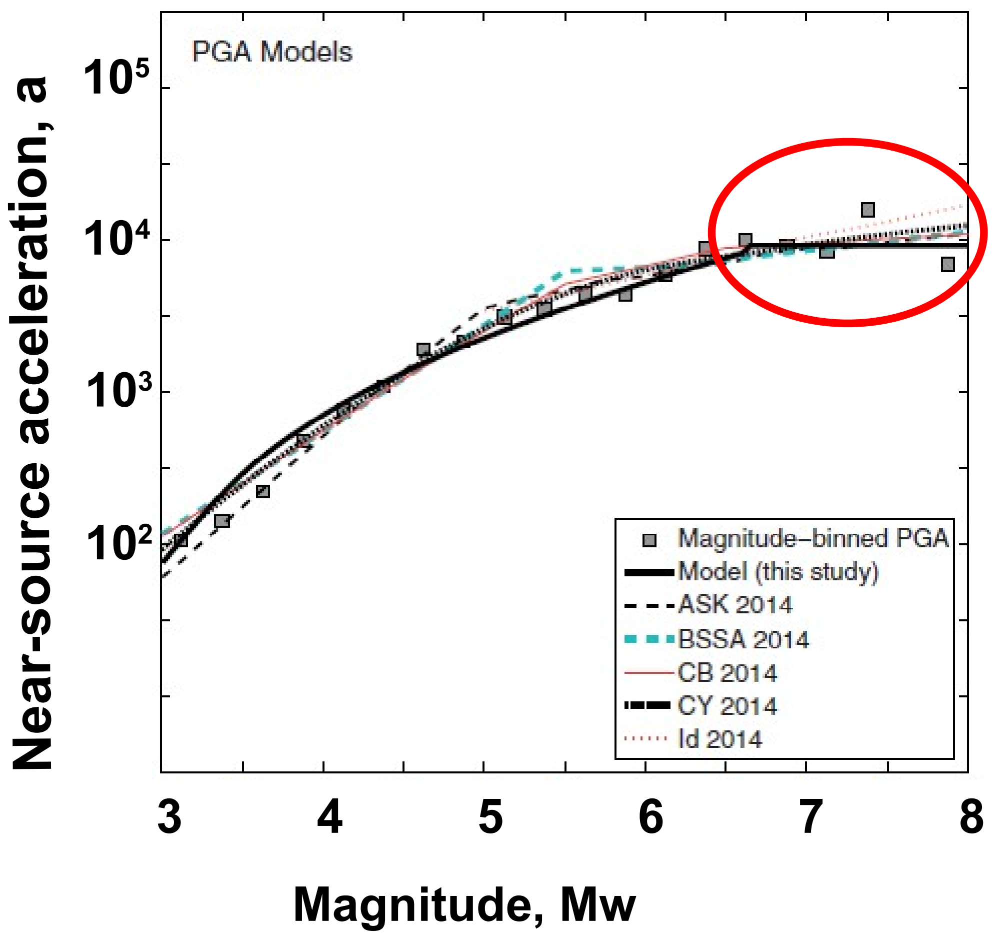
→ **What controls wave amplitude?**

Wave amplitude attenuates from depth to surface.

Multiple sources along the fault length rupture.

→ **What control fault length ?**

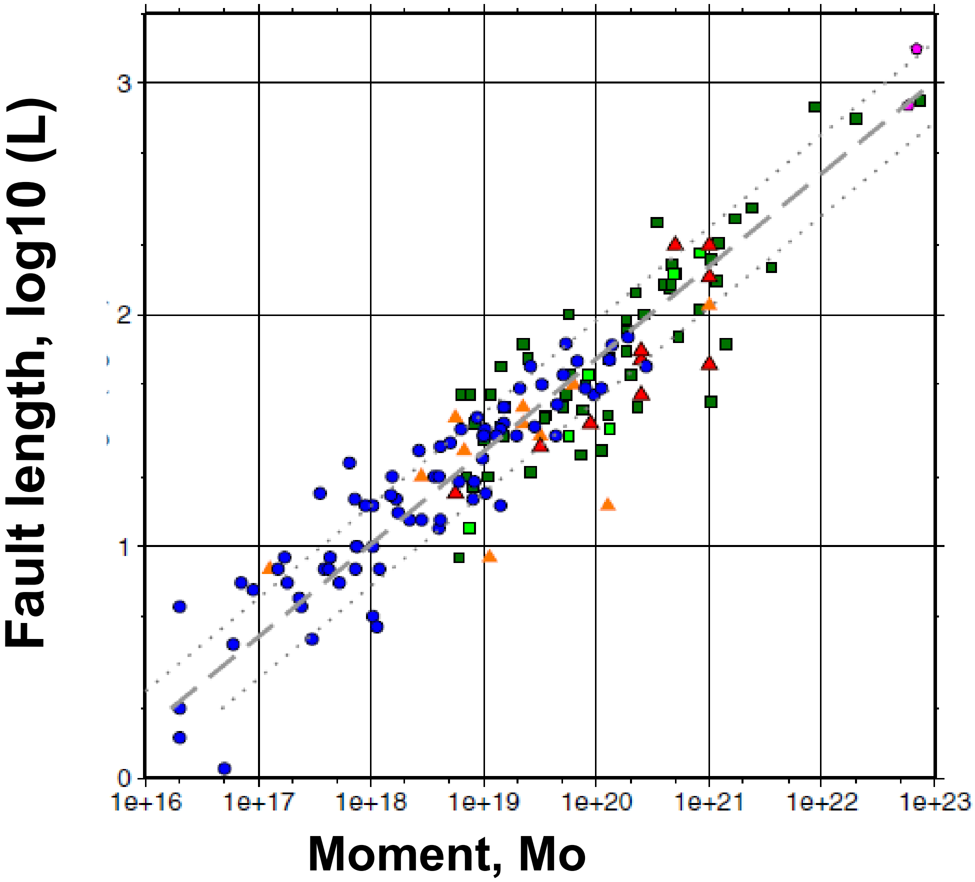
# Ground shaking intensity




→ Saturation before Mw ~7, due to the attenuation of high frequency waves.

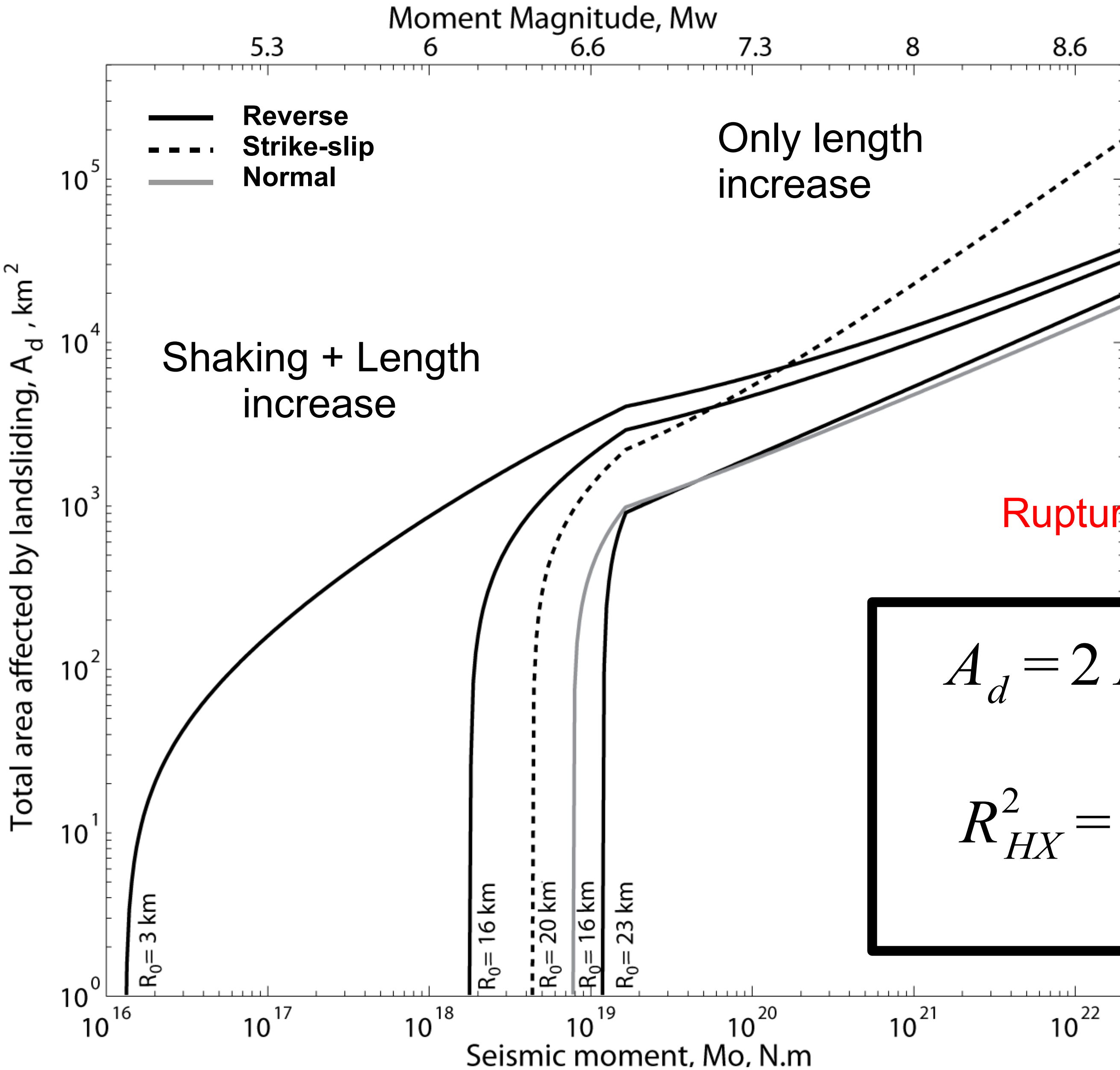
Boore and Atkinson 2008, Baltay and Hanks 2014

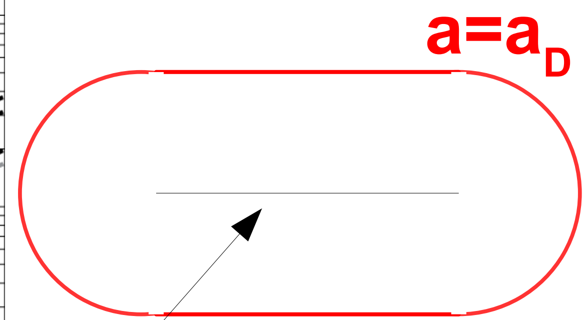
# Fault length scaling




Leonard, 2010

# Prediction for landslide distribution area




Rupture length

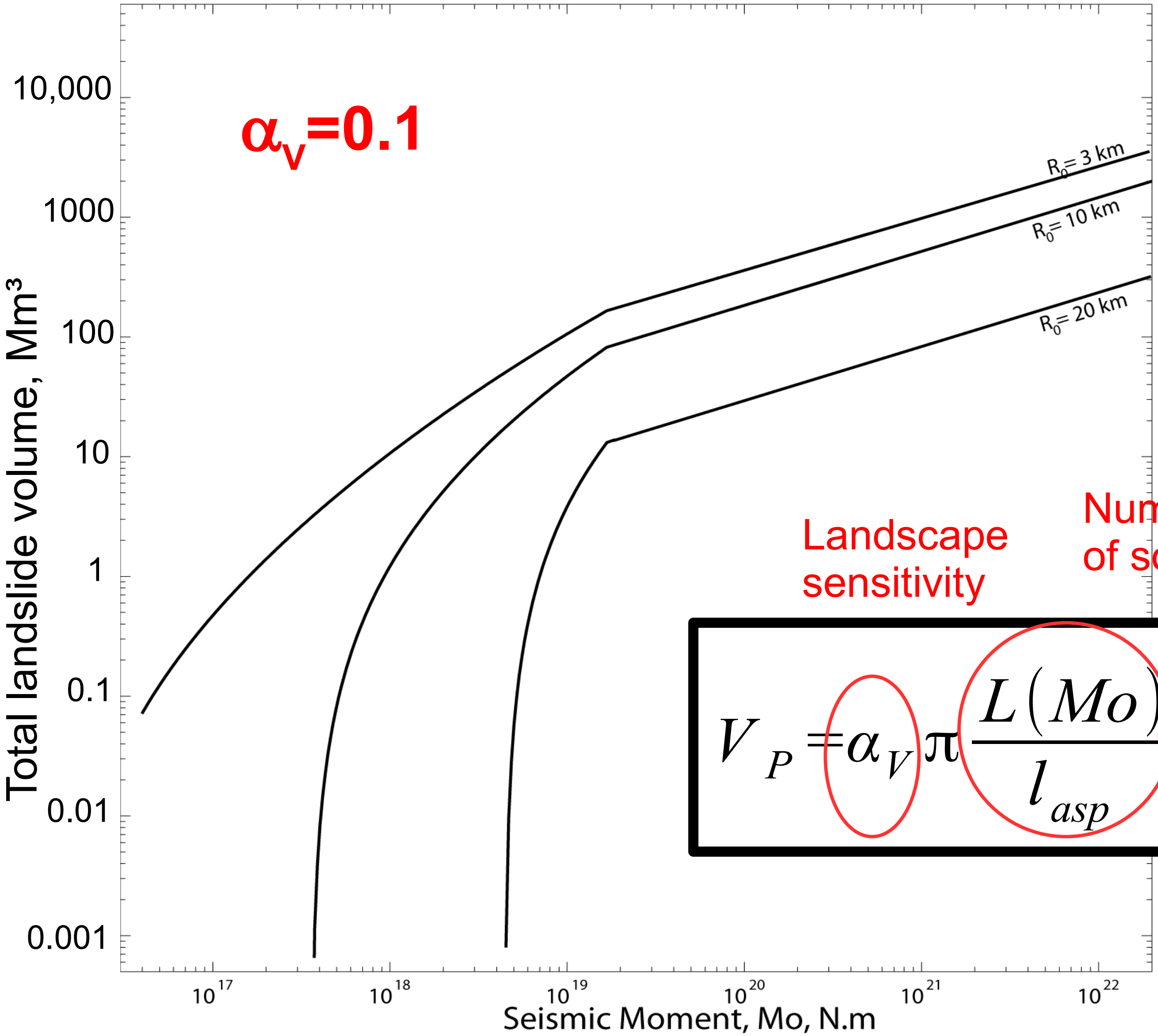
Horizontal extent of landsliding

$$A_d = 2\,L\,R_{HX} + \pi\,R_{HX}^2$$

$$R_{HX}^2 = \left(\frac{a}{a_D}\right)^2 - R_0^2$$

**Marc et al., 2017, NHESS**

# Prediction for total landslide volume or area




Landscape sensitivity sets constant.

Equivalent prediction for the total landslide area.

Landscape sensitivity

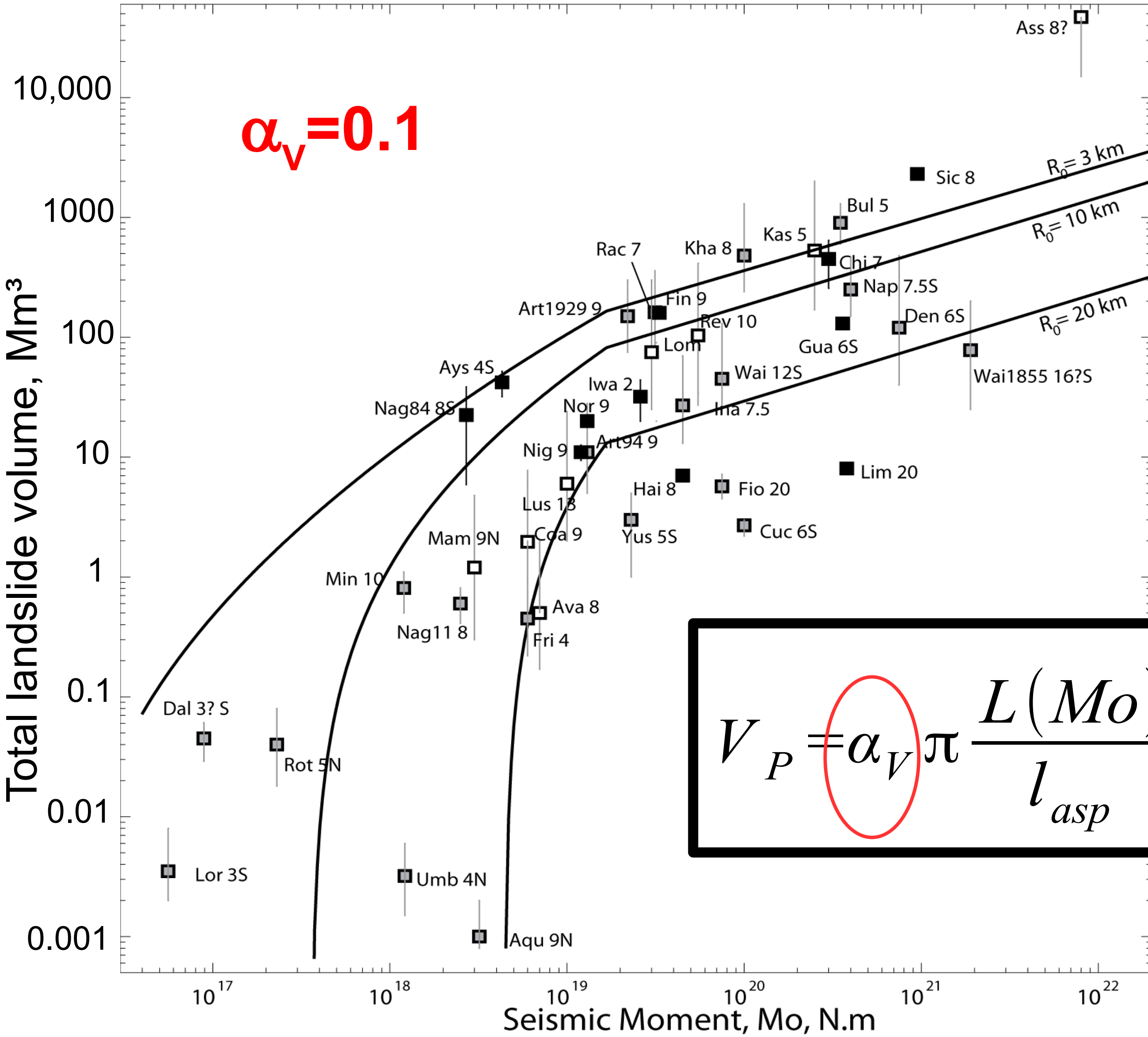
Number of sources

Source shaking

$$V_P = \alpha_V \pi \frac{L(Mo)}{l_{asp}} a_D R_0^2 \left( \frac{a(Mo)}{R_0 a_D} - 1 \right)^2$$

**Marc et al., 2016, JGR**

# Total landslide volume prediction




$$V_P = \alpha_V \pi \frac{L(Mo)}{l_{asp}} a_c R_0^2 \left( \frac{a(Mo)}{R_0 a_c} - 1 \right)^2$$

**Tested with a database of 40 earthquakes with:**

**Geophysical constraints;**

**Landslide volume estimate;**

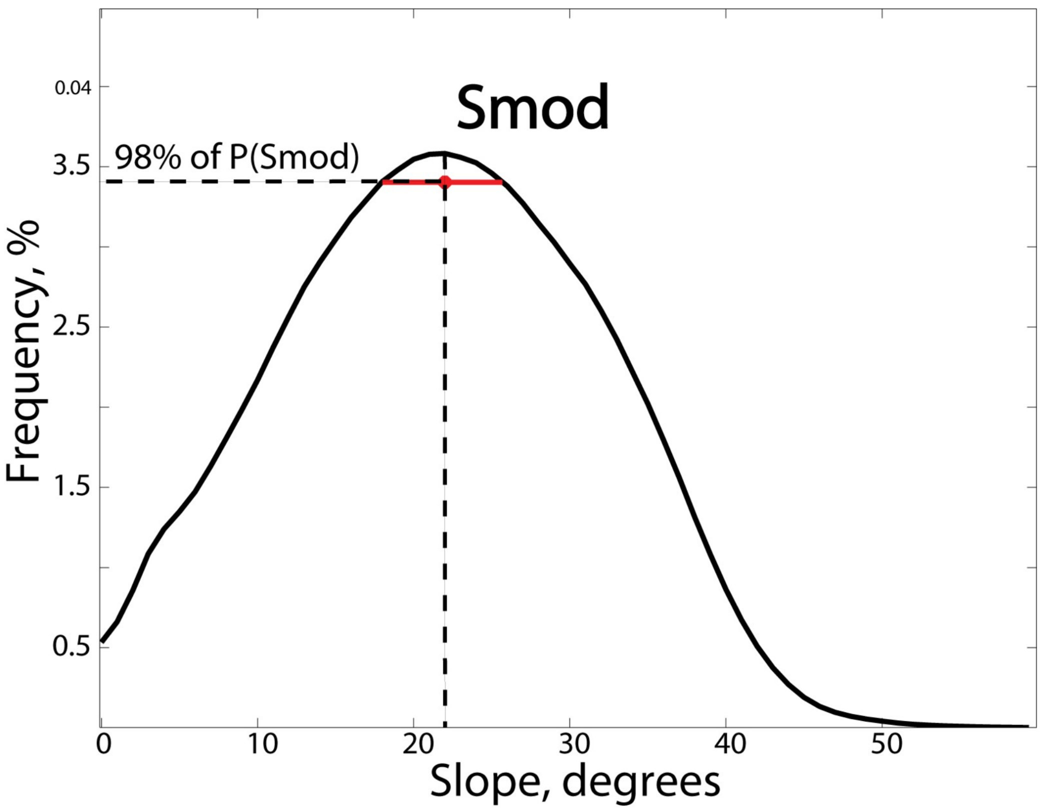
**→ How does slope gradient affect landscape sensitivity?**

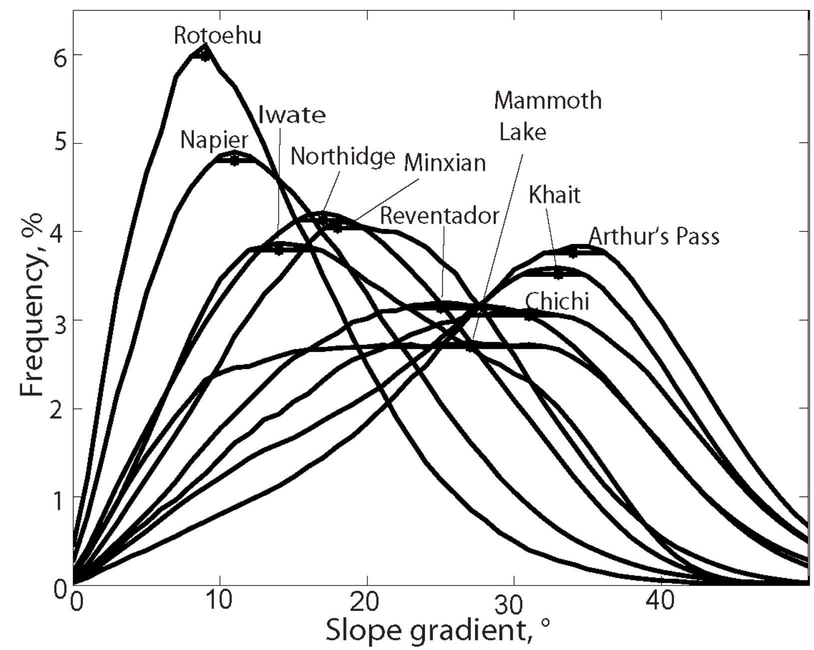
**Marc et al., 2016**

# Landscape sensitivity

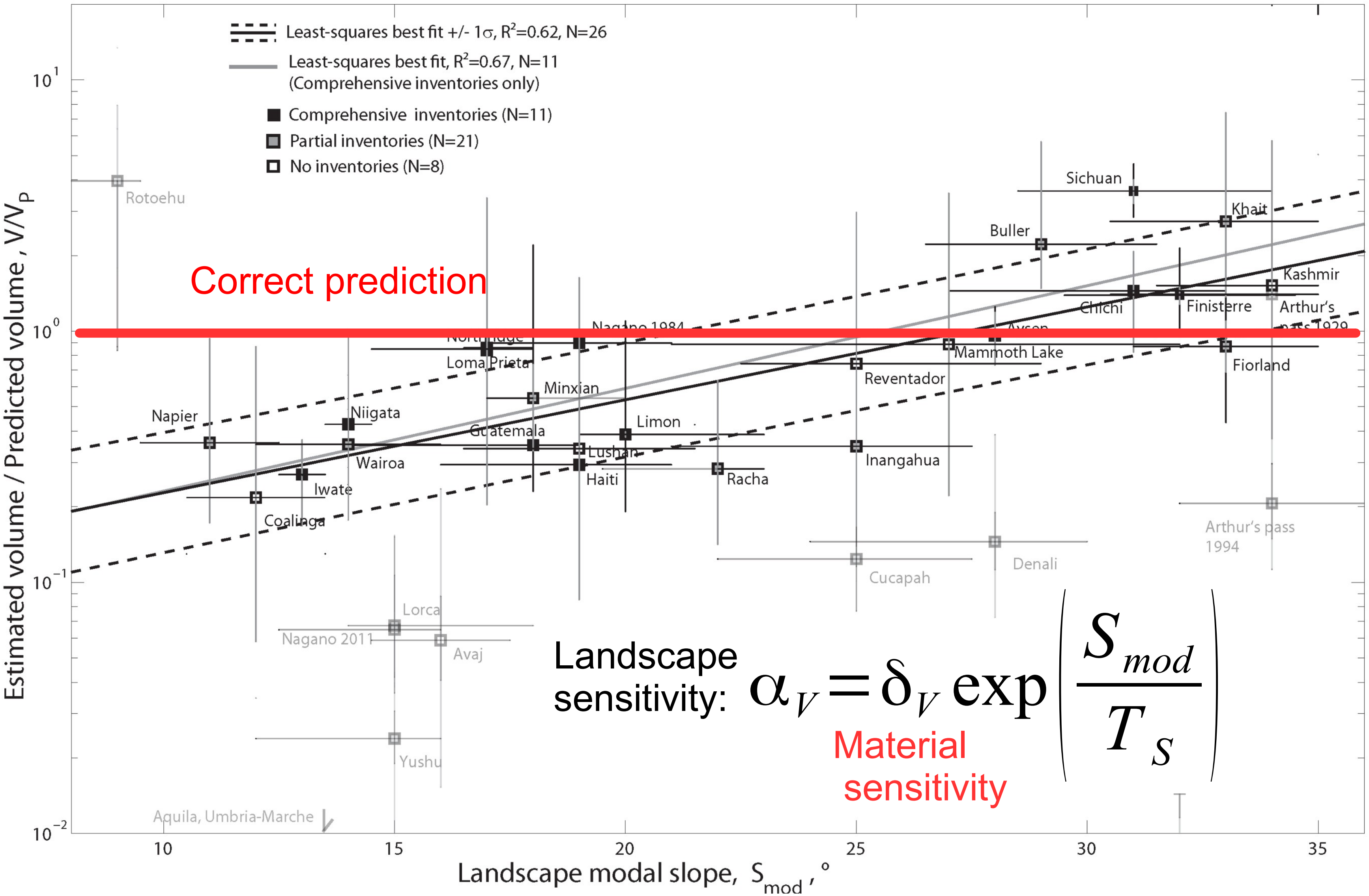
**Topographic threshold:**
**No landslide on insufficient slopes → correction for available topography.**

**Above the threshold steeper slopes should be more prone to landsliding.**



# Slope gradient influence




$$\alpha_V = \delta_V \exp\left(\frac{S_{mod}}{T_S}\right)$$

**Marc et al., 2016, JGR**

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**Hovius, N.**, Stark, C. P., and Allen, P. A.: **1997, Sediment flux from a mountain belt derived by landslide mapping,** https://doi.org/10.1130/0091-7613(1997)025

**Marc, O.**, Behling, R., Andermann, C., Turowski, J. M., Illien, L., Roessner, S., and Hovius, N.: **2019, Long-term erosion of the Nepal Himalayas by bedrock landsliding: the role of monsoons, earthquakes and giant landslides**, https://doi.org/10.5194/esurf-7-107-2019