Can we use earthquake probability to predict landslide probability?

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Abstract

Landslides are often viewed together with other natural hazards, such as earthquakes and fires, as phenomena whose size distribution obeys an inverse power law. Inverse power law distributions are the result of additive avalanche processes, in which the final size cannot be predicted at the onset of the disturbance. Volume and area distributions of submarine landslides along the U.S. Atlantic continental slope follow a lognormal distribution and not an inverse power law. Using Monte Carlo simulations, we generated area distributions of submarine landslides with a characteristic size and with few smaller and larger areas, which can be fit well by a lognormal distribution. To generate these distributions we assumed that the area of slope failure depends on earthquake magnitude, i.e., that failure occurs simultaneously over the area affected by horizontal ground shaking, and does not cascade from nucleating points. Furthermore, the downslope movement of failed sediments does not excavate significant amounts of additional material. Area distribution of slope failures along the Atlantic continental slope can be fit well by our simulations, if we assume that the slope has been subjected to earthquakes of magnitude ≤ 6.3. Regions of submarine landslides, whose area distributions obey inverse power laws, such as off the north coast of Puerto Rico, may be controlled by different generation mechanisms, such as the gradual development of fractures in the headwalls of cliffs.

Because the size distribution and recurrence interval of earthquakes is generally better known than those for submarine landslides, we propose here to estimate the size and recurrence interval of submarine landslides from the size and recurrence interval of earthquakes in the near vicinity of the said landslides. To do so, we calculate maximum expected landslide size for a given earthquake magnitude, use recurrence interval of earthquakes to estimate recurrence interval of landslide, and assume a threshold landslide size that can generate a destructive tsunami. The maximum expected landslide size for a given earthquake magnitude is calculated by slope stability analysis for catastrophic slope failure on the Atlantic continental margin. The results suggest that a M_w=7.5 earthquake (the largest expected earthquake in the eastern U.S.) must be located offshore and within 100 km of the continental slope to induce a catastrophic slope failure. Thus, a repeat of the 1755 Cape Anne and 1881 Charleston earthquakes are not expected to cause landslides on the continental slope. The observed rate of seismicity offshore the U.S. Atlantic coast is very low with the exception of New England, where some micro-seismicity is observed. An extrapolation of annual strain rates from the Canadian Atlantic continental margin suggests that the New England margin may experience the equivalent of a magnitude 7 earthquake on average every 600-3000 years. A minimum triggering earthquake magnitude of 5.5 is suggested for a sufficiently large submarine failure to generate a devastating tsunami and only if the epicenter is located within the continental slope.

What can the statistical distribution of submarine and subaerial landslides tell us about the initiation process of landslides and about landslide tsunami probability

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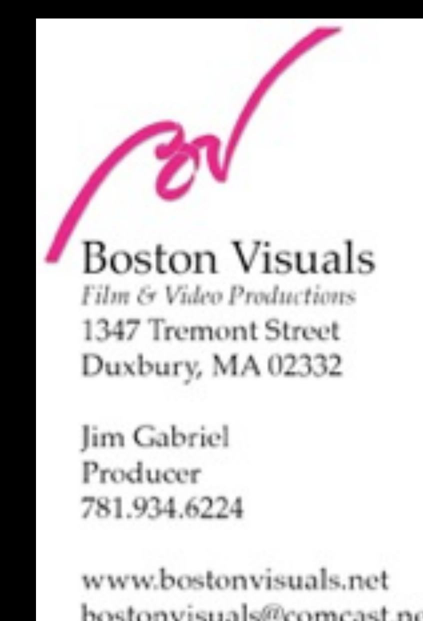

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Landslide, earthquakes, and tsunamis in carbonate and siliciclastic margins

Rationale

Because

- ~90% of landslide-generated tsunamis worldwide are associated with earthquakes.
- The magnitude distribution and recurrence interval of earthquakes is better known than those for submarine landslides.

And if

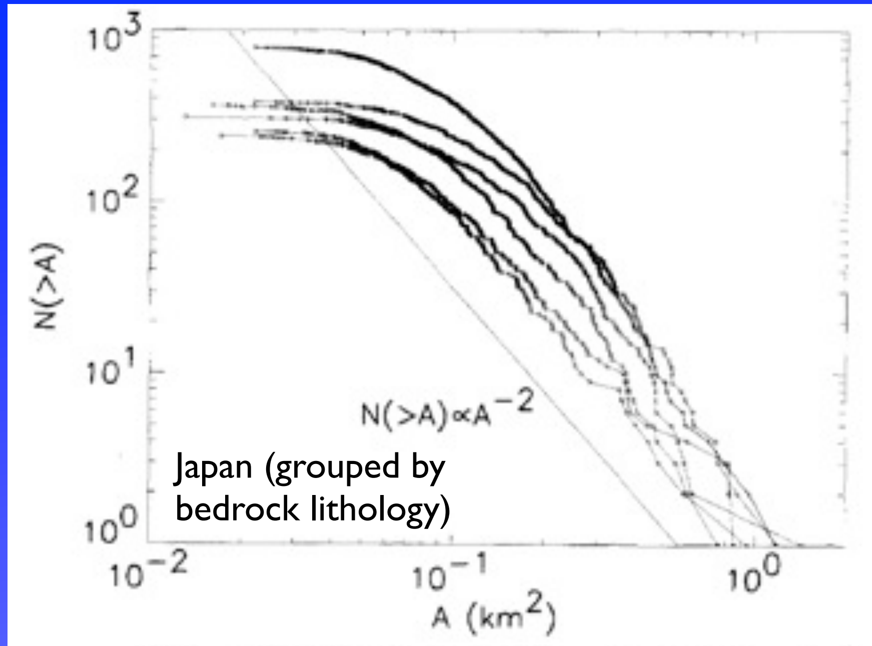
A relationship can be established between landslide volume and earthquake magnitude

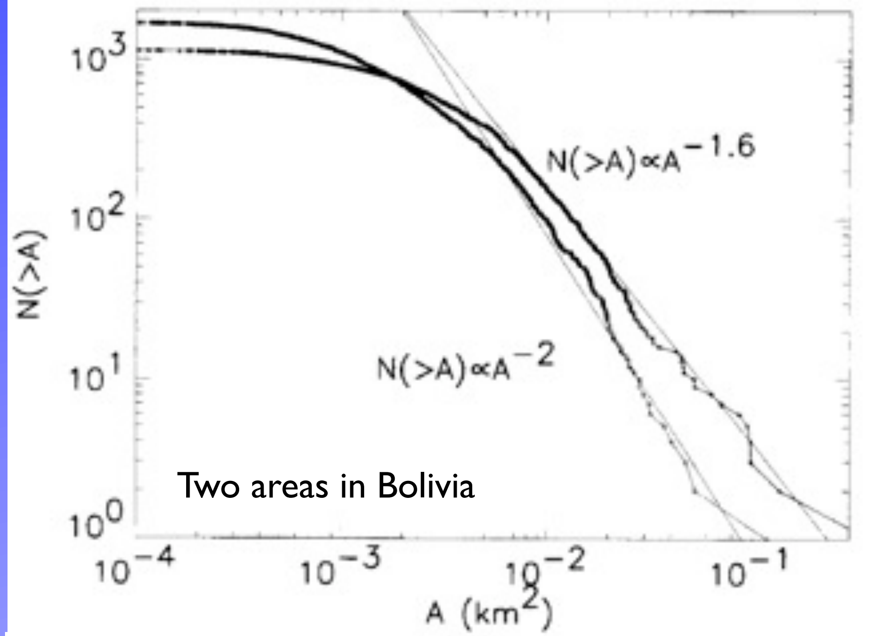
Then

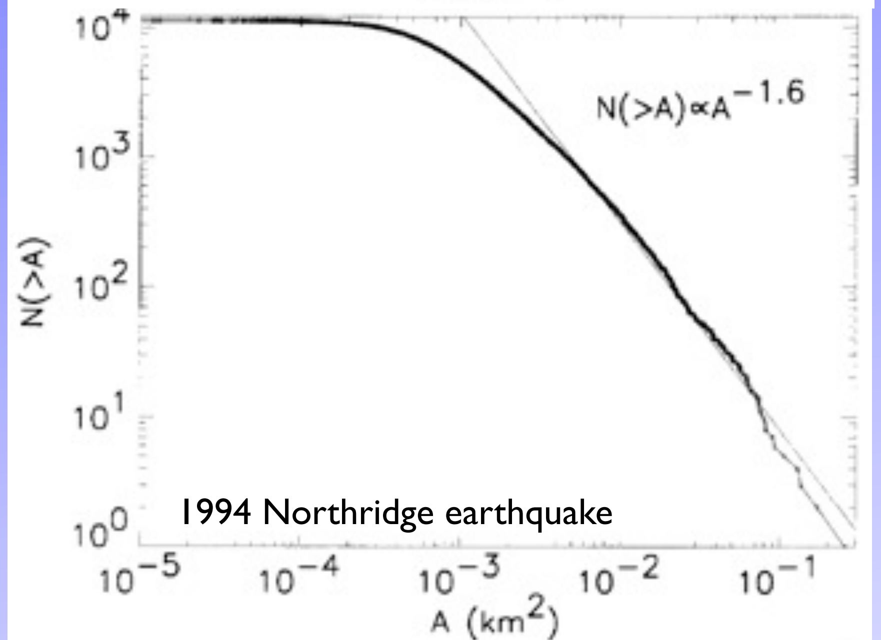
Earthquake magnitude distribution and recurrence interval may be used to estimate landslide volume distribution and recurrence interval?

Subaerial landslide statistics

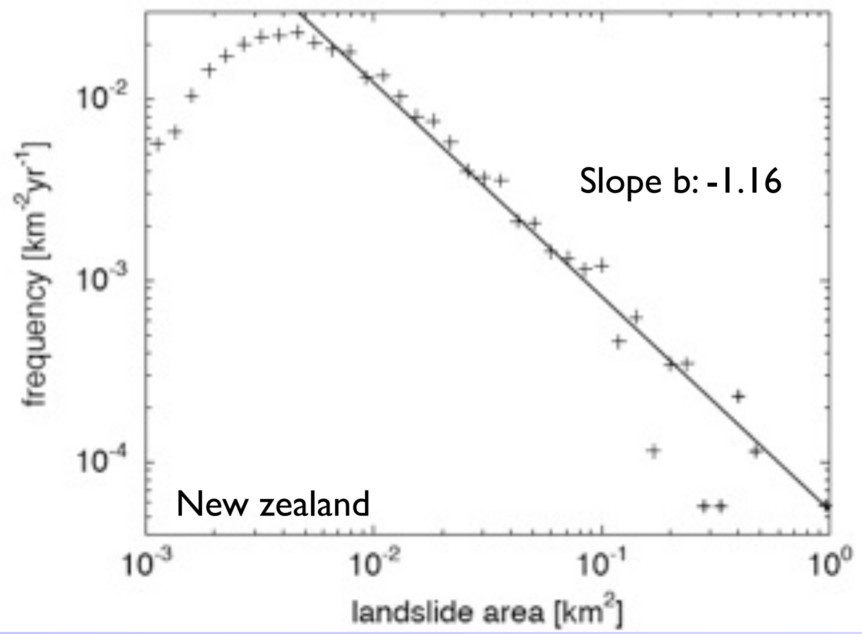
Inverse power law.
Also attempted fit with double Pareto and inverse Gamma functions



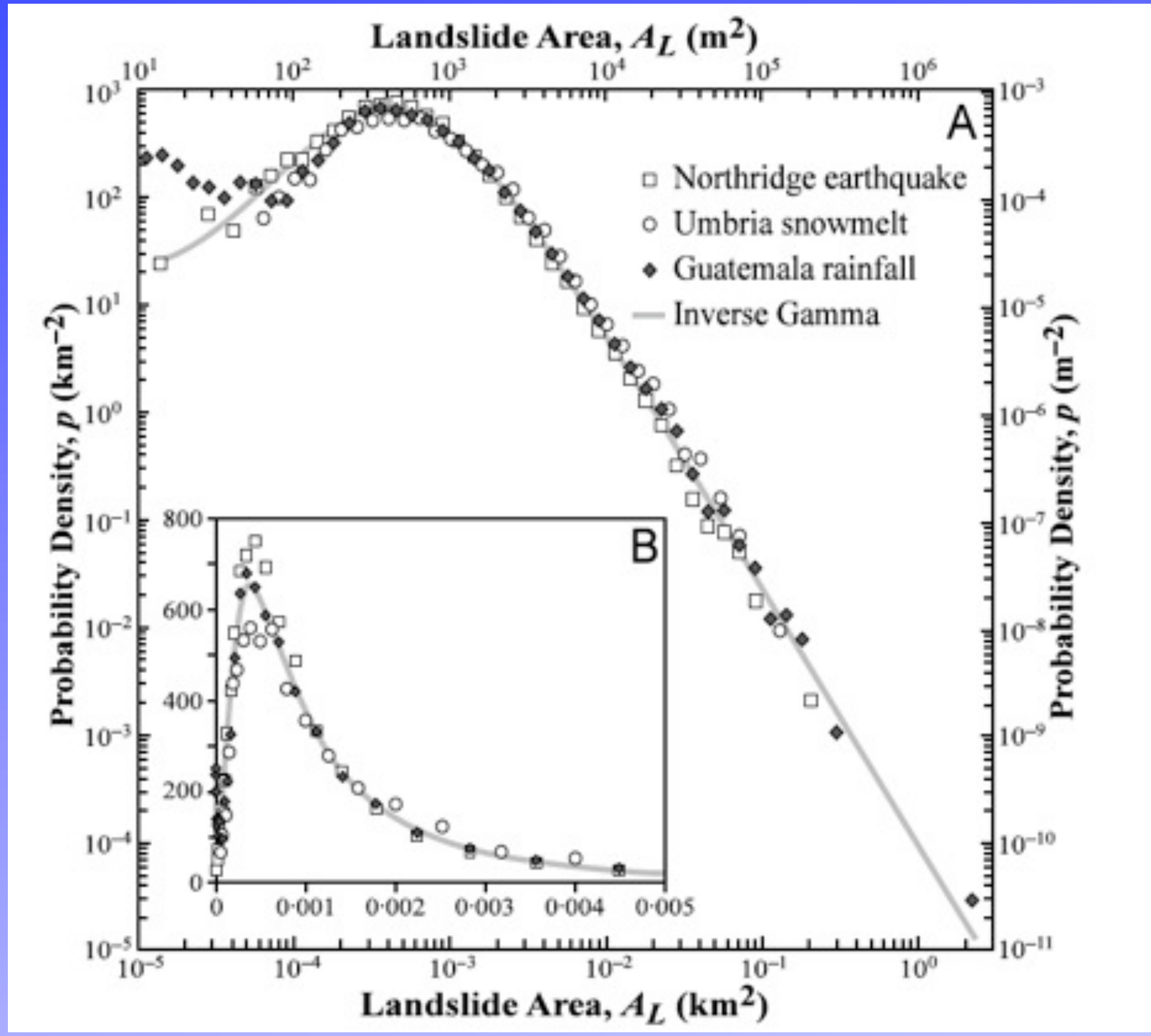




From Pelletier, Malamud, Blodget, and Turcotte, 1997



From Hovius et al., 1997



11,111 landslides triggered by 1994 Northridge earthquake
4,233 landslides triggered by 1997 snowmelt event in Umbria, Italy
9,594 landslides triggered by heavy rainfall from the 1998 Hurricane Mitch, Guatemala

From: Malamud, Turcotte, Guzzetti, Reichenbach (2004)

An inverse cascade explanation for the power-law frequency–area statistics of earthquakes, landslides and wildfires

BRUCE D. MALAMUD[1] & DONALD L. TURCOTTE[2]

Geological society of London Spec. Pub., 2006

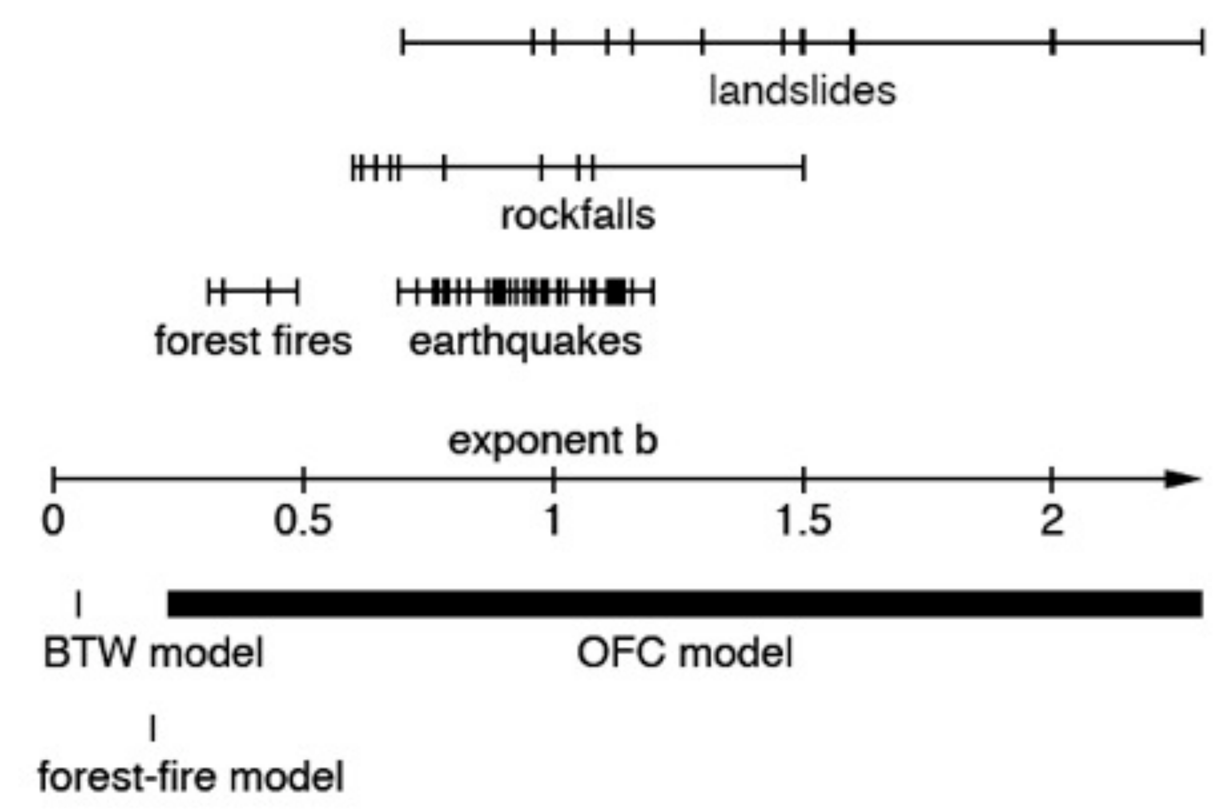


Fig. 2. Power-law exponents of the cumulative size distributions of some natural hazards (upper part) and results of the most widespread self-organized critical models (lower part).

(Hegarten, 2003)

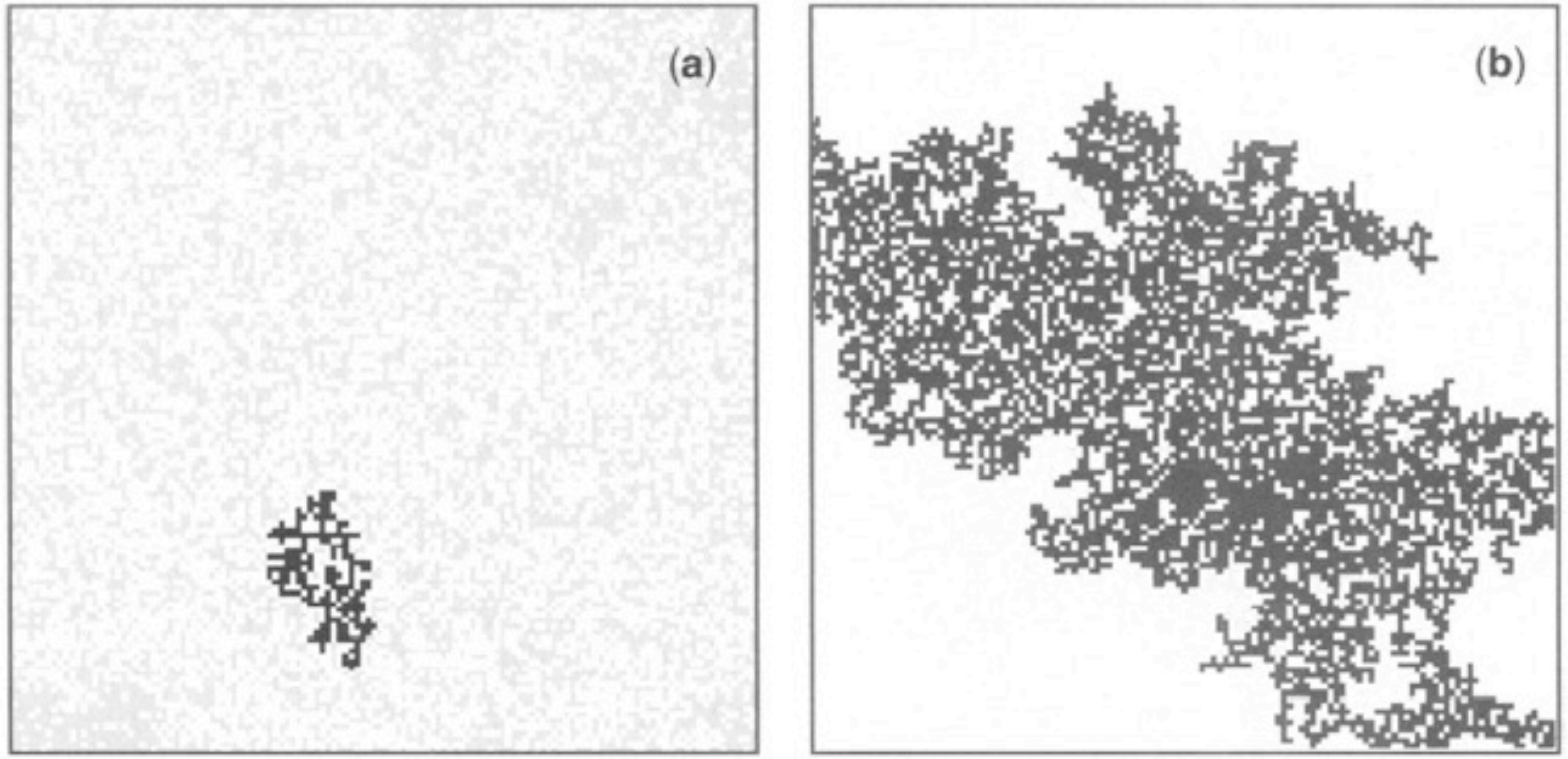


Fig. 3. Two forest-fire model examples using a grid of 128 × 128 cells and a forest-fire run with sparking frequency $1/f = 2000$. The black squares constitute the model forest fires. The light grey squares are unburned trees. The white regions are unoccupied grid points (i.e. no trees). The area of the model fire in (**a**) is $A_F = 204$ trees and in (**b**) $A_F = 5237$ trees; the latter is seen to span the entire grid.

Inverse power law implies an avalanche process whose final size cannot be predicted at the onset of the event

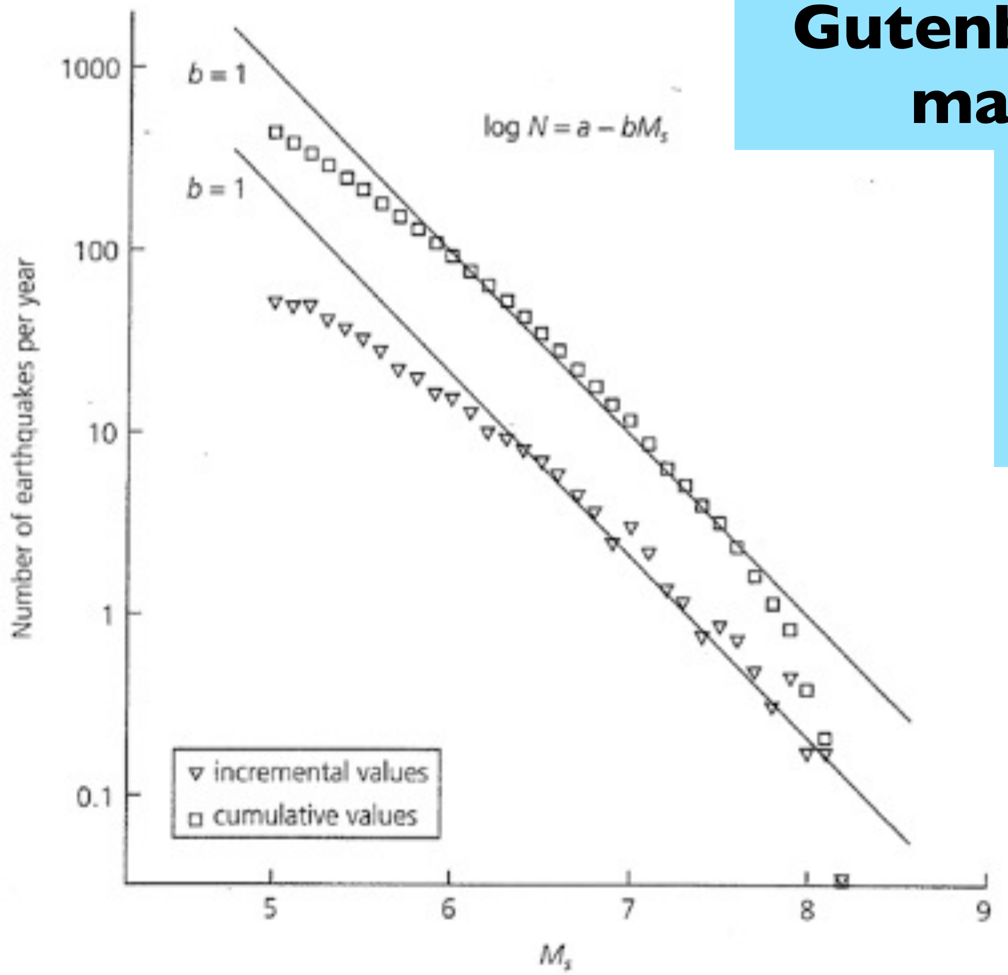
Gutenberg-Richter frequency-magnitude relationship

Log N = a - bM

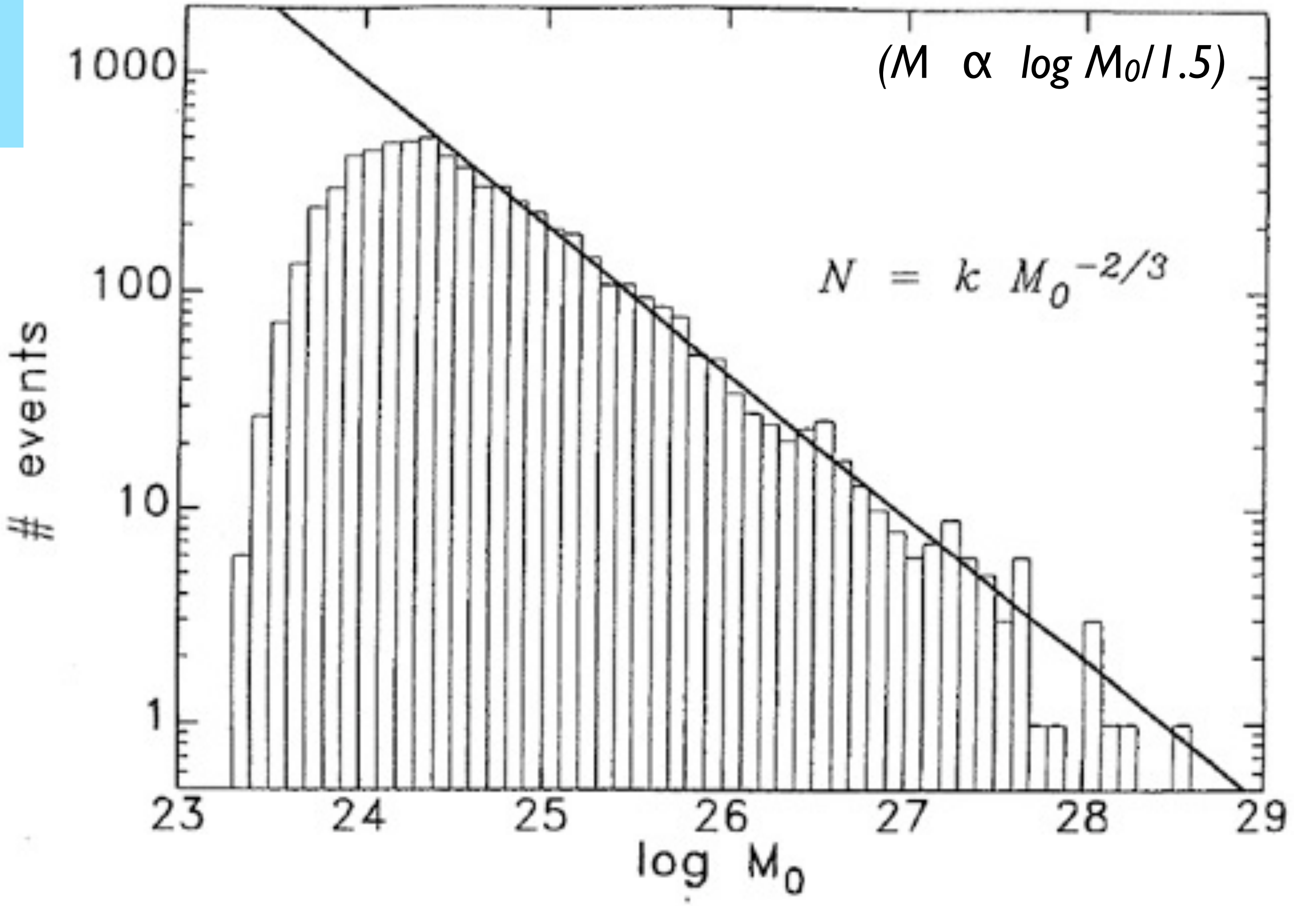
N - # earthquakes > M

b - slope (exponent)

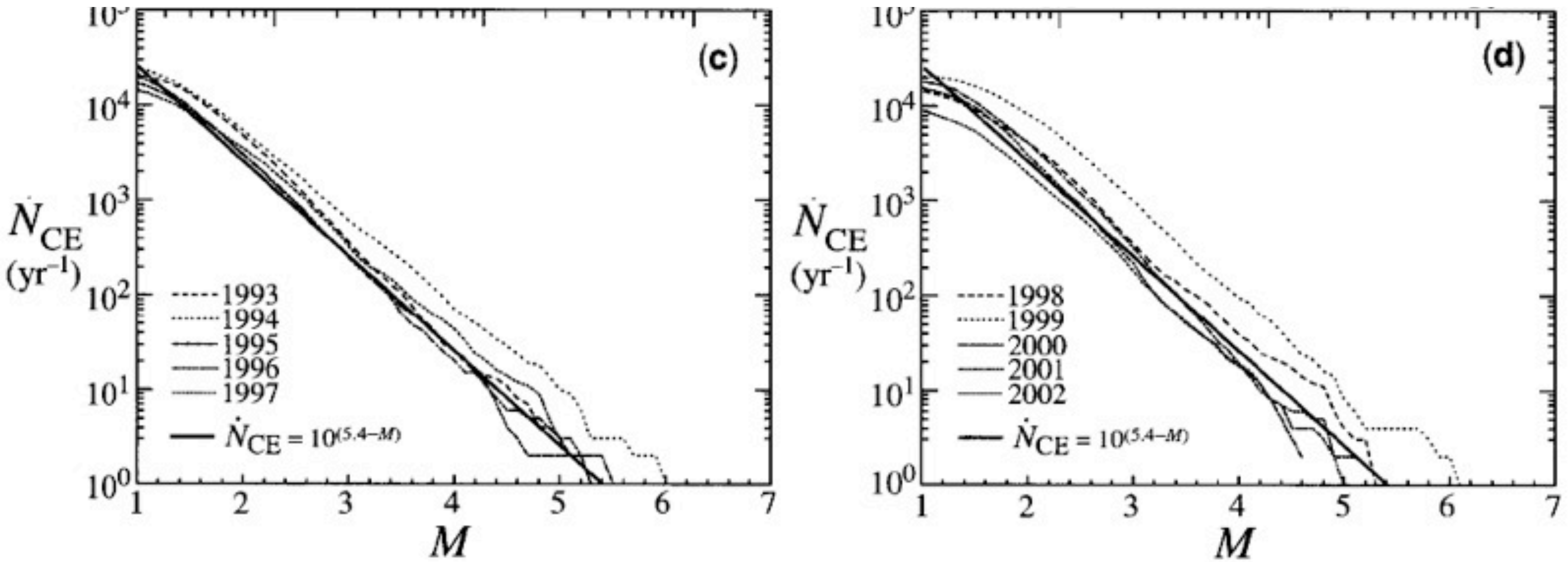
a - constant



Cumulative and incremental plots for all earthquakes 1968-1997 as a function of magnitude (Stein and Wysession, p. 274)



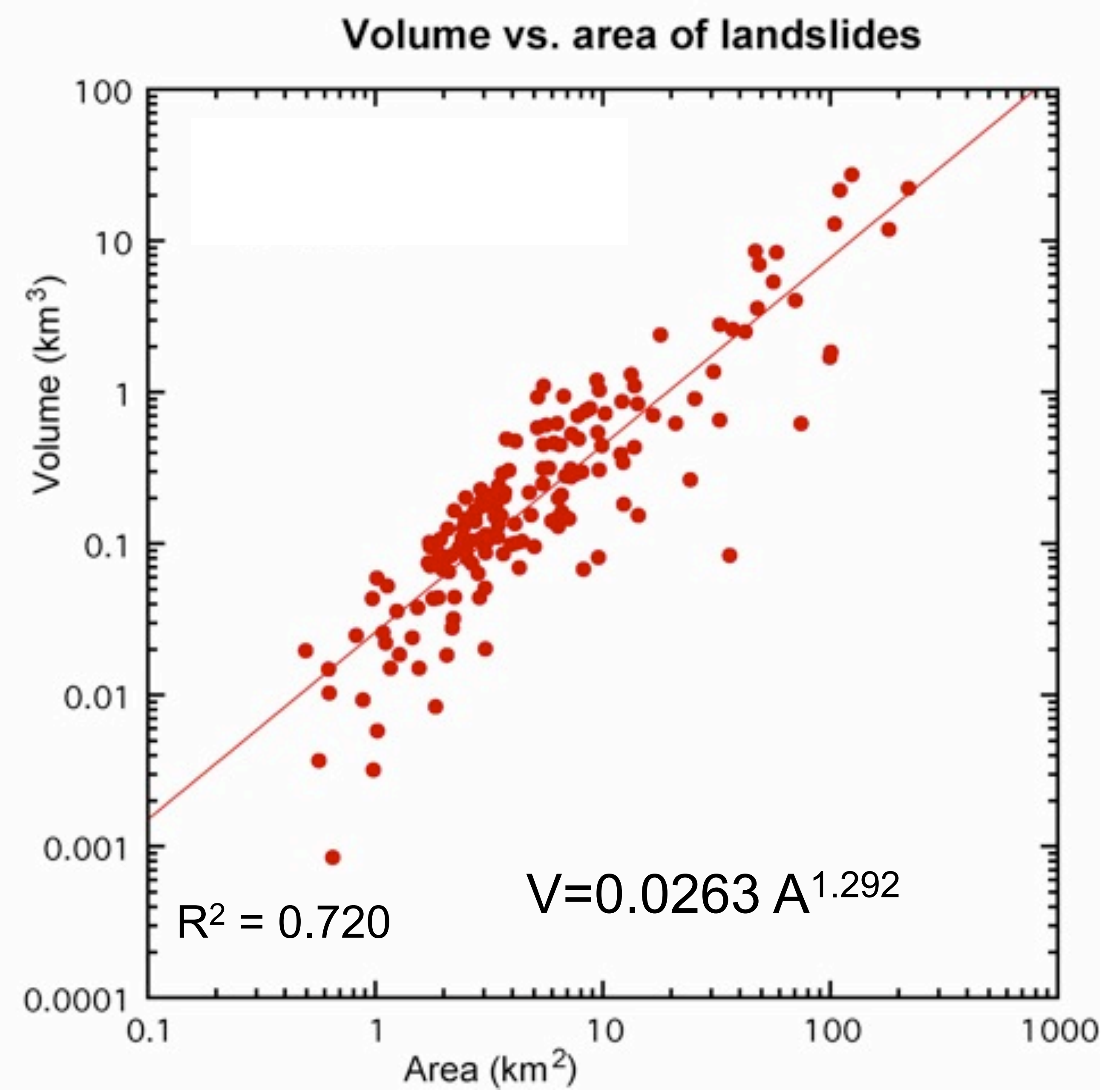
Number of earthquakes as a function of seismic moment - Global shallow events since 1977 (Lay and Wallace, p. 394)

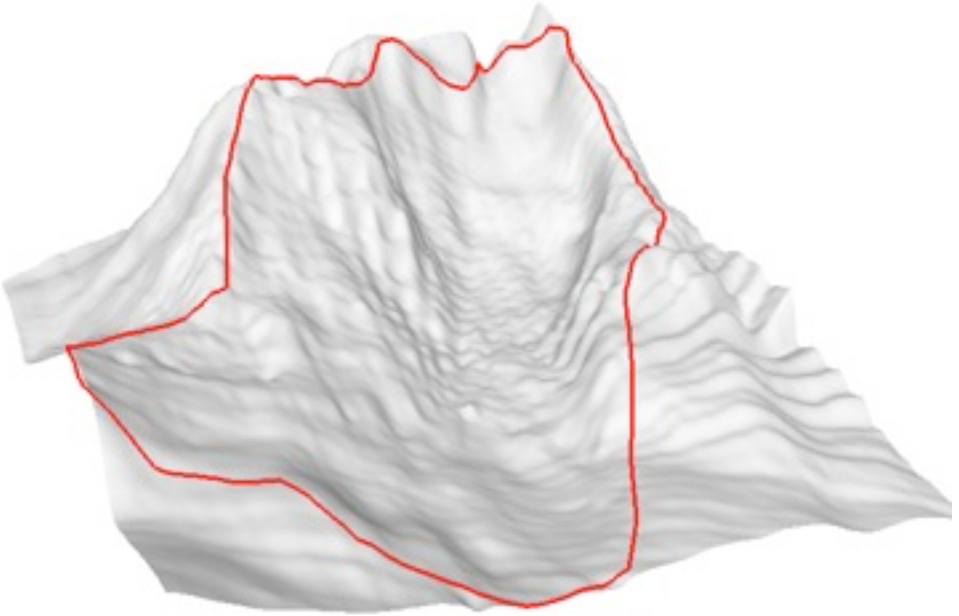


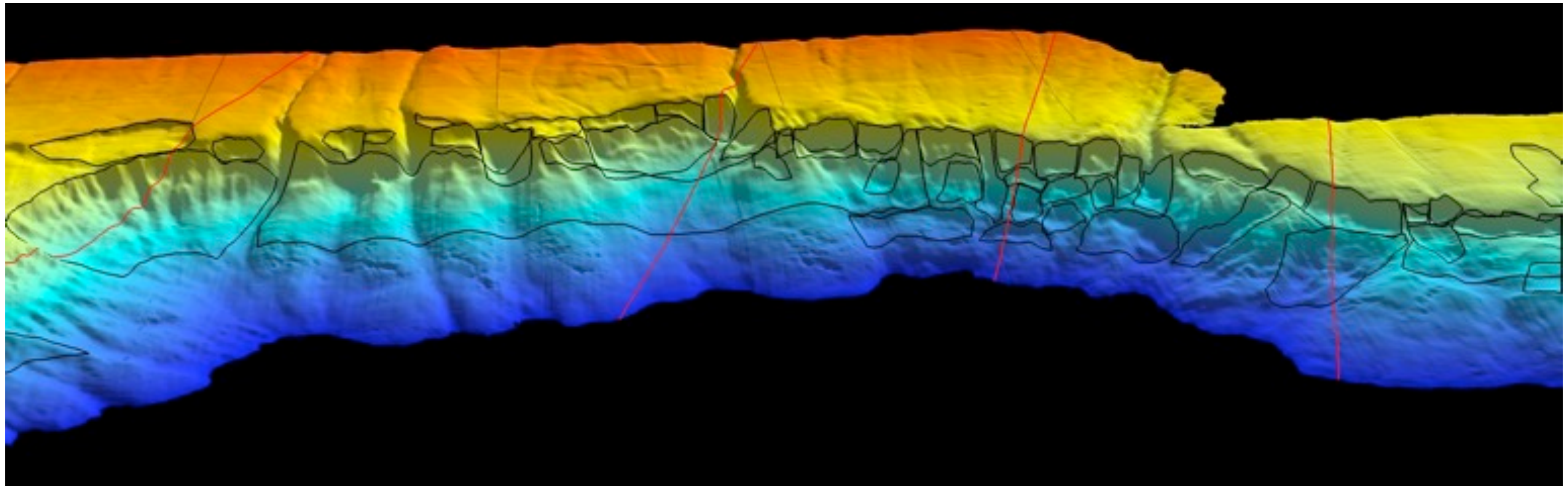
Cumulative number of earthquakes, N_{ce}, in S. California as a function of magnitude for individual years.

(Rundle et al., 2003)

Puerto Rico carbonate platform
Rotational slides



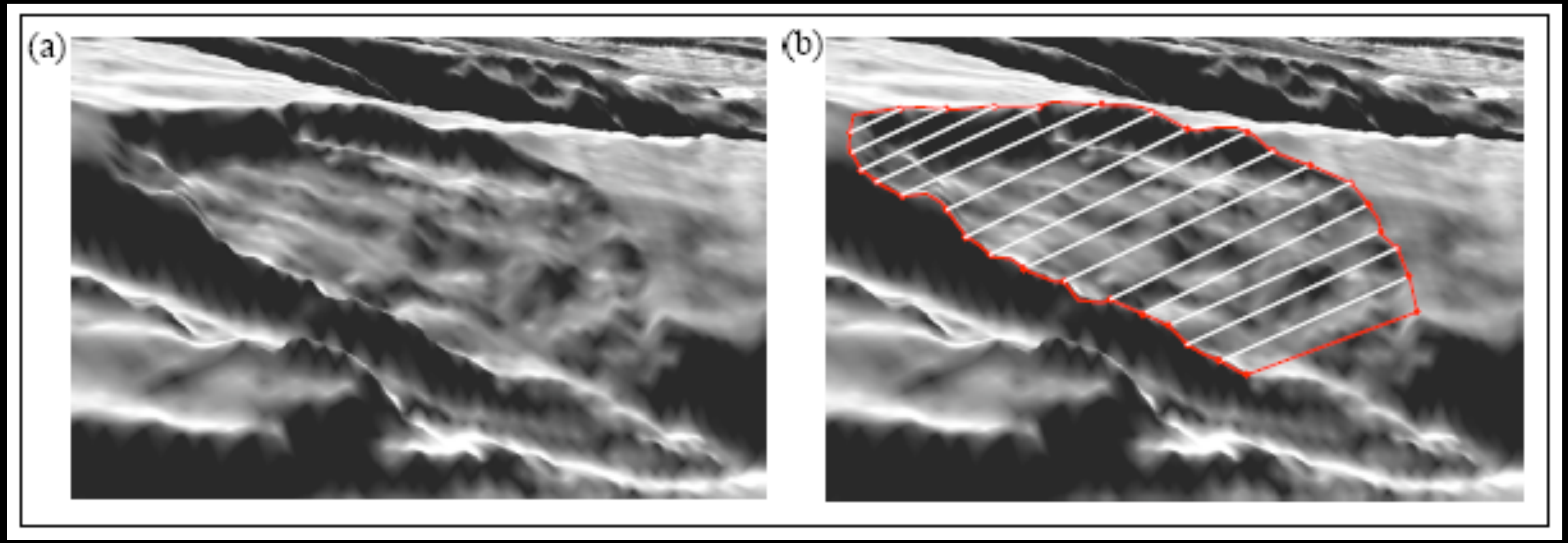




Siliciclastic margins

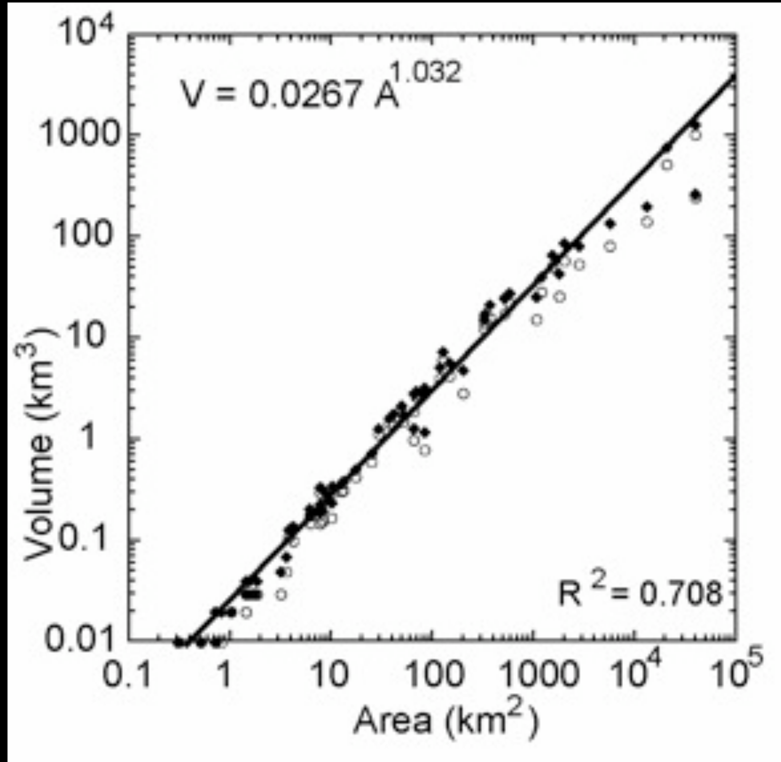
Translational landslides

(~1:1 relationship between volume and area)



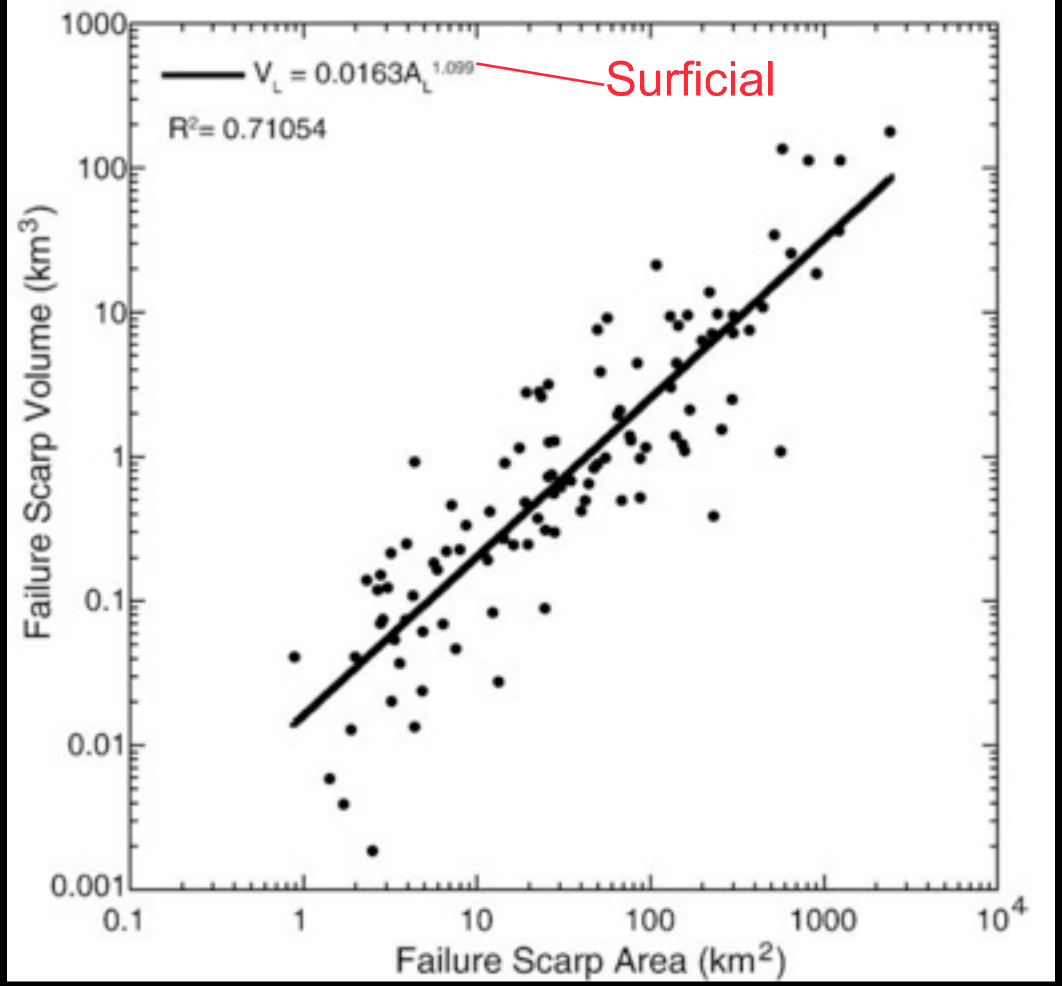
10x vertical exag.

Storegga slide
Relationship between volume and area of 63 submarine debris lobes



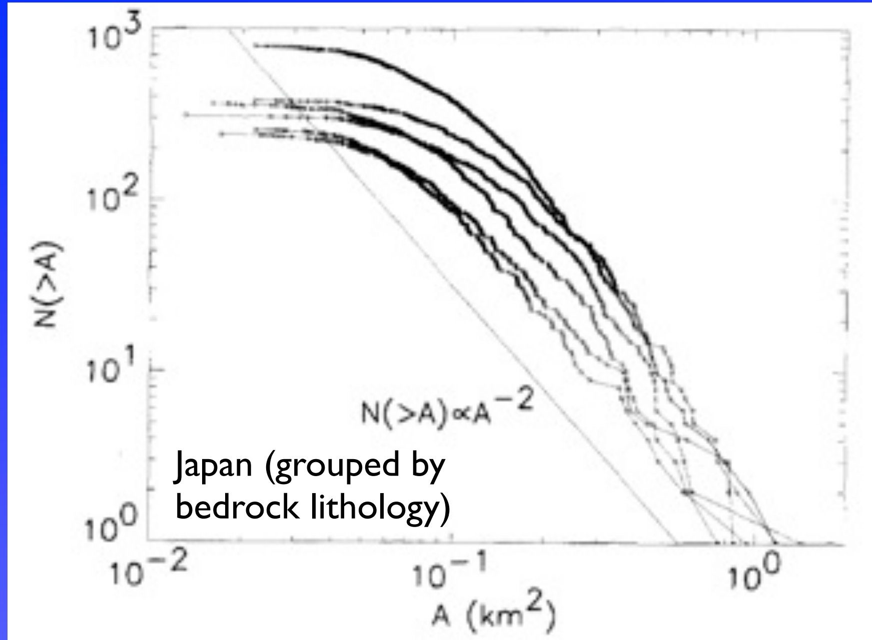
(from tabulation by Halfidason et al., 2005).

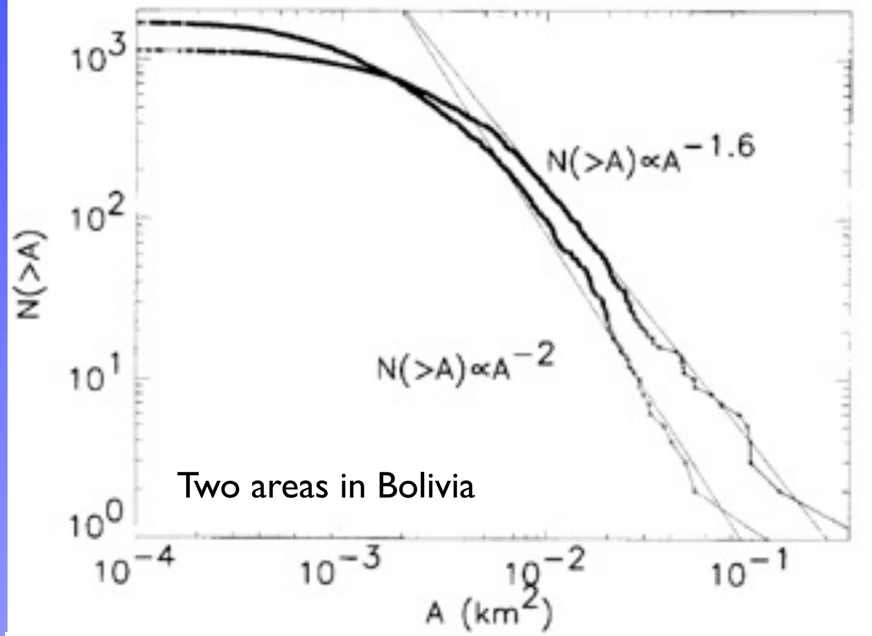
Atlantic margin
Volume vs. Area relationship

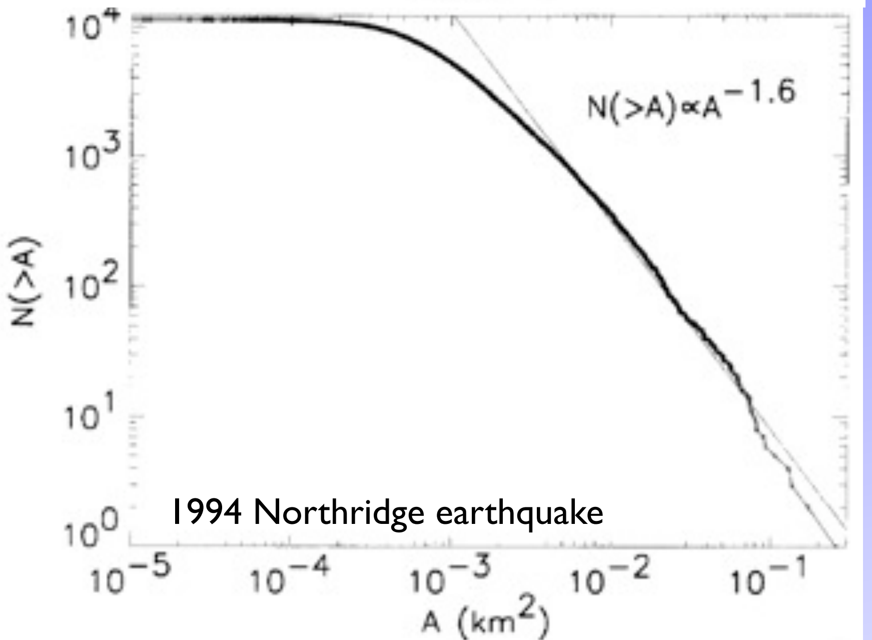


Subaerial landslide statistics

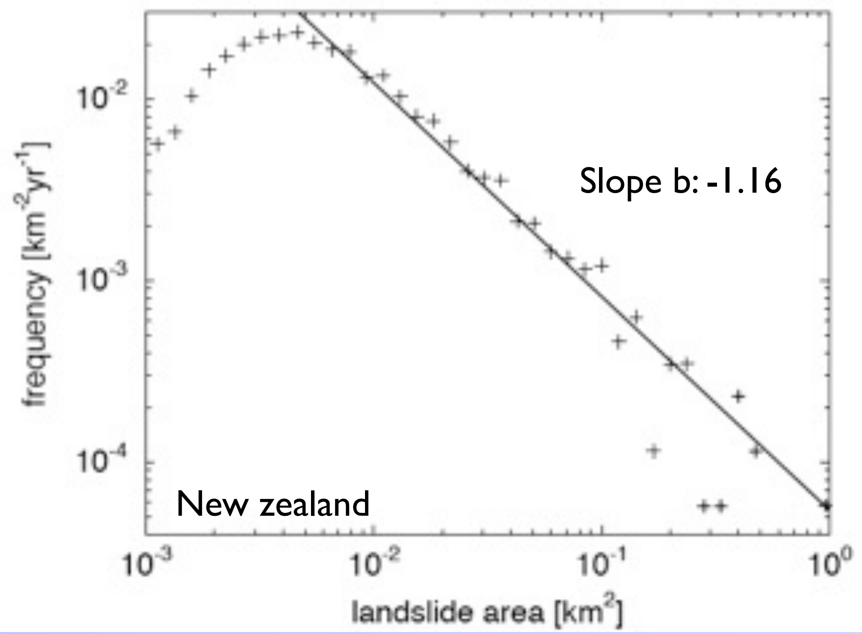
Inverse power law.
Also attempted fit with double Pareto and inverse Gamma functions







From Pelletier, Malamud, Blodget, and Turcotte, 1997



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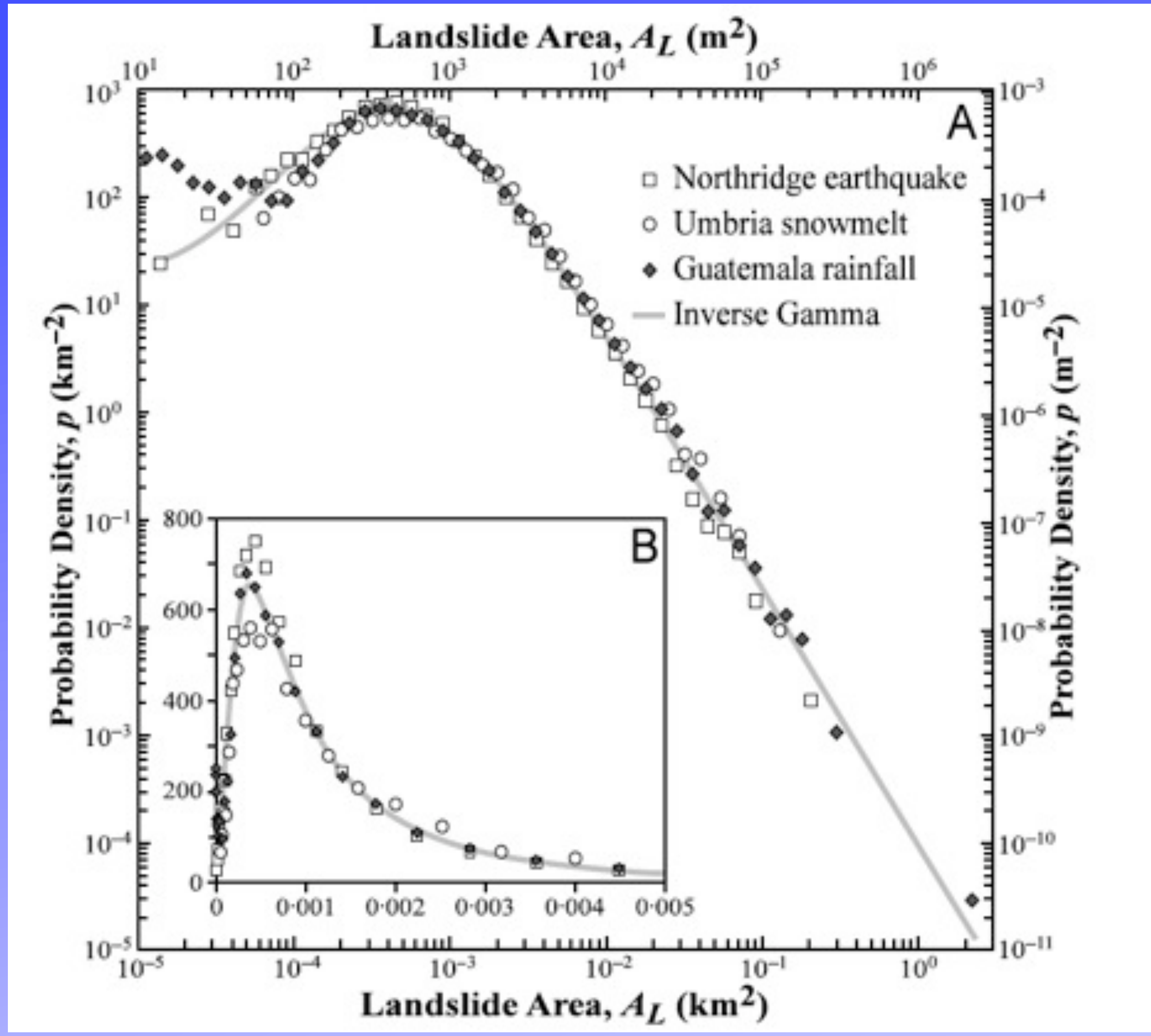

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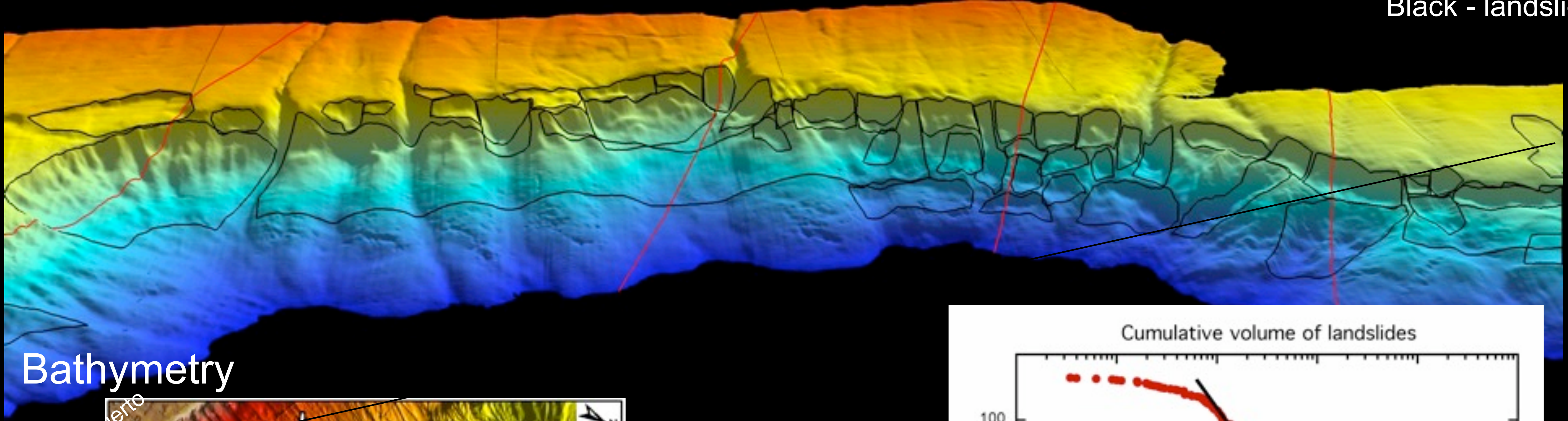
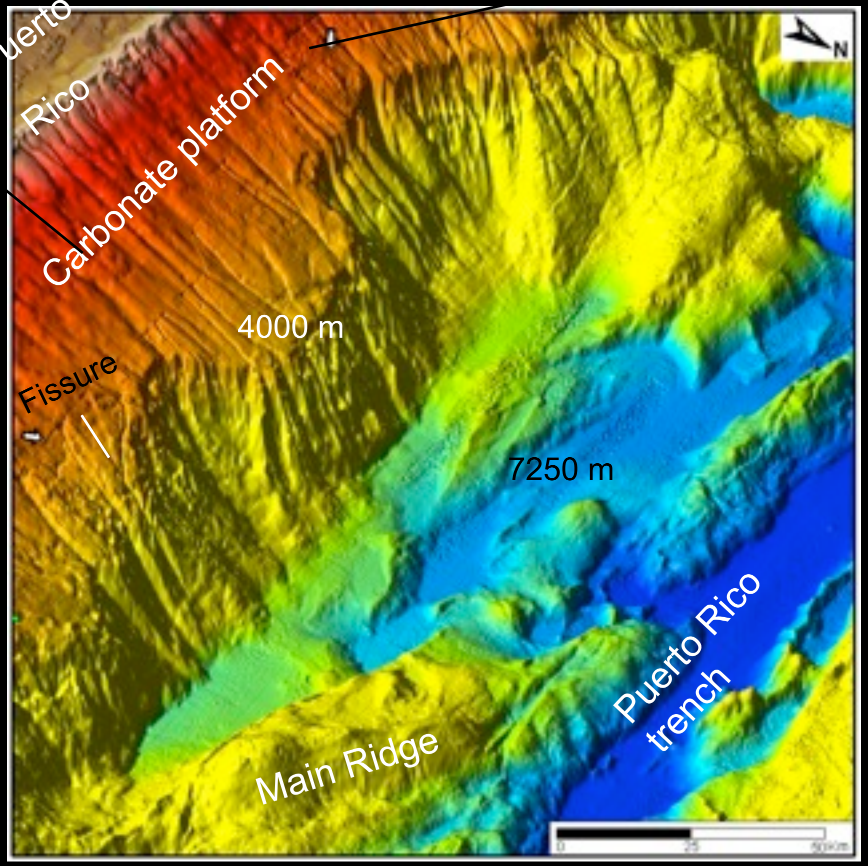
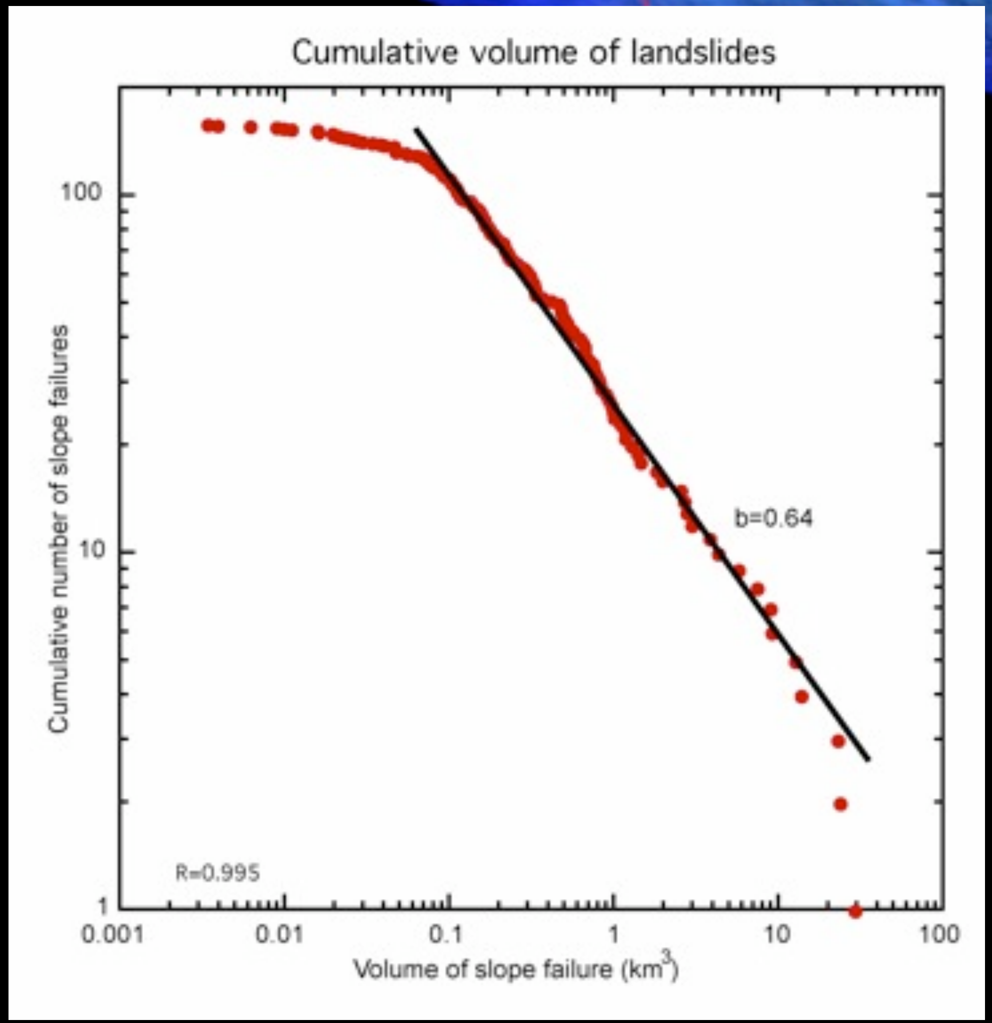
From: Malamud, Turcotte, Guzzetti, Reichenbach (2004)

Red - seismic lines

Black - landslide scarps

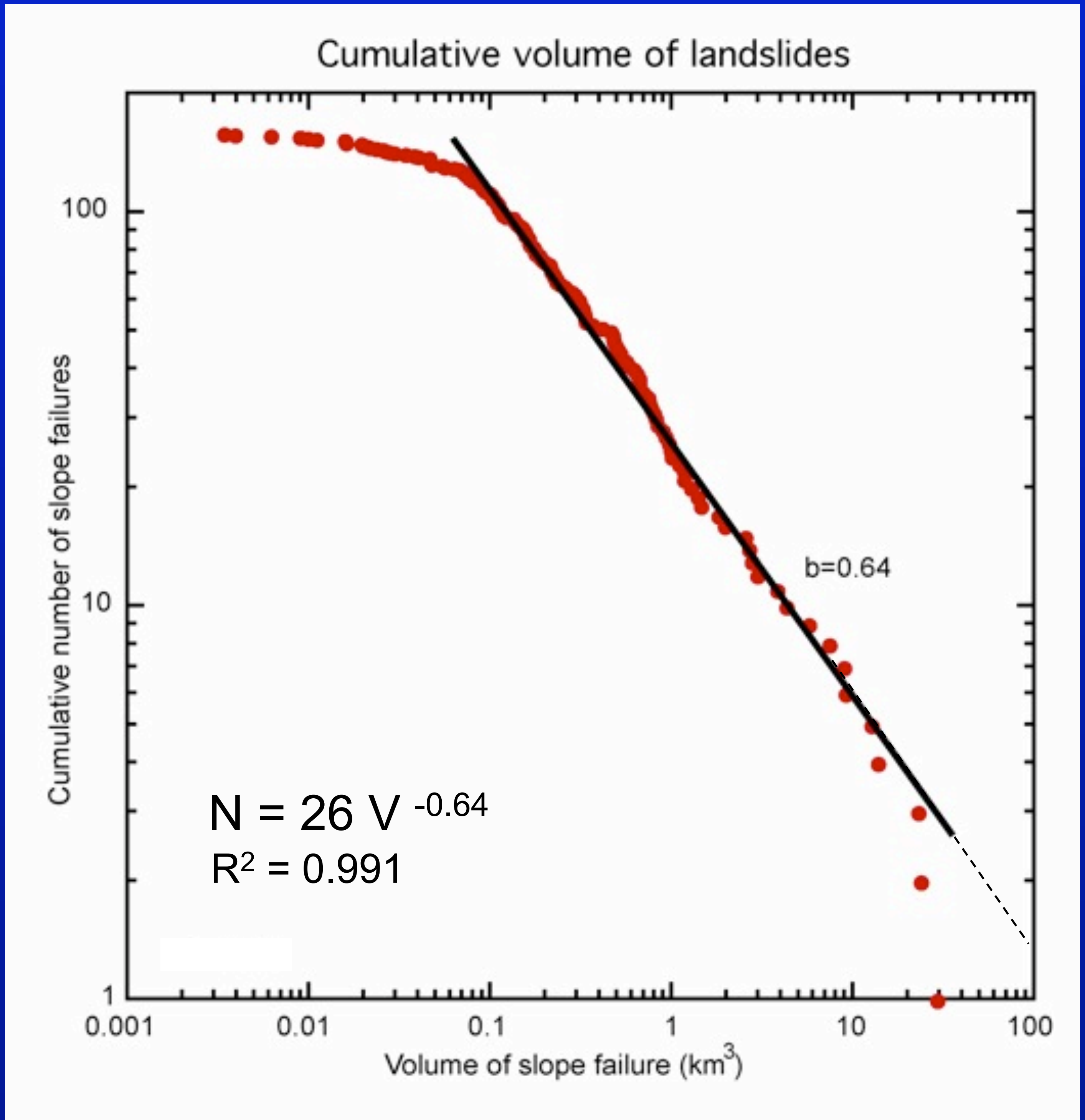




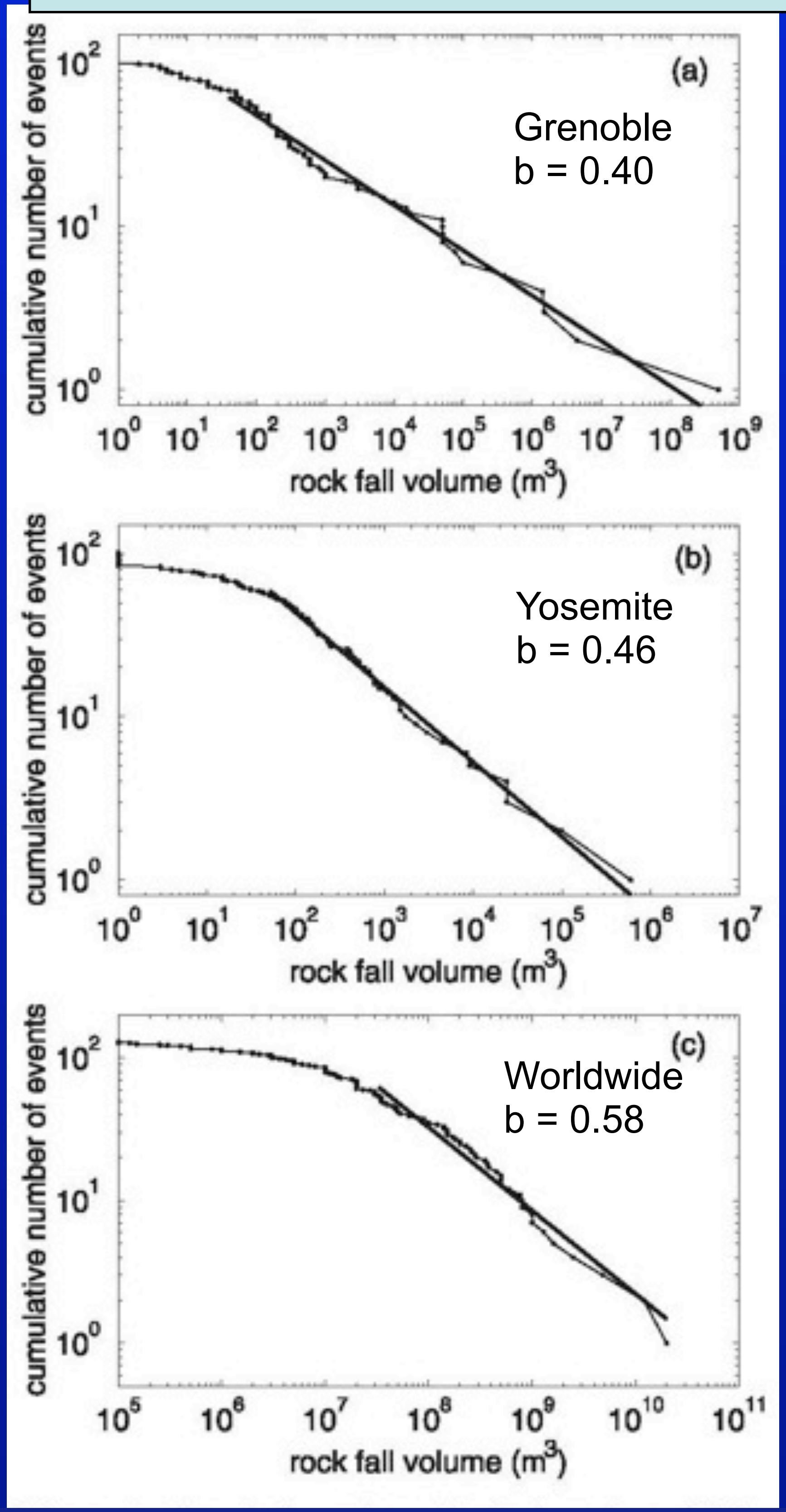


Size distribution of landslides in Puerto Rico follows a Power Law distribution.

Submarine:
Edge of carbonate platform, Puerto Rico = 0.64

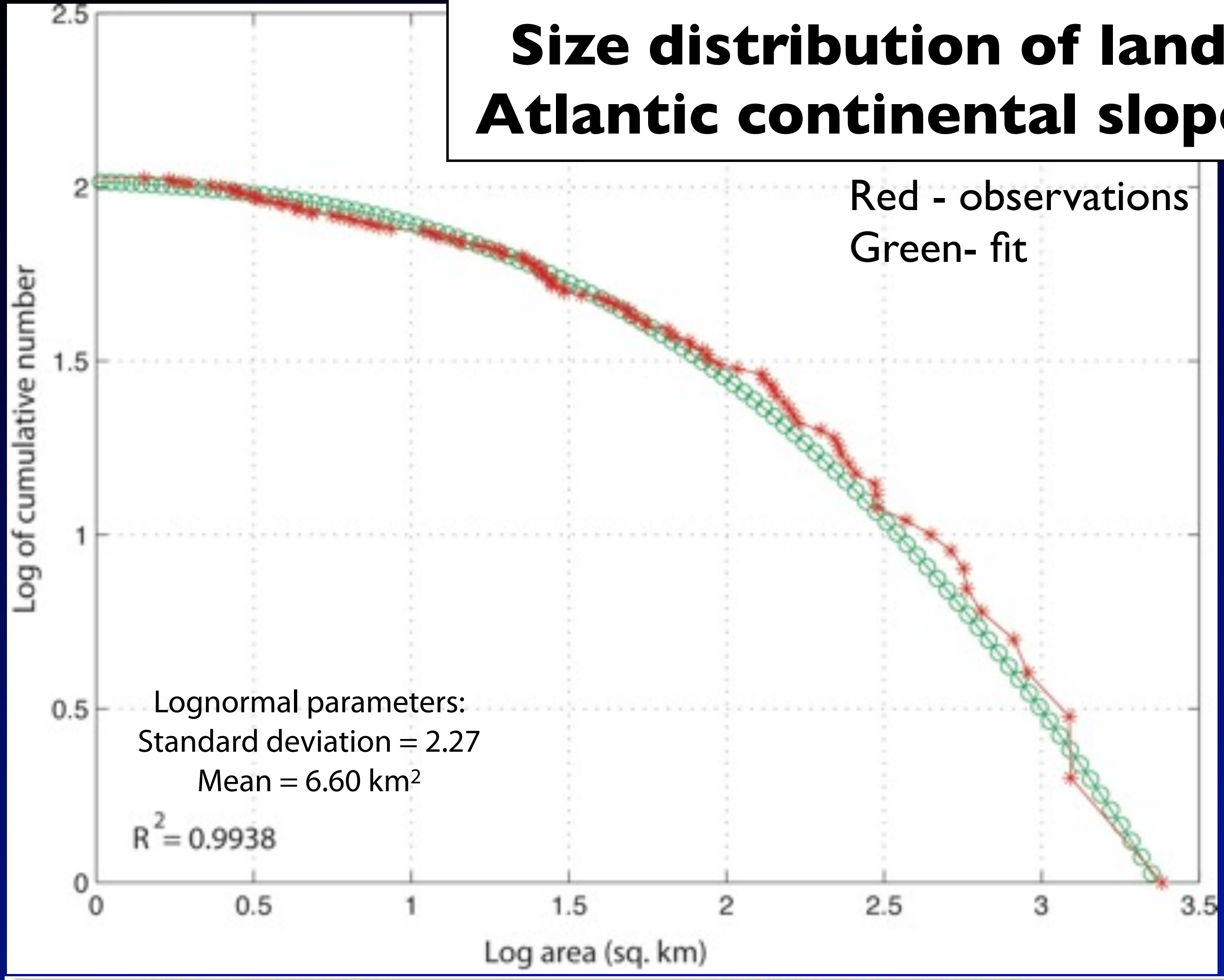


Subaerial: For rockfall volume on subvertical cliffs, b = 0.5±0.2

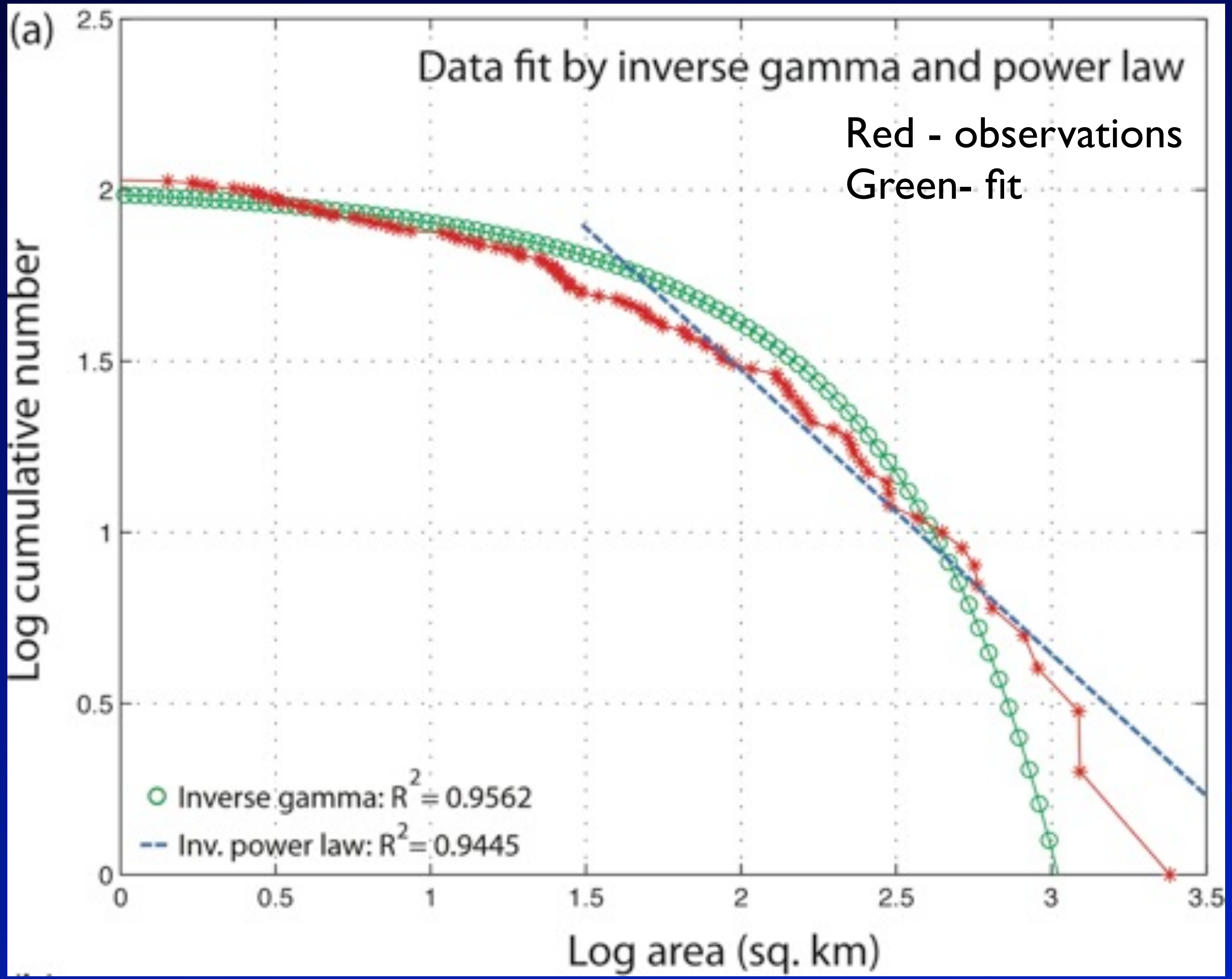


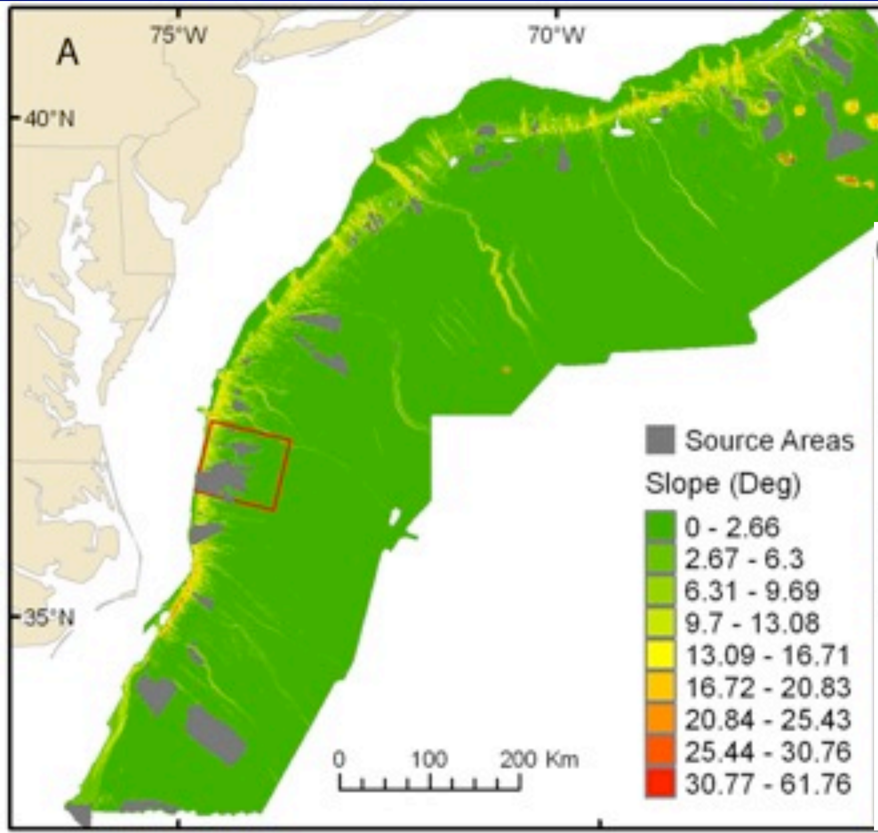
(Dussauge et al., 2003)

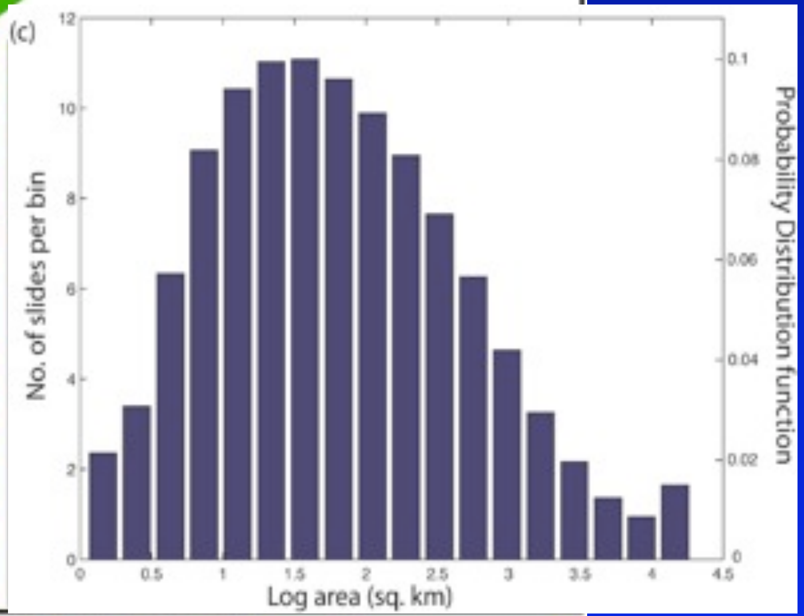
Size distribution of landslides on the Atlantic continental slope is lognormal

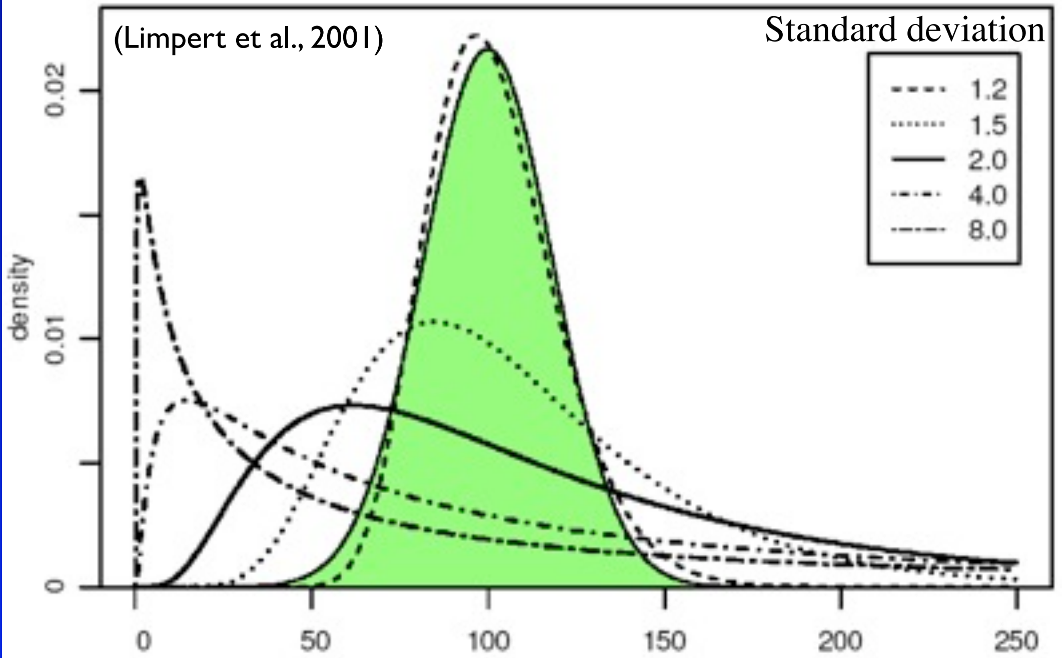


Most landslide areas are betwen 1-10 km^2, fewer larger and smaller landslides







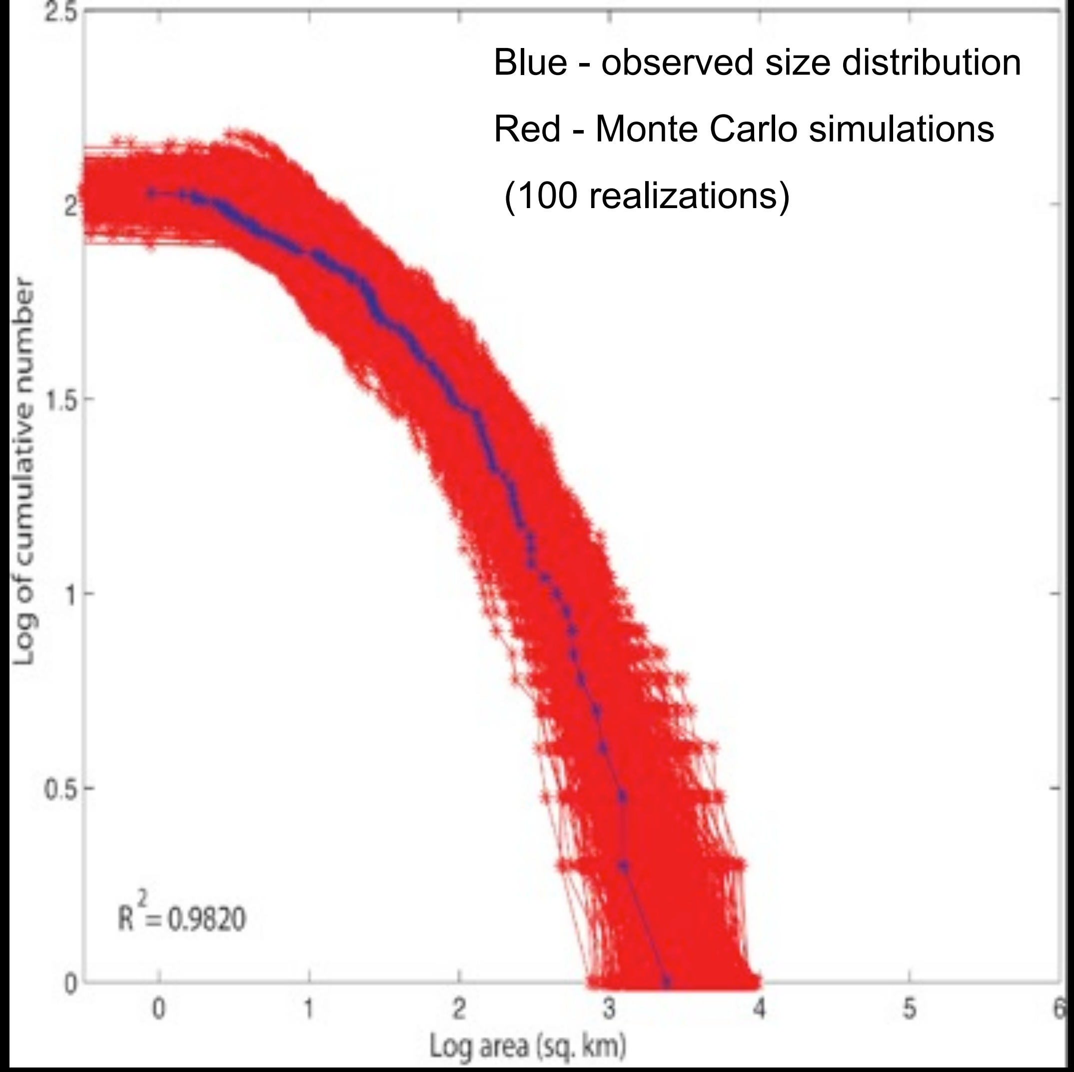


Density functions for log-normal distributions with different standard deviations, compared with a normal distribution

Log-normal landslide distributions can be generated if we assume:

1. that the area of slope failure is a function of earthquake magnitude, and

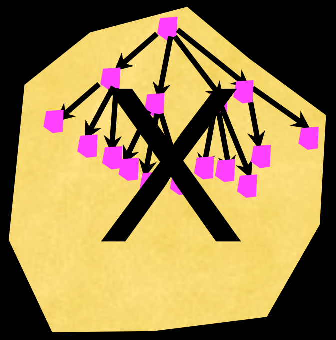
2. that earthquakes follows the Gutenberg-Richter distribution

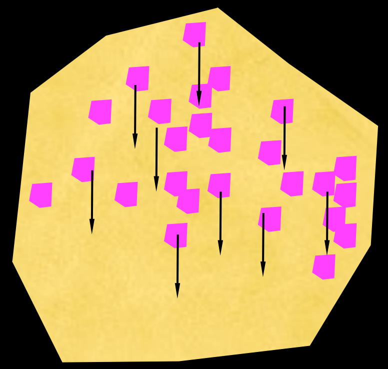


In other words, we assume that:

1. failure occurs simultaneously over the area affected by horizontal ground shaking,

and does not cascade from one or a few nucleating points.

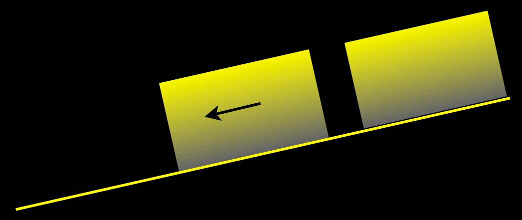




2. Landslides do not entrain significantly new material during mass movement.

If correct , we can predict landslide size (and tsunami probability) from earthquake probability.

Assumption 1: The area of slope failure is related to earthquake magnitude



<u>Infinite slope analysis</u> -
A simple force balance on a slope with the following assumptions: Translational failure along a single plane failure; Surface parallel to slope surface; Ratio of depth to failure surface to length of failure zone is <10%.

Failure initiates when the pseudo-static stress (downslope gravitational stress + horizontal earthquake loading) ≥ undrained shear strength (Factor of Safety=1).

The pseudo-static stress depends on the slope, sediment density, and the ratio of shear strength to vertical load, *c/p*.

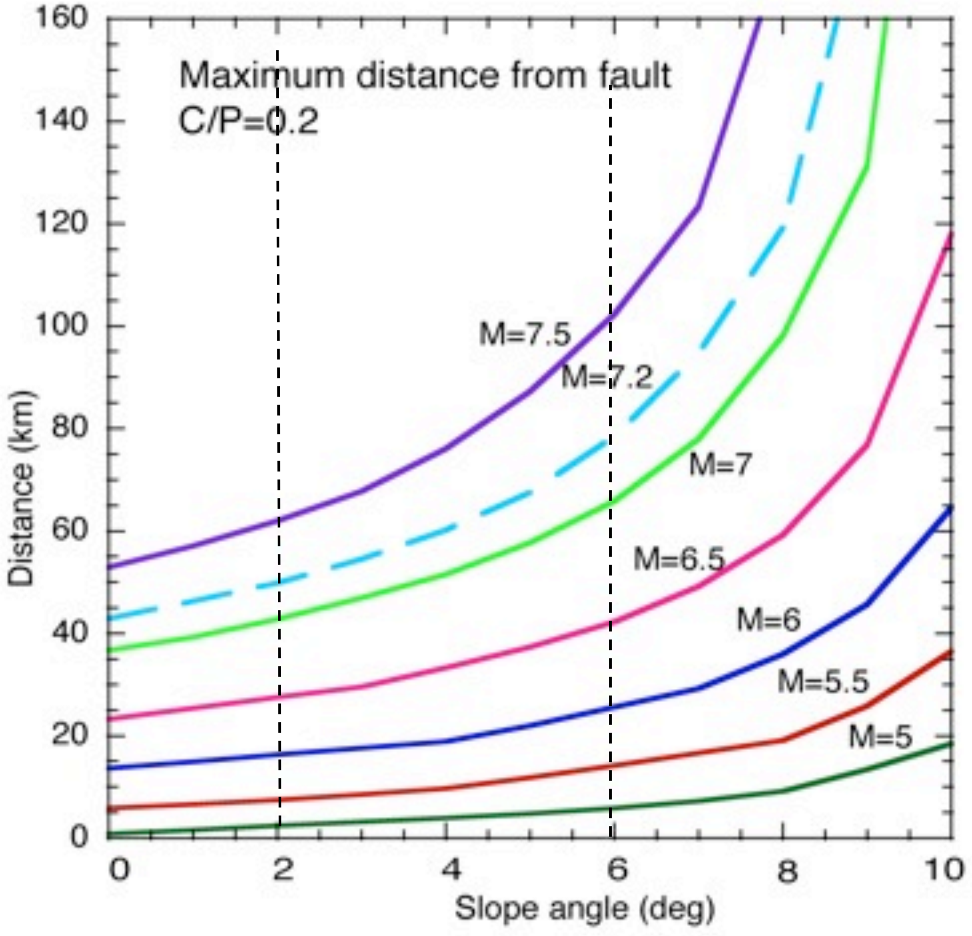
To cause catastrophic displacement, peak earthquake acceleration, k_{PSA} must exceed sediment shear strength k_y, by a considerable amount: $k_{PSA} / k_y \geq 6.7$ *(Lee et al., 2000; Hynes-Griffin and Franklin, 1984)*.

$K_{PSA}(r) \;\alpha\; Mw$. $K_{PSA}(r)$ is based on attenuation relationships for the eastern USA (*Campbell, 2003; Tavakoli & Pezeshk, 2005*) for resonance period *=0.75 s (~100m layer)*, measured shear velocity *=300 m/s (Ewing et al., 1992)*, and site amplification *=3.5 (Boore and Joyner, 1997)*.

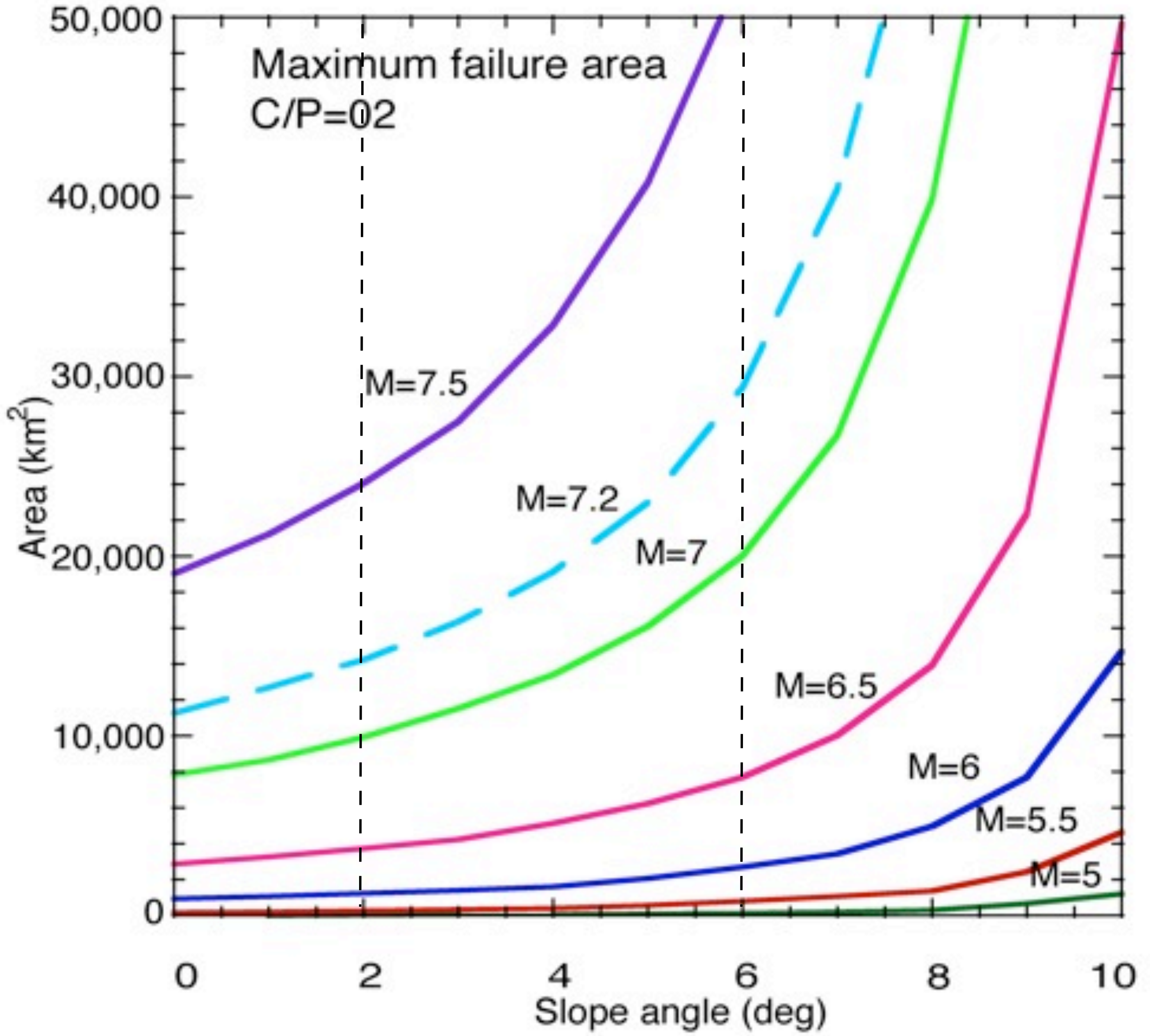
Hence, the calculated <u>maximum</u> failure distance, r_{max} is the distance at which

$$3.5 / 6.7 \times k_{PSA} \leq k_y \quad \Rightarrow \quad \sim 0.5\, k_{PSA} \leq k_y \quad \textit{(earthquake acceleration} \leq \textit{double the sediment shear strength)}$$

Maximum distance to failure, r_{max} as a function of earthquake magnitude and slope



Maximum failure area as a function of slope and earthquake magnitude



Spectral acceleration is proportional to earthquake magnitude and decreases with distance from fault.

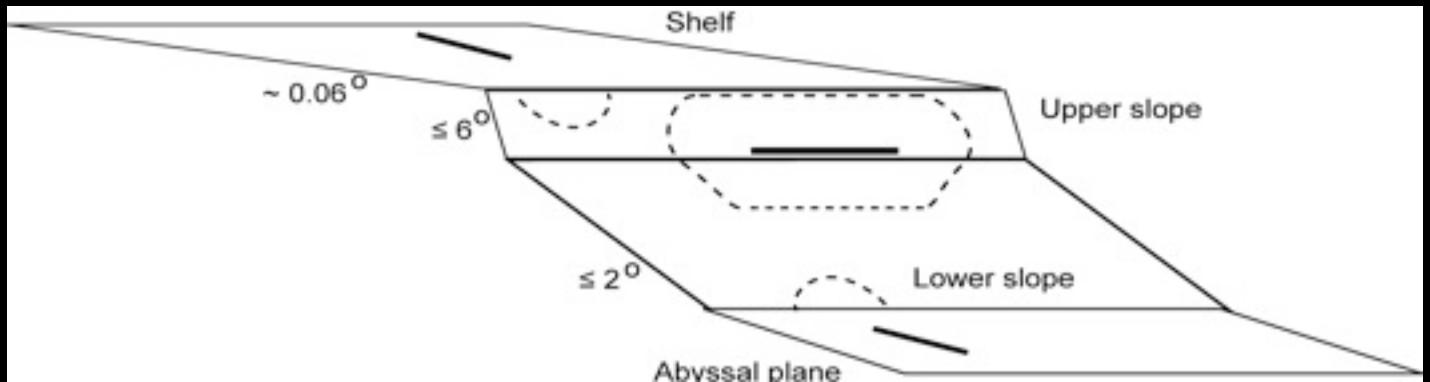
Failure occurs at distances where the spectral acceleration is larger than twice the shear strength.

t $r_{max}^2 + L \times 2\, r_{max}$

$2.44 + 0.59M$

Coppersmith, 1994)

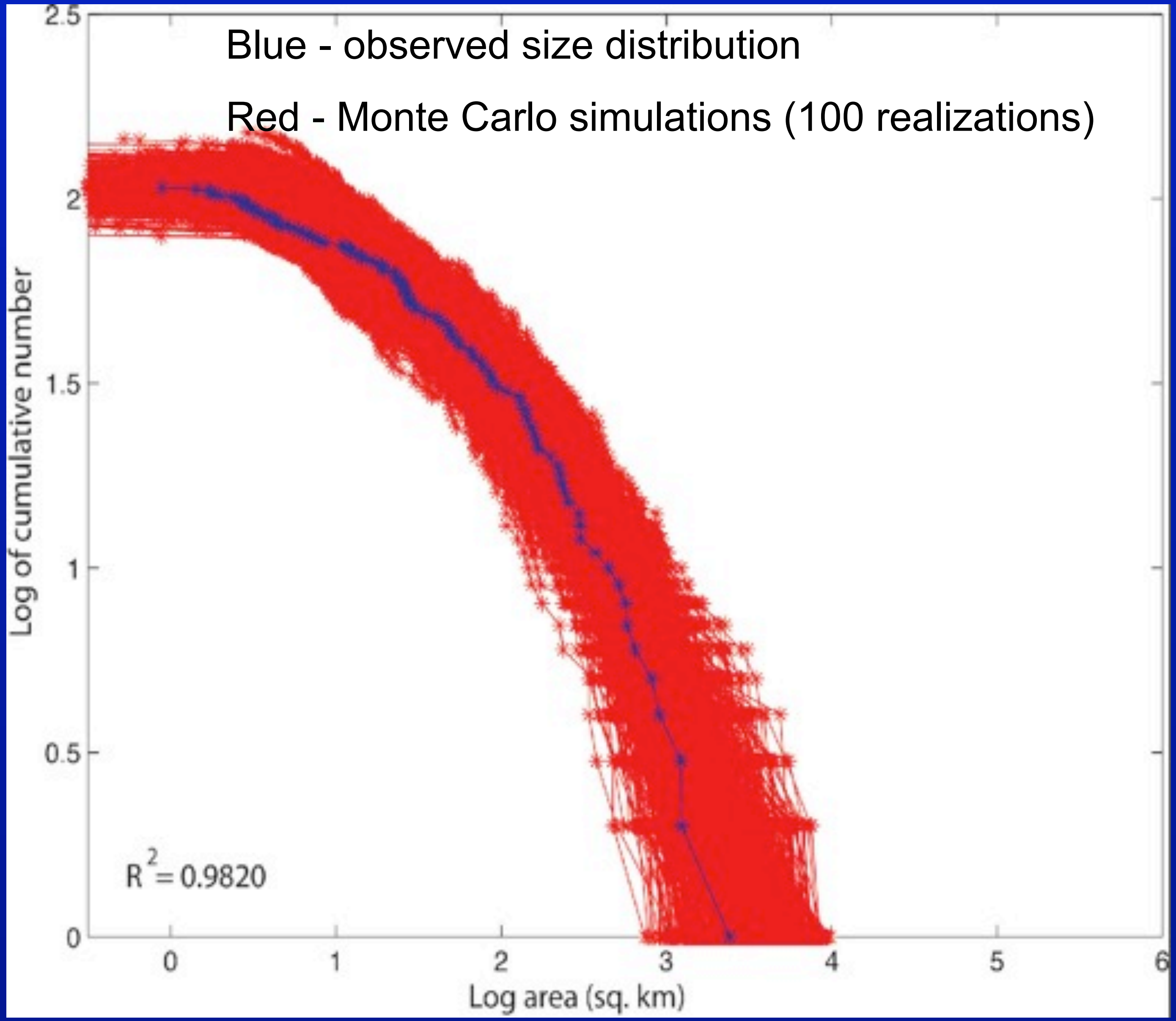
Why maximum area?



Log-normal landslide distributions can be generated if we assume that:

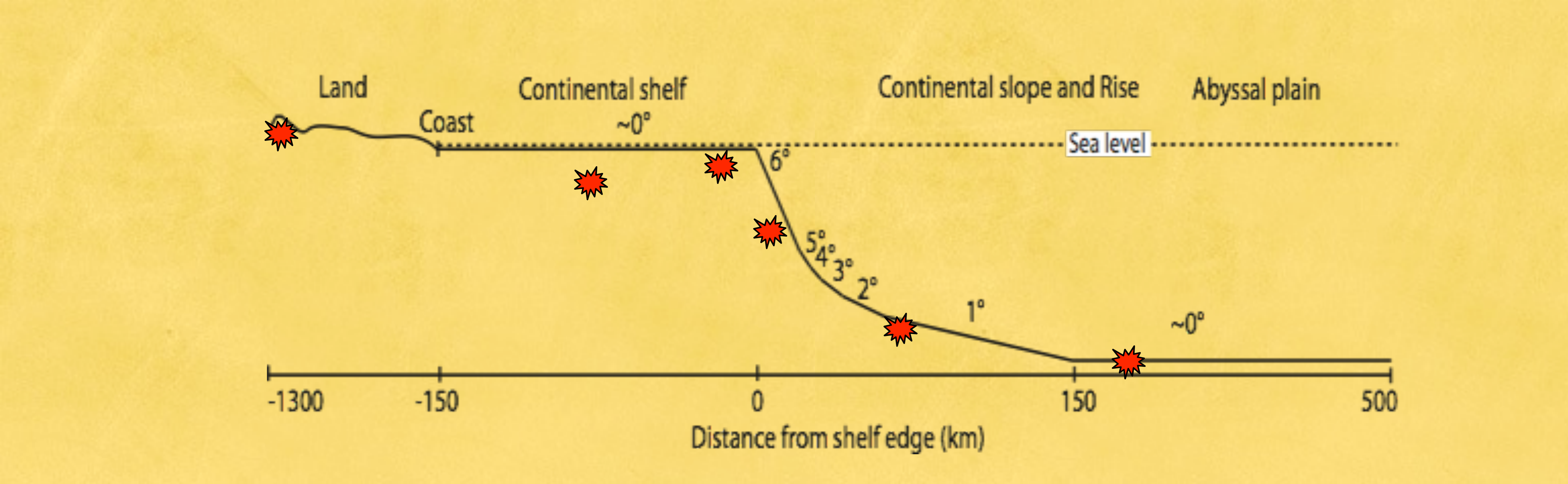
1. the area of slope failure is a function of earthquake magnitude

2. Gutenberg-Richter frequency-magnitude earthquake distribution



Monte Carlo simulations with random locations along profile.

- Earthquake magnitudes follow Gutenberg-Richter distribution (1 M7.5, 10 M6.5, 100 M5.5 etc.) with magnitude interval 0.25; a total of 2348.
- $4.5 \leq M \leq 7.5$ earthquakes placed randomly along 1800 km profile.



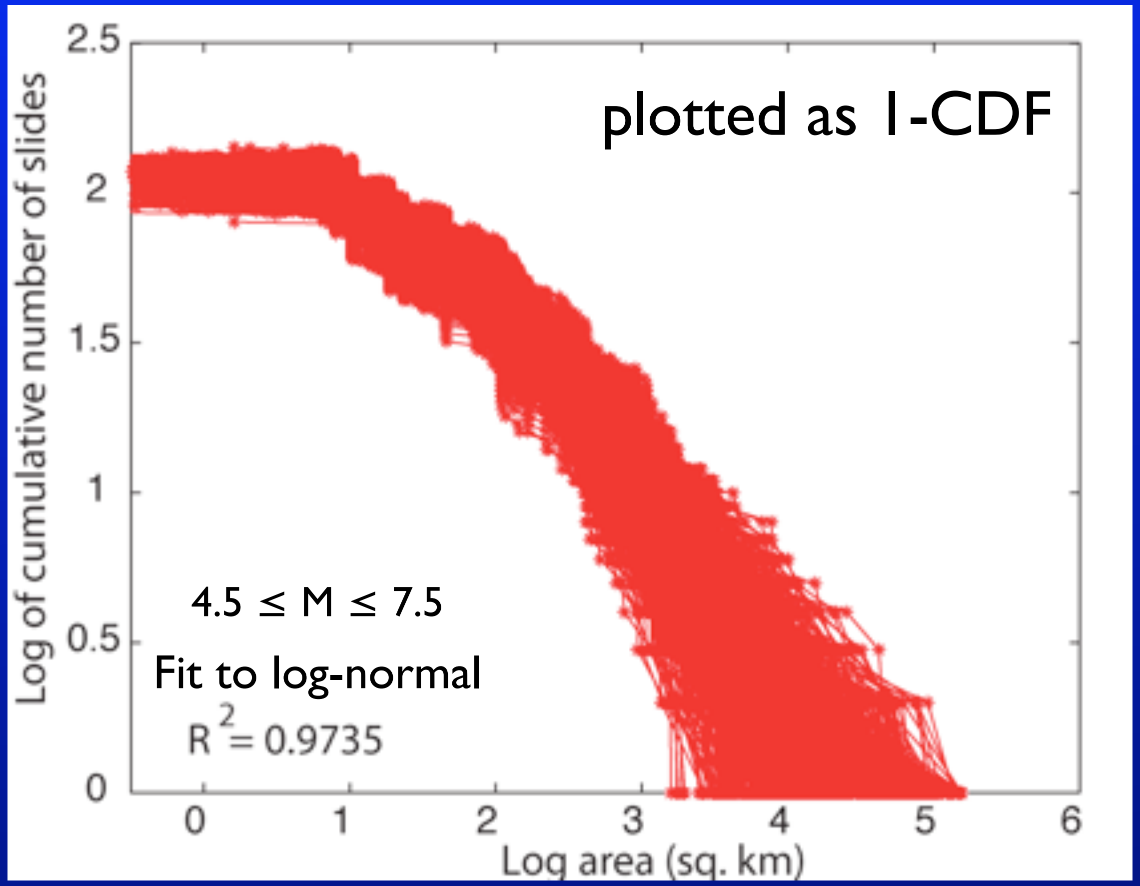
No earthquakes < 4.5 because:

★ No landslides predicted from analysis at slopes ≤6° for earthquakes < M4.5.
★ Slopes ≥6° occupy only ~10 km wide zone of upper slope out of 1500 km.
★ The ~10 km wide zone is cut by canyons into pre-Pleistocene rock. Easier failure on slopes steeper > 6° is balanced by need for stronger ground acceleration than calculated here, to cause landslide in cohesive rock.
★ Land observations indeed show landslides only in earthquakes > M_L 4 - 5 (*Keefer, 1984*)

No earthquakes > 7.5 because:

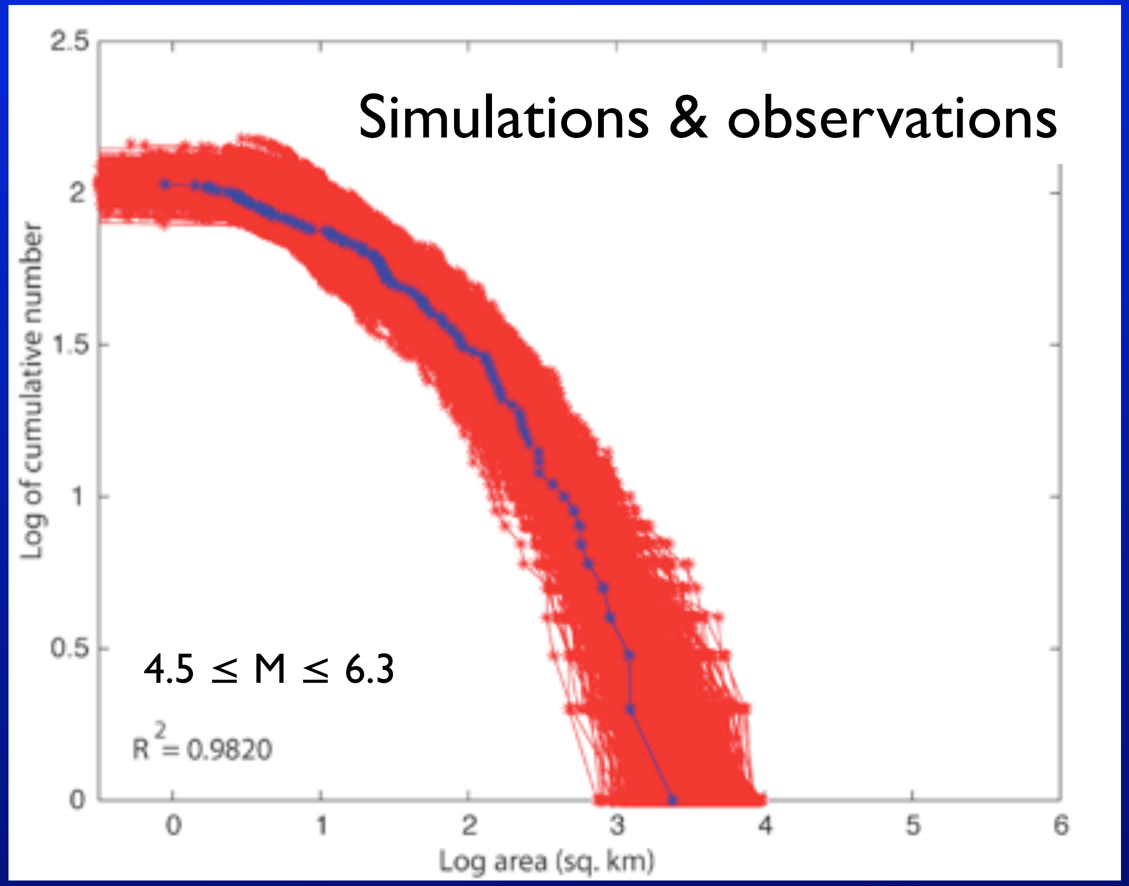
No earthquakes > 7.5 are estimated for the Eastern seaboard (*Frankel et al., 1996*)

Results of 1000 Monte Carlo simulations



Assumptions:

1. Max. area α Mw
2. G-R EQ distribution

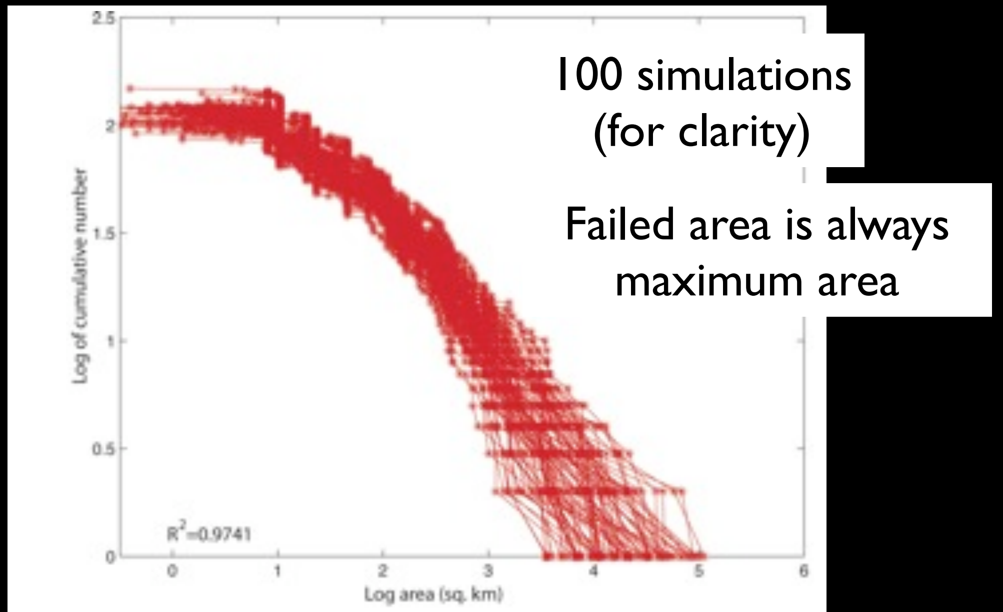


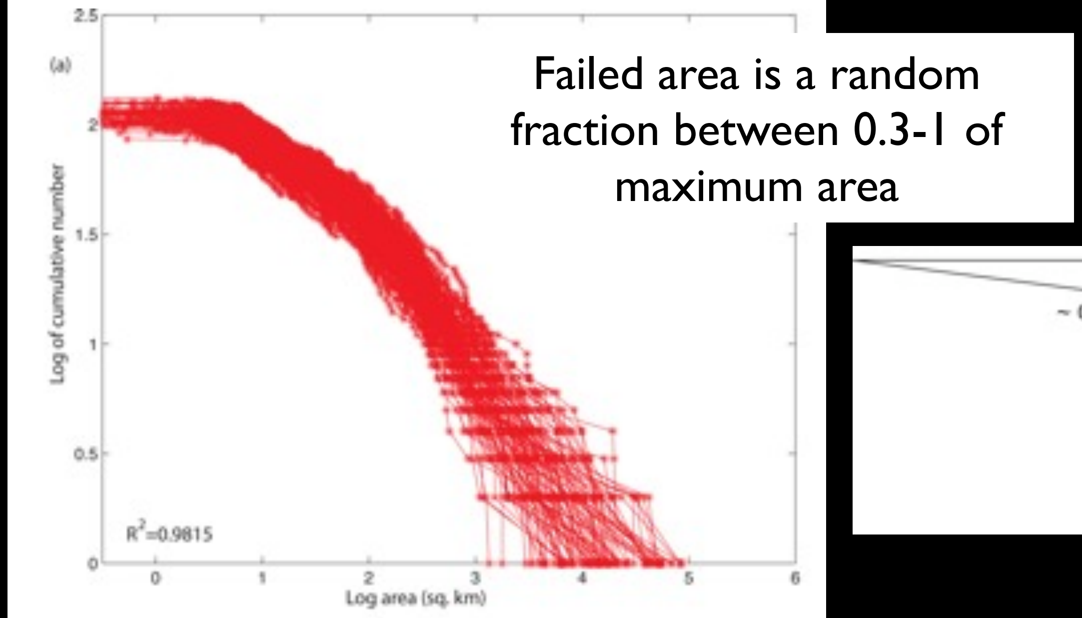
Why is distribution log-normal?

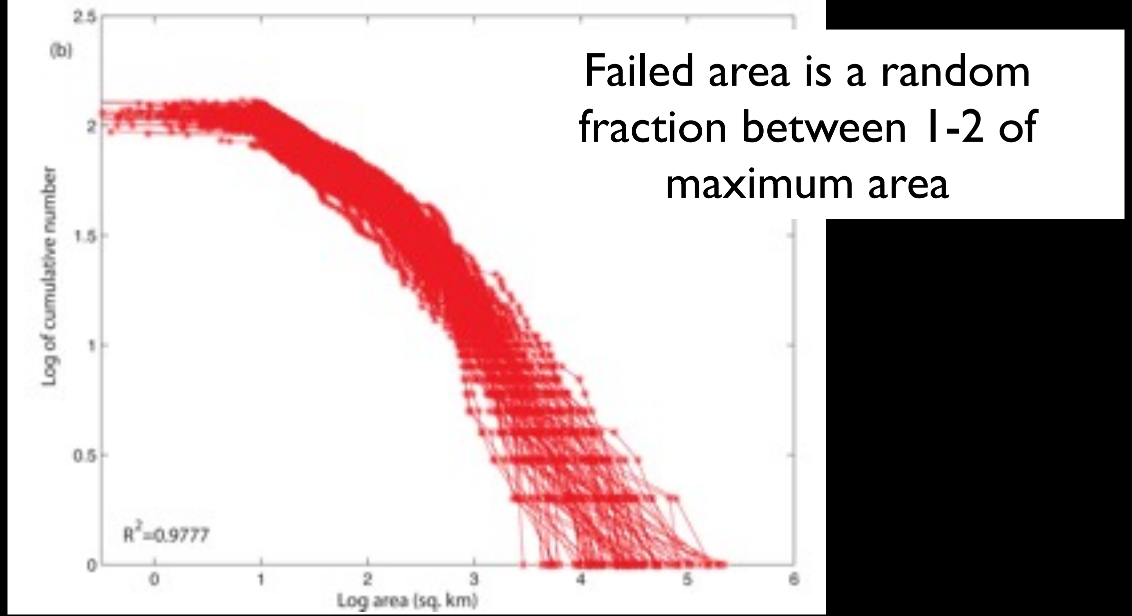
Many landslides with areas of 1-10 km^2 and fewer number of smaller and larger slides,

BECAUSE earthquakes > 6.5 are rare and no landslides are generated by earthquakes <4.5.

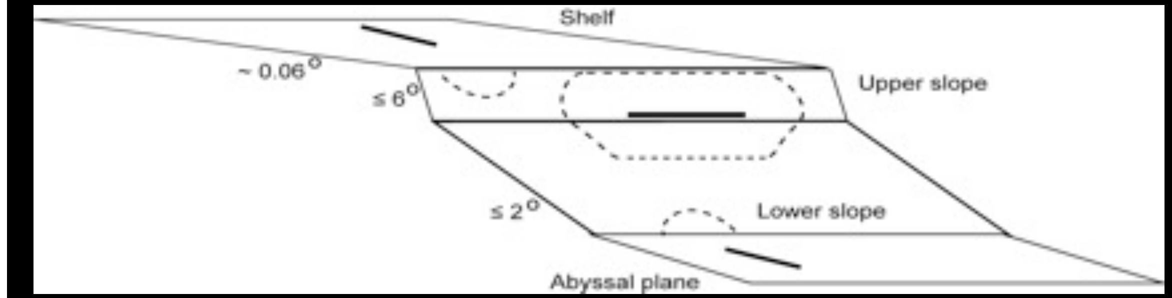
Sensitivity of assumptions



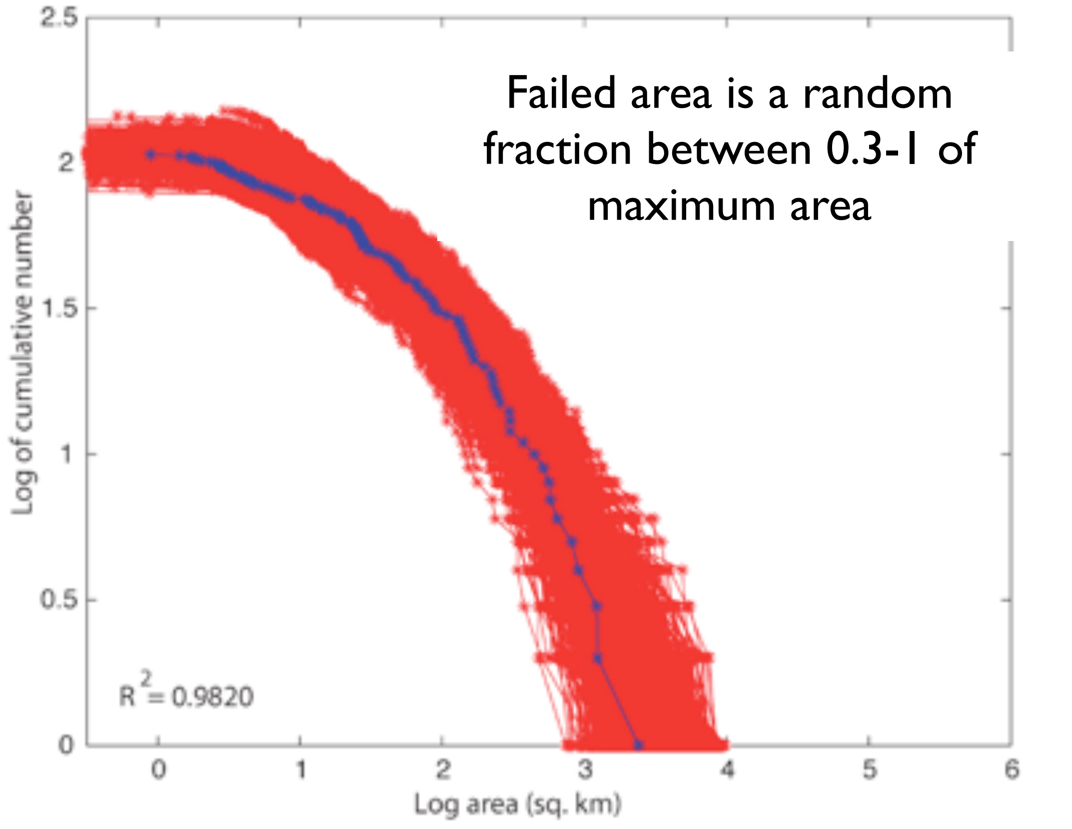


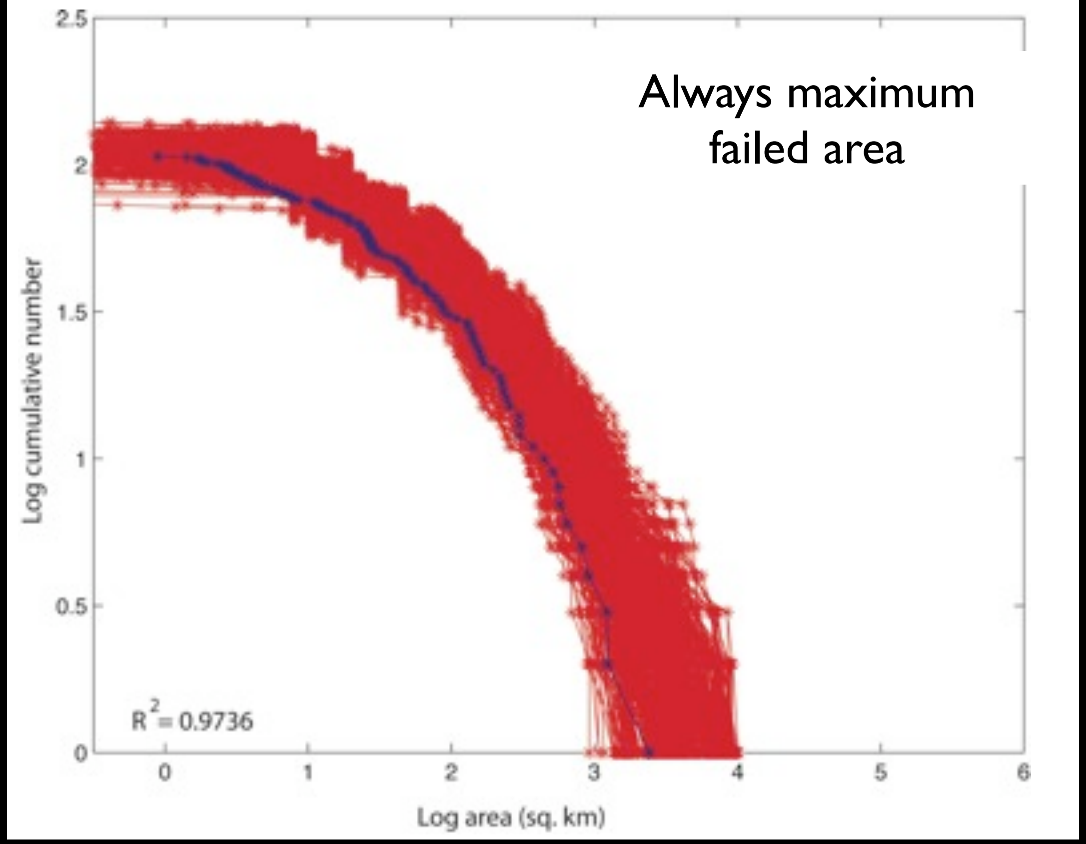


1. Only a fraction of maximum area fails

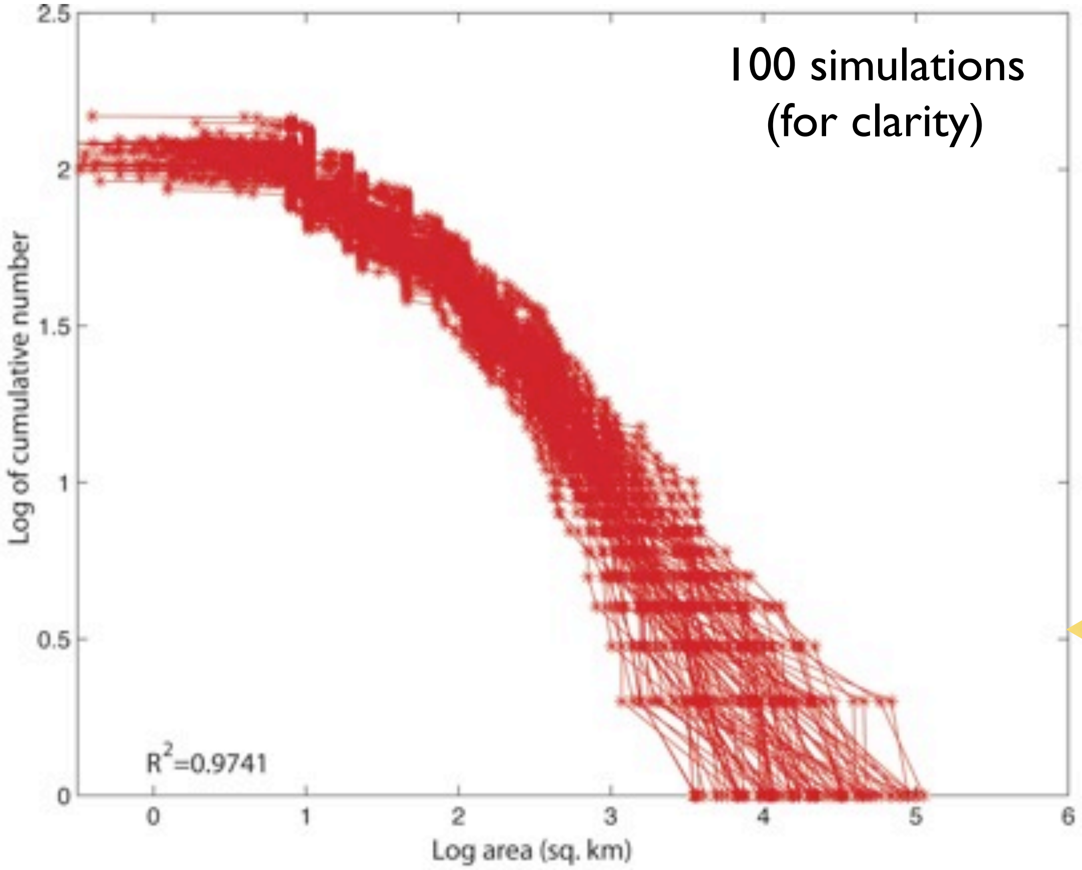


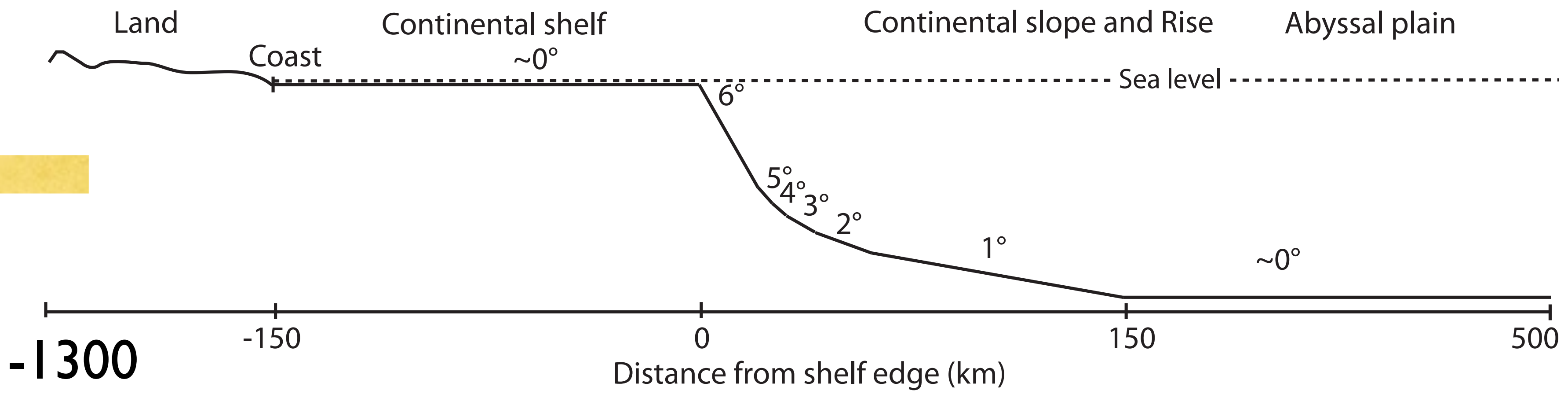
Comparison to observations (in blue)

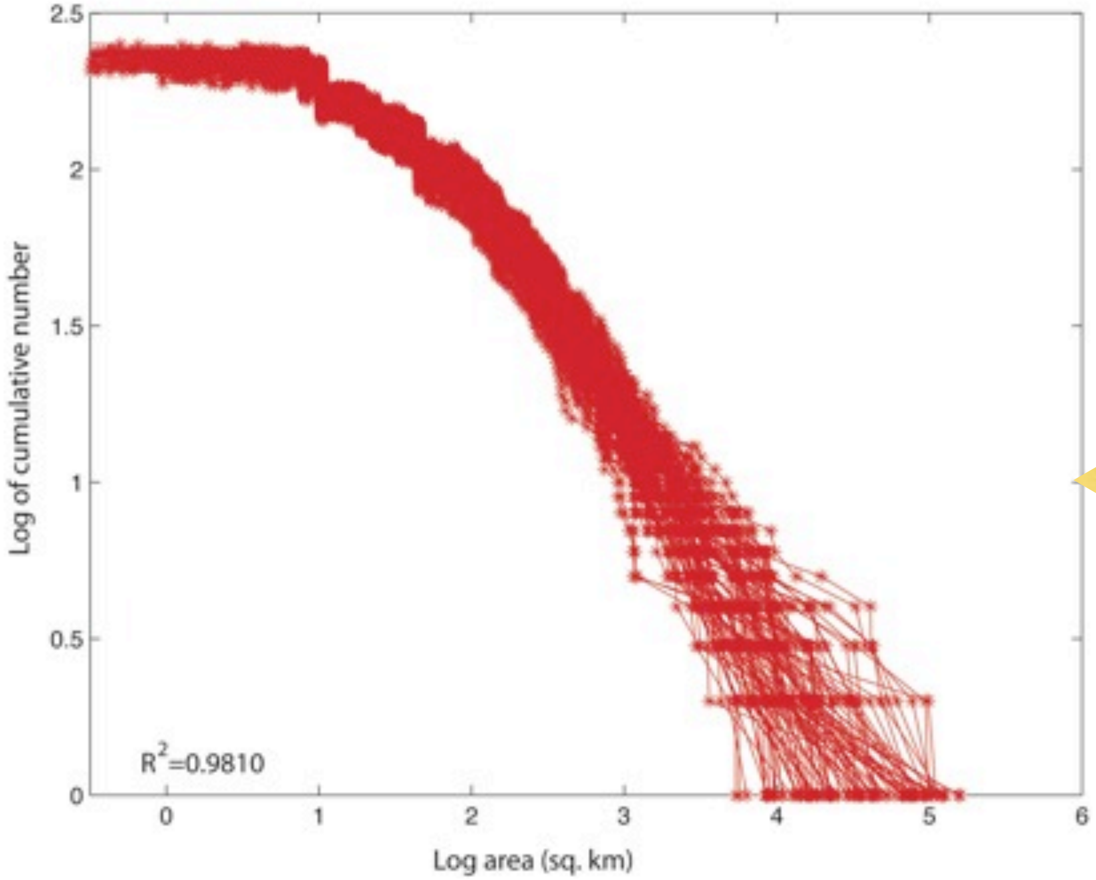


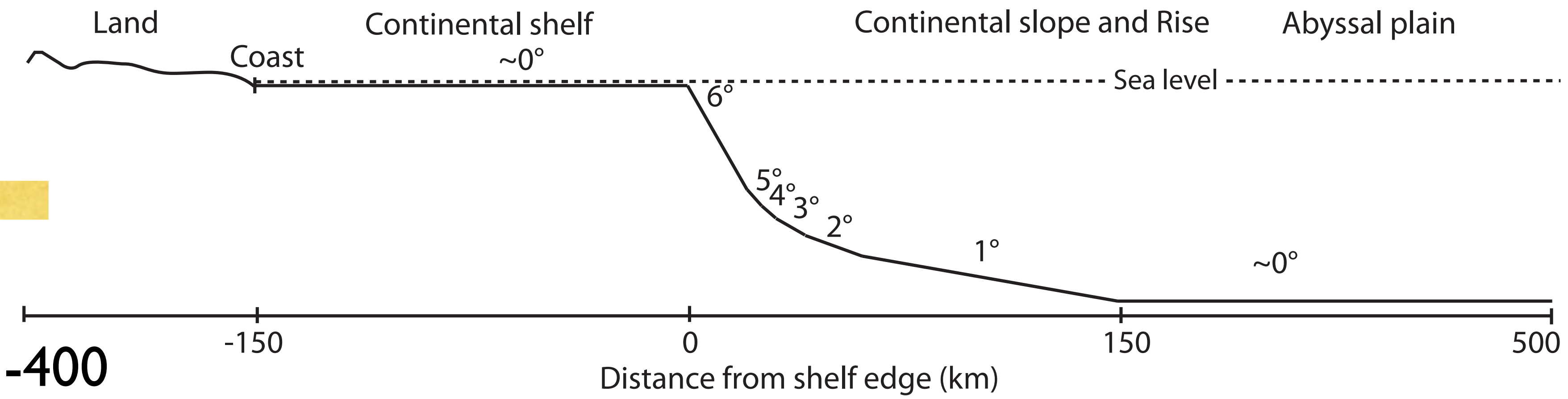


2. Effect of assumed earthquake region: Size of G-R region cut by half





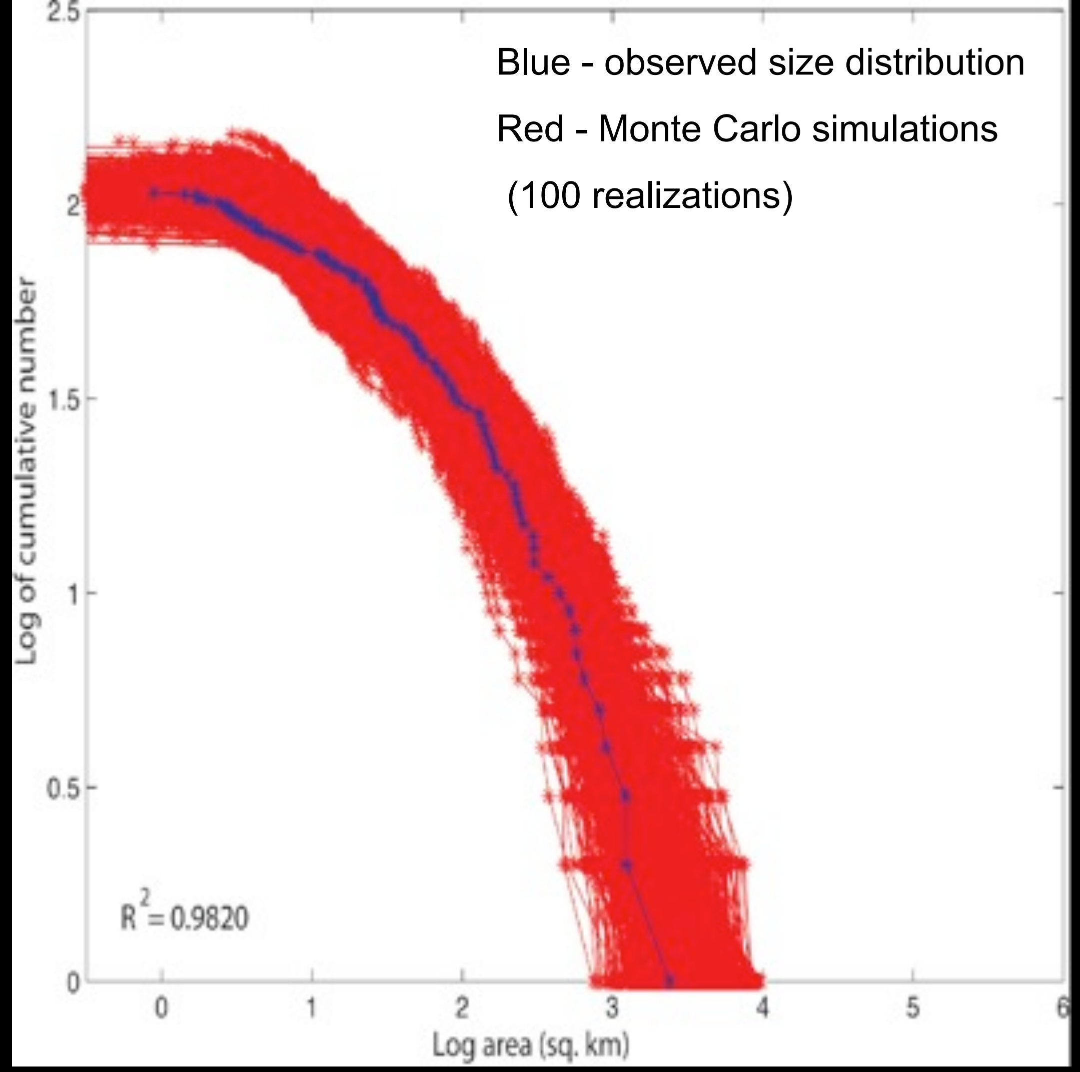




Log-normal landslide distributions can be generated if we assume:

1. that the area of slope failure is a function of earthquake magnitude, and

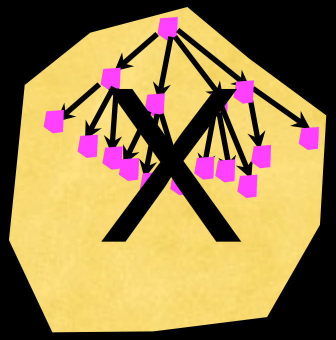
2. that earthquakes follows the Gutenberg-Richter distribution

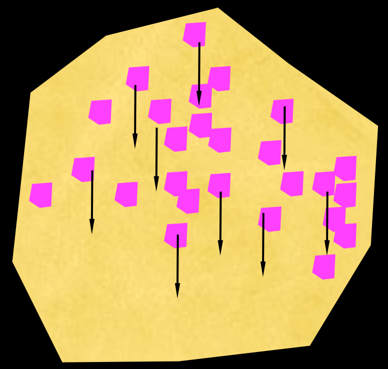


In other words, we assume that:

1. failure occurs simultaneously over the area affected by horizontal ground shaking,

and does not cascade from one or a few nucleating points.





2. Landslides do not entrain significantly new material during mass movement.

If correct , we can predict landslide size (and tsunami probability) from earthquake probability.

Qualitative evidence

Seismological record

1. No double-couple earthquake during large landslide Landslides (e.g., 1929 Grand Banks.

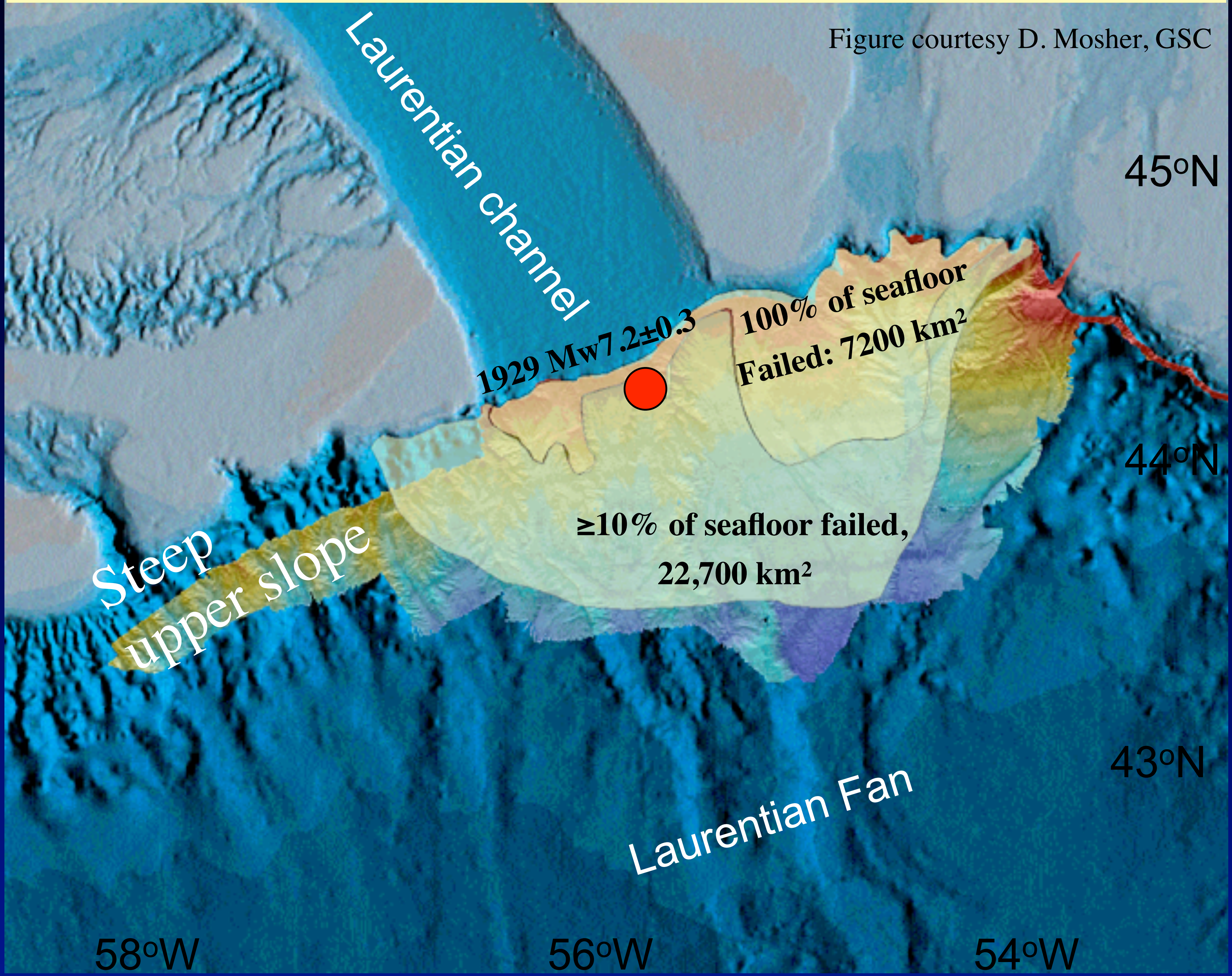
2. Landslide earthquakes are abnormal: Rich in long-period surface waves, probably excited by accelerating/decelerating sliding masses during runout (*Kanamori and Given*, 1982).

Geological record

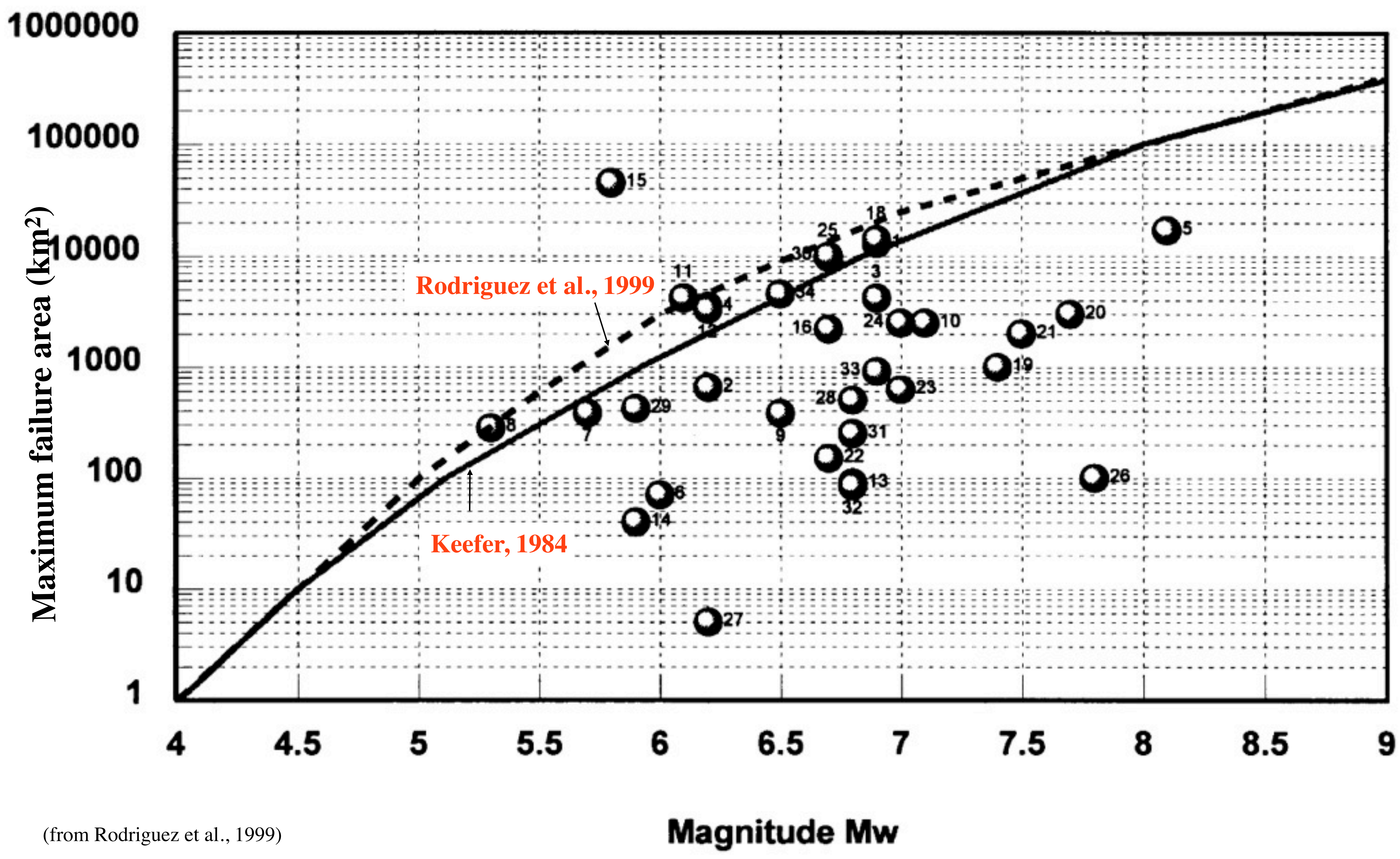
Many small independent landslides can be observed over an area affected by earthquake or heavy rain and snow

1929 Grand banks earthquake and landslide

In 2/3 of area: Patchy failures with intervening areas showing no sign of failure. No single massive slump.

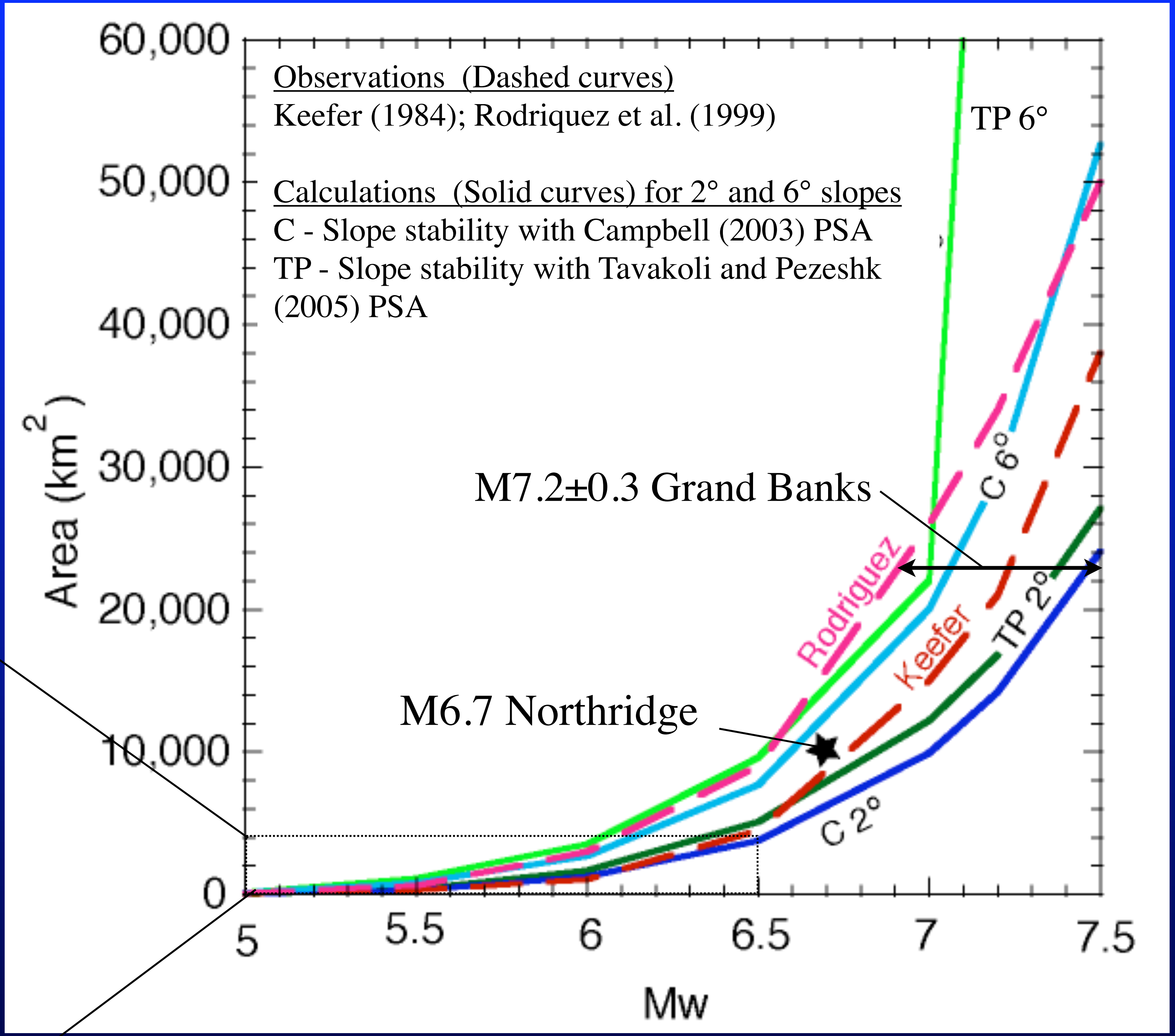


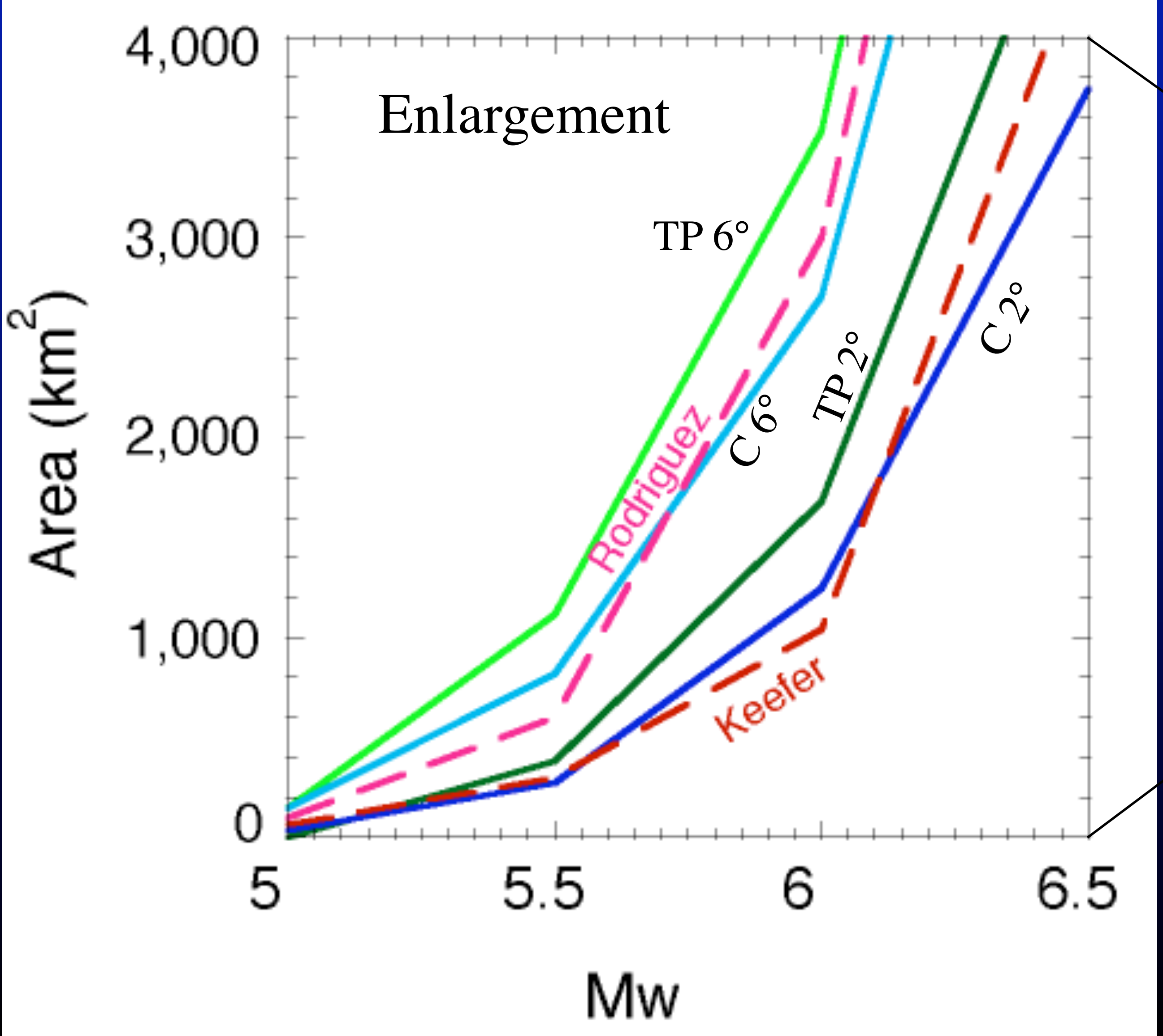
Observed area encompassing subaerial slope failures as a function of earthquake magnitude



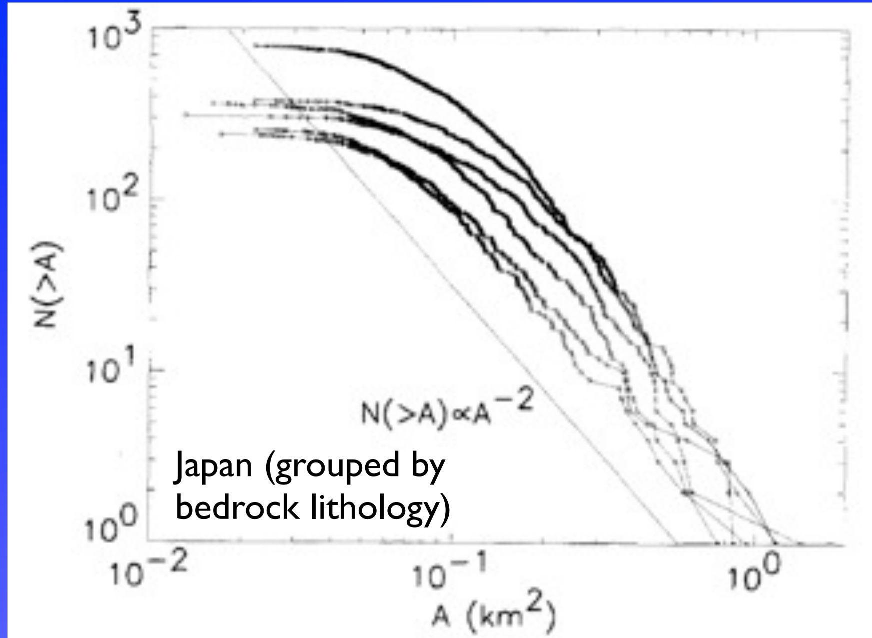
(from Rodriguez et al., 1999)

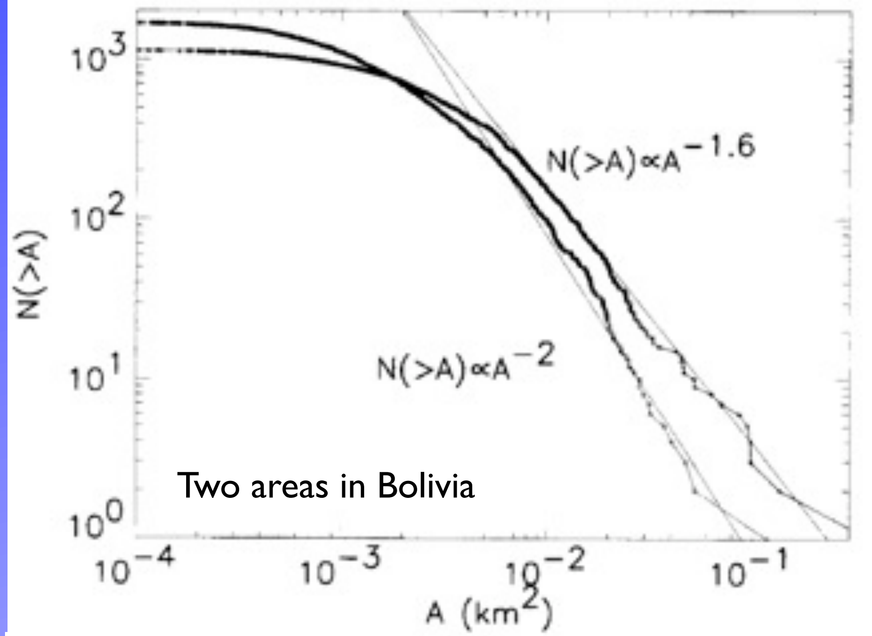
Comparison between observations of total failed area on land and maximum predicted area from slope stability analysis

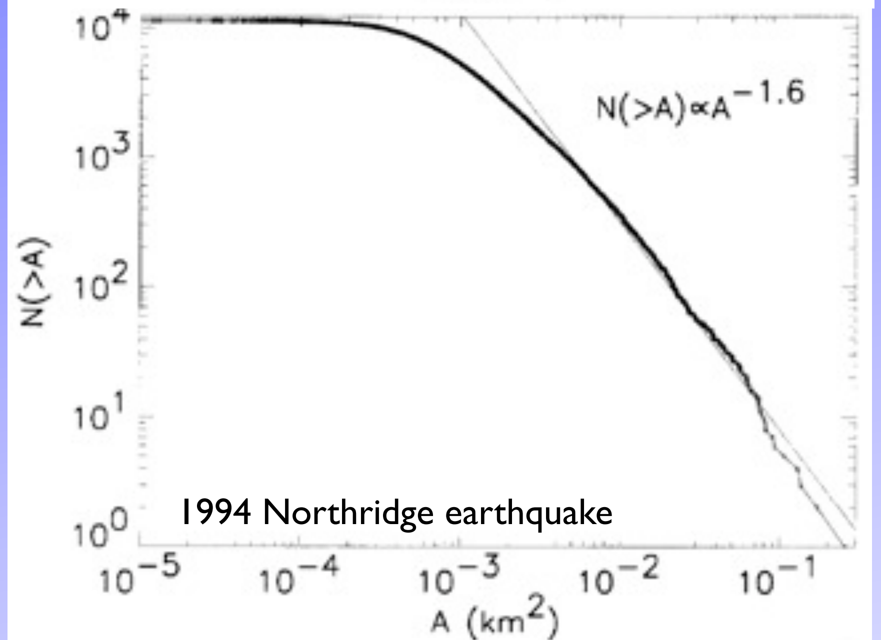




Conclusion:
For a given magnitude, total area encompassing landslides is similar to predictions by slope stability analysis

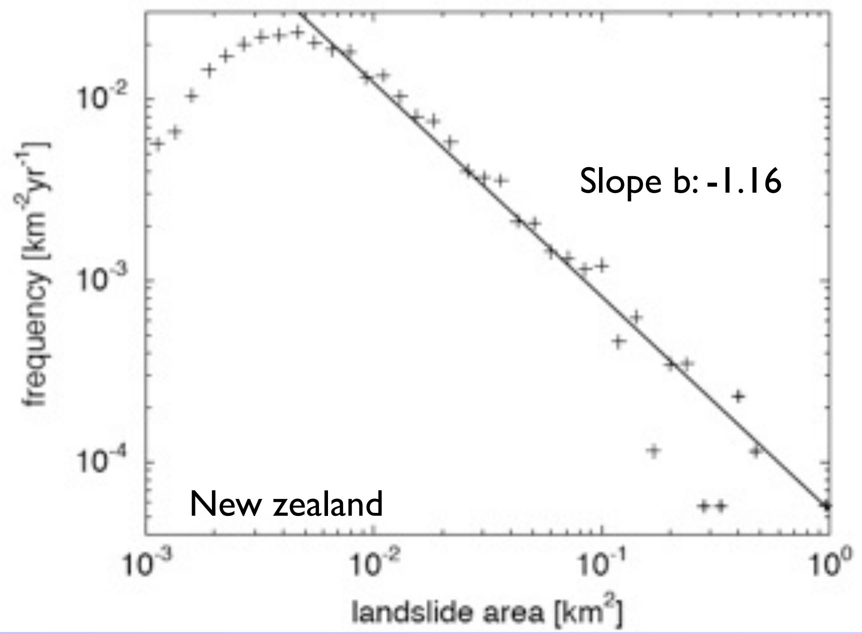




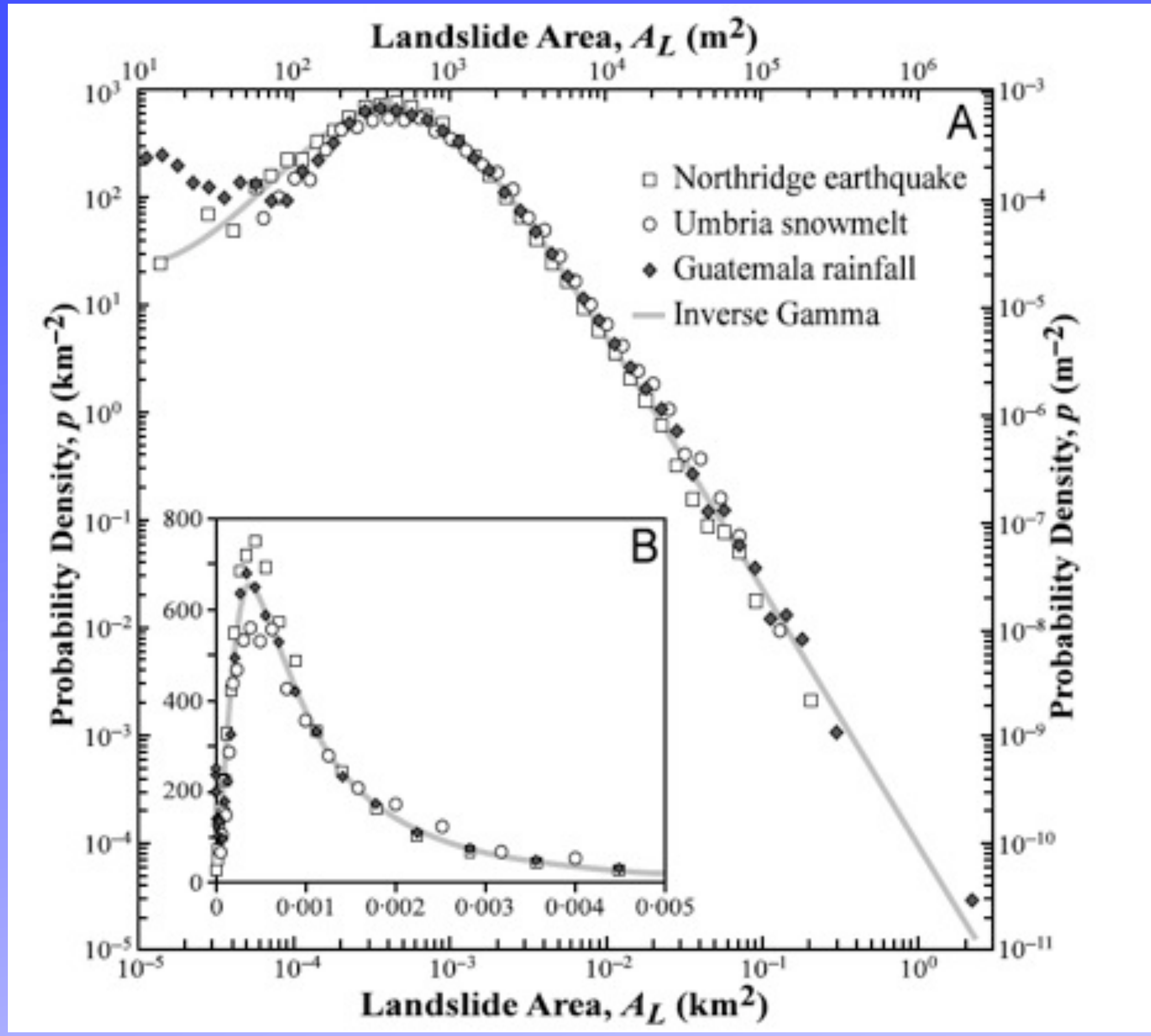


From Pelletier, Malamud, Blodget, and Turcotte, 1997

Are subaerial landslides different?



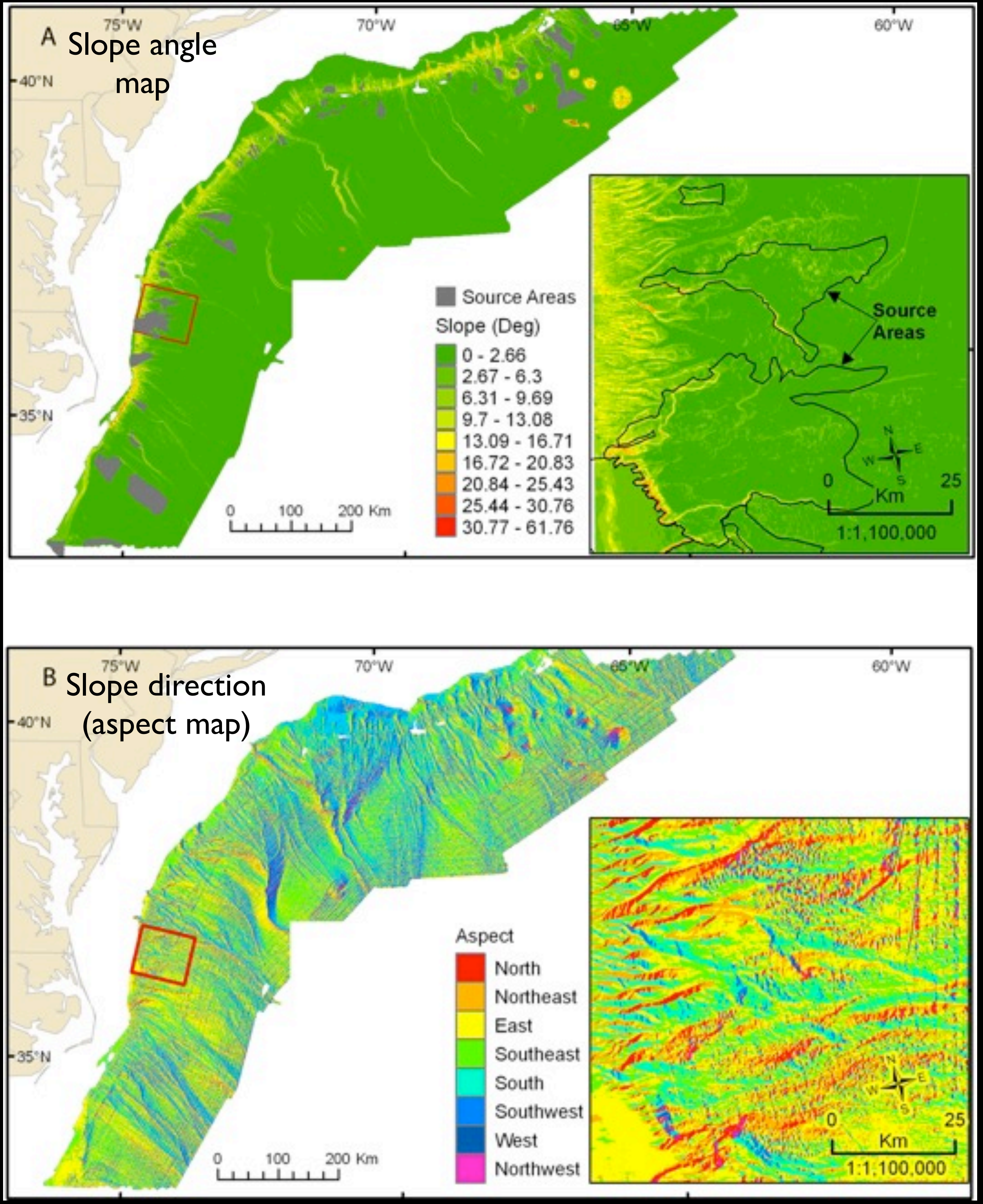
From Hovius et al., 1997



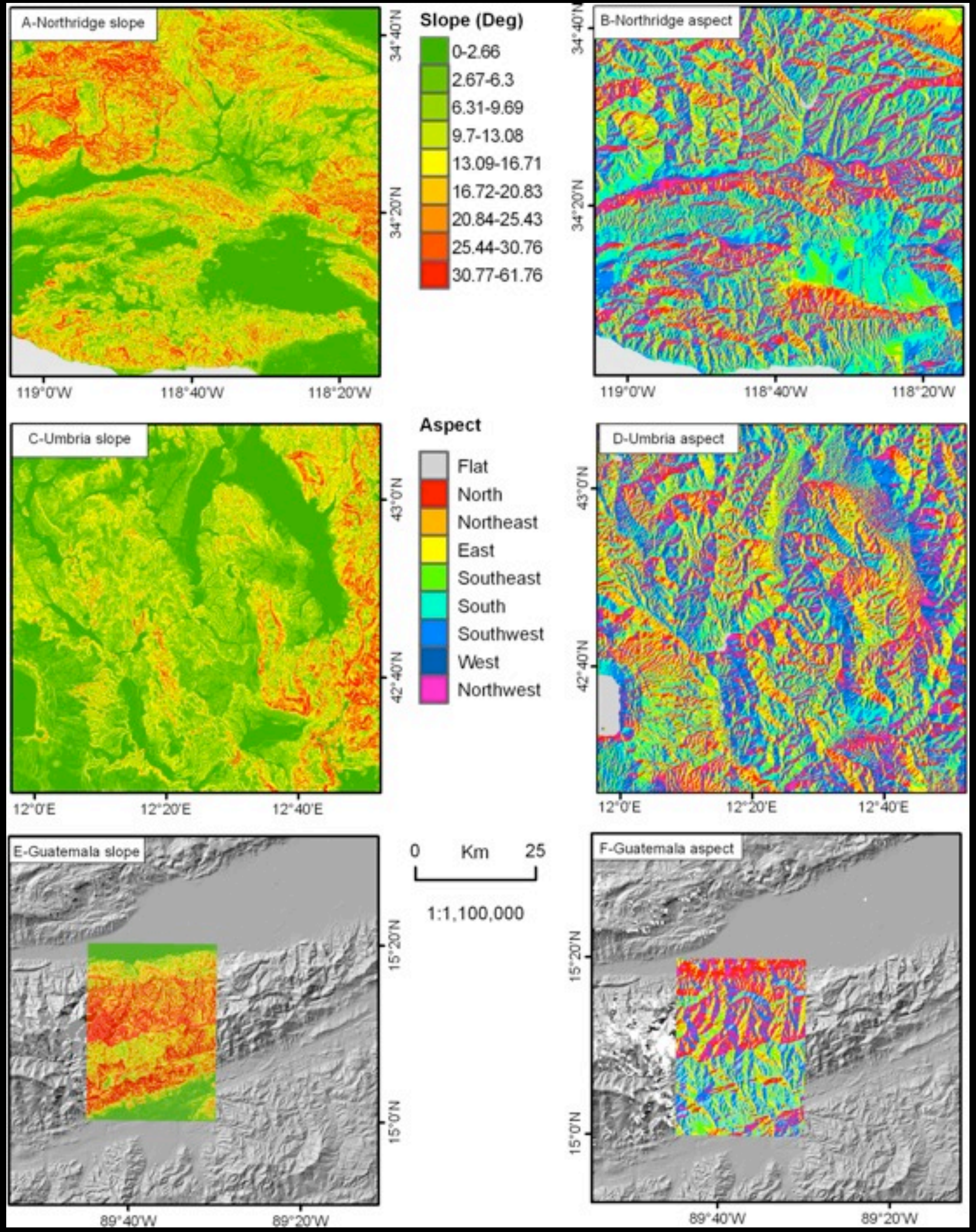
11,111 landslides triggered by 1994 **Northridge** earthquake
4,233 landslides triggered by 1997 snowmelt event in **Umbria**, Italy
9,594 landslides triggered by heavy rainfall from the 1998 Hurricane Mitch, **Guatemala**

From: Malamud, Turcotte, Guzzetti, Reichenbach (2004)

Differences between subaerial and submarine morphology

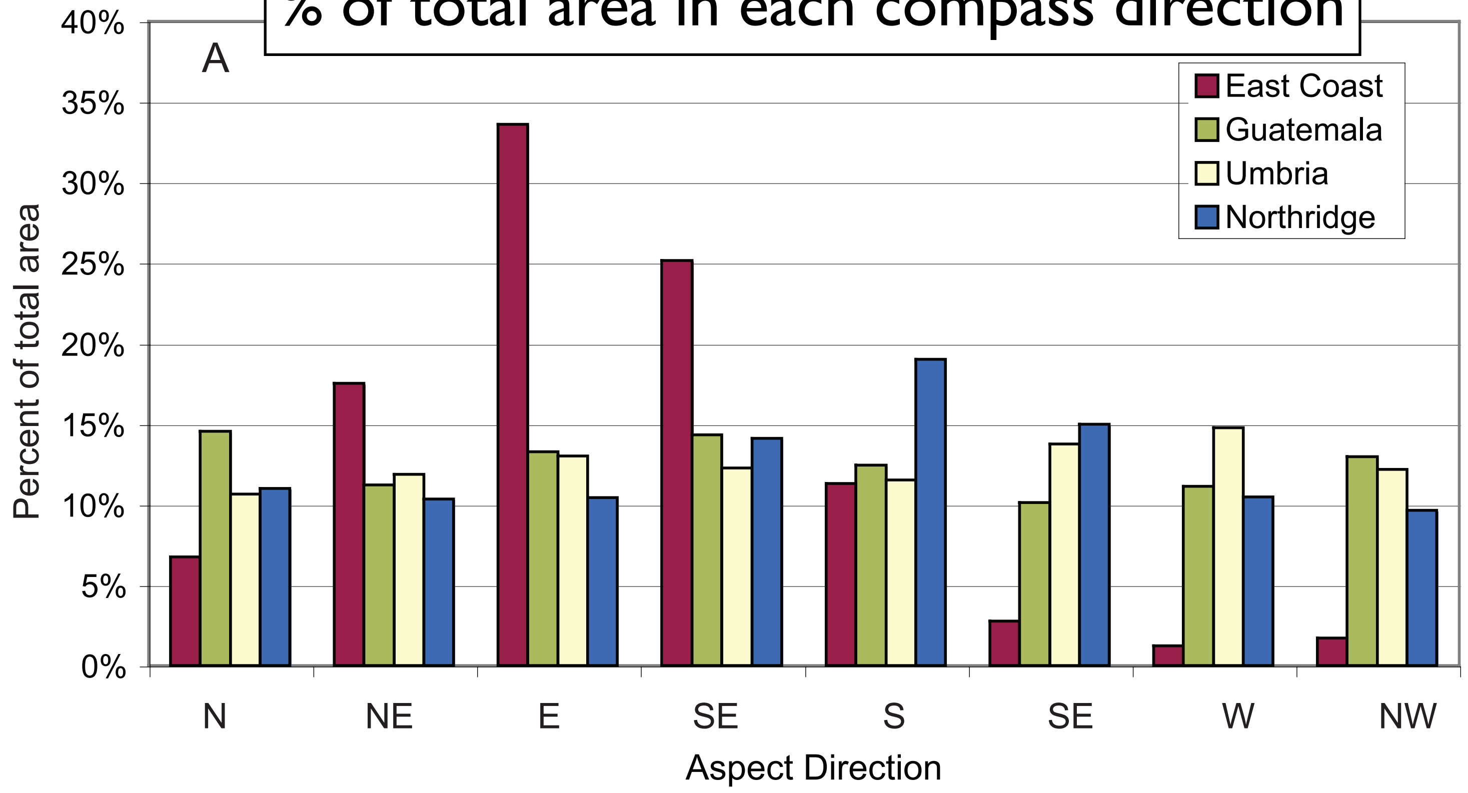


Size of area and grid size are similar for all 4 boxes

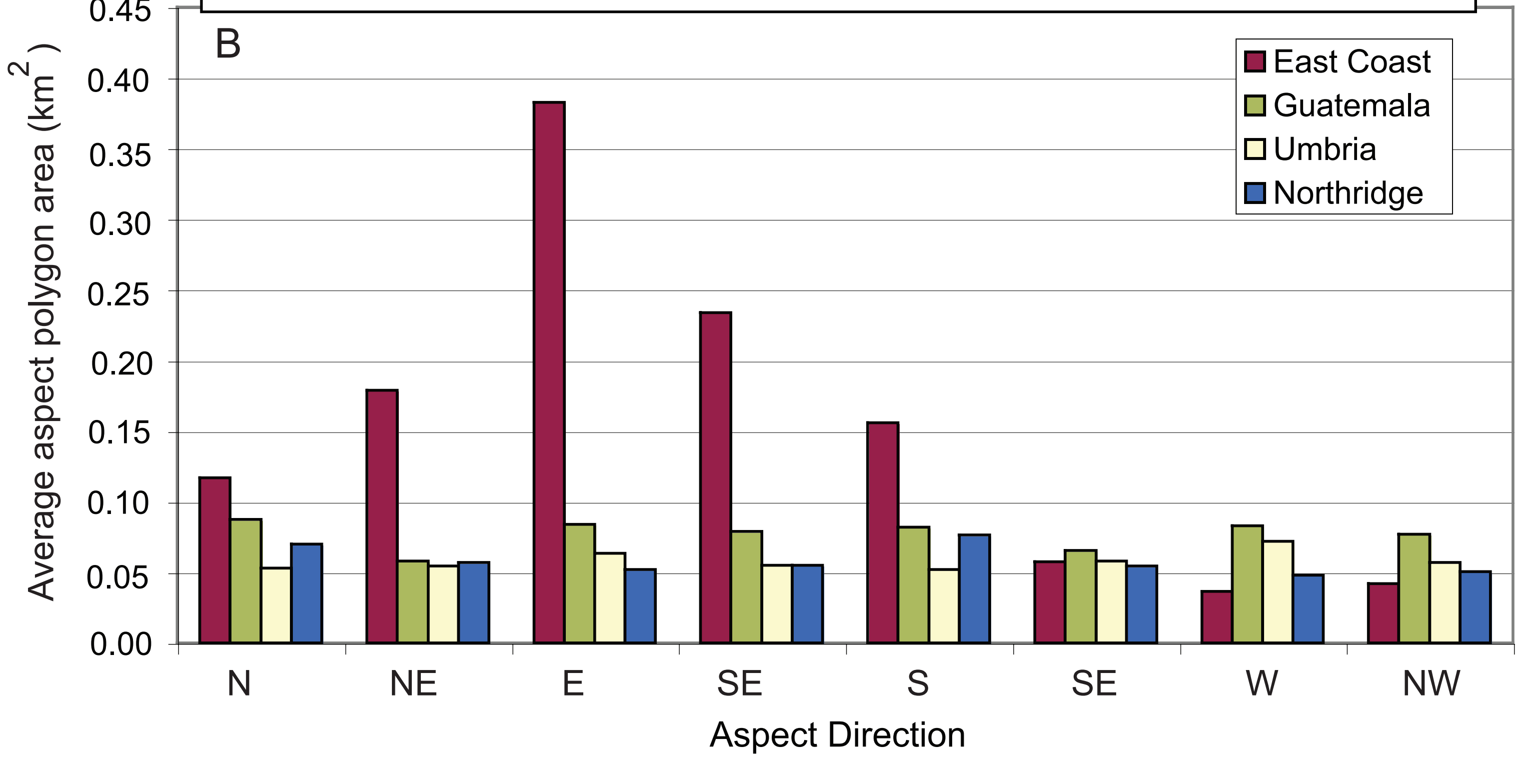


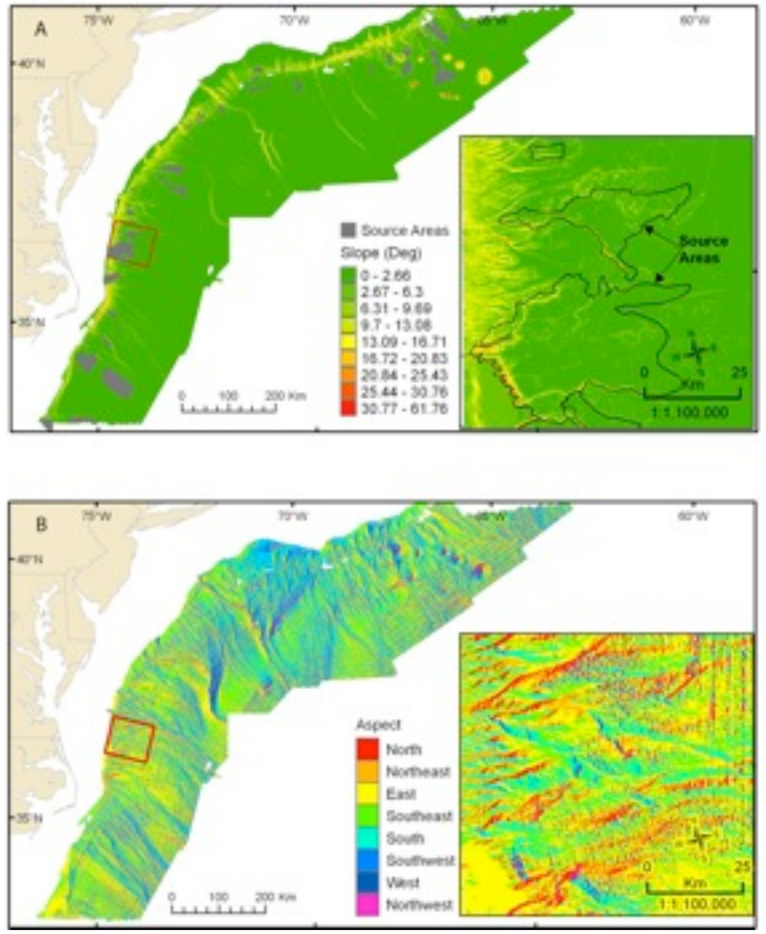
Quantifying morphological differences between submarine and subaerial zones of landslides

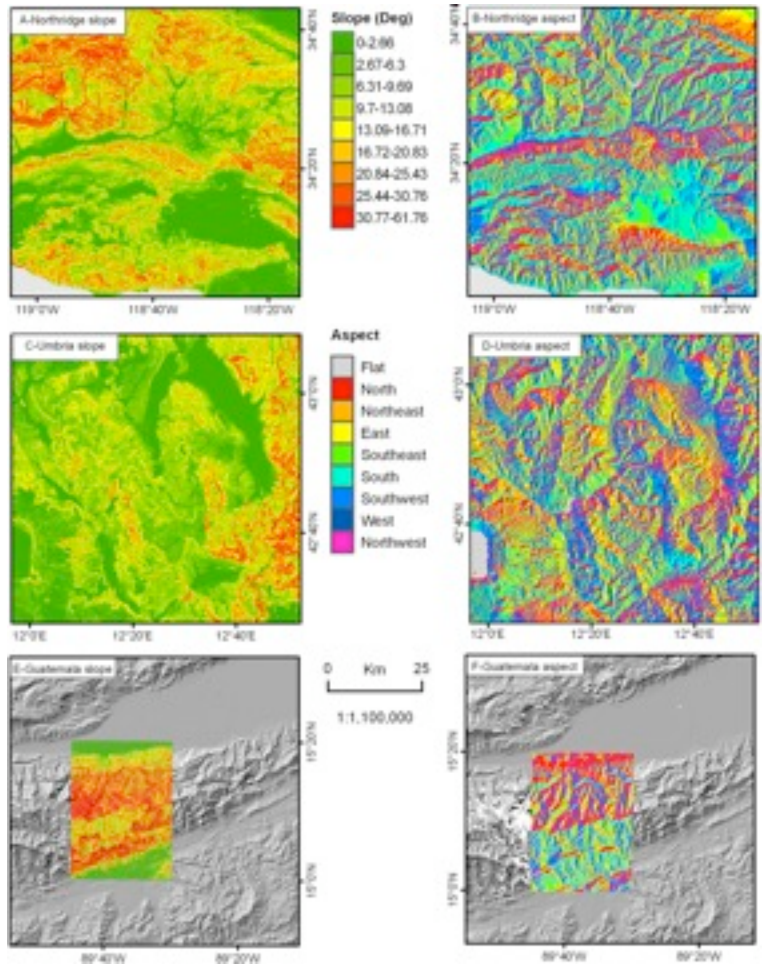
% of total area in each compass direction



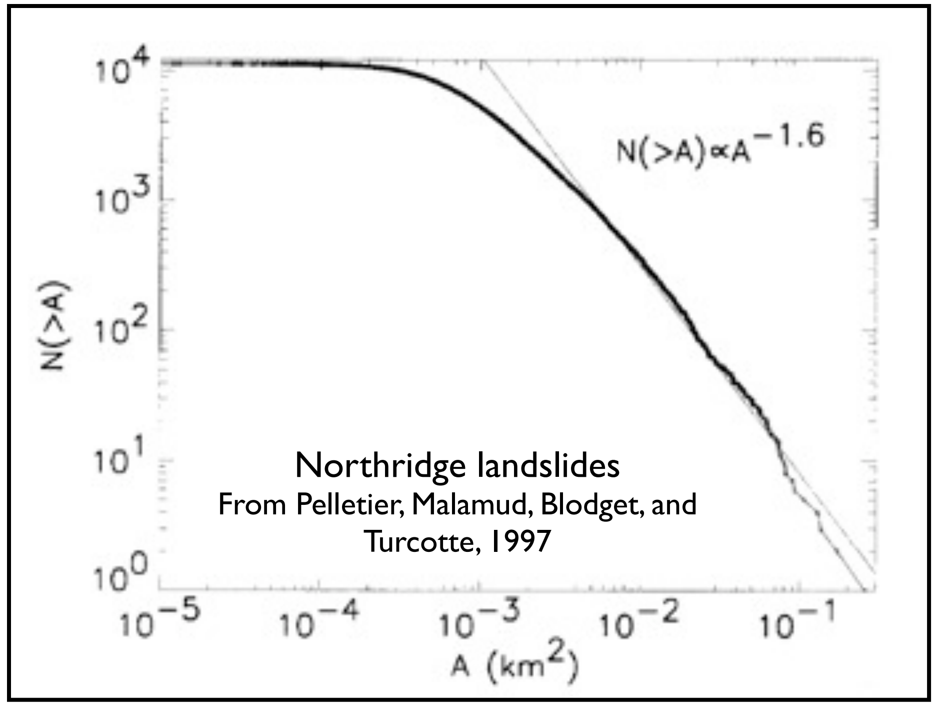
Average polygon area in each compass direction

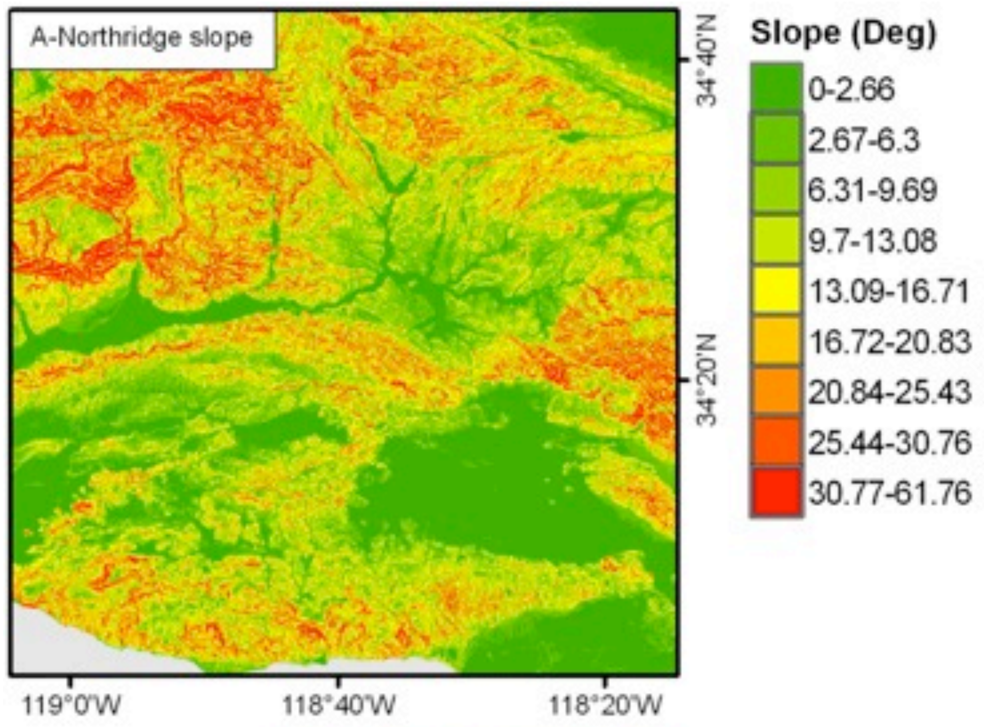


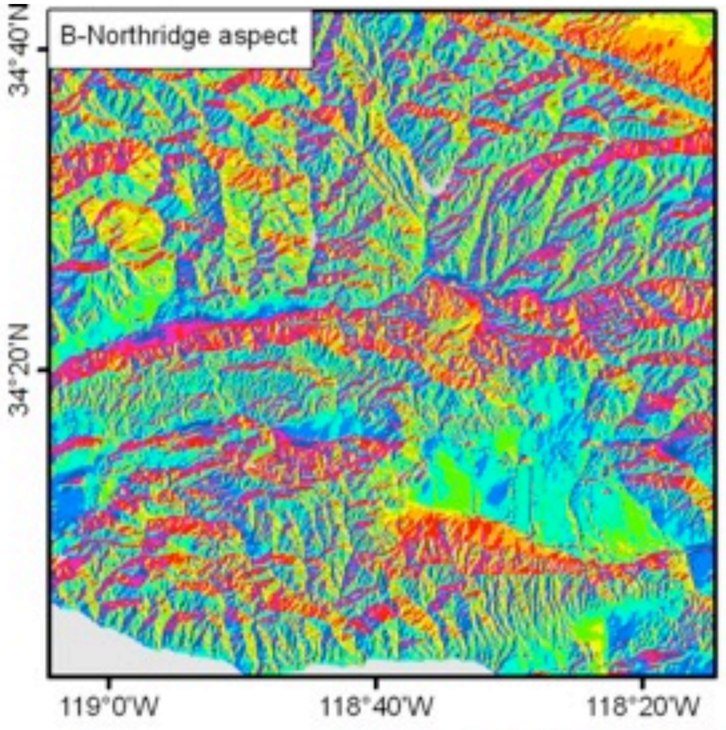


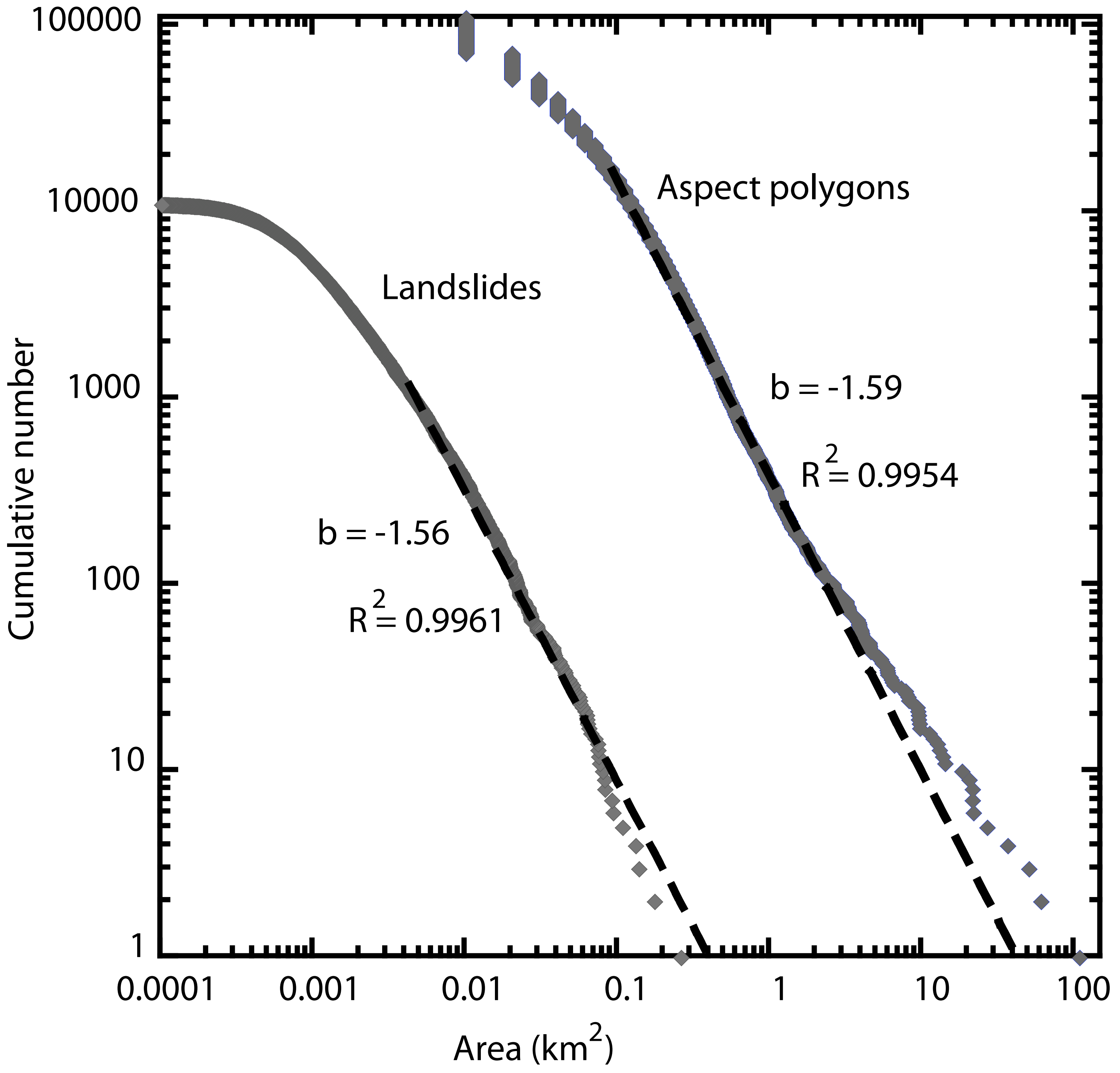


Power law exponent of landslide distribution is same as that of area of polygon distribution, likely because landslide area is limited by available area



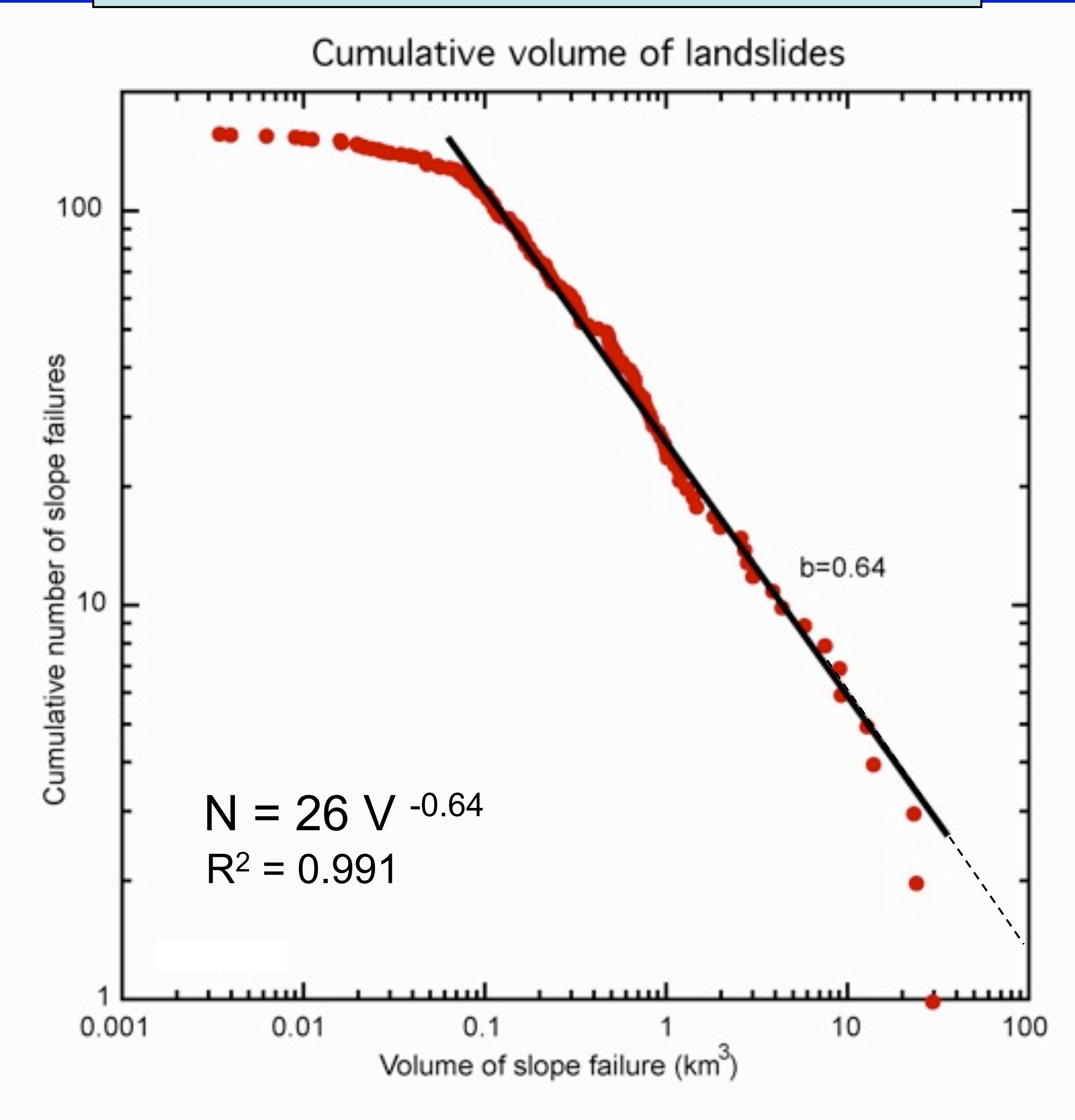




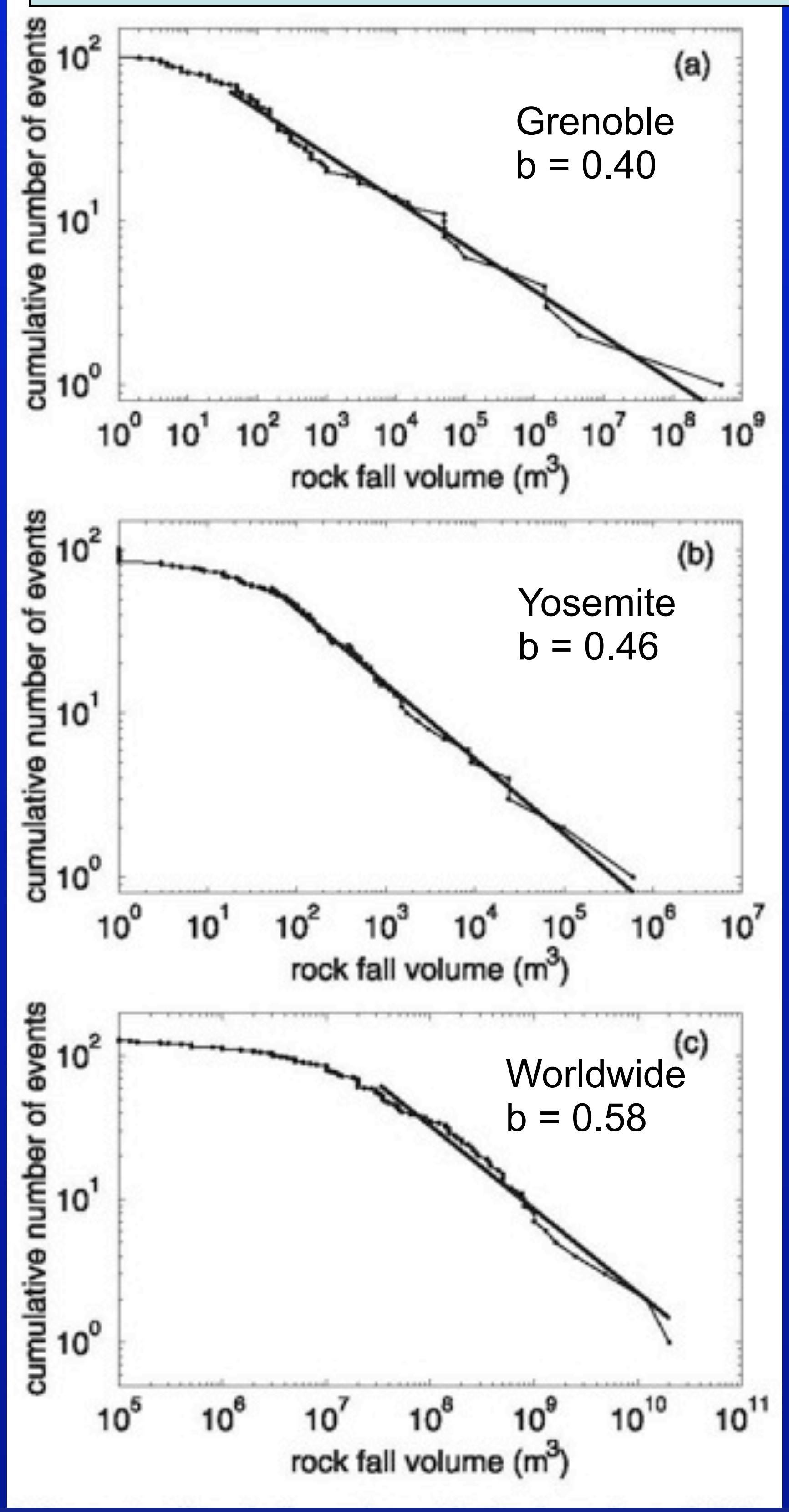


Note: Only largest 8% of landslide areas and 7.5% of polygon areas were fit to achieve high degree of correlation with inverse power law

Submarine:
Edge of carbonate platform, Puerto Rico = 0.64



Subaerial: For rockfall volume on subvertical cliffs, $b = 0.5 \pm 0.2$



(Dussauge et al., 2003)

Size distributions of landslides in Puerto Rico and of rock falls on land follow a Power Law distribution, perhaps because size of landslides is governed by fissures that develop at the platform edge by carbonate dissolution (an on-going process).

Conclusions

Size distribution of submarine landslides along the Atlantic continental margin fits log-normal distribution better than inverse power law.

This distribution can be mimicked if we assume that size of landslide area is related to earthquake magnitude via slope stability analysis, and that earthquakes follow the G-R relationship.

If these assumptions are correct, it implies that:

1. Landslides initiate simultaneously across the entire area affected by ground shaking, and are not a cascading process from a few nucleating sources.
2. The downward mass movement does not excavate significantly more material (except when turbidity flows develop).
3. Maximum size of landslides can be predicted from earthquake magnitude.

(Cont.)

Conclusions

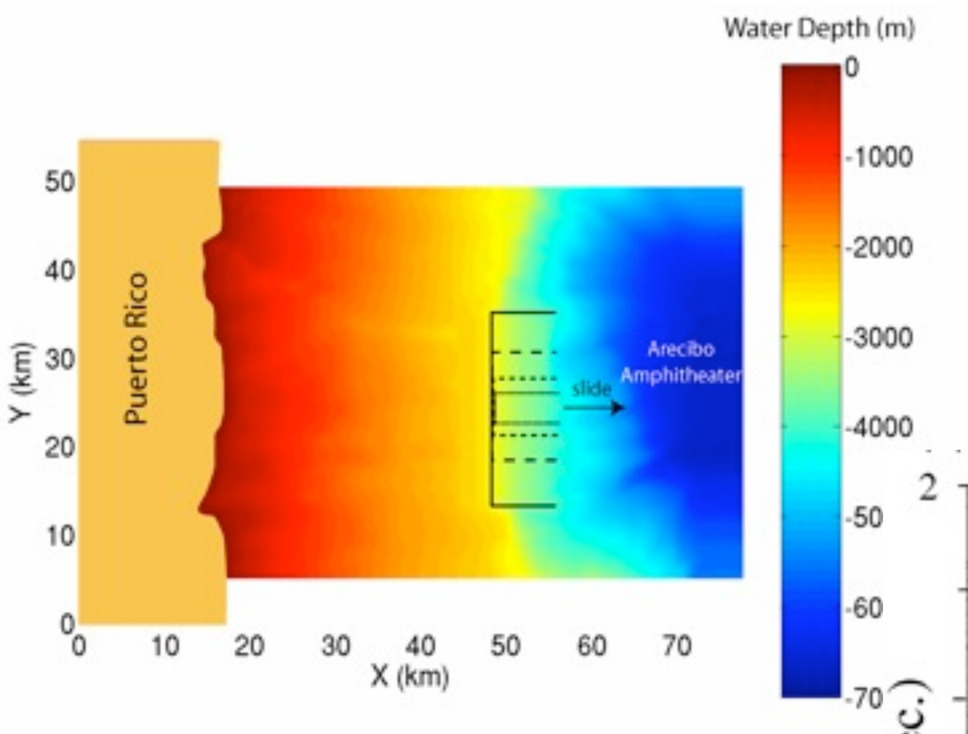
Subaerial landslides behave similar to submarine landslides. The total area affected by an earthquake can be predicted by peak ground acceleration.

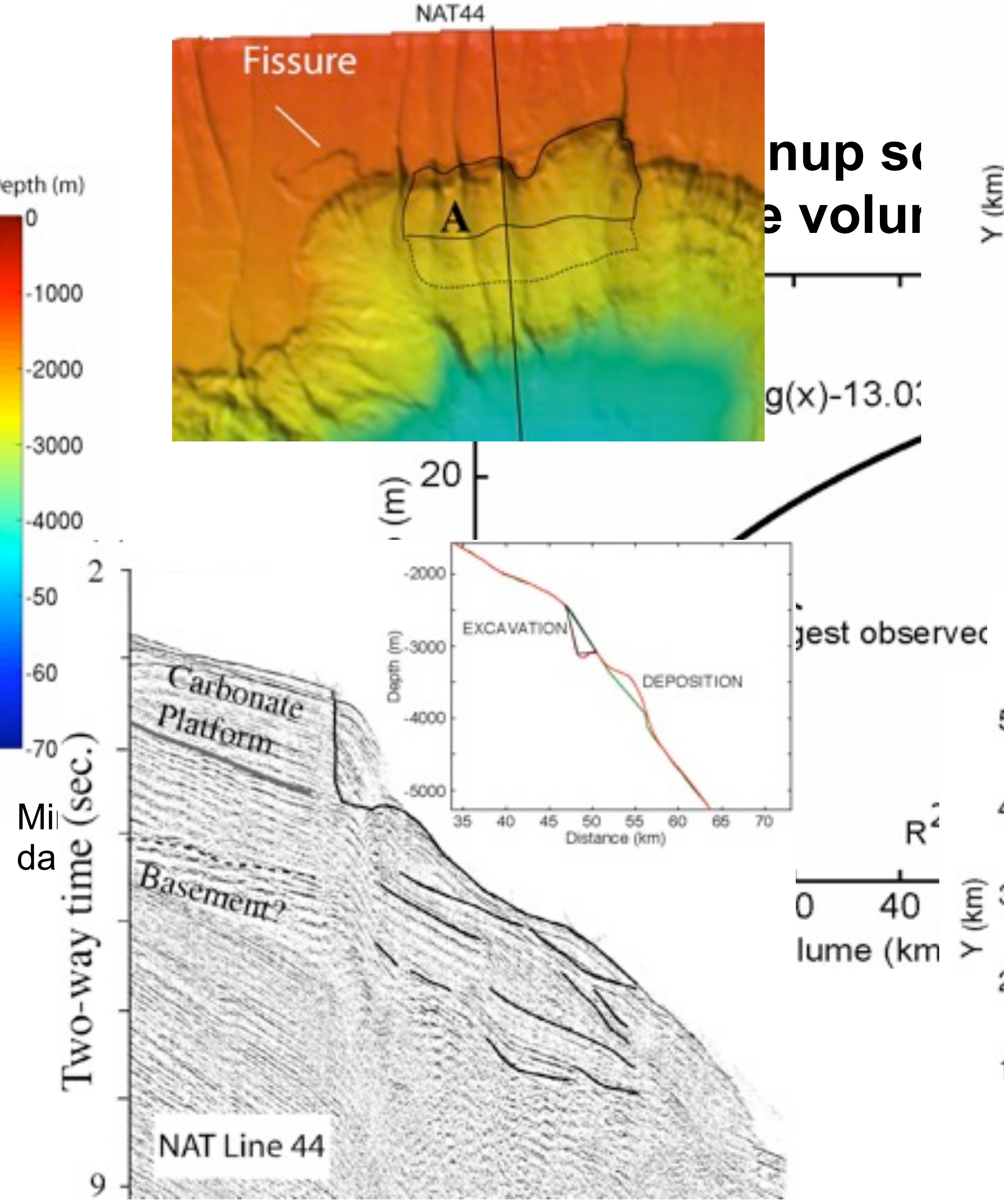
The apparent inverse power law distribution of subaerial landslides is a function of the size distribution of the morphology of the landslide region, because, unlike submarine landslides, the potential area of each landslide is limited by the morphology.

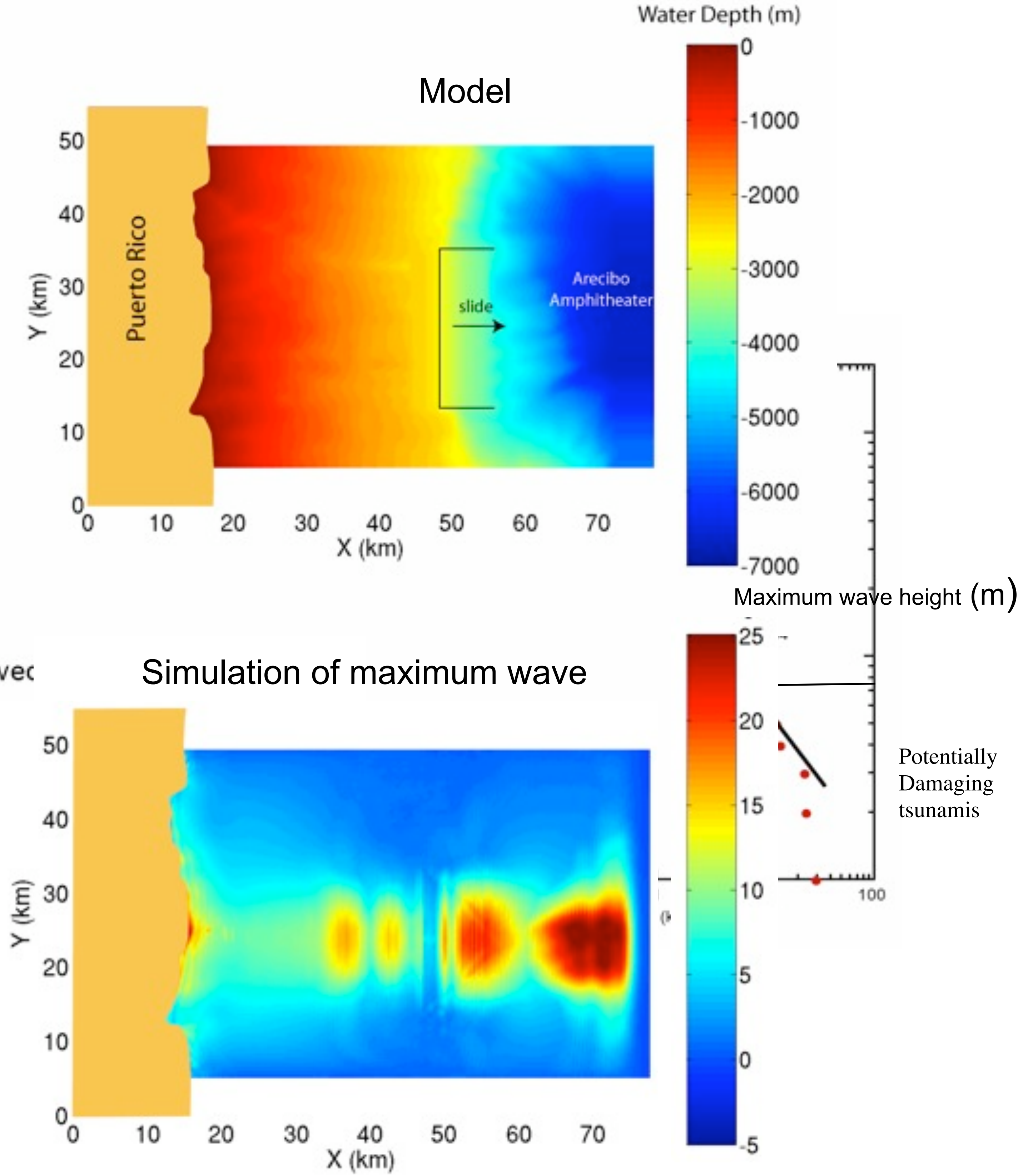
Power law distribution of submarine landslides in Puerto Rico may be controlled by the existence of fractures and fissures that develop progressively at the edge of the carbonate platform.

APPLICATIONS OF LANDSLIDE STATISTICS

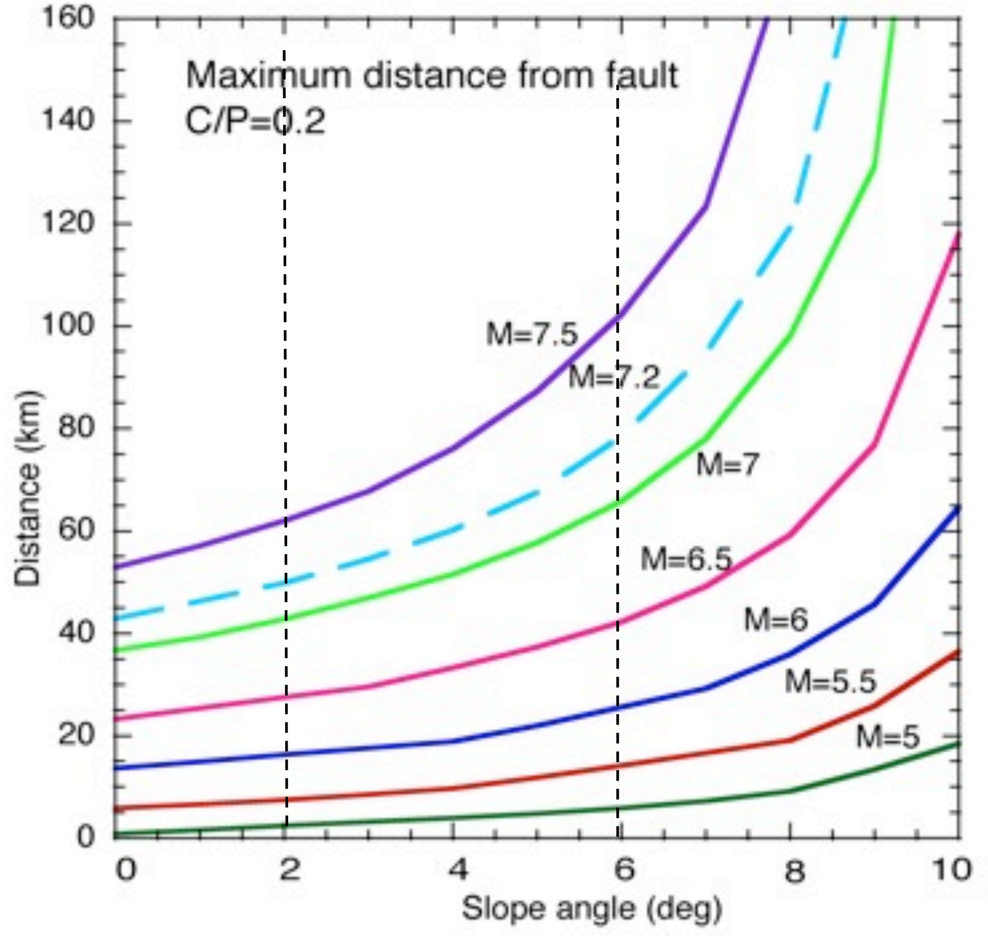
1. **Tsunami amplitude is most directly related to volume of excavated area, allowing us to estimate the number of potentially damaging tsunamis from landslide distribution**

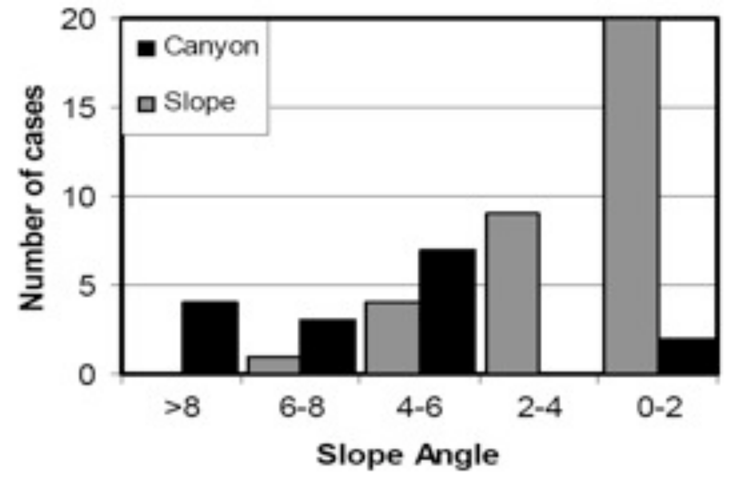






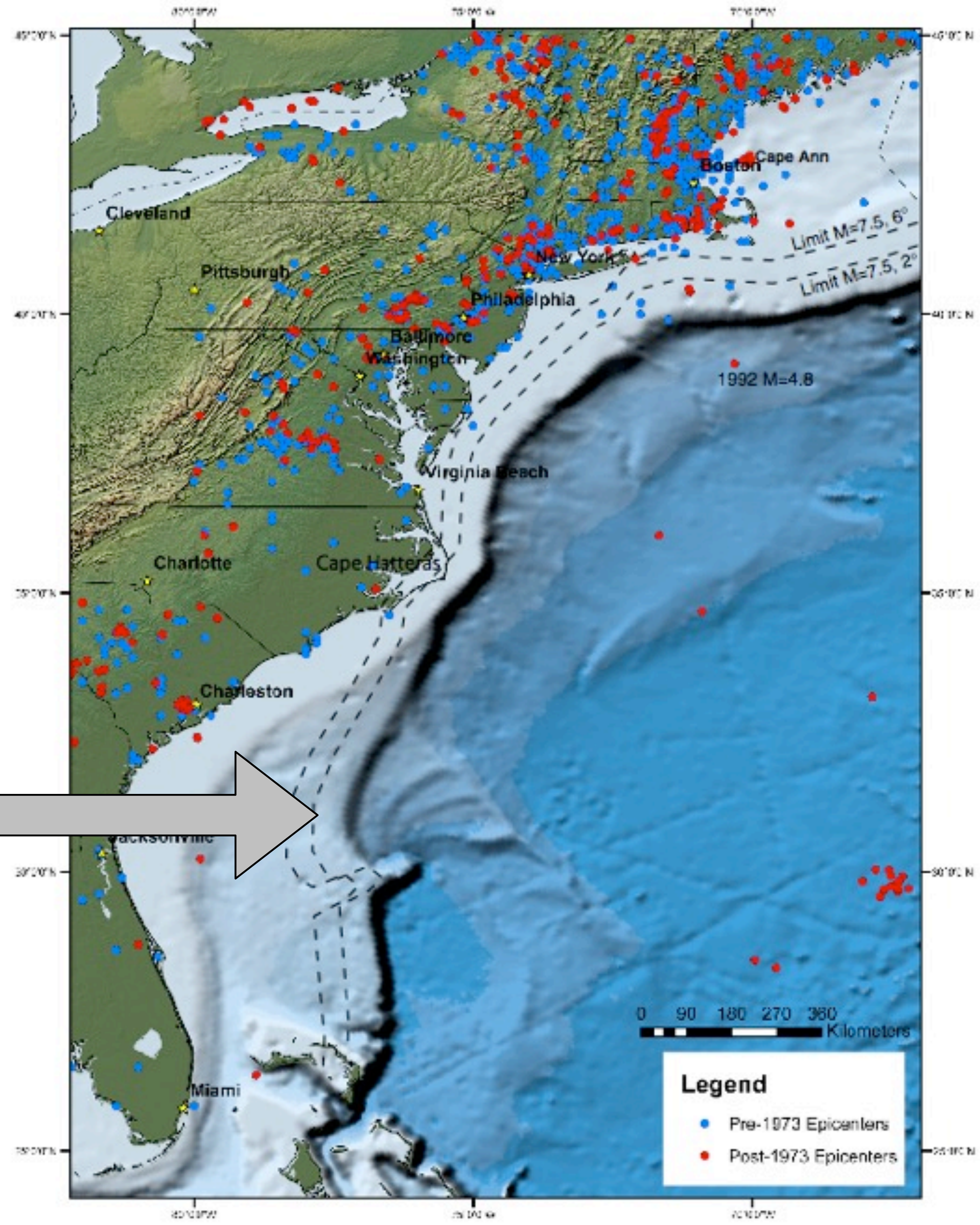
Maximum distance to failure, r_{max} as a function of earthquake magnitude and slope





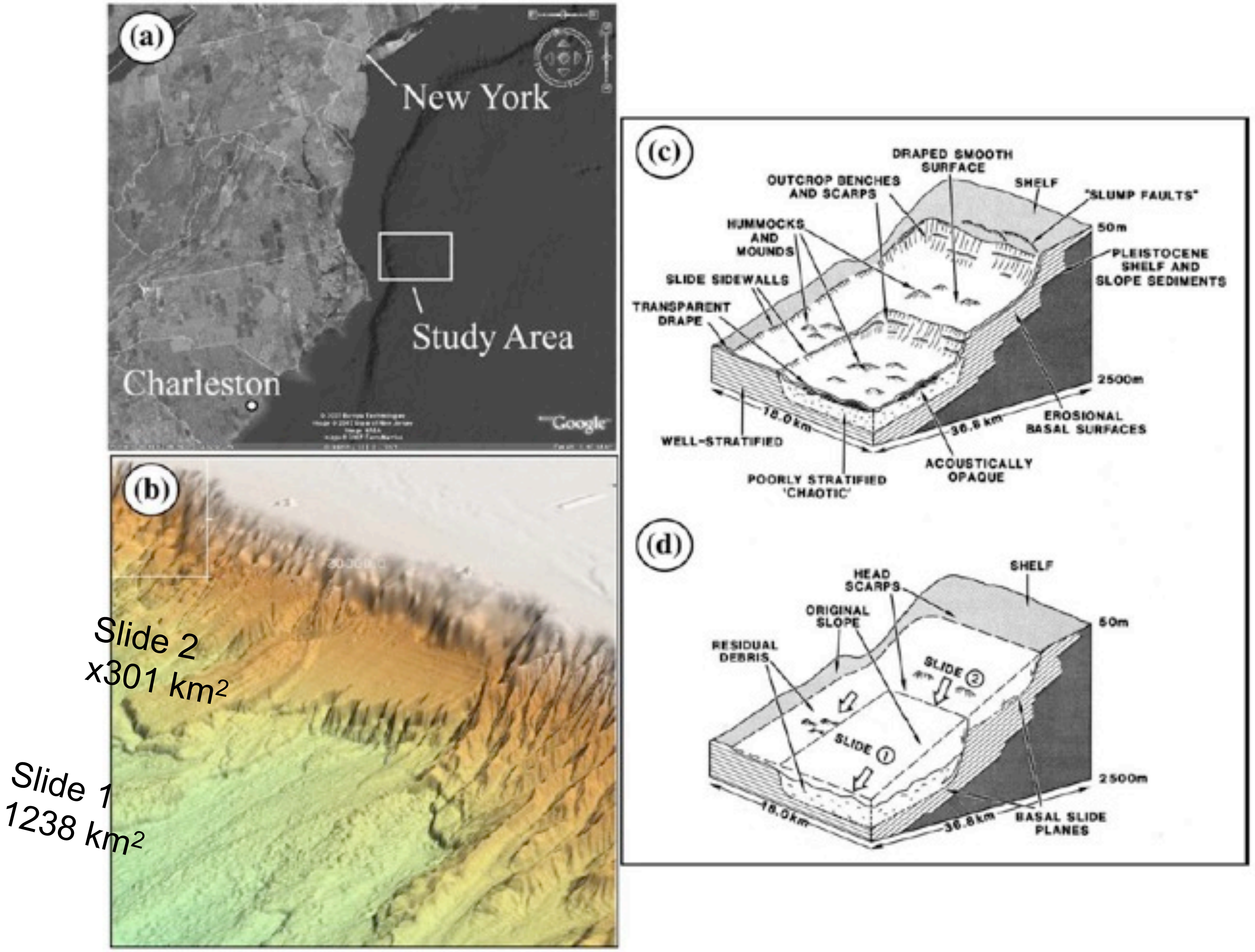
2. Earthquake region that can generate landslide tsunamis is limited to outer shelf and slope

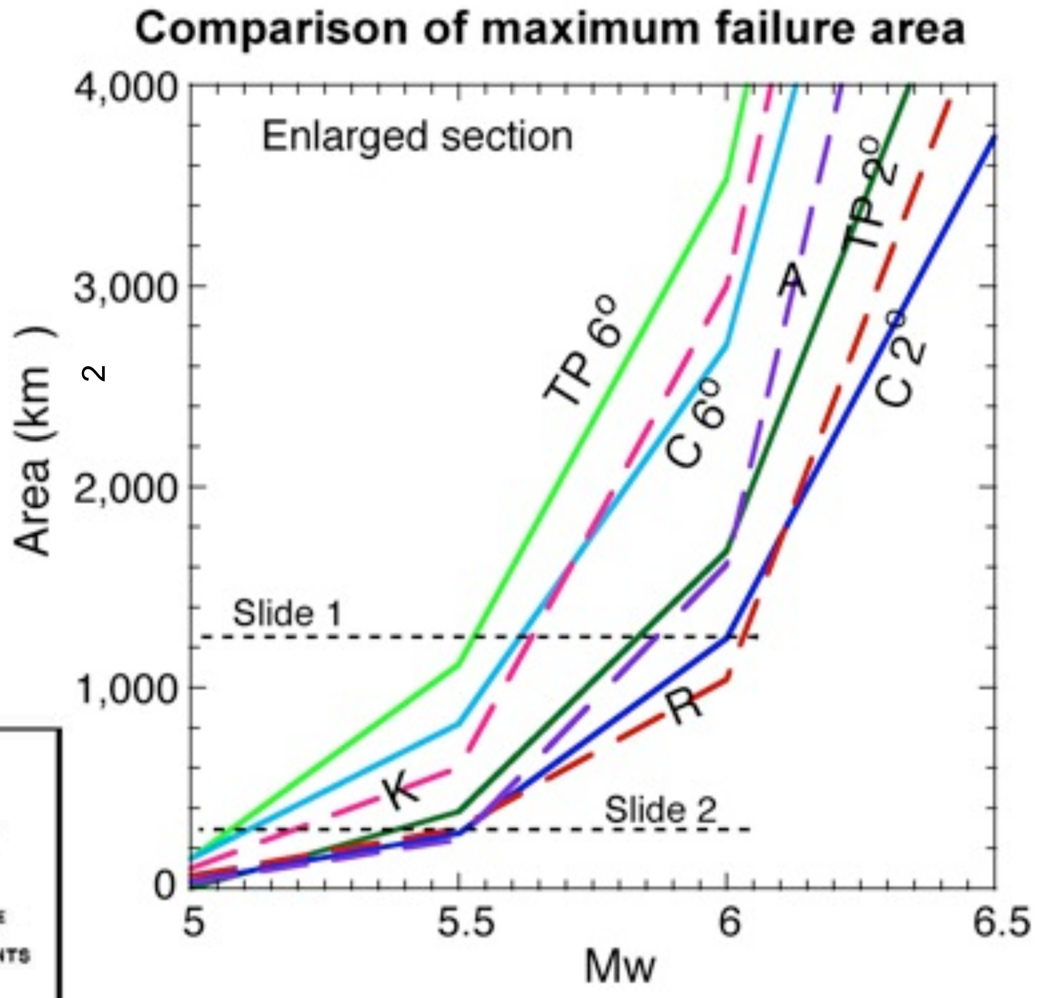
Earthquakes in the East Coast of the U.S.



3. Minimum earthquake magnitude that may cause a devastating tsunami in the Atlantic:

Based on hydrodynamic models of Currituck slide offshore North Carolina

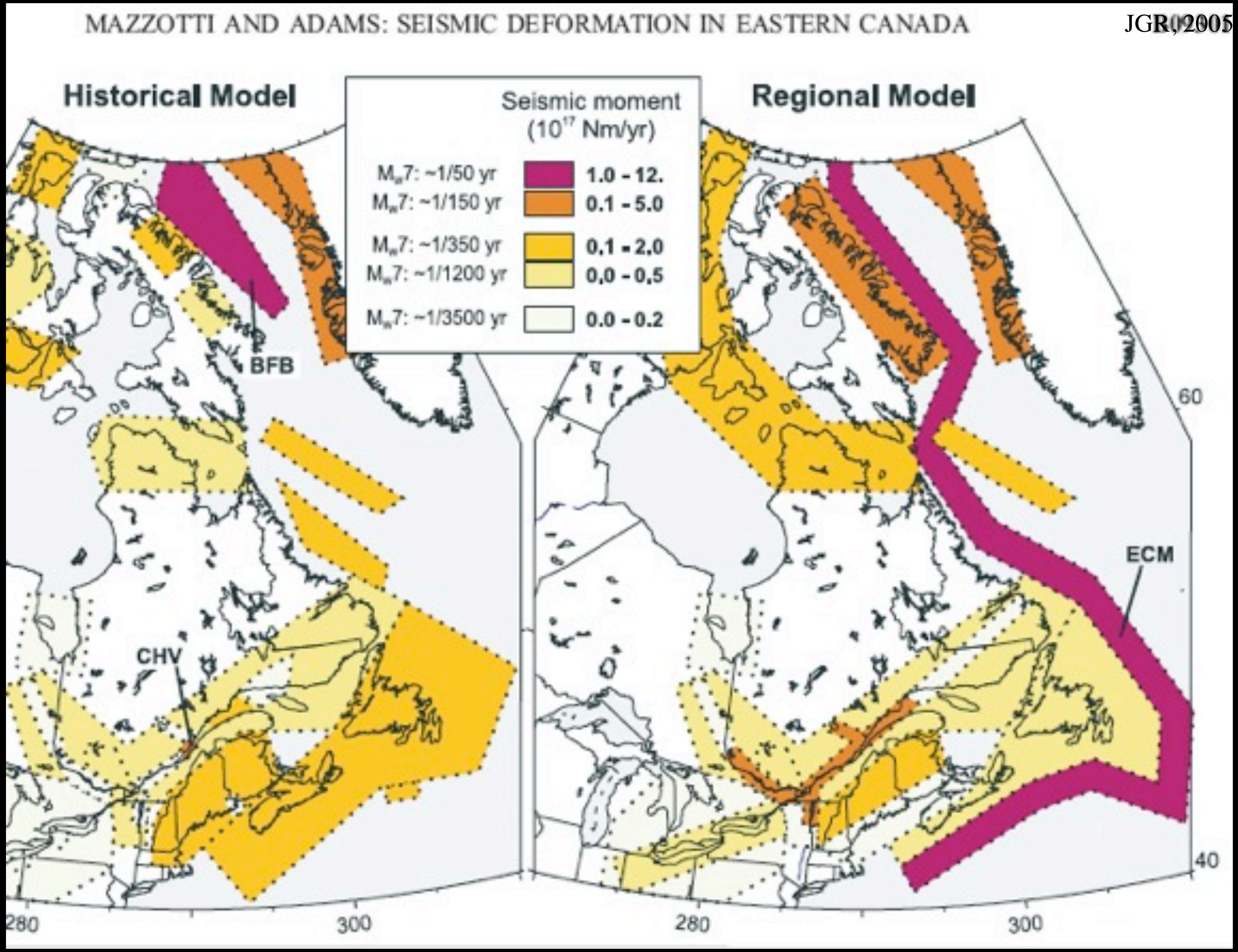




Wave height at 18 m water depth:
Slide 1: 3 -5 m; Slide 2: 1-3 m
(Geist et al., 2009)

More case studies are needed to develop reliable relationships

4. Probability of landslide recurrence along the Atlantic margin



Average annual seismic release along the 6000-km-long continental slope of eastern Canada = 2-10x10^{17} Nm/yr or equivalent to M7 every 40-200 y (Mazzotti and Adams, 2005).

If same regional model extends to the 400-km-long New England, an equivalent M7 is expected off New England every 600-3000 y.

Summary of applications

1. Earthquakes must be located offshore and close to the continental slope to cause a landslide.
2. For the Atlantic margin, earthquakes with $M \geq 5.5$ can cause a devastating tsunami if located optimally on the slope.

- Landslide recurrence in an area may be deduced from earthquake recurrence for that region, which is easier to estimate.
- Landslide statistics can reveal initiation mechanism and style of failure.
- Size of landslides in carbonate environment may be governed by fissure distribution, not by earthquake magnitude.

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