2464-35

Earthquake Tectonics and Hazards on the Continents

17 - 28 June 2013

Landslides

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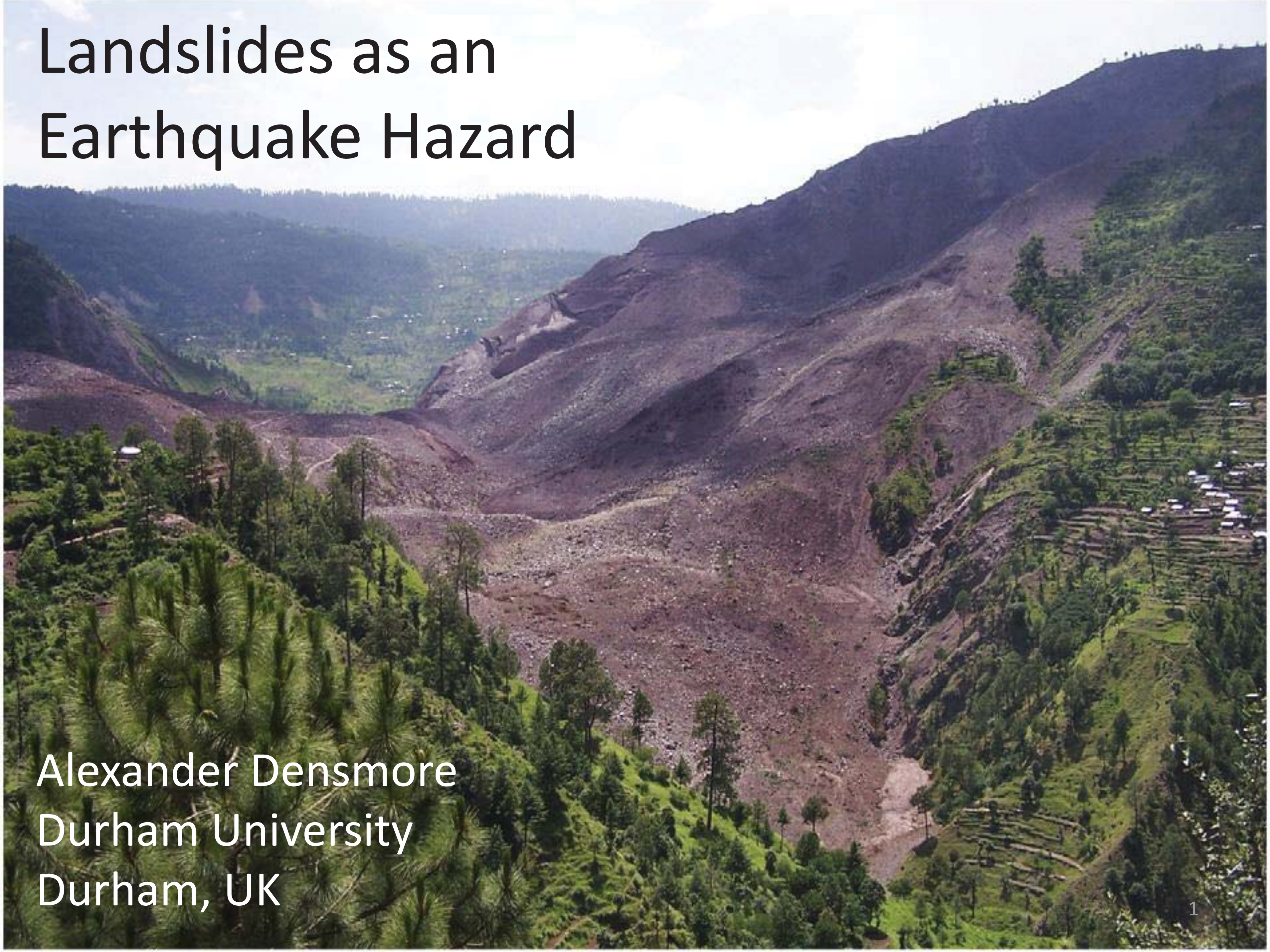


Landslides as an Earthquake Hazard

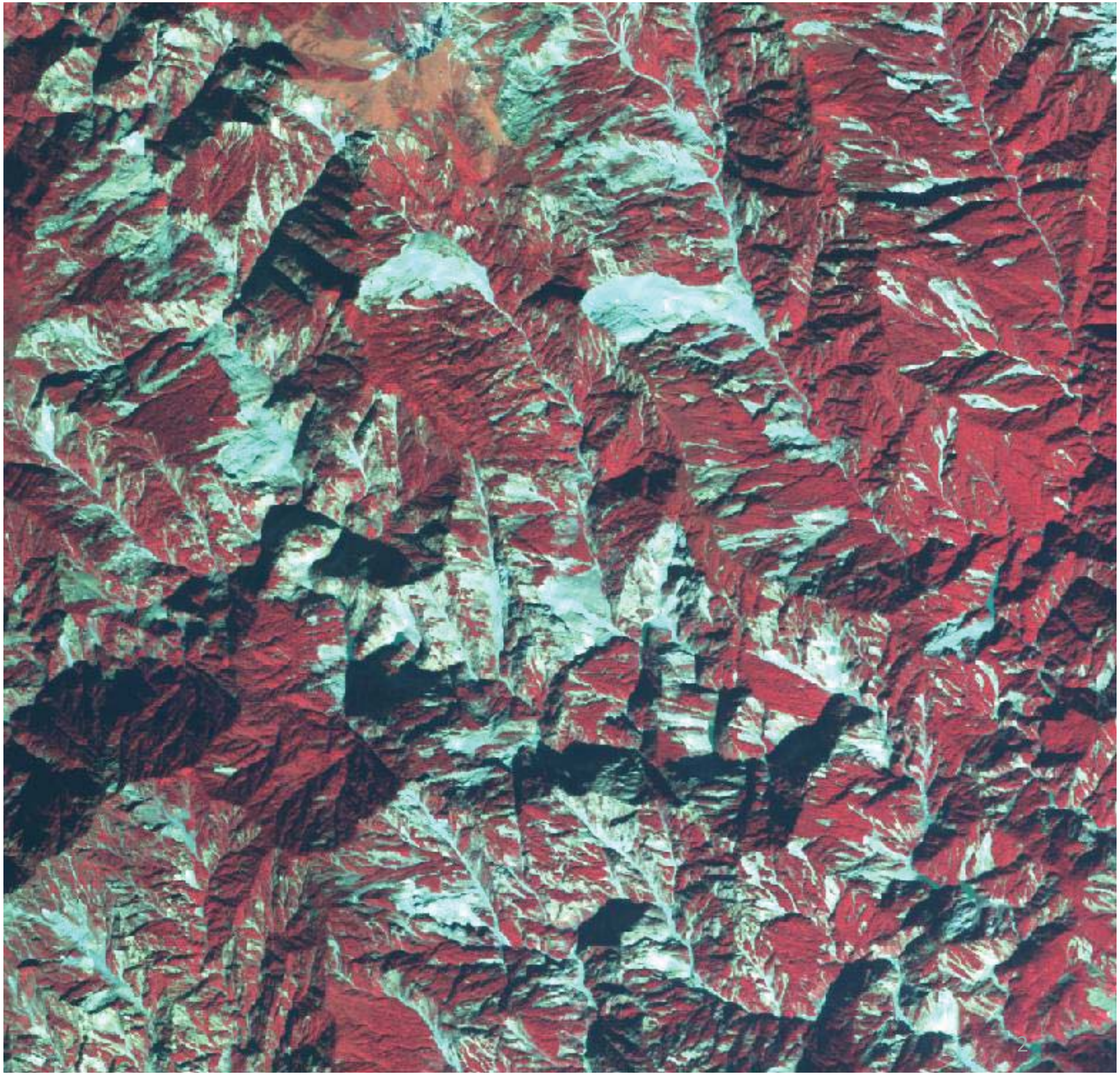
Alexander Densmore
Durham University
Durham, UK

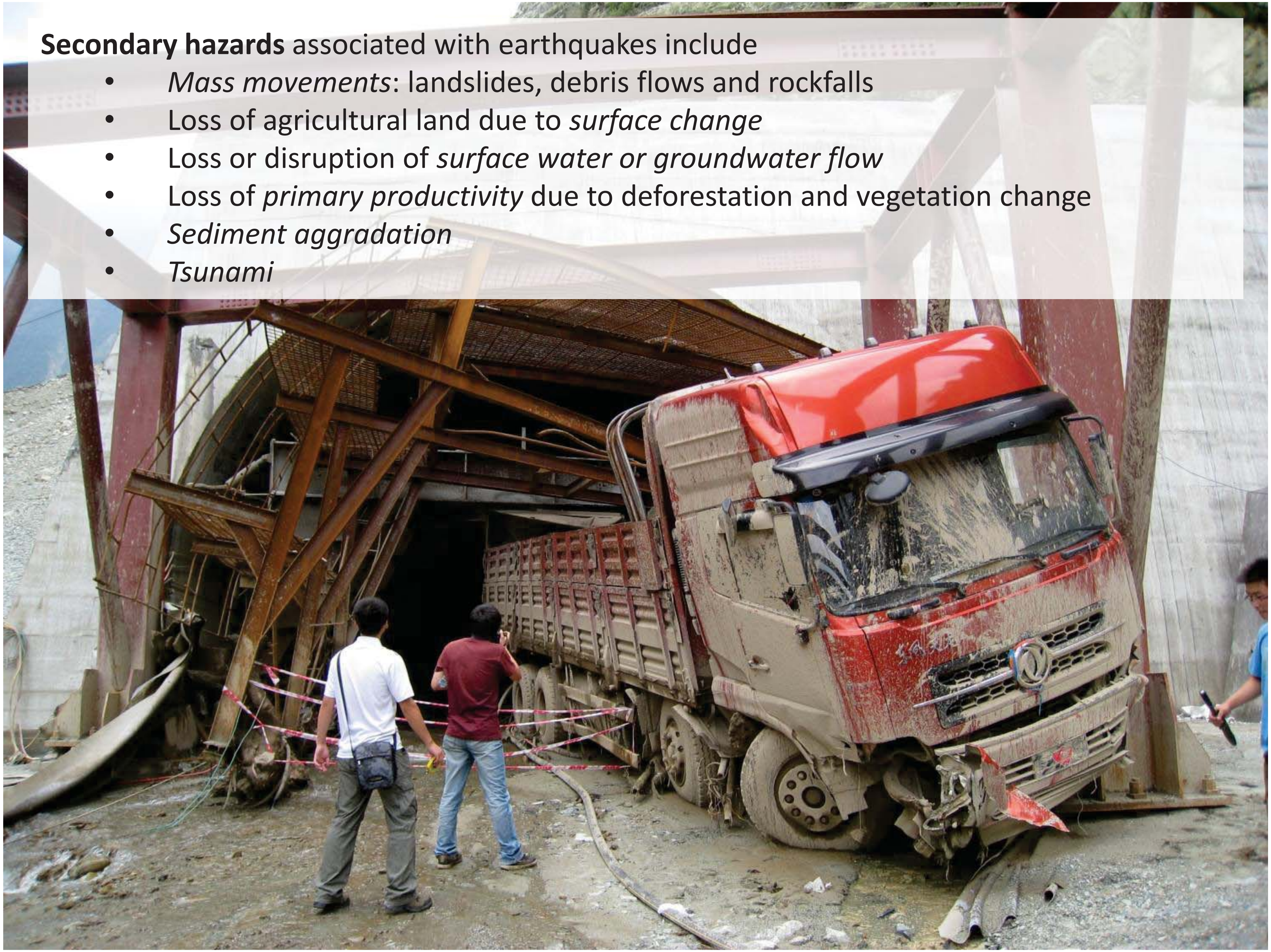
Pengguan massif

Landsat 7
September 2007

Pengguan massif

SPOT 5
October 2008





Secondary hazards associated with earthquakes include

- *Mass movements*: landslides, debris flows and rockfalls
- Loss of agricultural land due to *surface change*
- Loss or disruption of *surface water or groundwater flow*
- Loss of *primary productivity* due to deforestation and vegetation change
- *Sediment aggradation*
- *Tsunami*

Why might secondary hazards be particularly difficult to deal with?

- They are likely to **persist in the landscape for long periods of time**, frustrating efforts at reconstruction of infrastructure and resilience, and perhaps exceeding the time scale of relief funding
- They are likely to be **spatially variable in their severity**, and to extend over a wider area than that directly affected by seismic shaking

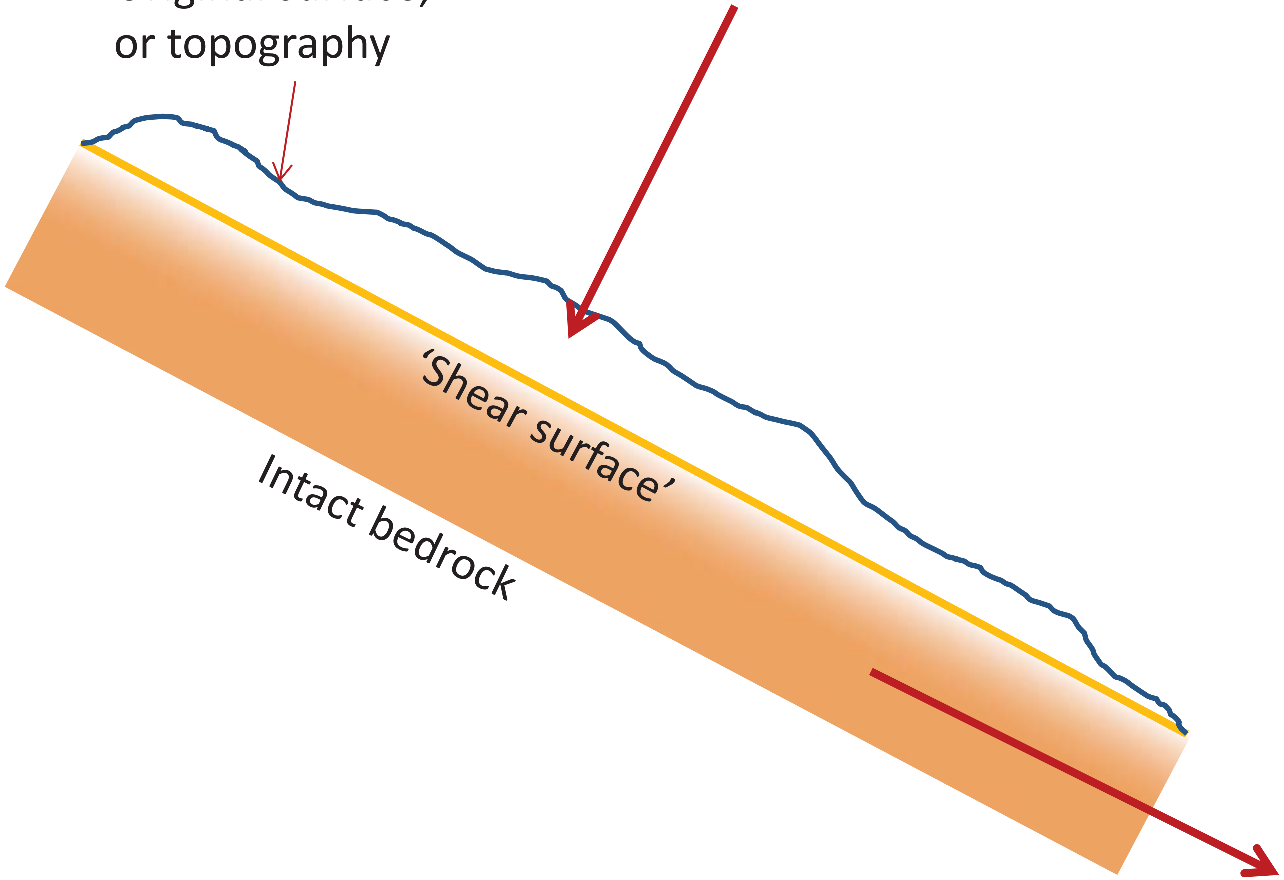
Aim of this section

To familiarize you with key aspects of earthquake-triggered landslides and their importance as an earthquake-related hazard

What you should learn:

1. Basic understanding of rock slope failure
2. Appreciation of earthquake-triggered landslide size distributions, and why this matters
3. Understanding of the spatial patterns of landslides, and long-term importance
4. Appreciation of distribution in time – evolution and persistence

A primer on landslides



Original surface,
or topography

What holds the material in place?

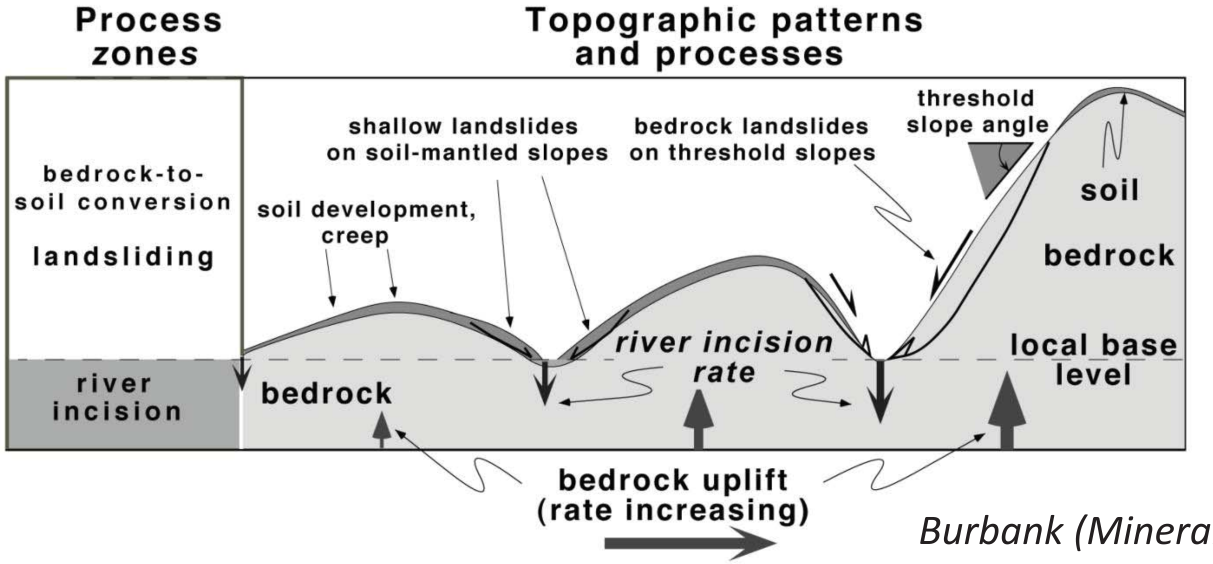
What pulls the material downhill?

A common first step is to simplify the problem into **driving** and **resisting** forces

Sawmill Canyon, Sierra Nevada, US

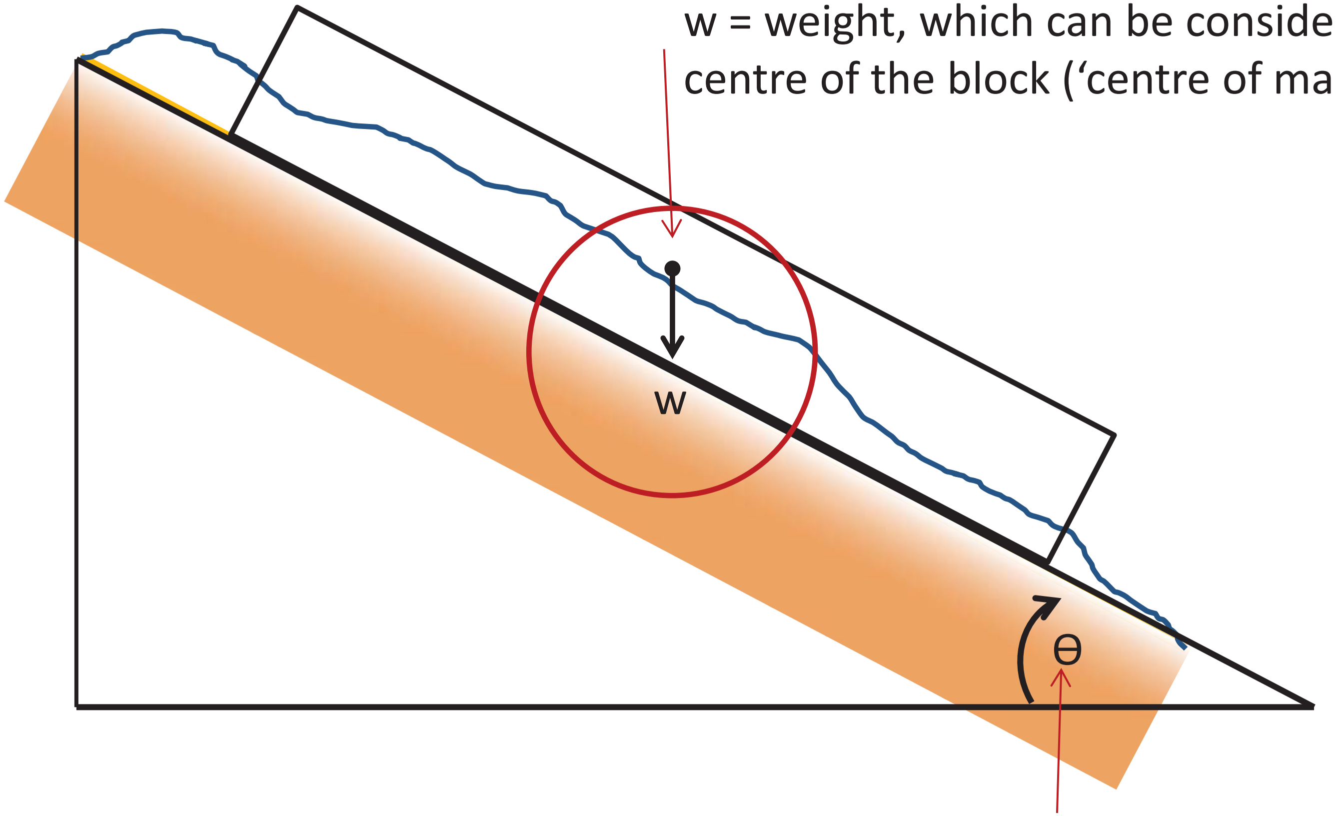
An aside: in most tectonically-active mountain ranges, we are interested in failure of **bedrock hillslopes**

This is because the rate at which loose **regolith** can be produced is less than the rate at which it’s removed, so most regolith is stripped away by erosion and we’re left with a thin or discontinuous regolith cover



Burbank (Mineralogical Magazine, 2002)

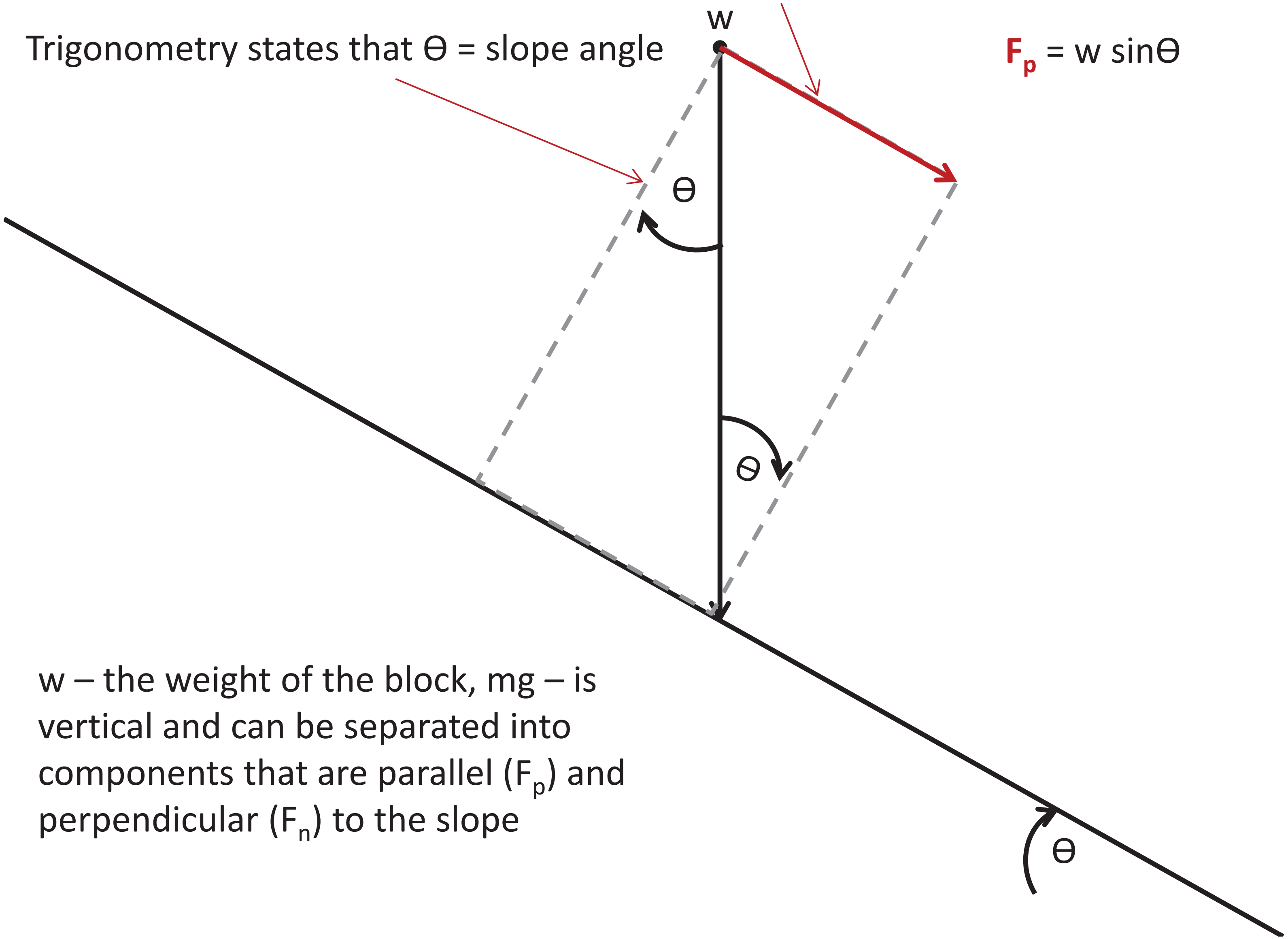
A primer on landslides



w = weight, which can be consider to act at the centre of the block (‘centre of mass’)

θ = slope angle

A primer on landslides



F_p = component of weight parallel to slope

F_p = w sinΘ

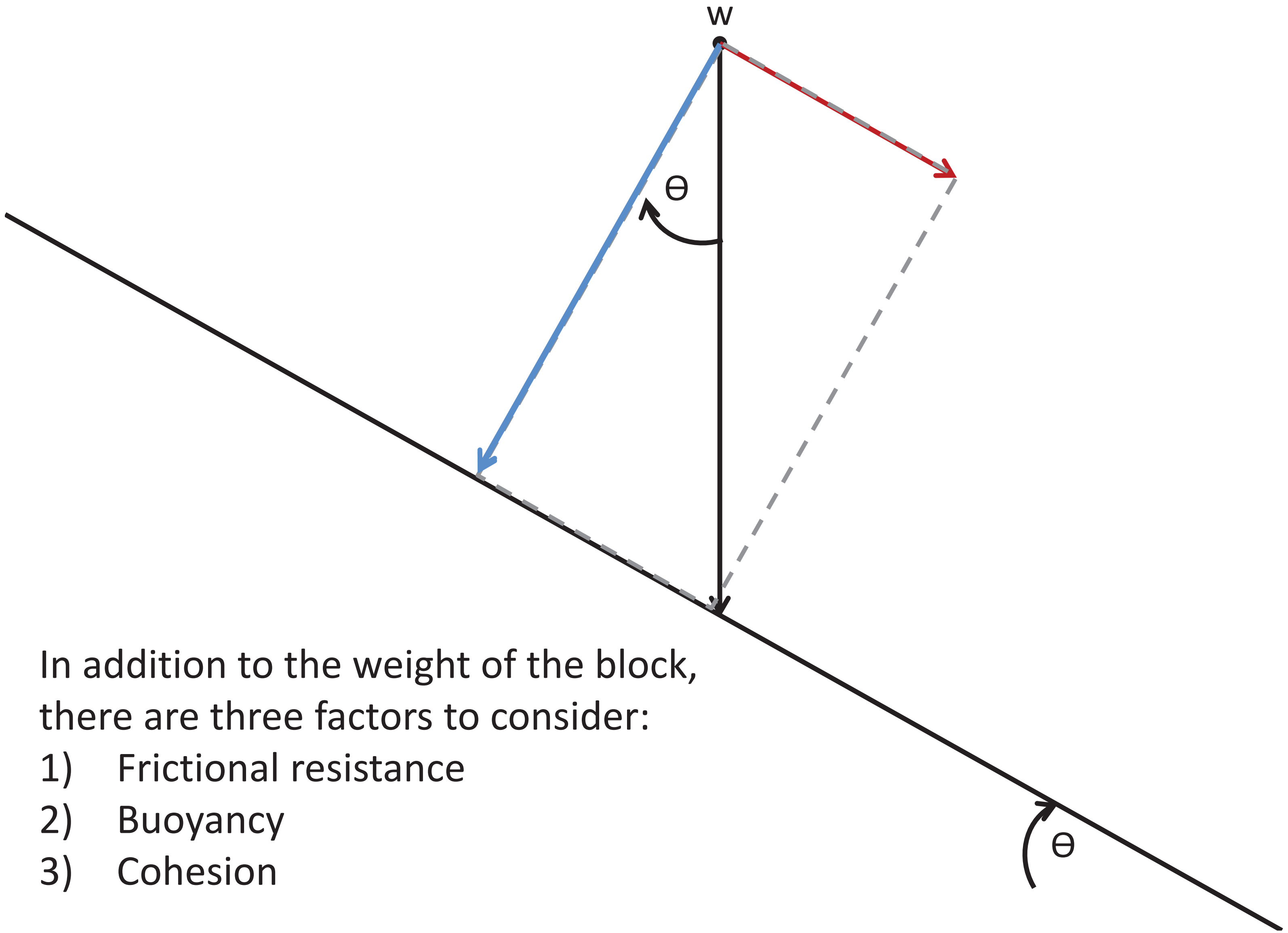
Trigonometry states that Θ = slope angle

w – the weight of the block, mg – is vertical and can be separated into components that are parallel (F_p) and perpendicular (F_n) to the slope

A primer on landslides

F_n = component of weight normal or perpendicular to the slope

F_n = w cosΘ



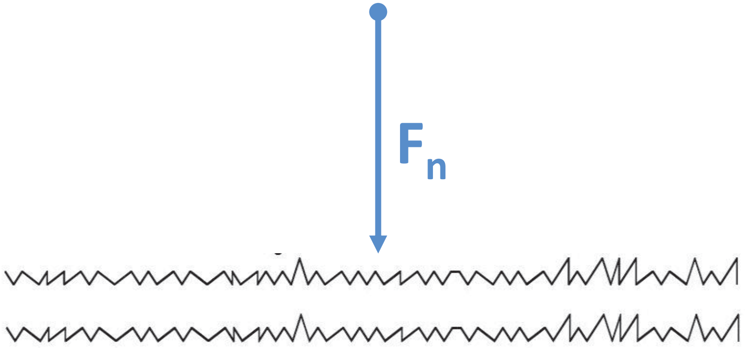
In addition to the weight of the block, there are three factors to consider:

1) Frictional resistance
2) Buoyancy
3) Cohesion

Frictional resistance

$$F_f = \text{friction force} = F_n\,\mu$$

So, $F_f \uparrow$ if $F_n \uparrow$ and / or $\mu \uparrow$



Rough surface

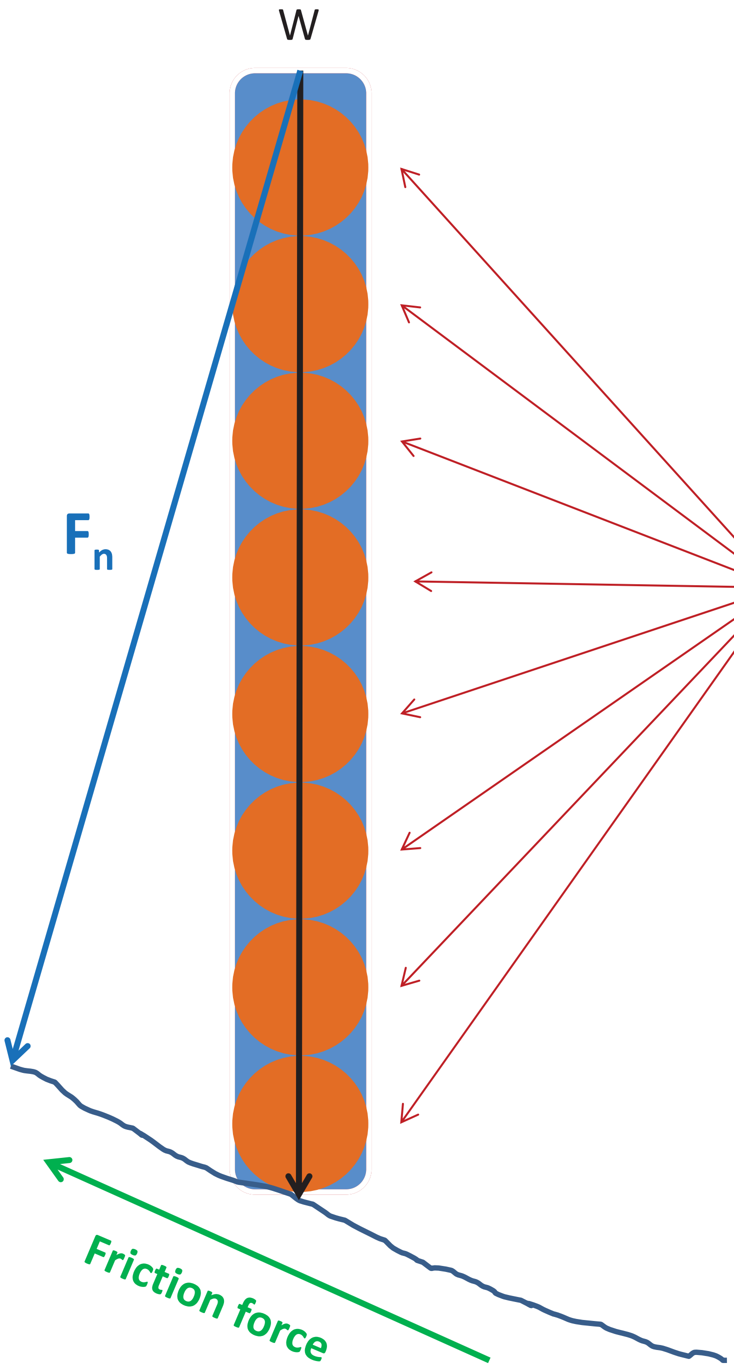
The coefficient of friction μ (mu) changes with material

Clay	0.1 – 0.3
Sand	0.4 – 0.8
Broken rock	0.5 – 0.9

Coefficient of friction is also controlled by:

- Mineralogy (quartz is strong, olivine is not)
- Grain shape (angular v rounded)
- Packing arrangement (loose v tight)

No units, but ranges from 0 to 1



Buoyancy

The presence of pore fluid (usually water) alters the force balance by imposing a buoyancy force = weight of the volume of the water displaced by the grains

The weight of each grain is reduced by the buoyancy force

So, the **total weight** pushing on the shear surface is reduced and

$$F_f \downarrow = \downarrow F_n \mu$$

Cohesion

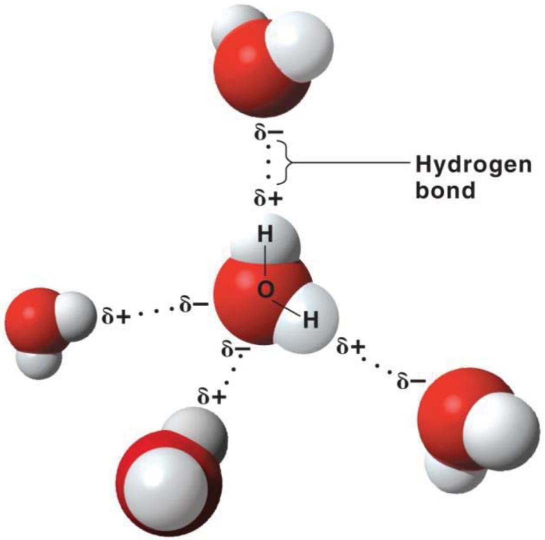
A measure of the intrinsic strength of a material, caused by:

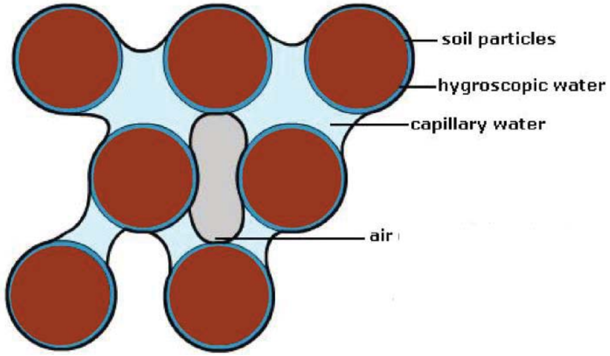
- Electrostatic forces: e.g., via water molecules
- Capillary forces are created due to this attraction within pore spaces
- Clay minerals attract water as they have a negative surface charge
- Cementation (e.g. carbonates)
- Roots

As a force, the units of cohesion are Pa

kPa (kilopascal)	(1.0 x 10^3 Pa)
MPa (megapascal)	(1.0 x 10^6 Pa)

Commonly represented by a ‘**c**’





Combined, and written in terms of stress rather than force (by dividing by the area of the failure plane), this is often called the **Coulomb failure criterion**:

$$\tau_{crit} = \mu\left(\sigma - P\right) + c$$

τ_{crit}: critical shear stress for failure to occur

σ: normal stress

P: pore fluid pressure (to account for buoyancy)

c: cohesion

μ: coefficient of friction (sometimes written as $\tan\phi$)

When does a slope move? Newton's 1st Law of Motion:

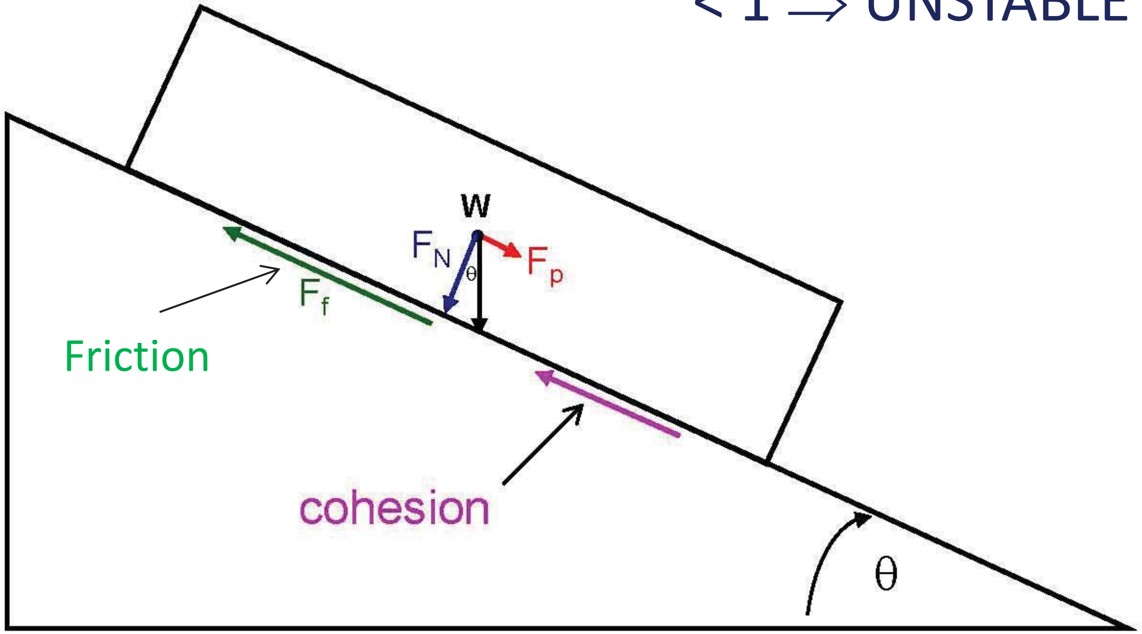
"An object at rest will remain at rest unless acted on by an unbalanced force."

The Infinite Slope Model

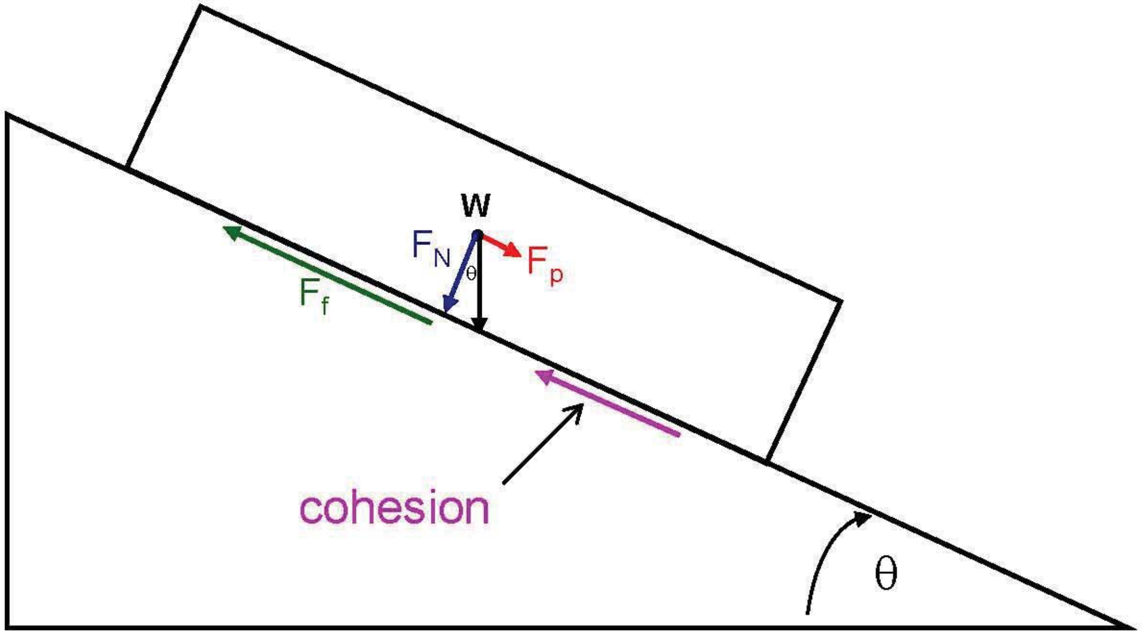
$$\text{Stability of the block} = \frac{\text{Resisting forces}}{\text{Driving forces}}$$

Factor of Safety (FS): $> 1 \Rightarrow$ STABLE

$< 1 \Rightarrow$ UNSTABLE



$$FS = \frac{\text{Resisting forces}}{\text{Driving forces}} = \frac{\text{friction} + \text{cohesion}}{F_p} = \frac{(w \cos\theta \times \mu) + c}{w \sin\theta}$$

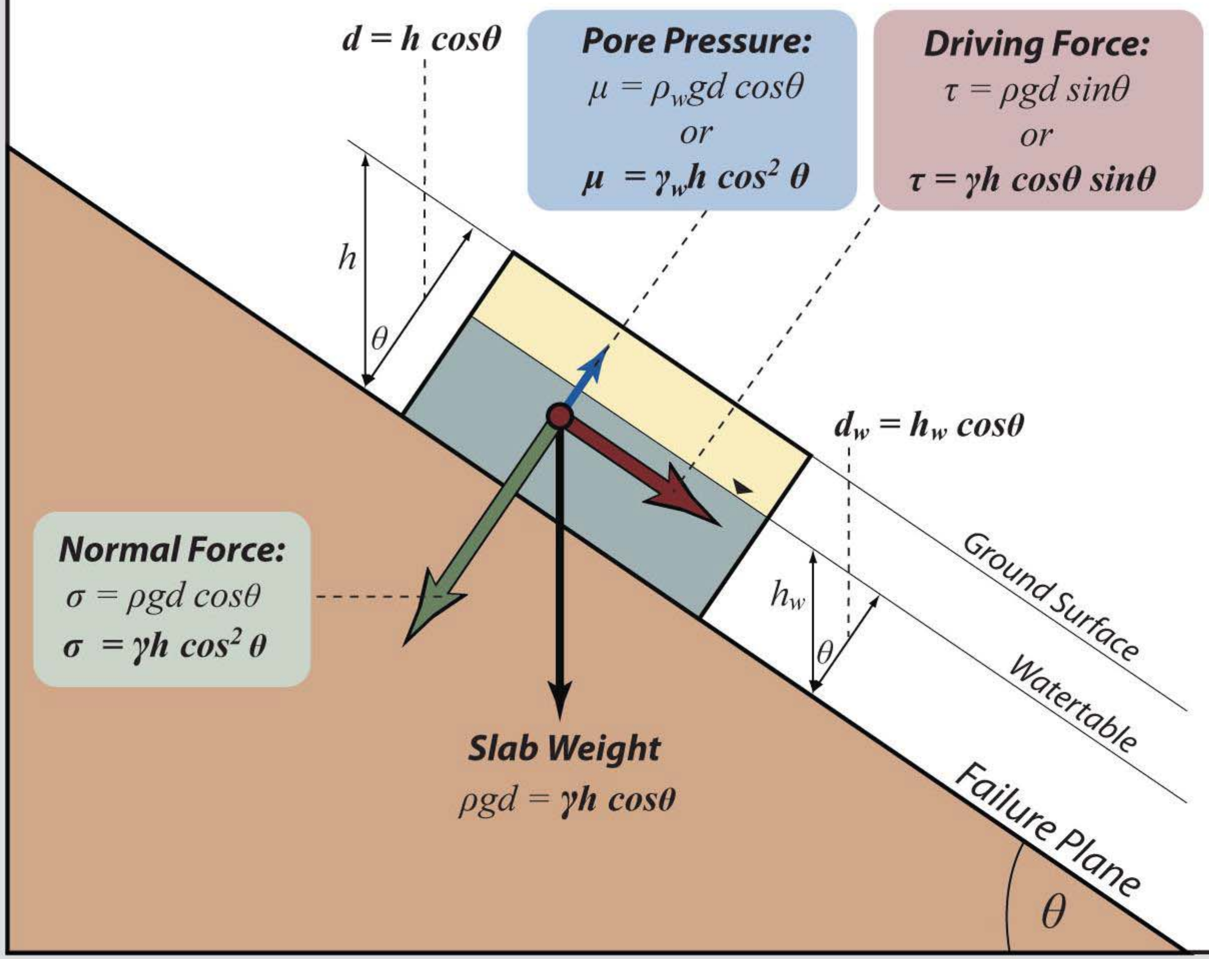


Hillslope Stability vs. Slope Failure - *Infinite Slope Model*

$$\textit{Factor of Safety (FS)} = \frac{\textit{Resisting (S)}}{\textit{Driving }(\tau)}$$

Definitions

Forces Acting on a Hillslope:



Pore Pressure:

$\mu = \rho_w g d \cos\theta$

or

$\mu = \gamma_w h \cos^2\theta$

Driving Force:

$\tau = \rho g d \sin\theta$

or

$\tau = \gamma h \cos\theta \sin\theta$

Normal Force:

$\sigma = \rho g d \cos\theta$

$\sigma = \gamma h \cos^2\theta$

Slab Weight

$\rho g d = \gamma h \cos\theta$

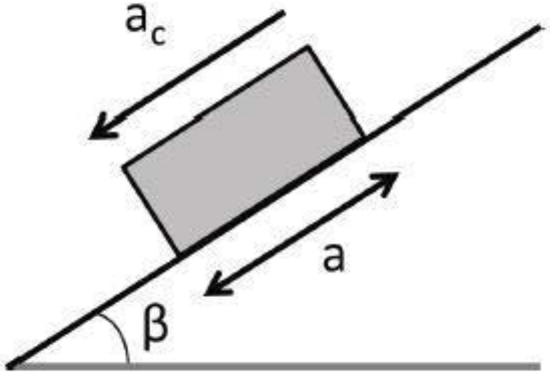
Definition of Terms:

h = vertical slab height
d = slab depth normal to failure plane
h_w = vertical water table height
d_w = watertable depth normal to failure plane
ρ = slab density (DRY)
ρ_w = water density
ρ_{ws} = slab density (WET)
g = gravity
γ = unit weight of slab (DRY)
γ_w = unit weight of water
γ_{ws} = unit weight of slab (WET)
C = soil cohesion
$m = d_w/d$ = fractional percent of watertable above the failure plane

θ = failure plane angle above horrizontal
ϕ = angle of internal friction

σ = normal force
μ = pore pressure

$\tau = D$ = Driving Force
$S = R$ = Resisting Force
FS = Factor of Safety



Newmark analysis

Infinite slope analysis provides a static view of stability. But earthquakes introduce a dynamic acceleration of hillslope materials. How to account for that?

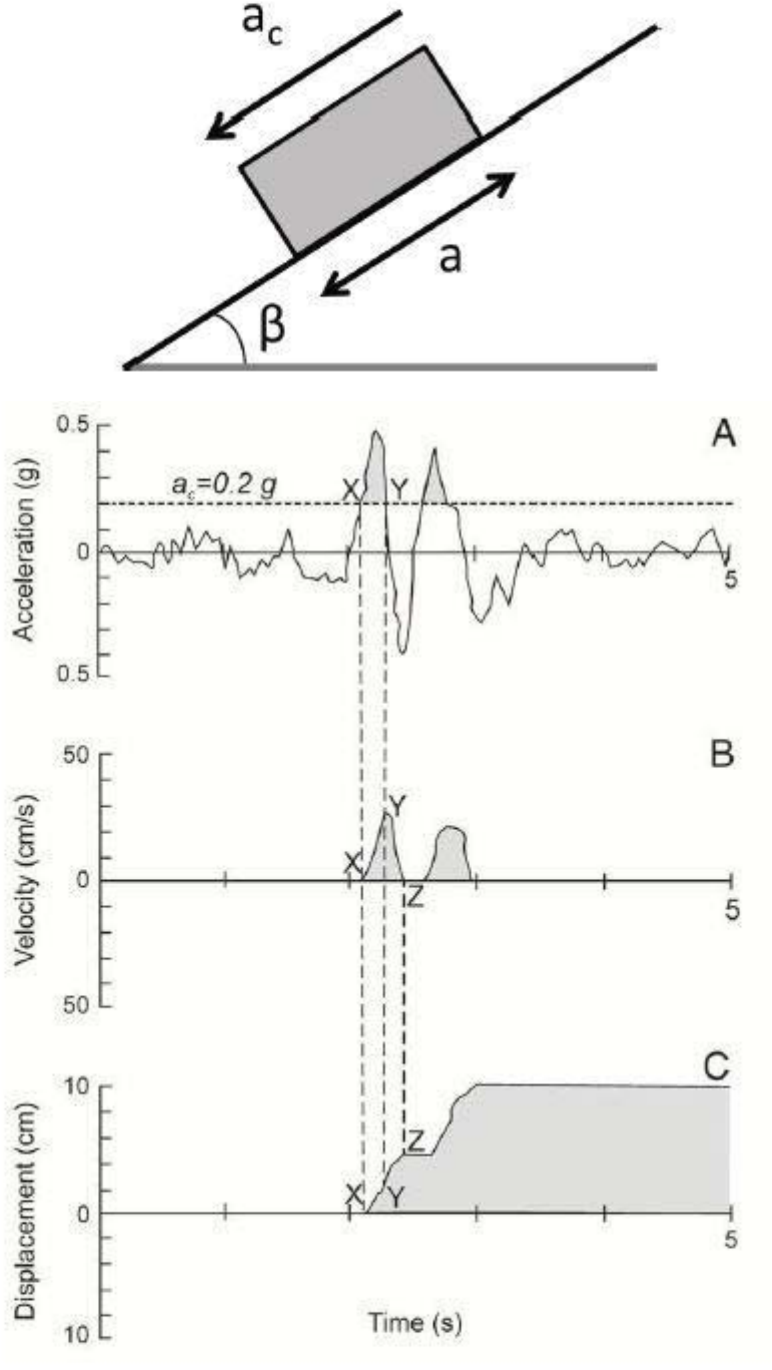
Newmark (1965) proposed that hillslope material could be modelled as a rigid block that has a critical acceleration a_c that is required to overcome resistance and begin to slide

$$a_c = (FS - 1) g \sin \beta$$

This has units of acceleration (e.g., 0.2 m/s^2)

Jibson (2011)

Newmark analysis



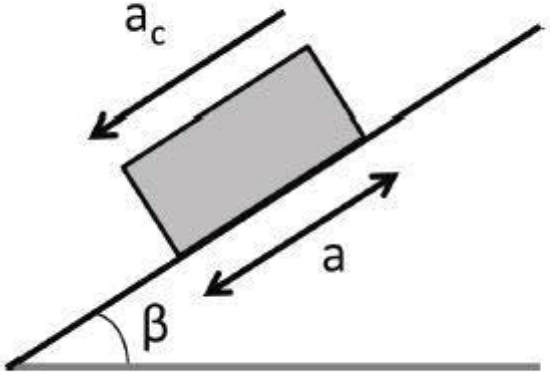
When a_c is exceeded, the combination of static (see above) and dynamic (due to the earthquake) shear stress exceeds the shear strength of the material

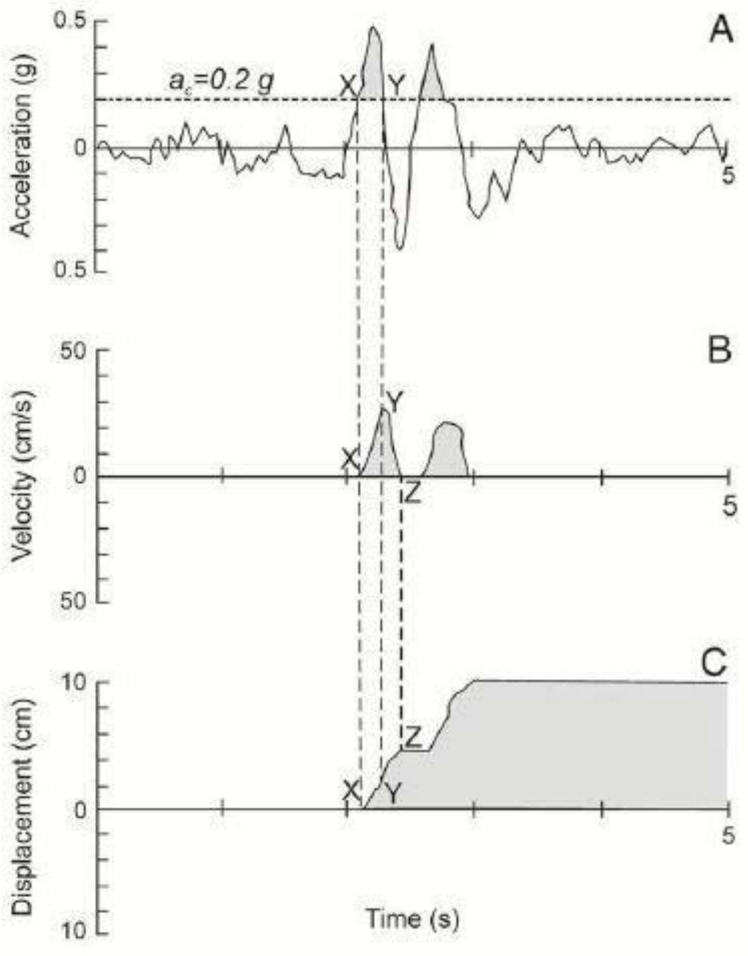
$\Rightarrow$ FS < 1 and the block fails

The permanent displacement of the block due to $a > a_c$ is called the Newmark displacement D_N (lower panel)

Jibson (2011)

Simplified Newmark analysis





Full Newmark analysis requires the acceleration time series and is really only suited to site-specific studies

There have been various attempts to relate Newmark displacements to other (measurable) parameters, including

Moment magnitude (M_w)

Arias intensity (I_a):

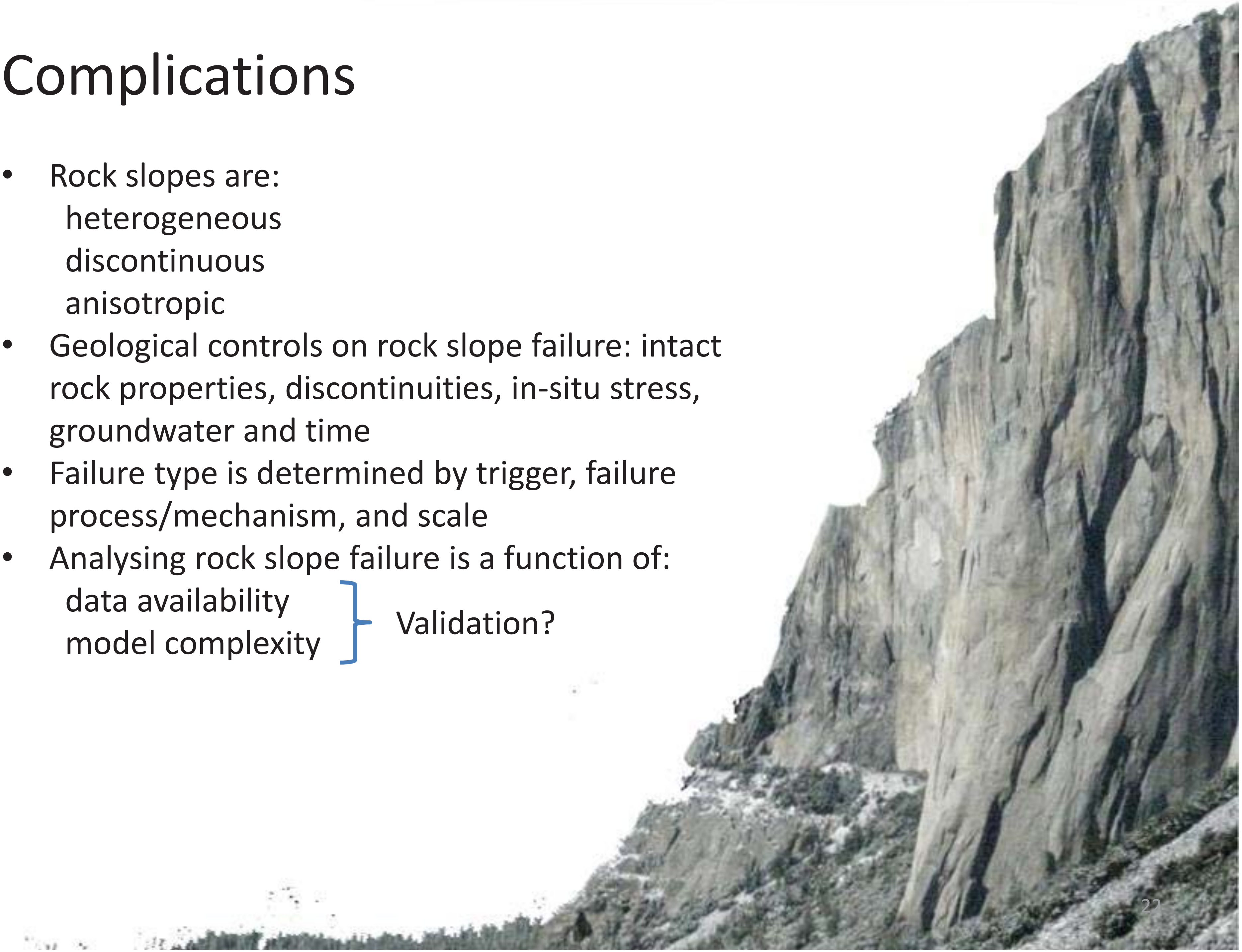
$$I_a = \frac{\pi}{2g}\int_0^\infty a(t)^2\,dt$$

[typically ~0.1 to 0.5 m/s required for failure]

Peak ground acceleration (PGA)

ID	Equation	Number of seismic records (Number of earthquakes)	R^2 goodness of fit	Source
1	$\log D_N = 0.90 + \log\left[\left(1 - \frac{a_c}{PGA}\right)^{2.53}\left(\frac{a_c}{PGA}\right)^{-1.09}\right] \pm 0.30$	50 (11)	-	Ambraseys and Menu (1988)
2	$\log D_N = 1.460 \log I_a - 6.642 a_c + 1.546 \pm 0.409$	11	0.87	Jibson (1993)
3	$\log D_N = 1.521 \log I_a - 1.993 \log a_c - 1.546$	555 (13)	0.83	Jibson et al. (1998), Jibson et al. (2000)
4	$\log D_N = 0.215 + \log[\left(1 - \frac{a_c}{PGA}\right)^{2.341}\left(\frac{a_c}{PGA}\right)^{-1.438}] \pm 0.510$	2270 (30)	0.84	(Jibson, 2007)
5	$\log D_N = -2.710 + \log[\left(1 - \frac{a_c}{PGA}\right)^{2.335}\left(\frac{a_c}{PGA}\right)^{-1.478}] + 0.424 M_W \pm 0.454$	2270 (30)	0.87	(Jibson, 2007)
6	$\log D_N = 2.401 \log I_a - 3.481 \log a_c - 3.230 \pm 0.656$	2270 (30)	0.71	(Jibson, 2007)
7	$\log D_N = 0.561 \log I_a - 3.833 \log\left(\frac{a_c}{PGA}\right) - 1.474 \pm 0.616$	2270 (30)	0.75	(Jibson, 2007)

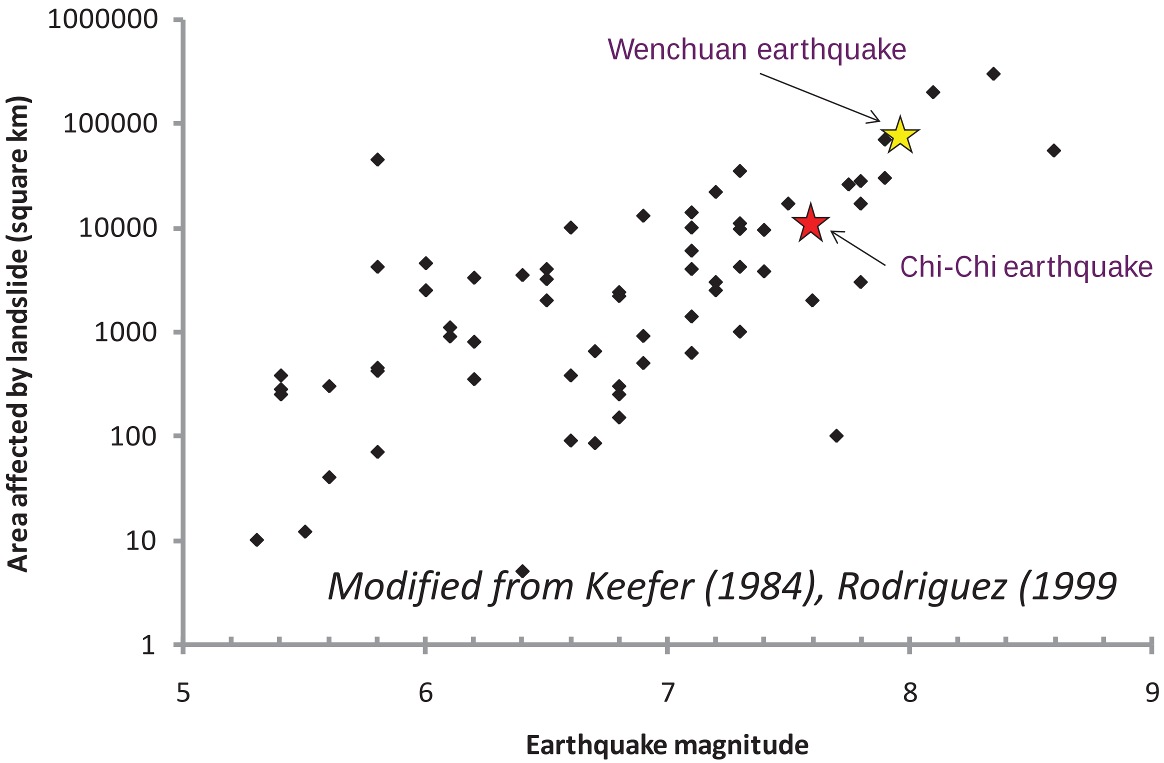
Complications



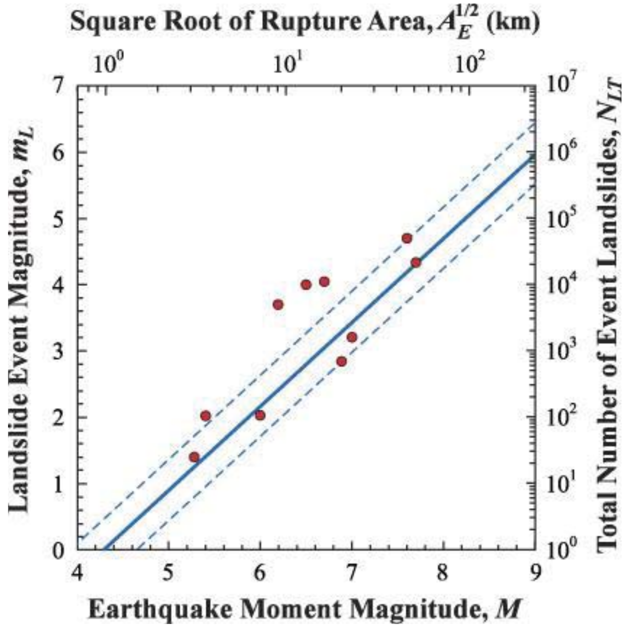
- Rock slopes are:
  - heterogeneous
  - discontinuous
  - anisotropic
- Geological controls on rock slope failure: intact rock properties, discontinuities, in-situ stress, groundwater and time
- Failure type is determined by trigger, failure process/mechanism, and scale
- Analysing rock slope failure is a function of:
  - data availability
  - model complexity

$\left.\begin{array}{l}\text{data availability}\\ \text{model complexity}\end{array}\right\}$ Validation?

Distributions and scaling



Modified from Keefer (1984), Rodriguez (1999



Malamud et al. (2004) EPSL

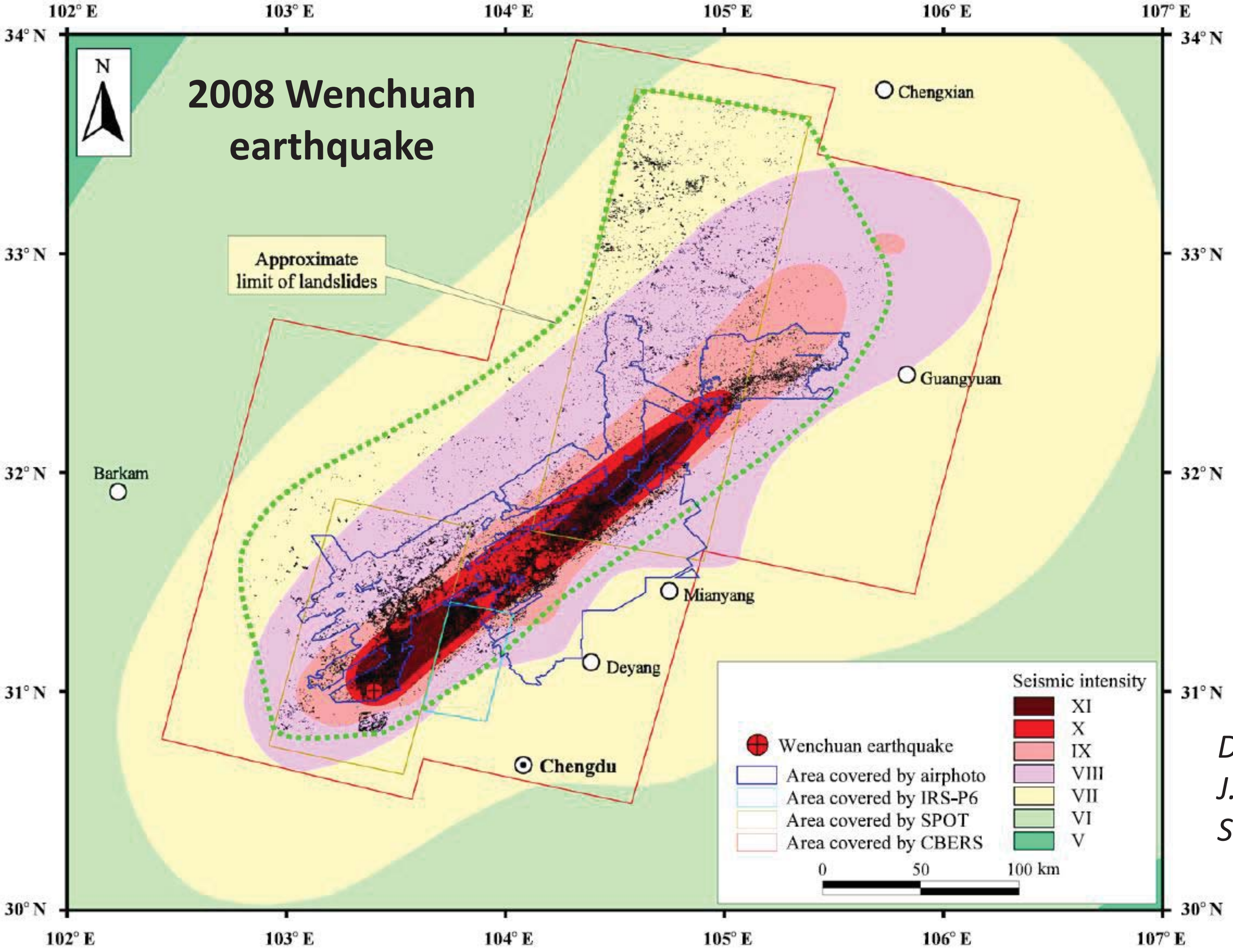
There have been many attempts to correlate earthquake magnitude with some measure of landslide occurrence, including

- Area affected by landslides
- Number of landslides triggered
- Maximum distance from epicenter to landslide
- Minimum intensity necessary for landsliding

See Keefer (2002) for a review

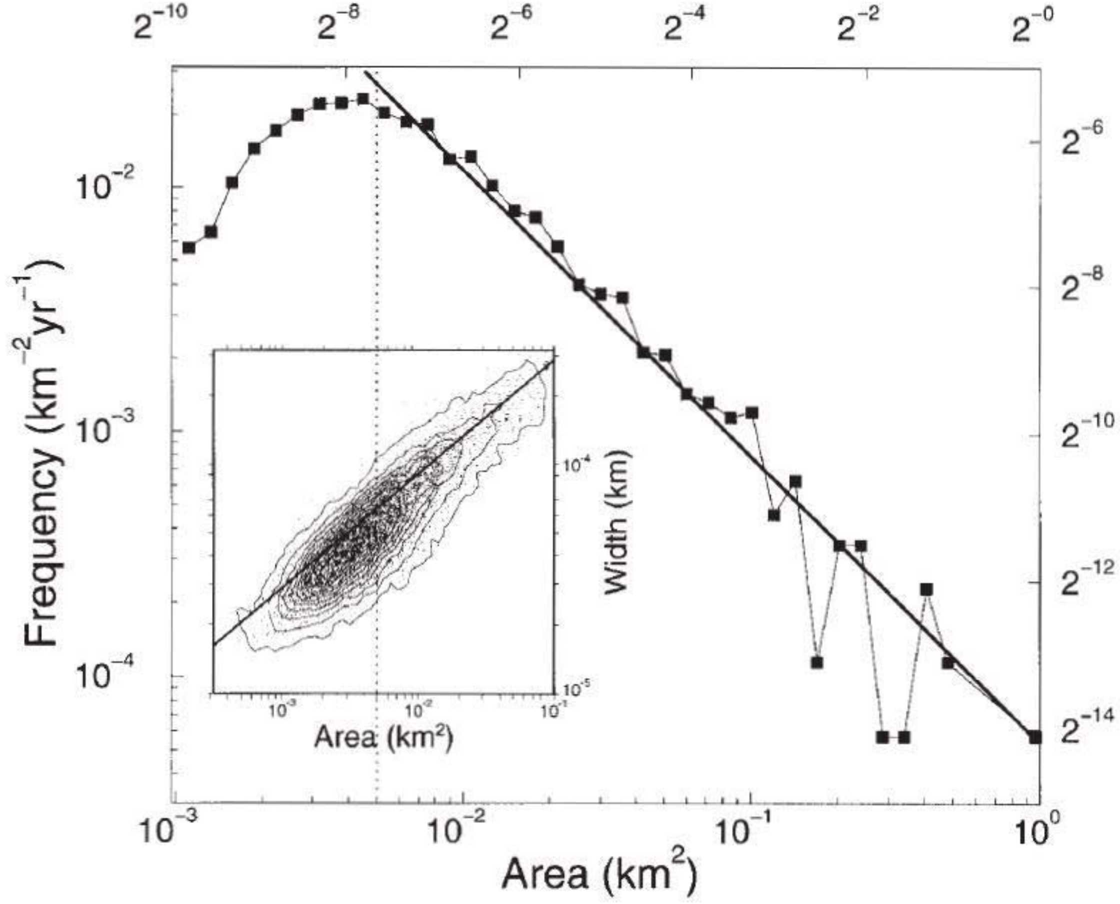
Distributions and scaling

This area can be larger than that affected by high seismic intensity (e.g., >VIII)



Dai et al. (2011) J. Asian Earth Sci.

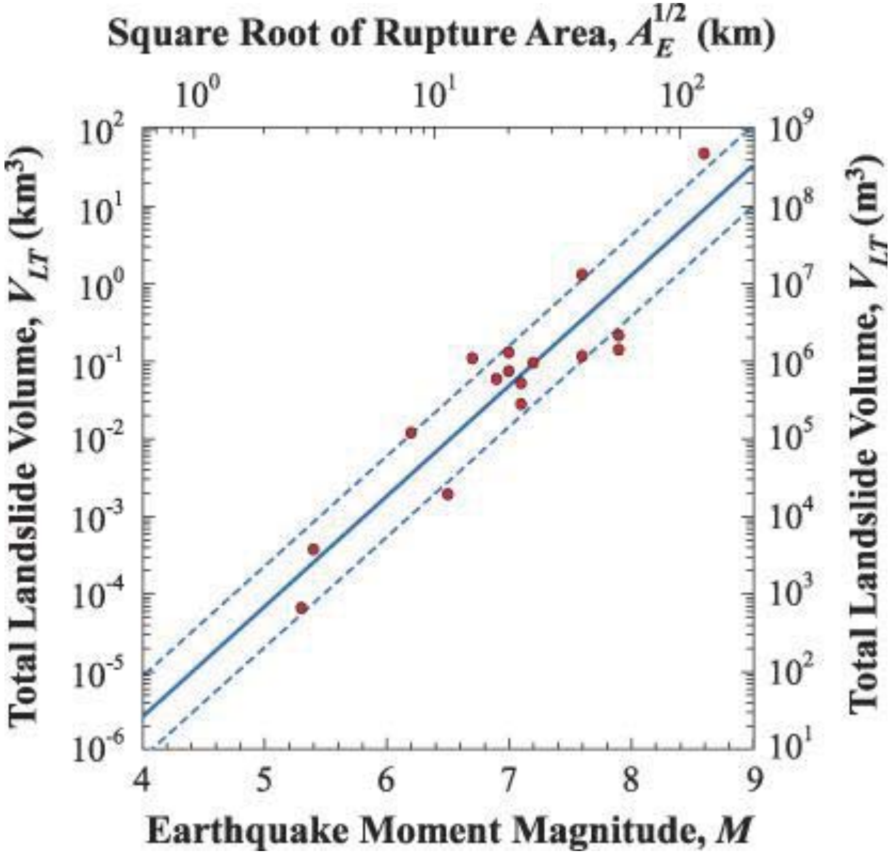
Distributions and scaling



Hovius et al. (1997) Geology

Many authors have suggested that landslide areas follow a particular **magnitude-frequency distribution** – importantly, this nearly always has a ‘heavy’ or power-law tail

Such a distribution is very useful, because the frequency yields the **probability of occurrence** of a landslide with a given area, per unit area, per unit time



Malamud et al. (2004) EPSL

Malamud et al. (2004) noted the relationship between earthquake magnitude and landslide area. By converting landslide area to volume with an assumed *scaling relationship*, they can estimate the volume of sediment that is produced by earthquakes of a given magnitude. Two key points:

- If you knew the earthquake a- and b-values for a given region, you could convert this into the total volume of landsliding over time, V_{LT}
- AND, if you know the time interval between earthquakes of a given magnitude (the recurrence interval τ), you can calculate the **erosion rate** ε:

$$\varepsilon = \frac{V_{LT}}{A_R \tau}$$

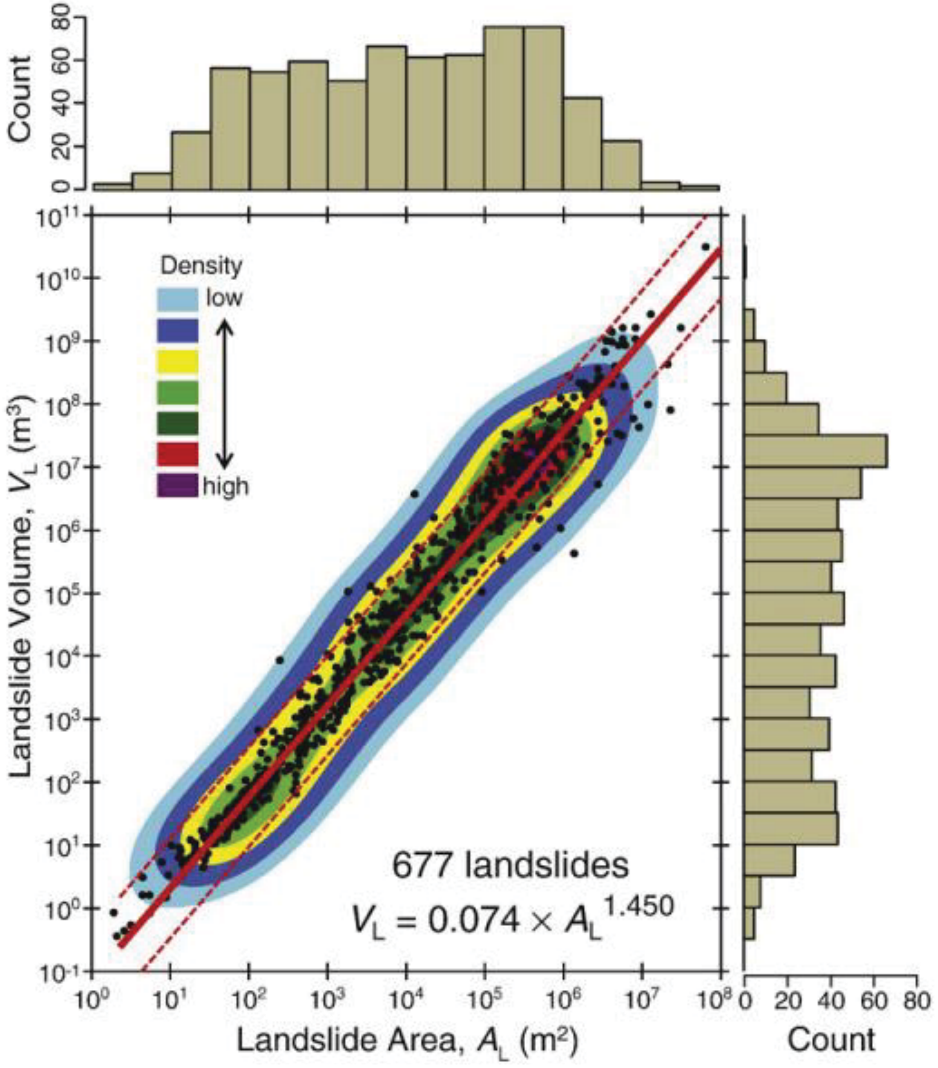
where V_{LT} is the total landslide volume and A_R is the area that's affected

This scaling relationship is a key part of the story

Landslide **area** simply measures the space on the ground that is affected; if we want to understand landslides as a hazard and as a geomorphic agent, we need to understand them in terms of the **volume of sediment** that they are capable of moving

So, how can we relate landslide area to volume?

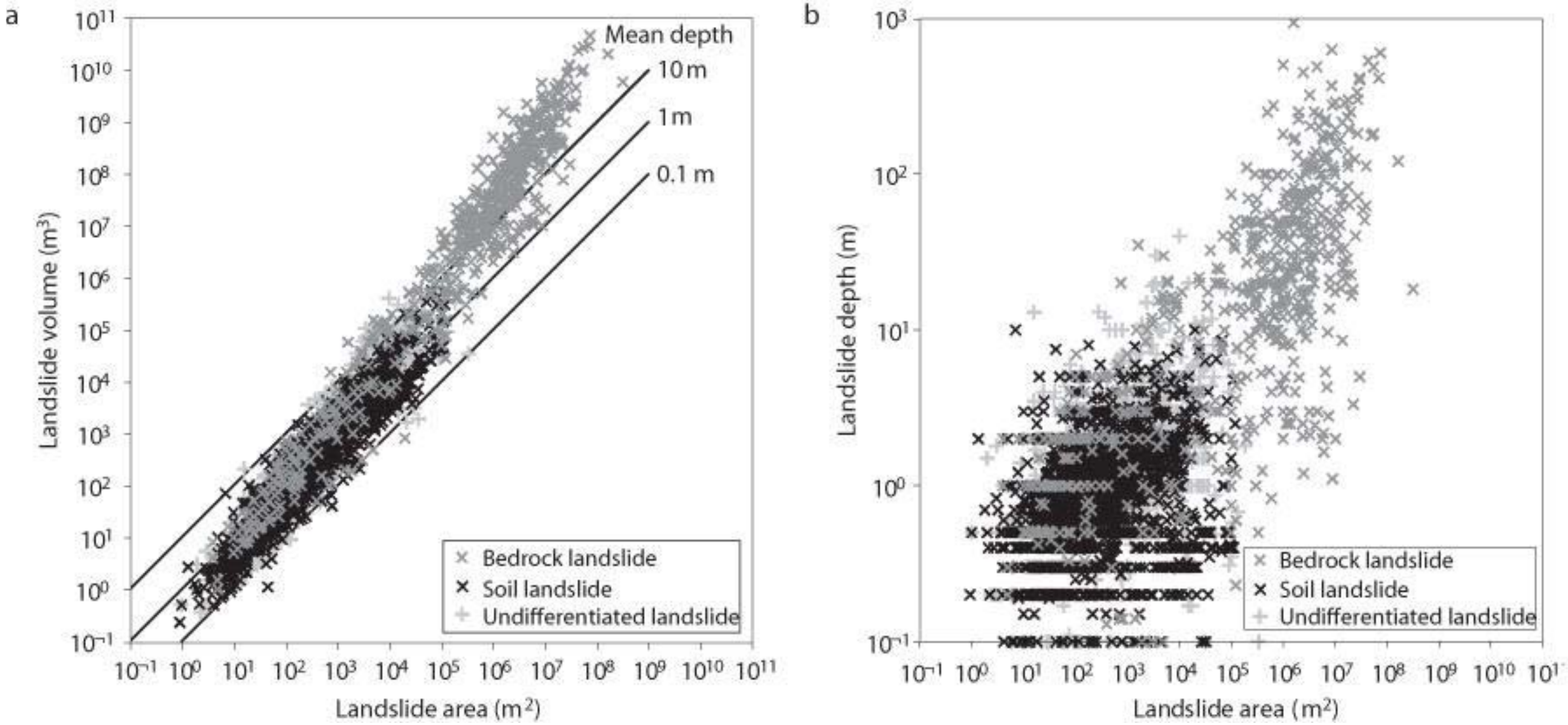
F. Guzzetti et al. / Earth and Planetary Science Letters 279 (2009) 222229



Guzzetti et al. (2009 EPSL) compiled data on 677 landslides into a scaling relationship of the form

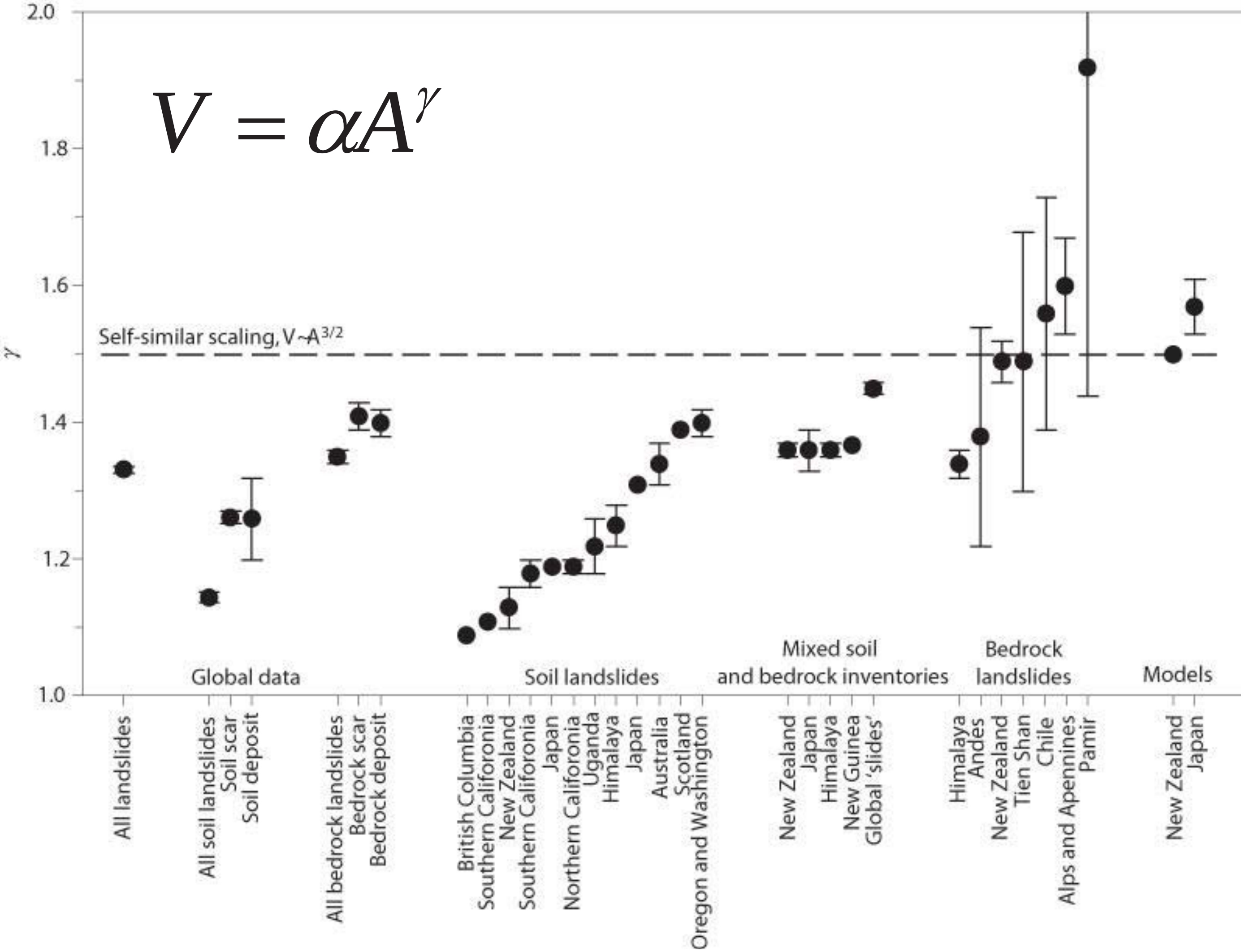
$$V_L = 0.074 A_L^{1.450}$$

where V_L and A_L are the area and volume of an individual landslide. This seems to hold over nearly 8 orders of magnitude, and is similar to the relationship employed by Malamud et al. (albeit based on much more data)



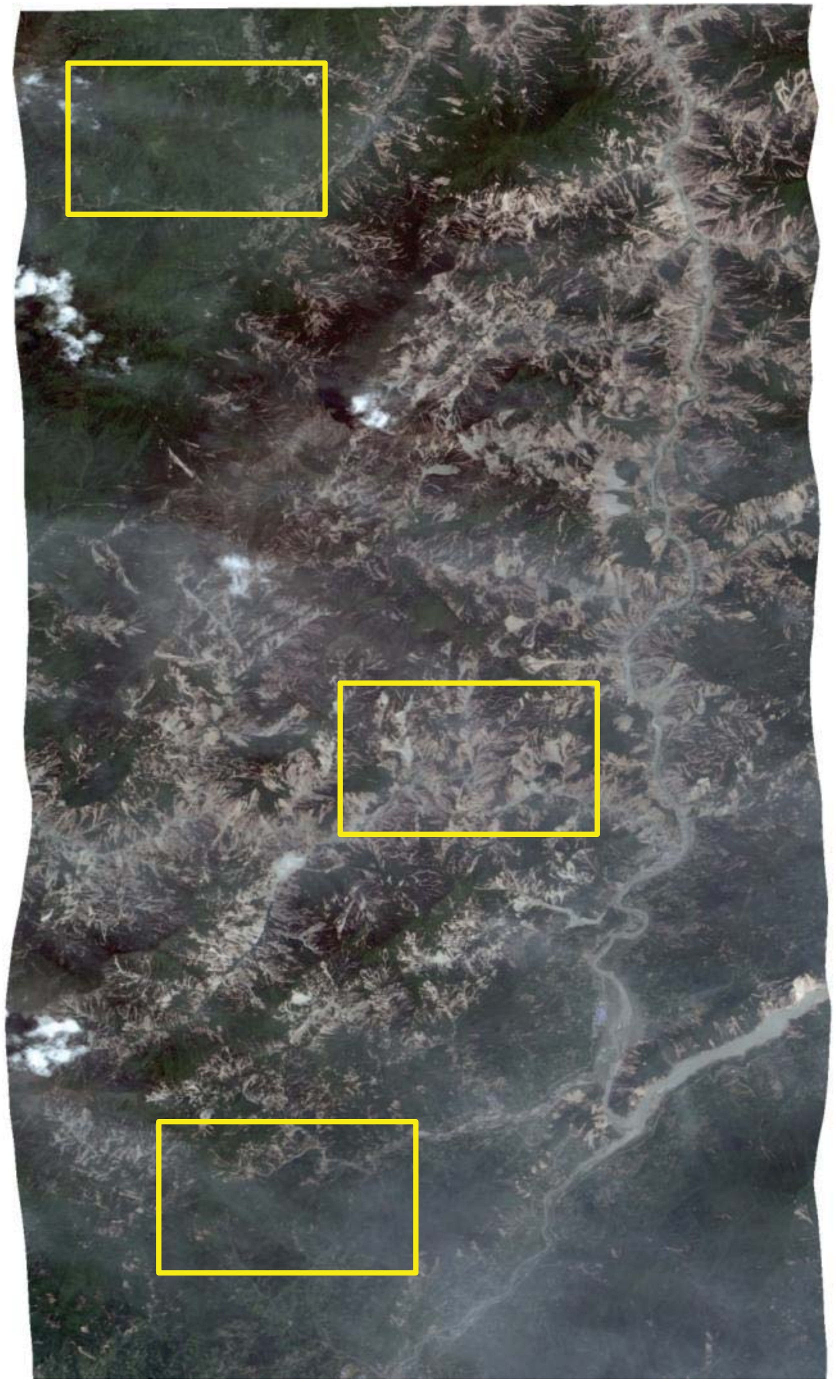
Larsen et al. (Nature Geoscience 2010) showed with an even larger dataset that

(1) the scaling is not quite linear – that is, the exponent is slightly greater than 1, so there is a definite trend toward greater landslide depths at large areas
(2) shallow landslides (those confined to the soil only) are limited in area and depth, probably by the thickness of available soil



$$V = \alpha A^{\gamma}$$

They compared scaling relationships defined on the basis of a large number of different data sets and showed that the scaling exponent is typically 1.1 to 1.6, with rare examples outside this range



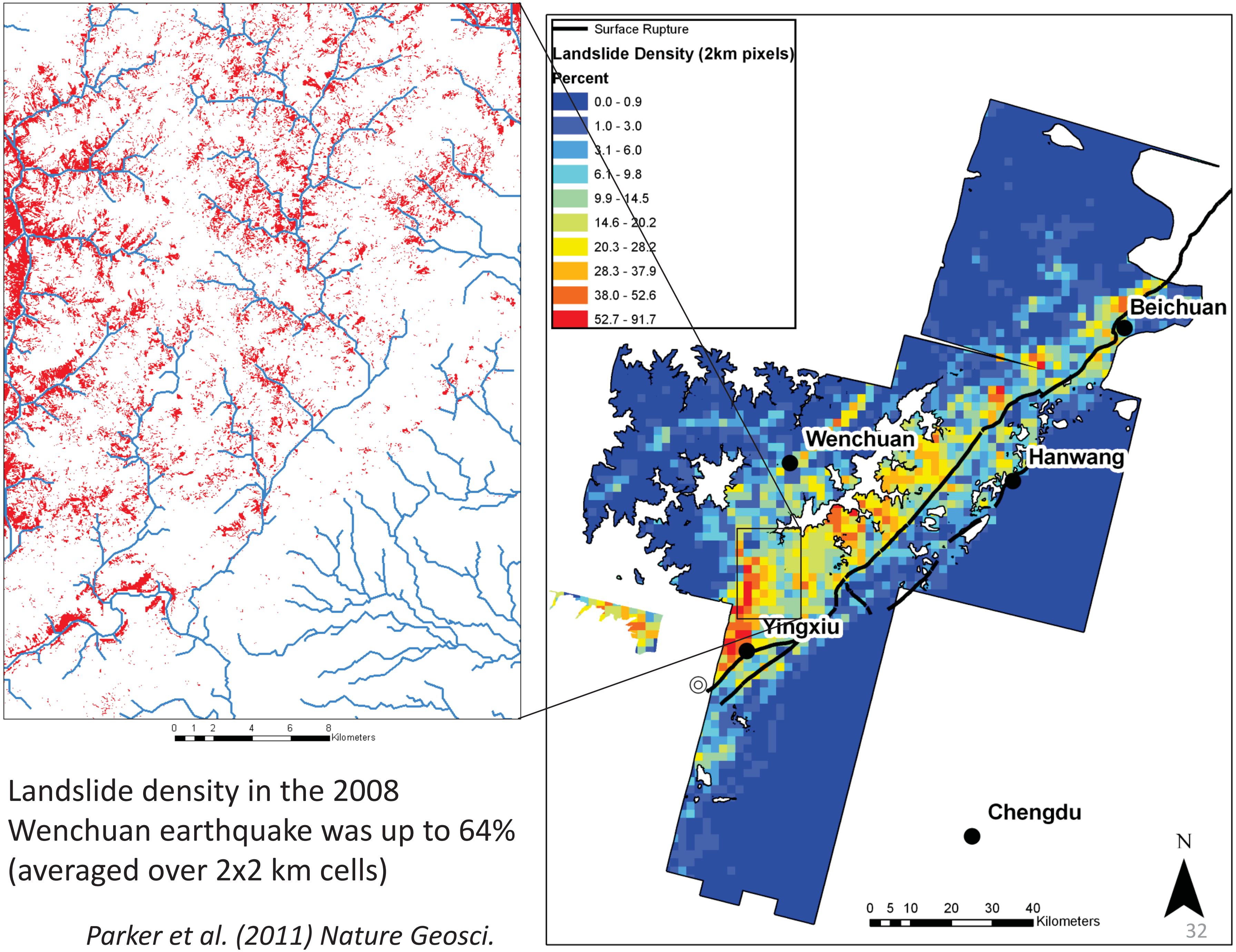
Spatial patterns

The effects of earthquake-triggered landslides are highly spatially variable. Estimating the distribution of a single aspect of the hazard (e.g. area, volume, magnitude) throws away all information on the spatial distribution of this aspect

Let’s now consider spatial variations and patterns of landsliding. These can be defined at different scales:

- Across a region
- On individual hillslopes (in a statistical sense)

Note that this is often expressed not by landslide occurrence but by landslide density (area of landsliding / area of study region)

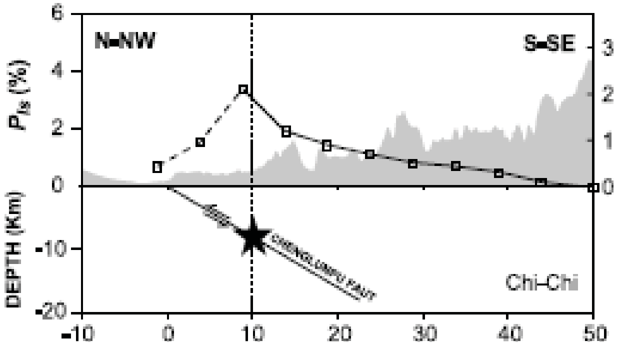


Landslide density in the 2008 Wenchuan earthquake was up to 64% (averaged over 2x2 km cells)

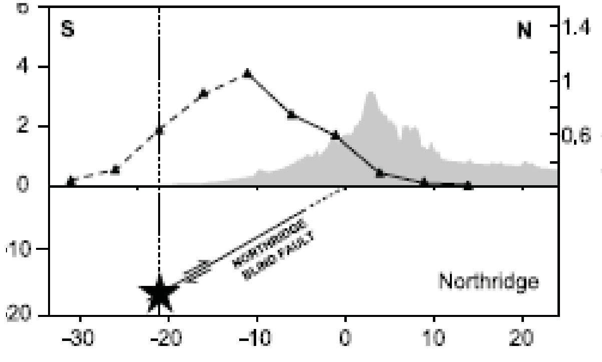
Parker et al. (2011) Nature Geosci.

Distance from coseismic fault rupture

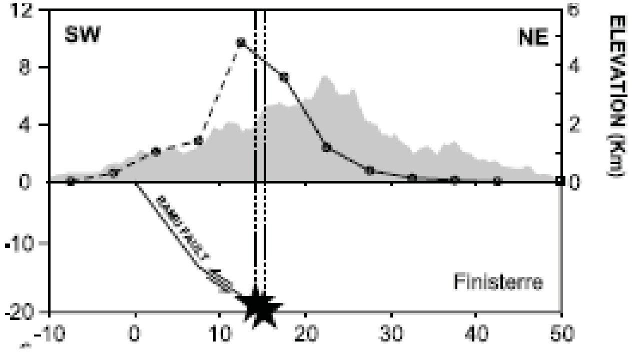
1999 Chi Chi



1994 Northridge



1993 Finisterre

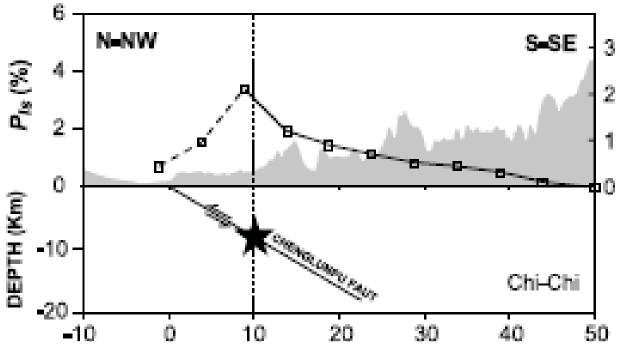


Meunier et al. (2007) GRL

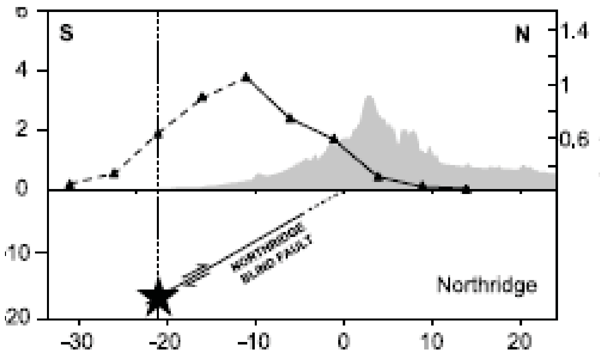
Meunier et al. (2007) showed that peak landslide density P_{ls} occurred above the epicenter in Chi-Chi and Finisterre, while in Northridge it occurred some distance up-dip in the hangingwall

Distance from coseismic fault rupture

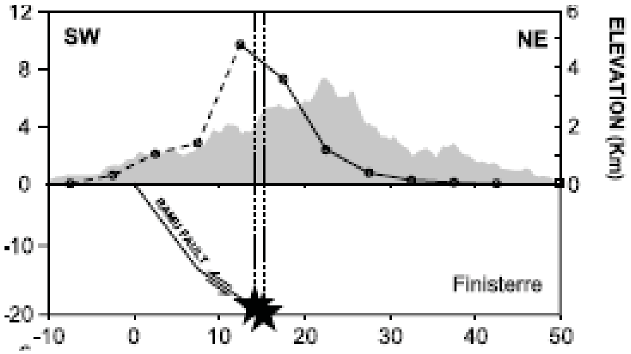
1999 Chi Chi



1994 Northridge

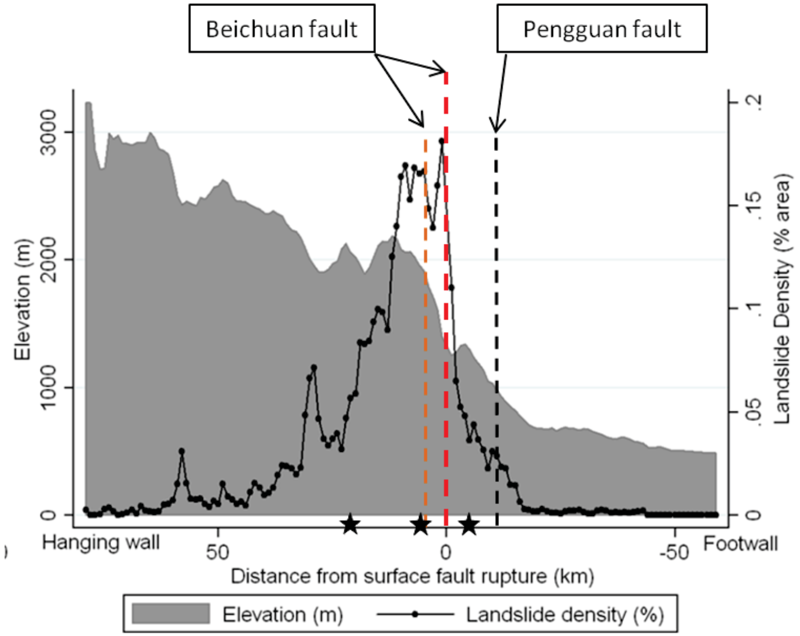


1993 Finisterre



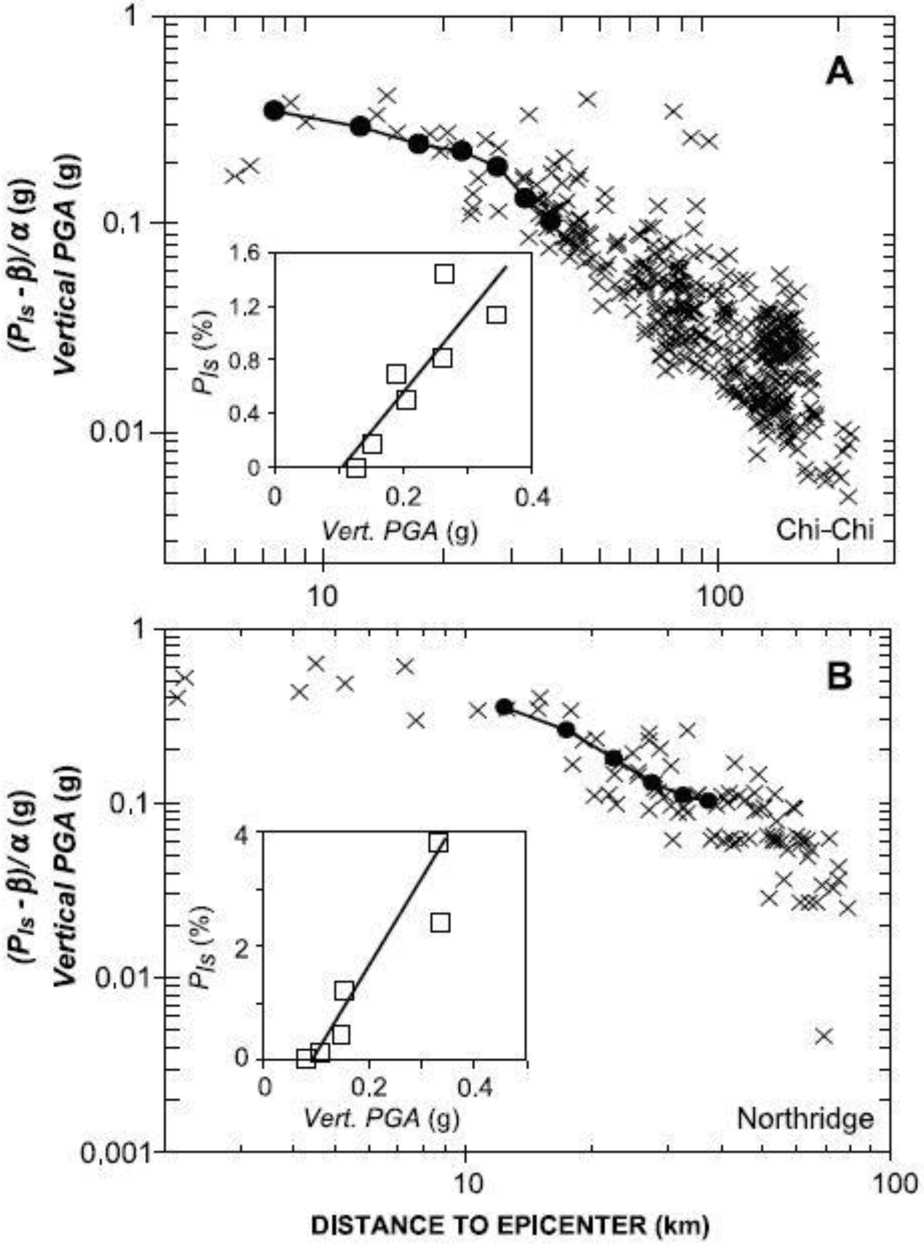
Meunier et al. (2007) GRL

2008 Wenchuan



Meunier et al. (2007) showed that peak landslide density P_{ls} occurred above the epicenter in Chi-Chi and Finisterre, while in Northridge it occurred some distance up-dip in the hangingwall

In Wenchuan the peak landslide density occurred at the fault trace



Meunier et al. (2007) used this relationship to propose an attenuation law for landslide density that depends on two terms:

- A geometric term, related to expansion of seismic wave field
- A non-geometric term, related to exponential decay of energy (via a 'damping factor')

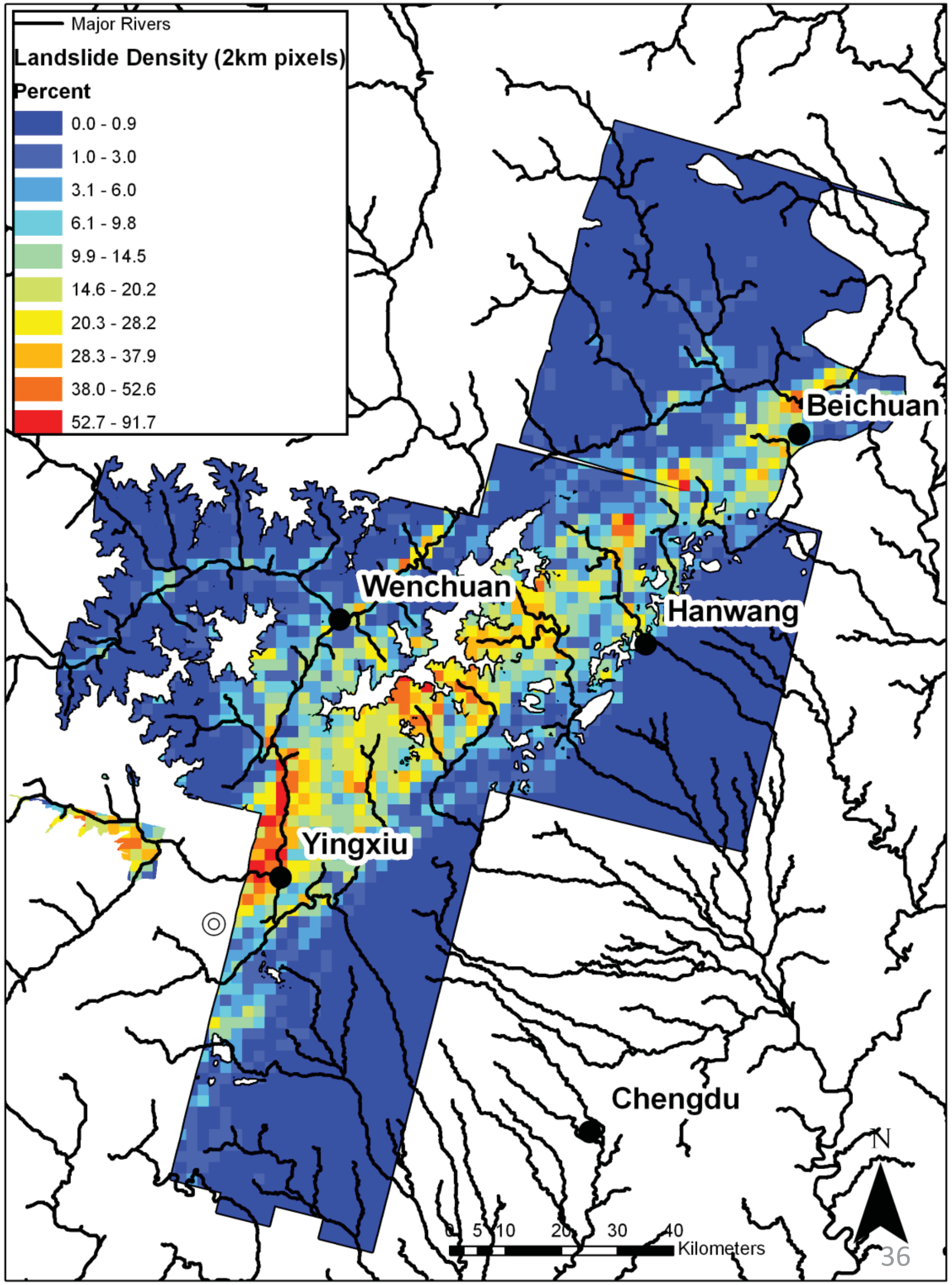
You can see that such a relationship (properly calibrated) would allow the use of landslides as a distributed network of seismometers

Dots: observed landslide density (scaled)
Crosses: peak vertical ground acceleration measurements (g)

Spatial patterns

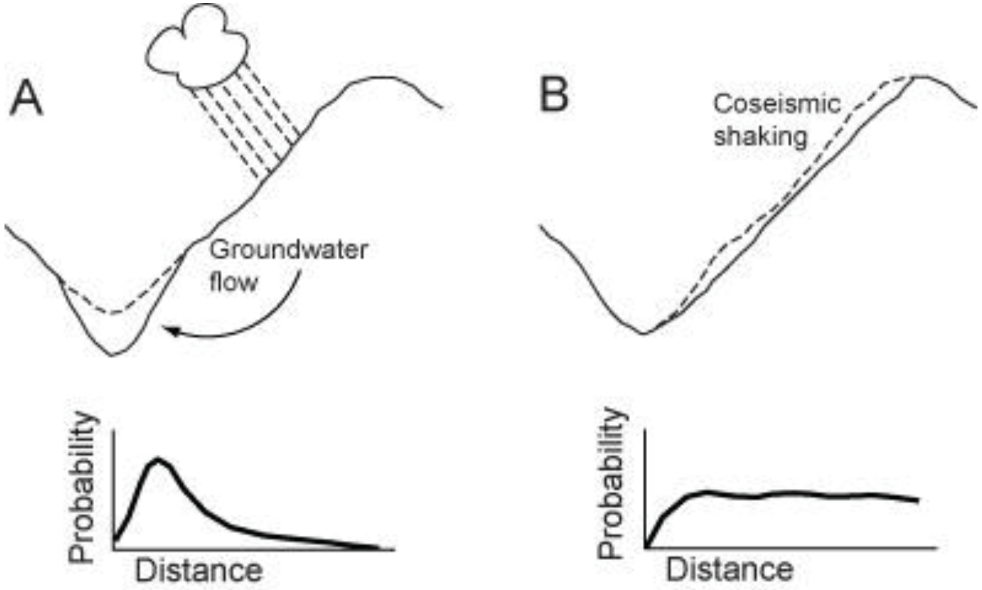
Strong spatial agreement between 2008 Wenchuan landsliding and high-relief (2-4 km) river valleys points to the role of **relief** in controlling landslide locations – and the feedback mechanisms between river incision and hillslope response

Parker et al. (2011) Nature Geosci.



Spatial patterns

At an even finer level, we might be interested in **where** events occur relative to other elements in the landscape. Densmore and Hovius (2000 Geology) hypothesized that the location of a landslide depends at least in part on its triggering mechanism:

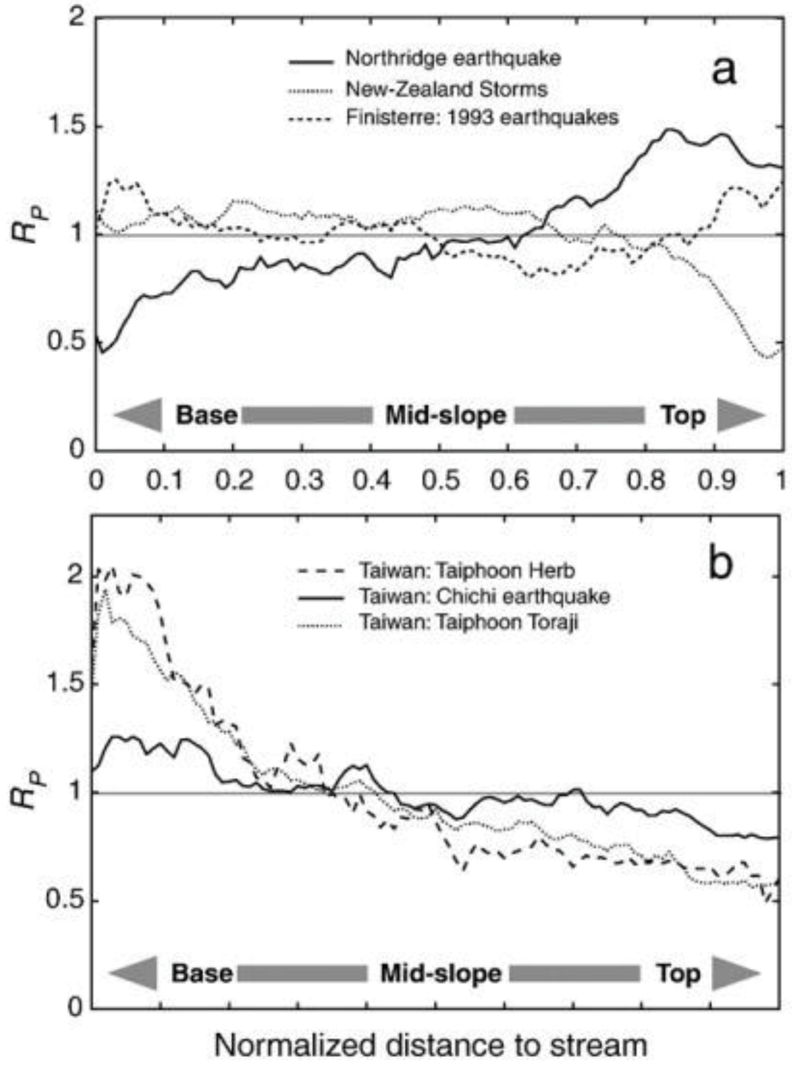


Landslides triggered by rainstorms should occur predominantly where pore pressures are greatest – that is, at the toe of the hillslope

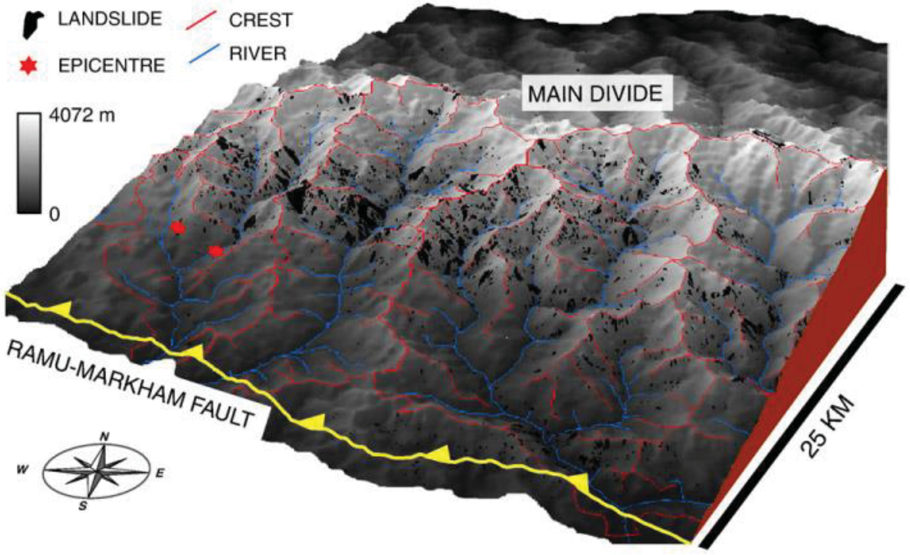
Landslides triggered by earthquakes, in contrast, should be triggered near ridge crests (because that's where seismic accelerations are likely to be greatest), and so will affect most or all of the hillslope

Is this pattern visible in real landslide distributions?

1993 Finisterre



P. Meunier et al. / Earth and Planetary Science Letters 275 (2008) 221 –232

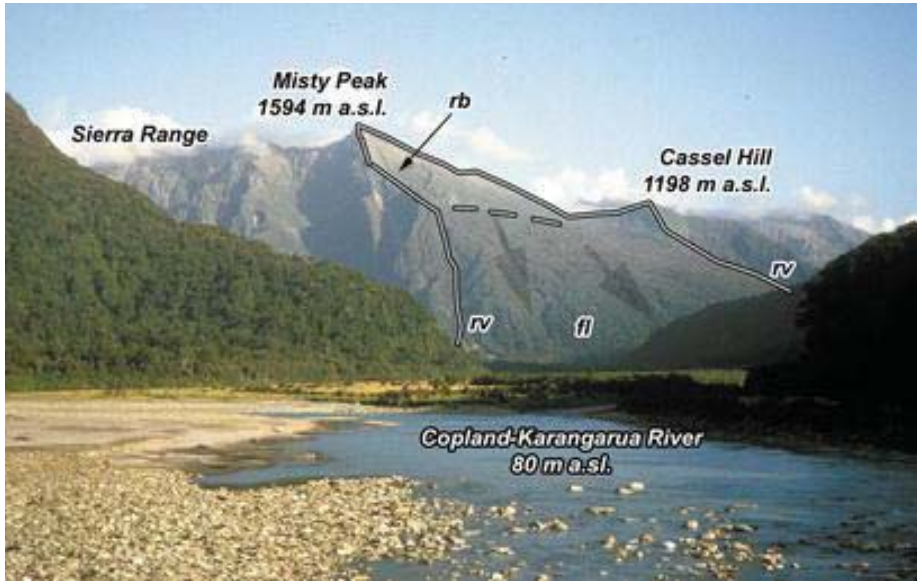


P. Meunier et al. / Earth and Planetary Science Letters 275 (2008) 221 –232

Meunier et al. (2008 EPSL) found roughly that pattern: earthquake-triggered landslides tended to cluster near ridge crests (Northridge) or were quasi-evenly distributed (Finisterre, Chi Chi earthquakes), while rainfall-triggered landslides were strongly clustered toward valley floors

R_p is the probability of a landslide occurring at a given distance from the stream, divided by the probability of all cells occurring at that distance

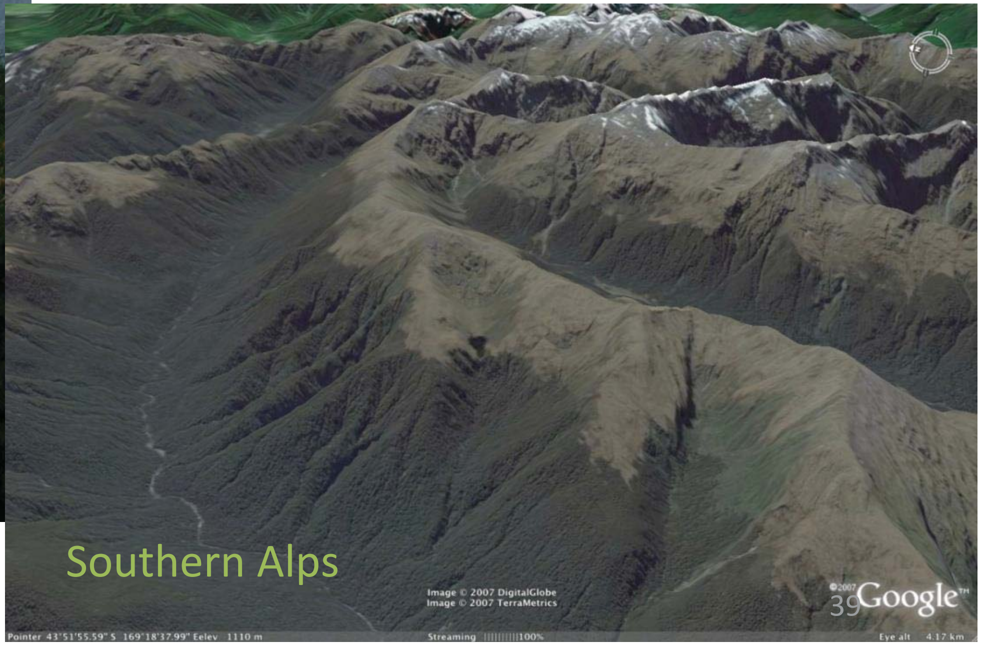
Spatial patterns



Repeated earthquake-triggered bedrock landslides leave a characteristic **fingerprint** on the landscape

- planar hillslopes
- sharp-crested, sometimes scalloped divides
- hummocky or blocky terrain at hillslope toes

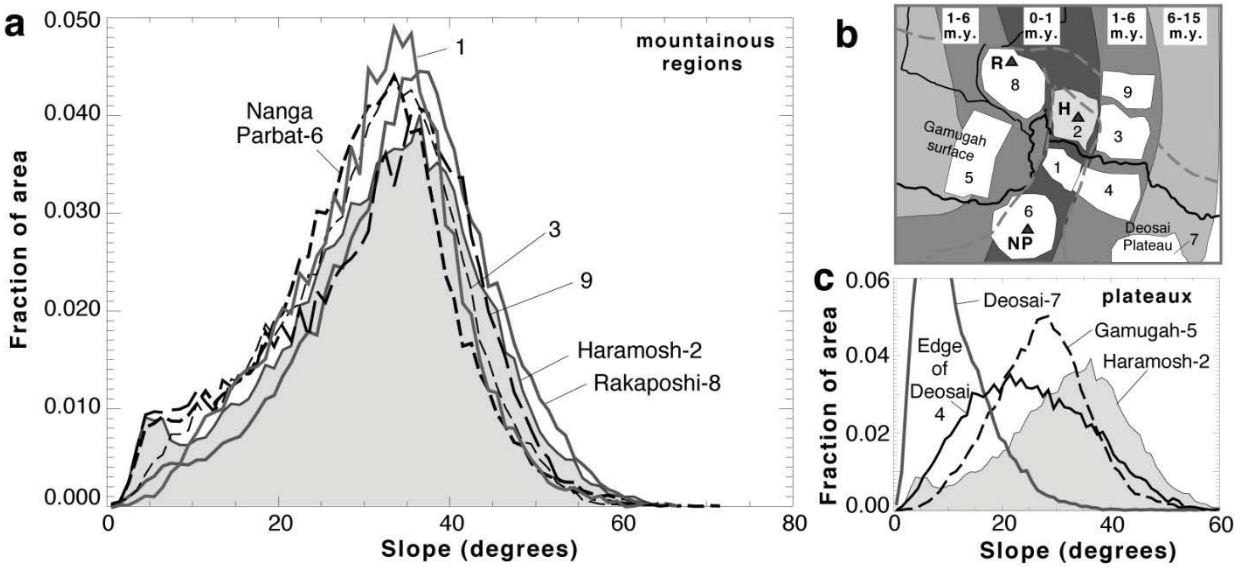
Sichuan, China



Southern Alps

Spatial patterns

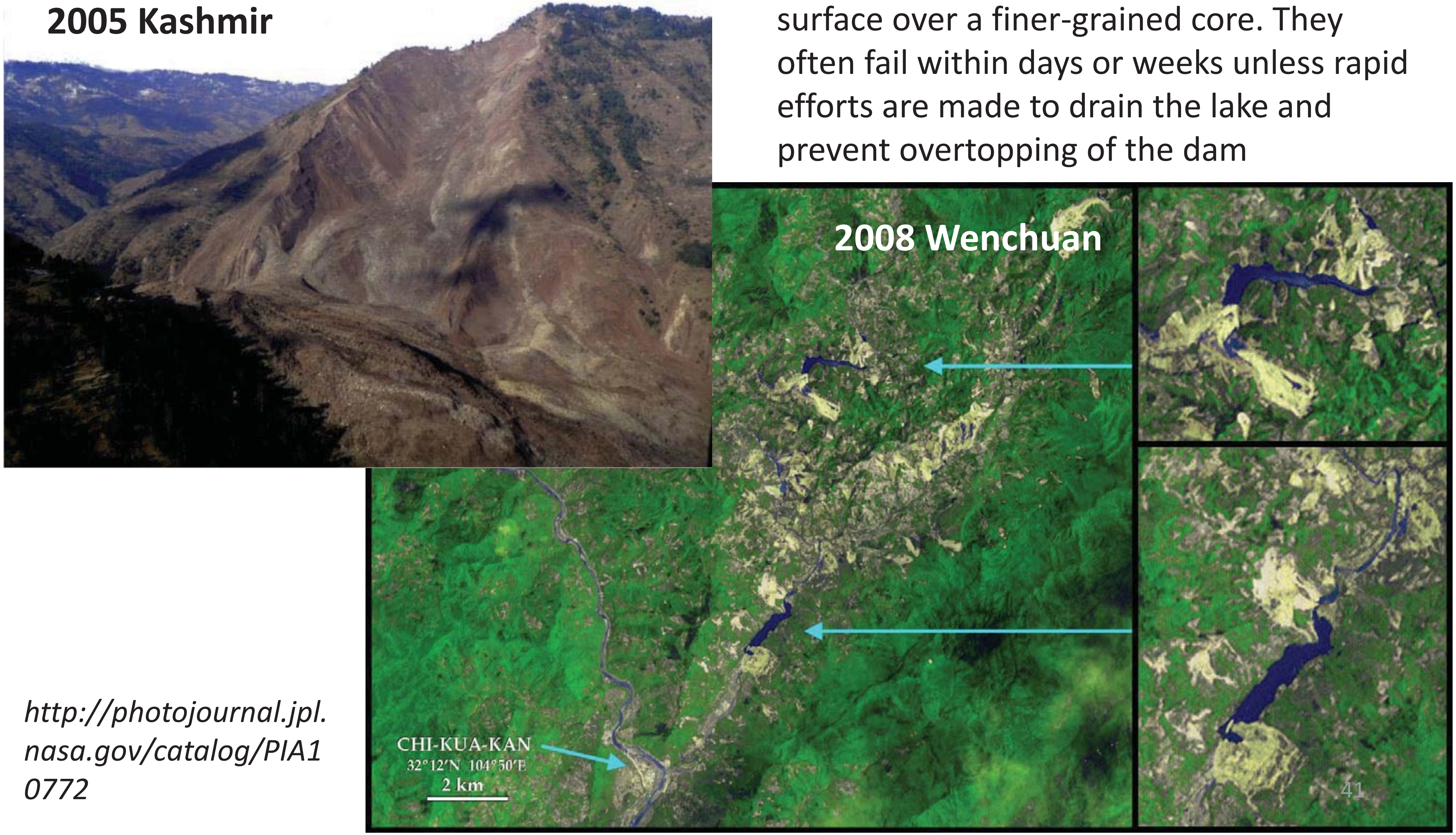
Large landslides (like the one at left along the Karakoram Highway in Pakistan) reset the entire hillslope and impose a dominant slope angle (typically 30-40˚) on the landscape



Burbank (2002) Mineralogical Magazine

Spatial patterns

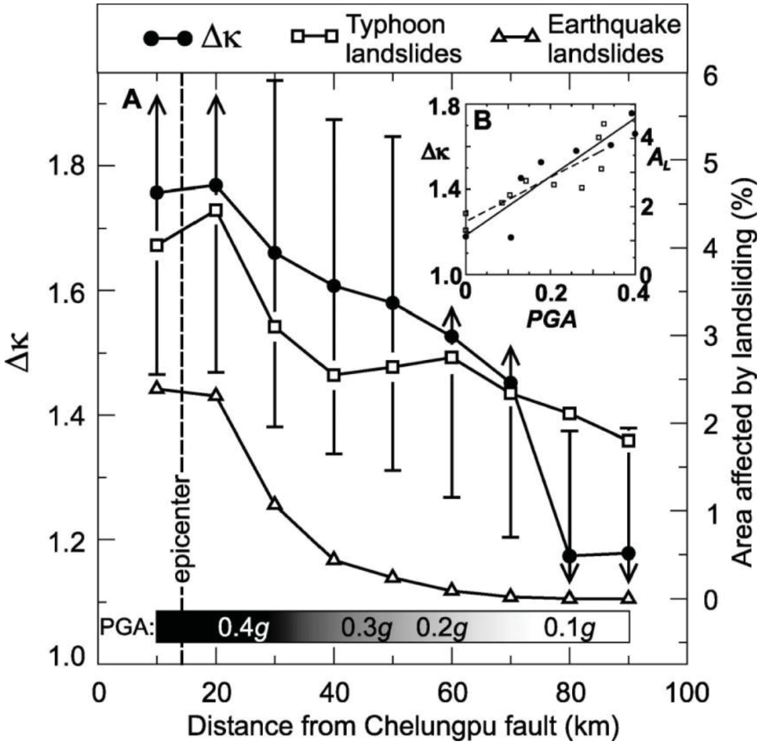
A common consequence of widespread landsliding in high-relief terrain is the formation (and eventual failure) of **landslide dams**. These are typically highly unstable, with a coarse-grained upper surface over a finer-grained core. They often fail within days or weeks unless rapid efforts are made to drain the lake and prevent overtopping of the dam

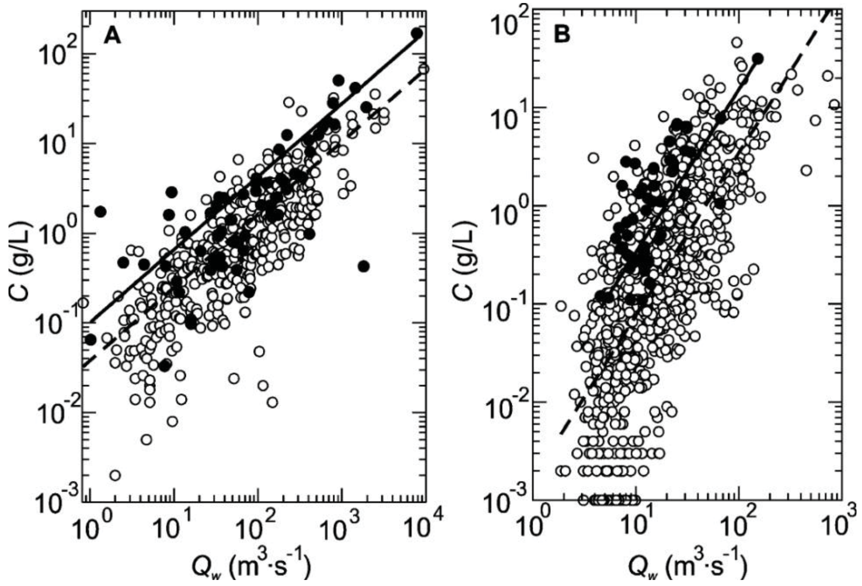


http://photojournal.jpl.nasa.gov/catalog/PIA10772

Eventual breaching of the landslide dams – whether by natural failure or by artificial channel excavation – can lead to locally serious flooding in the confined river valleys downstream, as in Beichuan town after the 2008 Wenchuan earthquake

Temporal persistence and long-term effects



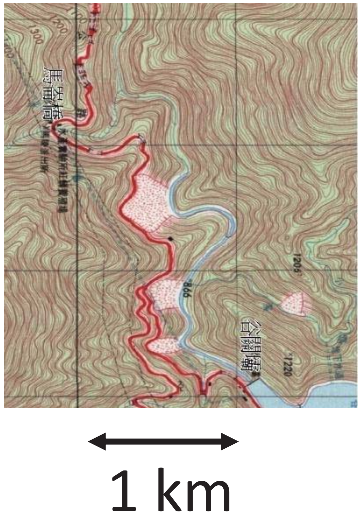


In one of the first coordinated studies of post-earthquake impacts, Dadson et al. (2004) showed that

1. The area affected by landsliding decreased with distance from fault that caused the 1999 M_w 7.6 Chi-Chi earthquake, Taiwan
2. Landslides in 2001 Typhoon Toraji also decreased with distance from the fault (slopes were pre-conditioned to fail)
3. Sediment concentrations in rivers increased 2-5x in most major Taiwanese rivers (white: before earthquake; black: after) but decayed within a few years to pre-EQ ‘background’ levels

Dadson et al. (2004) Geology

Temporal persistence and long-term effects



Topographic map

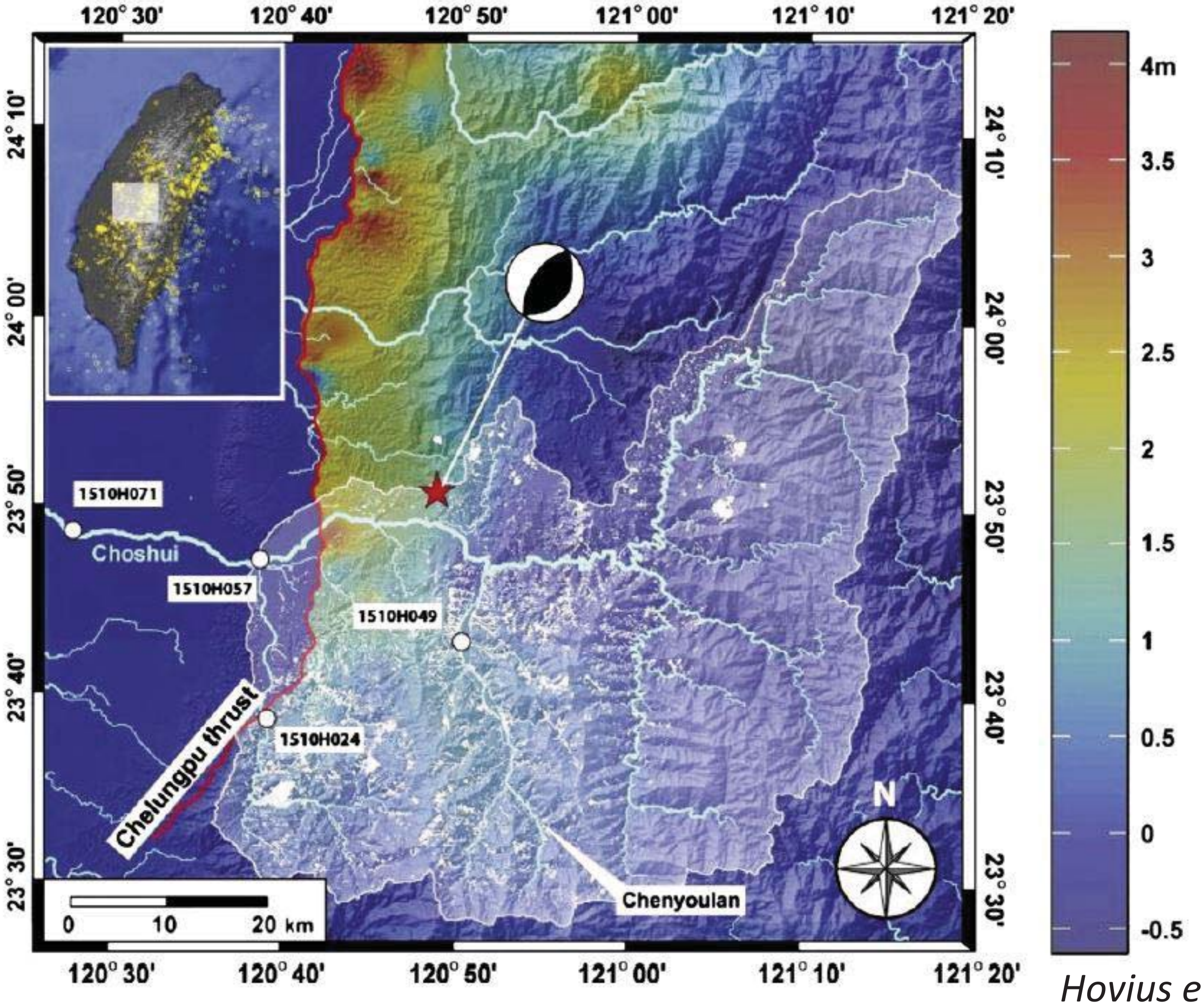
Image pre-1999

After 1999 Chi-Chi

After 2001 Typhoon Toraji

After 2009 Typhoon Morakot

Temporal persistence and long-term effects

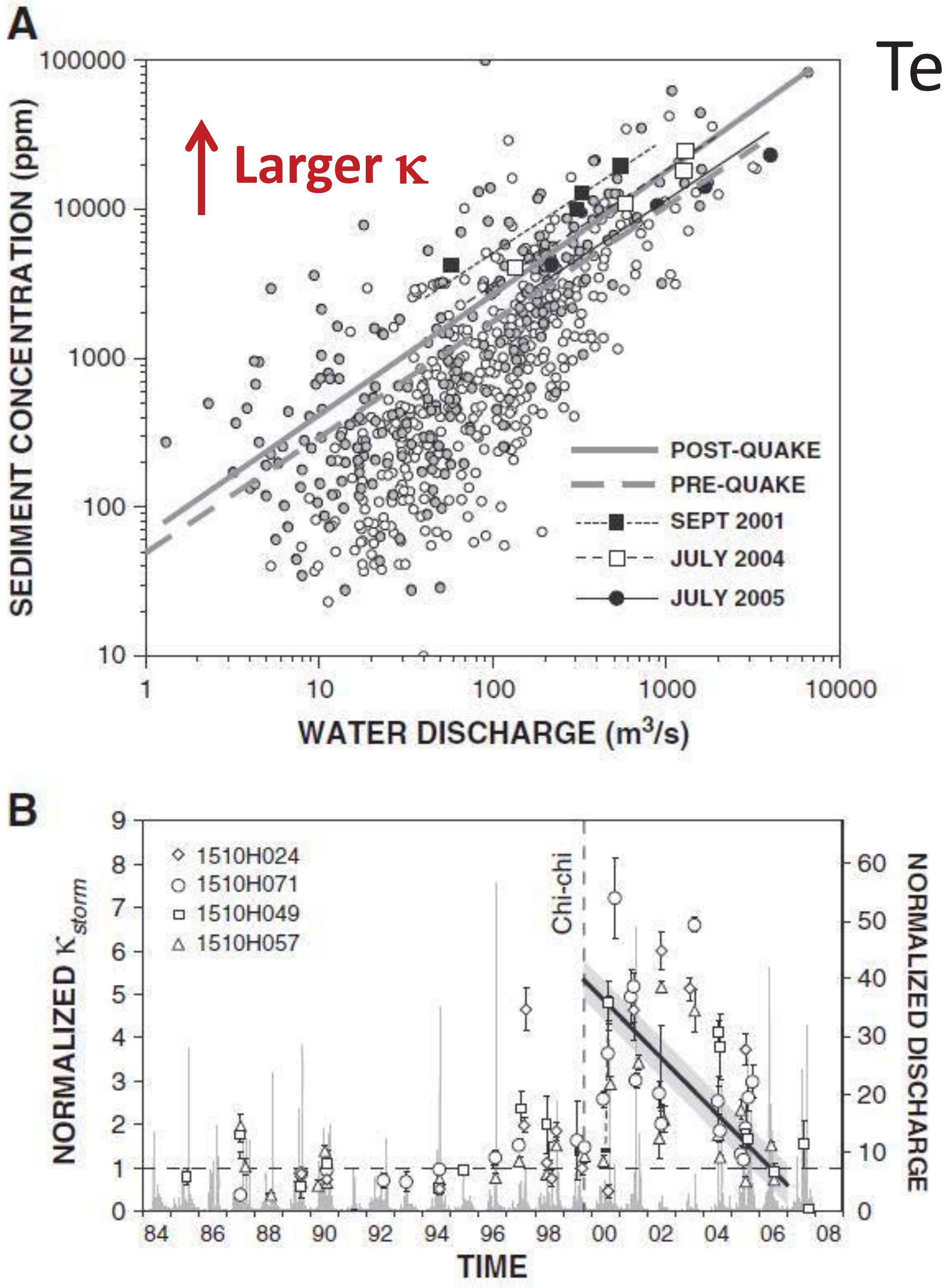


Hovius et al. (2011) EPSL

Hovius et al. (2011) continued this work by comparing the mass of sediment released by landsliding with the mass of sediment added to the Taiwan orogen via rock uplift

White dots show earthquake-triggered landslides, colors show coseismic surface uplift

Temporal persistence and long-term effects



Landslide input led to elevated suspended sediment concentration, indicated by κ

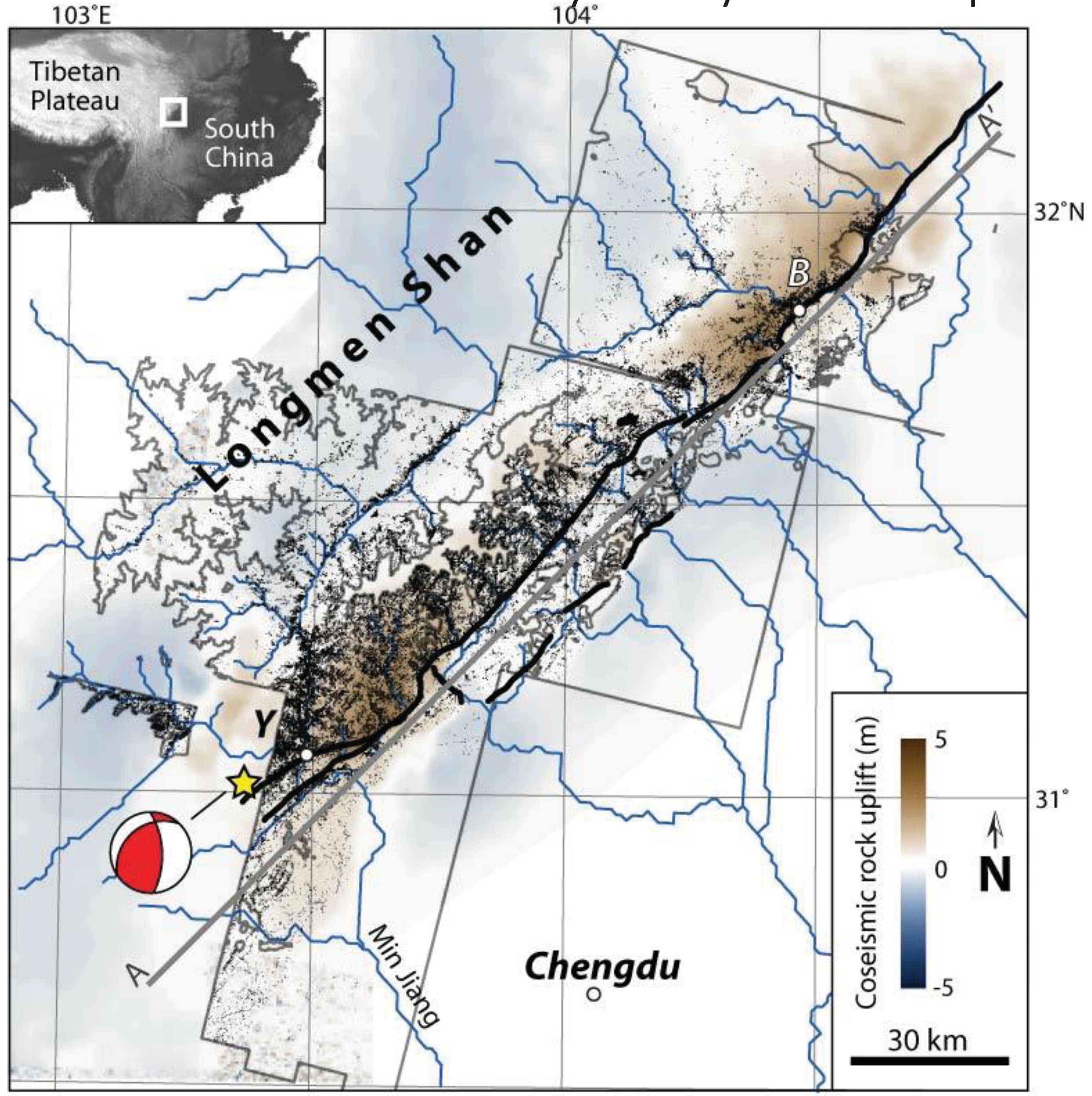
These elevated values have gradually decayed since 1999, implying that most of the **available** landslide debris (or at least the fine fraction) has been removed since the earthquake

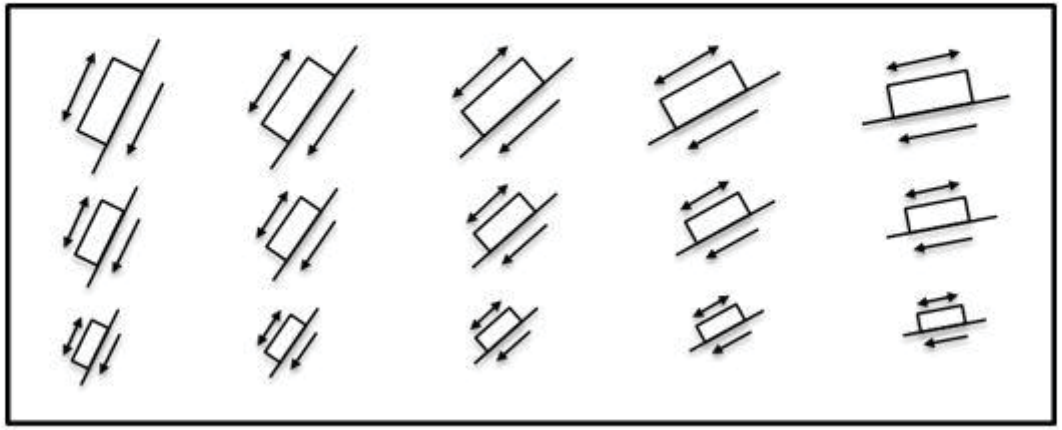
Hovius et al. (2011) EPSL

Outstanding issues

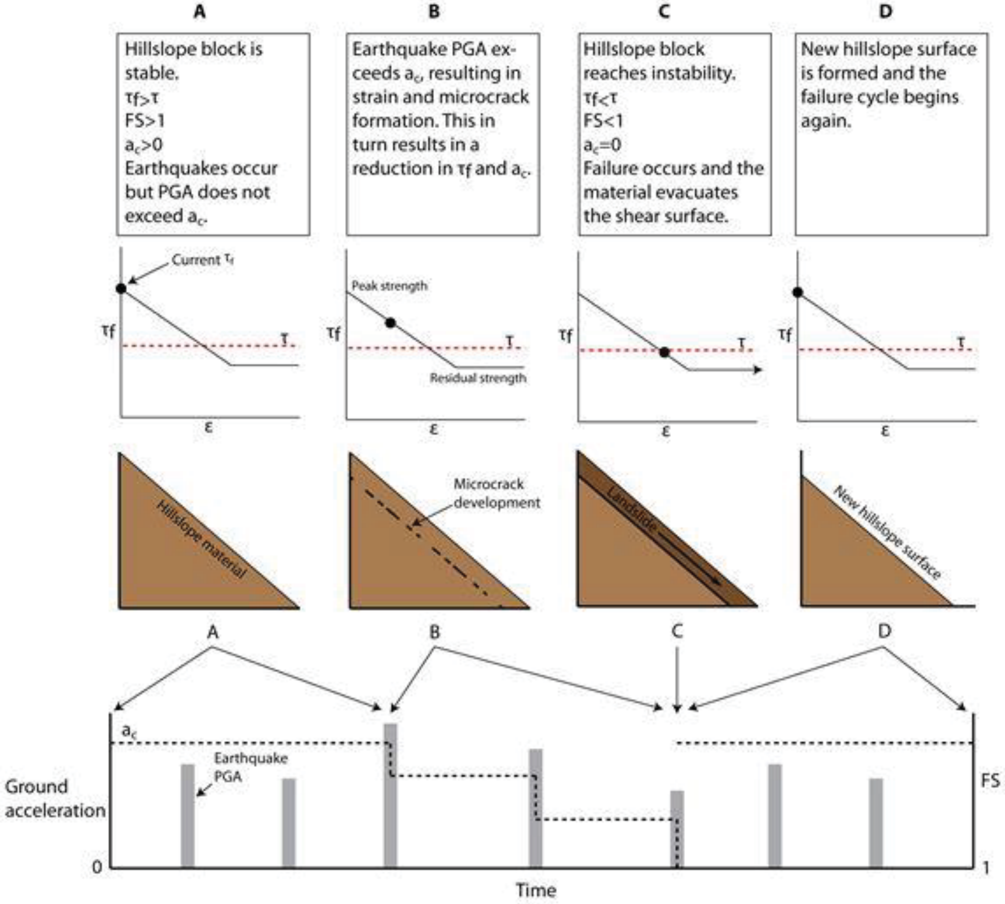
1. Why do only some susceptible slopes fail?

Parker et al. (2011) Nature Geosci.





It’s possible to think of every hillslope in a mountain belt as a separate Newmark sliding block, each with its own threshold a_c and its own history of failure



A

Hillslope block is stable.
τf>τ
FS>1
a_c>0
Earthquakes occur but PGA does not exceed a_c.

B

Earthquake PGA exceeds a_c, resulting in strain and microcrack formation. This in turn results in a reduction in τf and a_c.

C

Hillslope block reaches instability.
τf<τ
FS<1
a_c=0
Failure occurs and the material evacuates the shear surface.

D

New hillslope surface is formed and the failure cycle begins again.

Outstanding issues

2. What is the fate of earthquake-triggered landslide debris?

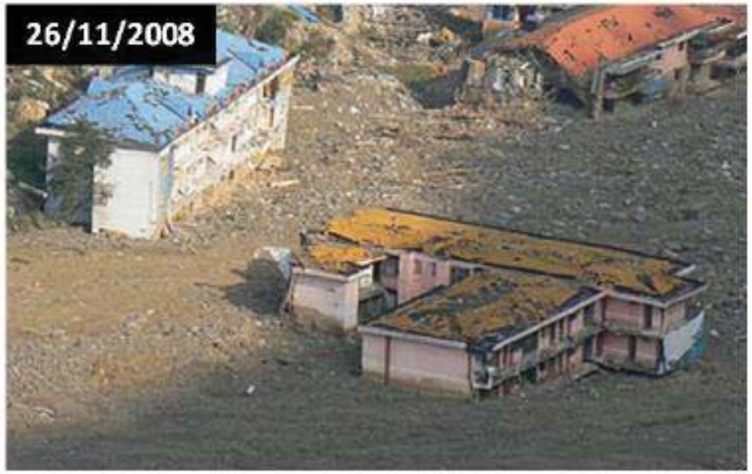
November 2008

August 2008

6.8 m scarp near Leigu, SW of Beichuan

>10 m of **aggradation** observed after 2008 Wenchuan earthquake (e.g., Beichuan town, right and below); removal of sand fraction only (10% of total volume) will take 10-60 yr

Up to 18 m observed after 1999 Chi-Chi earthquake (Chen and Petley, 2005)



How can we quantify this process? Difficult to measure fill depths remotely (e.g. on satellite imagery)...

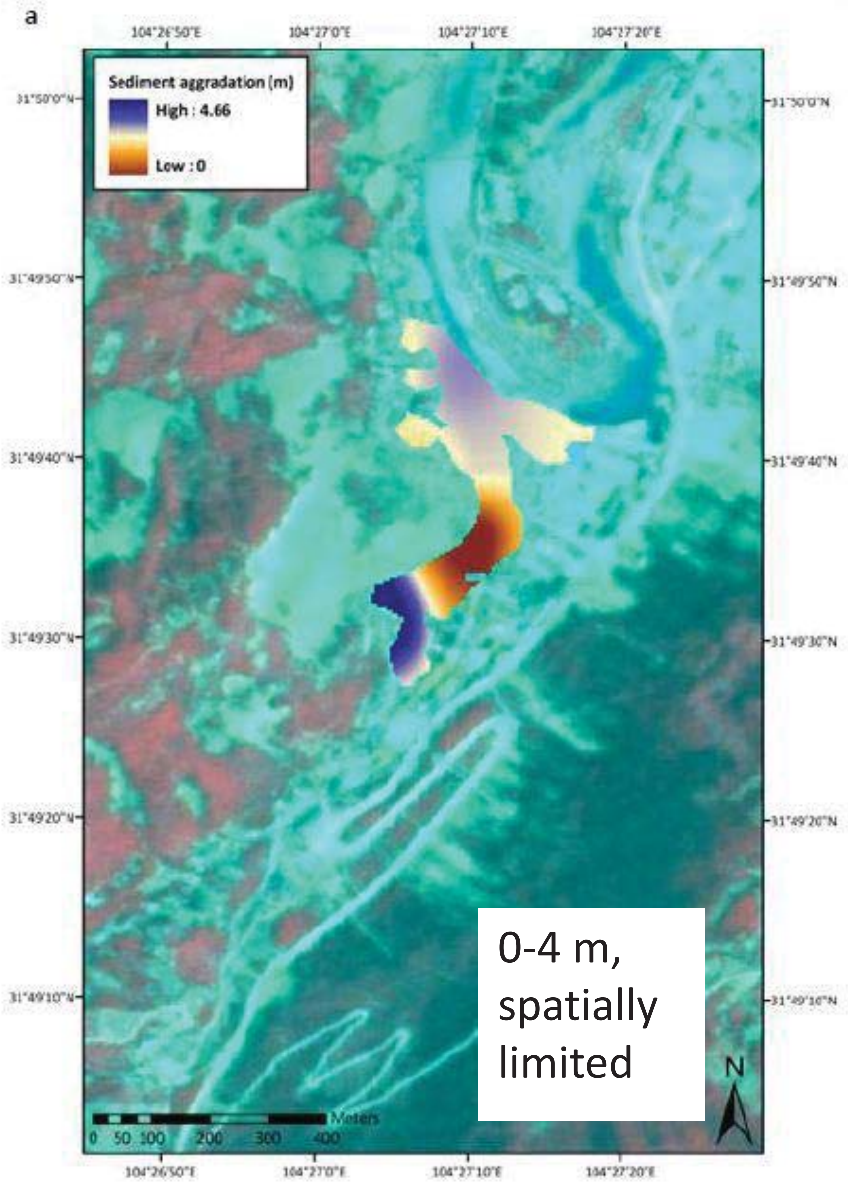
The 2008 Wenchuan earthquake is perhaps the first large earthquake that is highly ‘accessible’ via internet and mobile phone coverage

There has been some use of social networking sites (Flickr, Google Earth, Facebook) to collect oblique photographs of particular areas in the Longmen Shan to monitor surface change

Photos at left show aggradation and burial of buildings in Beichuan over the 6 months after the earthquake

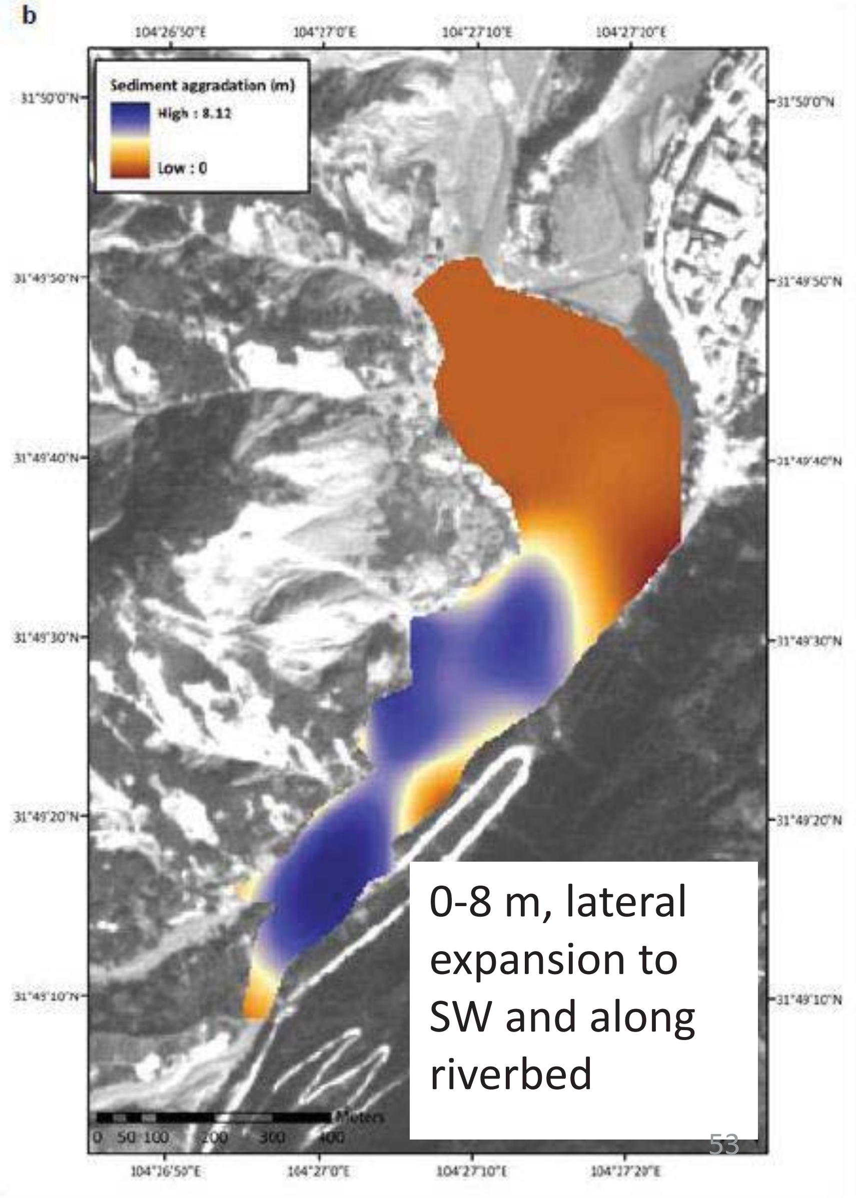
By scaling these observations to near-standard building dimensions, we can obtain estimates of aggradation depths and volumes over time

To June 2008



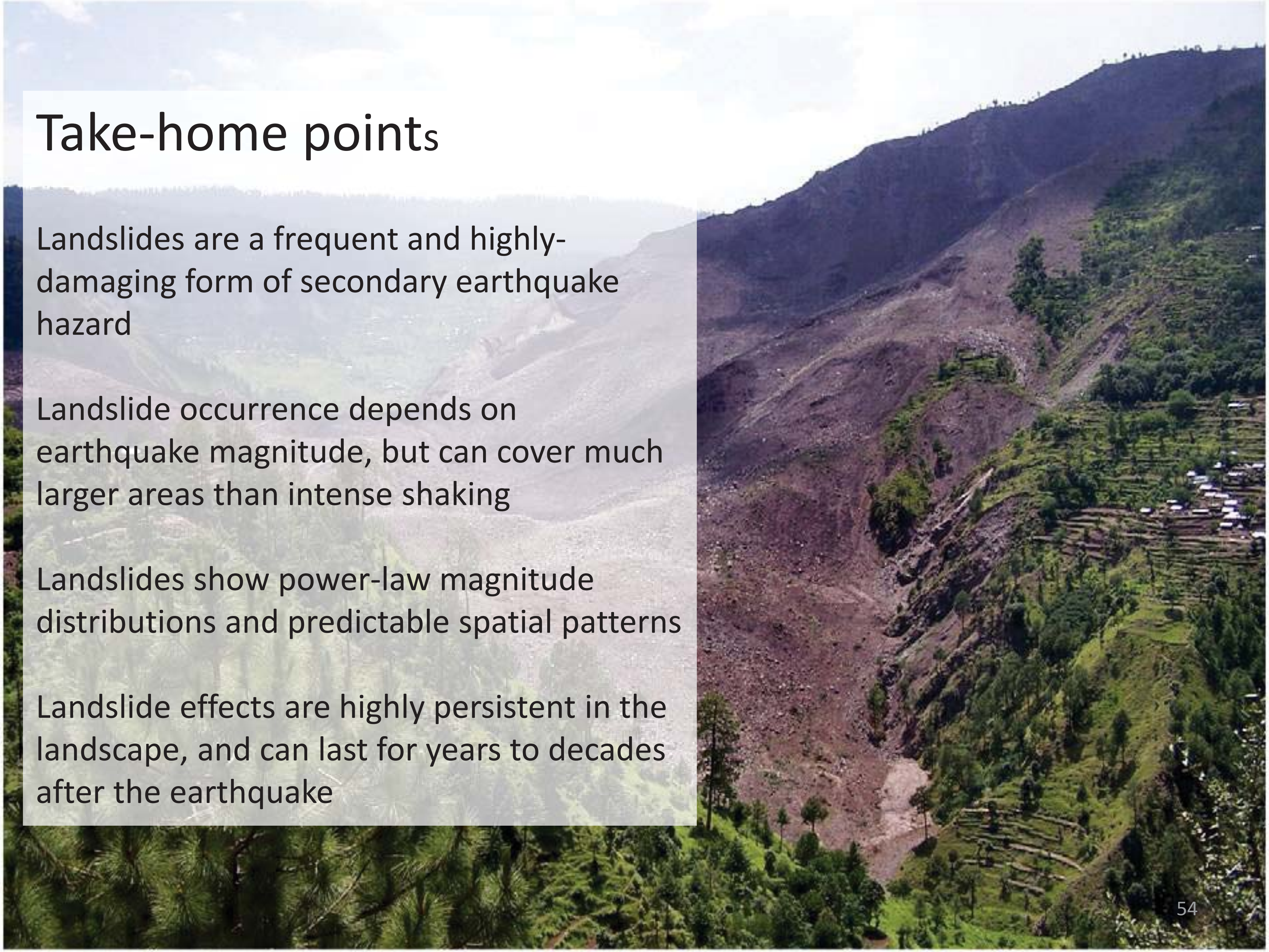
0-4 m, spatially limited

To October 2008



0-8 m, lateral expansion to SW and along riverbed

Take-home points



Landslides are a frequent and highly-damaging form of secondary earthquake hazard

Landslide occurrence depends on earthquake magnitude, but can cover much larger areas than intense shaking

Landslides show power-law magnitude distributions and predictable spatial patterns

Landslide effects are highly persistent in the landscape, and can last for years to decades after the earthquake