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Quantifying the hazard of catastrophic rock avalanches

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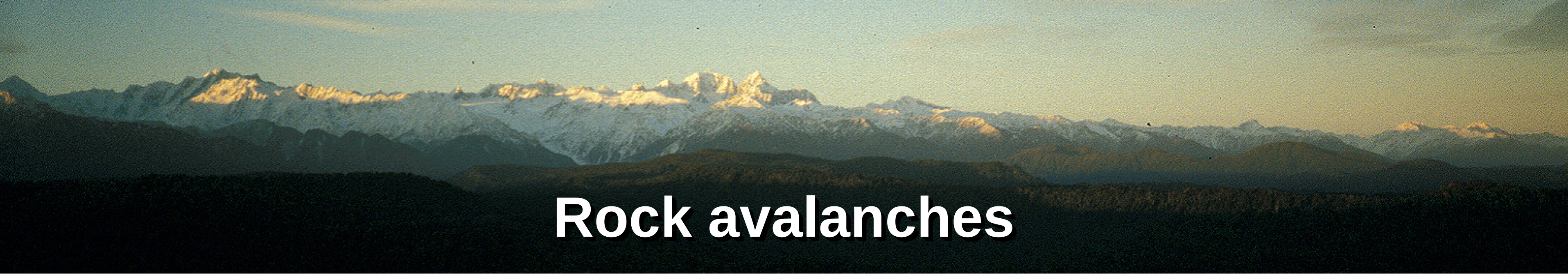
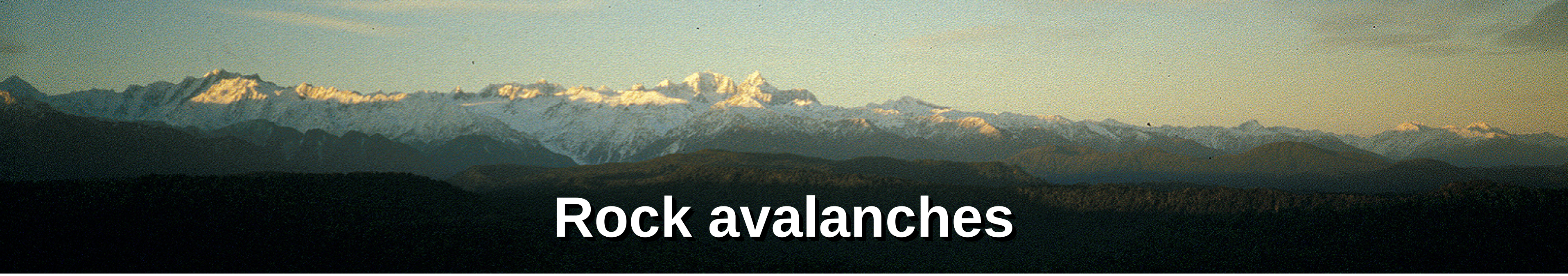


Rock avalanches

1. Characteristics
2. Size-frequency scaling
3. Implications for hazard assessments



Rock avalanches

1. Characteristics
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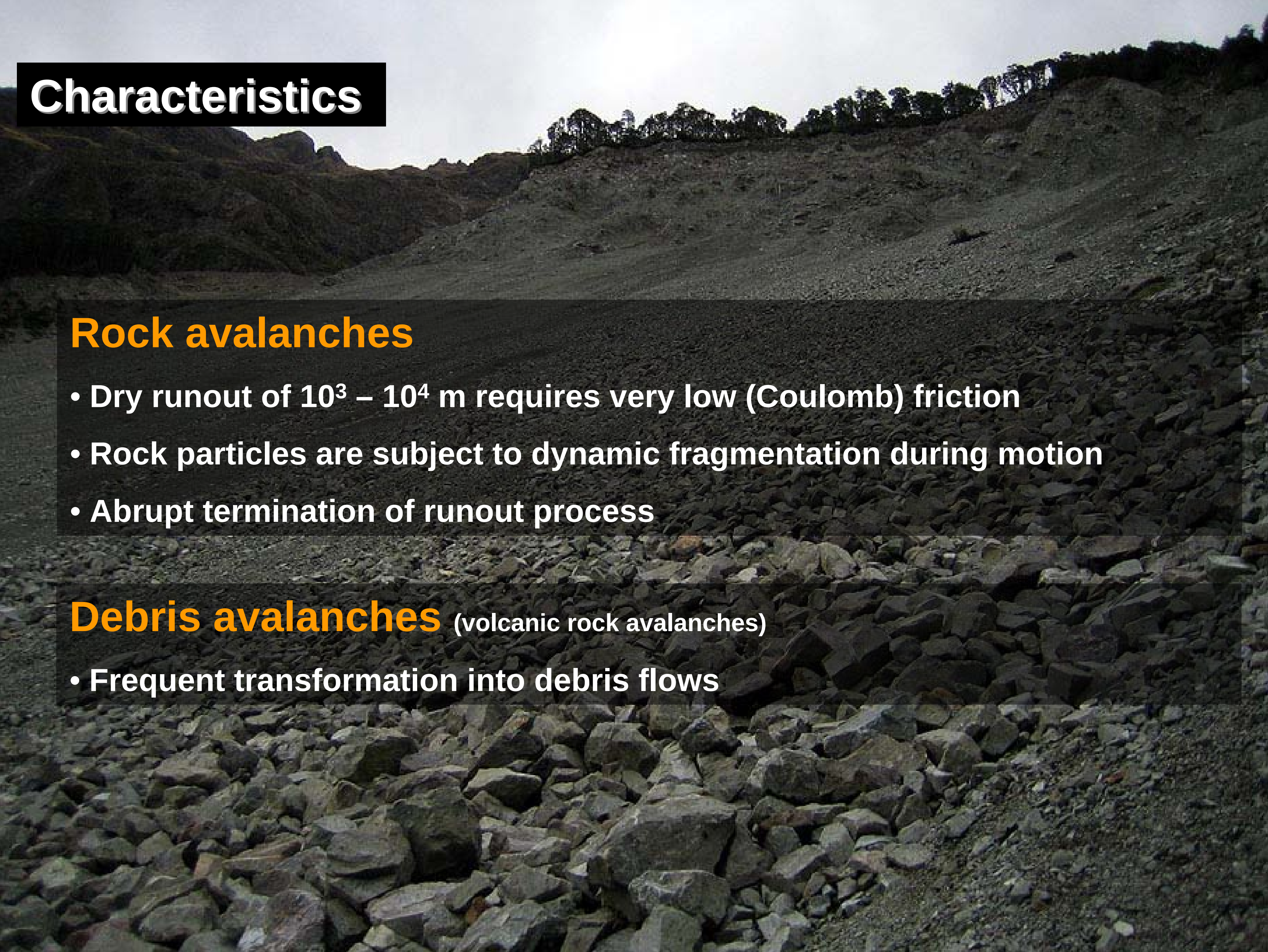
Characteristics

Rock avalanches

- Extremely rapid (~10^1 m s^{-1}) flow of rock particles
- Volumes 10^6 – 10^{10} m^3
- Frequently derived from large rock falls and rockslides

Debris avalanches (= volcanic rock avalanches)

- Higher content of H_20 and clay minerals (hydrothermal alteration)
- Higher mobility (H/L)
- Frequently triggered by sector collapse



Characteristics

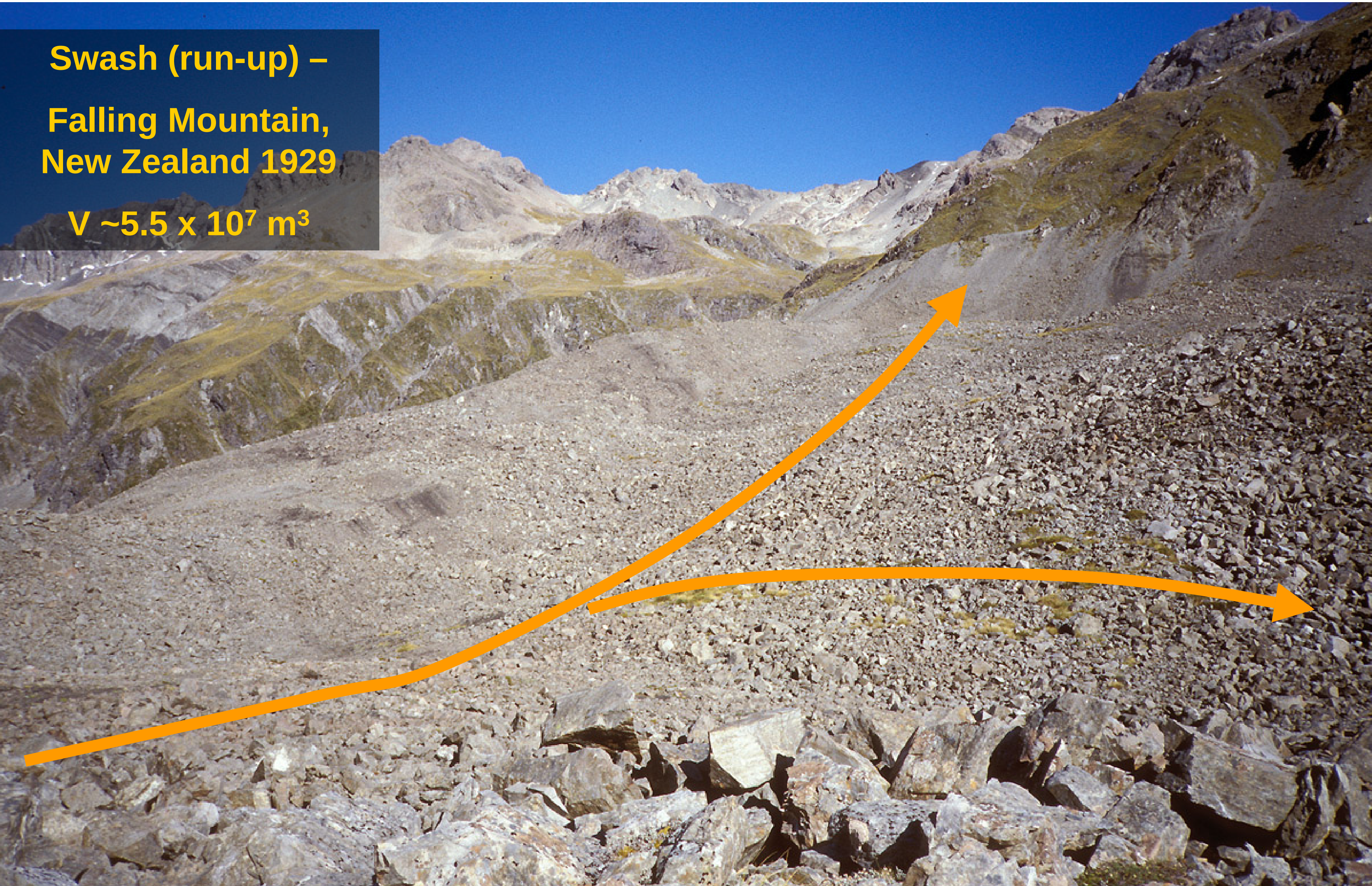
Rock avalanches

- Dry runout of $10^3 – 10^4$ m requires very low (Coulomb) friction
- Rock particles are subject to dynamic fragmentation during motion
- Abrupt termination of runout process

Debris avalanches (volcanic rock avalanches)

- Frequent transformation into debris flows

Characteristics



Swash (run-up) –

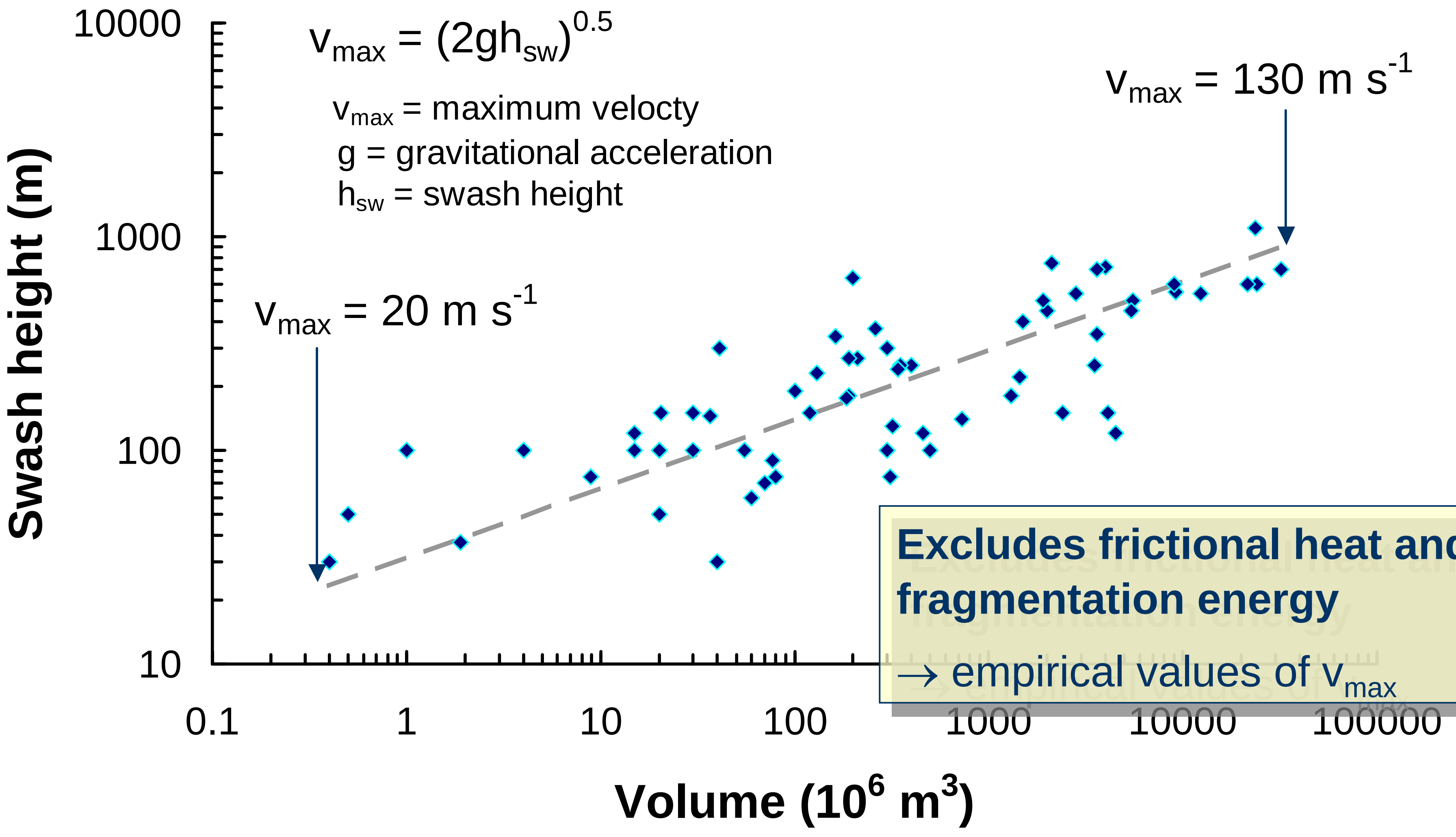
Falling Mountain, New Zealand 1929

V ~5.5 x 10^7 m^3

Characteristics

$v_{max} = (2gh_{sw})^{0.5}$

v_{max} = maximum velocty
g = gravitational acceleration
h_{sw} = swash height



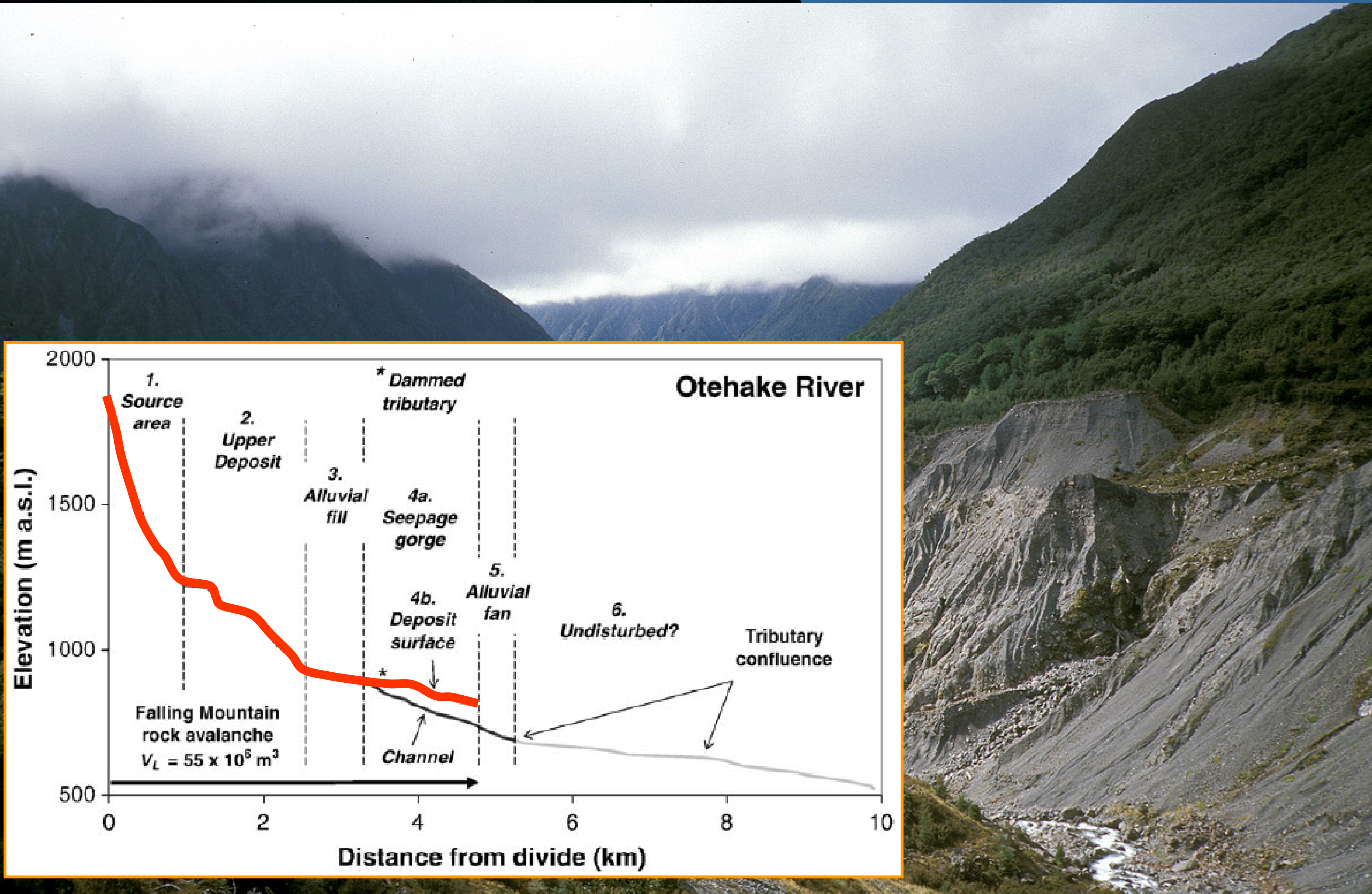
Excludes frictional heat and fragmentation energy

→ empirical values of v_{max}

Characteristics

Characteristics

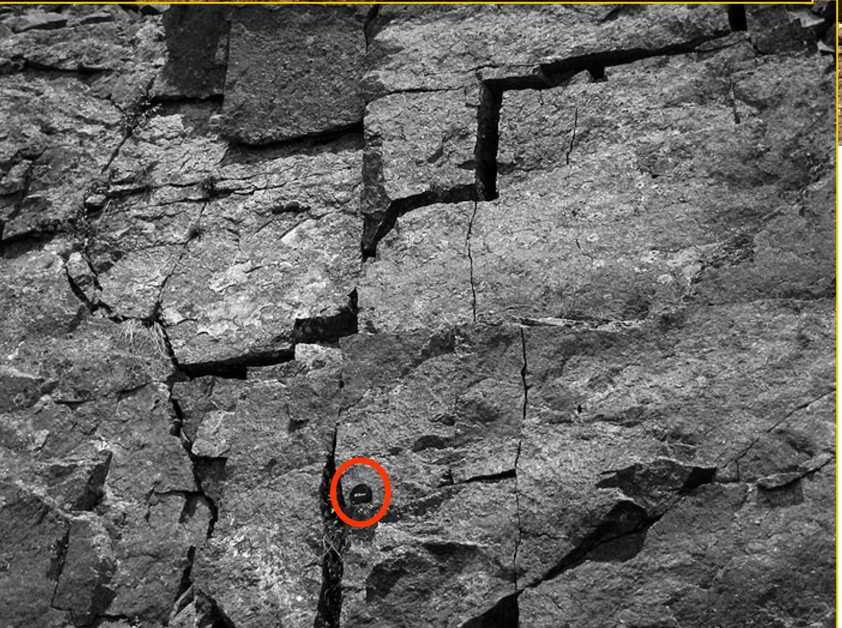
Characteristics



Characteristics

- *Fragmentation (typically very angular clasts)*
- *Preservation of lithologic bedding (negligible vertical particle mixing)*
- *Furrows, lobes, and levees*

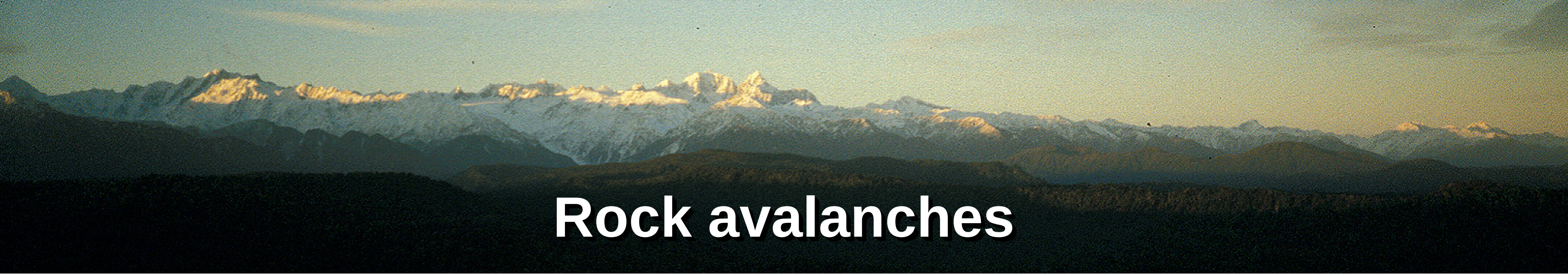
Characteristics



„Jigsaw“ puzzle texture

Causes and triggers

	Rock avalanches	Debris avalanches
Causes	• Rock-mass discontinuities (fault zones, joints, etc.) • Slope oversteepening (e.g. glaciation, fluvial undercutting)	• Rock-mass discontinuities (fault zones, joints, etc.) • Hydrothermal activity • Slope oversteepening (e.g. expansion of magma chambers)
Triggers	• Earthquakes • Rainfall and snowmelt • Anthropogenic (mining, blasting)	• Volcanic eruption • Sector collapse • Earthquakes



Rock avalanches

1. Characteristics
2. **Size-frequency scaling**
3. Implications for hazard assessments

Quantifying hazard

- **Landslide hazard** = probability of spatial landslide impact within a specified area per unit time (e.g. annual)

- Quantitative **landslide hazard assessment** thus requires a mathematical expression of the relationship between landslide size and frequency

- Empirical approach using records of landslide occurrence:

  Size-scaling relationships = *statistical models that* ***lump the complexity*** *of spatio-temporal landslide occurrence into very few parameters*

Quantifying hazard

Scaling range of rock avalanches

Source: www.gns.cri.nz

10^6 m^3

10^{10} m^3

>4 orders of magnitude

Size-frequency scaling

- Most studies on size-frequency scaling focus on **landslide area**
- Largest **landslide inventories** contain area (volume) information on *n* ~10^4 (*n* ~10^3) data points *(though few rock avalanches...)*
- Most distributions have **power-law interval *O*(2) to *O*(3)**

Landslide area $$f(A) = c_A A^{-\alpha_A}$$

Landslide volume $$f(V) = c_V V^{-\alpha_V}$$

- Little is known about the scaling properties of **large catastrophic landslides** (*A* >1 km²)
- Distributions **fitted to smaller landslides** imply inverse power law

Size-frequency scaling

Most popular distributions

- Power law
- Double Pareto
- Weibull
- Inverse gamma

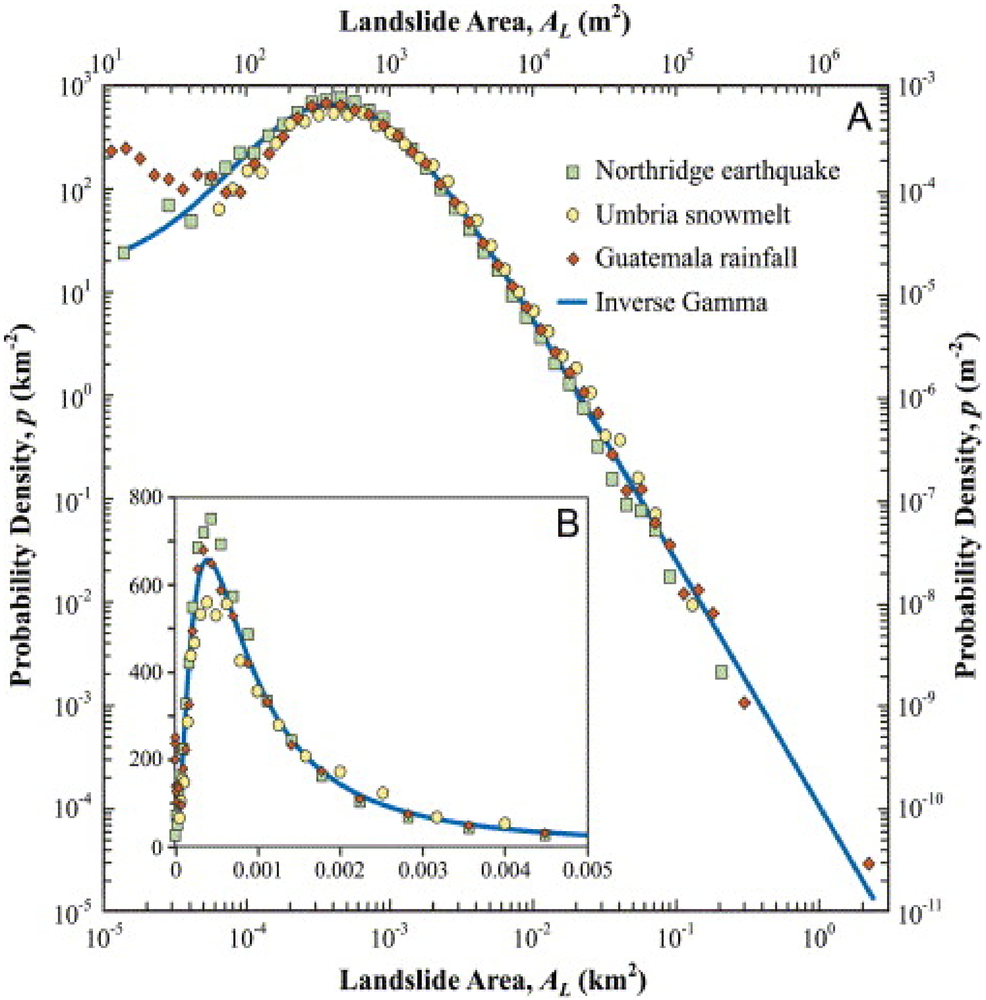
$$p(A_L;\rho,a,s)=\frac{1}{a\Gamma(\rho)}\left[-\frac{a}{A_L-s}\right]^{\rho+1}\exp\left[-\frac{a}{A_L-s}\right]$$

A_L = Landslide area

$\rho = 1.40$

$a = 1.28 \times 10^{-3}$ km²

$s = -1.32 \times 10^{-4}$ km²



Source: Malamud et al. (2004)

Size-frequency scaling

Estimated range of scaling exponents

$$f(A) = c_A A^{-\alpha_A}$$

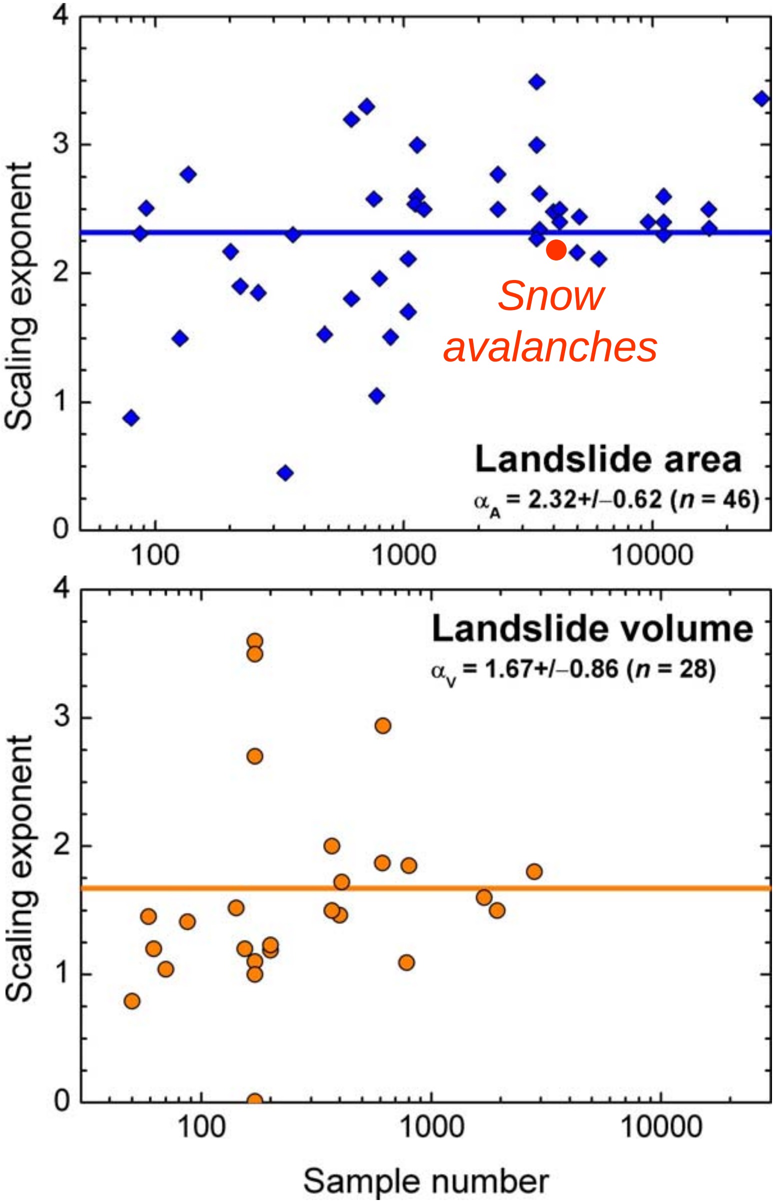
where $2.2 < \alpha_A < 2.4$

($\mu \pm 1$ s.e.)

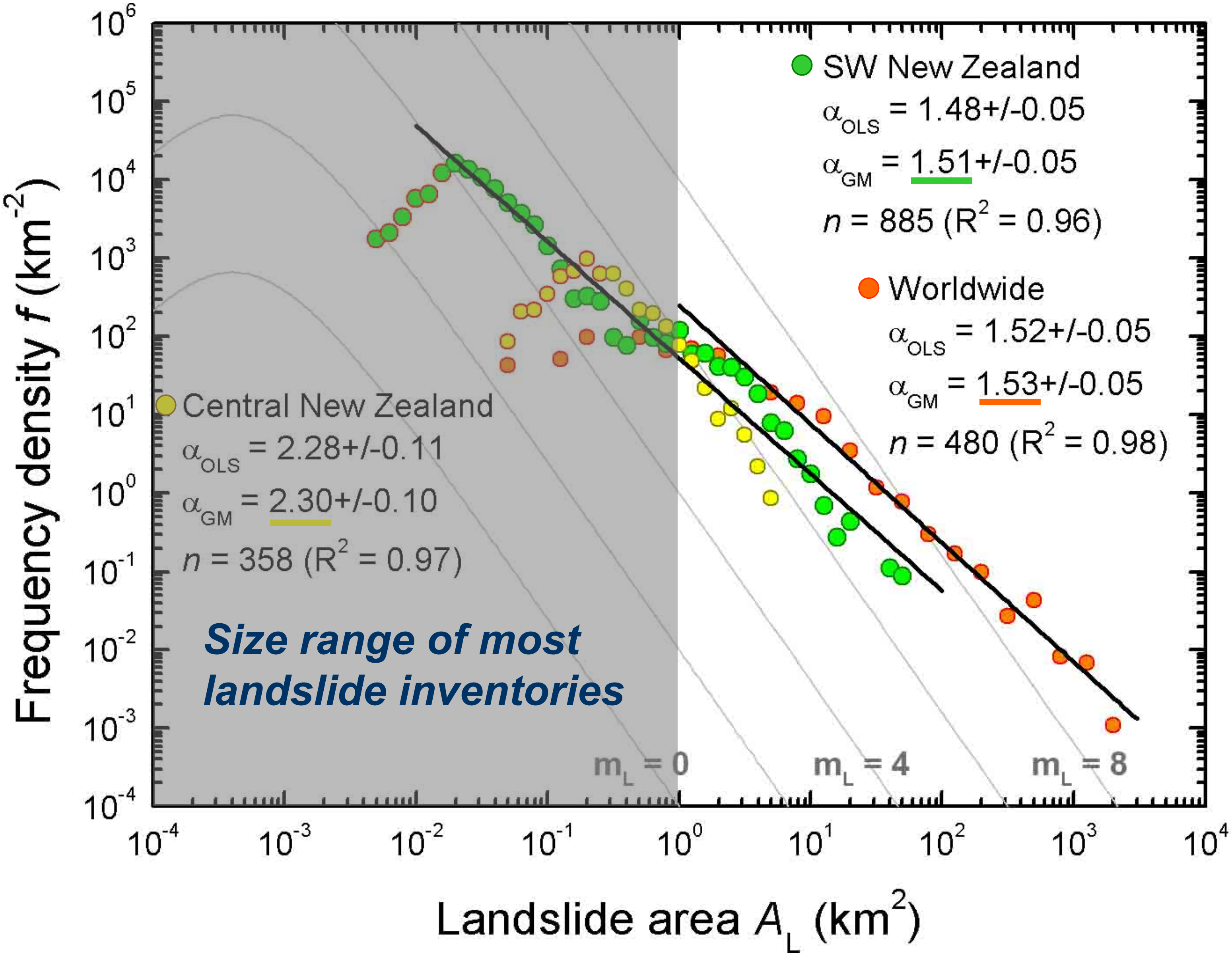
$$f(V) = c_V V^{-\alpha_V}$$

where $1.6 < \alpha_V < 1.9$

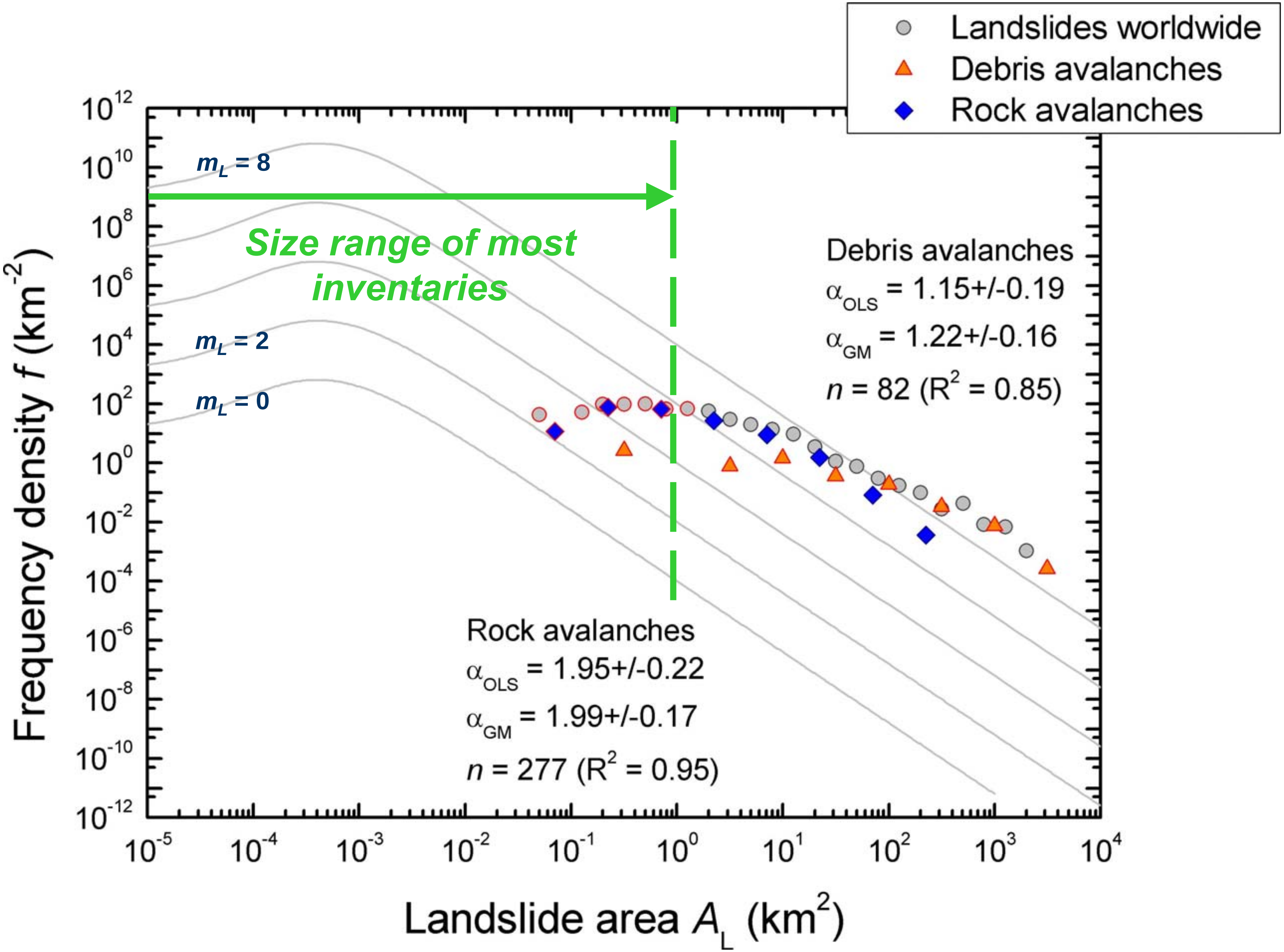
($\mu \pm 1$ s.e.)



Size-frequency scaling



Size-frequency scaling



Size range of most inventaries

Debris avalanches

$\alpha_{OLS} = 1.15 \pm 0.19$

$\alpha_{GM} = 1.22 \pm 0.16$

$n = 82$ ($R^2 = 0.85$)

Rock avalanches

$\alpha_{OLS} = 1.95 \pm 0.22$

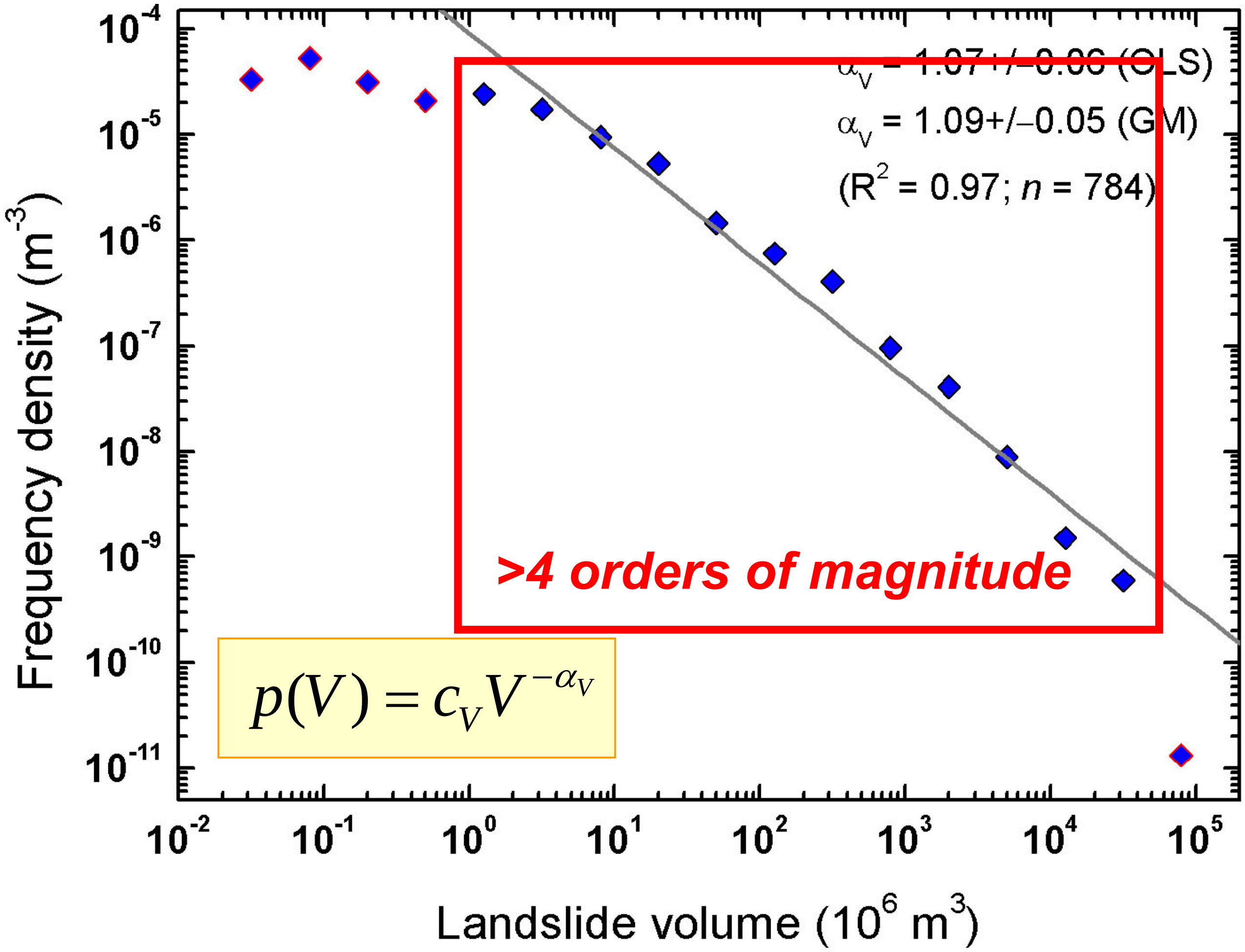
$\alpha_{GM} = 1.99 \pm 0.17$

$n = 277$ ($R^2 = 0.95$)

Size-frequency scaling

Scaling properties of volume (up to 10^{10} m^3):

Catastrophic rock-slope failures (mainly rock and debris avalanches)



$$p(V) = c_V V^{-\alpha_V}$$

Limitations of the method

Estimates of scaling exponents depend on

- *Sample size*
- *Bin size*
- *Regression method (OLS, GM, Max Likelihood)*
- *Lithology*
- *Landslide type*

Additional scatter comes from

- *Map projection (alpine topography)*
- *Subjective mapping*
- *Use of scar, deposit, or total affected areas*

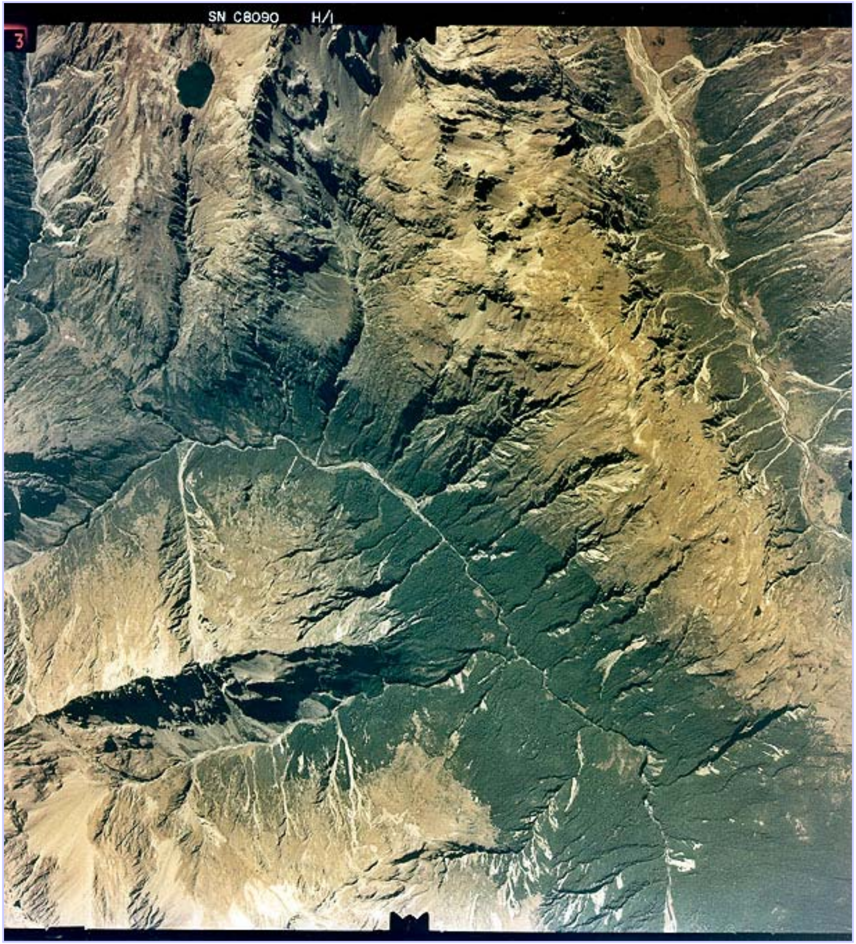
Potential pitfalls

Detection of rock avalanches using remote sensing data is limited by

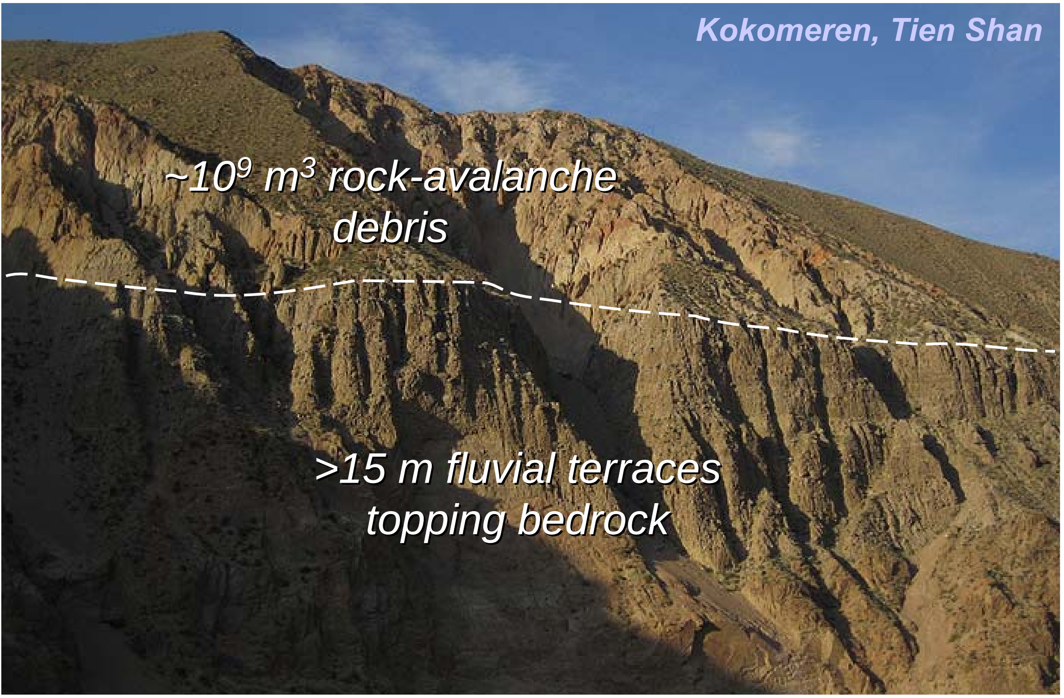
- *Undersampling*: dense vegetation cover may mask deposits from rock avalanches

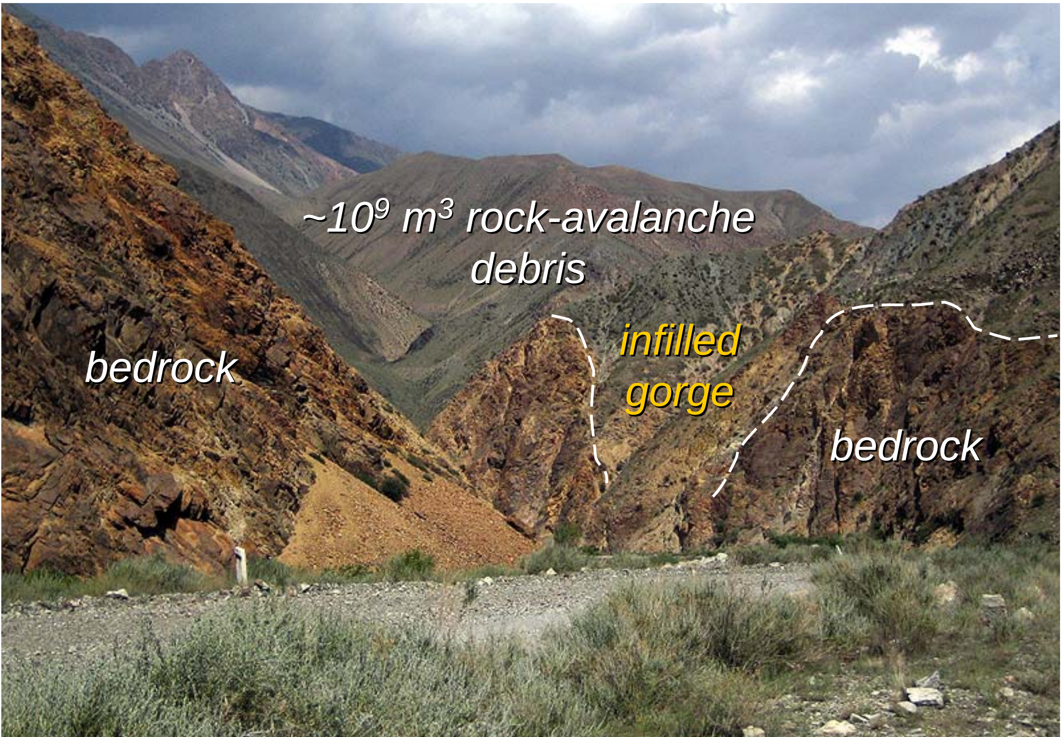
- *Erosional censoring*: older rock-avalanche deposits may have been largely eroded

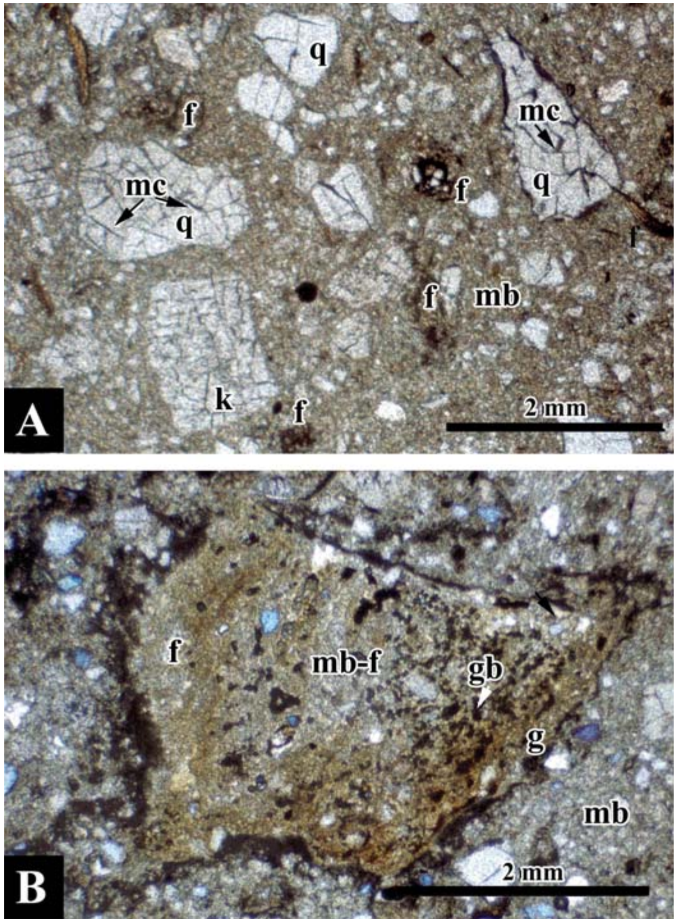
- *Depositional censoring*: older rock-avalanche debris may have been buried by subsequent failures at the same site (reactivation)



Source: www.linz.govt.nz



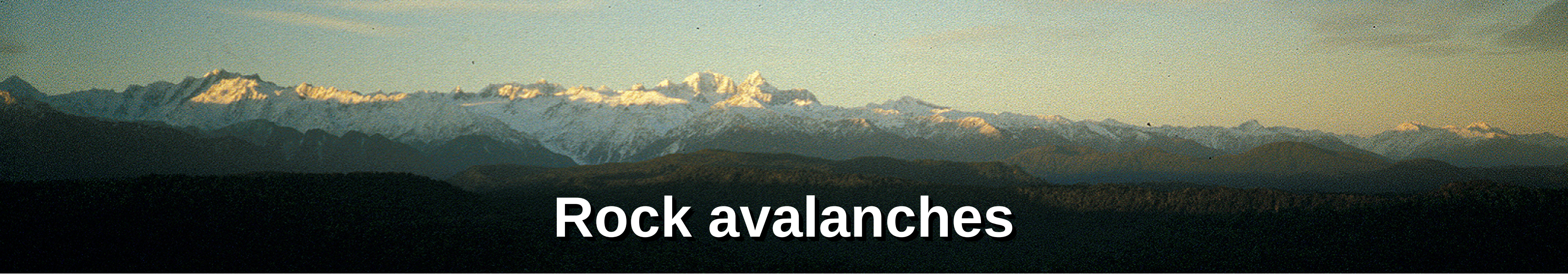




Frictionite (= hyalomylonite) in thin section

~600℃ for partial melting of biotite

Source: Weidinger & Korup (in press) *Geomorphology*.



Rock avalanches

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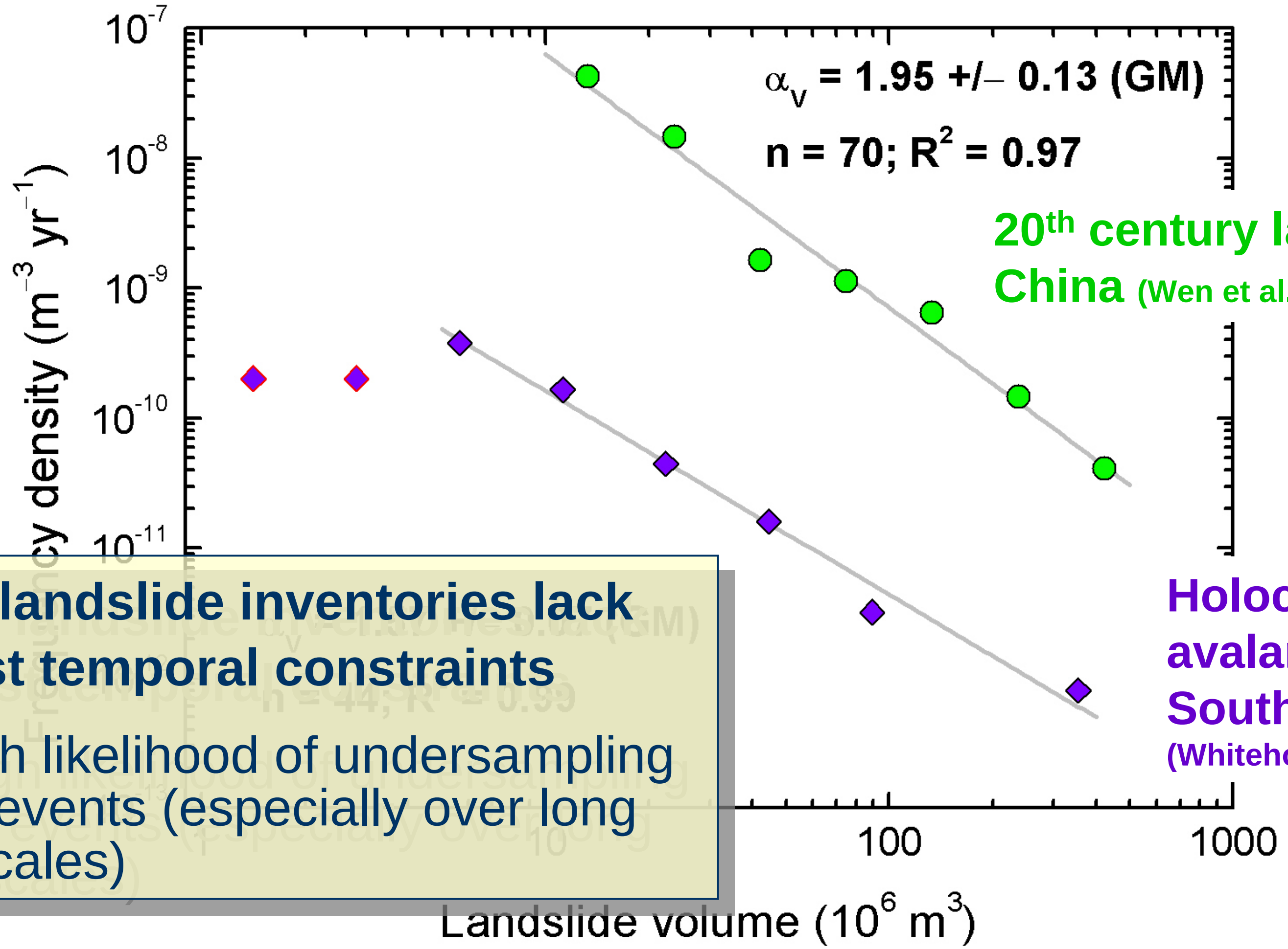
Temporal constraints



20th century landslides, China (Wen et al., 2004)

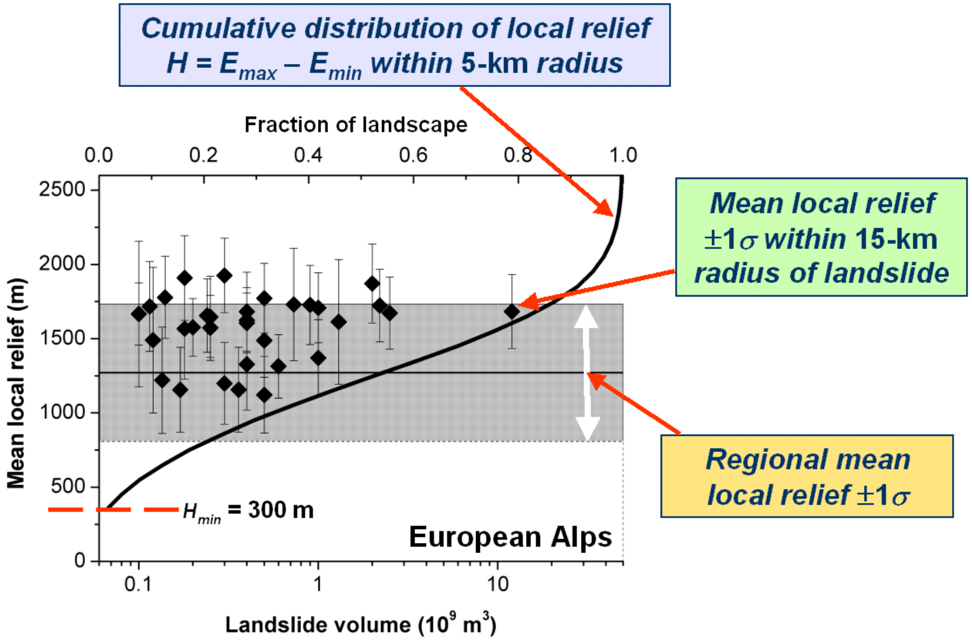
Holocene rock avalanches, NZ Southern Alps (Whitehouse, 1983)

Most landslide inventories lack robust temporal constraints

→ high likelihood of undersampling large events (especially over long timescales)

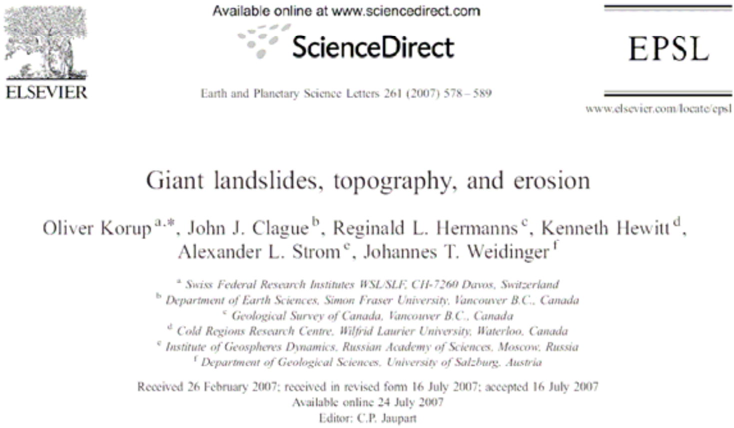
Spatial constraints

- **Scaling-derived hazard estimates lump all spatial information and thus do not predict where a rock avalanche of a given size will occur**
- **Topography can be used as a first-order predictor of rock-avalanche occurrence, although failure often obliterates the geometric initial conditions**


Cumulative distribution of local relief $H = E_{max} - E_{min}$ within 5-km radius

Mean local relief ±1σ within 15-km radius of landslide

Regional mean local relief ±1σ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Giant landslides, topography, and erosion

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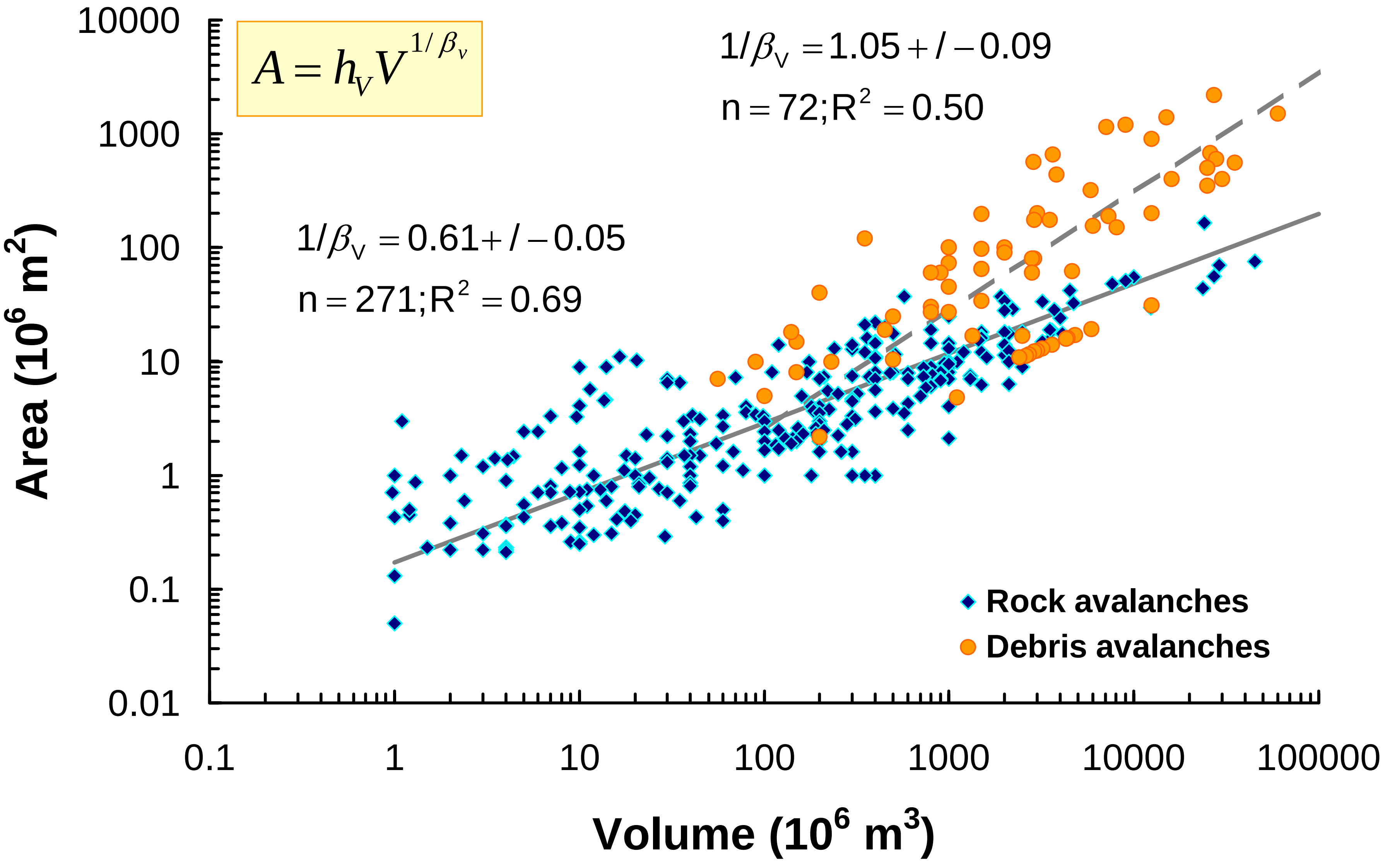
Topographic constraints



$$A = h_V V^{1/\beta_v}$$

$1/\beta_V = 1.05 +/- 0.09$

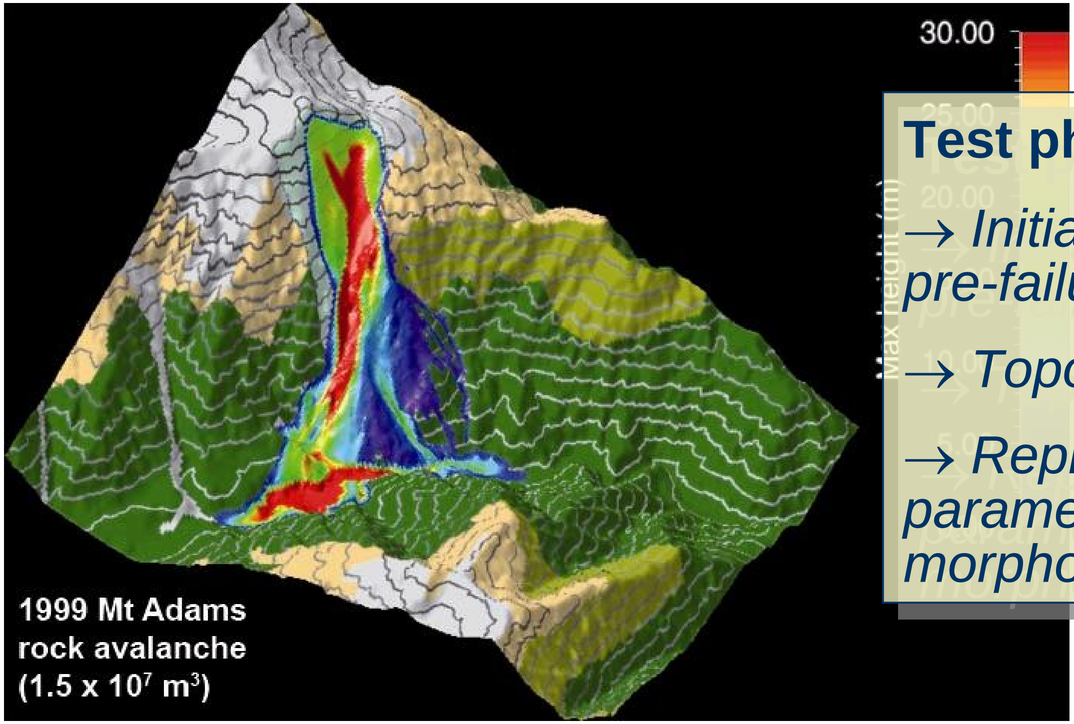
$n = 72; R^2 = 0.50$

$1/\beta_V = 0.61 +/- 0.05$

$n = 271; R^2 = 0.69$

Dynamic modelling

- **Modified runout model** used for snow avalanches and debris flows yields promising results for rock-ice and rock avalanches *(i.e. the IRASMOS spectrum of extremely rapid mass movements)*
- This model additionally considers **random kinetic energy** and **particle collisions**



1999 Mt Adams rock avalanche (1.5×10^7 m^3)

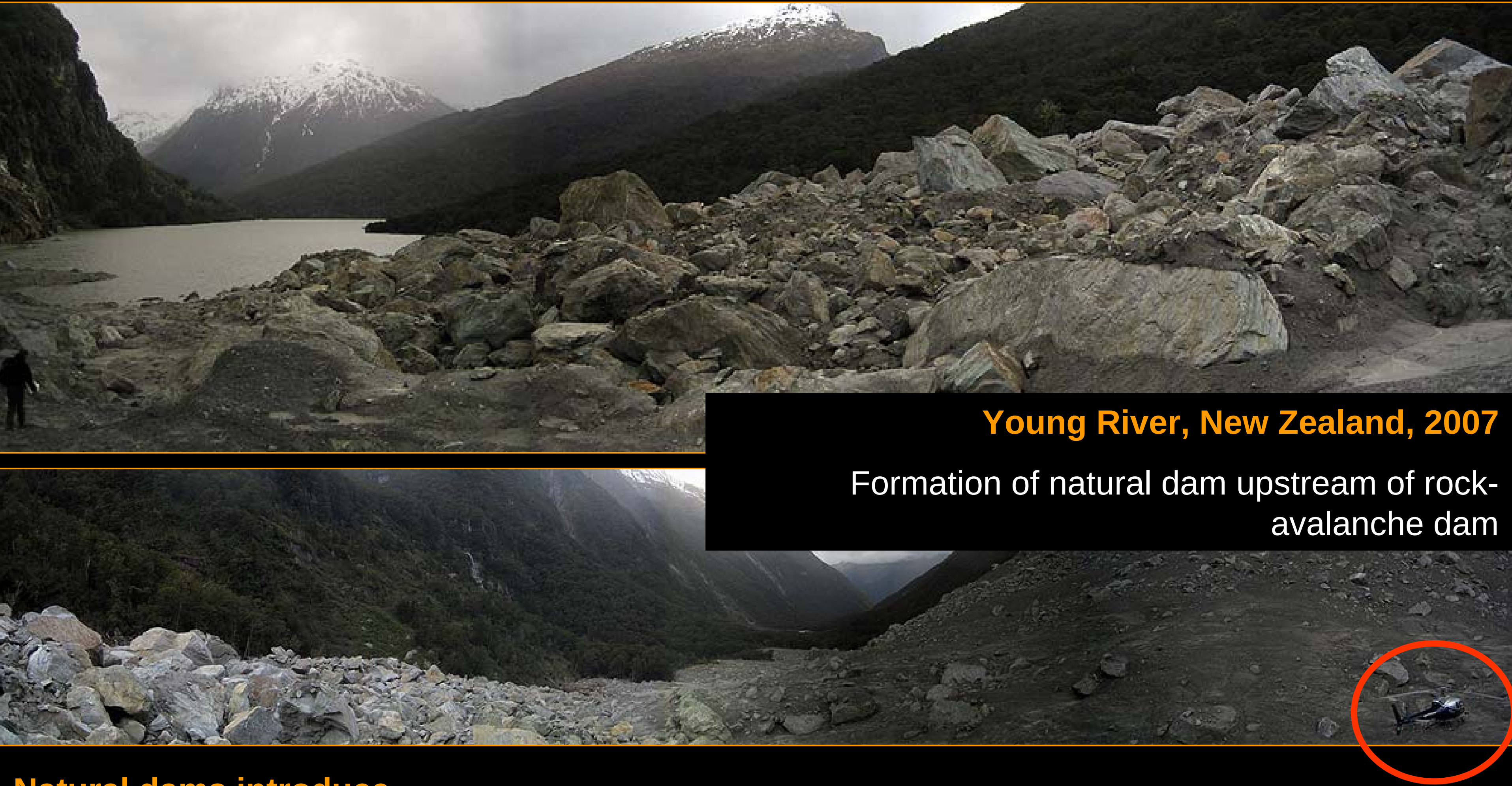
Test phase: Model sensitivity to

→ *Initial conditions (volume and pre-failure geometry)*

→ *Topography in runout zone*

→ *Representation of new parameters in deposit surface morphology*

Off-site hazards



Young River, New Zealand, 2007

Formation of natural dam upstream of rock-avalanche dam

Natural dams introduce

→ *Off-site hazards (inundation, catastrophic dam break and outburst flows)*

→ *Potential for a cascade of mainly hydrological hazards*

Conclusions

The use of scaling properties to quantify the hazard of catastrophic rock avalanches promises several prospects and pitfalls

- ***Area-frequency scaling of rock avalanches is well constrained by the power-law tail of an inverse gamma distribution. This trend is valid over >3 orders of magnitude, although exponents ($1.2 < \alpha_A < 2.0$) are lower than those for smaller landslides ($2.2 < \alpha_A < 2.4$).***

- ***This scaling relationship offers a regional-scale measure of quantifying to first order the hazard from rock avalanches, given that temporal constraints are tight enough.***

Conclusions

- ***Existing numerical models for simulating snow avalanches and debris flows show promising results for simulating rock avalanches. The use of these models appears to be limited more by the choice of appropriate initial conditions than parameter values.***
- ***Recommendations:***
  - ***Invest more resources to better constrain the initial conditions of large rock avalanches.***
  - ***Consider using a harmonized upscaling approach based on detailed case studies.***