Landslide flow history from long period seismic data

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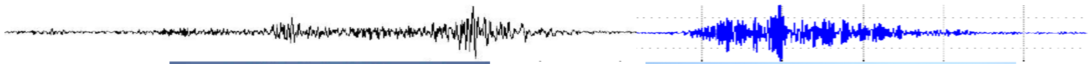
Listening to seismic signal from instabilities

Detection of instabilities and **prediction** of velocity and runout extent of landslides

Lack of field measurements of landslide dynamics

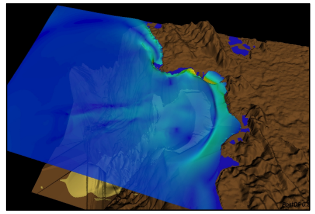
Analysis of the seismic signal generated by gravitational flows:



Antartica

La Réunion

El Salvador



Sumatra

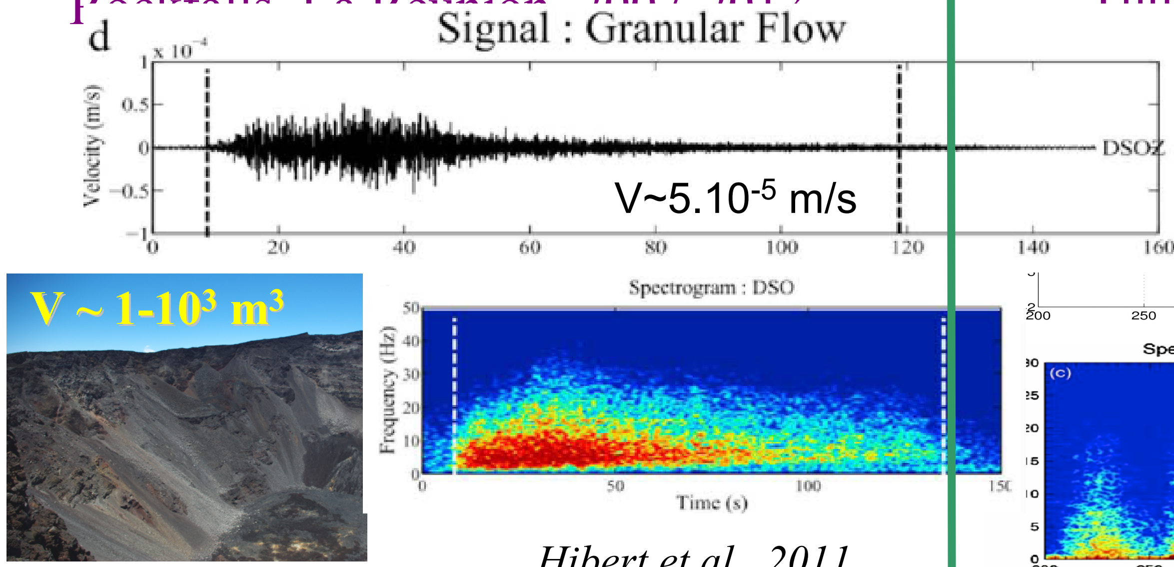
- Detection, monitoring
- Geometry and nature of the flow (mass, volume, fluid content …)
- Mechanical behavior (friction coefficient …)

? Respective role of topography, involved mass, flow dynamics, wave propagation ?

Kanamori and Given, 1982, Brodsky et al. 2003, La Rocca et al., 2004, Deparis et al. 2008, Favreau et al. 2010, Lin et al., 2010, Helmstetter and Garambois (2010), Hibert et al. 2011, Moretti et al. 2012, Yamada et al., 2013, Allstadt 2013, Ekström and Stark, 2013, Zhao et al., 2013…

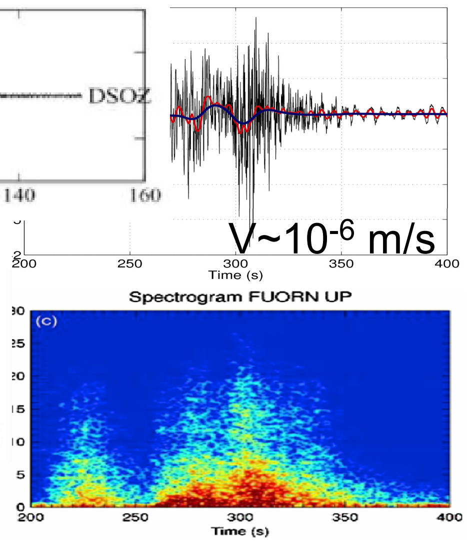
Landquakes : ≠ scales, physical processes, topography…

Rockfalls, La Réunion, 2007-2012



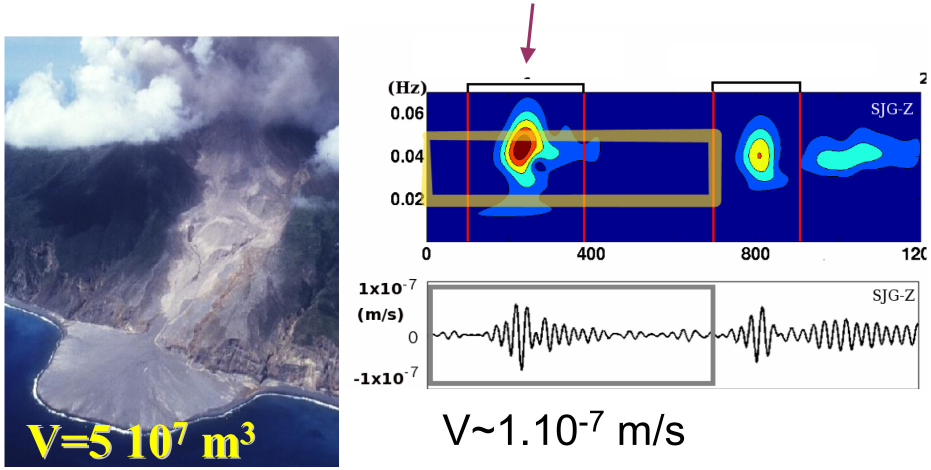
Hibert et al., 2011

Thurweiser landslide, Italie, 2004



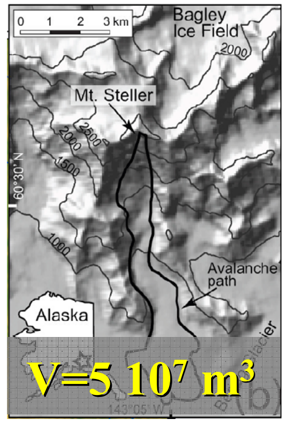
Favreau et al., 2010

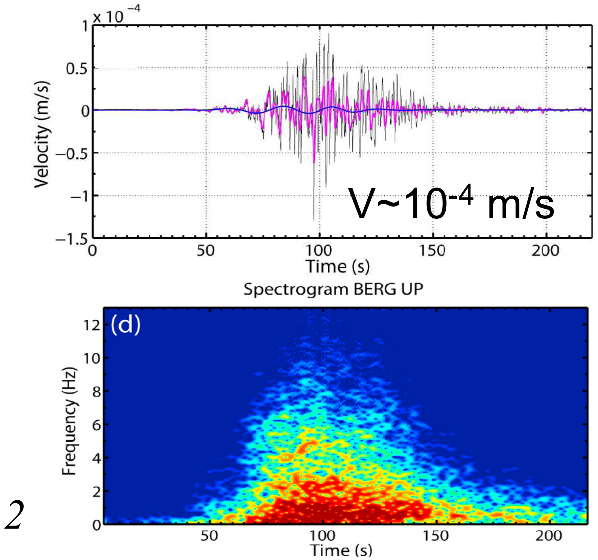
Debris avalanche, Montserrat, 1997



Zhao et al., 2013

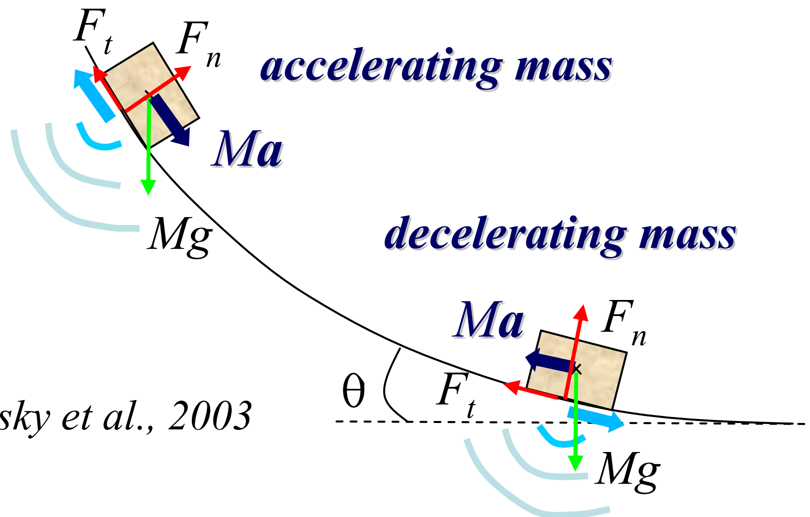
Mount Steller rock-ice avalanche, 2005





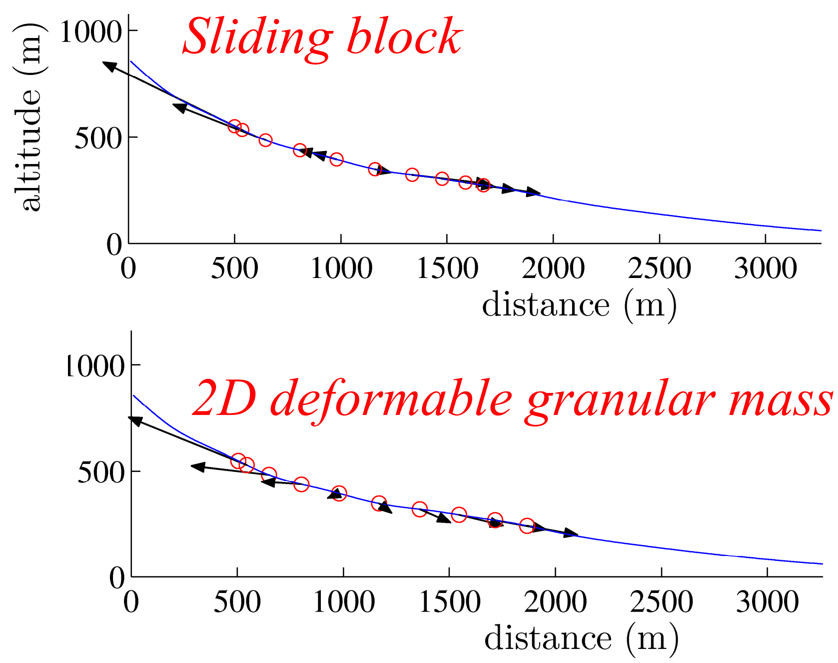
Moretti et al., 2012

Minimal force history model for landquakes



Brodsky et al., 2003

Montserrat topography profile

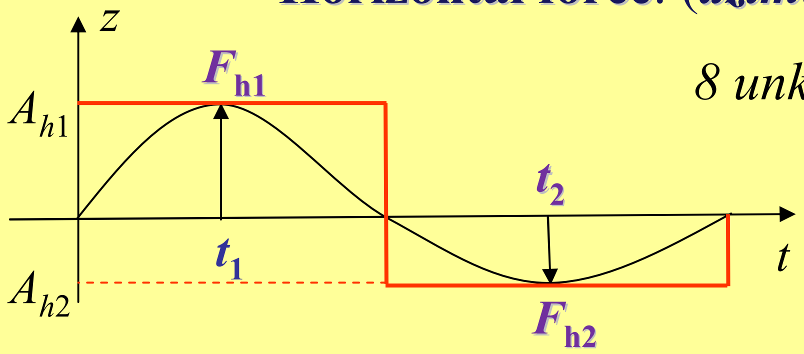


$$\begin{cases} \Delta F_h(t) = Mg\,[\mu \cos\theta(t) - \sin\theta(t)]\cos\theta(t) = -Ma_h(t) \\ \Delta F_v(t) = Mg\,[\mu \cos\theta(t) - \sin\theta(t)]\sin\theta(t) = -Ma_v(t) \end{cases}$$

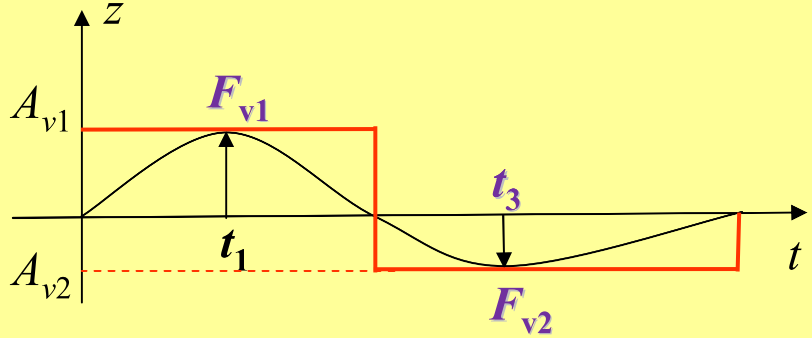
Moretti et al., 2012; Zhao et al., 2012

Horizontal force: ***(azimuth)***

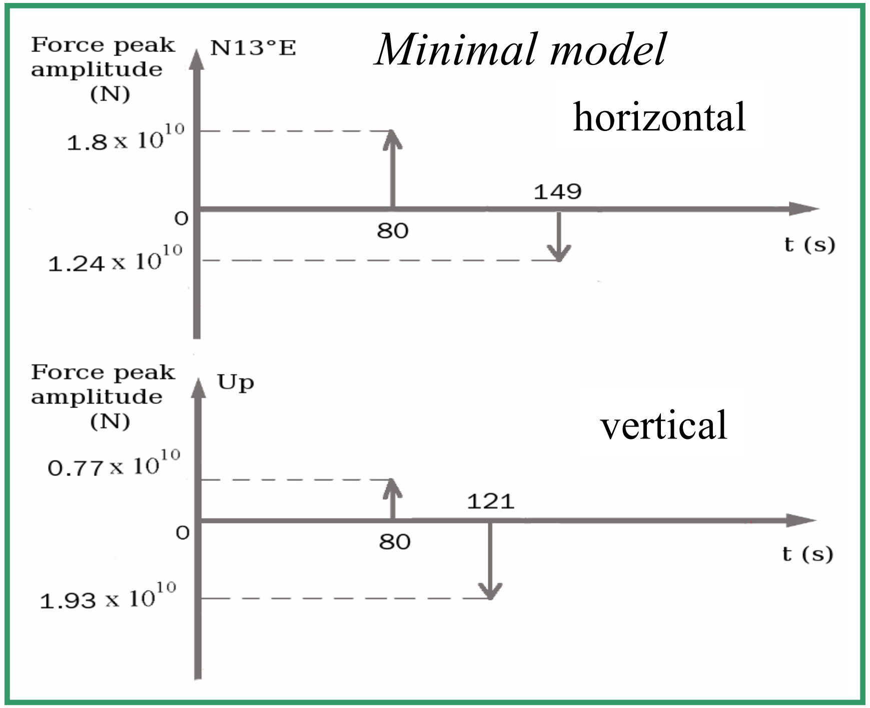
8 unknowns…



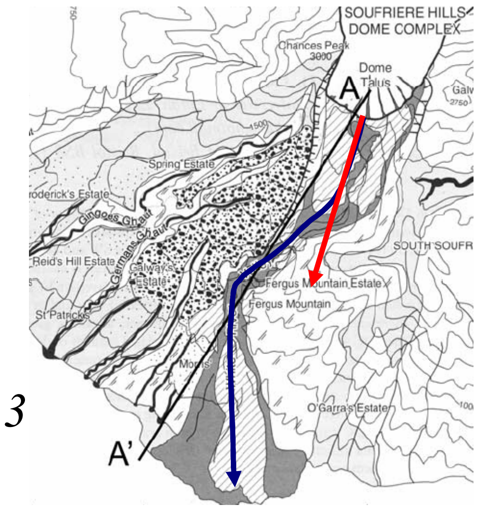
Vertical force:



Force history of the Montserrat landslide



M_{real}~8 10^{10} kg

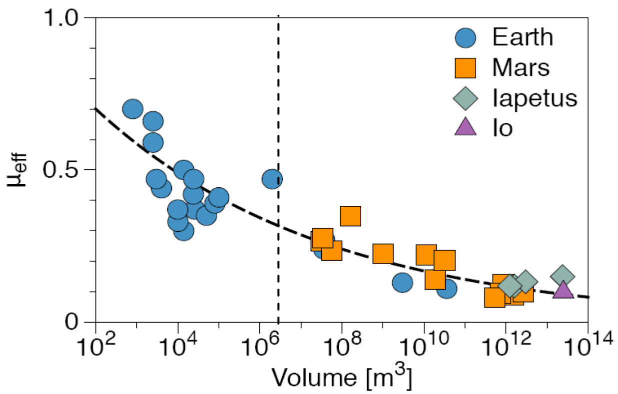


Zhao et al., 2013

- Azimuth of the force ➡ flow direction
- Ratio horizontal over vertical force: $\frac{\Delta F_z}{\Delta F_h}(t) = -\tan\theta(t)$ ➡ slope angle θ=23°
- Force amplitude ➡ mass $M = \left|\frac{F_h}{g(\mu\cos\theta - \sin\theta)\cos\theta}\right|$

with μ=0.27, we get $M = 0.77 F_h$ so that M ~2 10^{10} kg

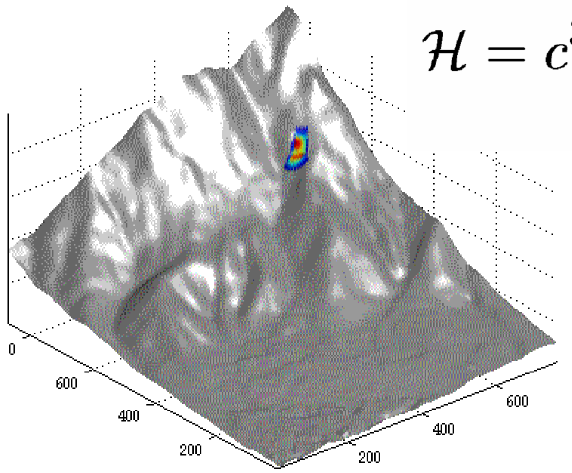
(*Ekström and Stark, 2013:* M=0.54 F_h)



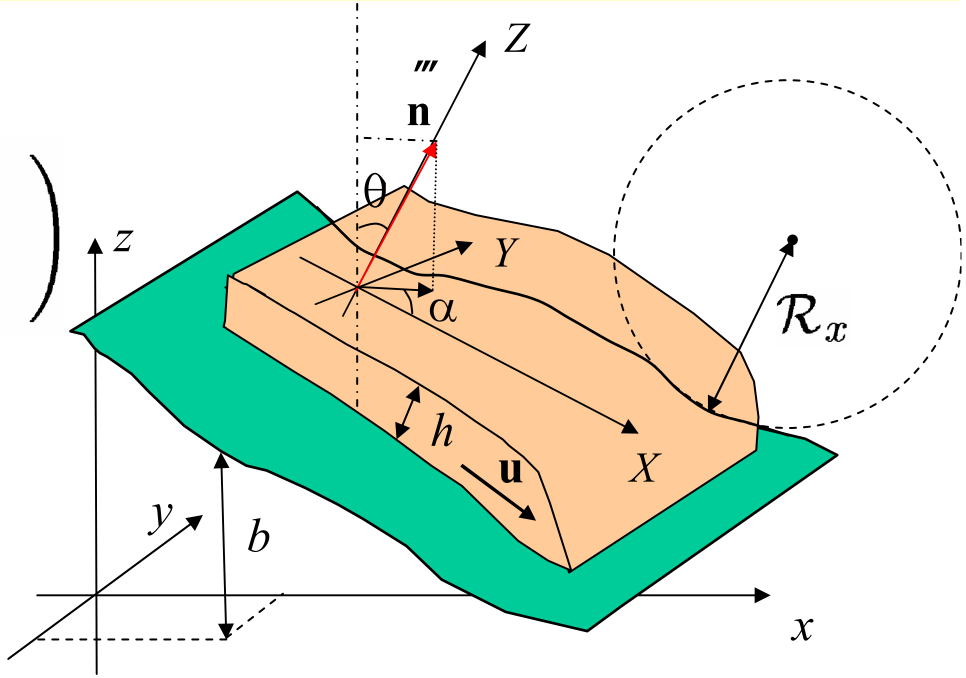
Lucas, Mangeney, Ampuero, 2013

Thin layer landslide model on 3D arbitrary topography

- **Curvature tensor of the topography**

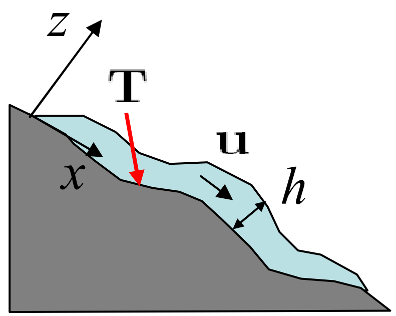


$$\mathcal{H} = c^3 \begin{pmatrix} \frac{\partial^2 b}{\partial x^2} & \frac{\partial^2 b}{\partial x \partial y} \\ \frac{\partial^2 b}{\partial x \partial y} & \frac{\partial^2 b}{\partial y^2} \end{pmatrix}$$



Bouchut et al., 2003; Bouchut and Westdickenberg, 2004; Mangeney et al., 2007

Time-dependent basal stress field applied on top of the terrain



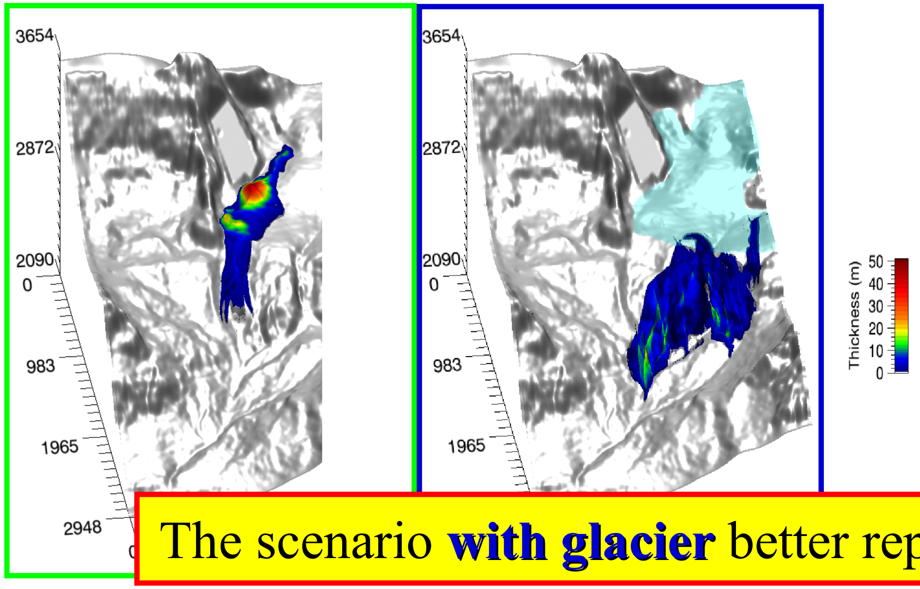
$$\mathbf{T} = \rho g h \left(\cos\theta + \frac{\mathbf{u}_h^t \mathcal{H} \mathbf{u}_h}{g \cos^2\theta} \right) \left(\mu \frac{u_X}{\|\mathbf{u}\|}, \mu \frac{u_Y}{\|\mathbf{u}\|}, -1 \right)$$

Curvature effects (centrifugal forces)

Simulation of the generated seismic waves

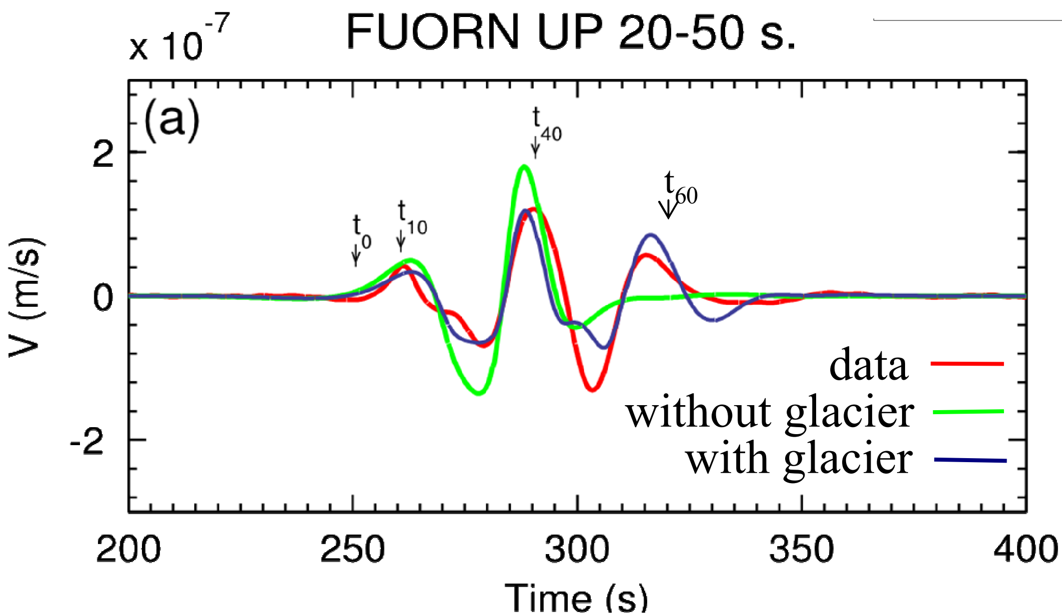
Thurweiser landslide $V \sim 2\ 10^5\ m^3$

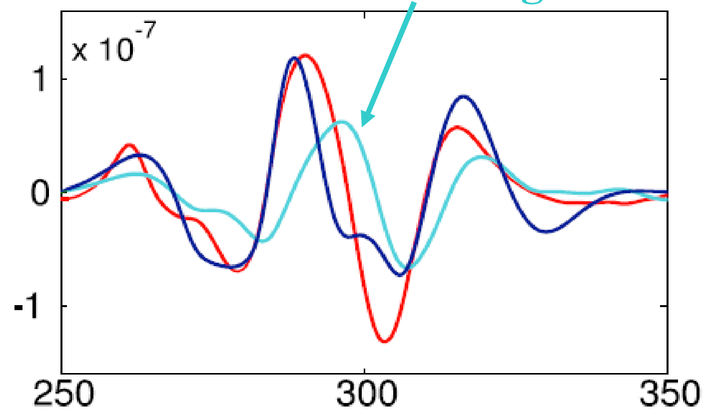
$t \approx 40$ s



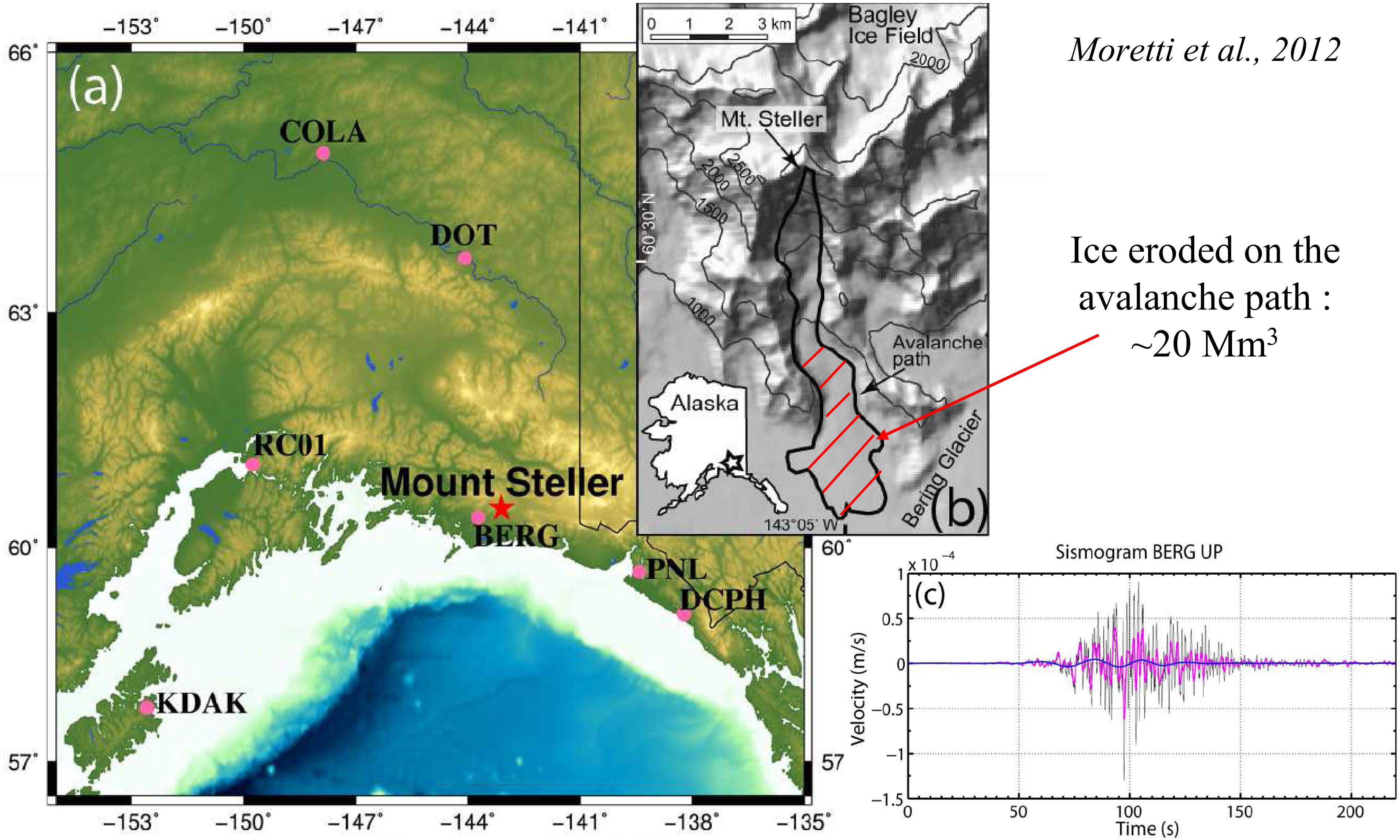
$t \approx 60$ s

The scenario with glacier better reproduces the seismc waveform





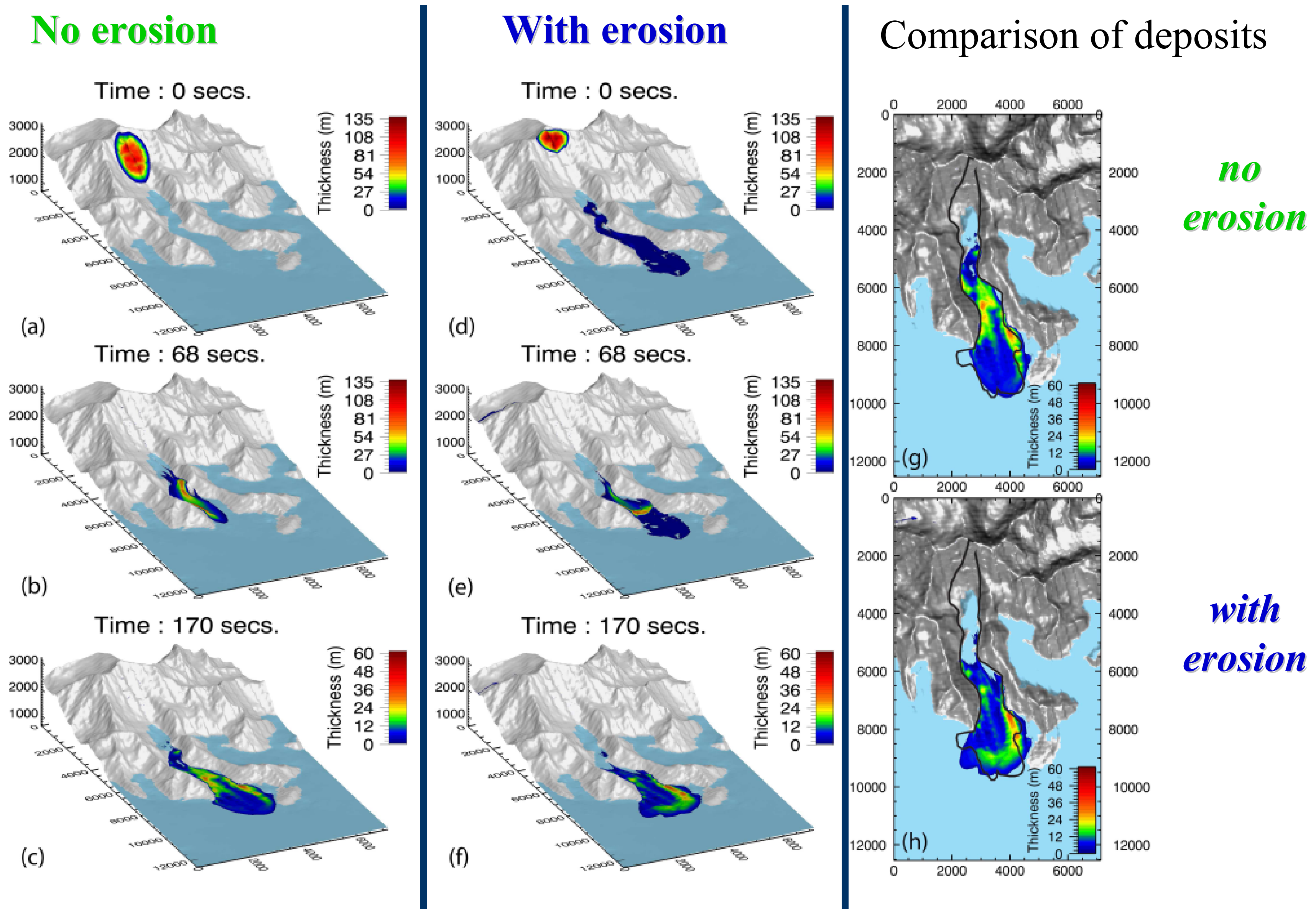
Mt-Steller rock-ice avalanche : 50 Mm^3



Moretti et al., 2012

Ice eroded on the avalanche path : ~20 Mm^3

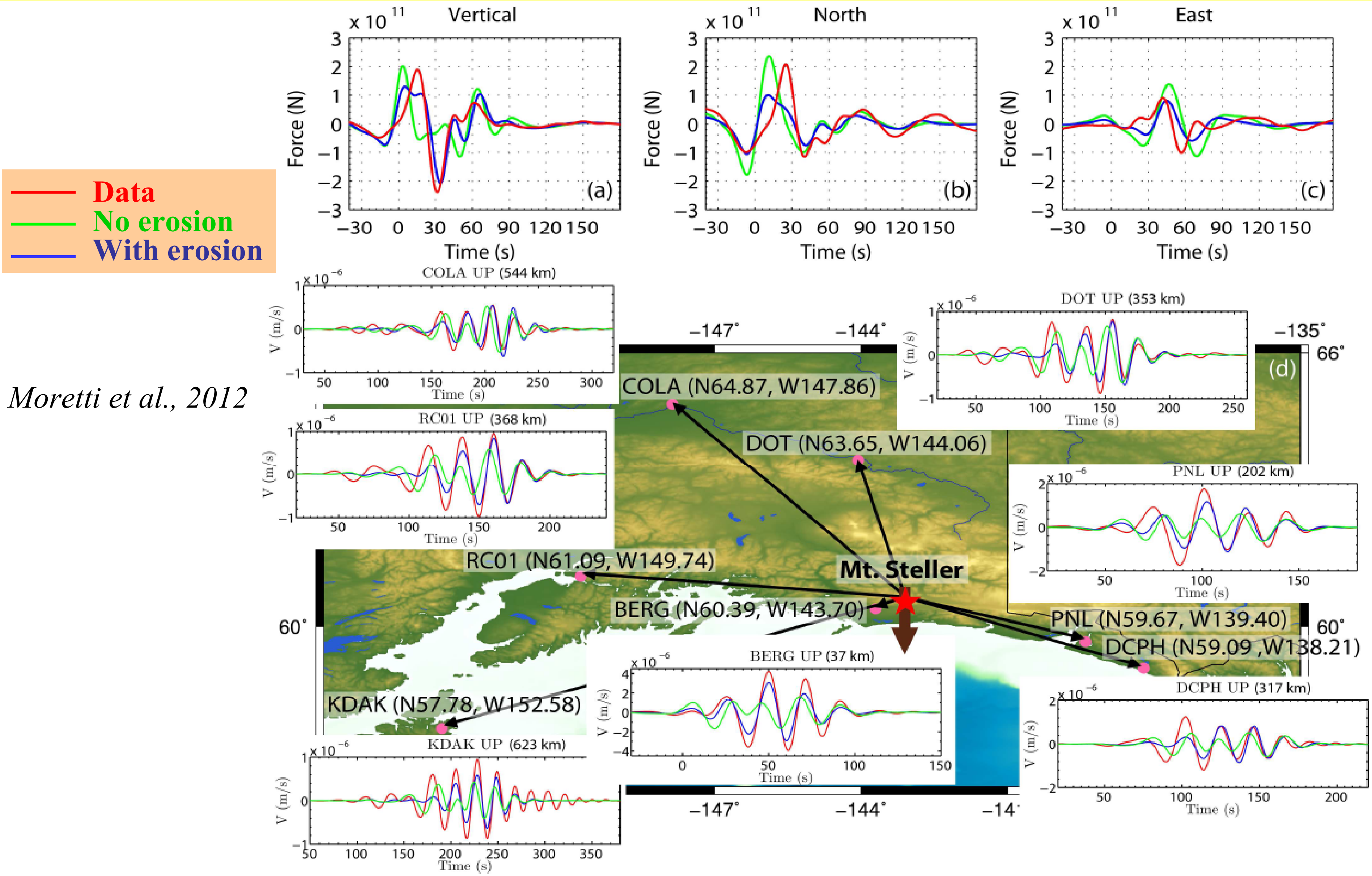
Mt-Steller : Scenarios with and without erosion



Same area of the deposit !!

Moretti et al., 2012

Mt-Steller : force history and generated waves



Moretti et al., 2012

Taking into account **erosion is necessary to reproduce the dynamics !**

Conclusion

- Force obtained by inversion of seismic data → first order flow direction, slope angle, mass, center of mass trajectory

- Using both seismic data and detailed landslide models → **discriminate** between alternative scenarios for **flow dynamics,** estimate the **basal friction** and **physical processes during the flow**

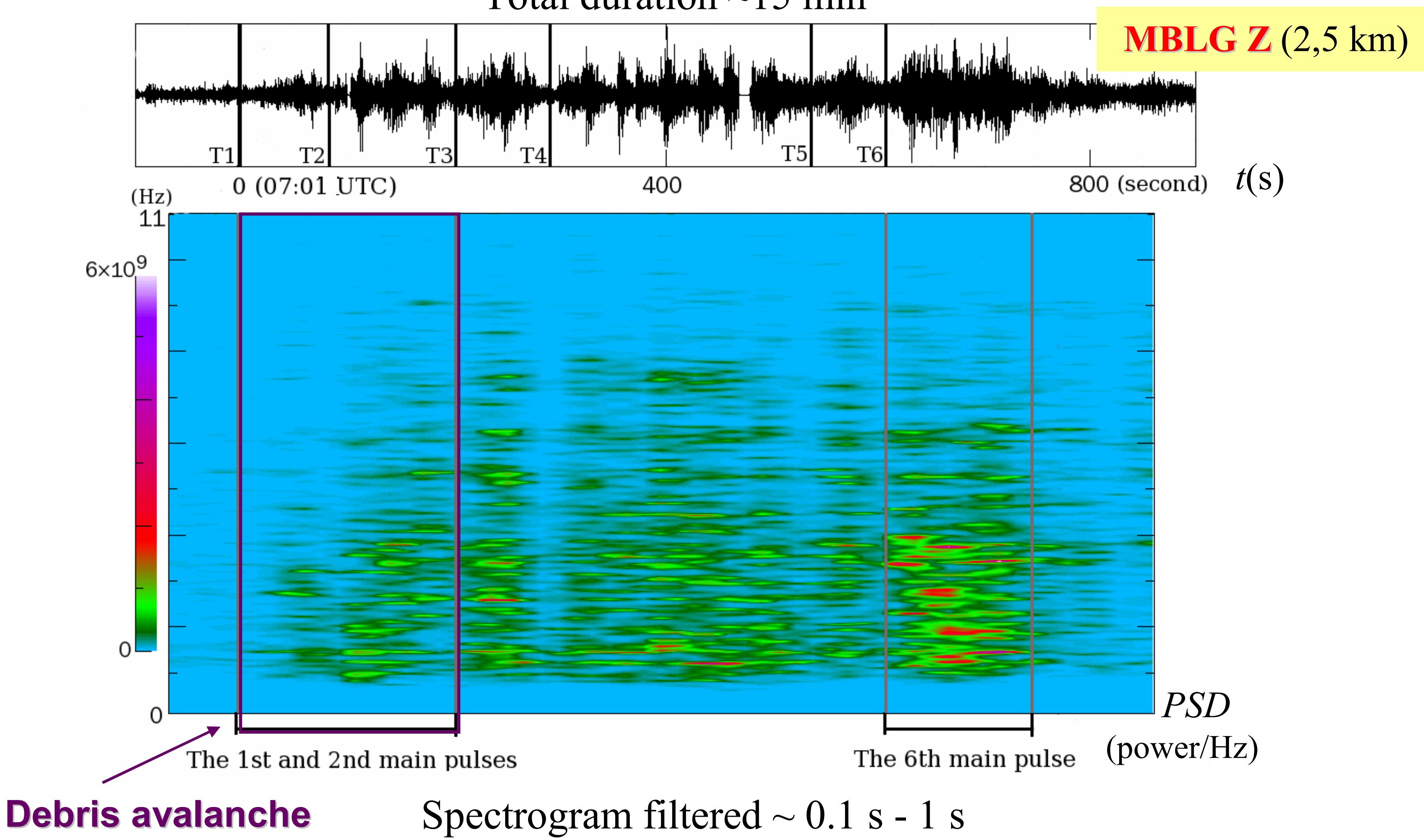
To do …

- Systematic study of the **influence of the volume, topography, friction coefficient** on the simulated seismic signal (i. e. inverted force)

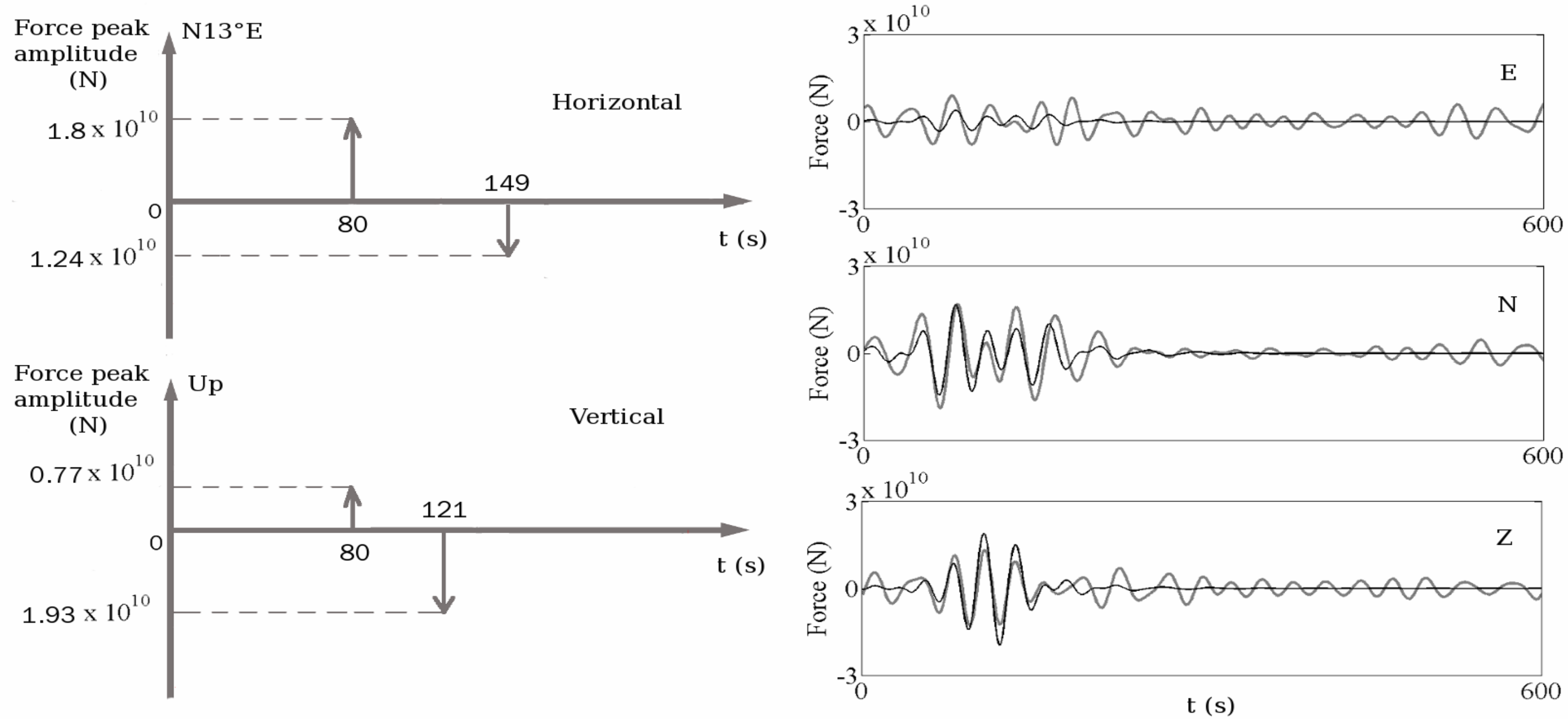
- **Coupling** landslide and wave propagation **models**

Seismic signal associated to the eruptive events

Local short period seismic stations



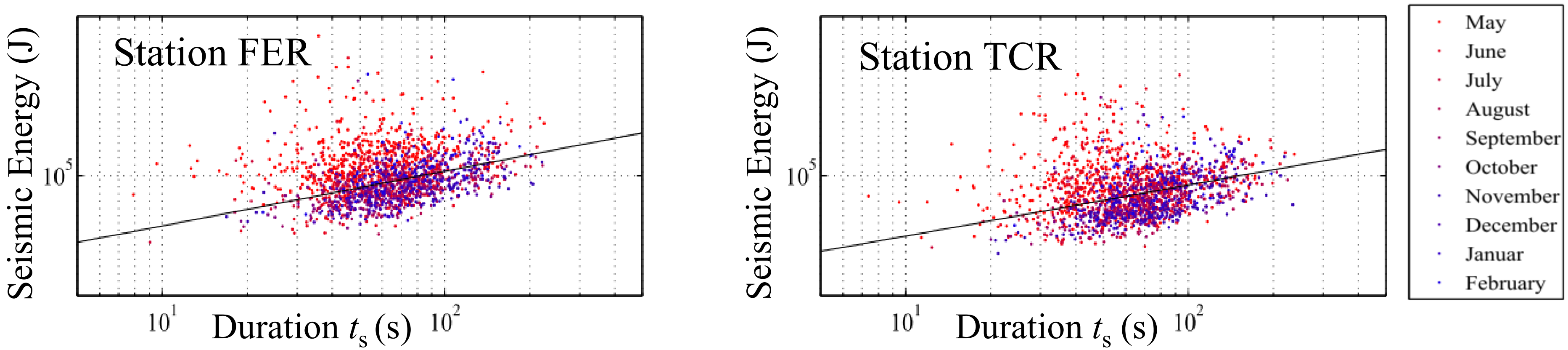
Spectrogram filtered ~ 0.1 s - 1 s



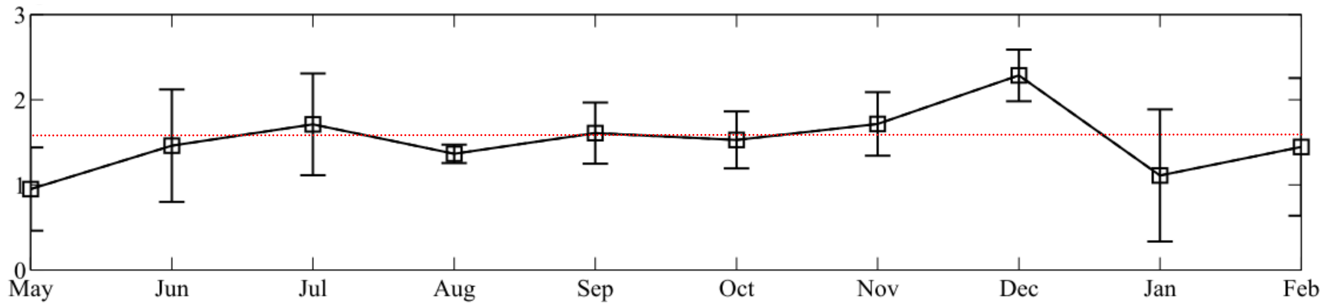
Force peak amplitude (N)
N13°E
Horizontal
1.8 x 10^10
0
80
149
1.24 x 10^10
t (s)
Force peak amplitude (N)
Up
Vertical
0.77 x 10^10
0
80
121
1.93 x 10^10
t (s)
3 x 10^10
Force (N)
0
-3
E
0
600
3 x 10^10
Force (N)
0
-3
N
0
600
3 x 10^10
Force (N)
0
-3
Z
0
600
t (s)

Scaling laws : seismic energy versus duration

Seismic energy : $$Es = \int_{t_1}^{t_2} 2\pi r \rho h c \, u_{env}(t)^2 e^{\alpha r} dt$$ *Vilajosana et al., 2008*



Regression lines and corresponding coefficients computed for each month

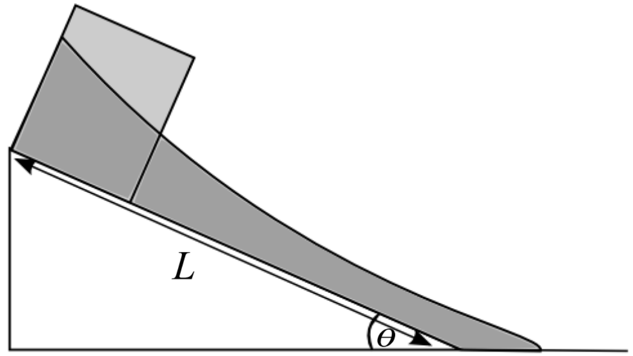


Scaling law between **seismic energy** and **duration** :

$E_s \; \alpha \; t_s^{\,\beta s}$ with $\beta_s \approx 1.56$

Scaling laws : potential energy versus flow duration

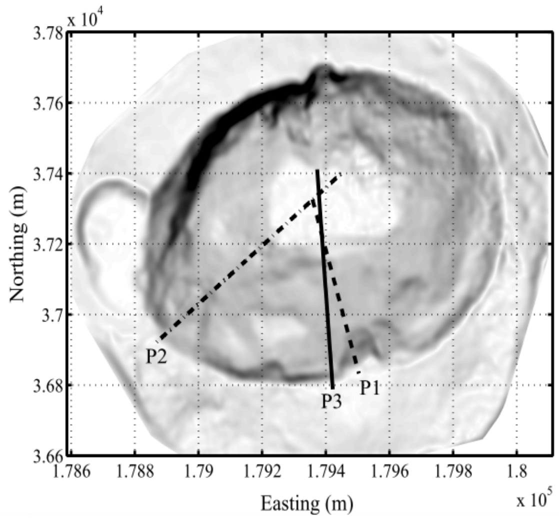
- Analytical development for a rectangular mass on a flat slope *Mangeney et al.*, 2010

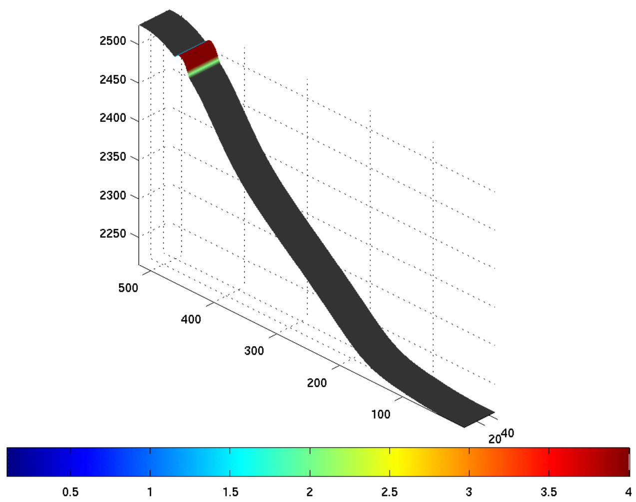


$$\Delta E_p \propto t_f^{\beta_a}$$

with $\beta_a = 2$

- Numerical simulation of granular flows over real topography using the code SHALTOP *Mangeney et al.*, 2007





$$\Delta E_p \propto t_f^{\beta_p}$$

with $\beta_p = 1.65$

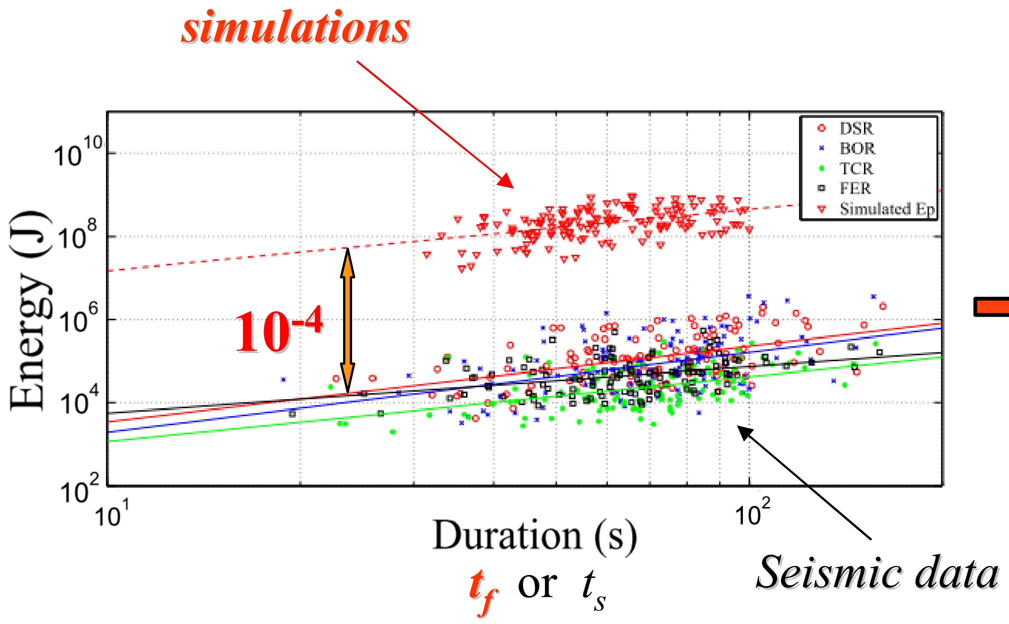
Topography Effects

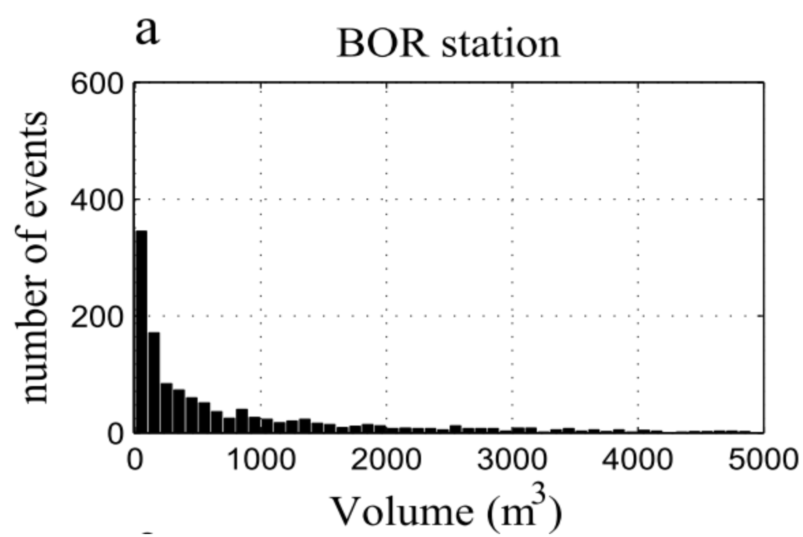
Rugosity ↗ ⇒ β_p ↘

From seismic energy to rockfall volume

- Scaling laws Energy/Duration : $E_{seismic} \propto t_s^{\beta}$ and $\Delta E_{potential} \propto t_f^{\beta}$

$R_{s/p} = E_s / \Delta E_p \sim 10^{-4}$ → **Volume** $V = \frac{3E_s}{R_{s/p} \cdot \rho g L(\tan\alpha\cos\theta - \sin\theta)}$

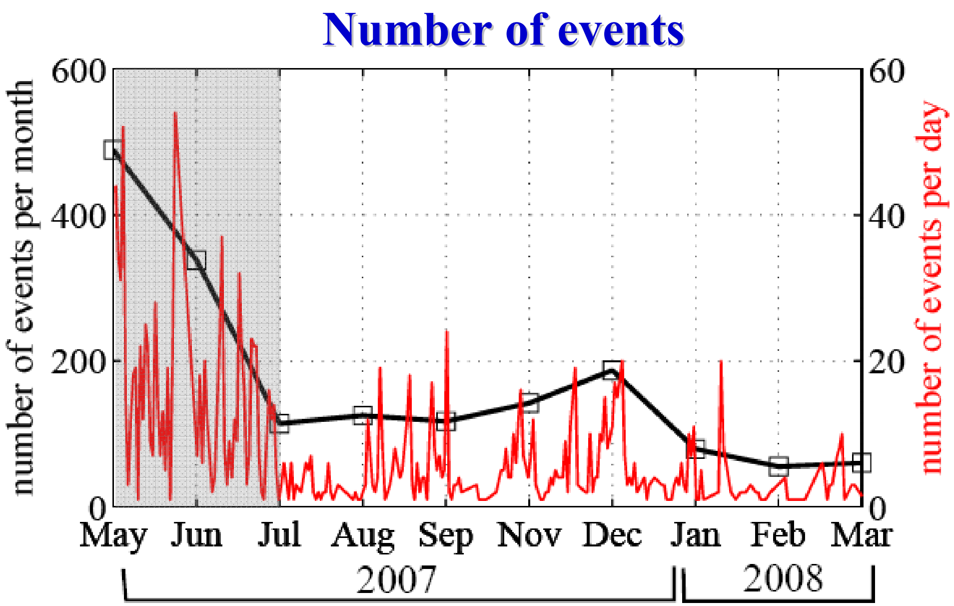


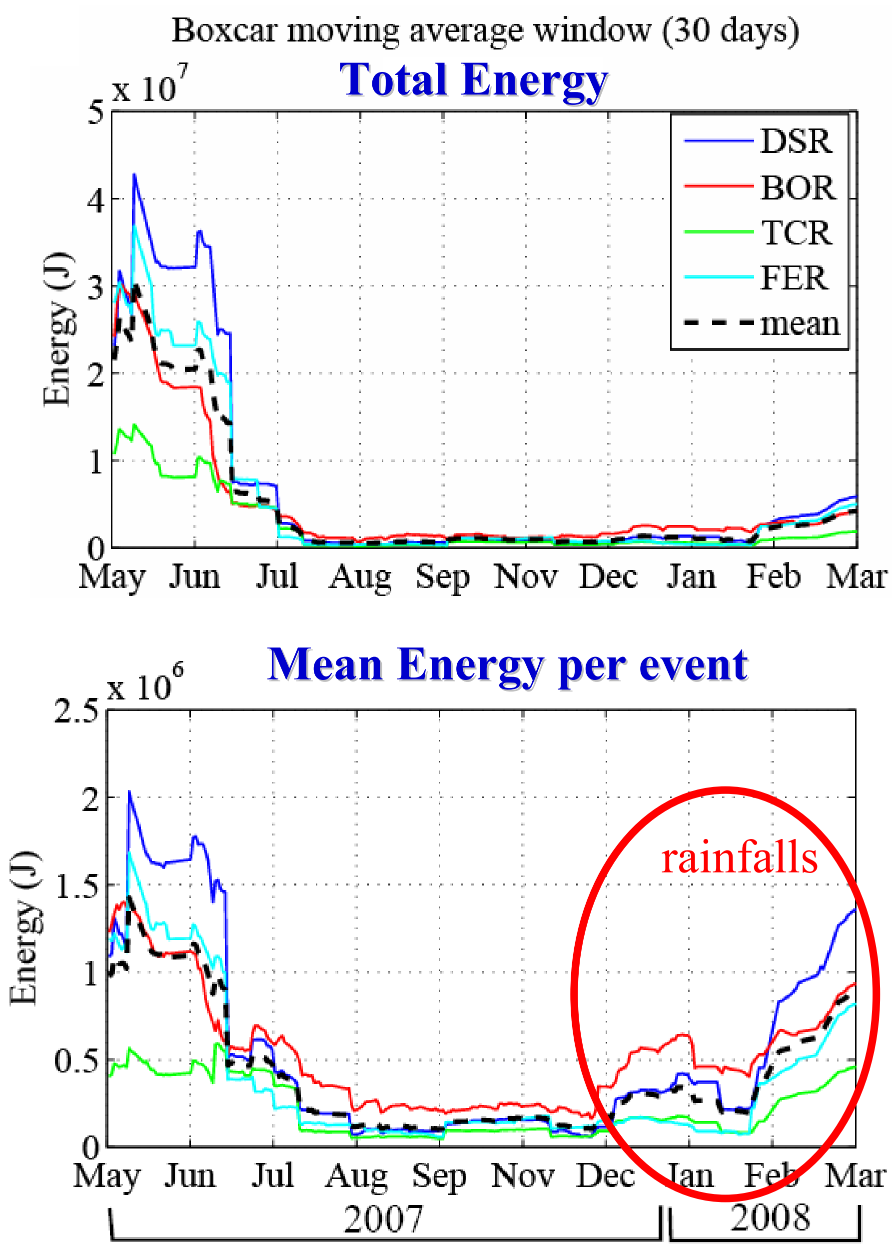


- Cumulative volume from May 2007 to February 2008 : $V = 1.85\ 10^6\ m^3$

Hibert et al., 2011

Monitoring rockfall activity in Crater Dolomieu





- Relaxation time of the crater walls :

~ 2 months

- Identification of a stable rockfall activity
- Rockfall size ↗ during rainfalls

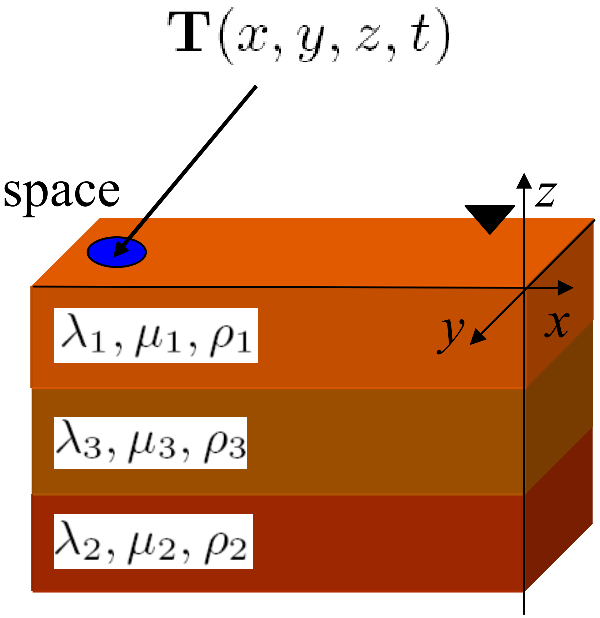
Hibert et al., 2011

Numerical simulation of seismic waves

Fast Green's functions calculation with a discrete frequency-wavenumber method

(*Kennet / Bouchon*)

- Spatio-temporal distribution of stress field at the surface
- Topographic and complex media effects are neglected
- Elastodynamic equations in an horizontally stratified half-space
- Continuity conditions at each interface
- Vanishing conditions at $z = -\infty$



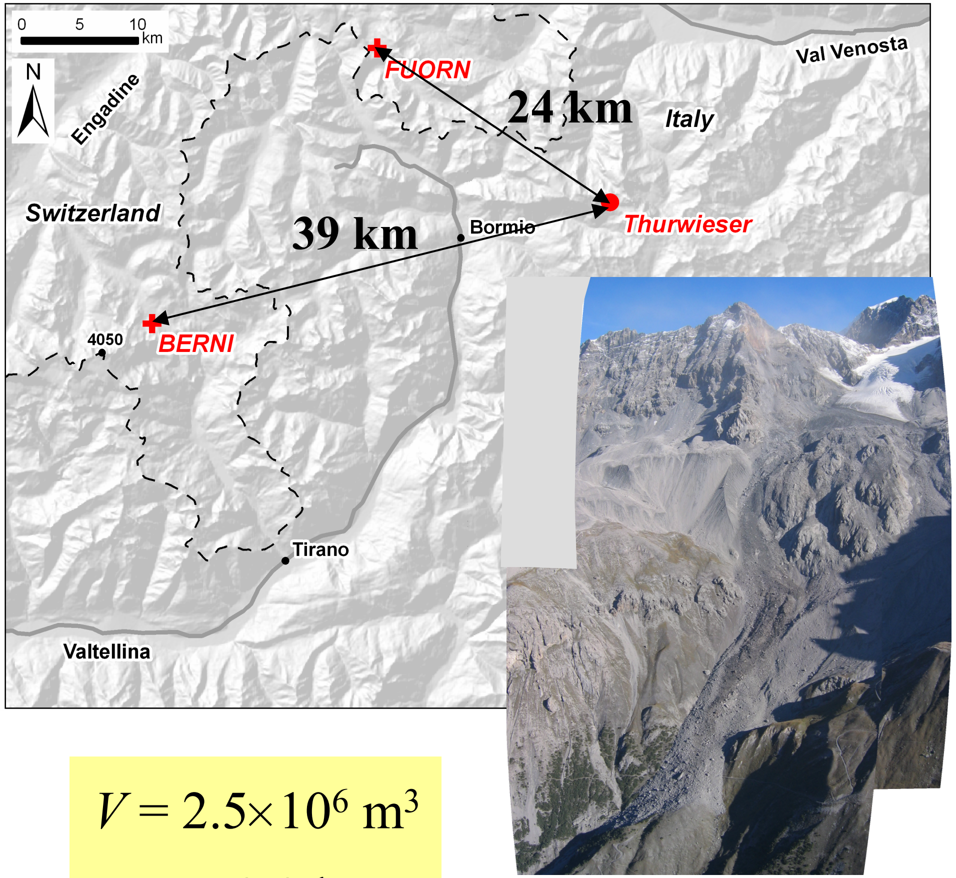
$$u_{ij}(t, r, \theta) = \sum_{n=0}^{2} R_{ijn}(\theta) \int_{\epsilon - i\infty}^{\epsilon + i\infty} dp\, e^{pt} \int_0^{\infty} dk\, T_n(p, k) J_n(kr) k$$

$R_{ijn}(\theta)$ radiation pattern

$T_n(p, k)$ frequency-wavenumber response

Simulation of the Thurweiser landslide

Thurweiser rock avalanche, Italie
September 2004

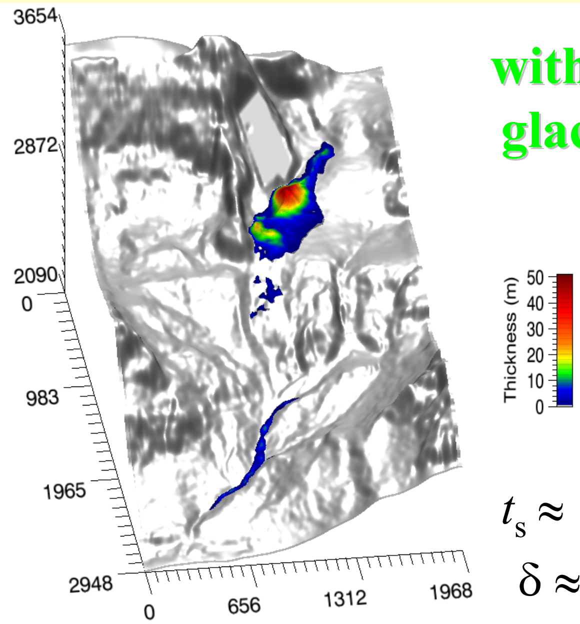


$V = 2.5\times10^6\ m^3$

$R_f = 2.9$ km

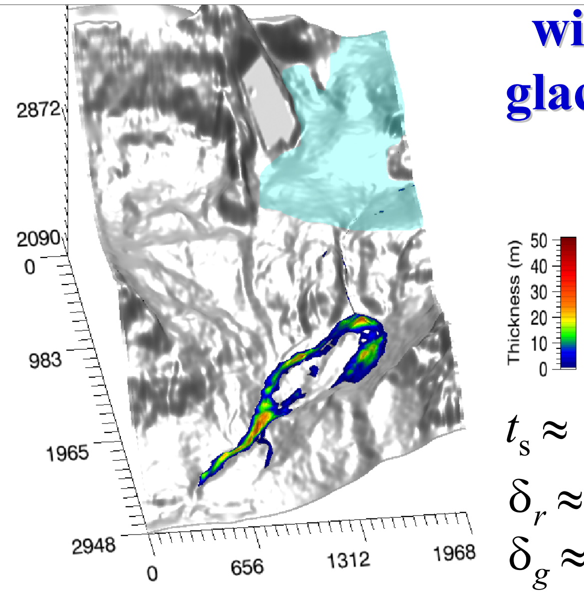
$T_f \approx 90$ s

Sosio et al., 2008, Favreau et al., 2010



$t_s \approx 100$ s

$\delta \approx 23°$

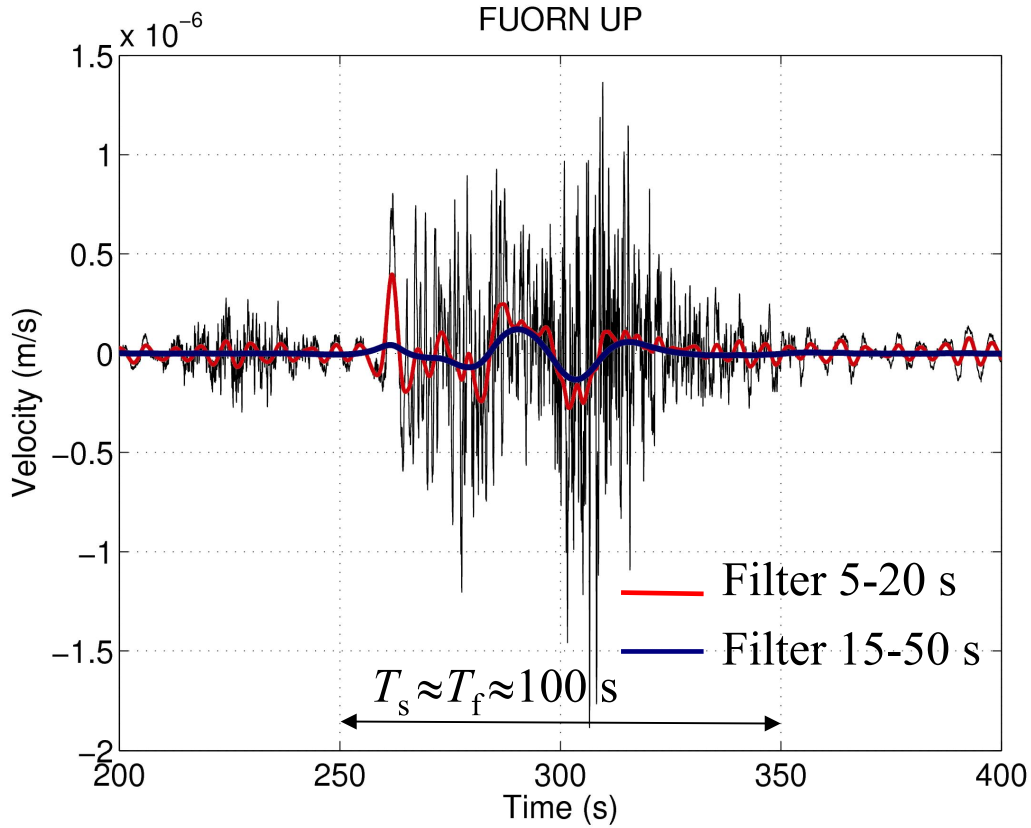


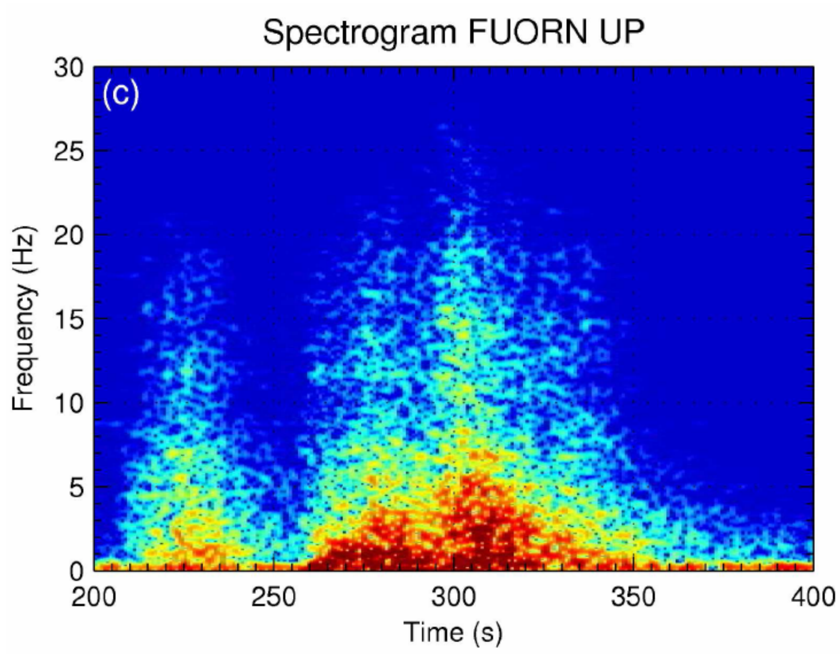
$t_s \approx 100$ s

$\delta_r \approx 26°$

$\delta_g \approx 6°$

STS2 Data





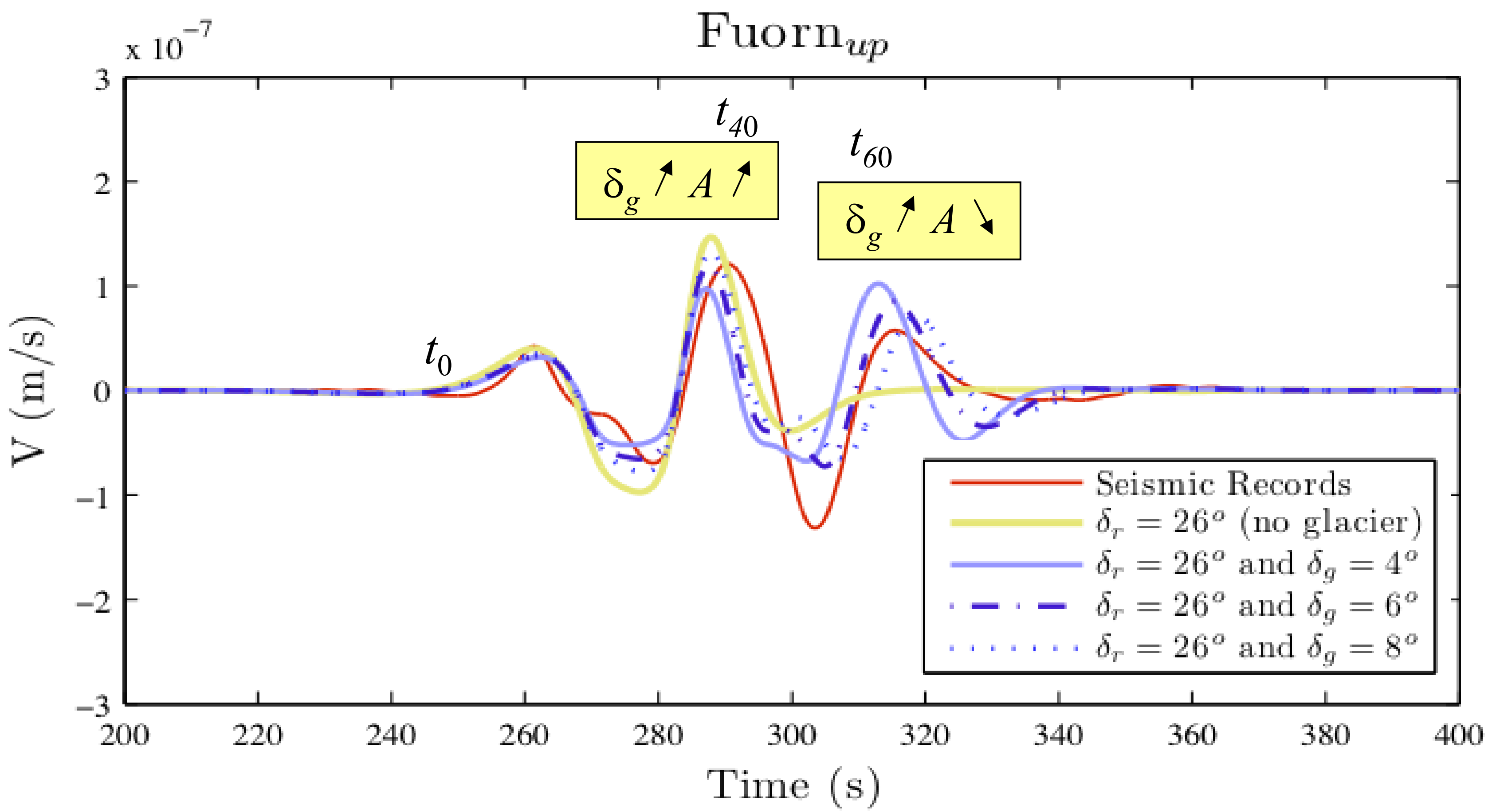
$0.01 \text{ Hz} < f < 15 \text{ Hz}$

$(L_{\text{source-station}} = 24 \text{ km})$

For $T > 15$ s, $\lambda = cT \approx 45$ km

Topographic and complex media effects on wave propagation are expected to be **small**

Friction coefficient and simulated seismic waves



Comparison between simulated and recorded seismic signal

⬇

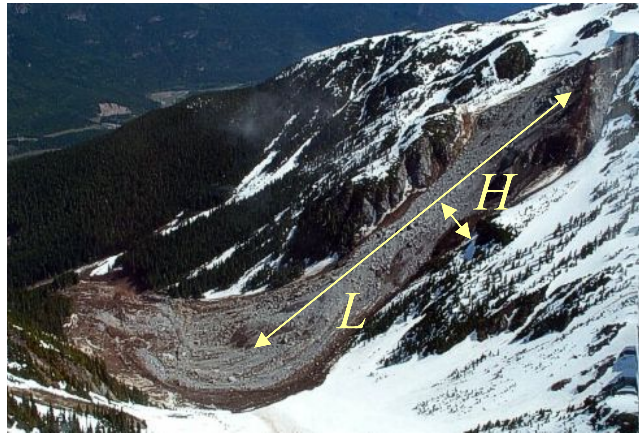
Calibration of the friction coefficients

Thin Layer Approximation on 2D topography

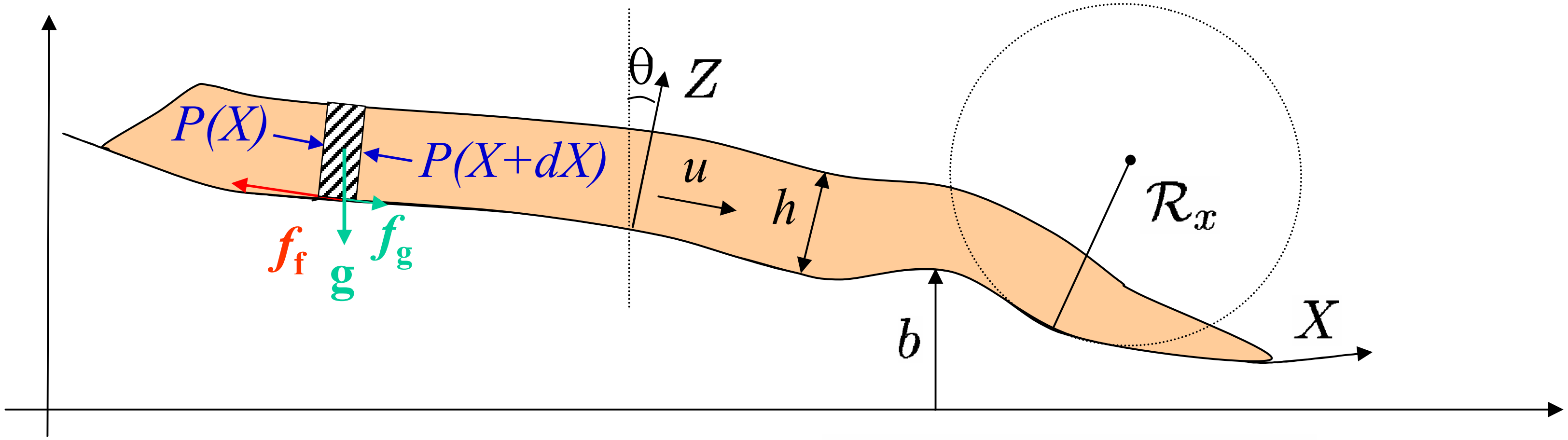
- Flow on **complex natural topography**

$\Downarrow$

high computational cost $\Rightarrow$ small **Aspect ratio** $a = \frac{H}{L} << 1$



- Depth-averaged thin layer model model



$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial X} = \gamma_X g - K\frac{\partial}{\partial X}(g\gamma_Z h) - \mu\left(g\gamma_Z + \frac{u^2}{\mathcal{R}_x}\right)\frac{u}{|u|}$$

inertia **gravity** **pressure gradient** **Coulomb friction :** $\mu = \tan\delta$

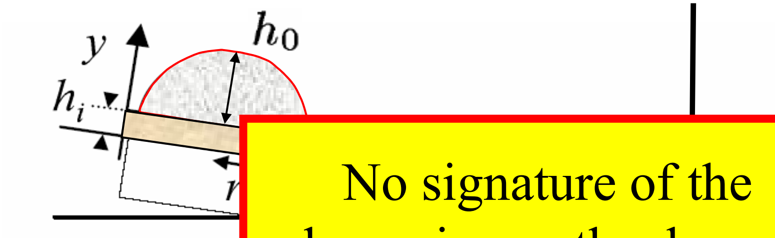
$\gamma_X = \sin\theta, \ \gamma_Z = \cos\theta$

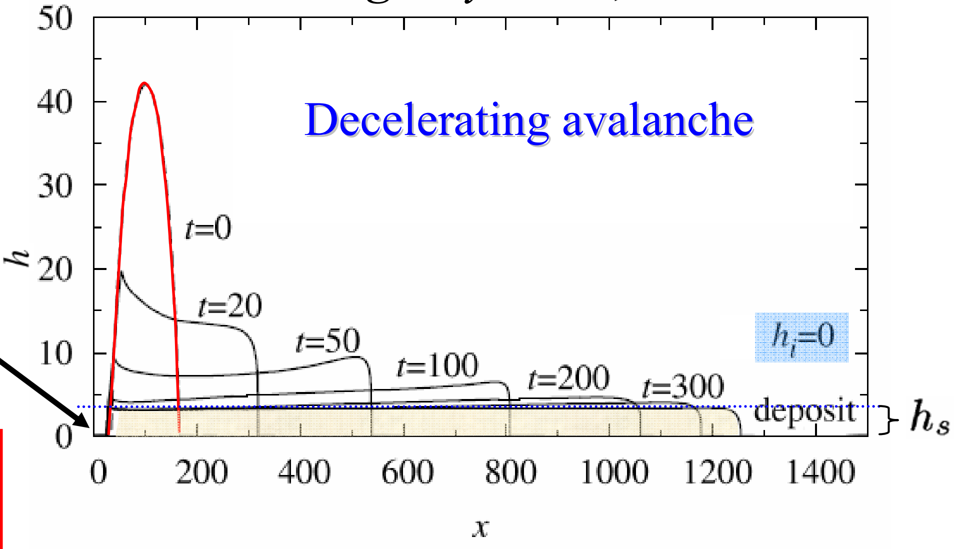
Savage and Hutter, 1989

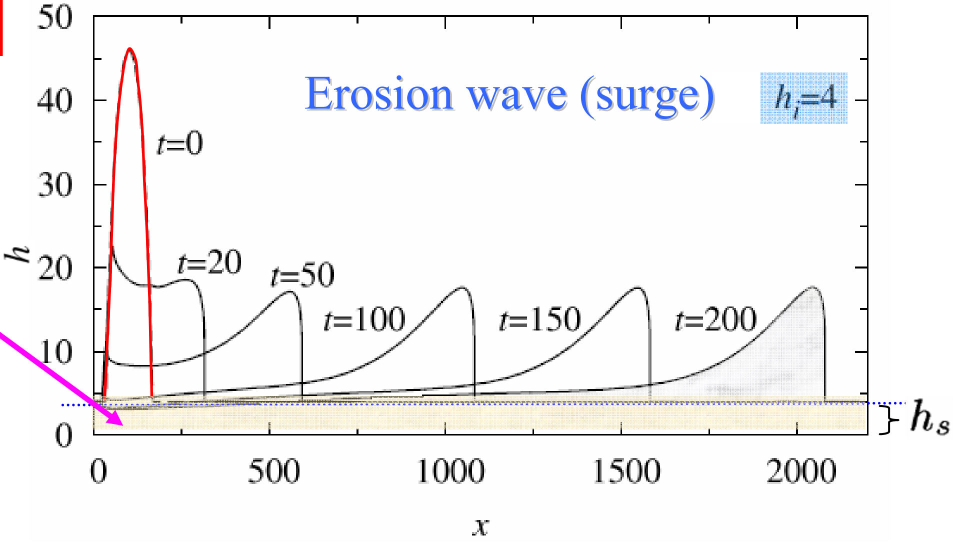
Erosion of a granular layer

IPGP and **INLS**, **UC San Diego**

Mangeney et al., 2007







rigid bed

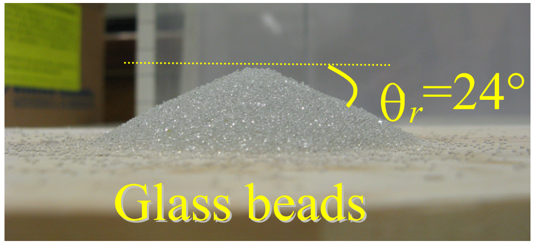
erodible bed

No signature of the dynamics on the deposit

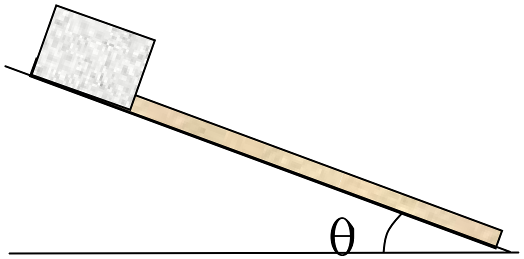
In agreement with experiments of
Pouliquen and Forterre, 2002,
Aranson et al., 2006,
Borzsönskyi et al., 2008


Thank you !

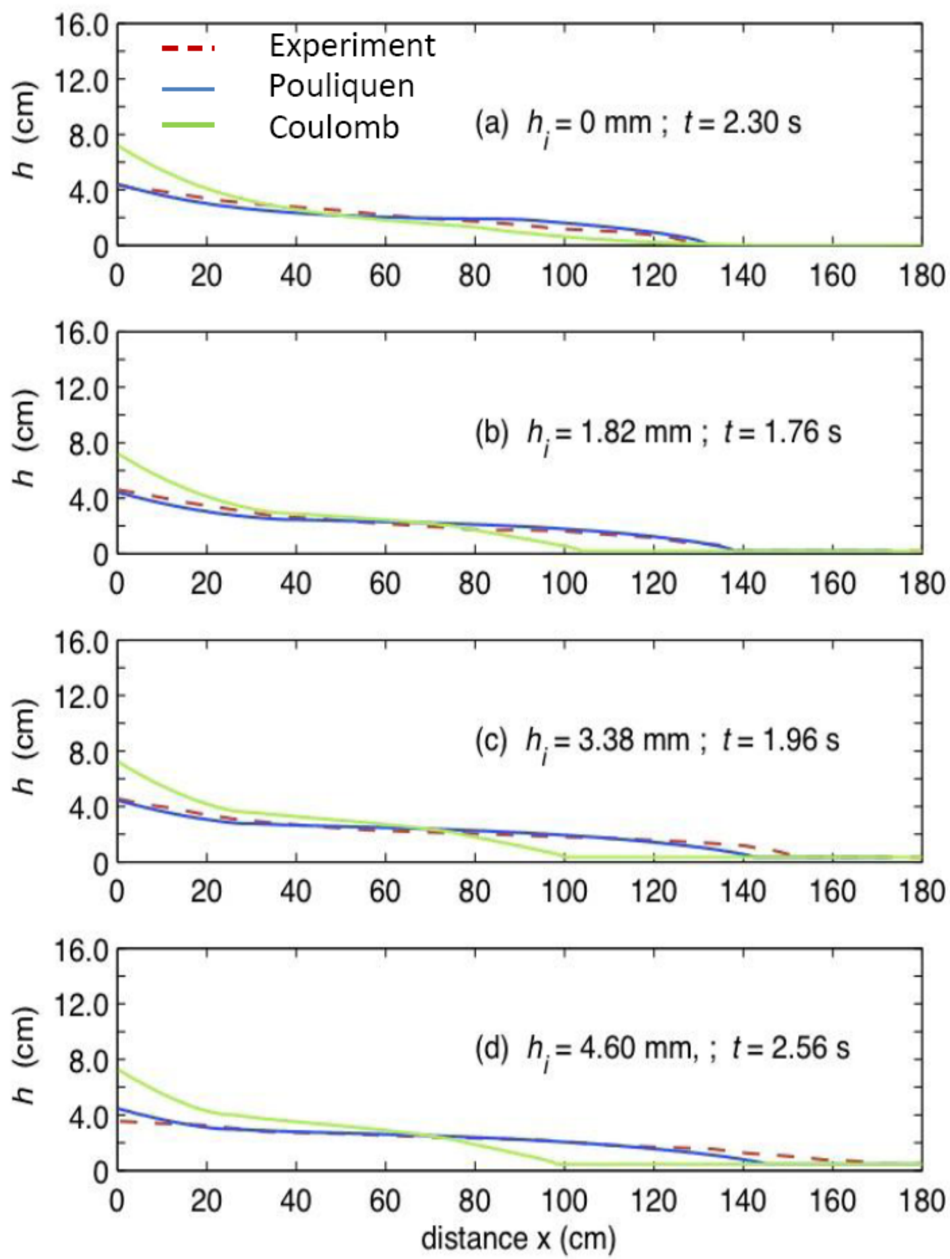
Numerical modeling of erosion in granular flows



$a = 0,7$

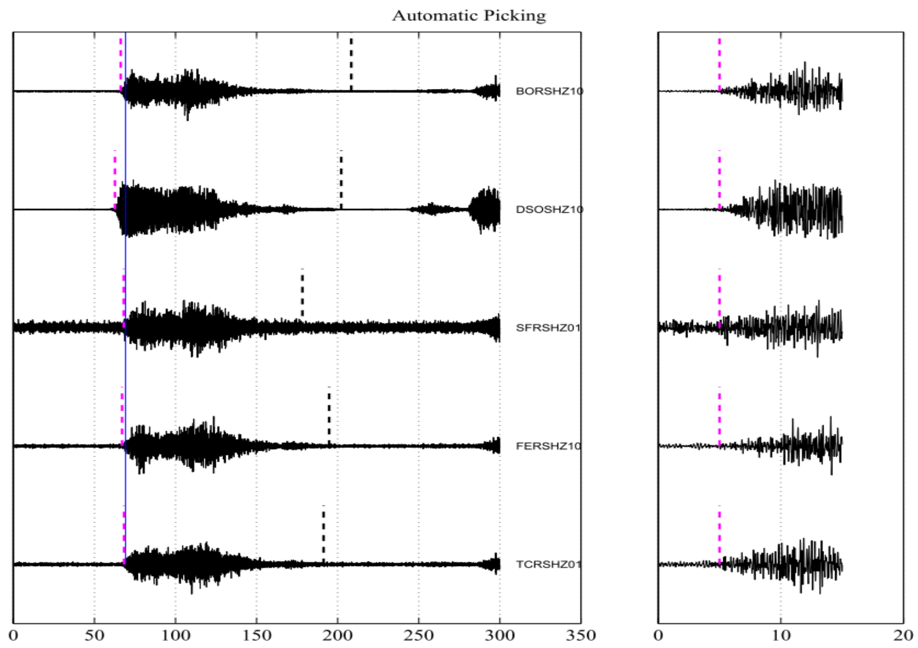


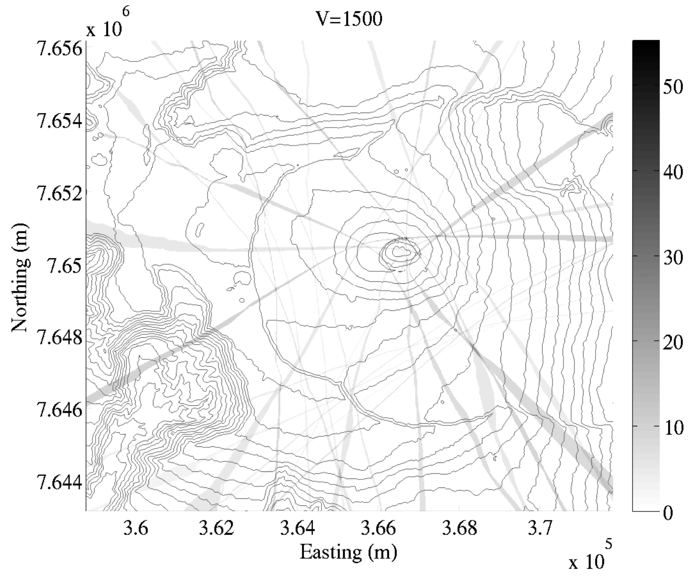
Mangeney et al., 2010

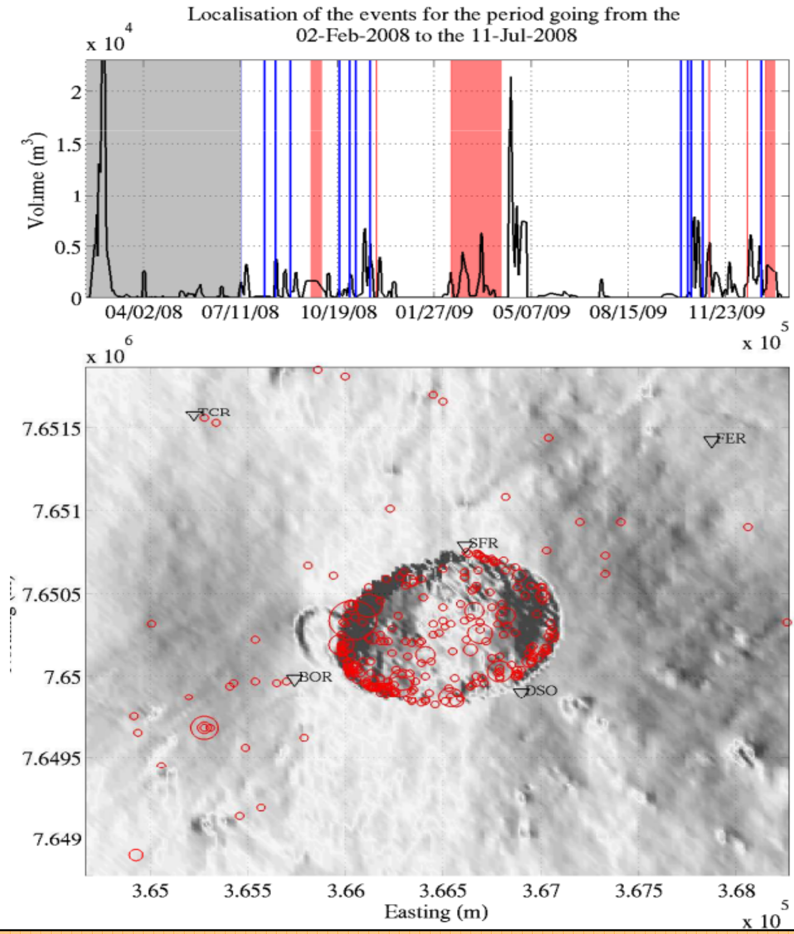


III – Picking automatique des effondrements et localisation

Picking automatique basé sur le calcul du Kurtosis de chaque trace



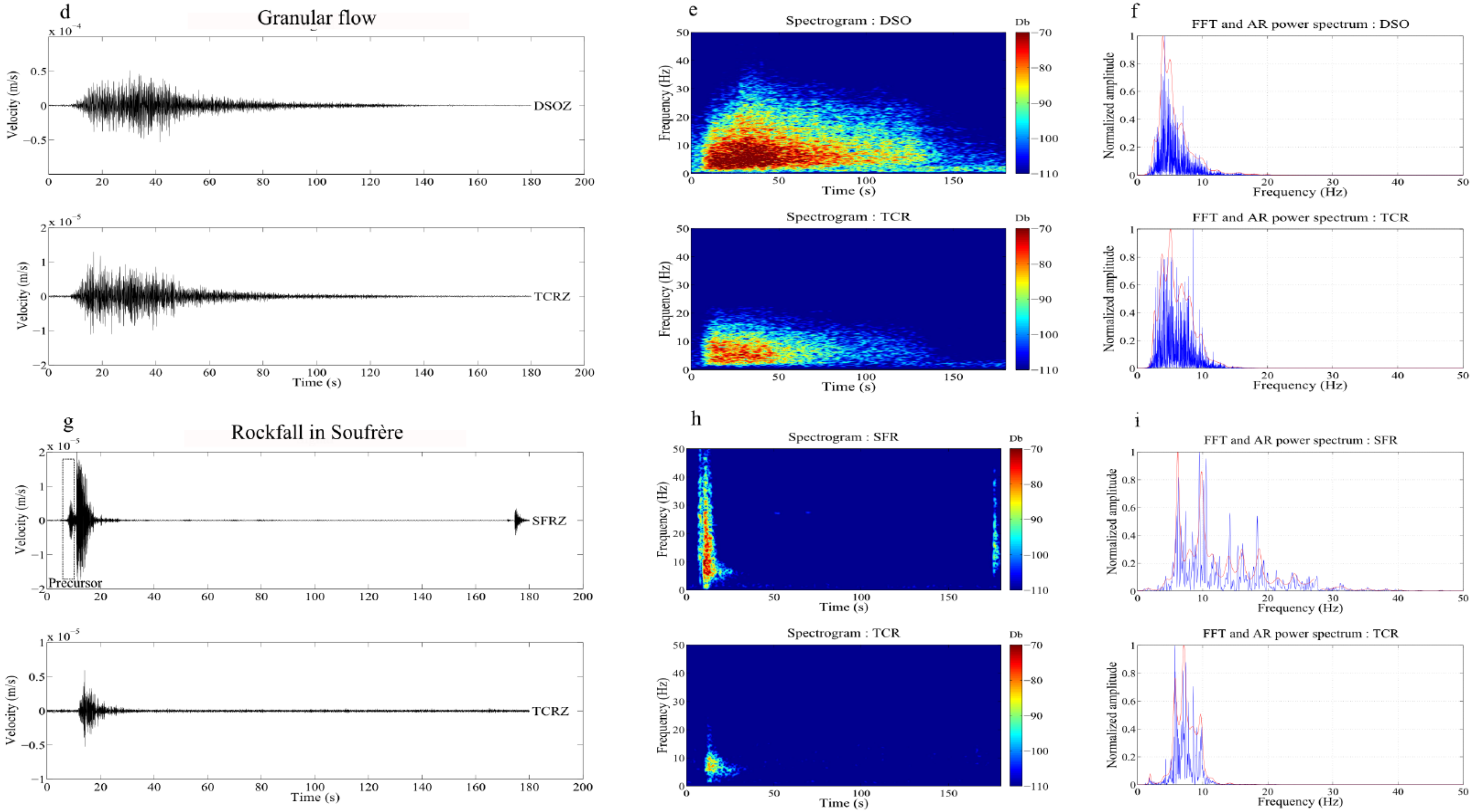


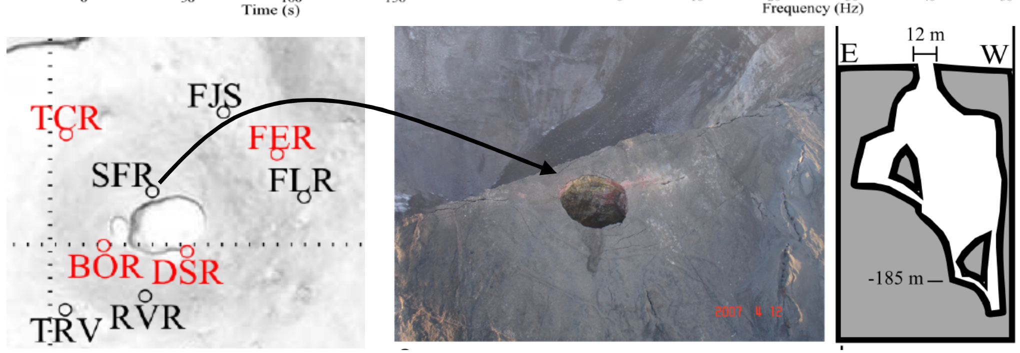


Localisation à partir des différences de temps d'arrivée (hyperboles) pour la période Février à Juillet 2008

ANR LandQuakes (2012-2016)

Characteristics of rockfall seismic signal



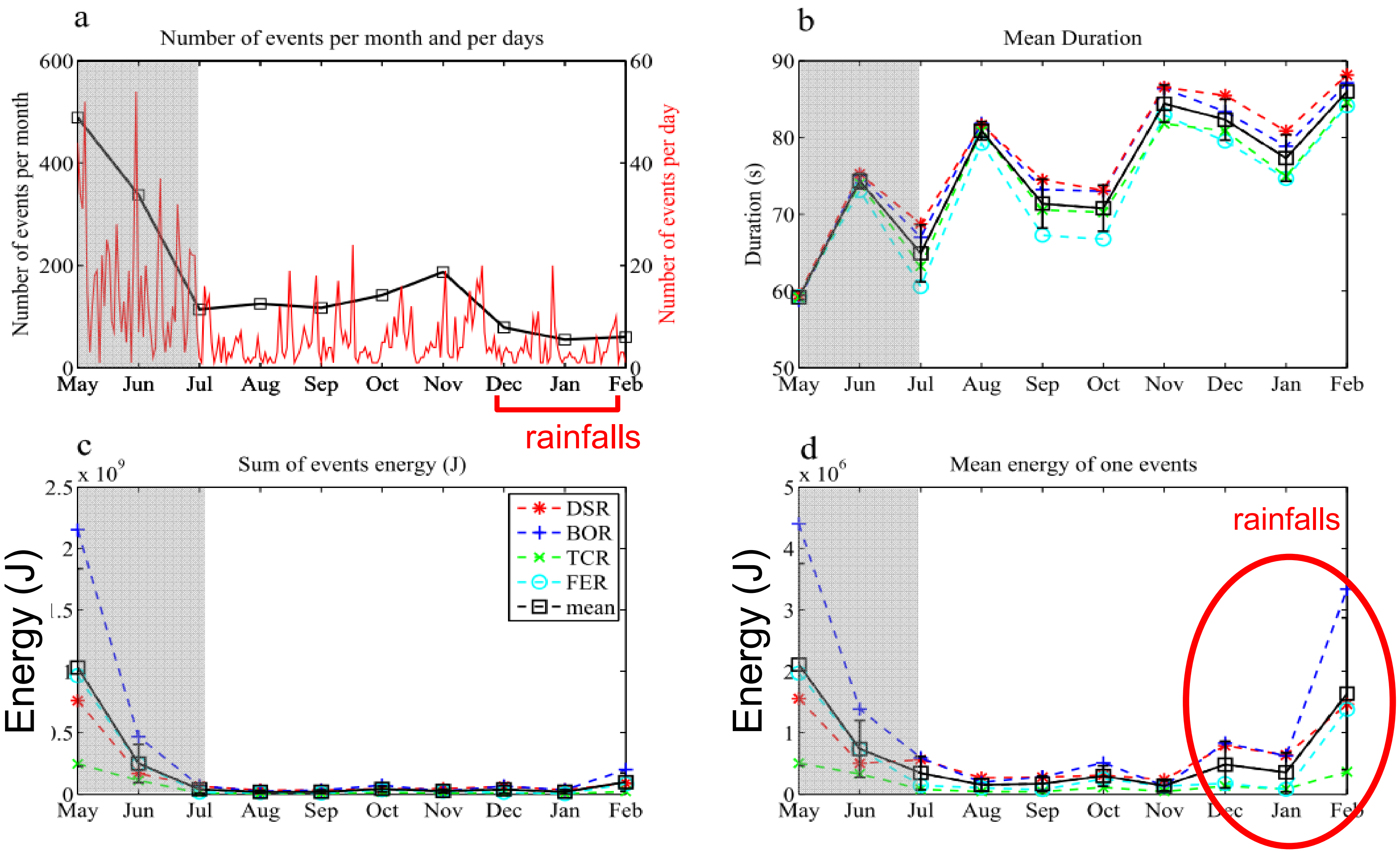


Seismic signal

Granular flows ≠ rockfalls

Time evolution of rockfall activity

- Study of **1706 events** between May 2007 and February 2008
- Temporal evolution of the seismic parameters **Energy** and **Signal duration**



Relaxation time ~ two months