EOST, le 7 février 2012

Du signal sismique à la dynamique des effondrements gravitaires

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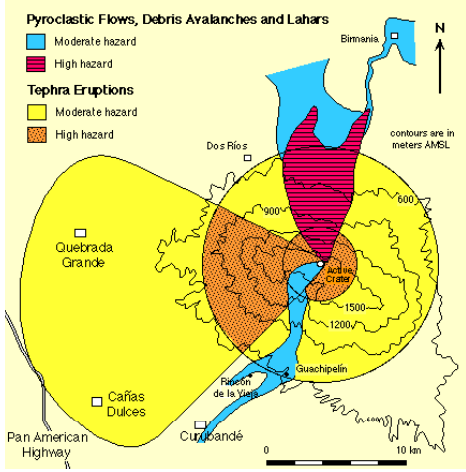
Modeling of landslides and avalanches

Motivation

- Erosion processes at the surface of the Earth and other telluric planets
- Interaction with climatic, seismic and volcanic activity
- Hazard assessment

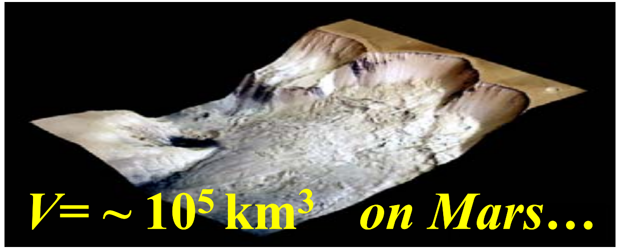


Volume scale : m^3 → 10^5 km^3
Time scale : second → year
≠ Sources, ≠ Topographies

V=10^{2}m^3 , T ~ jour

V=10^{3}m^3, T ~ sec.

V= ~ km^3 , T ~ min.



V= ~ 10^5 km^3 *on Mars…*

Granular flows dynamics : from field to laboratory scale

Natural flows

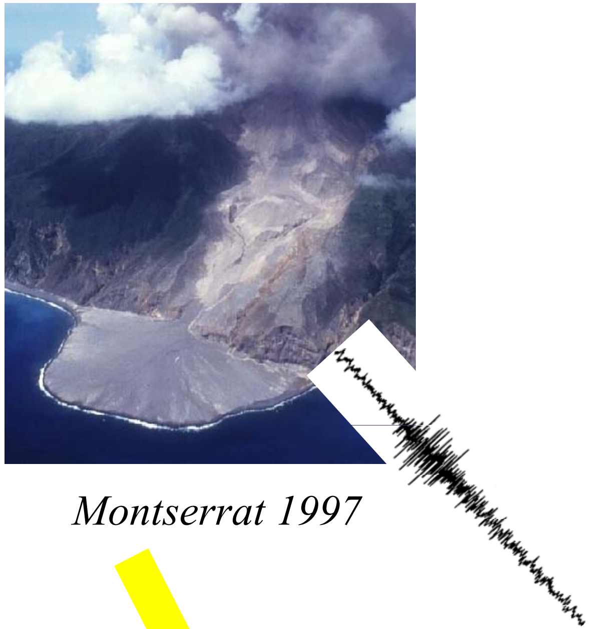
Heterogeneous materials
Few **data**: **deposit** area

Laboratory granular flows

Velocity and thickness **measurements**

Same physical processes ?

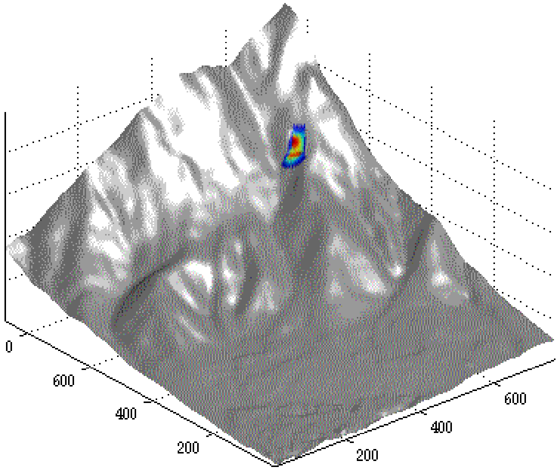
km^3



Montserrat 1997

Emplacement processes

Numerical simulation

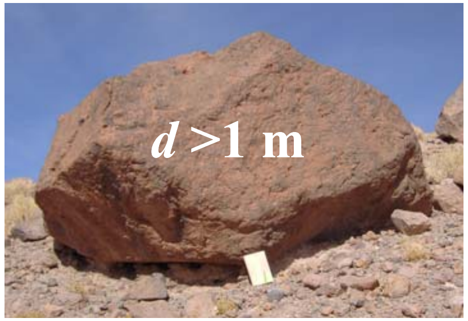


cm^3

Nathalie Thomas, IUSTI

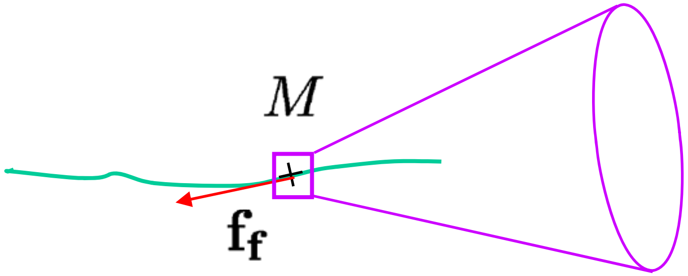
Numerical modeling of granular flows

- Natural materials



- Modeling

2D thin layer model

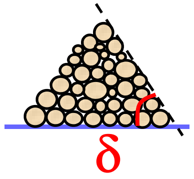


Mean scale

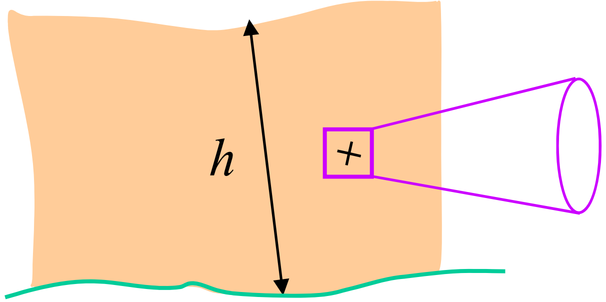
Reasonable computational cost

Empirical flow law …

$$\mu = \tan\delta$$



3D continuum model

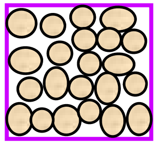


Local scale

High computational cost

Local flow law ???

Discrete element model



Grain scale

High computational cost

Particle size
distribution ???

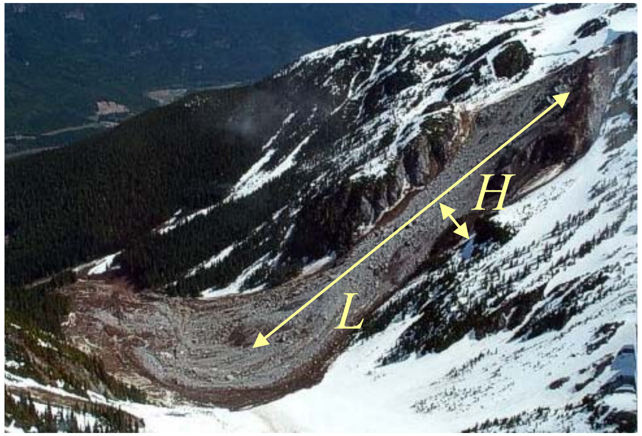
Thin Layer Approximation on 2D topography

- Flow on **complex natural topography**

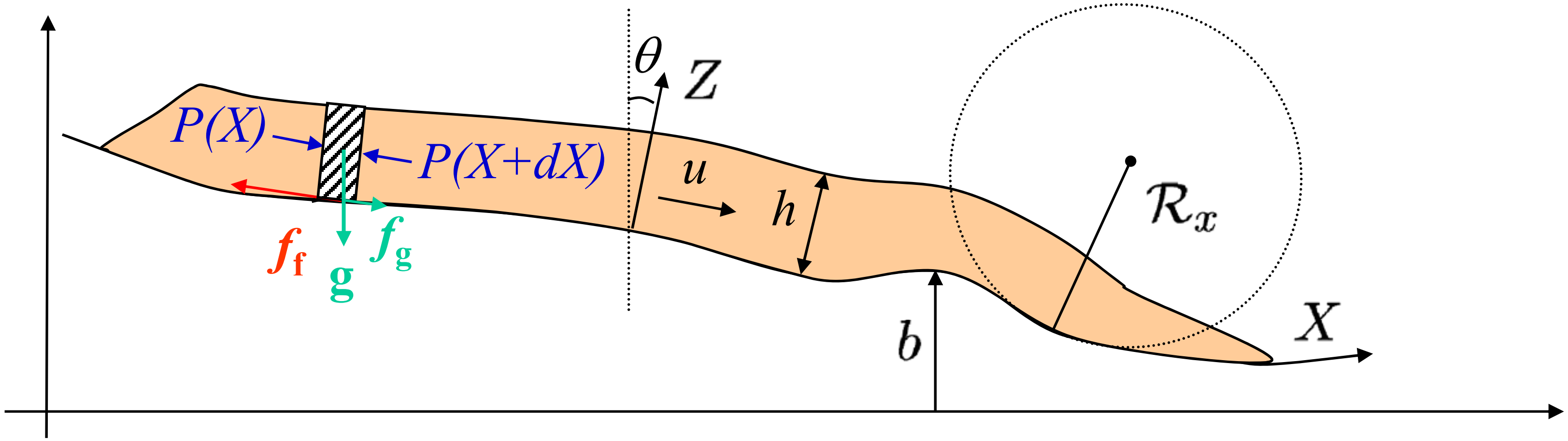
⇓

small **Aspect ratio**

high computational cost ⇒ $a = \frac{H}{L} << 1$



- Depth-averaged thin layer model model



$$\underbrace{\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial X}}_{\text{inertia}} = \underbrace{\gamma_X g}_{\text{gravity}} - \underbrace{K\frac{\partial}{\partial X}(g\gamma_Z h)}_{\text{pressure gradient}} - \underbrace{\mu\left(g\gamma_Z + \frac{u^2}{\mathcal{R}_x}\right)\frac{u}{|u|}}_{\text{Coulomb friction : } \mu = \tan\delta}$$

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

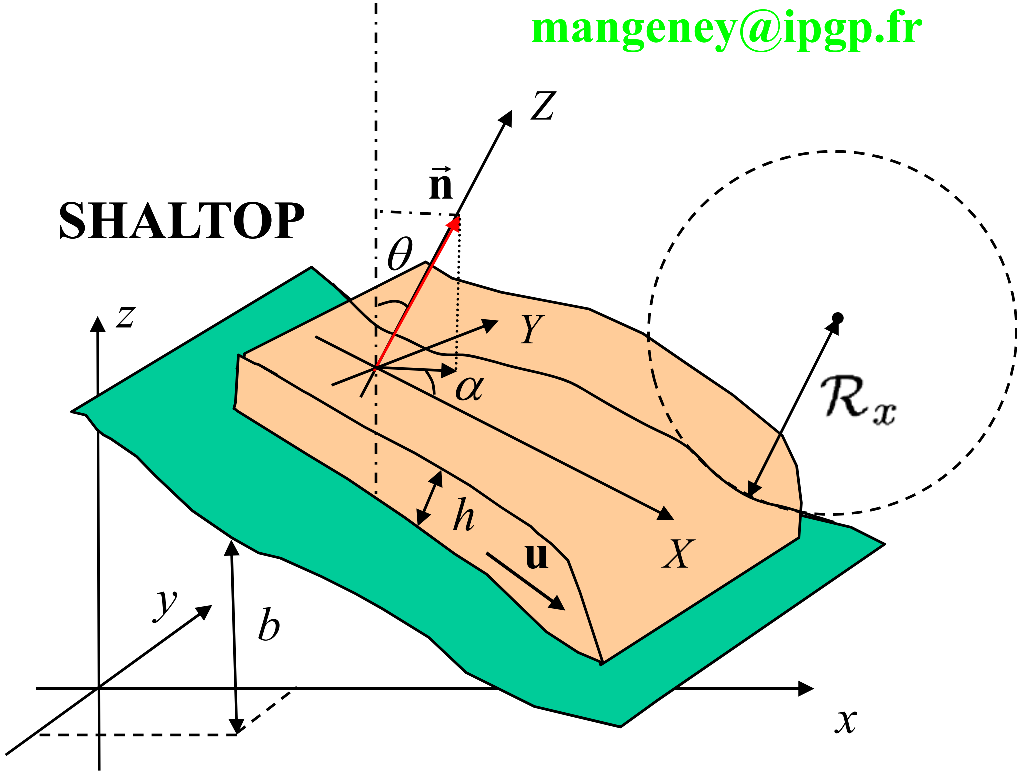
Savage and Hutter, 1989

Thin Layer Approximation on 3D arbitrary topography

- Until very recently : **arbitrary extension of 1D equations** …

Still used …

mangeney@ipgp.fr



SHALTOP

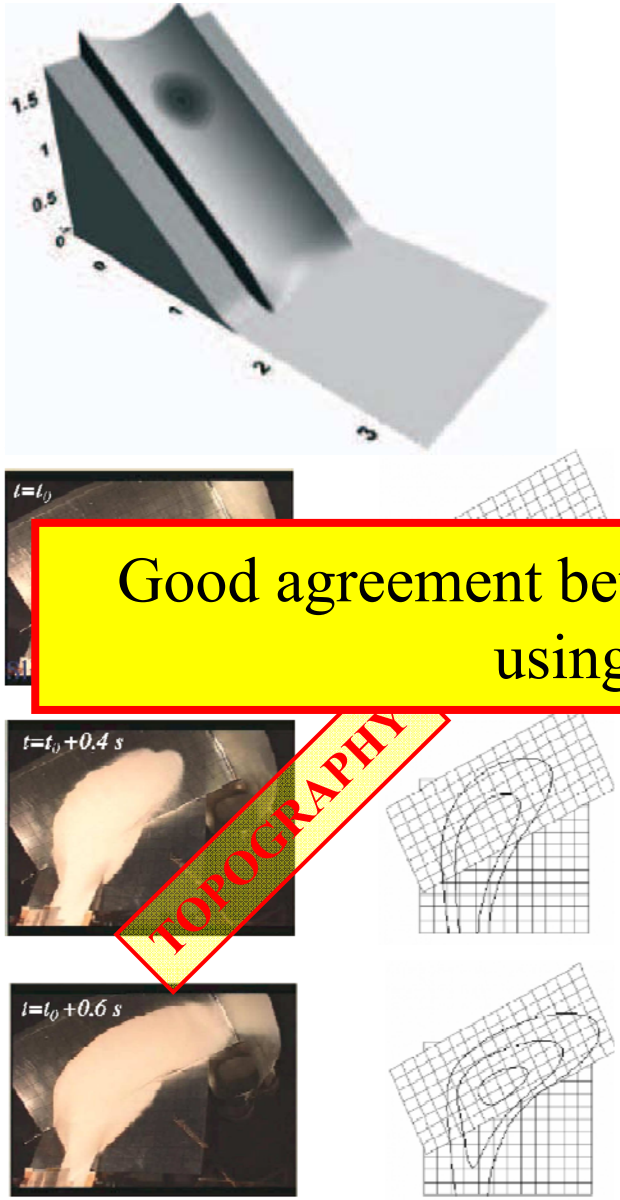
- **Full curvature tensor**

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

First equations including these effects: « centrifugal » forces

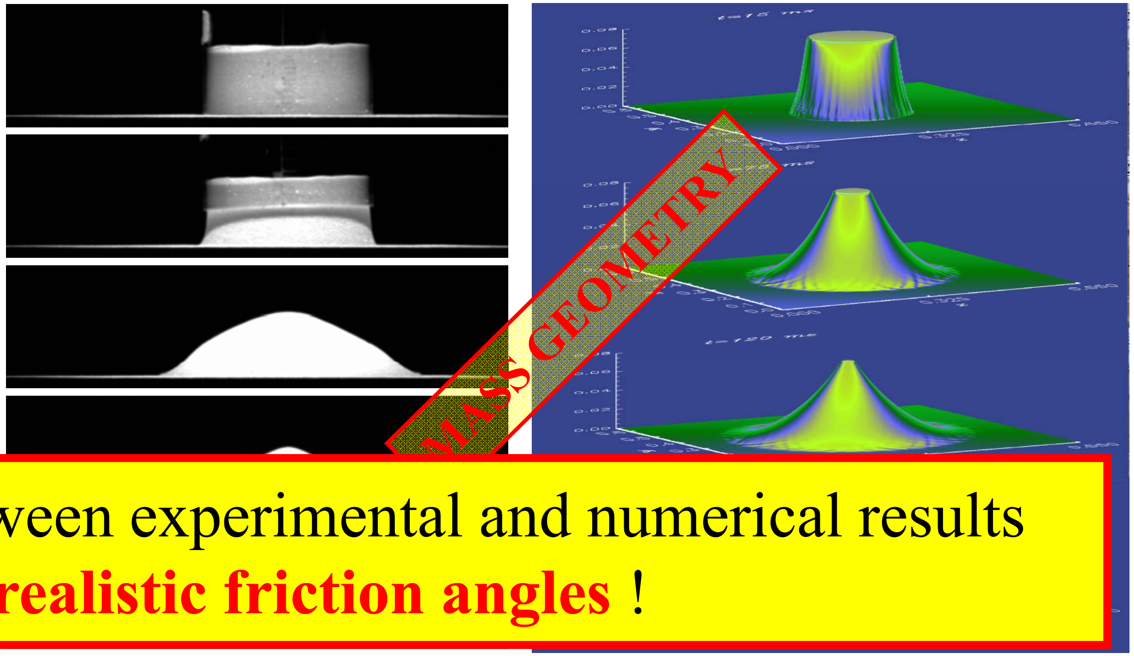
Bouchut et al., 2003; Bouchut and Westdickenberg, 2004; Mangeney et al., 2007

Simulation of laboratory experiments



TOPOGRAPHY

Pirulli et al., 2007



MASS GEOMETRY

Mangeney et al., 2005

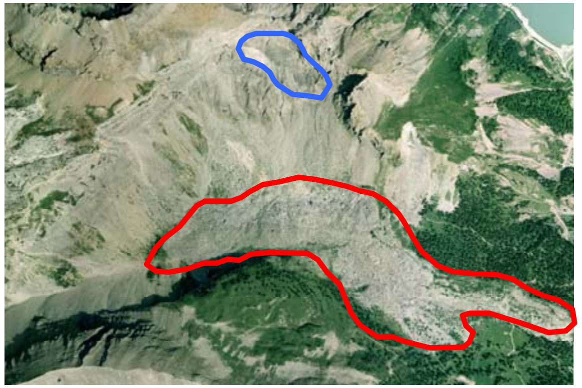
Good agreement between experimental and numerical results using **realistic friction angles** !

Hutter and co., Hungr, Iverson and Denlinger, Pouliquen and Forterre, …

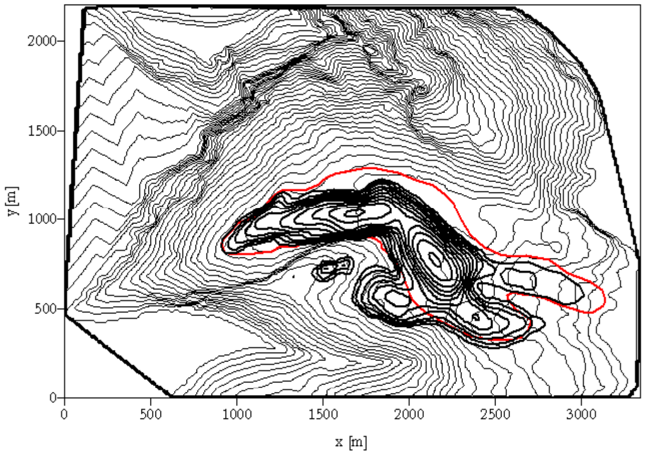
Simulation of natural flows

Simulation of **observed deposits** (Switzerland)
using thin layer depth-averaged model with Coulomb friction law:

$\mu = \tan\delta$: **empirical description** of the **mean dissipation**



t = 70 s



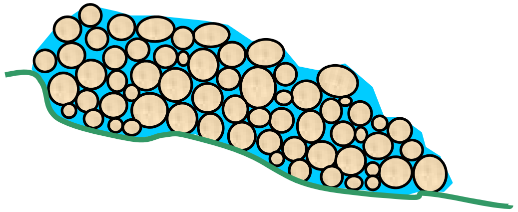
Friction angle used in the model : $\delta = 17°$

Small friction angle compared to angles typical of natural materials! $\theta_r \sim 35°$

Origin of the high mobility of natural flows ??

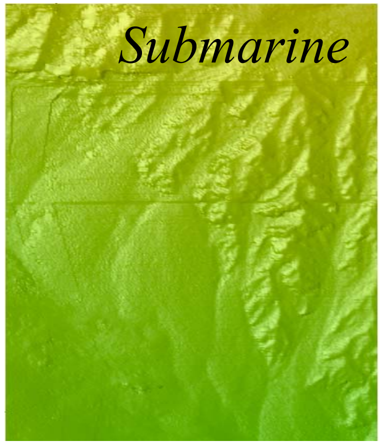
Pirulli and Mangeney, 2008

Different physical processes

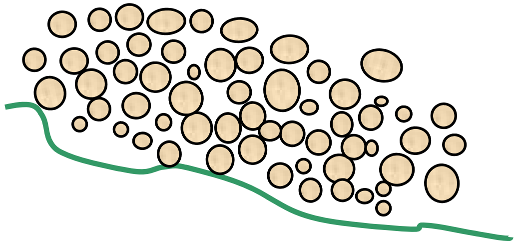


Fluid phase

Island

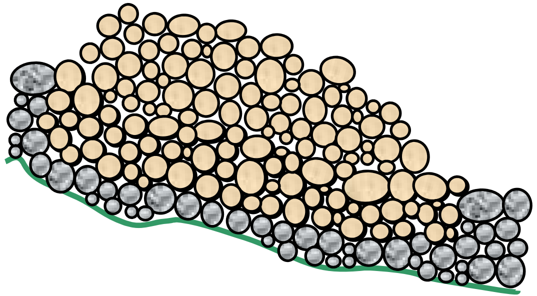


Submarine

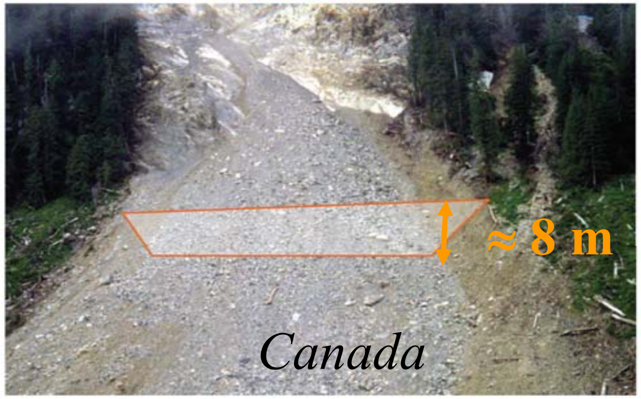


Fluidization

Lascar, Chili



Erosion

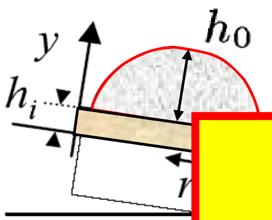


Canada

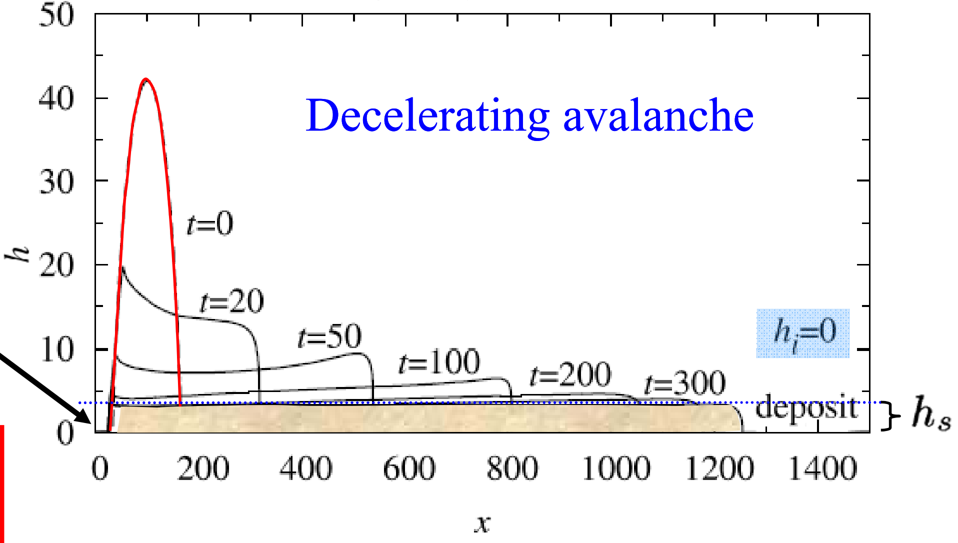
Erosion of a granular layer

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

Mangeney et al., 2007

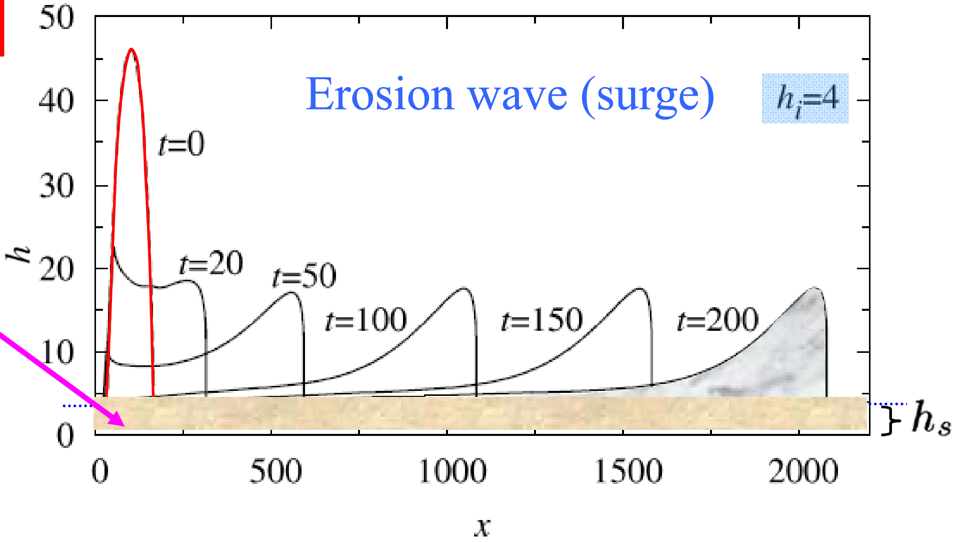


rigid bed



No signature of the dynamics on the deposit

erodible bed



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

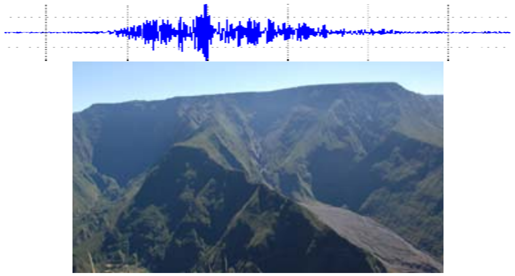
Listening to seismic signal from instabilities

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

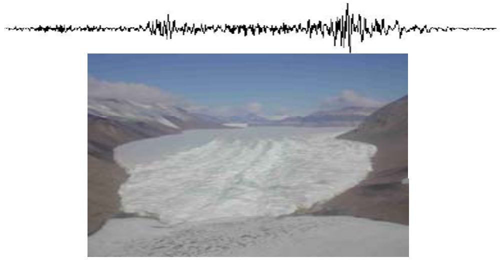
Challenge : explain and quantify the high mobility of natural landslides …

Lack of field measurements of landslide dynamics

Analysis of the seismic signal generated by gravitational flows:

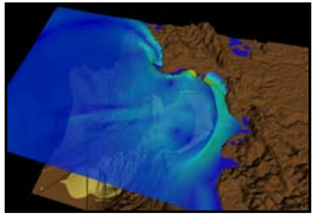


La Réunion



Antarctique

El Salvador



Sumatra

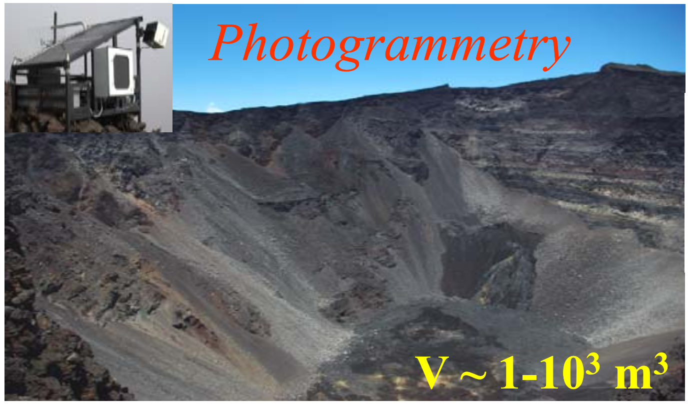
- Detection, monitoring
- Geometrical properties and nature of the flow (mass, volume, fluid content …)
- Mechanical behavior (friction coefficient …)

Brodsky et al., 2003, Deparis et al. 2008, Favreau et al., 2010, Hibert et al., 2011 …

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

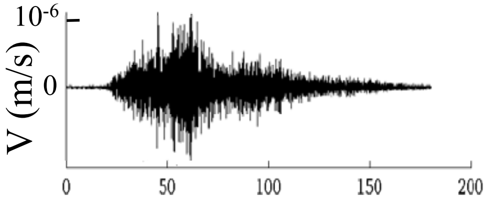
From small rockfalls to big landslides

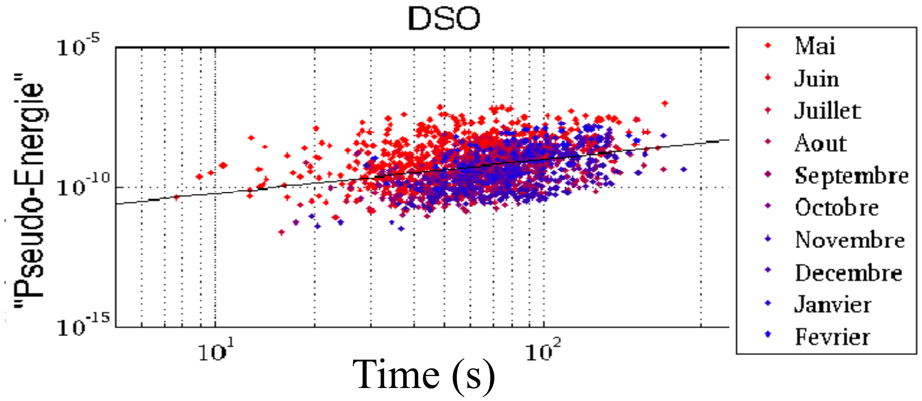
Rockfalls, La Réunion, 2007-2008



Photogrammetry

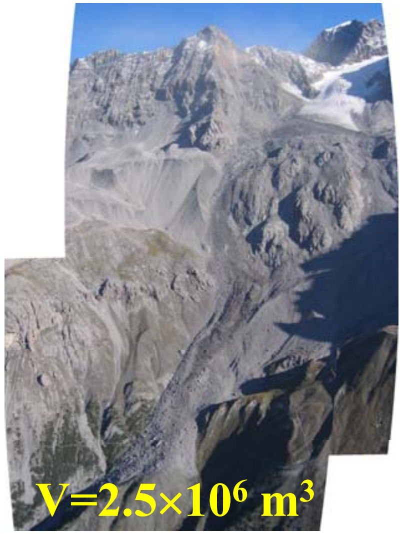
V ~ 1-10^3 m^3



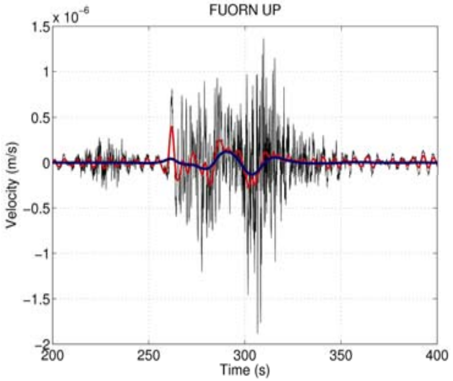


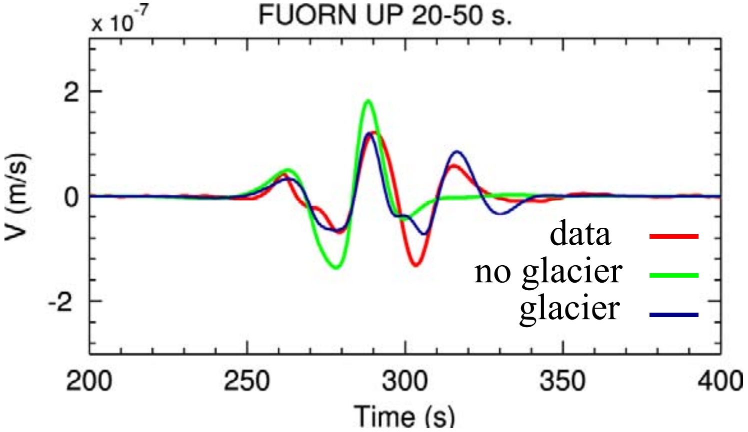
Hibert, Mangeney, Grandjean, Shapiro, 2011

Thurweiser landslide, Italie, 2004



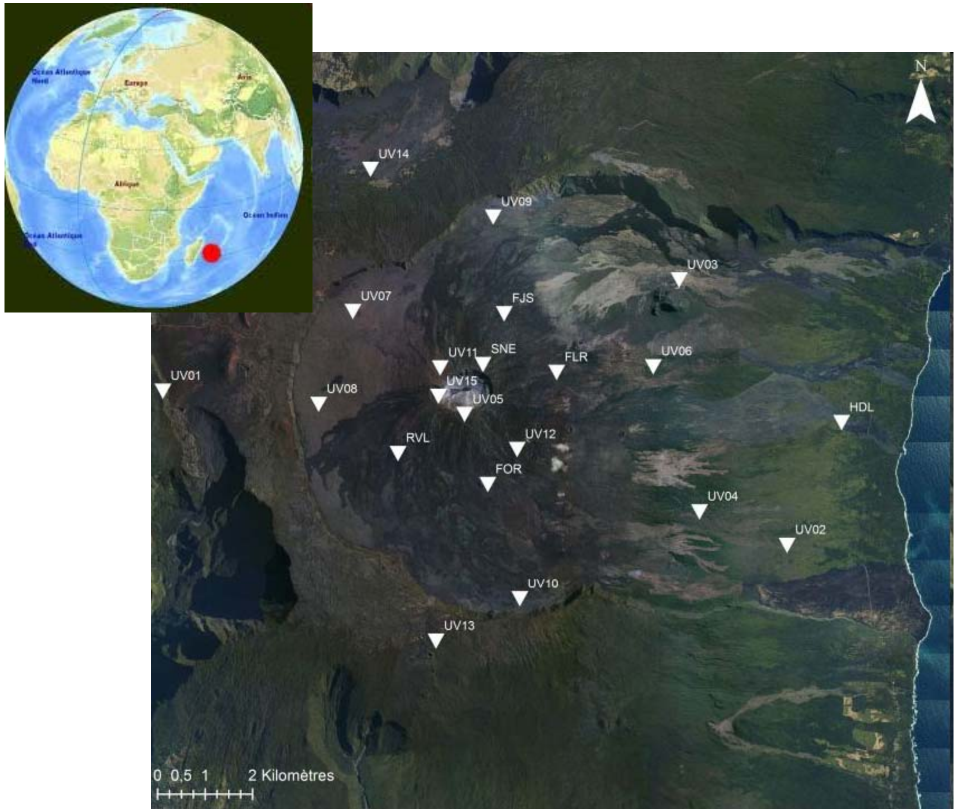
V=2.5×10^6 m^3





Favreau, Mangeney, Lucas, Crosta, Bouchut, 2010

Monitoring rockfall activity in Crater Dolomieu

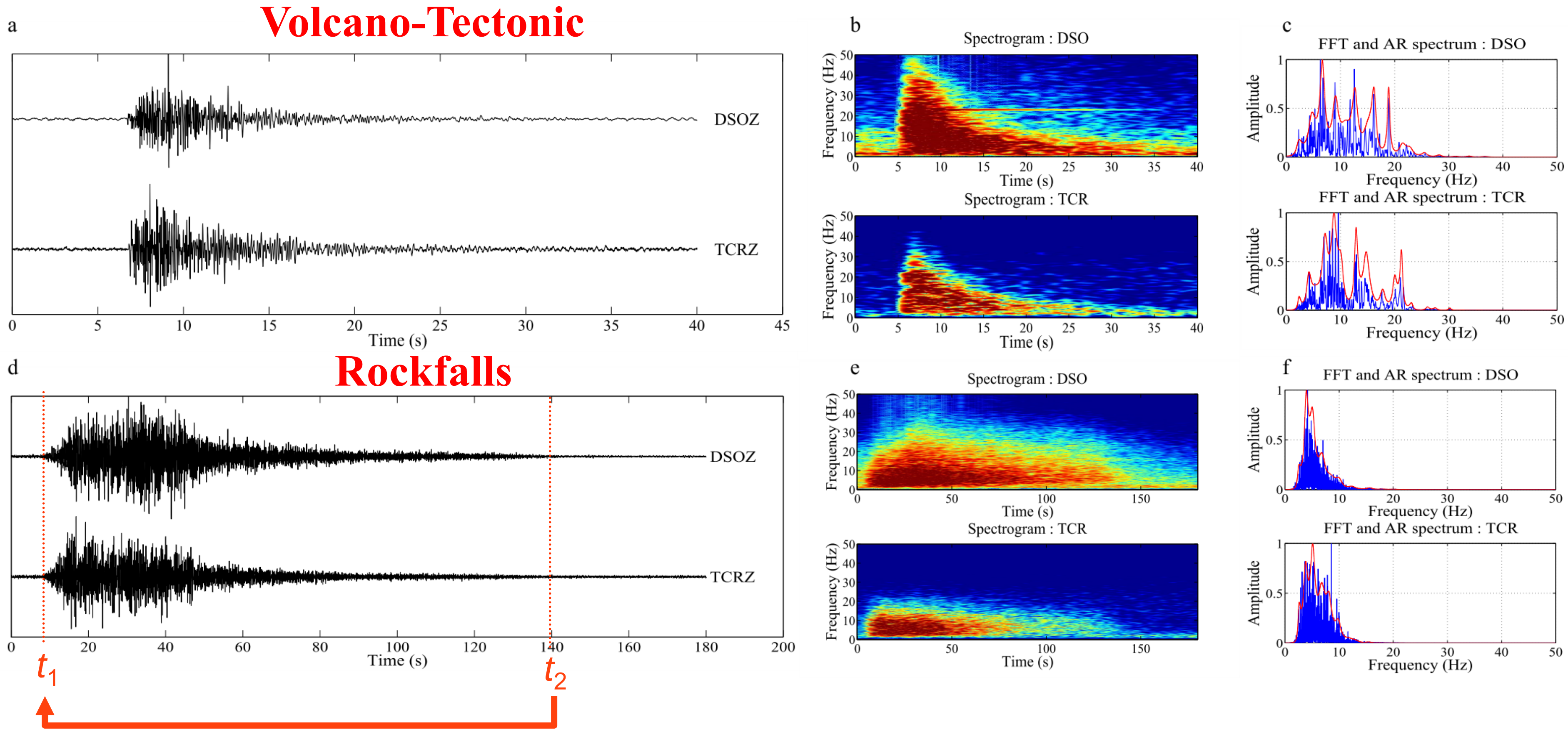


- **Strong volcanic activity :** 1 eruption occurring ~ every 9 months since 1998
- Dolomieu : main crater of the **Piton de la Fournaise volcano**, La Réunion island
- **Dense seismic network** set up by the OVPF + 15 stations (UNDERVOLC project)

OBSERVATOIRE VOLCANOLOGIQUE PITON DE LA FOURNAISE
SUPPORTED BY ANR

Characteristics of rockfall seismic signal

- Seismic signal characteristics make it possible to distinguish rockfalls from V-T



Field observation :

Seismic signal duration ≈ granular flow propagation time

Monitoring rockfall activity in Crater Dolomieu

A major event : the april 2007 collapse

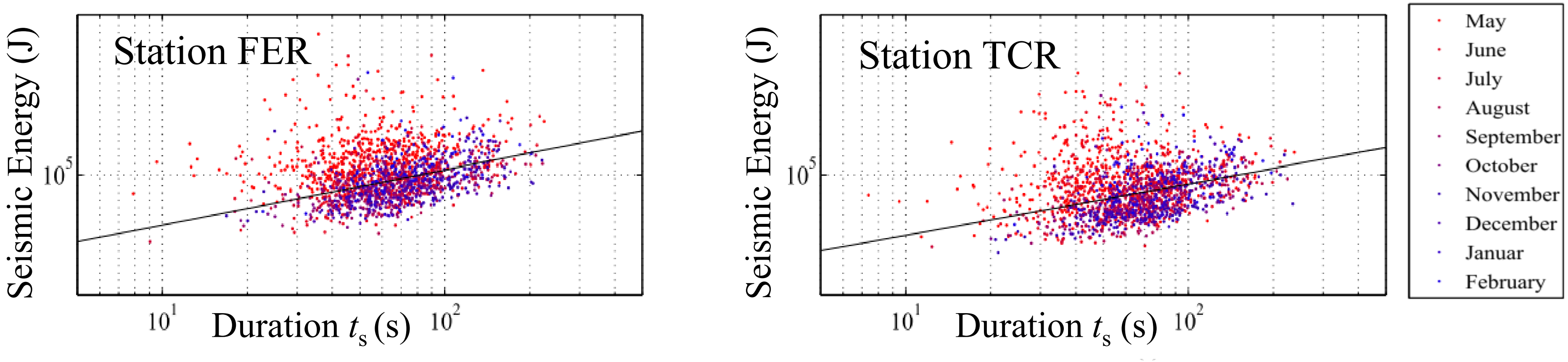
Before → After

Rockfall activity ↗

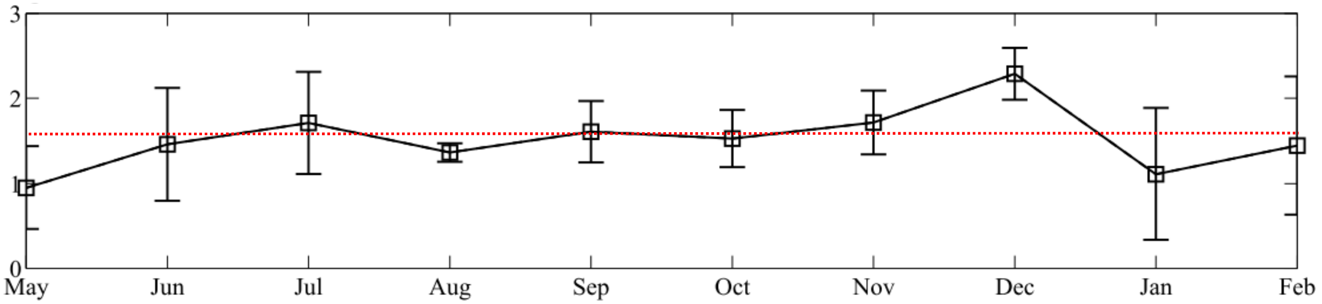
Scaling laws : seismic energy versus duration

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** :

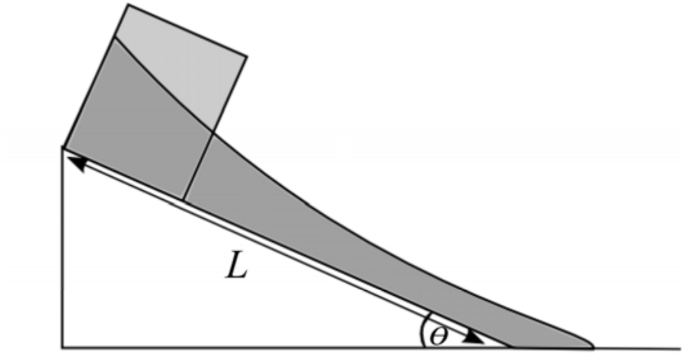
$E_s\ \alpha\ t_s^{\beta s}$

with

$\beta_s \approx 1.56$

Scaling laws : potential energy versus flow duration

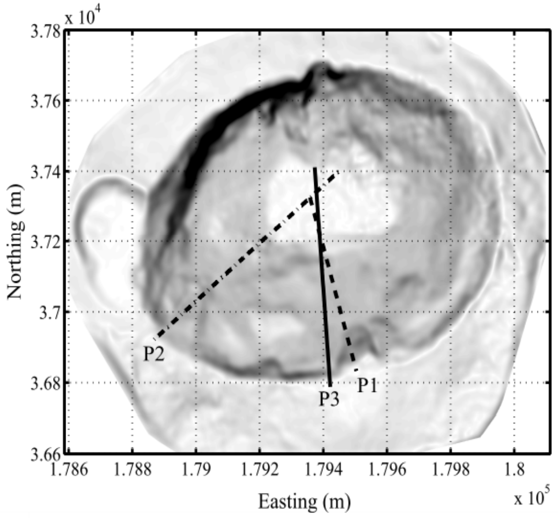
- Analytical development for a rectangular mass on a flat slope *Mangeney et al.*, 2010

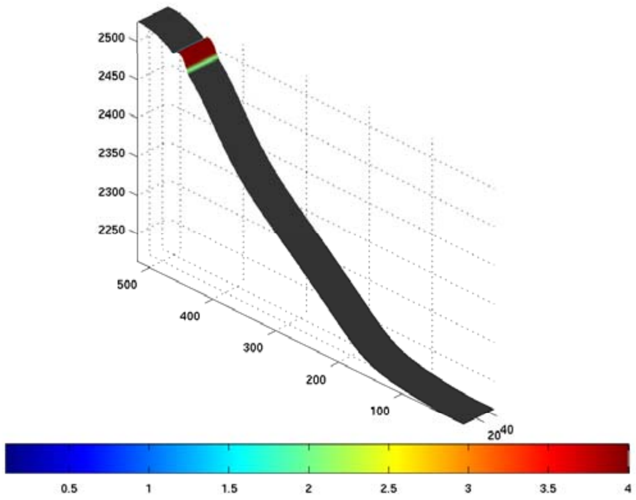


$$\Delta E_p \alpha\, t_f^{\beta a}$$

with $\beta_a = 2$

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





$$\Delta E_p \alpha\, t_f^{\beta p}$$

with $\beta_p = 1.65$

Topography Effects

Rugosity $\nearrow \Rightarrow \beta_p \searrow$

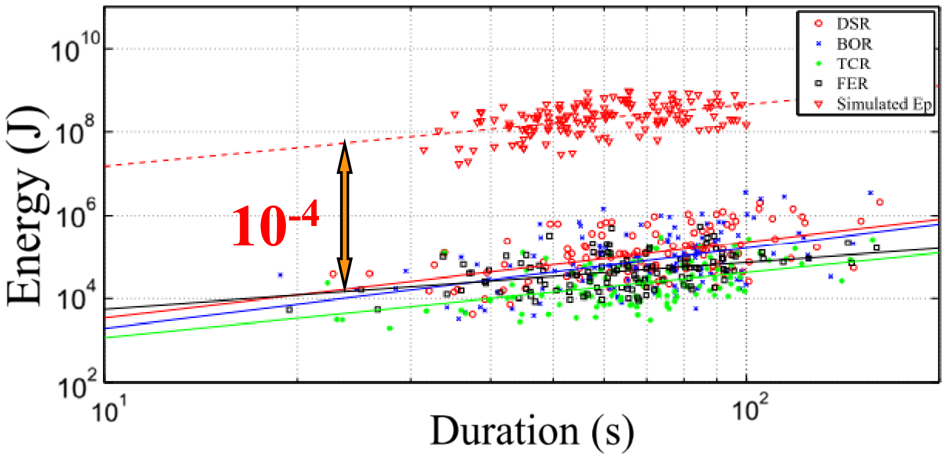
From seismic energy to rockfall volume

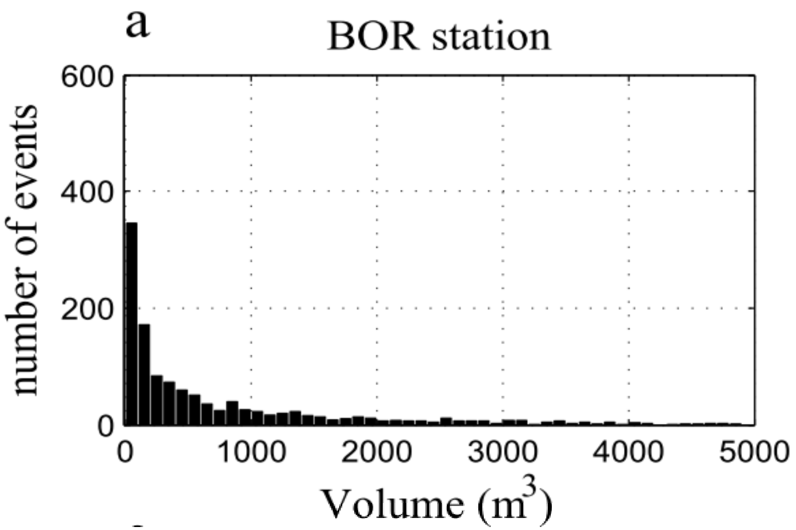
- Scaling laws Energy/Duration : $E_{\text{seismic}} \propto t_s^{\,\beta}$ and $\Delta E_{\text{potential}} \propto t_f^{\,\beta}$

$R_{s/p}=E_s/\Delta E_p \sim 10^{-4}$

Volume $$V = \frac{3E_s}{R_{s/p}.\rho g L(\tan\alpha\cos\theta - \sin\theta)}$$

Hibert et al., 2011

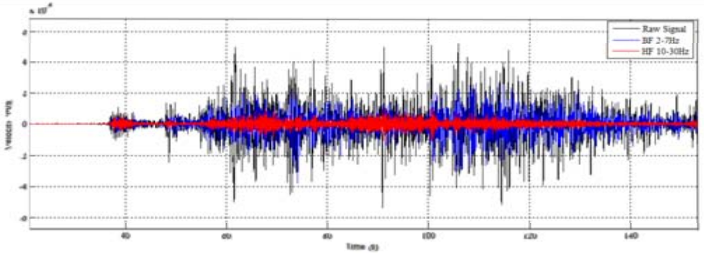




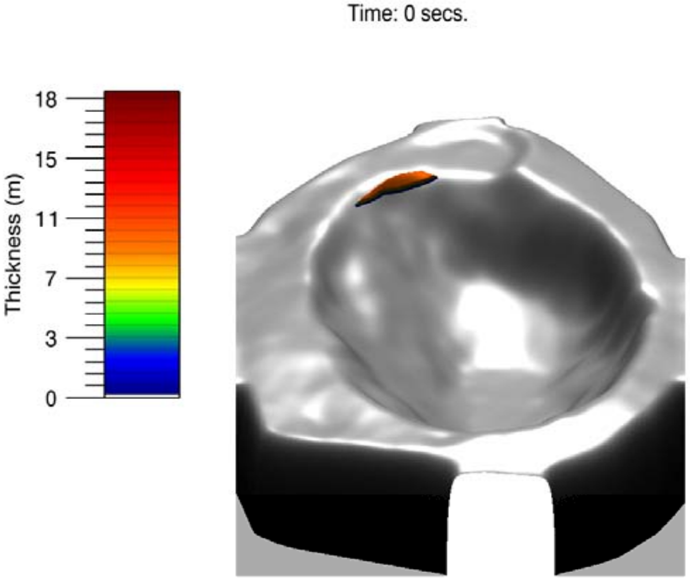
- Cumulative volume from May 2007 to February 2008 : V=1.85 10^6 m^3

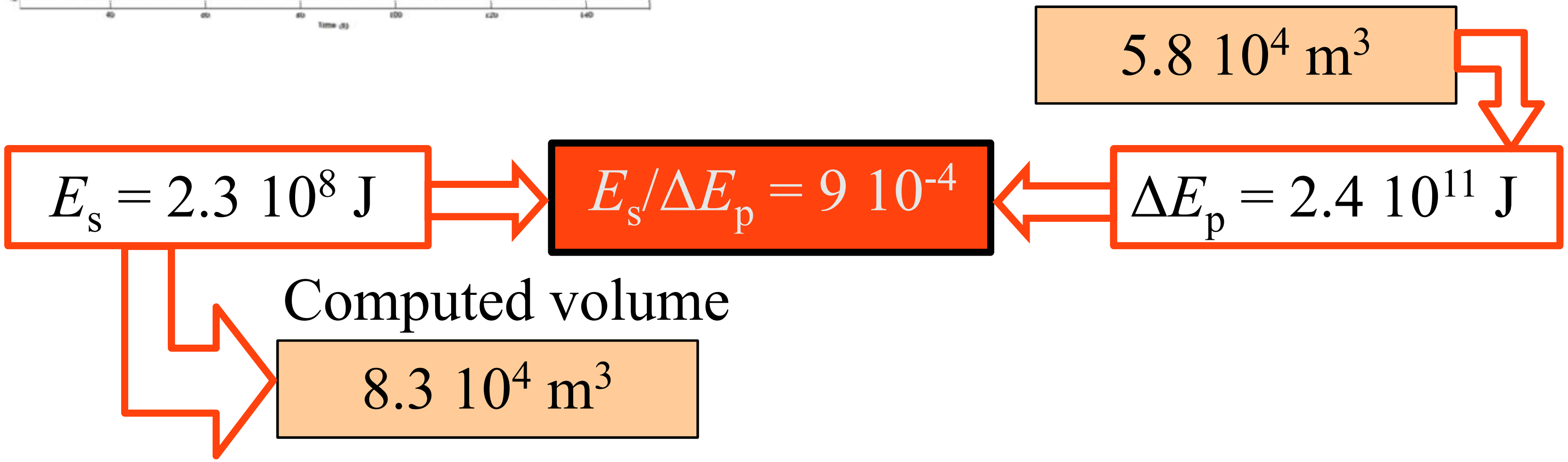
Validation on the 16/05/07 rockfall

Observations



Modeling





Estimated volume

$5.8\ 10^4\ \mathrm{m}^3$

$E_s = 2.3\ 10^8$ J

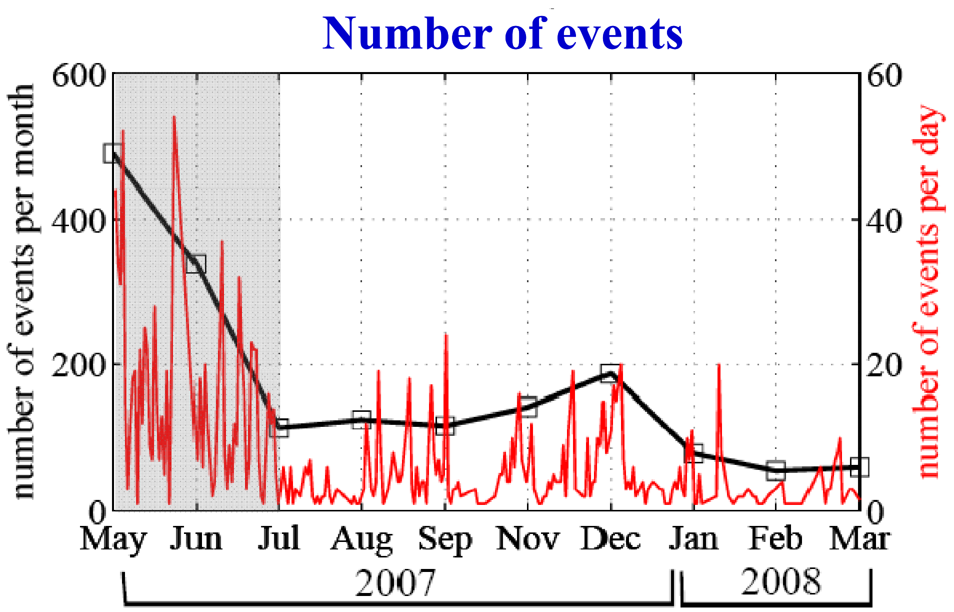
$E_s/\Delta E_p = 9\ 10^{-4}$

$\Delta E_p = 2.4\ 10^{11}$ J

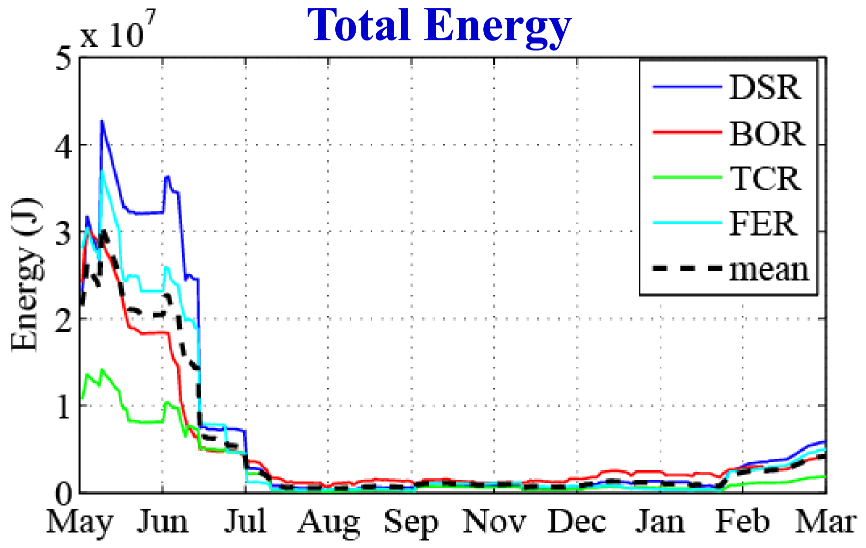
Computed volume

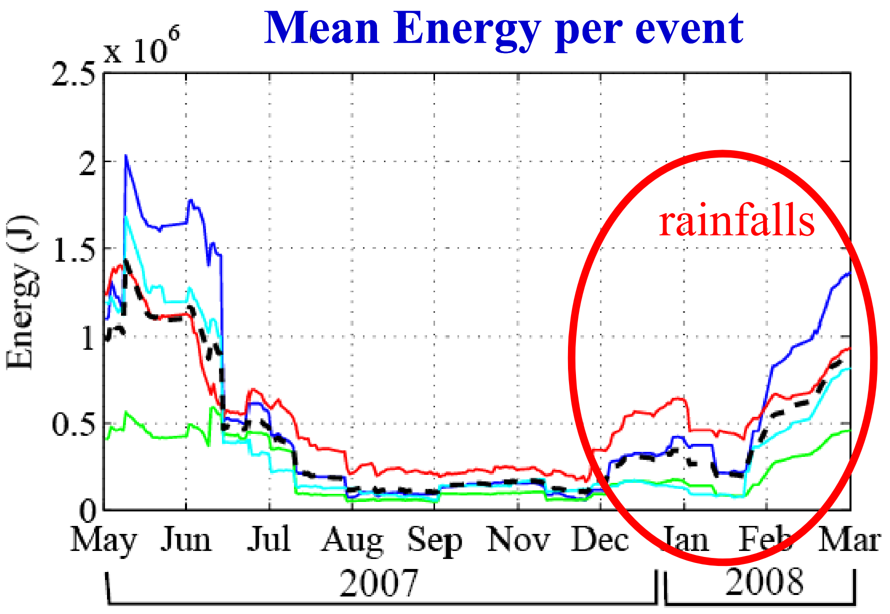
$8.3\ 10^4\ \mathrm{m}^3$

Monitoring rockfall activity in Crater Dolomieu


Number of events

Boxcar moving average window (30 days)


Total Energy


Mean Energy per event

- Relaxation time of the crater walls :

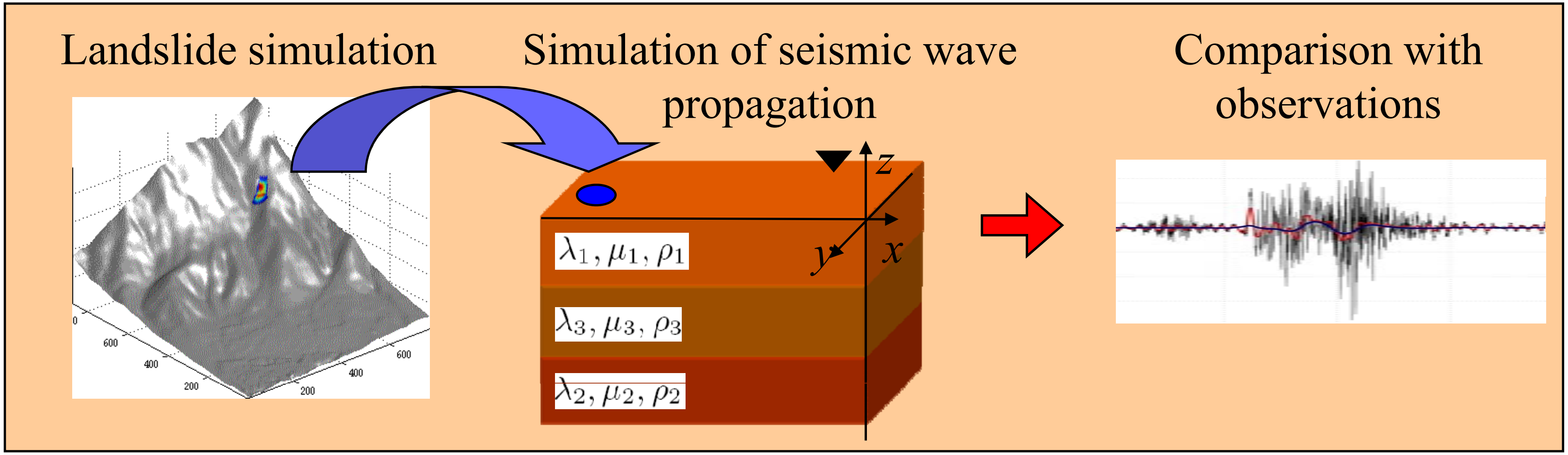
~ 2 months

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

Hibert et al., 2011

Numerical simulation of landslide and seismic waves

Direct problem



Landslide simulation

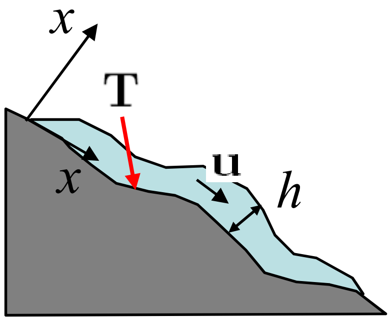
Simulation of seismic wave propagation

Comparison with observations

Mangeney et al., 2005, 2007

Favreau et al., 2010

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



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

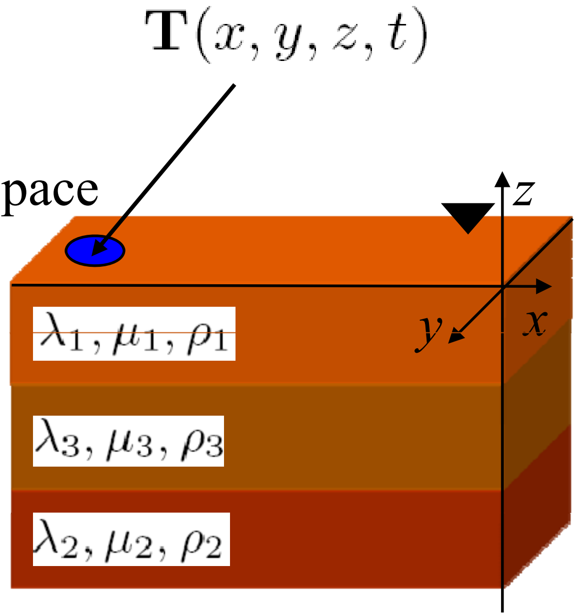
Curvature effects

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 $z = -\infty$



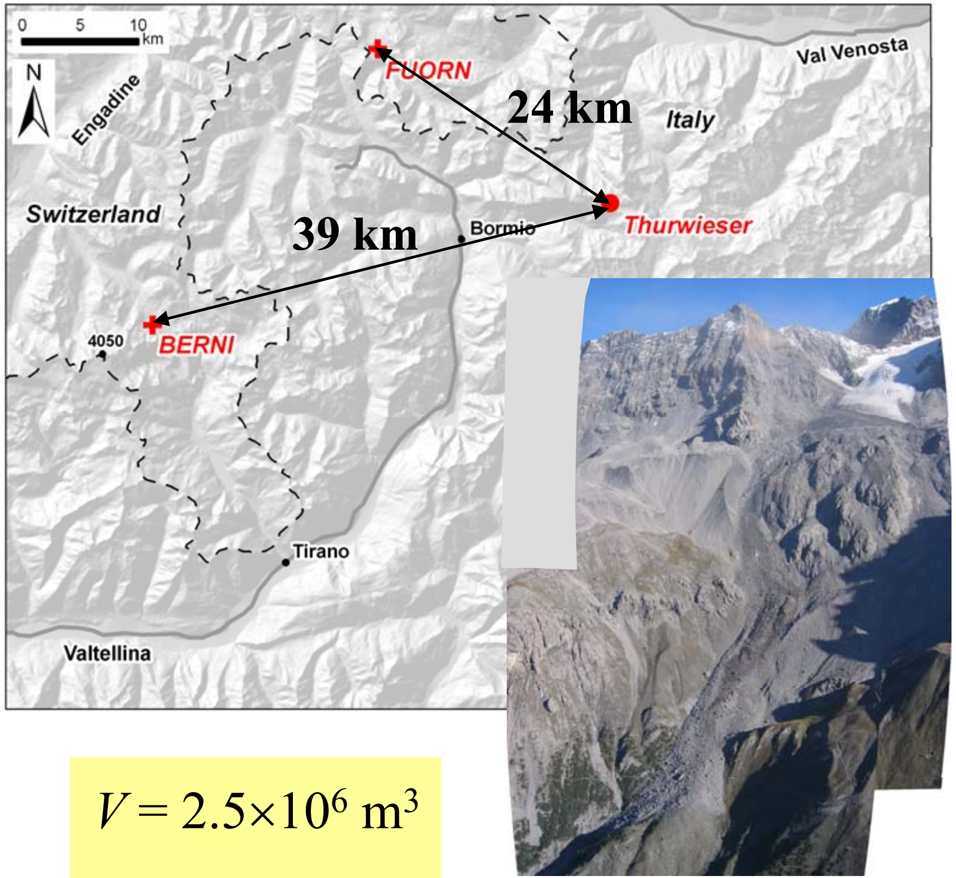
$$u_{ij}(t, r, \theta) = \sum_{n=0}^{2} R_{ijn}(\theta) \int_{\epsilon - i\infty}^{\epsilon + i\infty} dp\, e^{pt} \int_0^{\infty} dk\, T_n(p, k) J_n(kr) k$$

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

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

Simulation of the Thurweiser landslide

Thurweiser rock avalanche, Italie
September 2004

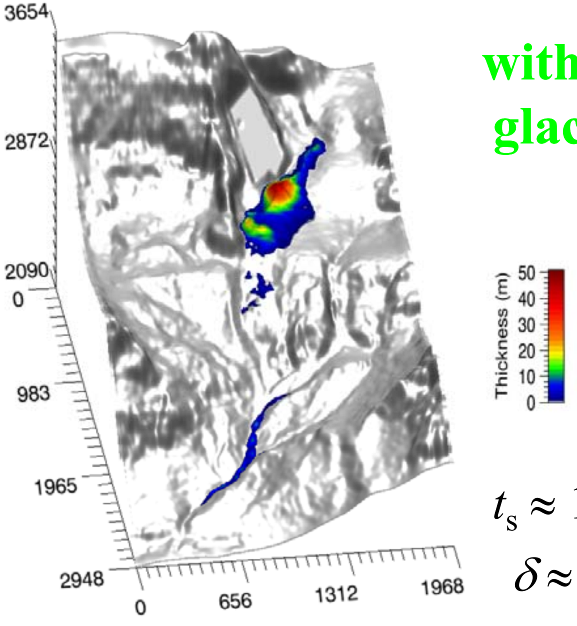


$V = 2.5\times10^6$ m^3

$R_f = 2.9$ km

$T_f \approx 90$ s

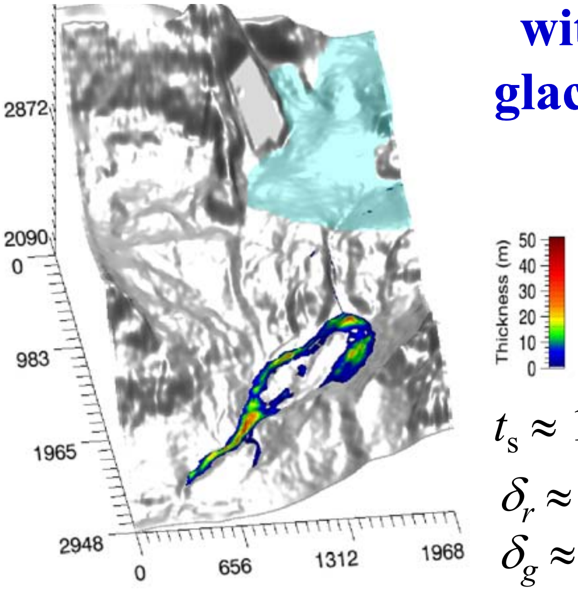
Sosio et al., 2008, Favreau et al., 2010



without glacier

$t_s \approx 100$ s

$\delta \approx 23°$



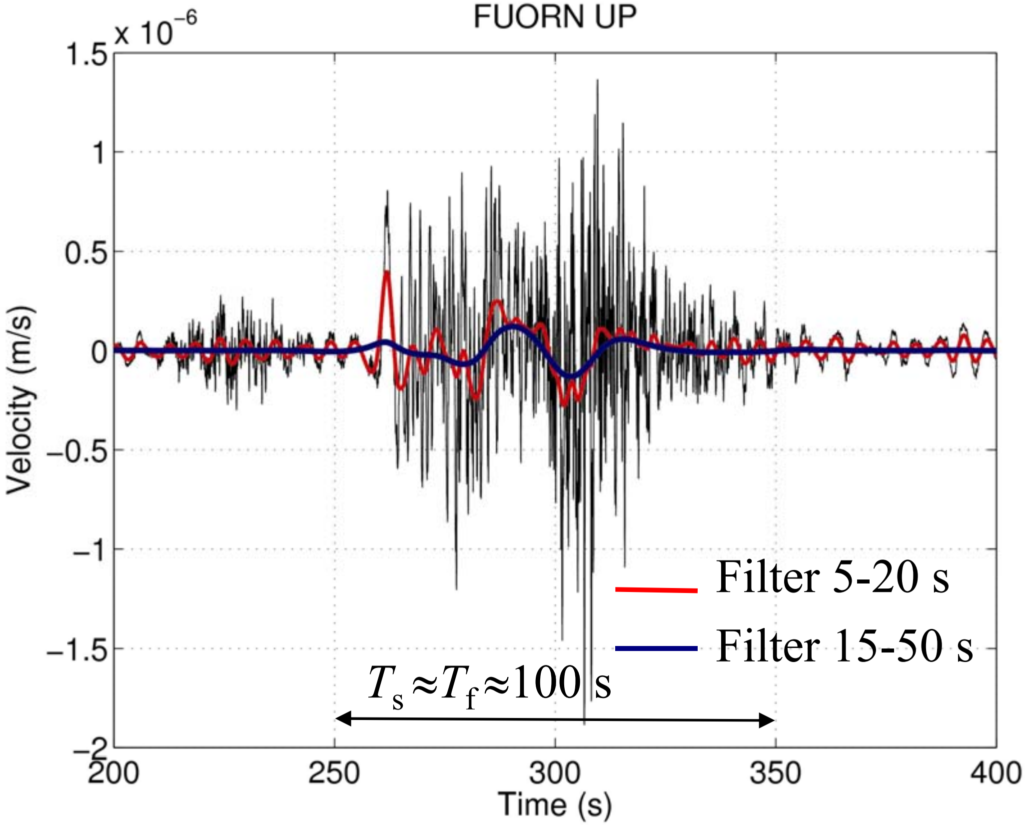
with glacier

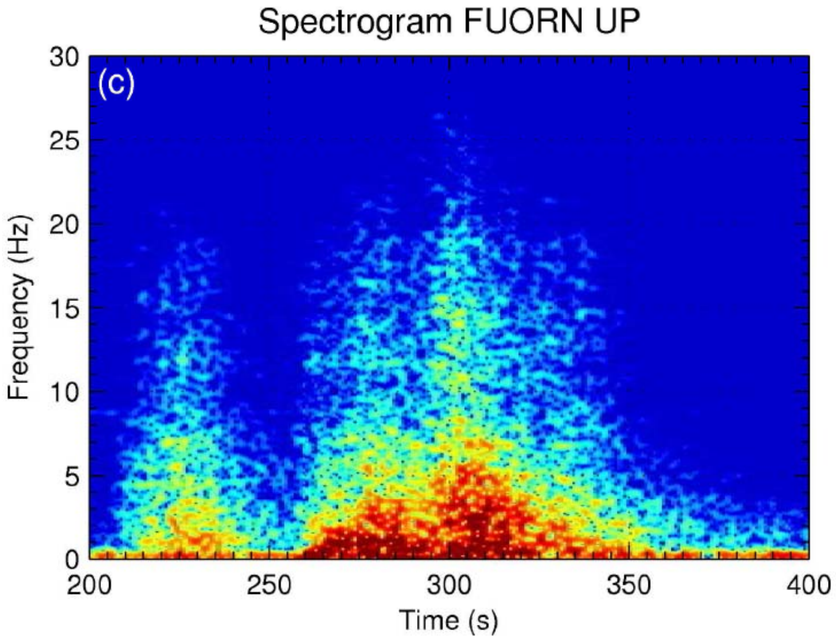
$t_s \approx 100$ s

$\delta_r \approx 26°$

$\delta_g \approx 6°$

STS2 Data





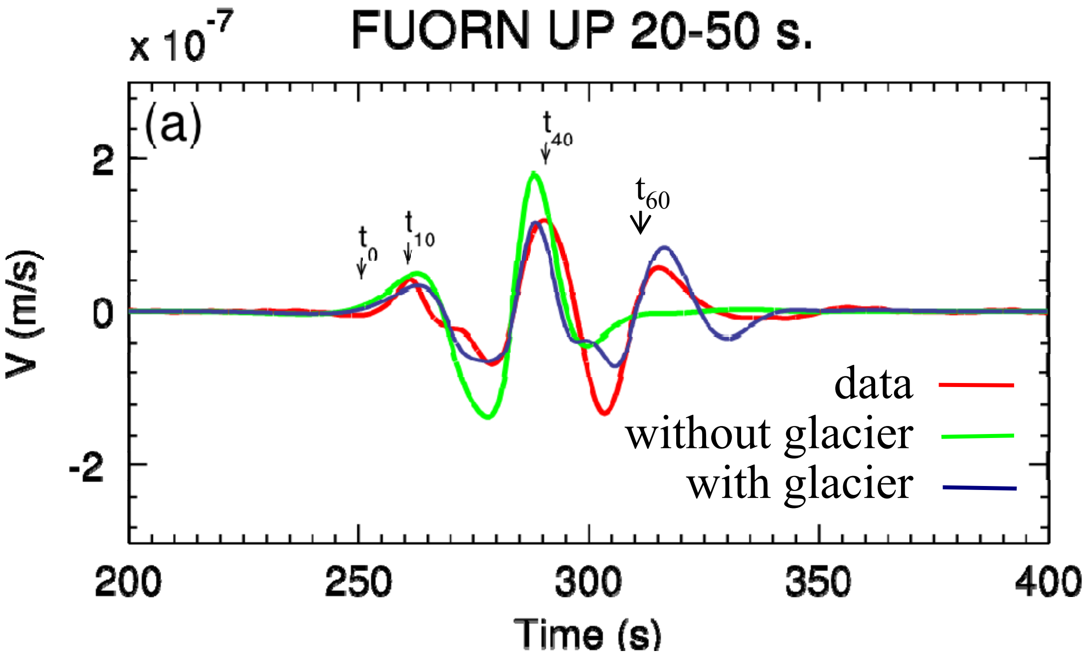
$0.01\ \text{Hz} < f < 15\ \text{Hz}$

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

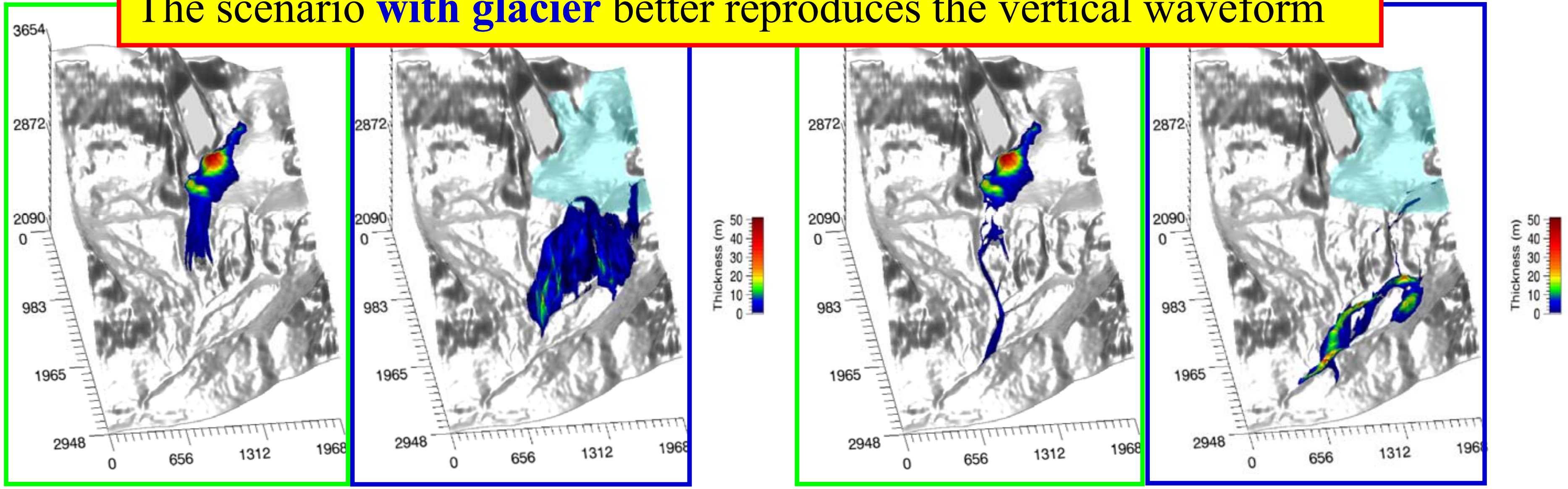
For $T > 15$ s, $\lambda = cT \approx 45$ km

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

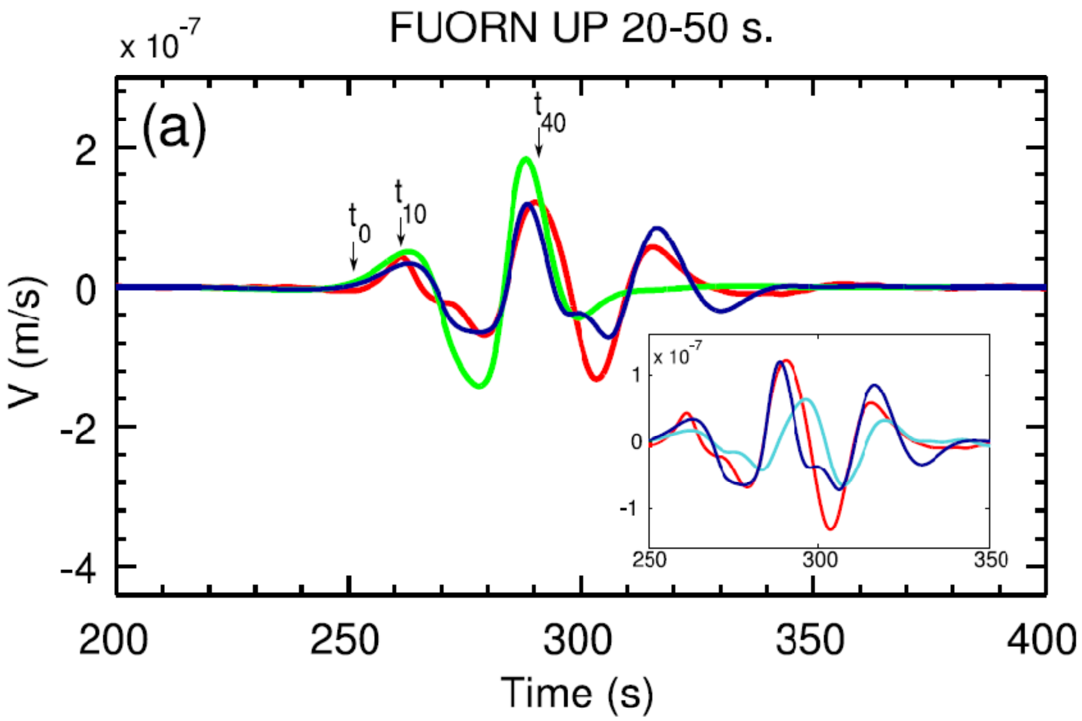
Simulation of the generated seismic waves

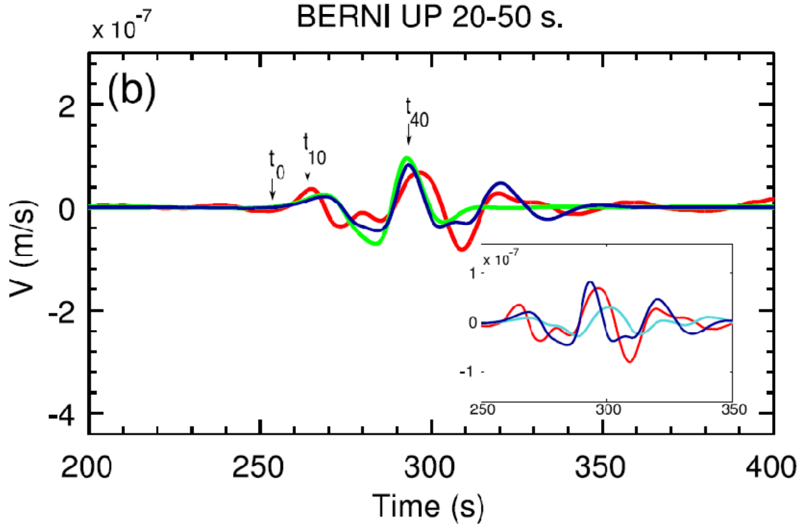


The scenario **with glacier** better reproduces the vertical waveform



Curvature effects on the generated seismic waves





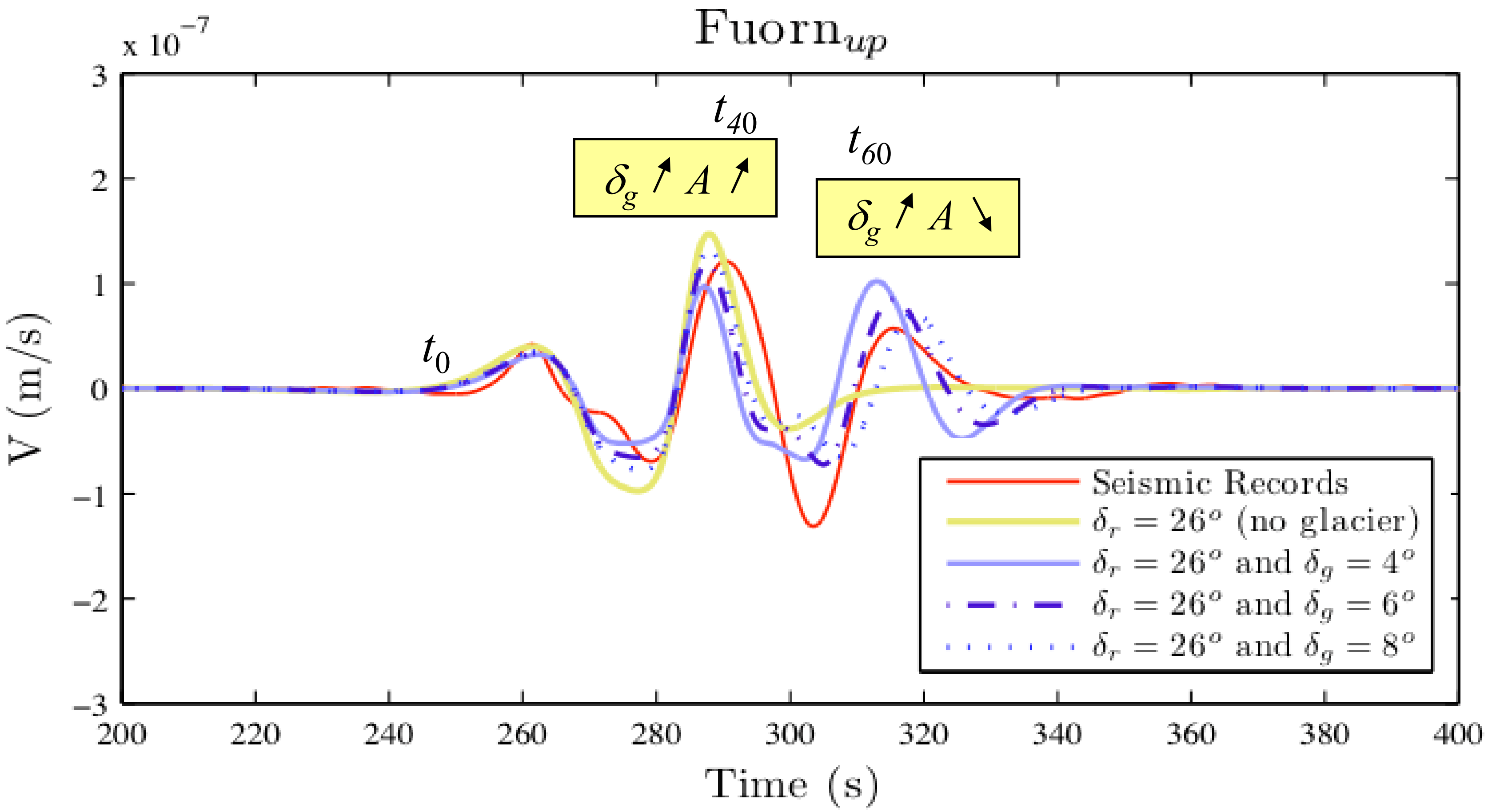
49 km from the landslide

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

Curvature effects

Curvature effects on flow dynamics has a major impact
on the generated seismic signal

Friction coefficient and simulated seismic waves



Comparison between simulated and recorded seismic signal

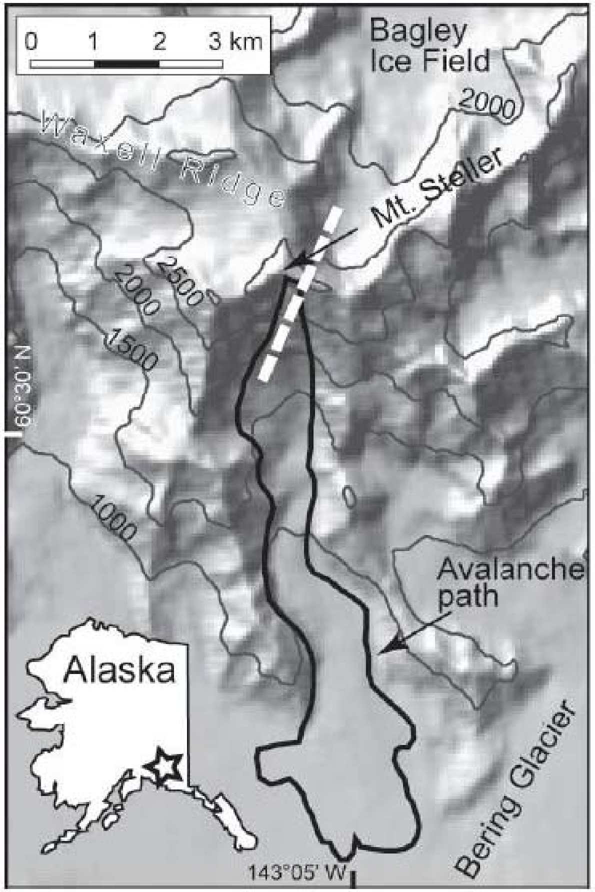
⬇

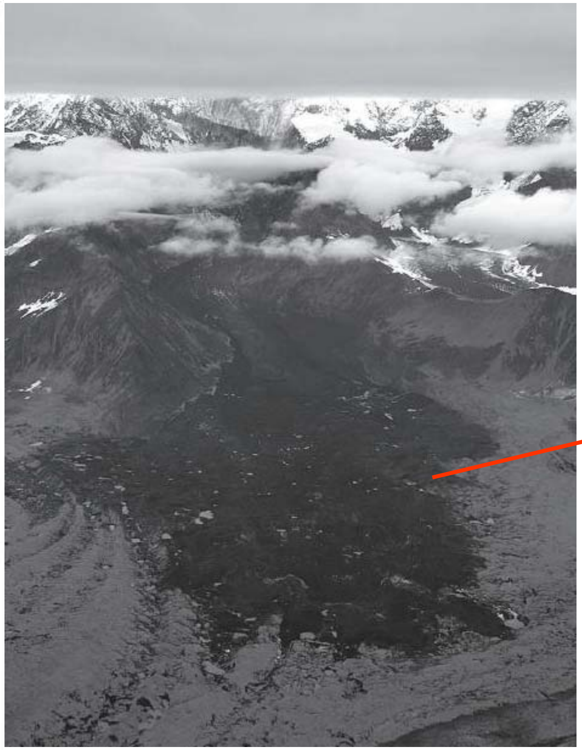
Calibration of the friction coefficients

Mt Steller rock-ice avalanche and associated landquake

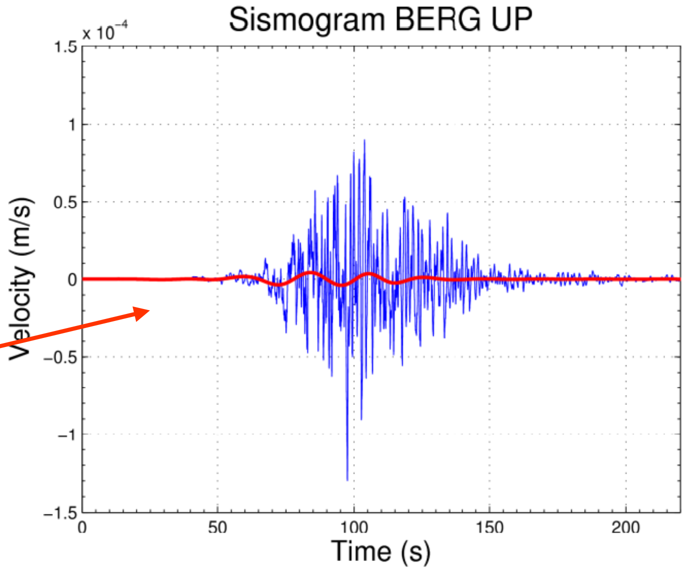
Alaska, September 2005

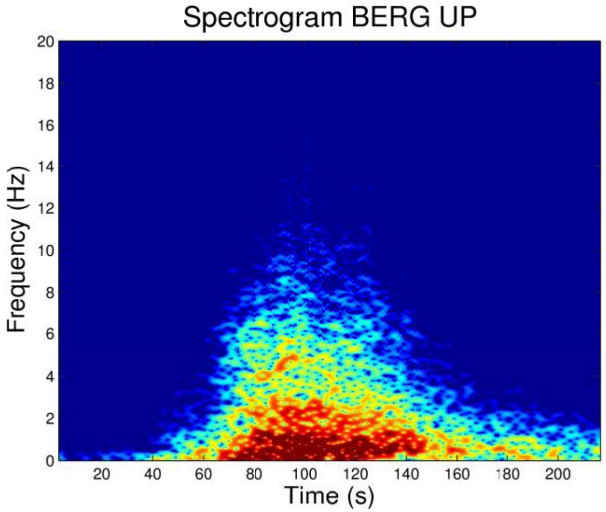
Recorded by 7 seismic stations from 37 km to 623 km





37 km from the source :





$V \sim 50\ \mathrm{Mm}^3$

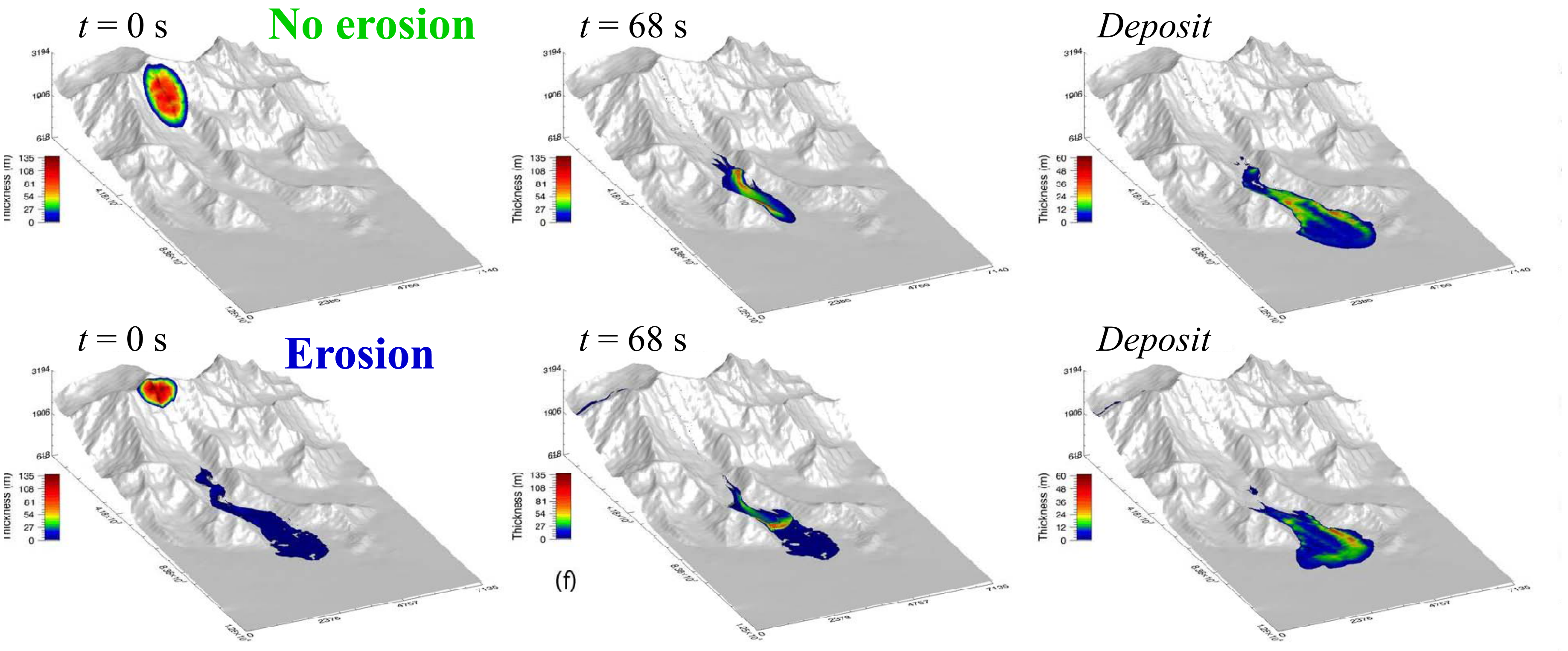
$R_f = 10$ km

$T_f \approx 130$ s

Ice **eroded** from the glacier:
$V \sim 20\ \mathrm{Mm}^3$

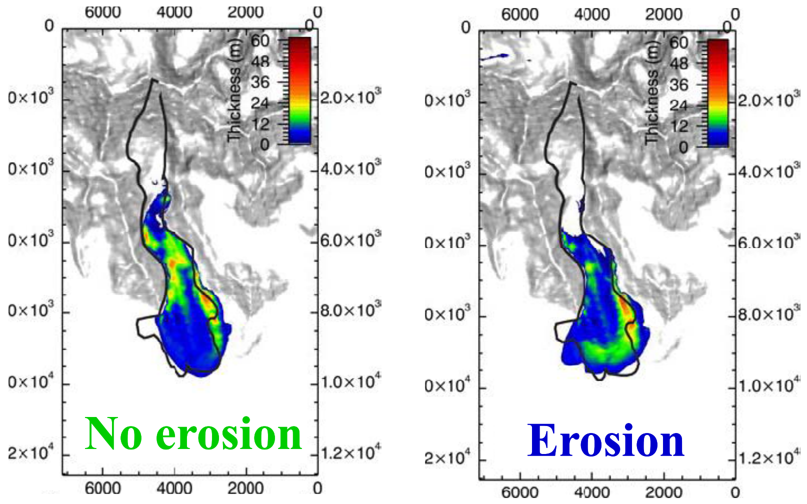
Huggel et al., 2008

Simulation of the Mt Steller rock-ice avalanche



$t = 0$ s **No erosion** $t = 68$ s *Deposit*

$t = 0$ s **Erosion** $t = 68$ s *Deposit*



No erosion **Erosion**

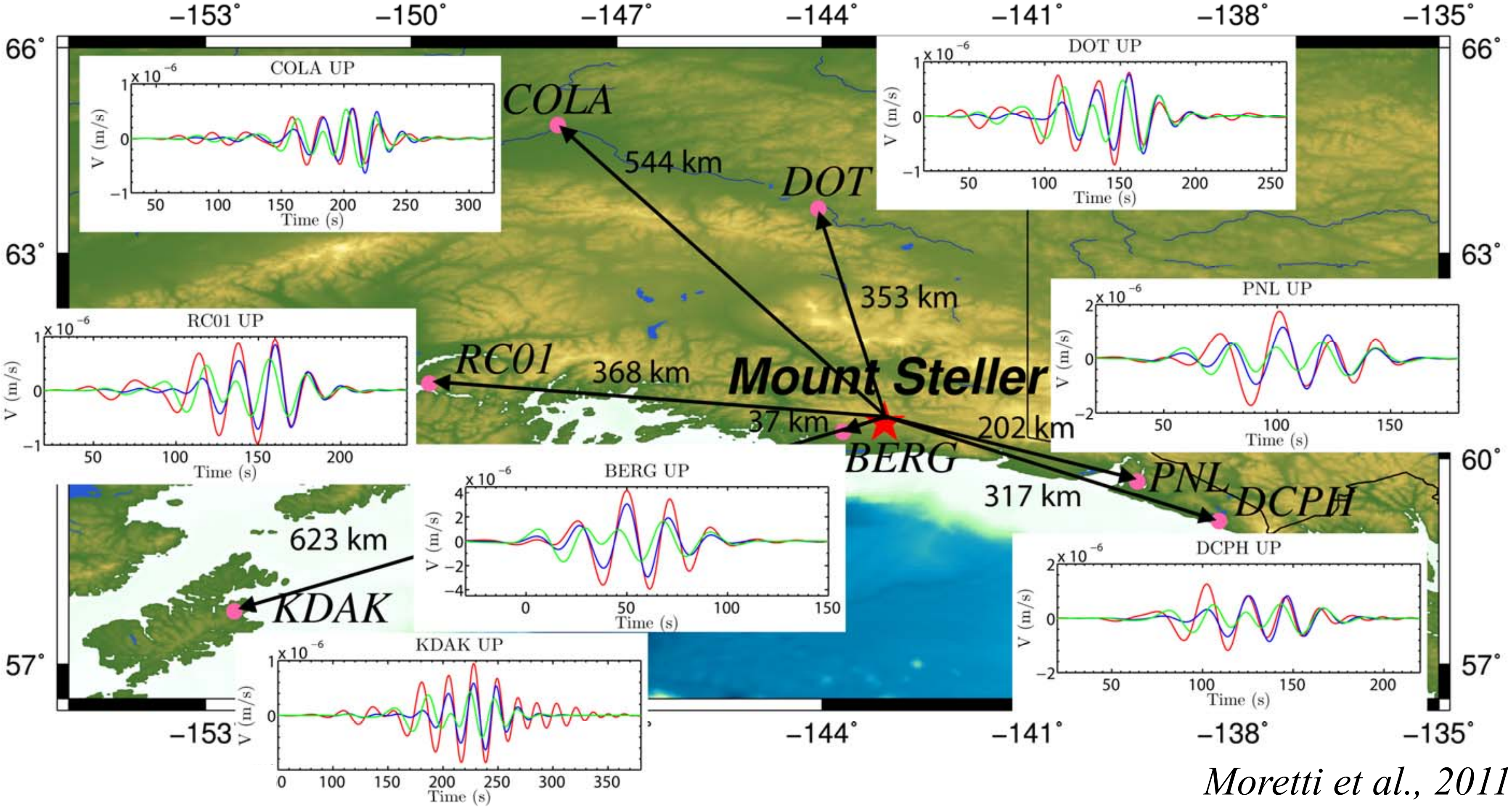
- **The two scenarios well match the deposit area**
- Mass accumulation at the front with erosion effects

Moretti et al., 2011

Simulation of the Mt Steller landquake

Vertical ground velocity *filtered between 20 s and 50 s* at 7 seismic stations

— **Data** — **No erosion** — **Erosion**



Moretti et al., 2011

The scenario with erosion better reproduces the observed waveform

Conclusion

- Seismic signal ➡ information on the temporal evolution of the volcano stability

- Scaling laws between seismic energy and signal duration

- Transfer ratio of potential energy to seismic energy ➡ **volume = *f* (seismic energy)**

- Near-field, long-period observations can **discriminate between alternative scenarios for flow dynamics**

- Estimation of the **basal friction** and **physical processes during the flow** can be inferred from simulation of the seismic signal

To do …

- Validation on well characterized events

- Systematic study of the **influence of the volume, topography, friction coefficient** on the simulated seismic signal

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