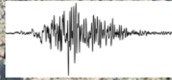
November 20th 2018, Le Studium, Orléans

Clues on gravitational flow dynamics from seismic inversion

Pauline Bonnet, 2018



Anne Mangeney[1,1']

with specialists in seismology (C. Hibert, E. Stutzmann, Y. Capdeville, C. Levy, etc.), mathematics (F. Bouchut, E. Fernandez-Nieto, G. Narbona-Reina, J. Sainte-Marie), acoustics (J. De Rosny, X. Jia; R. Toussaint)

[1] Institut de Physique du Globe de Paris, Université Paris Diderot, SPC

[1'] Equipe ANGE INRIA-Laboratoire Jacques Louis Lions

Outline

I – Introduction : landslides and seismic waves

II – Inversion/modelling of *low frequency* forces generated by landslides

III – Insight from *high frequency* seismic data

IV – Monitoring landslide activity in link with volcanic activity

V – Conclusion

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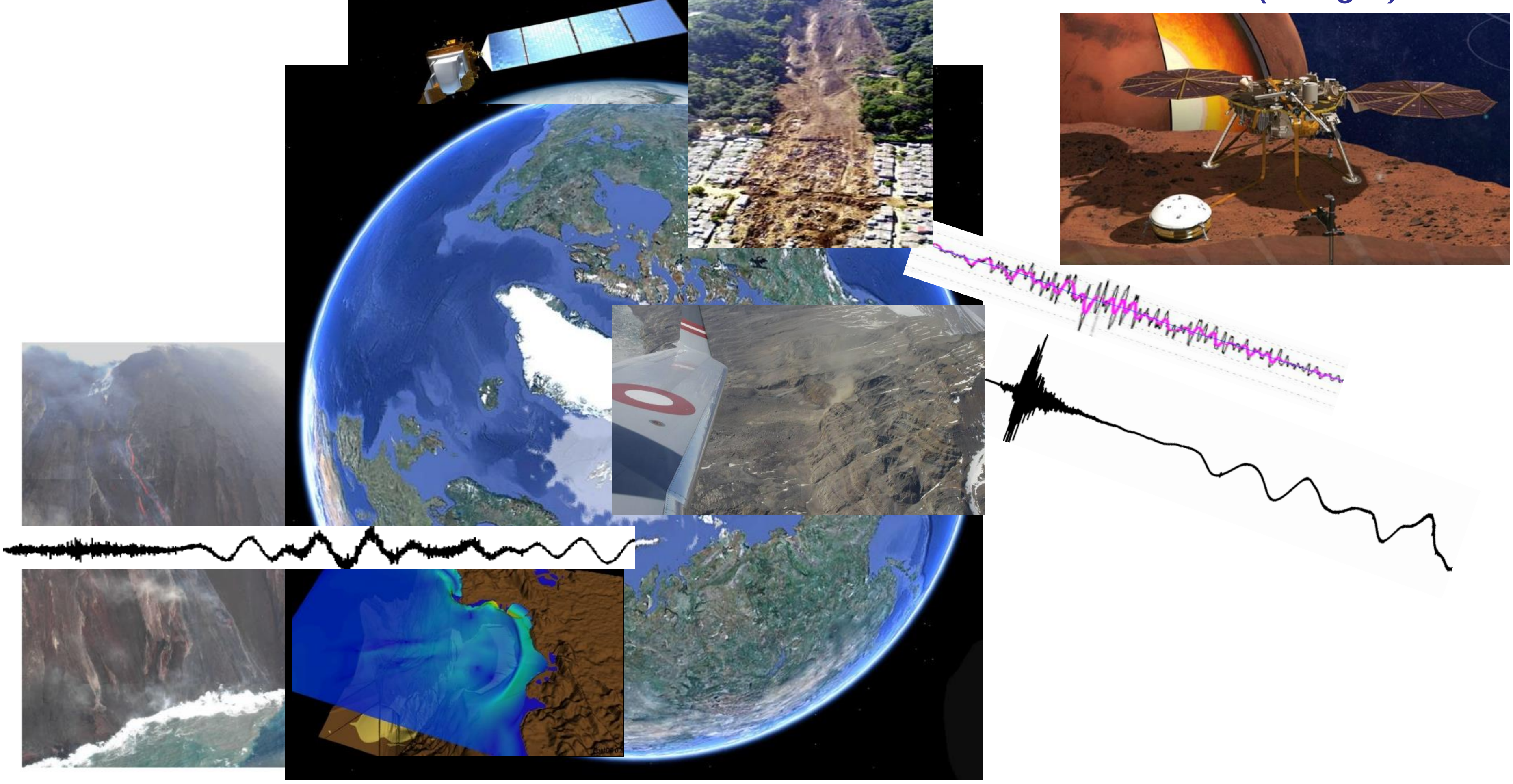
Landslides and seismic waves

- Erosion processes at the Earth surface and on telluric planets
- Risk assessment on Earth in relation with seismic, volcanic, climate forcing

Mars (InSight)



Challenges

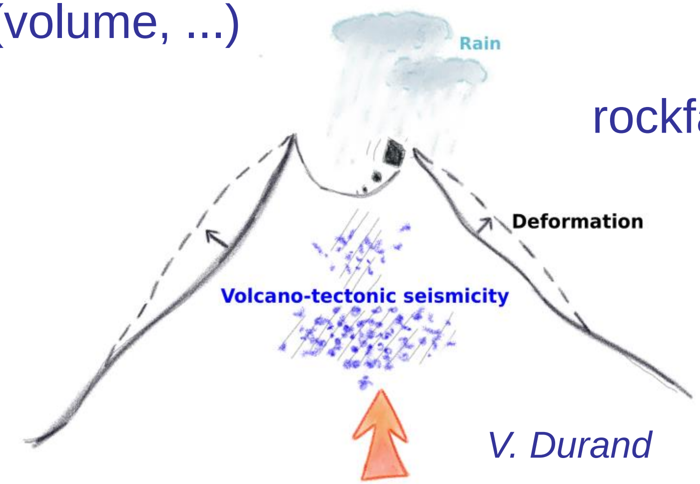
- Predict velocity and runout extent

explain and quantify the high mobility of natural landslides …

Lack of field measurements of their dynamics

- Understand and quantify their occurrence/properties in link with external forcing

detection, localization, characterization (volume, ...)



rockfalls triggering

V. Durand

Seismic data ⟷ Granular flow mechanics and modelling

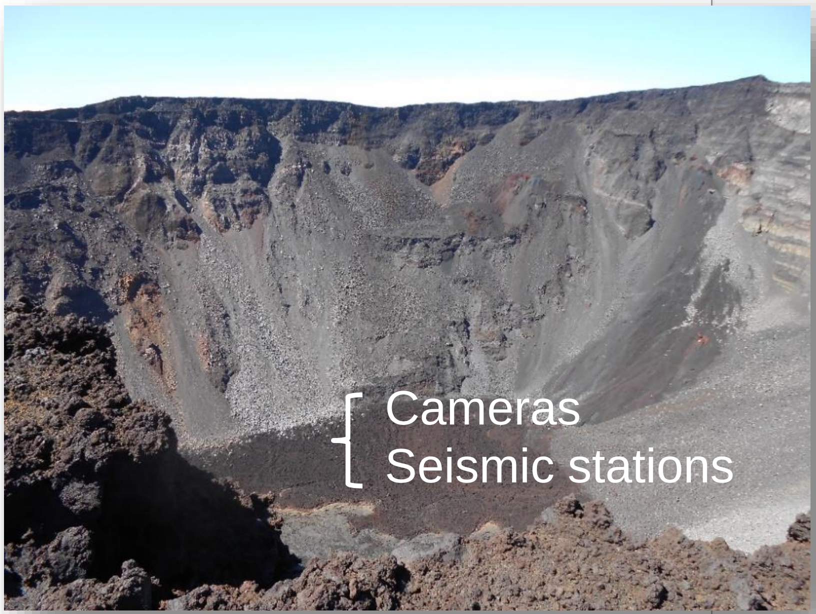
Seismic signal generated by rockfalls

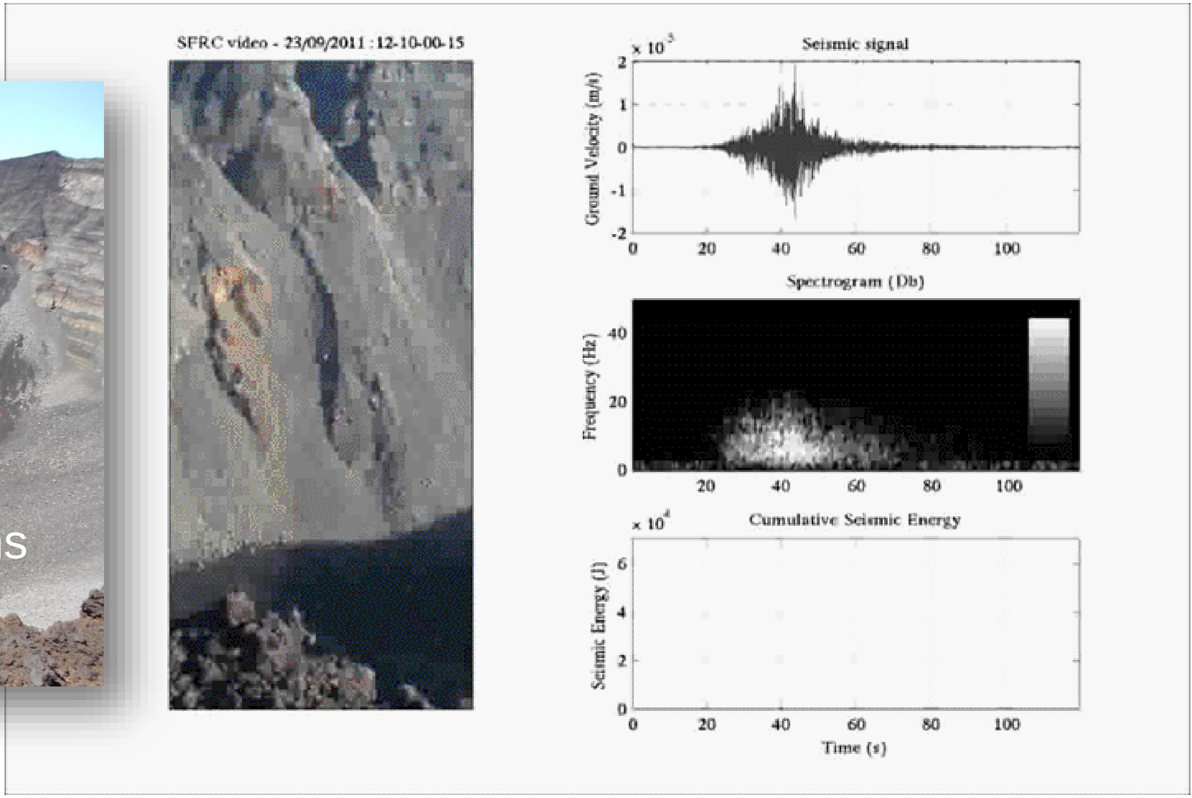
Piton de la Fournaise volcano, La Réunion

SLIDEQUAKES

European Research Council
Established by the European Commission

Hibert, et al. 2011, 2014, 2017, Durand et al., 2018

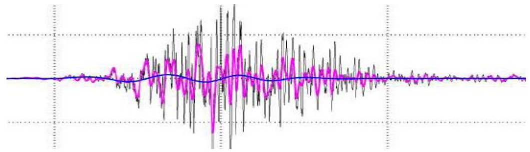




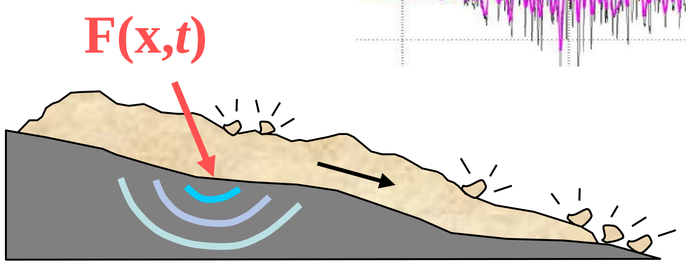
$$t_{\text{seismic}} \approx t_{\text{flow}}$$

Decrypt processes impacting seismic waveform ?

0.01 < f < 20 Hz

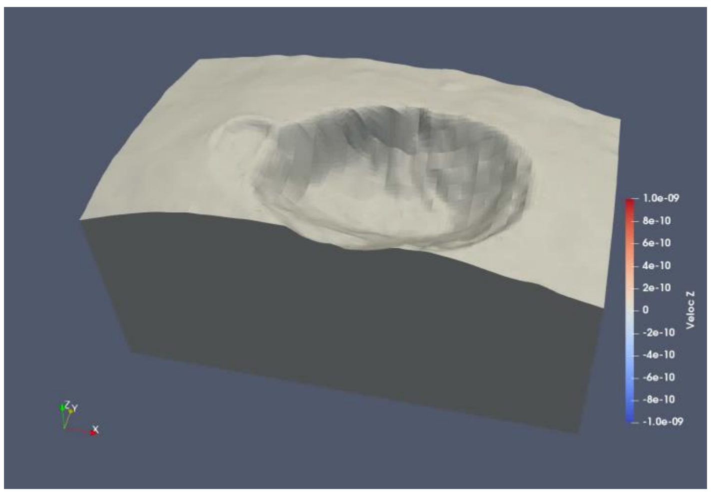


Convolution of :



- Source

Mass, geometry, rheology, topography, particle agitation, fluid content …



Kühnert et al., 2018

- Wave path from source to station

Ok at low frequencies f < 0.1-0.2 Hz (5-10 s)
Challenging at high frequencies f > 1Hz !

Earth heterogeneity, topography

How can we separate the processes ?

Physical simulation of field scale granular flows

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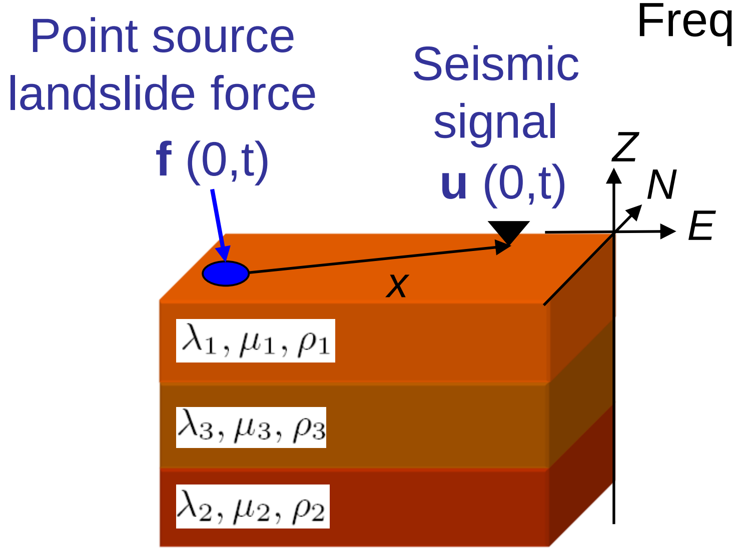
Force at the origin of seismic waves

Deconvolution of long period (T > 5-10 s) seismograms

$$\mathbf{u}_i(x,t) = \mathbf{g}_{ij}(x,t) * \mathbf{f}_j(0,t)$$

Green's function for signal component i and force direction j



Frequency domain : U, G, F Fourier transform of **u**, **g**, **f**

$$U(\omega) = G(\omega)F(\omega)$$

➡ Force : $F = (G'G)^{-1}G'U$

➡ Inverse Fourier transform **f** (0,t)

Kanamori and Given, 1982; Kanamori et al., 1984

Force at the origin of seismic waves

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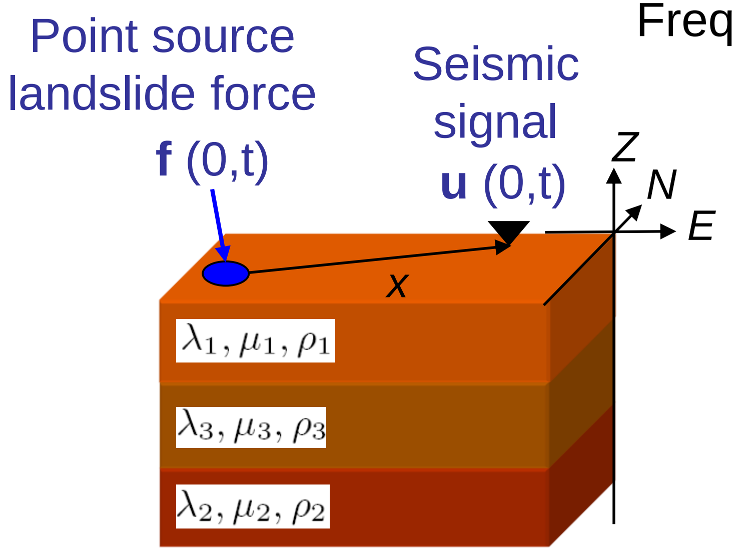

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Kanamori and Given, 1982; Kanamori et al., 1984

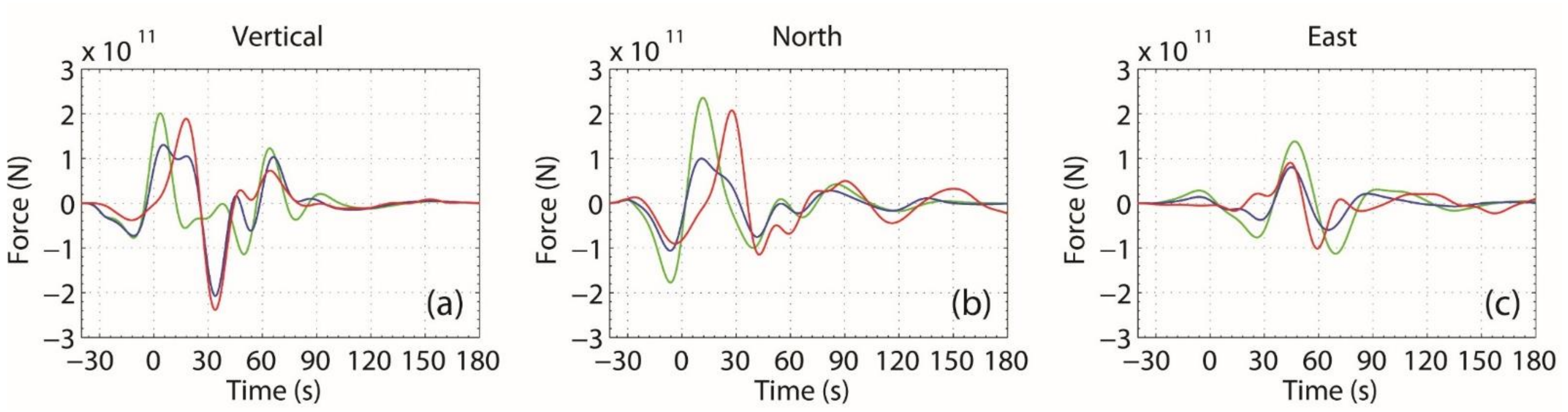
Recovered with good accuracy using one seismic station !

Kawakatsu, 1989

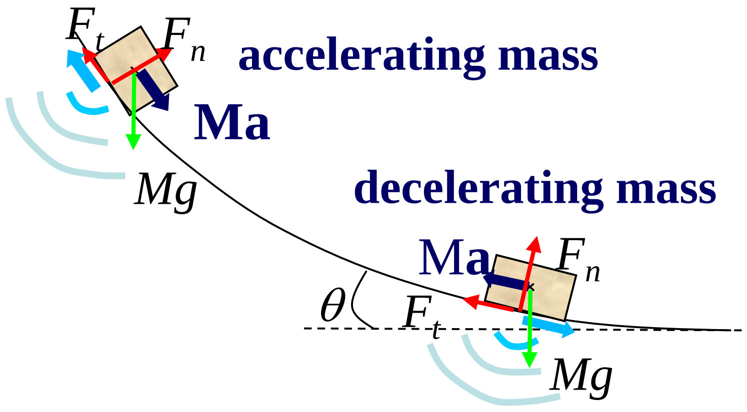
Zhao, Moretti, Mangeney, Stutzmann, Kanamori, Capdeville, Calder, Hibert et al., 2015

Sergeant, Mangeney, Stutzmann, Montagner, Walter, Moretti, and Castelnau, 2016

Force inverted from seismic data



Moretti, Mangeney, Capdeville, Stutzmann, Huggel, Schneider, Bouchut 2012

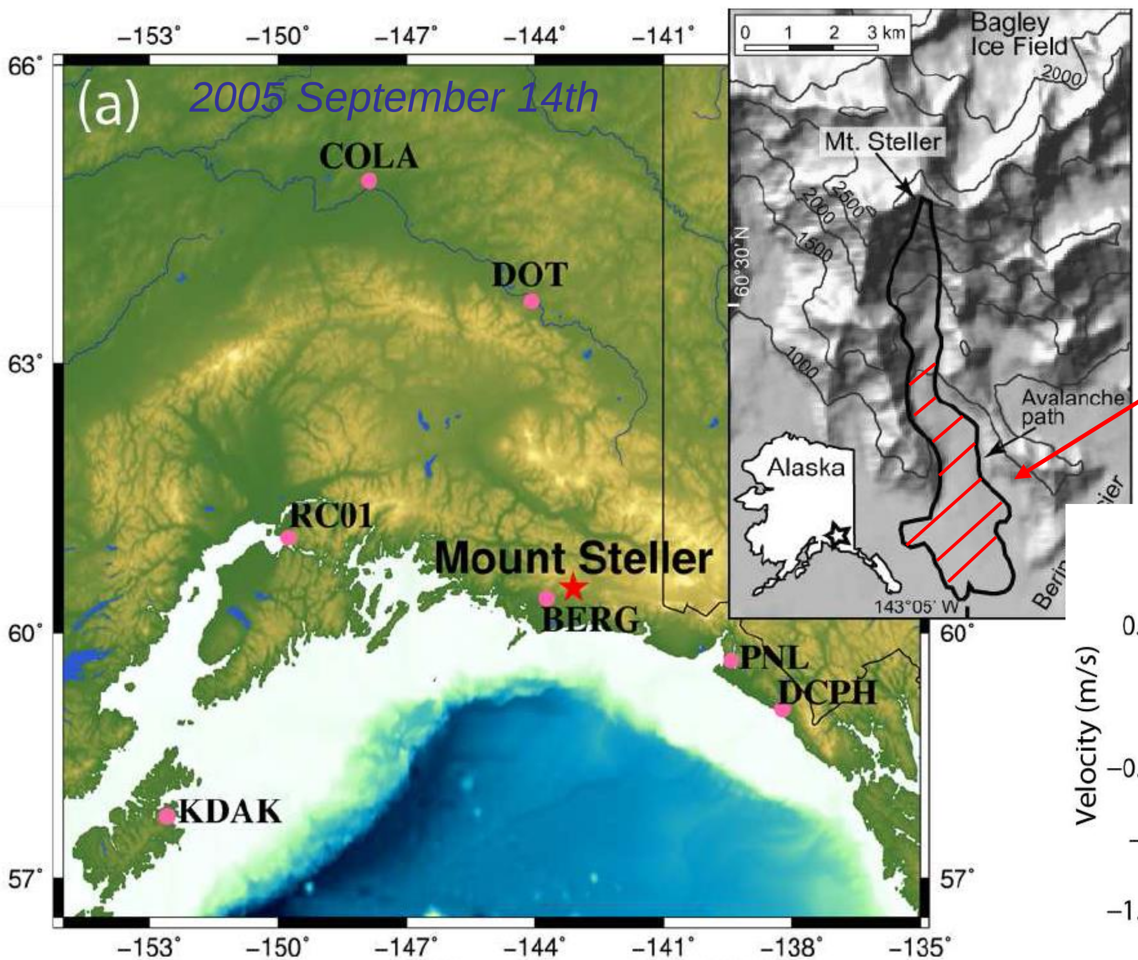


Brodsky et al. 2003

Mt-Steller rock-ice avalanche

Simulation of landslide and force history

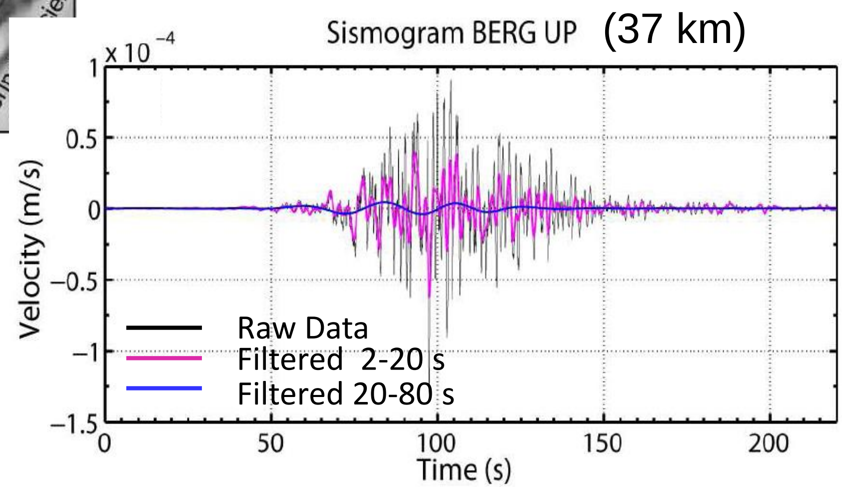
Quantify the role of erosion in landslide dynamics ?



Traveled distance ~9 km

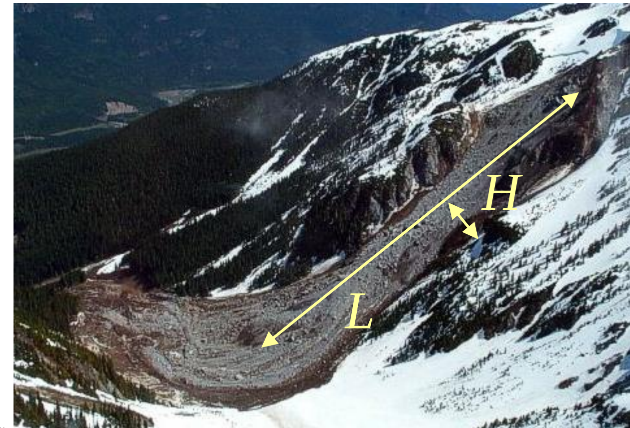
Volume : 40-60 $\times 10^6$ m^3

Material eroded along the path: ~20 $\times 10^6$ m^3



Moretti, Mangeney, Capdeville, Stutzmann, Huggel, Schneider, Bouchut 2012

Thin layer models for natural landslides

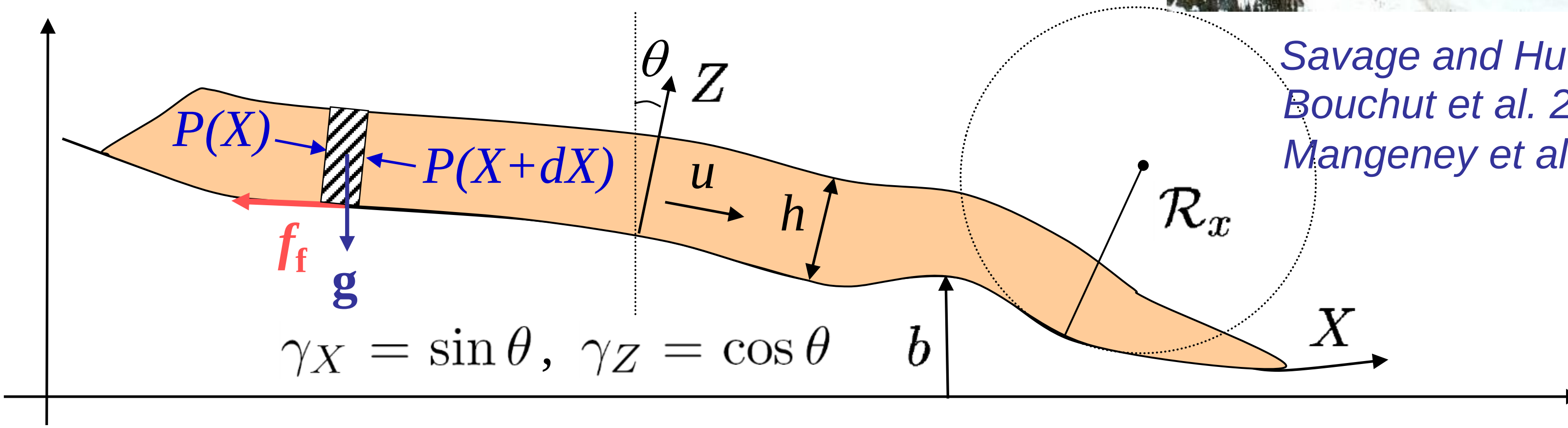


- Flow on complex natural topography

high computational cost $\Rightarrow$ $\epsilon = \frac{H}{L} << 1$ small aspect ratio

- Depth-averaged thin layer model

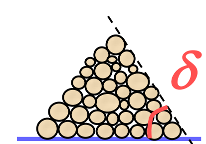
$$h = \mathcal{O}(\epsilon) \quad \nabla b = \mathcal{O}(\epsilon) \quad u^{\mathbf{x}} = \overline{u^{\mathbf{x}}}(t, \mathbf{x}) + \mathcal{O}(\epsilon^2)$$



Savage and Hutter, 1989
Bouchut et al. 2003,
Mangeney et al. 2005, 2007

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

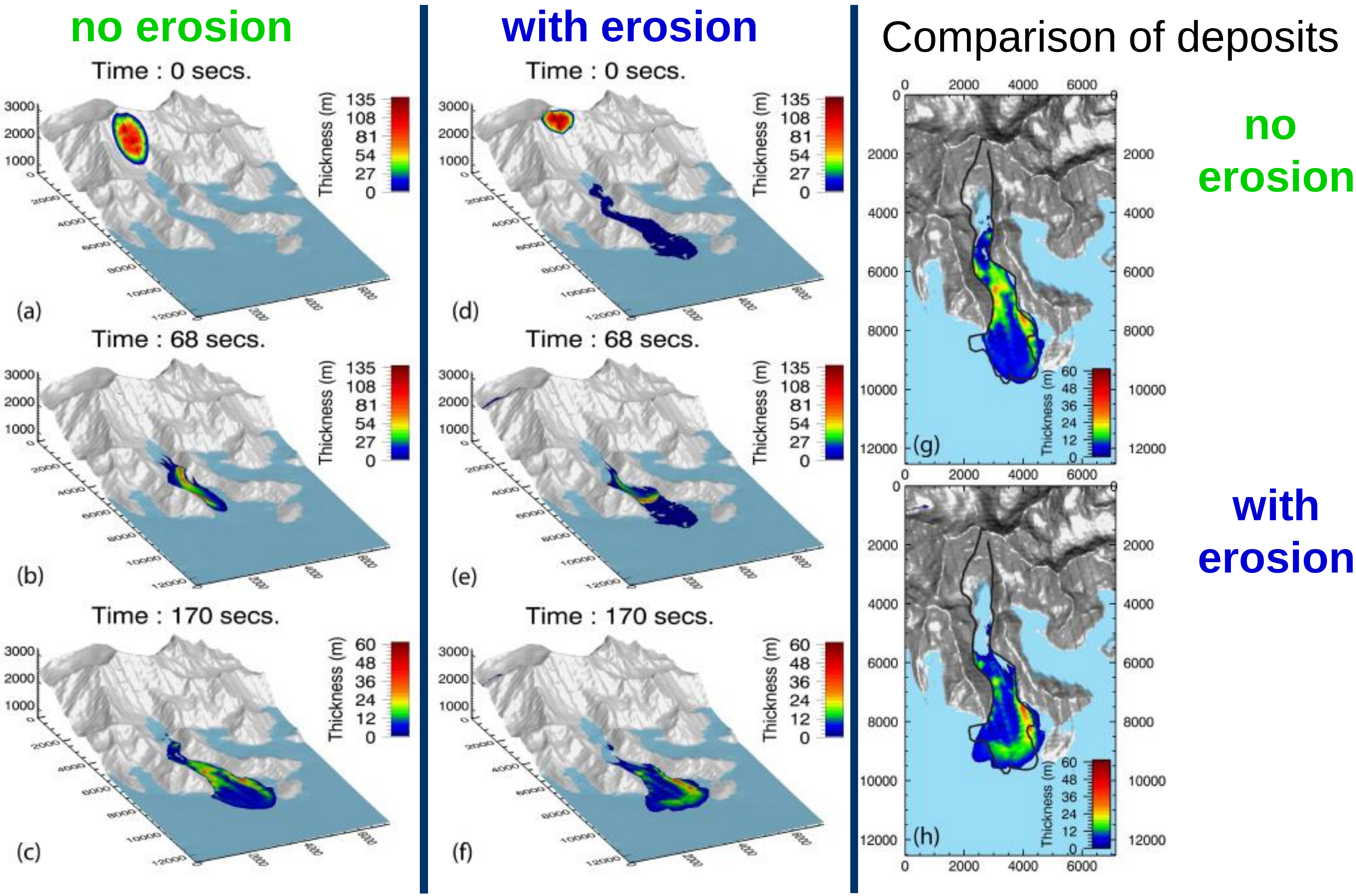
$\mu = \tan\delta$



3D topography (code SHALTOP)

$\delta \approx 25°$ (glass beads), $35°$ (debris)

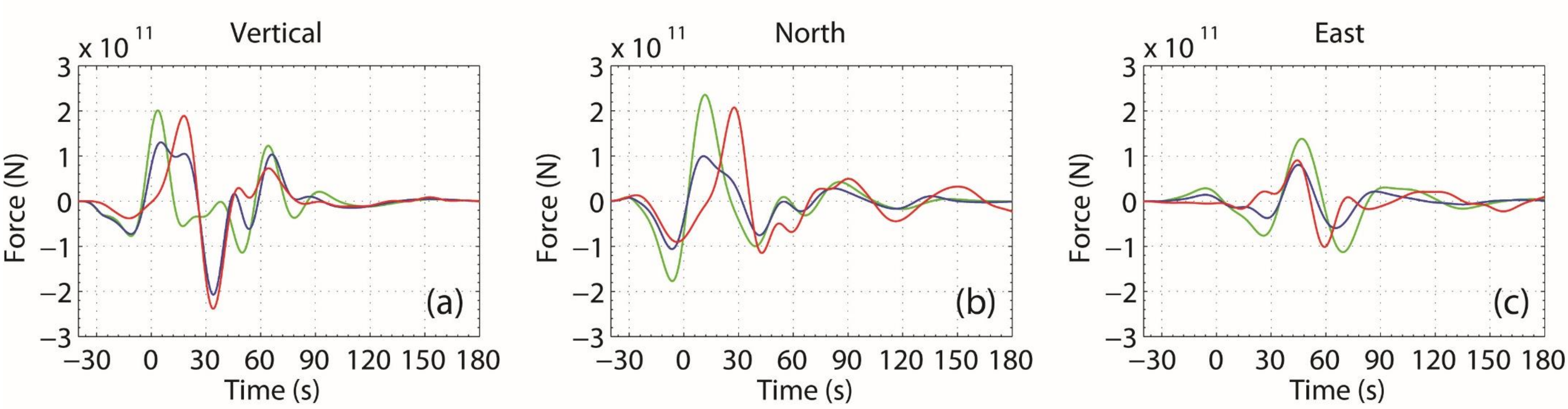
Simulation of the Mt-Steller landslide



The deposit area is not enough to constrain landslide models !!

Low frequency: inverted and simulated force

Force filtered between 20-80s



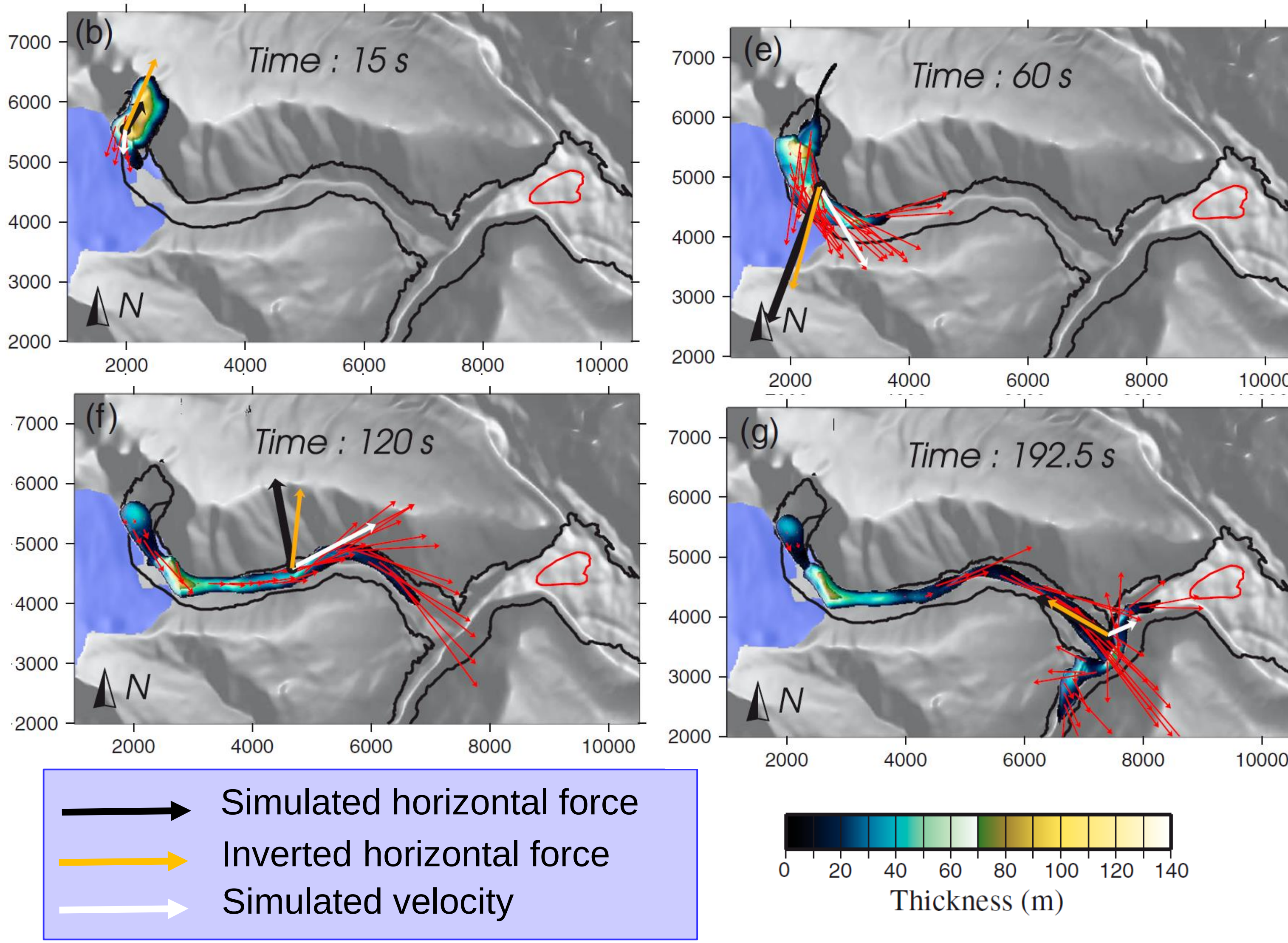
Data
Scenario without erosion
Scenario with erosion

Taking into account erosion is necessary to reproduce the dynamics

Moretti, Mangeney, Capdeville, Stutzmann, Huggel, Schneider, Bouchut 2012

Sensitivity to friction coefficient

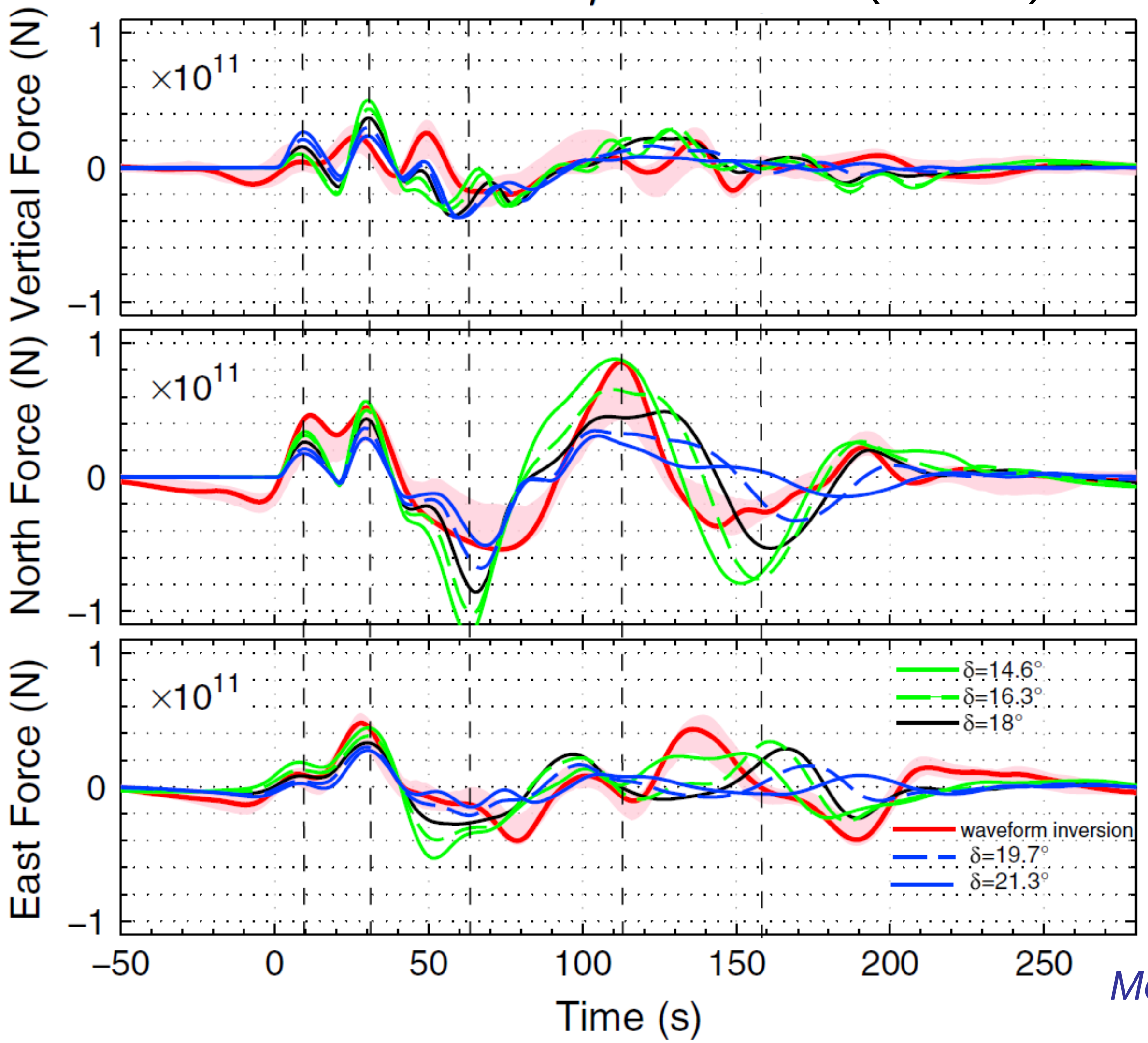
Simulation of Mount Meager landslide $V = 50 \times 10^6$ m^3



Moretti, Allstadt, Mangeney, Capdeville, Stutzmann, Bouchut 2015

Sensitivity to friction coefficient

Best scenario $\mu = 0.33$ (δ=18°)

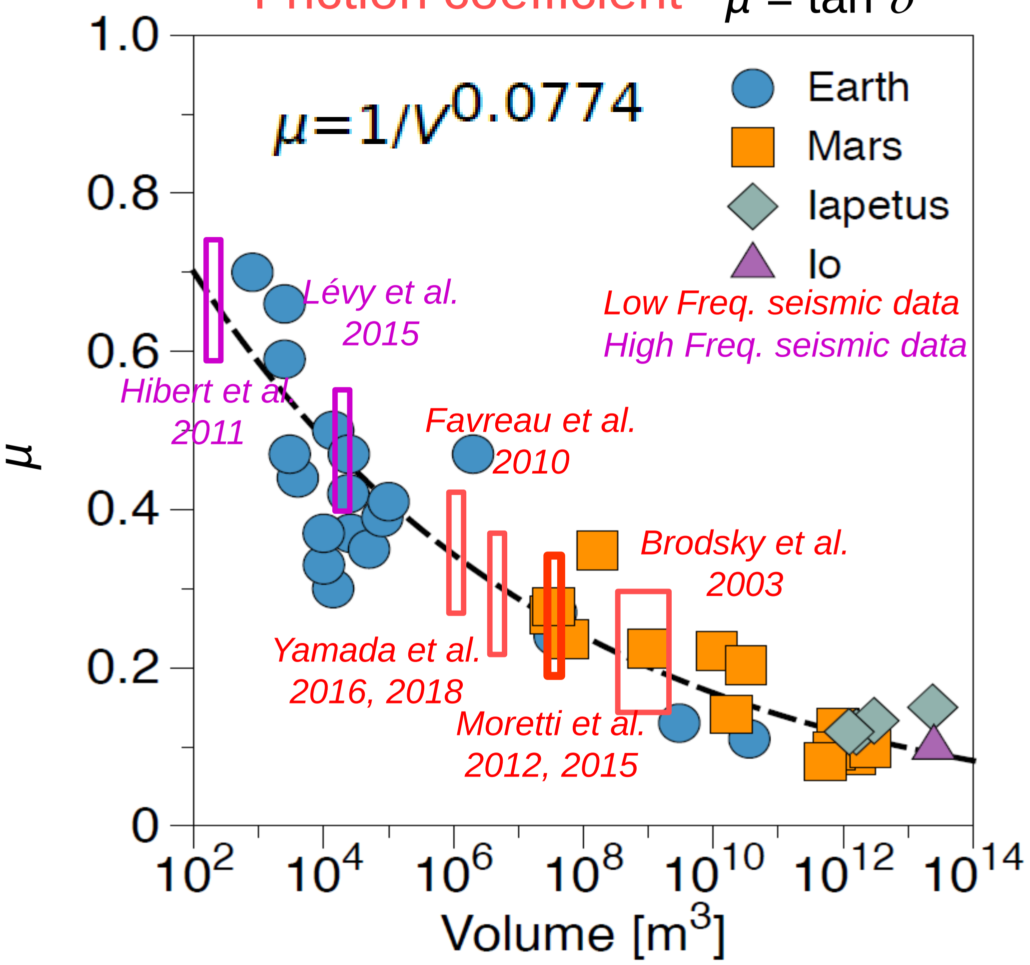


Moretti et al., 2016

Very small friction coefficient for this large landslide (V = 50 $\times 10^6$ m^3)

Empirical friction laws based on seismic data

Friction coefficient $\mu = \tan\delta$



Friction weakening with volume (or velocity, etc.)

Physical origin ?

Lucas et al., 2014, Delannay et al., 2018, Yamada et al., 2018

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- a – Laboratory experiments
- b – Field measurements/numerical modelling

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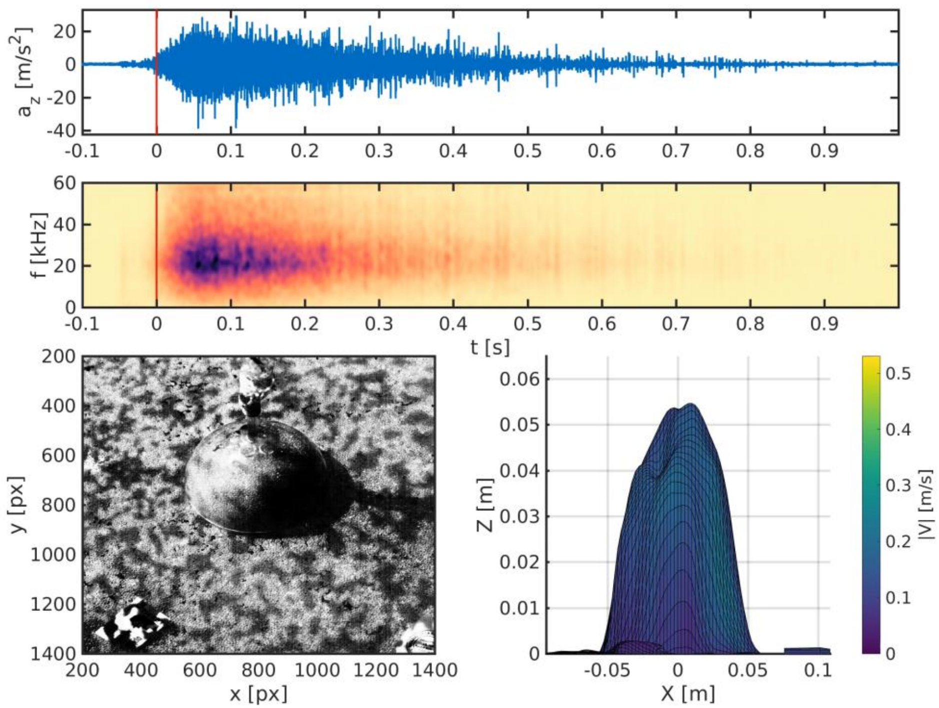
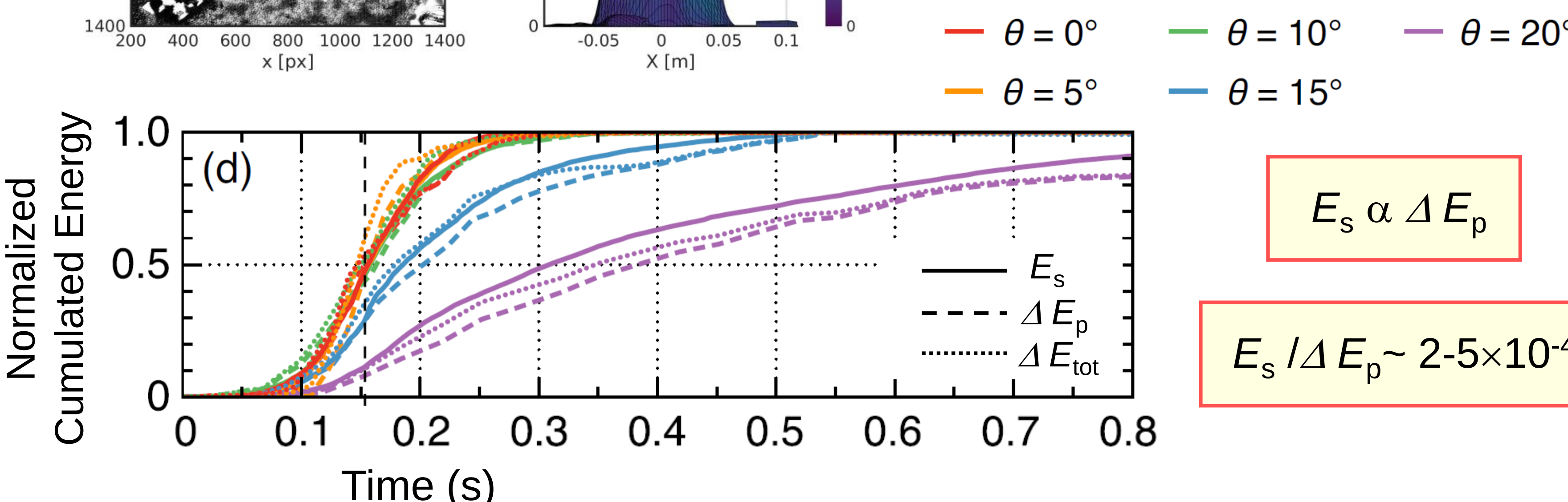
Physical origin of high frequency seismic waves ?



Laboratory experiments of granular flows and seismic emissions

Glass beads d = 2 mm

- Optics : fast camera 5000 fps
- Acoustics : accelerometers [10Hz-54kHz]



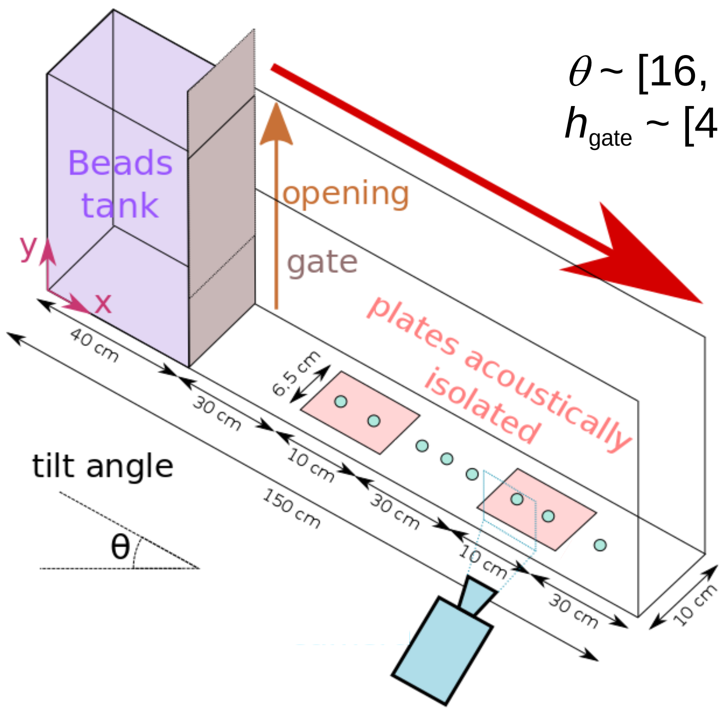
$E_s \, \alpha \, \Delta E_p$

$E_s / \Delta E_p \sim 2\text{-}5 \times 10^{-4}$

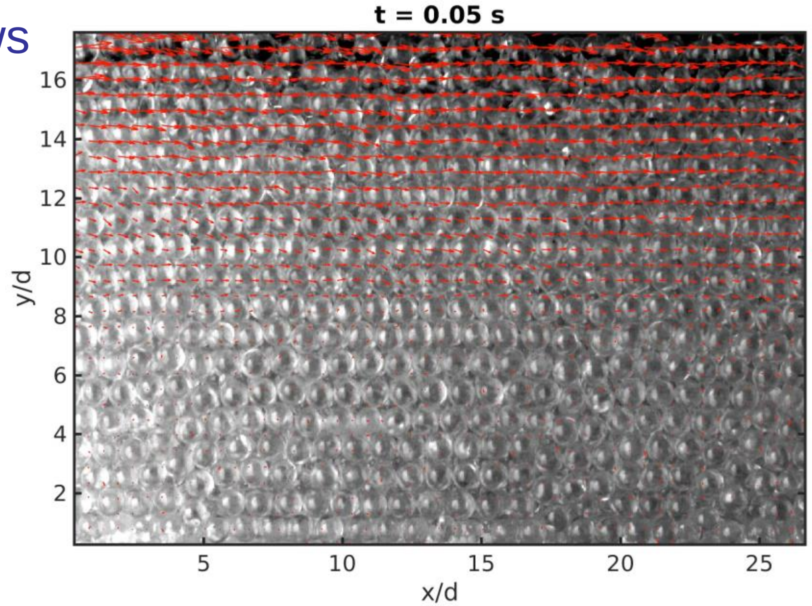
Farin et al. 2018, Bachelet et al. 2018, coll. Institut Langevin, EOST

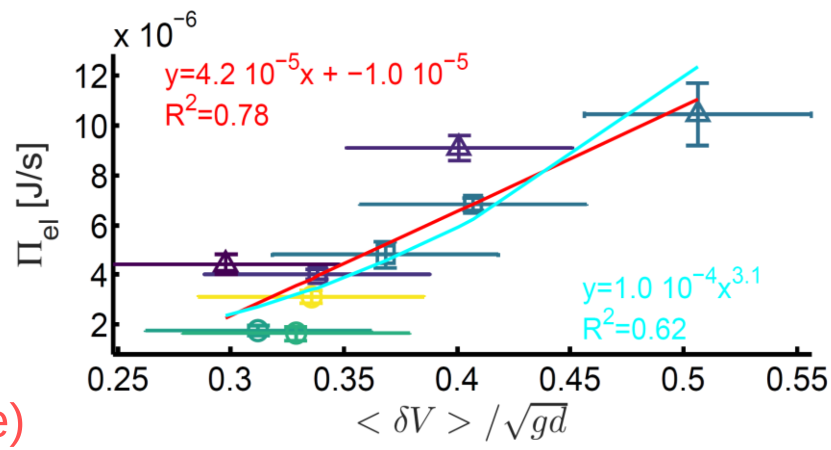
Physical origin of high frequency seismic waves ?

Almost steady and uniform free surface flows



$\theta \sim [16, 18]°$
$h_{gate} \sim [4, 8]$ cm





Velocity fluctuations

Seismic energy per second $\Pi_{el} \propto \delta V \propto V$

$f_{mean} \sim f_{\text{Hertz's contact theory}}$

➡ grain collisions (granular temperature)

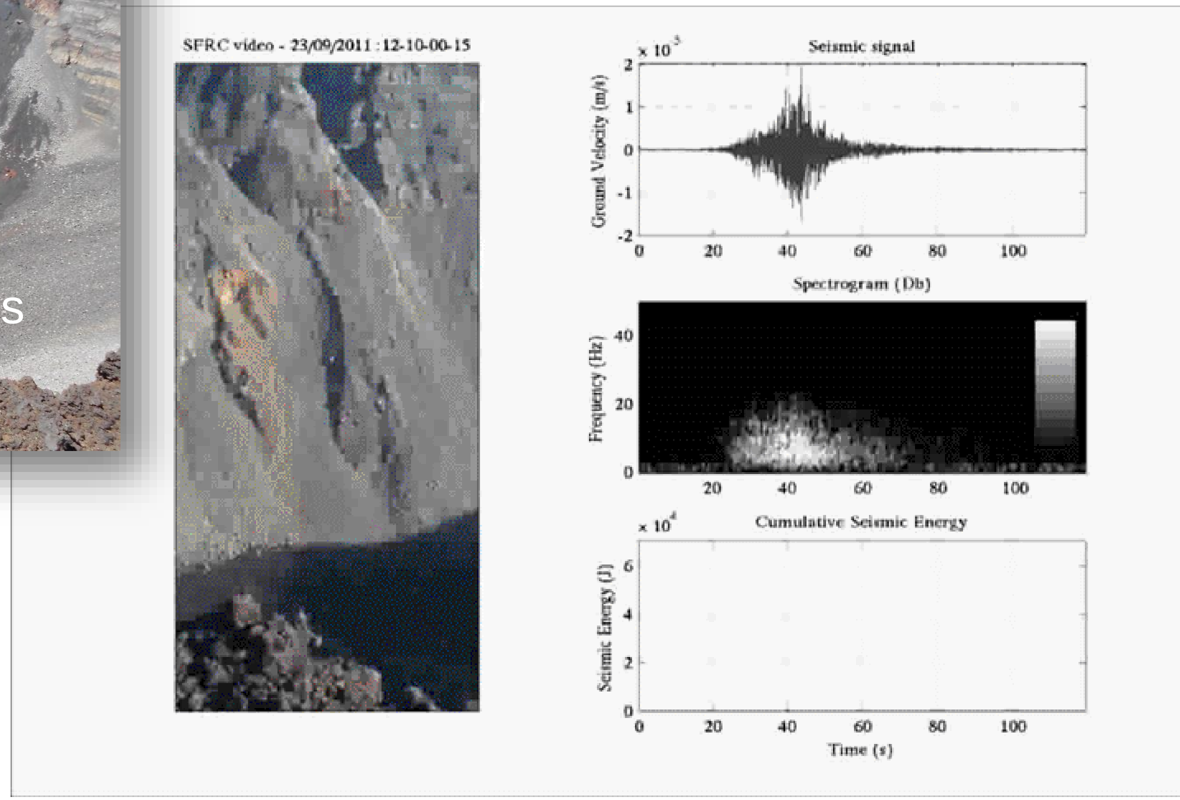
Bachelet et al. 2018, Taylor and Brodsky 2017

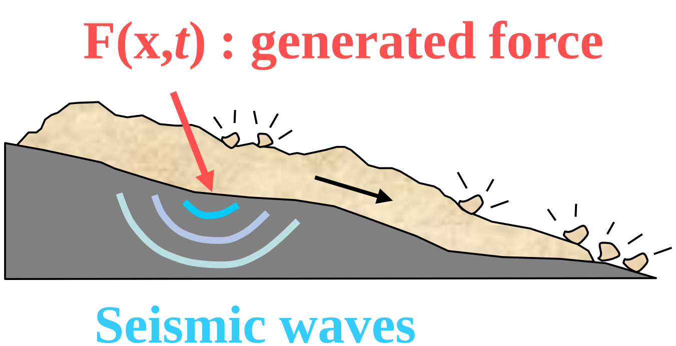
Seismic signal generated by rockfalls

SLIDEQUAKES

Piton de la Fournaise volcano, La Réunion

Hibert, et al. 2011, 2014, 2017, Durand et al., 2018





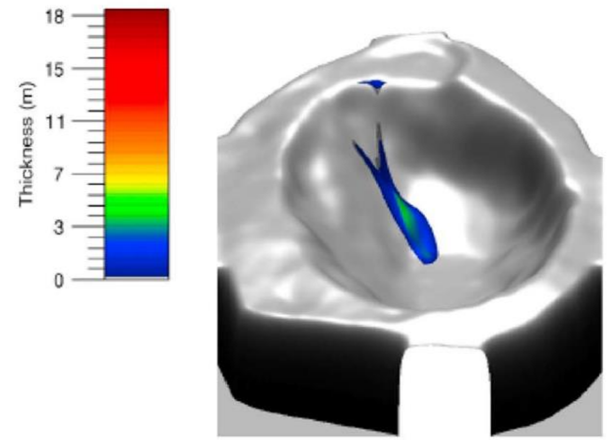
$$t_{\text{seismic}} \approx t_{\text{flow}}$$

From seismic energy to rockfall volume

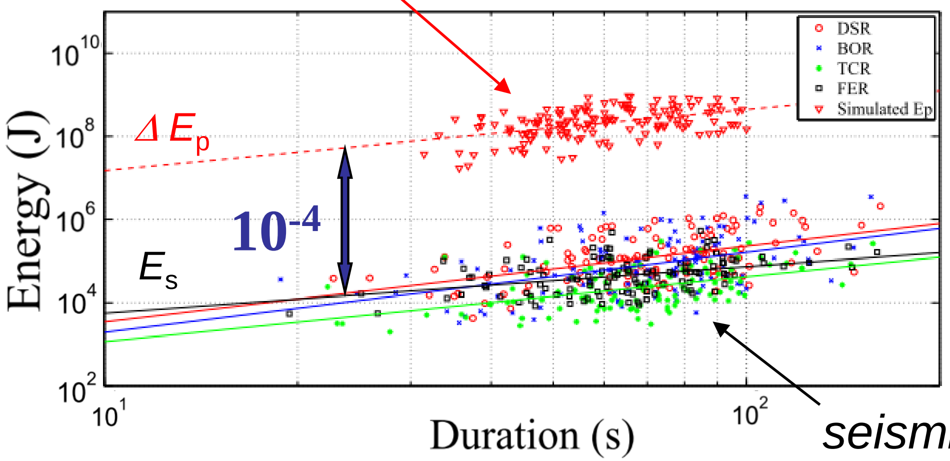
- Power law energy versus duration :

$$E_{\text{seismic}} \; \alpha \; t_s^{\;\beta} \quad \text{and} \quad \Delta E_{\text{potential}} \; \alpha \; t_f^{\;\beta}$$

Piton de la Fournaise



simulation with friction angle δ = 35°



seismic data

t_s or t_f ($t_s \sim t_f$)

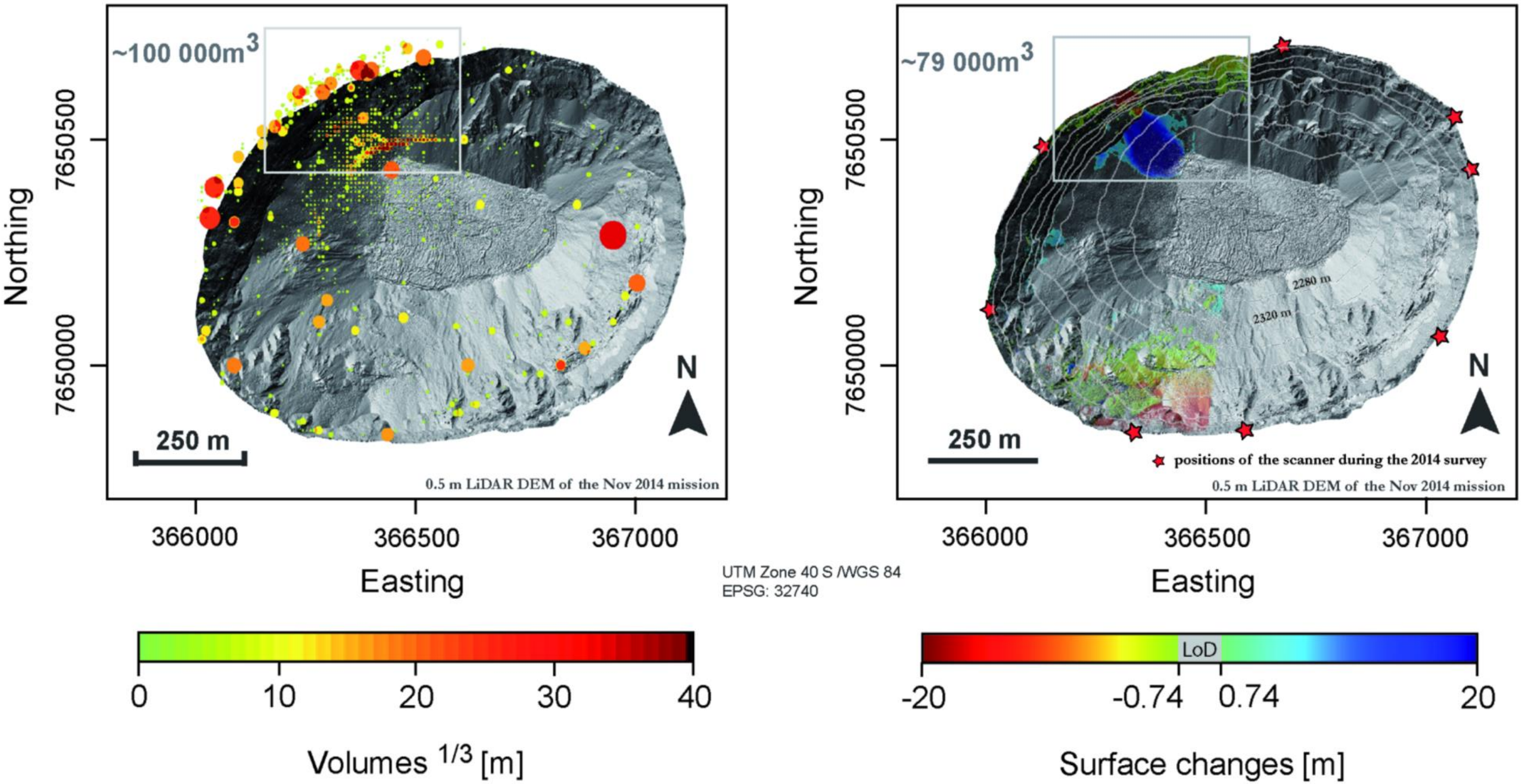
$$R_{s/p} = E_s / \Delta E_p \sim 10^{-4}$$

Hibert et al., 2011, 2014, 2017

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

Volumes: seismic and laser/photogrametry

Durand et al., 2018

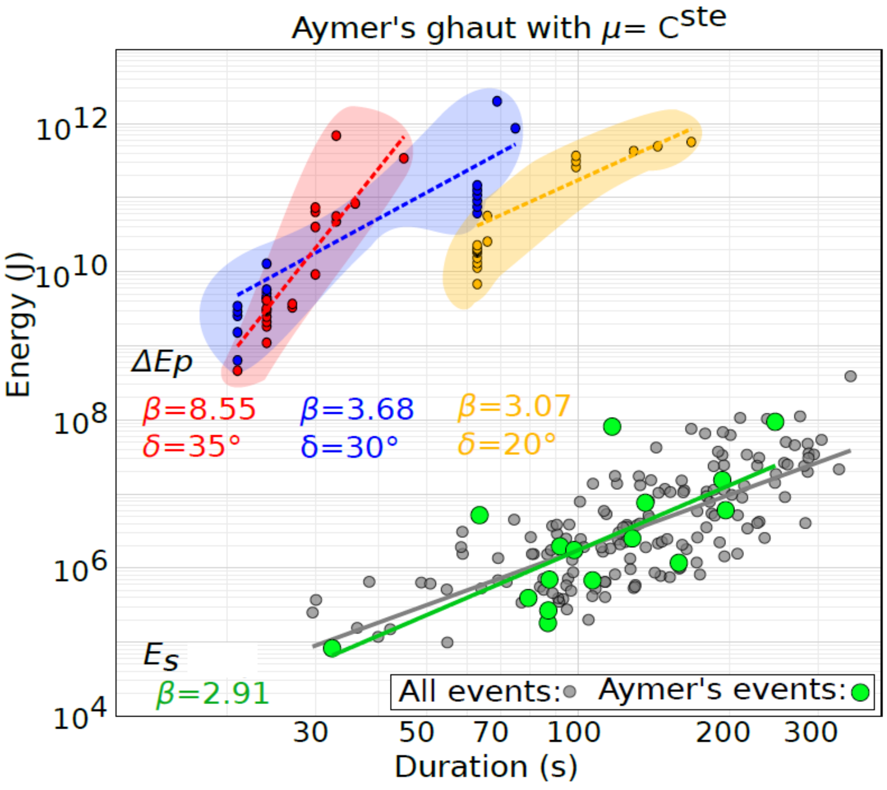


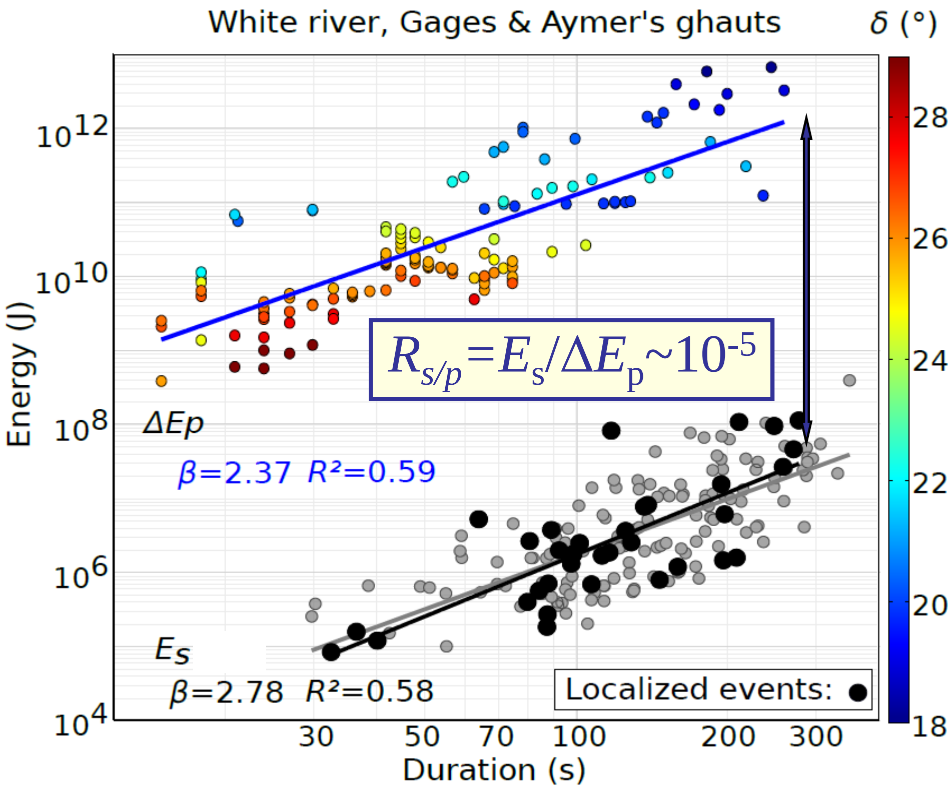
- Good agreement in the North-East part
- Seismic data: higher temporal resolution than photogrammetry

Friction weakening signature on seismic data

Rockfalls and pyroclastic flows in Montserrat

$\mu = \tan\delta = 1/V^{0.0774}$





Friction weakening makes it possible to reproduce seismic data

Levy, Mangeney, Bonilla, Hibert, Calder, Smith, 2015

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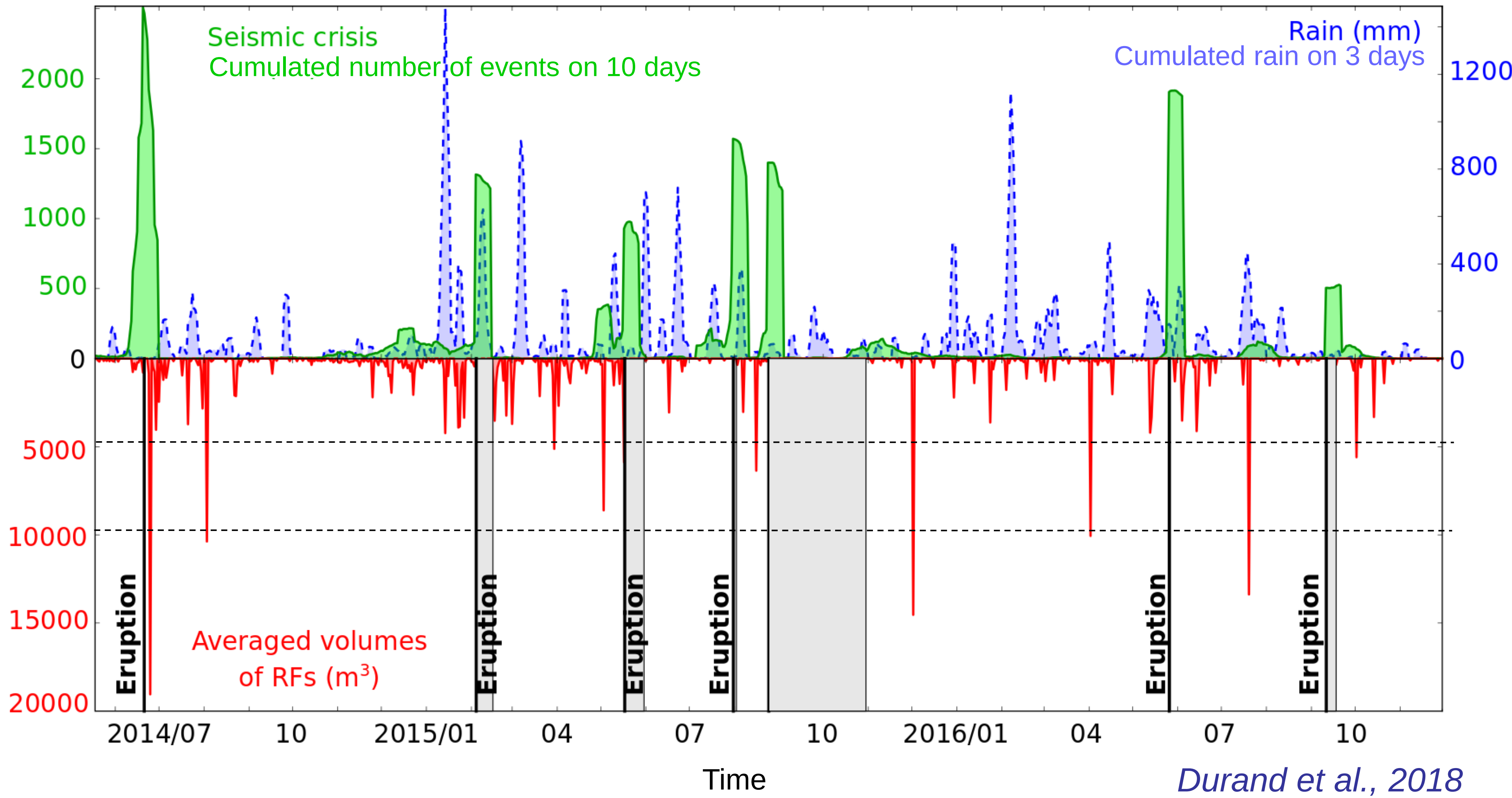
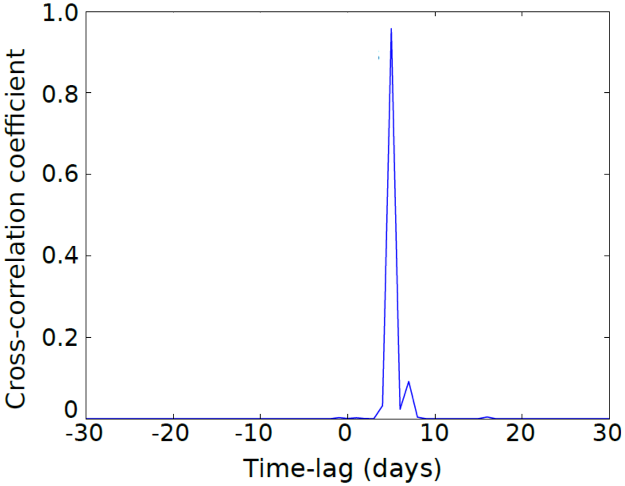
Rockfall triggering

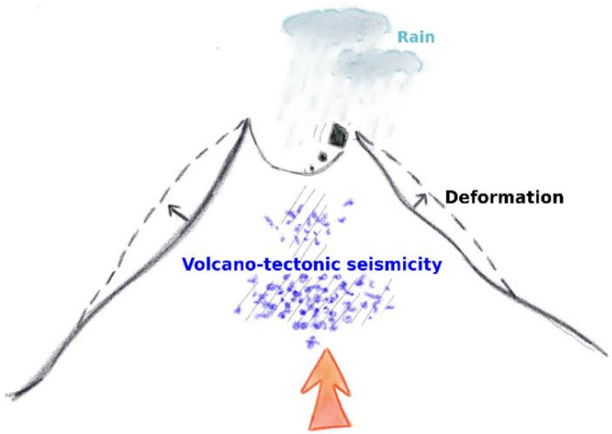


Durand et al., 2018

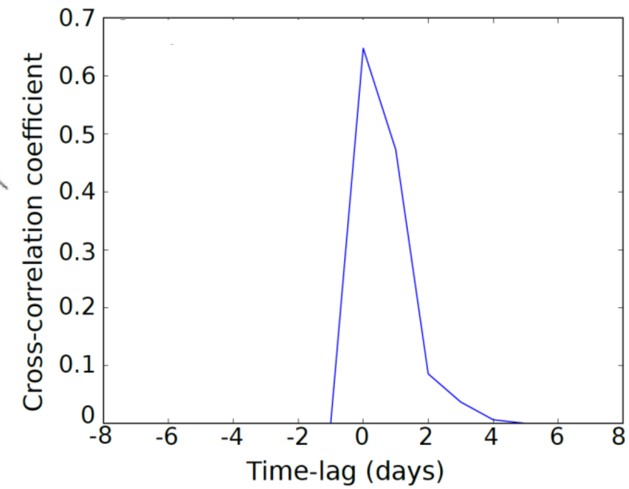
Rockfall triggering

Mean volume of rockfalls
& earthquakes magnitude





Mean volume of rockfalls
& rain



- Strong correlation between rockfall volume and cumulative magnitude/number of Volcano-Tectonic events (time-lag 1-20 days)
- Weak correlation with maximum amplitude of volcano-tectonic seismicity
- Moderate correlation with rain with time-lag of 1-5 days

Durand et al., 2018

Conclusion

- Force history at low frequency :

constrain on landslide volume, rheology, physical processes involved (erosion, fluid content, etc.) when compared to physical simulation

- Energy at high frequency :

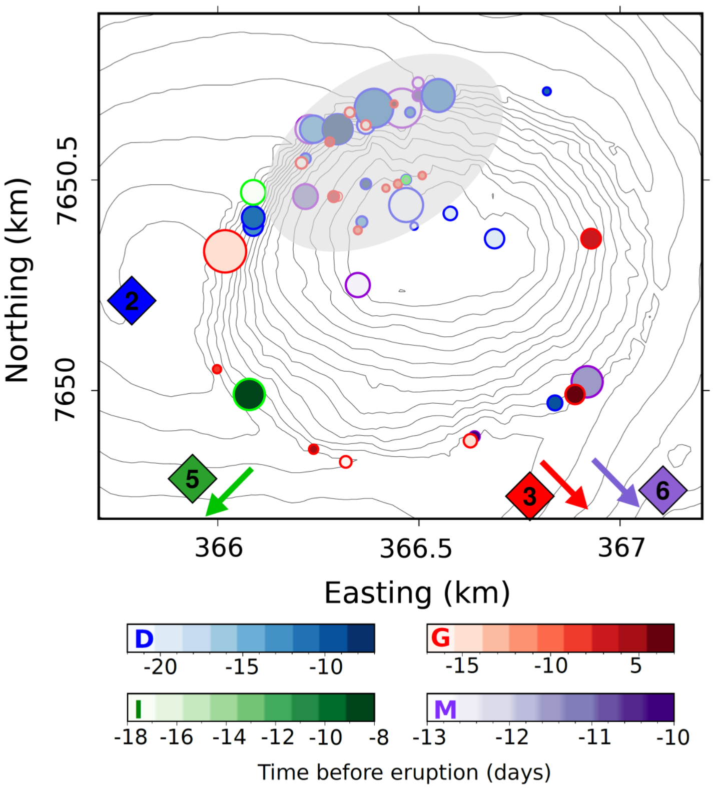
constrain on landslide volume, rheology, localization

- Monitoring rockfall activity:

link with seismic, volcanic, meteorological activity

Large rockfalls seem to occur close to the next eruption ?

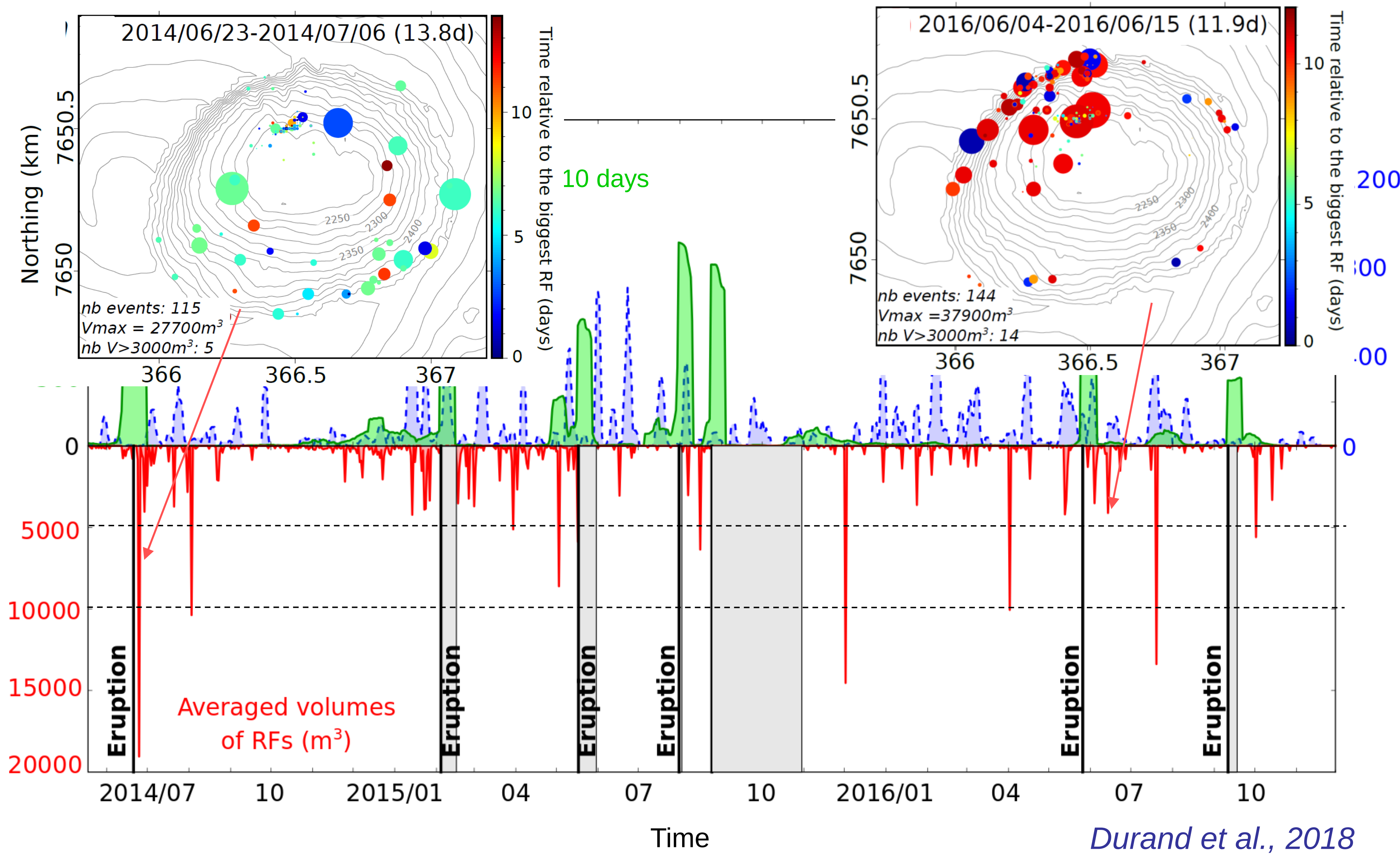
Durand et al., 2018



European Research Council
Established by the European Commission

SLIDEQUAKES

Rockfall triggering

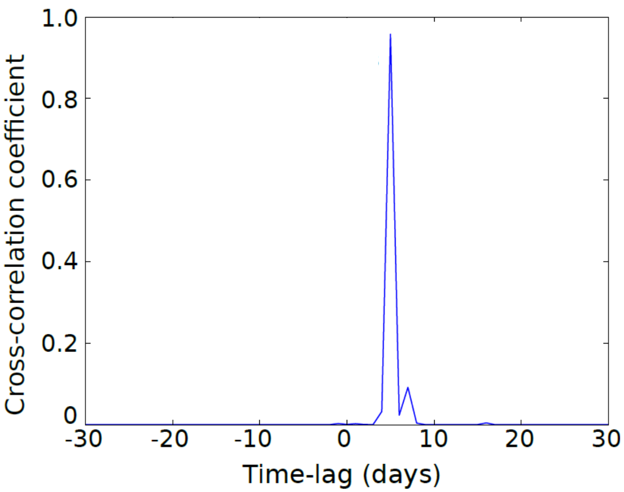


Durand et al., 2018

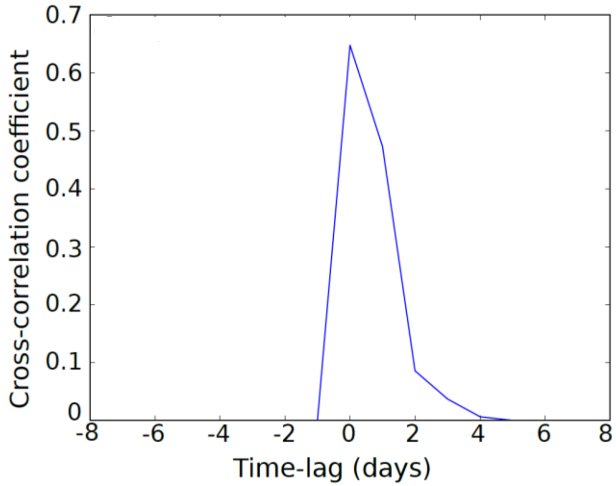
Rockfall triggering

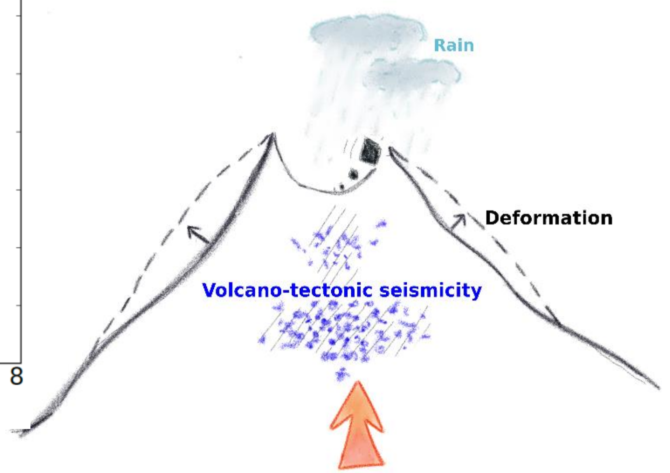
Durand et al., 2018

Daily mean volume of rockfalls vs daily magnitude of Volcano-Tectonic earthquakes



Daily mean volume of rockfalls vs daily rain



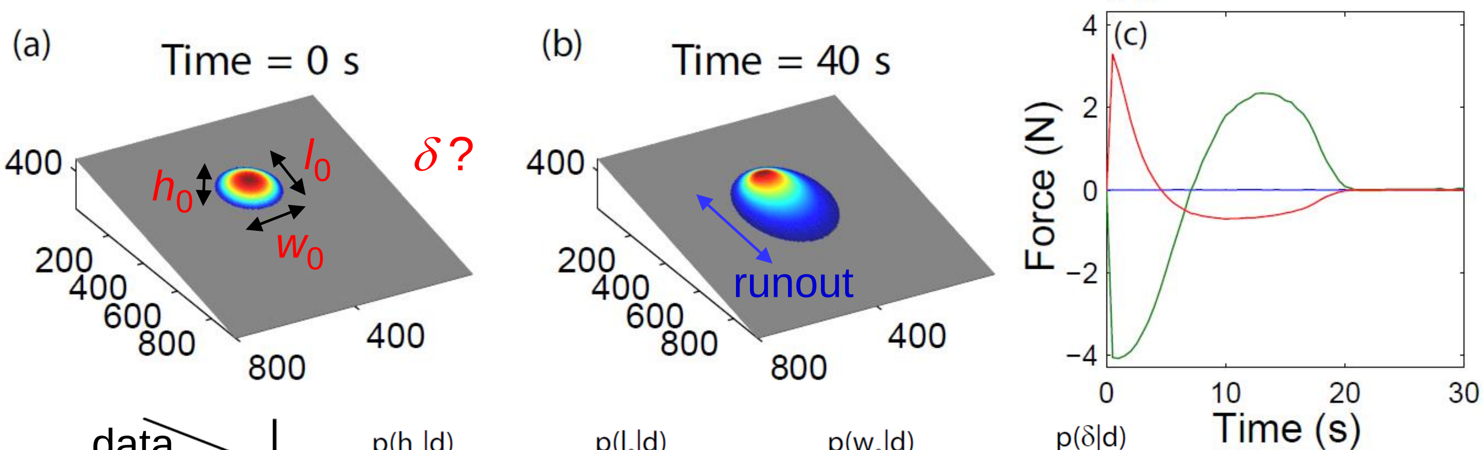


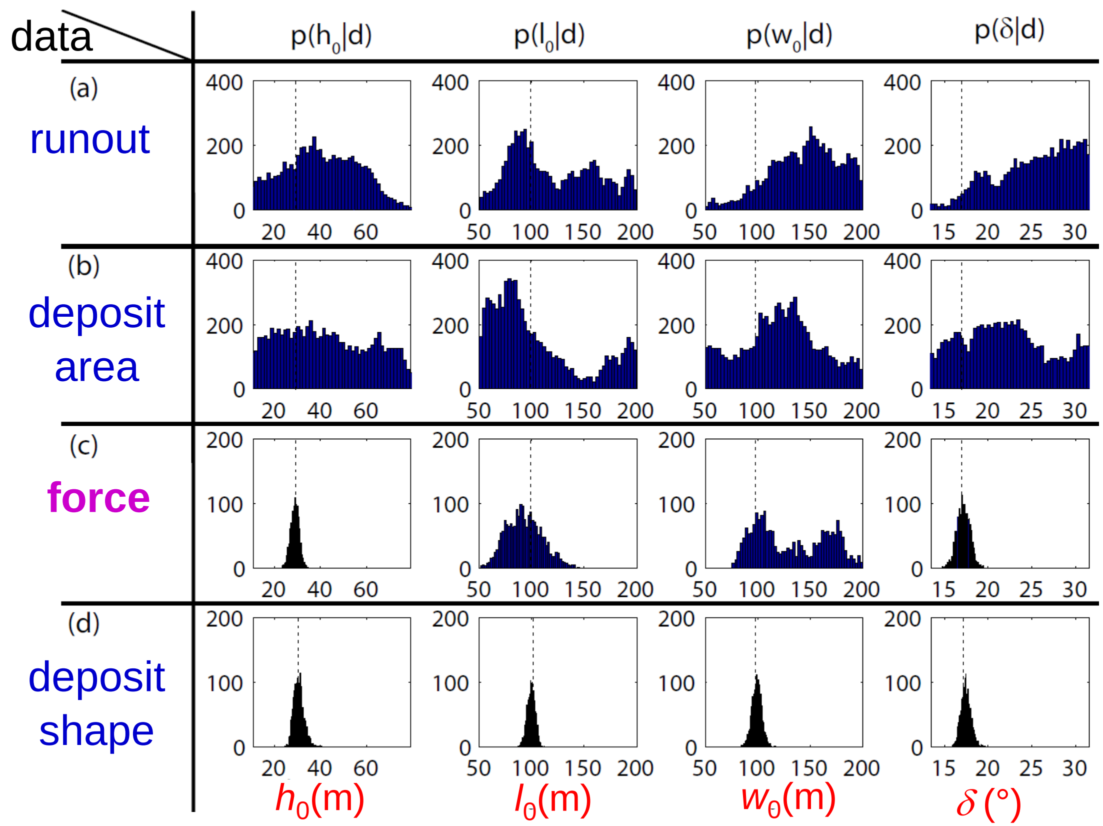
- Strong correlation between rockfall volume and cumulative magnitude/number of Volcano-Tectonic events (time-lag 1-20 days)
- Weak correlation with maximum amplitude of volcano-tectonic seismicity
- Moderate correlation with rain with time-lag of 1-8 days

Bontemps et al., 2018

Bayesian inversion of landslide characteristics

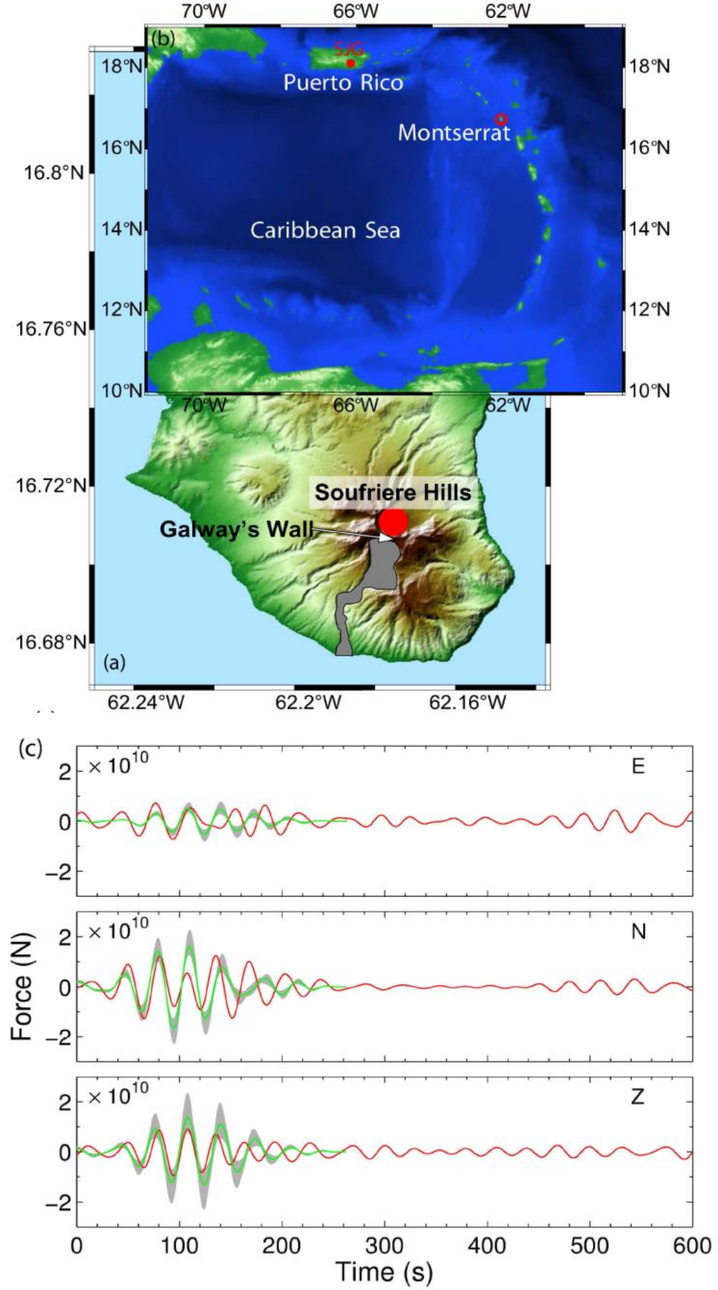
Synthetic data



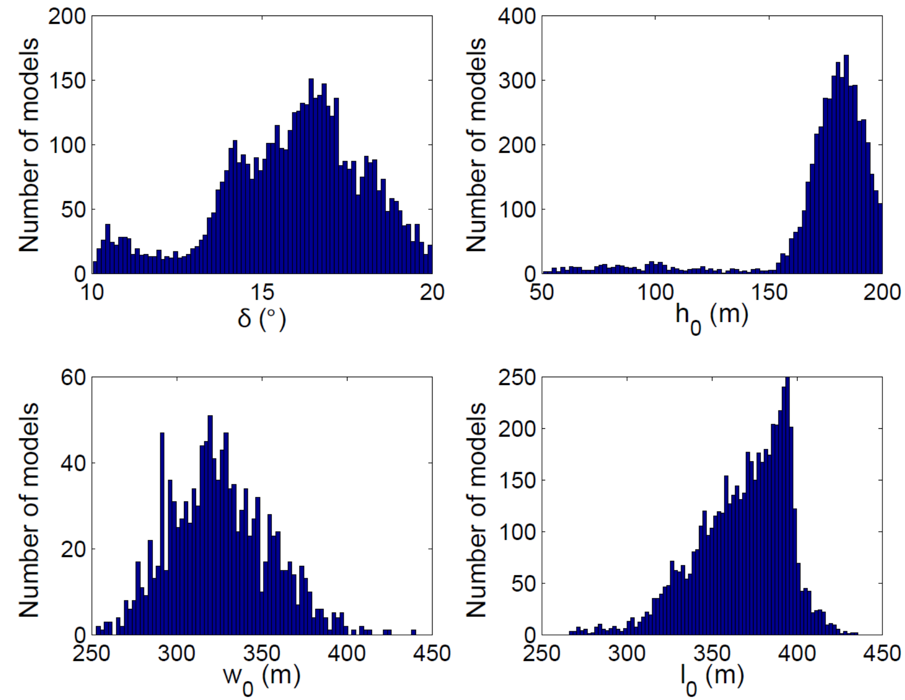


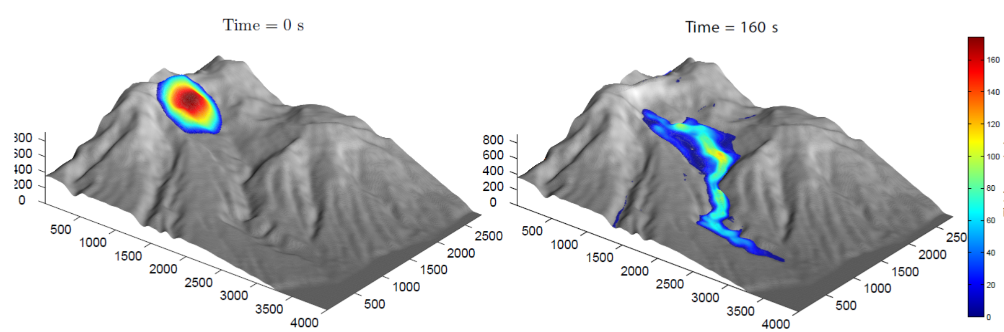
Moretti et al. 2017

Bayesian inversion of landslide characteristics



Boxing Day debris avalanche, Montserrat

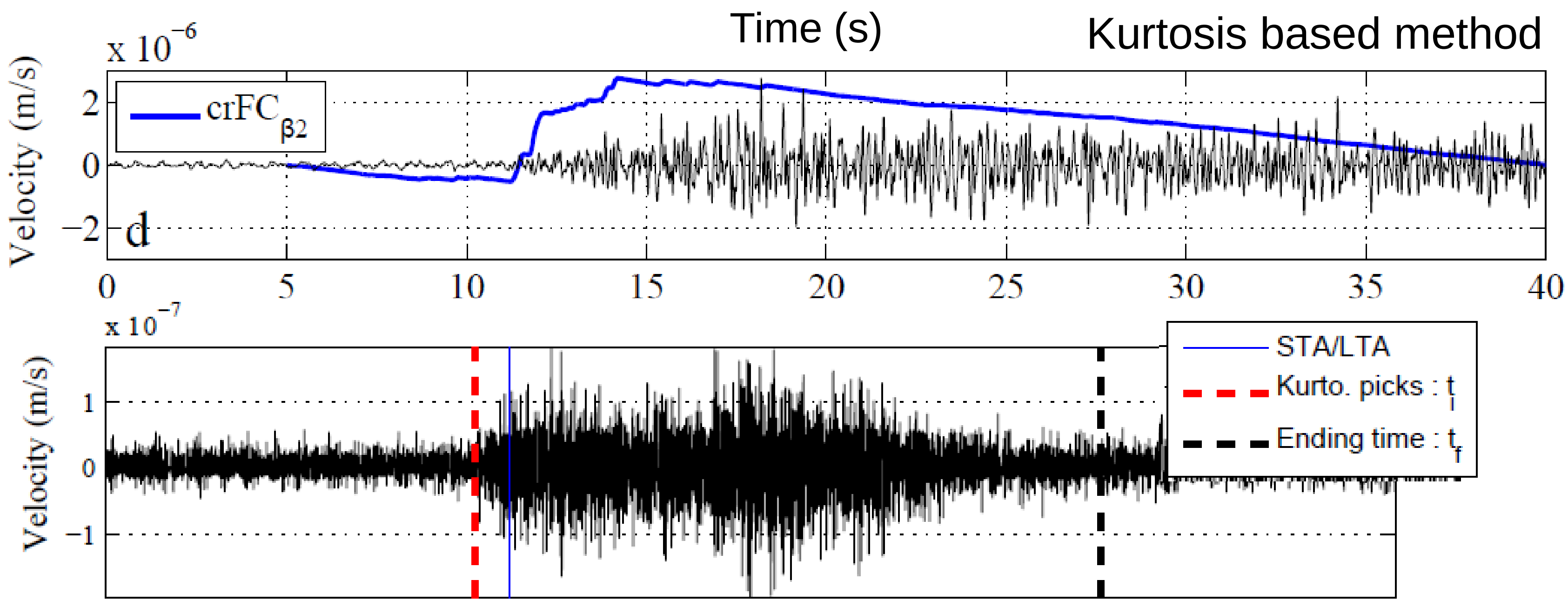




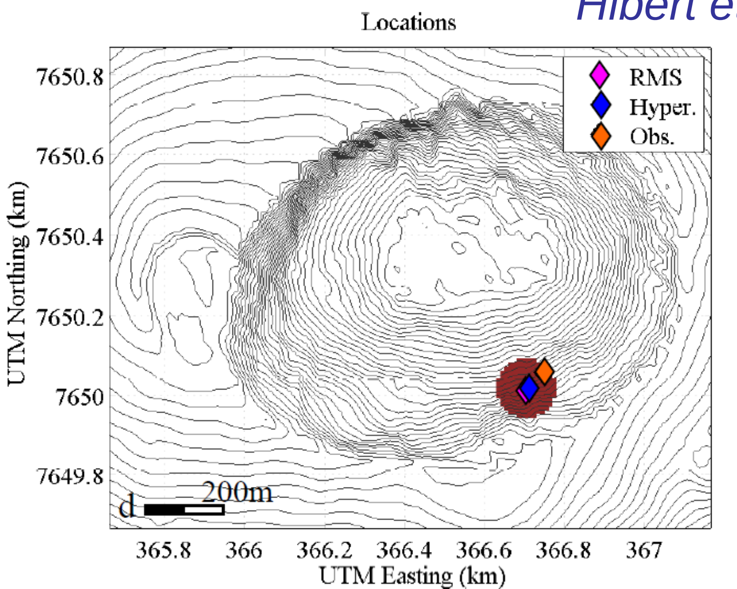
$V \in [32\ 59]$ Mm^3 with a central value of V =45.8 Mm^3

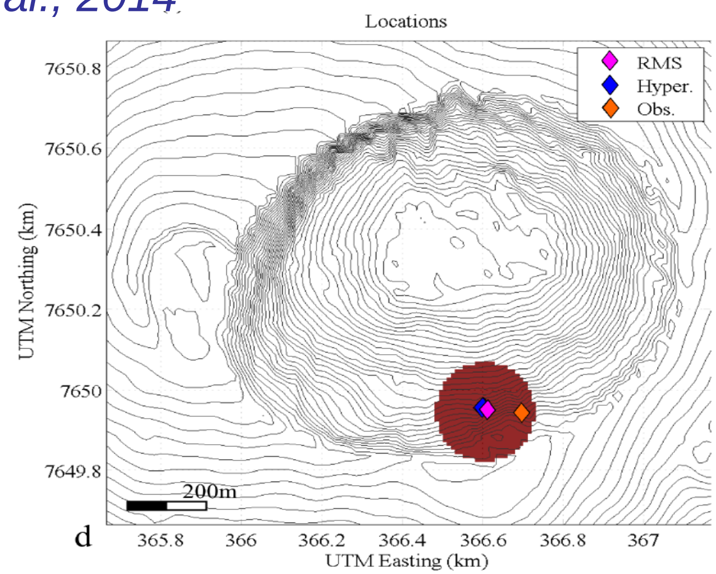
Moretti et al. 2017

High frequency Detection, localization, monitoring



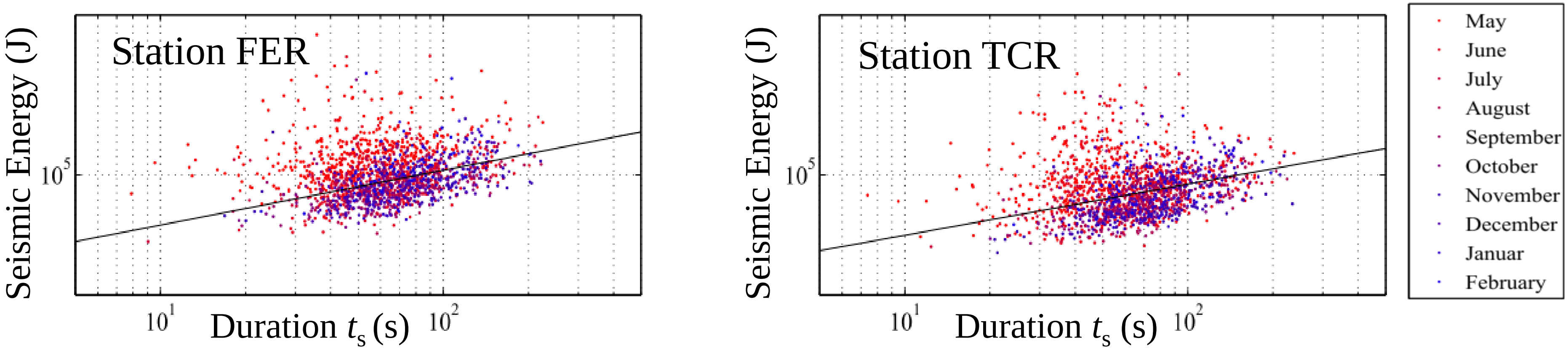
Hibert et al., 2014



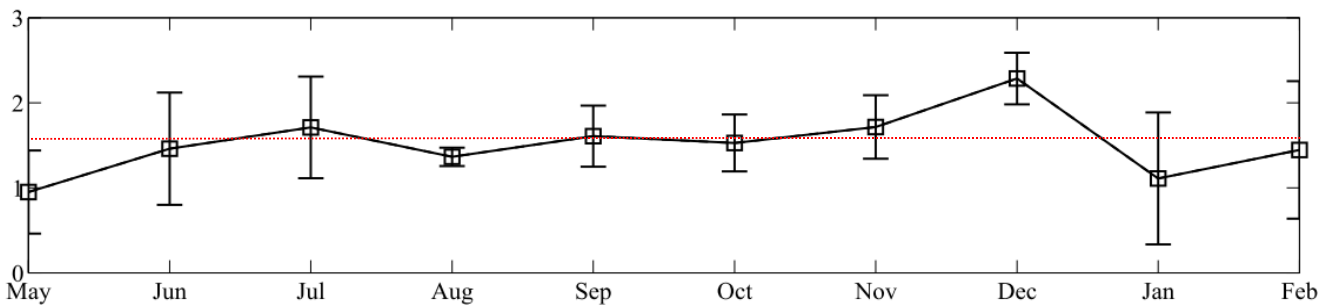


Power law: seismic energy versus duration

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

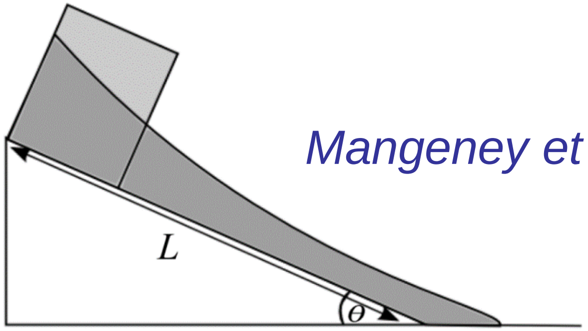


Scaling law between **seismic energy** and **duration** :

$E_s \propto t_s^{\beta_s}$ with $\beta_s \approx 1.56$

Power law: potential energy versus flow duration

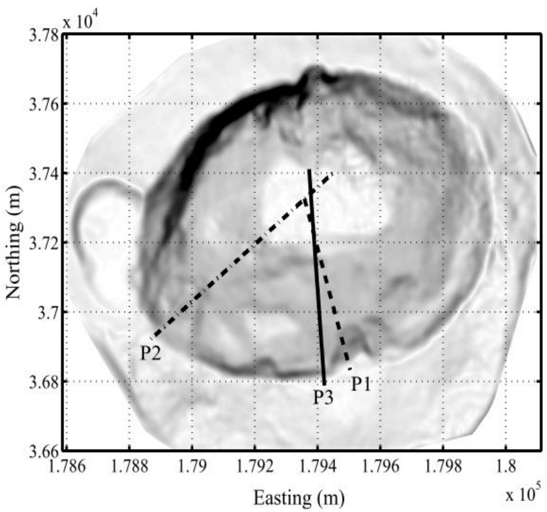
- Analytical development for a rectangular mass on a flat slope

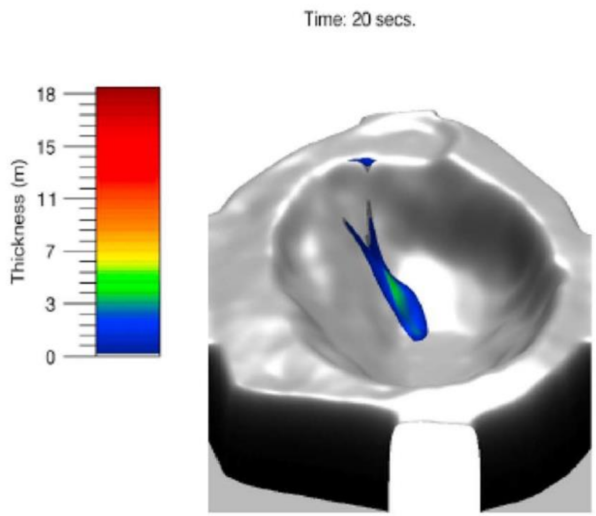


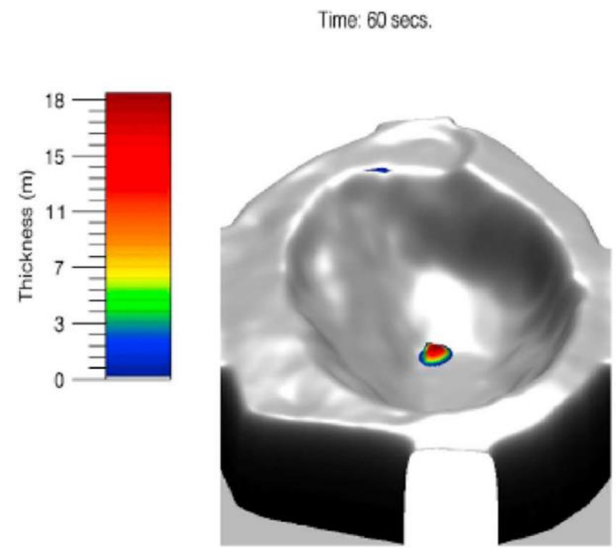
Mangeney et al., 2010

$$\Delta E_p \; \alpha \; t_f^{\beta a}$$ with $$\beta_a = 2$$

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





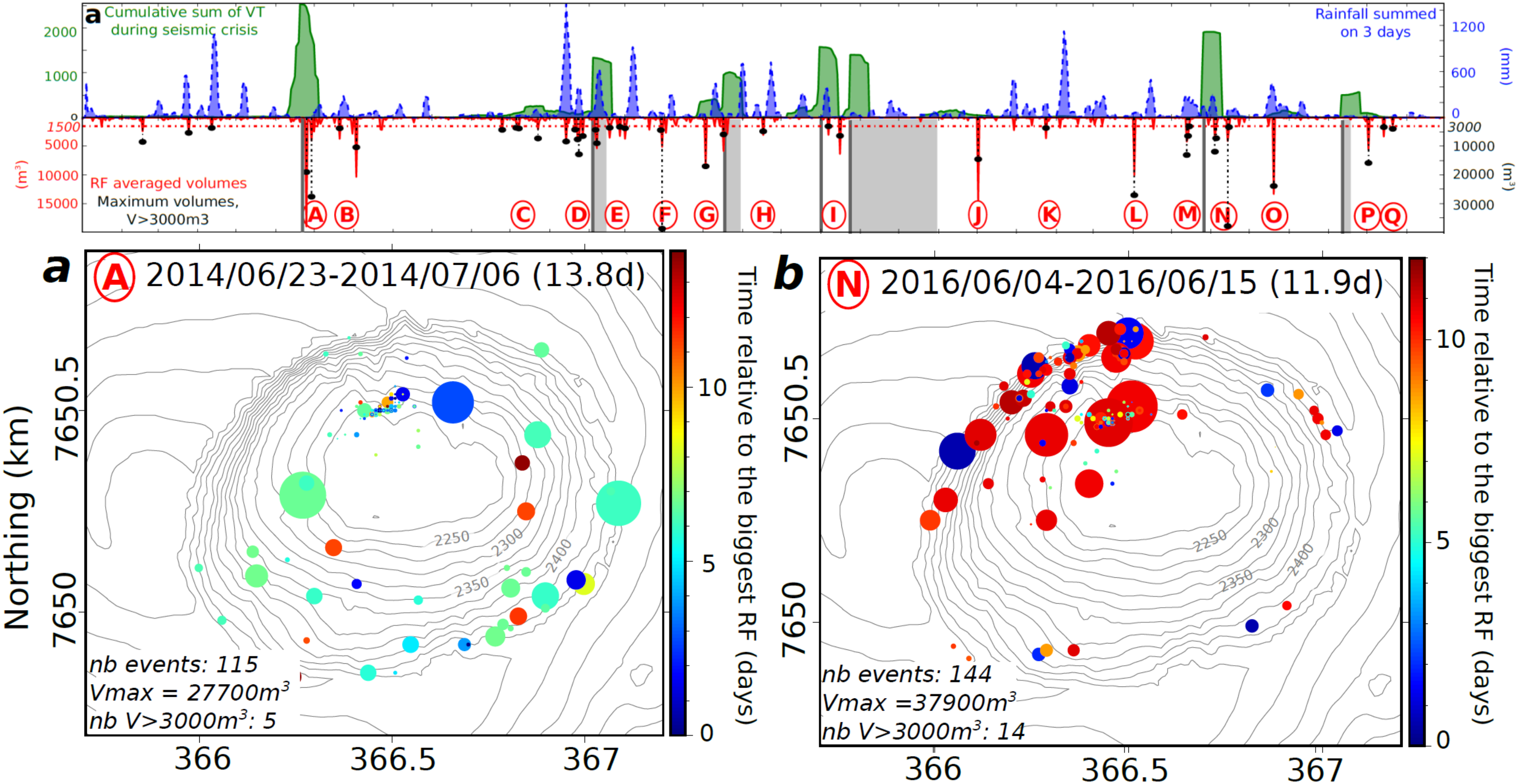


Topography Effects

Rugosity ↗ ⇒ β_p ↘

$$\Delta E_p \; \alpha \; t_f^{\beta p}$$ with $$\beta_p = 1.65$$

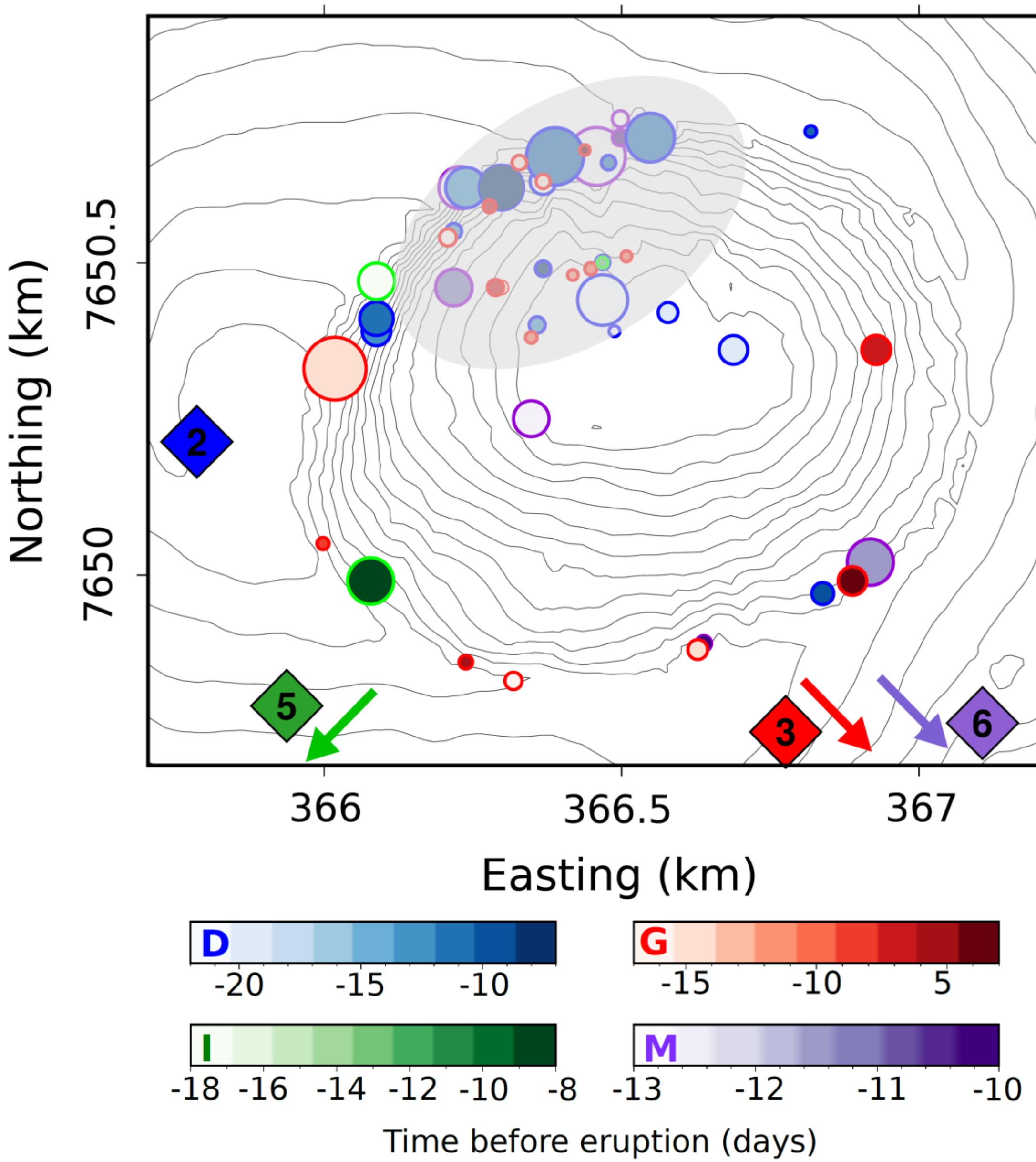
Spatio-temporal distribution



- Strong heterogeneity !

Rockfall triggering

Durand et al., 2018

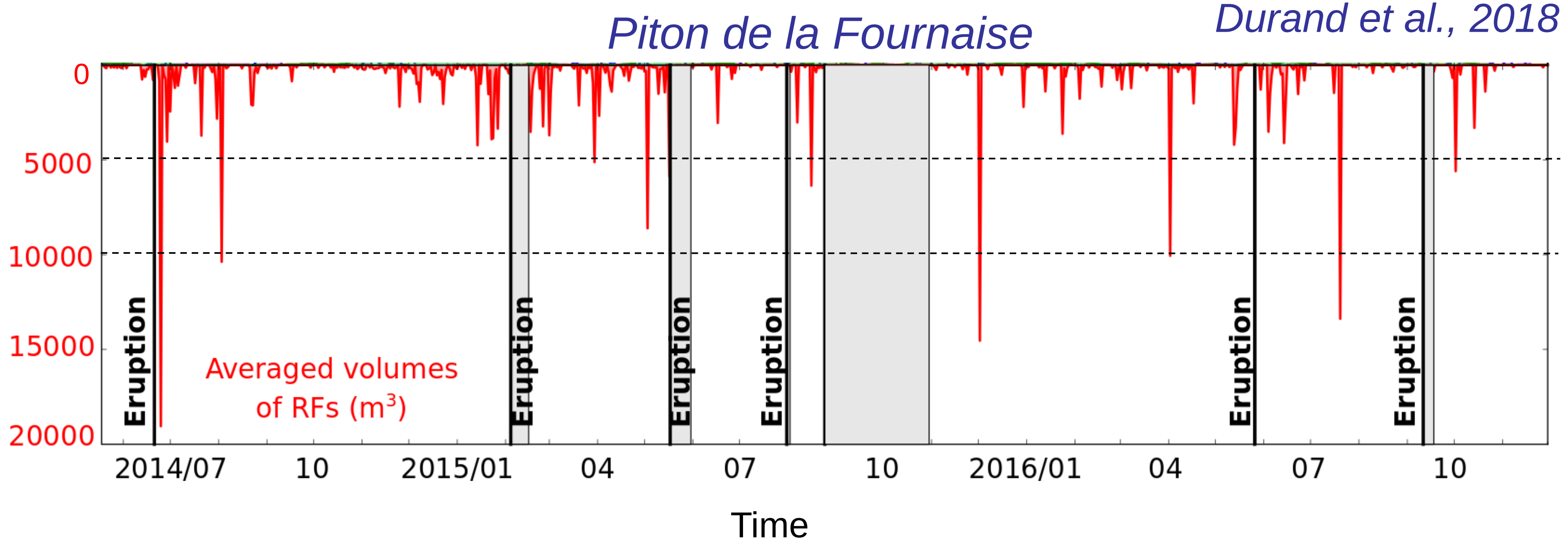


Large rockfalls seem to occur close to the next eruption ?

Rockfall triggering

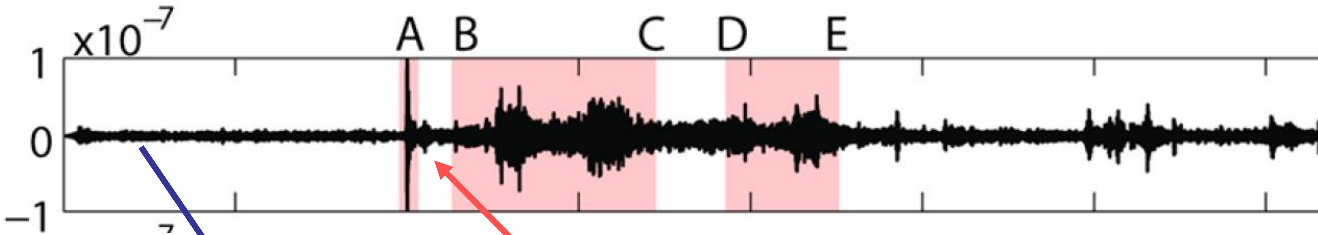
Rockfall crises with volume V> 3000 m^3

Durand et al., 2018



Correlation between rockfall volume and external forcing
(3-year time series)?

Permanent seismic waves all around us

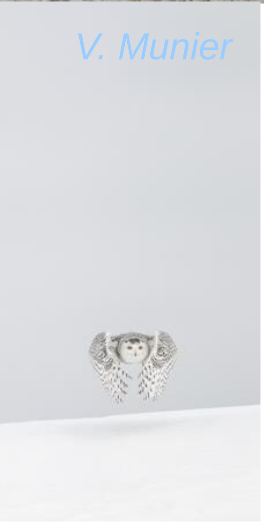


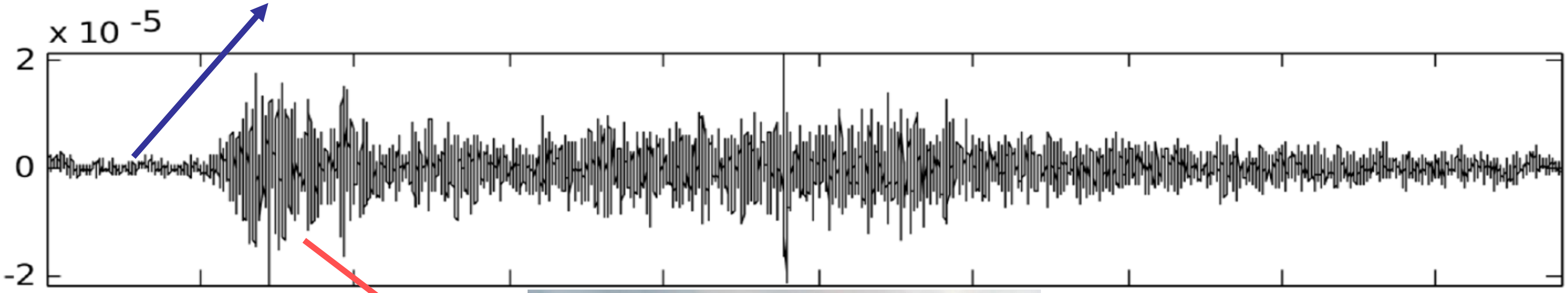
Ice avalanche and iceberg calving

Magnitudes up to 4-5

Recorded at 10’s to 100’s km !

Huge database since 10’s years

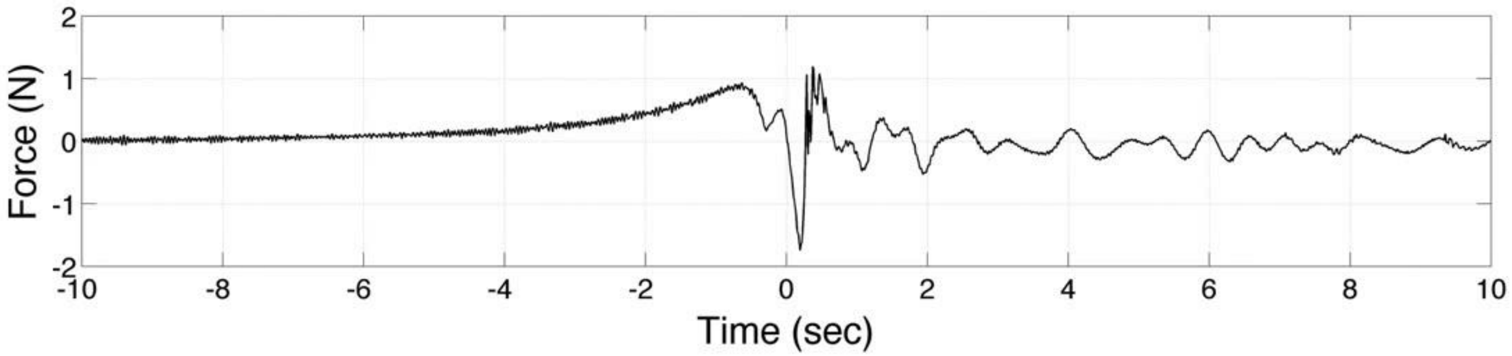


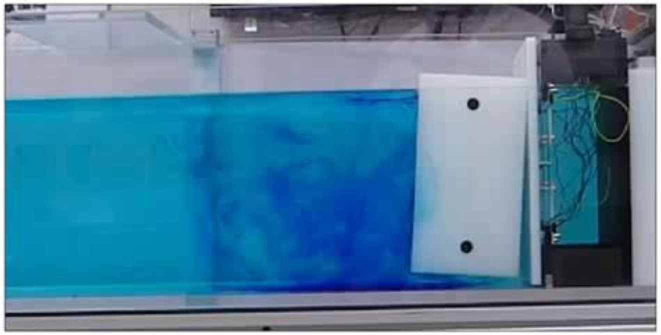


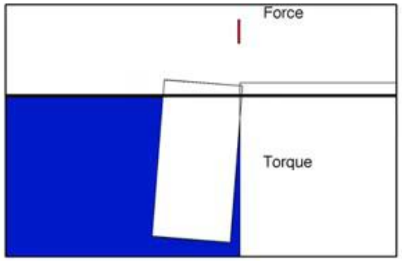
Landslide

Physical processes at the origin of seismic waves ?

Laboratory experiments of iceberg calving





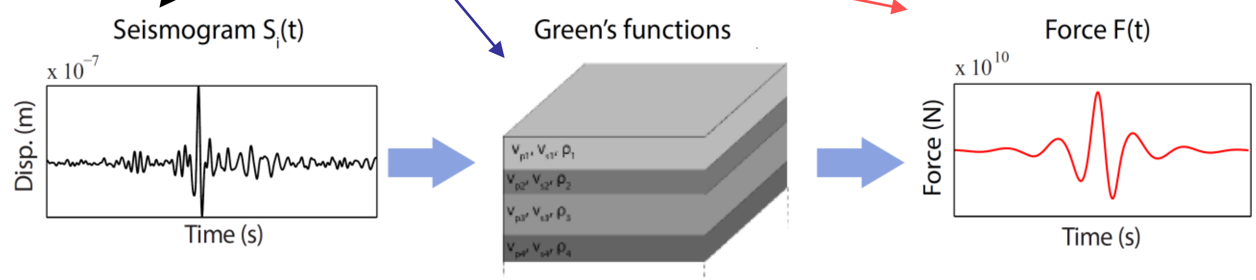


Burton, Admundsen et al., 2012

Recovering the force due to iceberg calving

$$\mathbf{u}_i(x,t) = \mathbf{g}_{ij}(x,t) * \mathbf{F}_j(0,t)$$

Force inversion

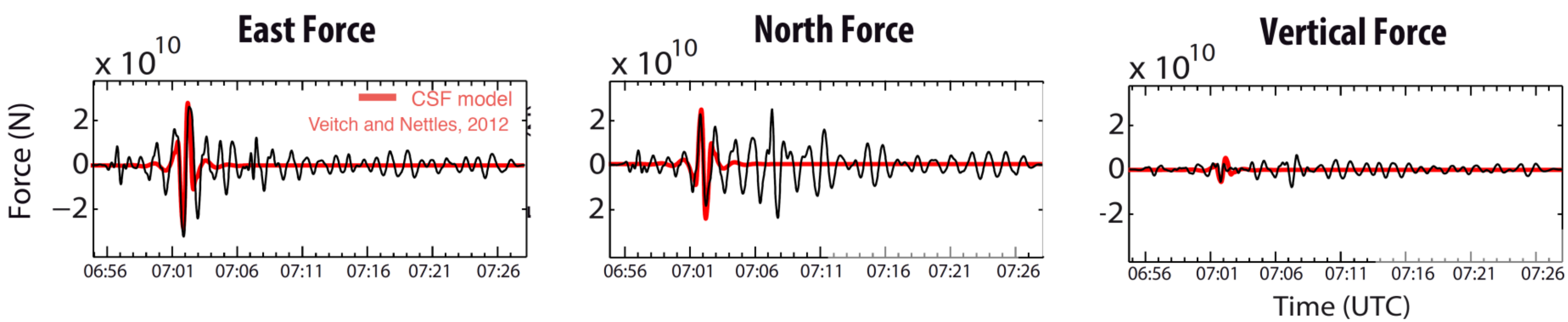


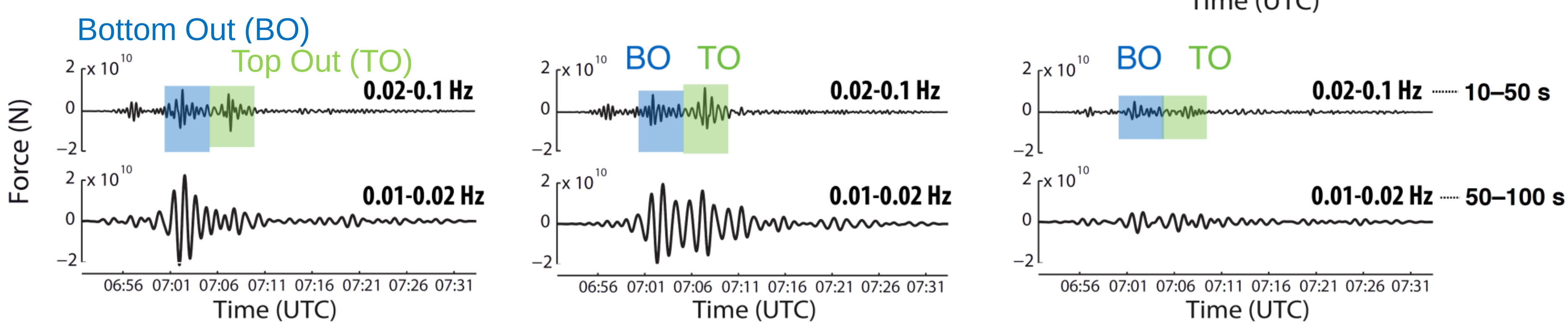
Low frequency

0.01-0.1Hz —- 10-100 s

Jakobshavn Isbrae, Geenland

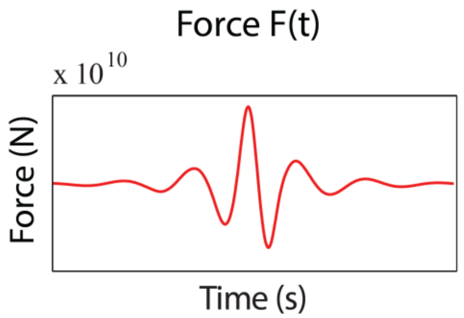
Sergeant et al. 2016





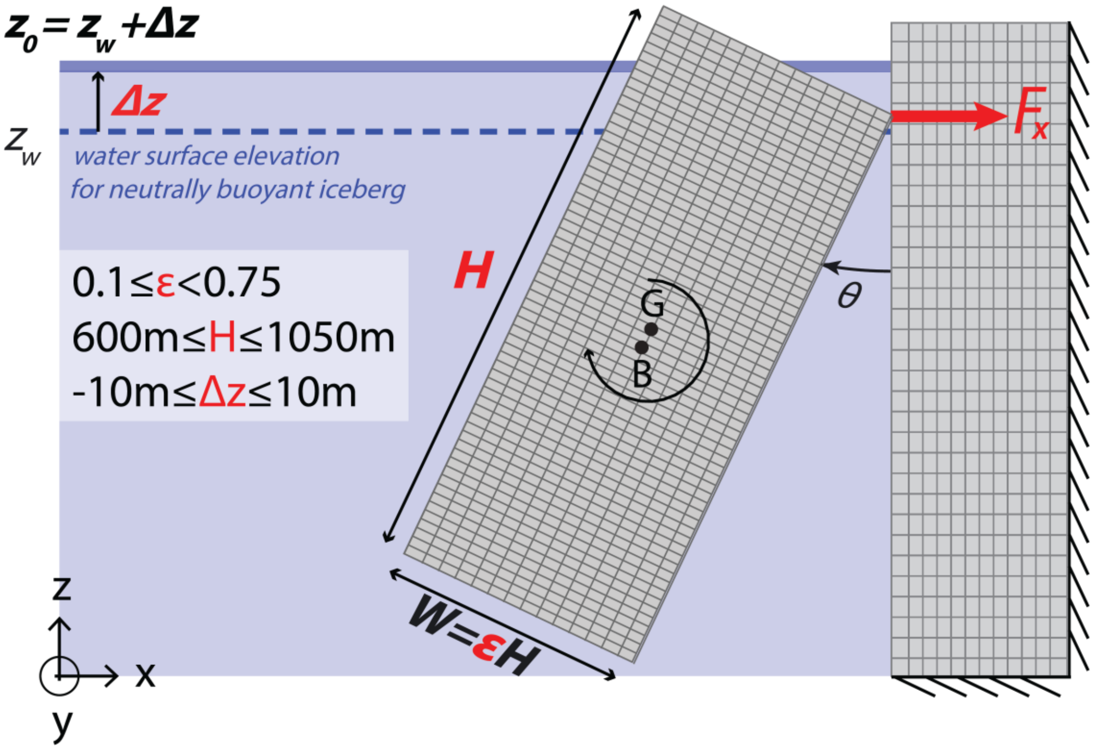
What do we expect from calving modelling ?

- Can we reproduce the force inverted from seismic records ?
- Can we estimate iceberg volume from the force ?



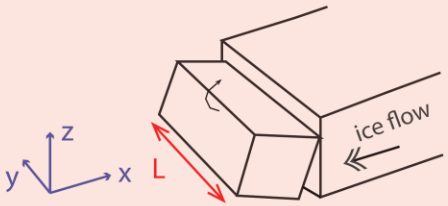
Finite element model Z-set

- Contact force computation with varying geometrical parameters:



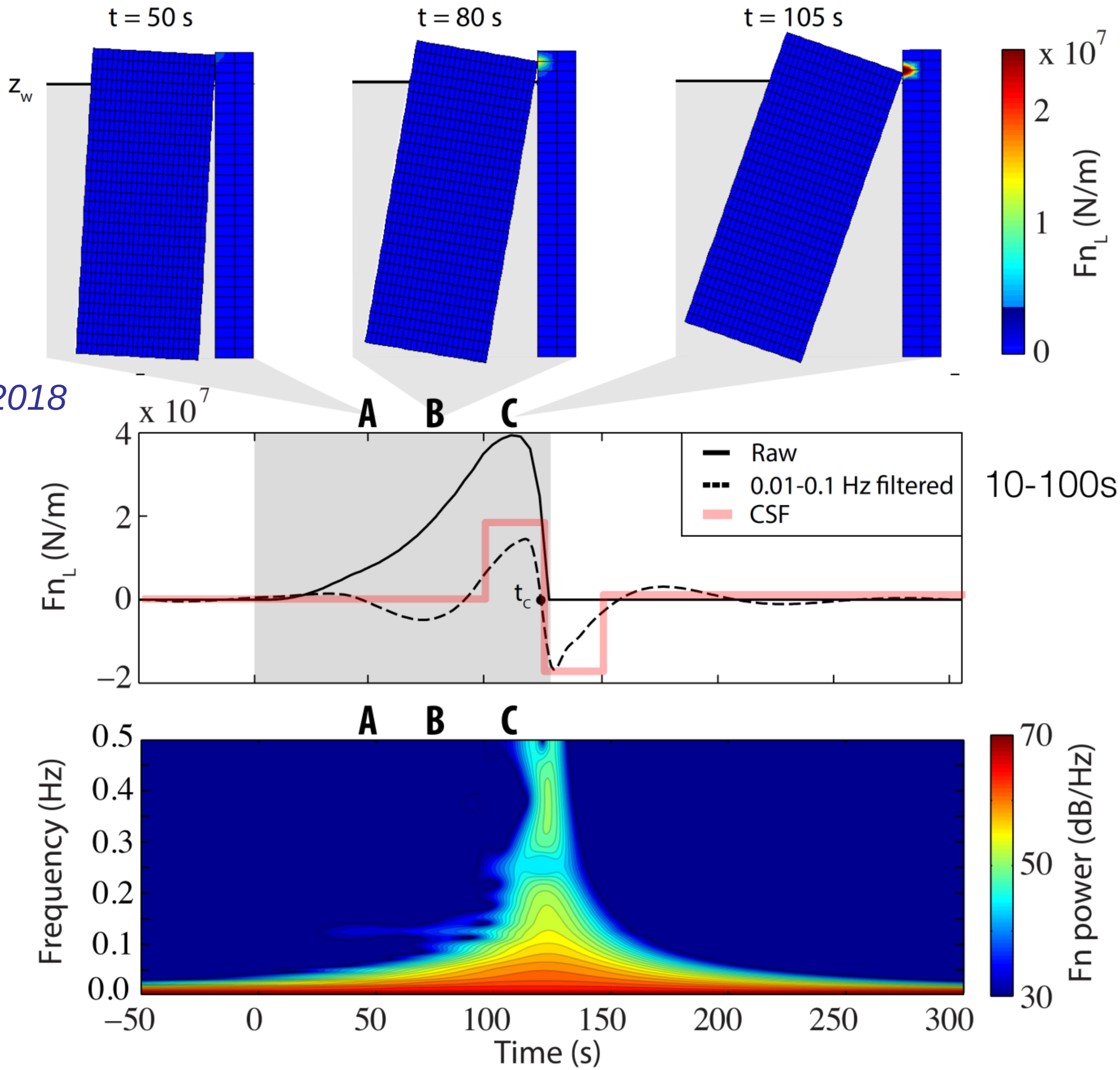
Total force from 2D modeling:

- $F^T(t) = LF(t)$
- Iceberg length $500m \leq L \leq 5000m$



Simulation of the contact force

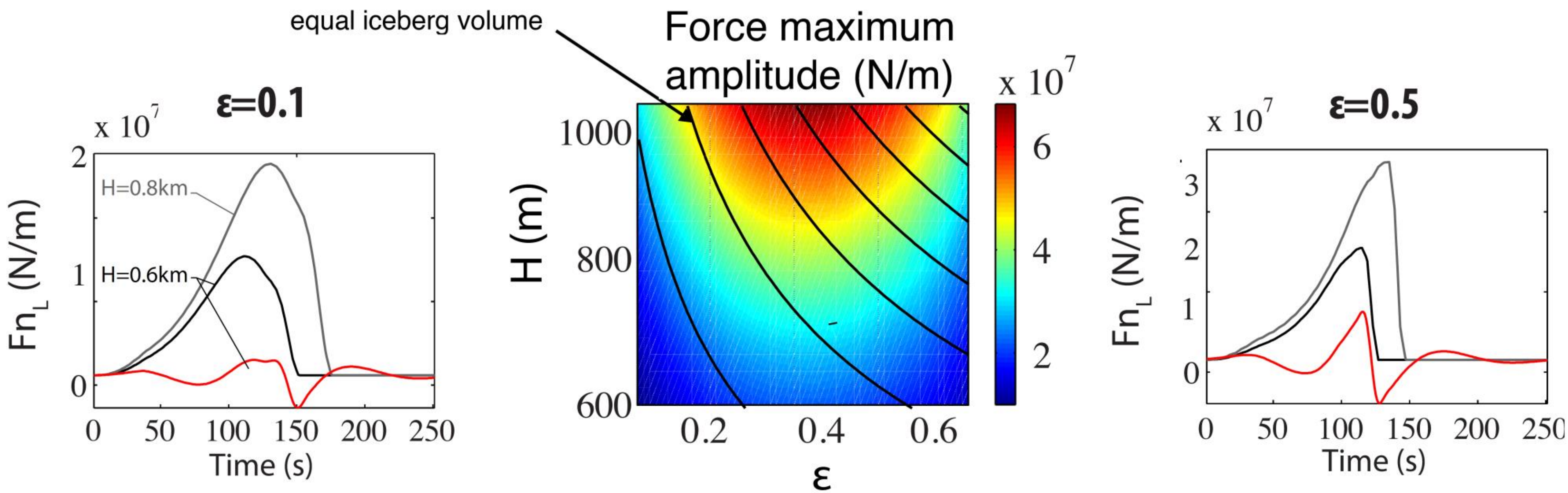
Sergeant et al. 2018



10-100s of periods

Force dependency on iceberg characteristics

- Catalog of 1000 models for BO capsizes and varying values of H and ε.
- Filtered force amplitudes match seismic observations *(Veitch an Nettles, 2012, Sergeant et al., 2016)*

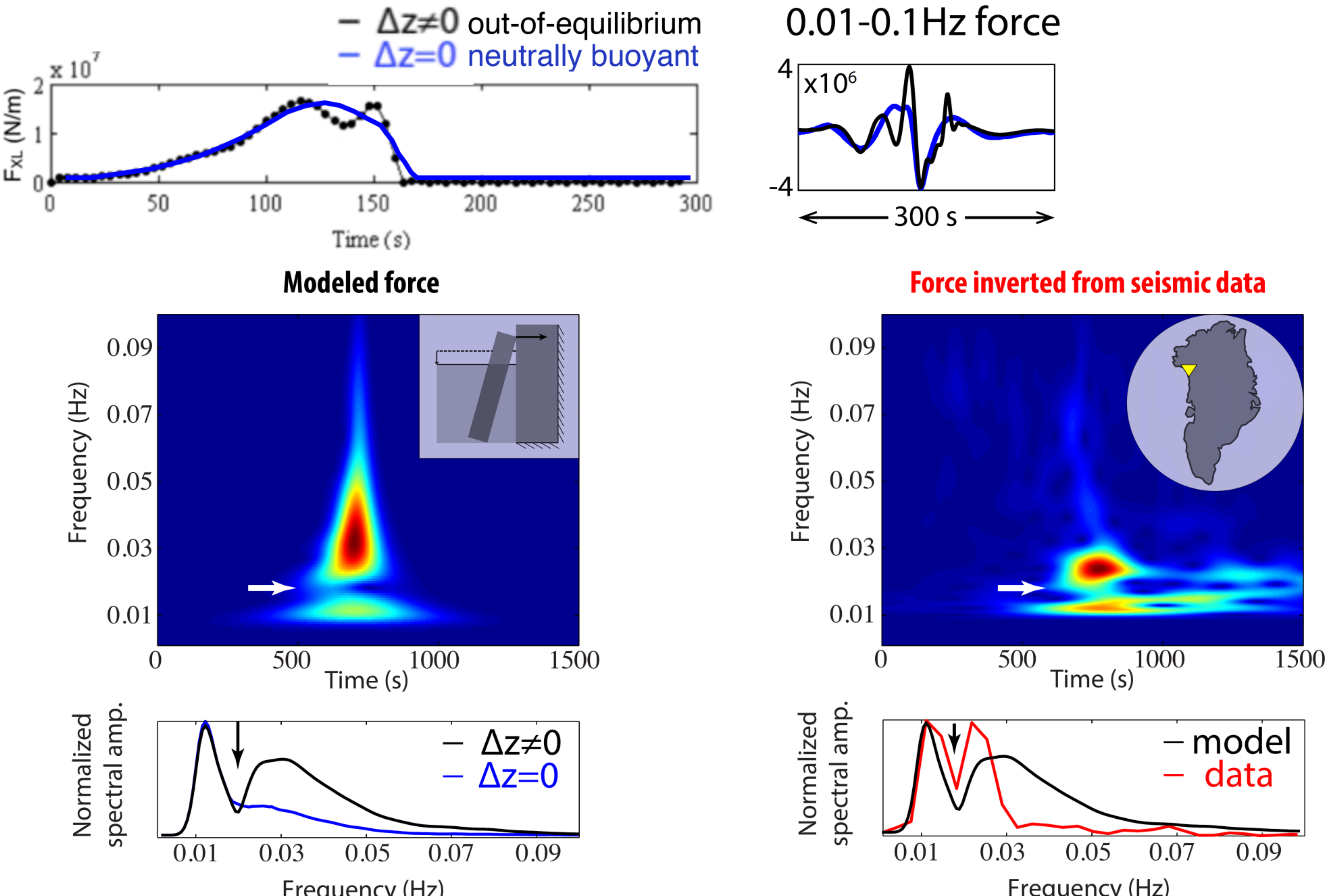


- Force amplitude, duration and history vary with H and ε.

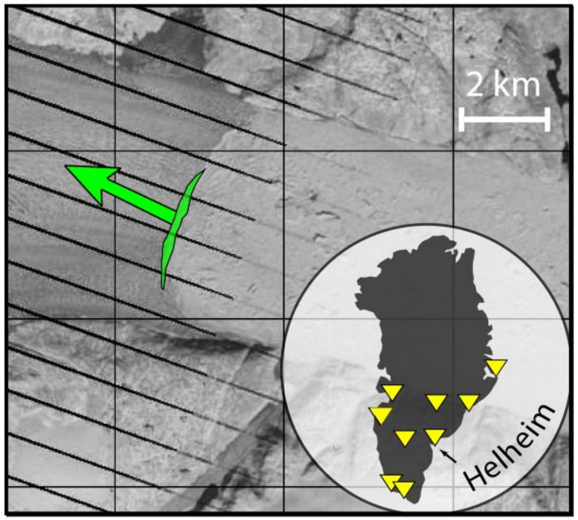
Impossible to recover the volume from F_{max} :
need of full force history F(*t*) !

Force Bottom-out
≠
Force Top-out

Influence of initial buoyant conditions



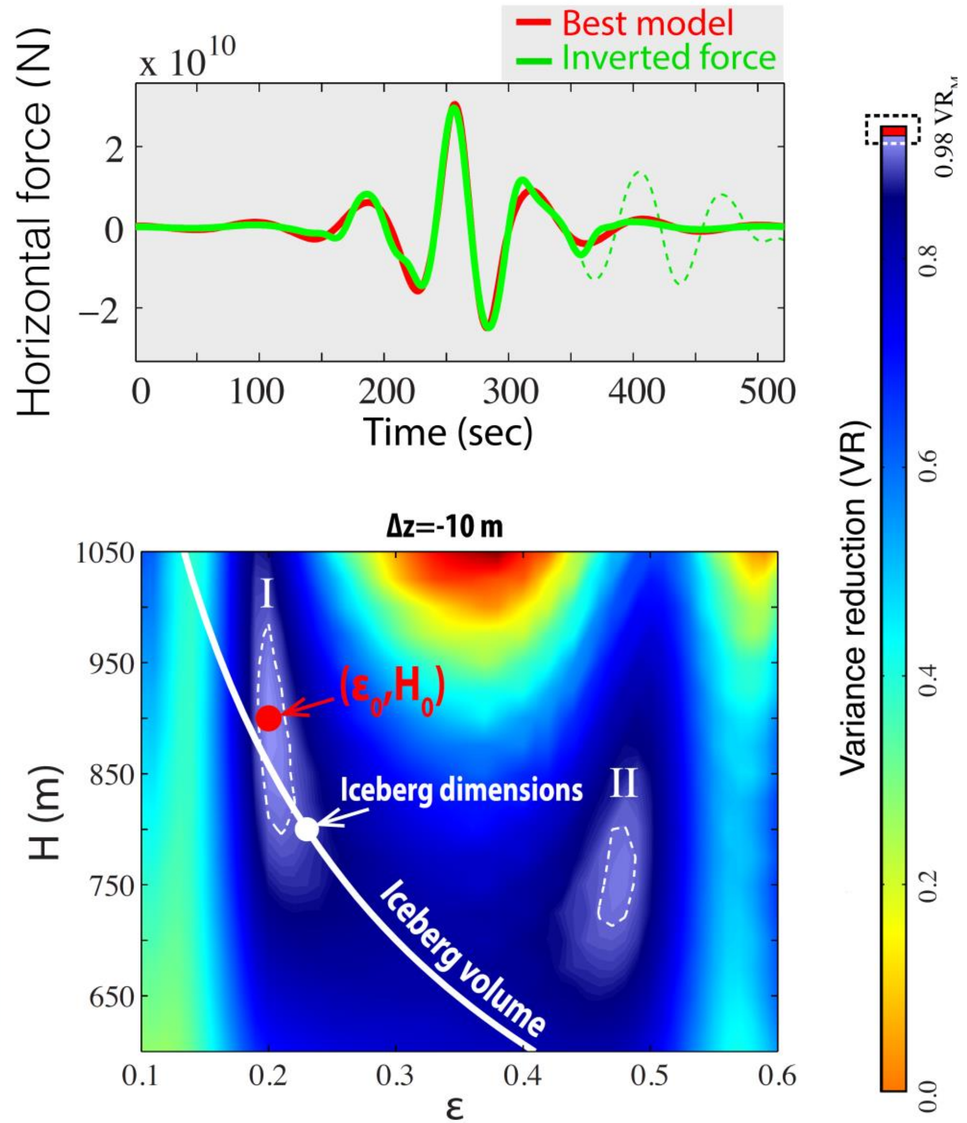
From the force to the iceberg volume



- BO capsize captured on cameras *(Murray et al., Science, 2015)*:

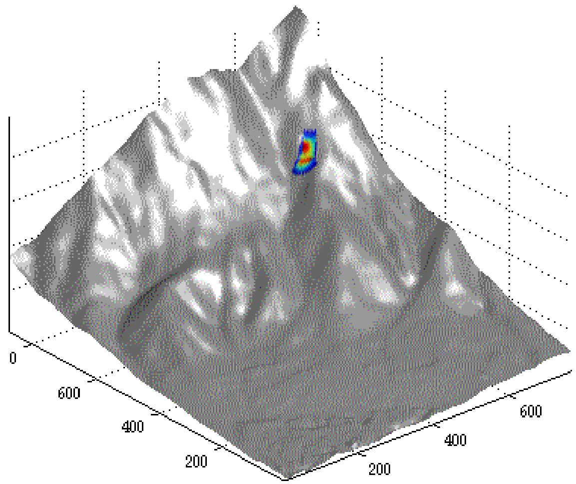
25/07/2013: $H \approx 800$ m $\epsilon \approx 0.23$ $L \approx 2500$ m $\longrightarrow \epsilon H^2 L \approx 0.37\ km^3$	$H_0 = 900$ m $\epsilon_0 = 0.2$ $L \approx 2500$ m $\epsilon H^2 L = 0.4 km^3$

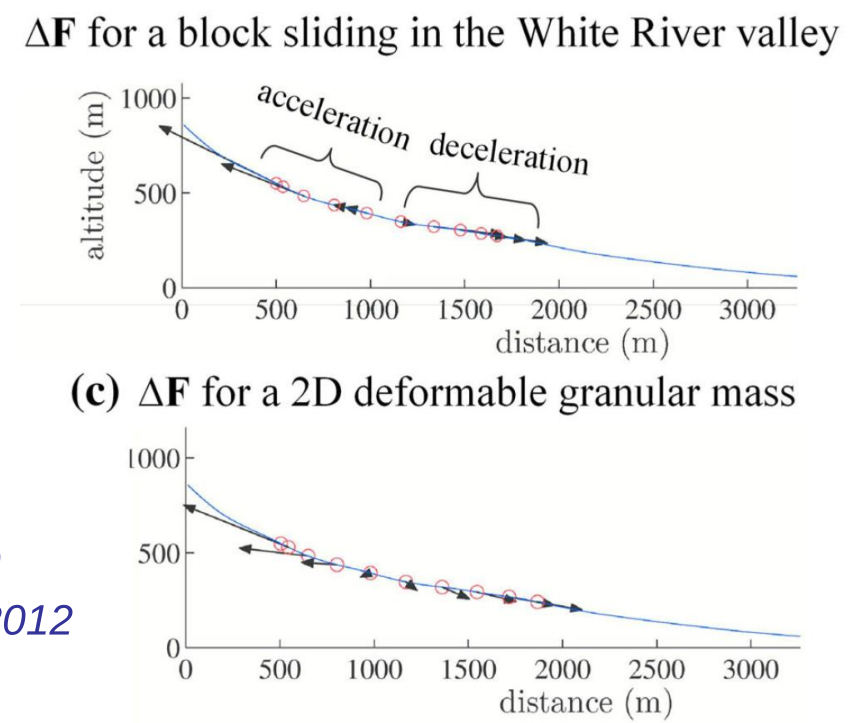
- Glacial earthquake (force ~ 3×10^{10}N)



Sergeant et al. 2018

Modelling of the basal force

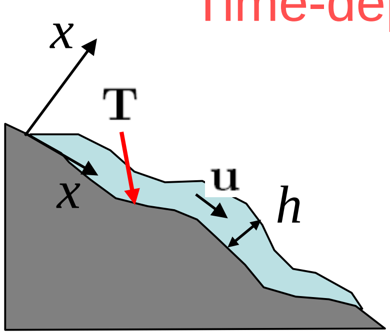




Favreau, Mangeney, Lucas, Crosta, Bouchut 2010
Moretti, Mangeney, Capdeville, Stutzmann, et al. 2012

Zhao, Moretti, Mangeney, Stutzmann, Kanamori, Capdeville, Calder, Hibert et al., 2015

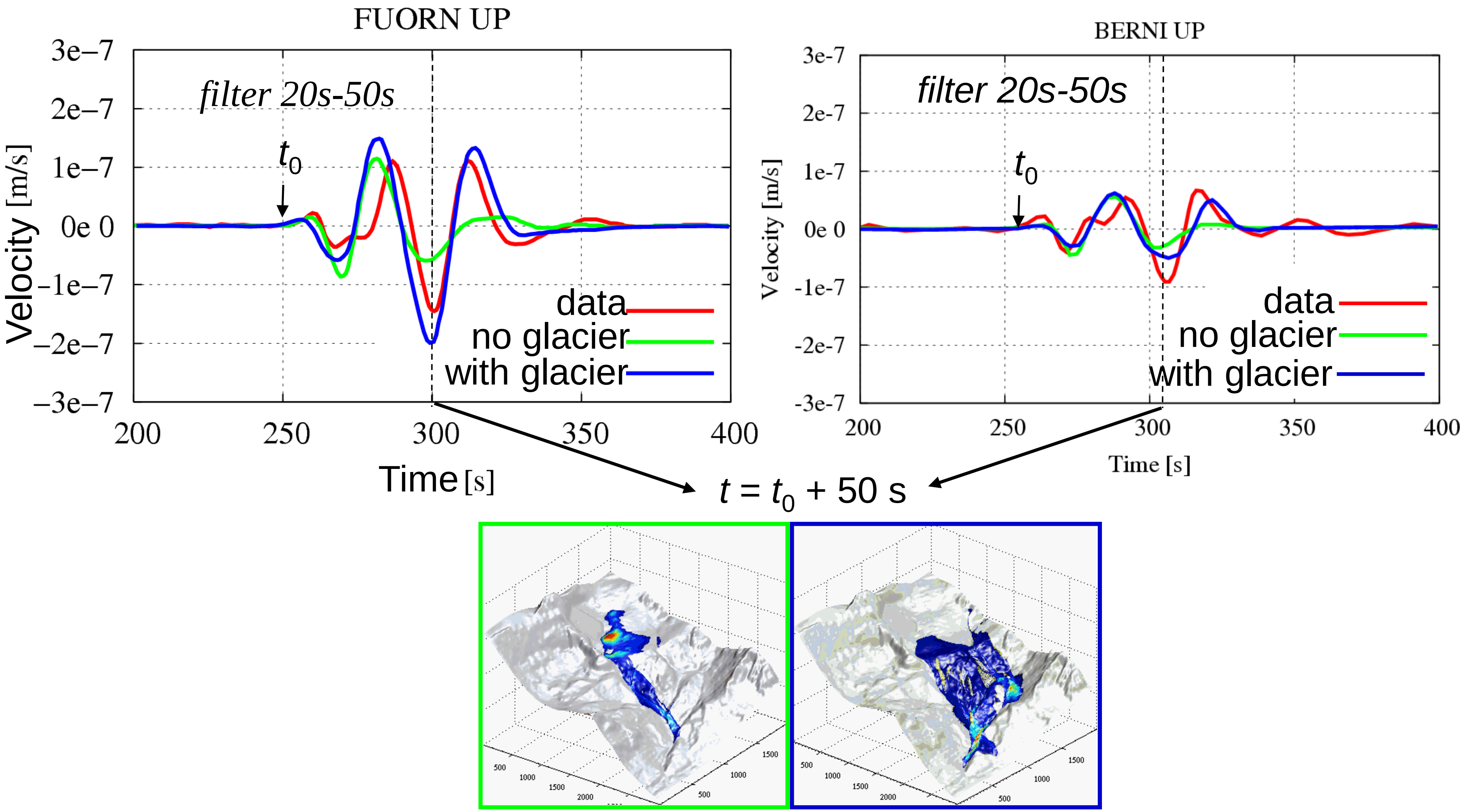
Time-dependent basal stress field applied on top of the terrain



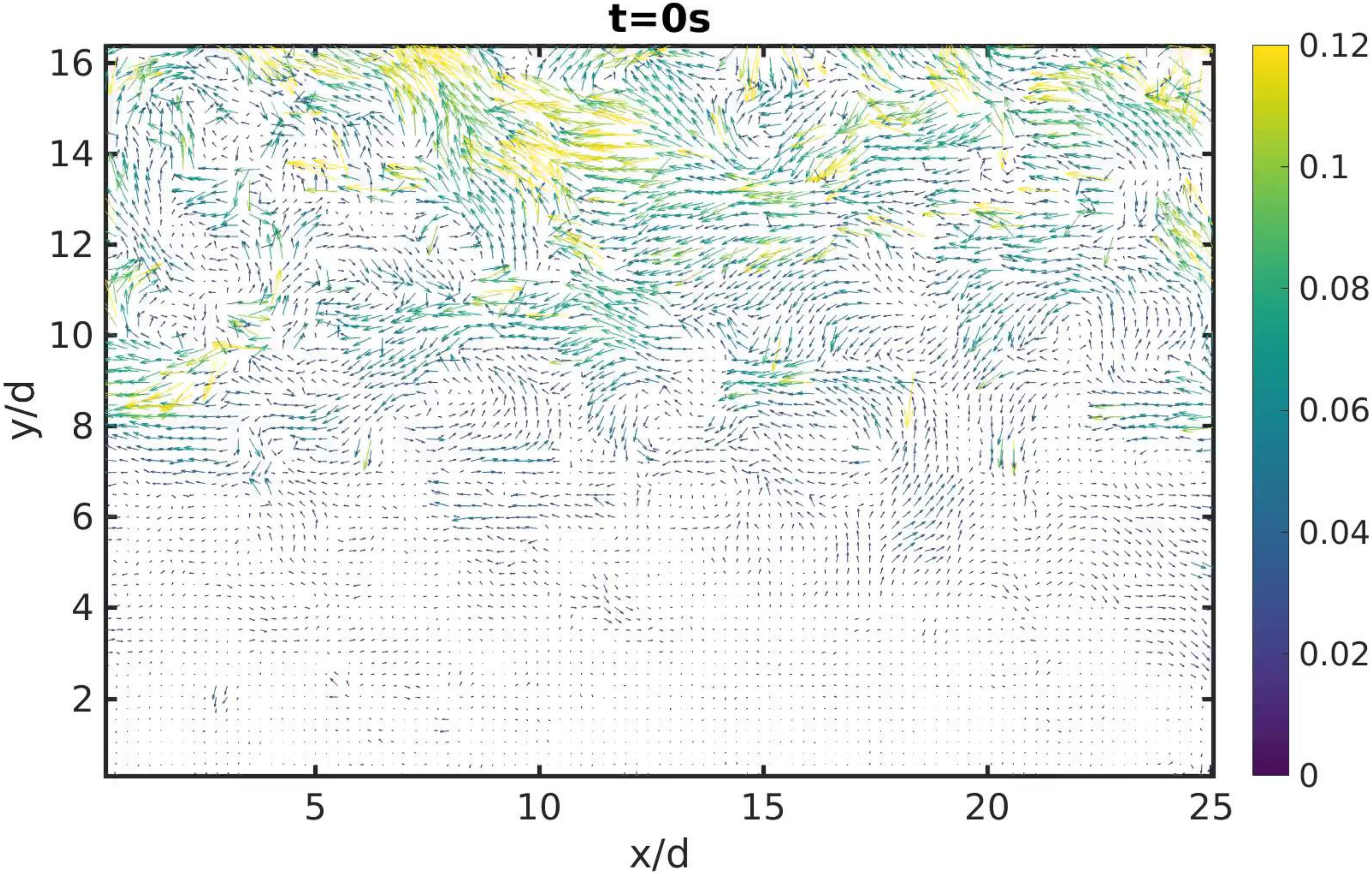
$$\mathbf{T} = \rho g h \left(\cos\theta + \frac{\mathbf{u}_h^t \mathcal{H} \mathbf{u}_h}{g \cos^2\theta} \right) \left(\mu \frac{u_X}{\|\mathbf{u}\|}, \mu \frac{u_Y}{\|\mathbf{u}\|}, -1 \right)$$

Curvature effects

Thurweiser landslide seismic waves



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


t=0s
y/d
x/d
16
14
12
10
8
6
4
2
5
10
15
20
25
0.12
0.1
0.08
0.06
0.04
0.02
0

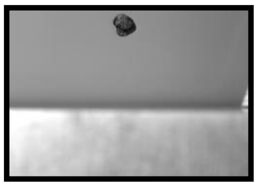
Acoustic waves in laboratory experiments

Grain impact

Seismic signal

⬇

Impactor's characteristics



On thin plates

mass $m \propto W_{el}^{3/16} f_{mean}^{-33/16}$

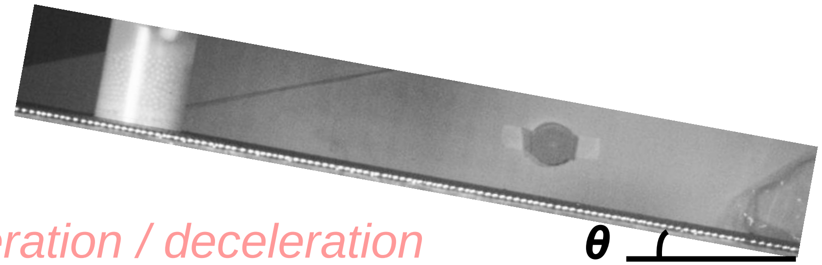
speed $V_z \propto W_{el}^{5/16} f_{mean}^{25/16}$

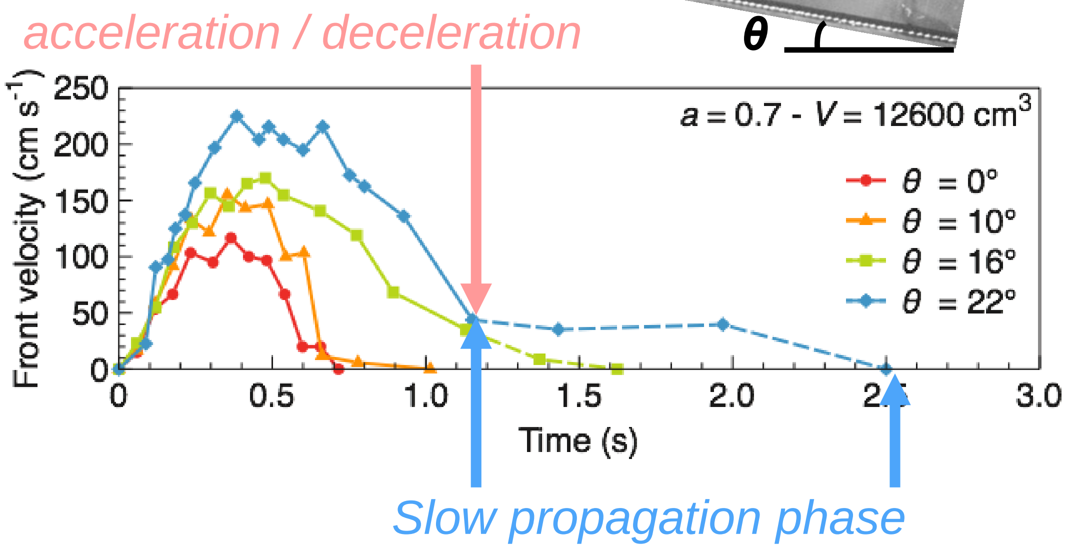
W_{el} = radiated seismic energy
f_{mean} = mean frequency

Validated experimentally

Farin, Mangeney, Toussaint, De Rosny, Shapiro, Dewez, Hibert et al. 2015

Granular flows on sloping beds





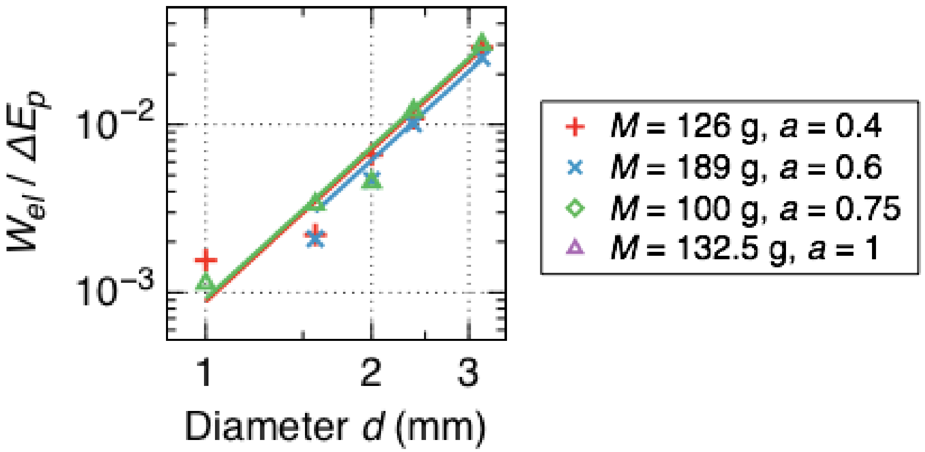
The dynamic regime of granular flows changes at high slopes θ>15°

Seismic signal ?

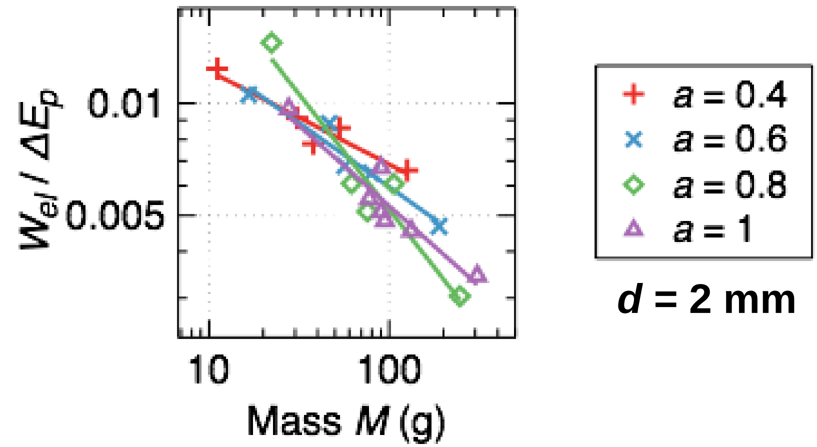
Mangeney et al. 2010, Farin et al. 2014, 2015

Seismic efficiency

Diameter



Mass



***d* = 2 mm**

$$W_{el} / \Delta E_p \propto d^{\,3}$$

$$W_{el} / \Delta E_p \propto M^{-0.4}$$

W_{el} / ΔE_p depends essentially on particle diameter, flow mass and slope angle

May explain dispersion observed on the field **$W_{el} / \Delta E_p = 10^{-5} - 10^{-3}$**

e.g. Hibert et al. 2011, 2014, Lévy et al. 2015

Farin, Mangeney, De Rosny, Toussaint, Trinh, 2017

Laboratory/field for impacts/flows

Single impacts

Laboratory

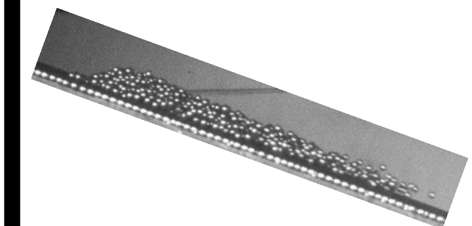
Farin et al., 2014

Field

Farin et al., 2014

Granular flows

Laboratory



Field

Characteristic Frequency

- Single impacts, laboratory: ~ 100 kHz
- Single impacts, field: ~ 100 Hz (/ 1000)
- Single impacts laboratory → granular flows laboratory: / 5 - 20
- Granular flows, laboratory: ~ 5 - 20 kHz
- Granular flows, field: ~ 5 - 20 Hz (/ 1000)

Seismic efficiency $W_{el} / \Delta E_p$

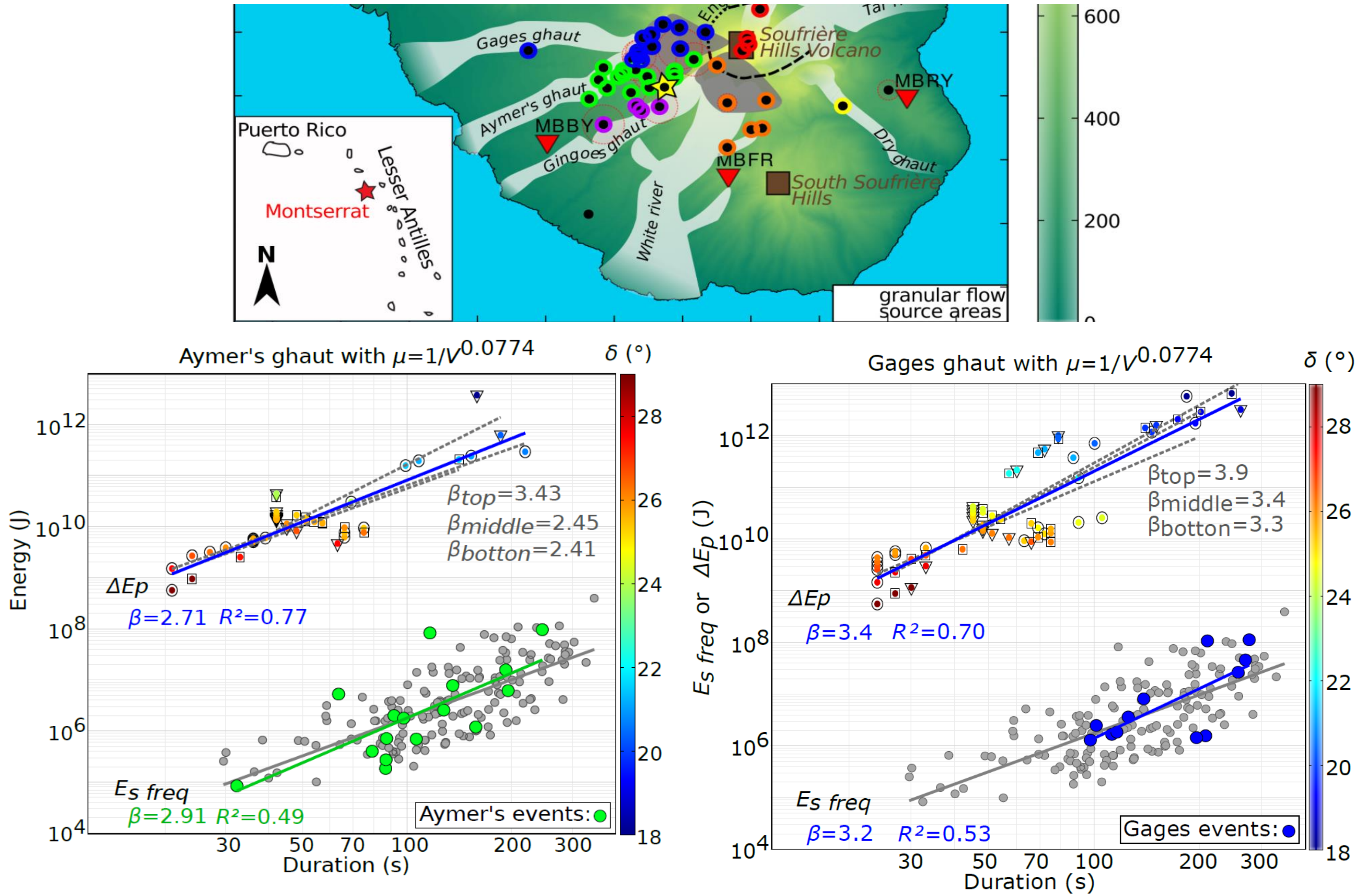
- Single impacts, laboratory: ~ 0.2
- Single impacts, field: 10^{-3} - 10^{-2} (/ 20 - 200)
- Single impacts laboratory → granular flows laboratory: / 10-100
- Granular flows, laboratory: 2.10^{-3} - 2.10^{-2}
- Granular flows, field: 10^{-5} - 10^{-3} (/ 20 - 200)

deduced values (granular flows, field)

in agreement with field studies

Hibert et al., 2011, 2014, Levy et al., 2015

Friction weakening signature on seismic data



The parameters of the power law depend on the valley !

Granular flows over complex topography

$$\partial_t(h/c) + \nabla_x \cdot (h\boldsymbol{u}') = 0$$

$$\partial_t \boldsymbol{u}' + c\boldsymbol{u}' \cdot \nabla_x \boldsymbol{u}' + \frac{1}{c}(Id - \boldsymbol{s}\boldsymbol{s}^t)\nabla_x(g(hc+b)) =$$
$$\frac{-1}{c}(\boldsymbol{u}'^t H\boldsymbol{u}')\boldsymbol{s} + \frac{1}{c}(\boldsymbol{s}^t H\boldsymbol{u}')\boldsymbol{u}' - \frac{g\mu c\boldsymbol{u}'}{\sqrt{c^2\|\boldsymbol{u}'\|^2 + (\boldsymbol{s}\cdot\boldsymbol{u}')^2}}\left(1 + \frac{\boldsymbol{u}'^t H\boldsymbol{u}'}{gc}\right)_+$$

$$\vec{n} = \left(-\frac{\nabla_{\mathbf{x}} b}{\sqrt{1+||\nabla_{\mathbf{x}} b||^2}}, \frac{1}{\sqrt{1+||\nabla_{\mathbf{x}} b||^2}}\right) \equiv (-\mathbf{s}, c) \in \mathbb{R}^2 \times \mathbb{R}$$

$$\mu = \mu_s$$

or

$$\mu(Fr, h) = \mu_s + \frac{\mu_2 - \mu_s}{\dfrac{\beta h}{\mathscr{L} Fr} + 1}$$

Other empirical terms can be added …. with more unconstrained parameters…

Long period observed and simulated seismograms

Filtered between 20 and 80s