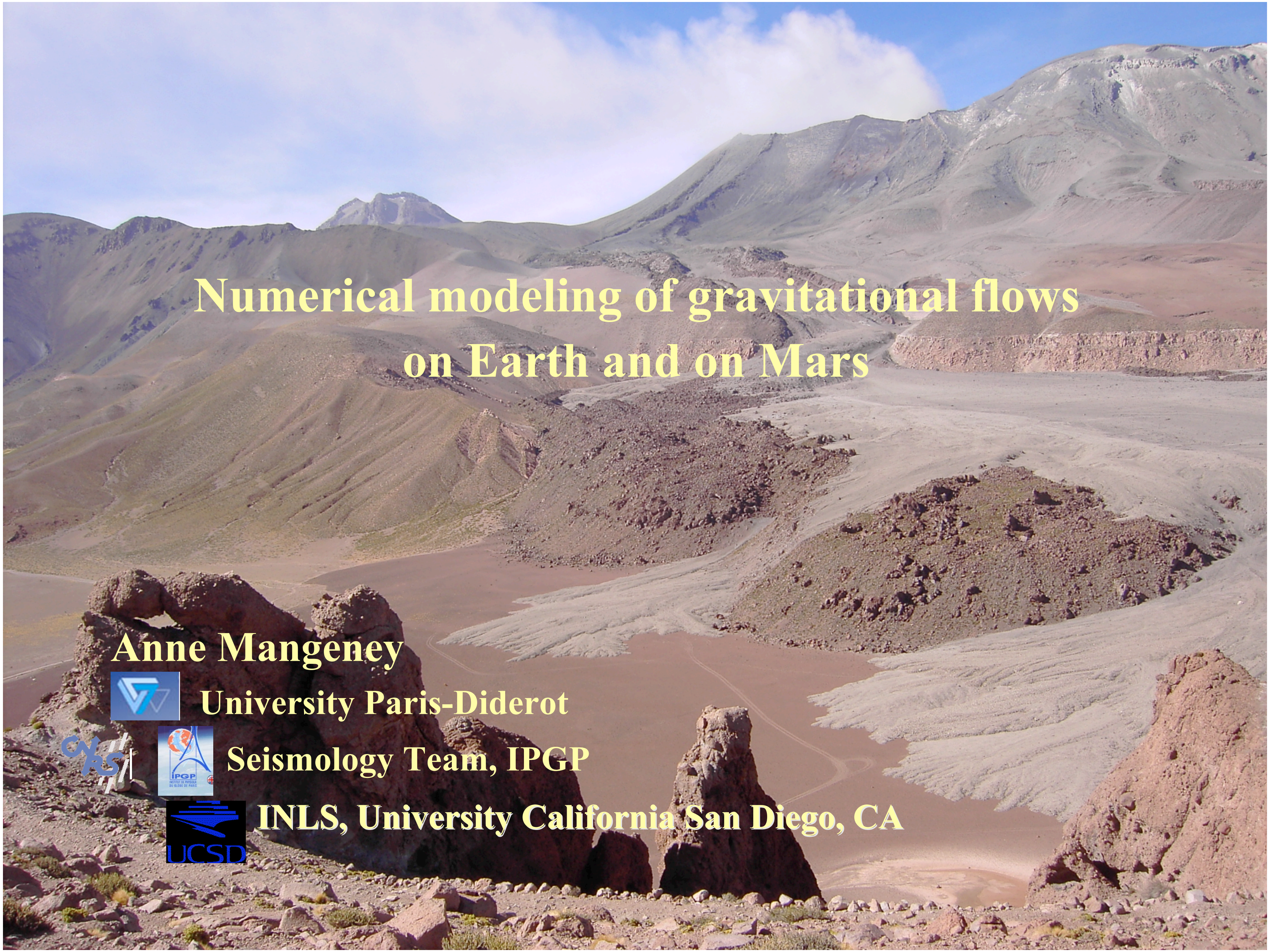

Numerical modeling of gravitational flows on Earth and on Mars

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Seismology Team, IPGP
INLS, University California San Diego, CA

Collaborations

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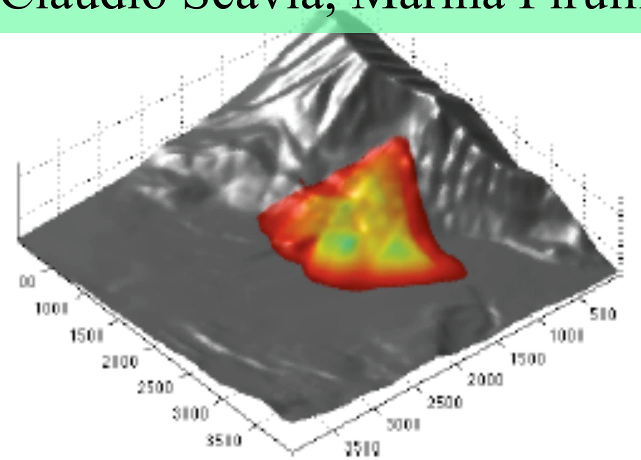
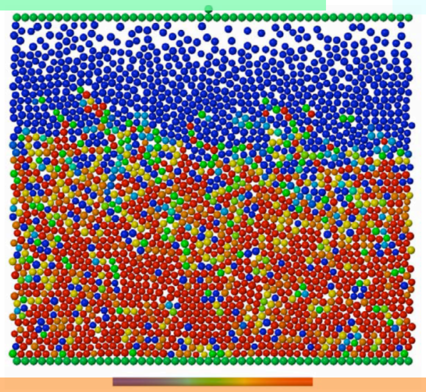
Philippe Labazuy, Karim Kelfoun, *LMV*, *Clermont*

Nicolas Mangold, *IDES-Orsay*

Claudio Scavia, Marina Pirulli, *Politecnico, Turin*

Daniel Mège, *LPG*, *Nantes*



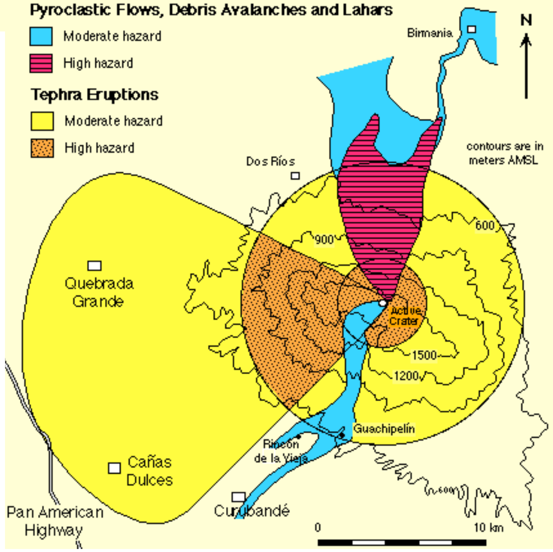


Dmitri Volfson, Lev Tsimring, *INLS*, *UC San Diego*

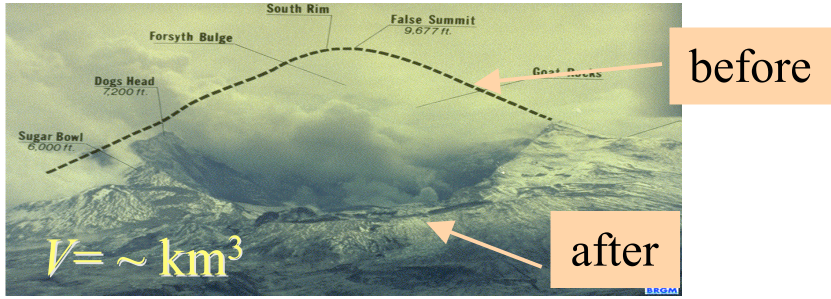
Numerical modeling of avalanches and landslides

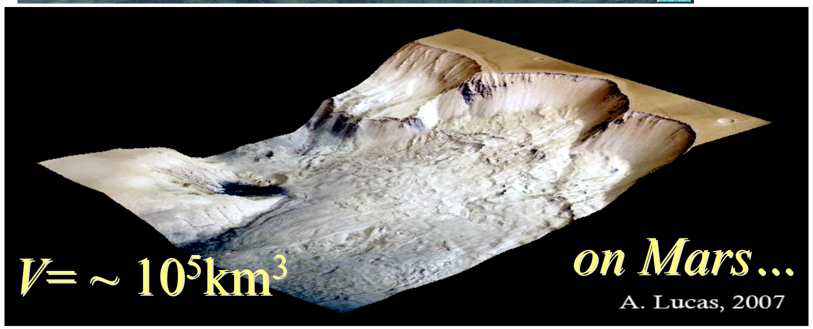
Motivation

- Understanding erosion processes
at the earth surface and on telluric planets
- Risk assessment
- Precursors of volcanic activity?



Wide variety of geophysical granular flows: avalanches, landslides, debris flows…





Several sources (earthquakes, precipitation, volcanism…), various scale, composition

Avalanche dynamics: Field scale to laborary scale

• Physics and mechanics of **granular flows in laboratory**

Simplified systems

Velocity and thickness measurements

• Physics and mechanics of **natural flows** ?

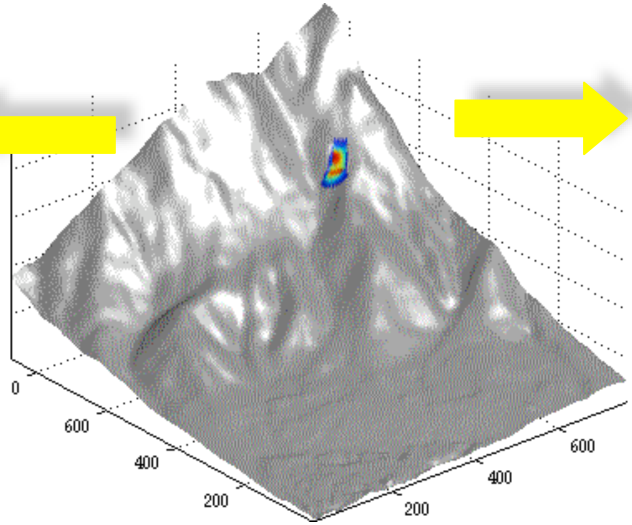
Very complex flows

Few **data**: essentially on the **deposit**

Emplacement conditions

Same physical processes ?

Numerical simulation

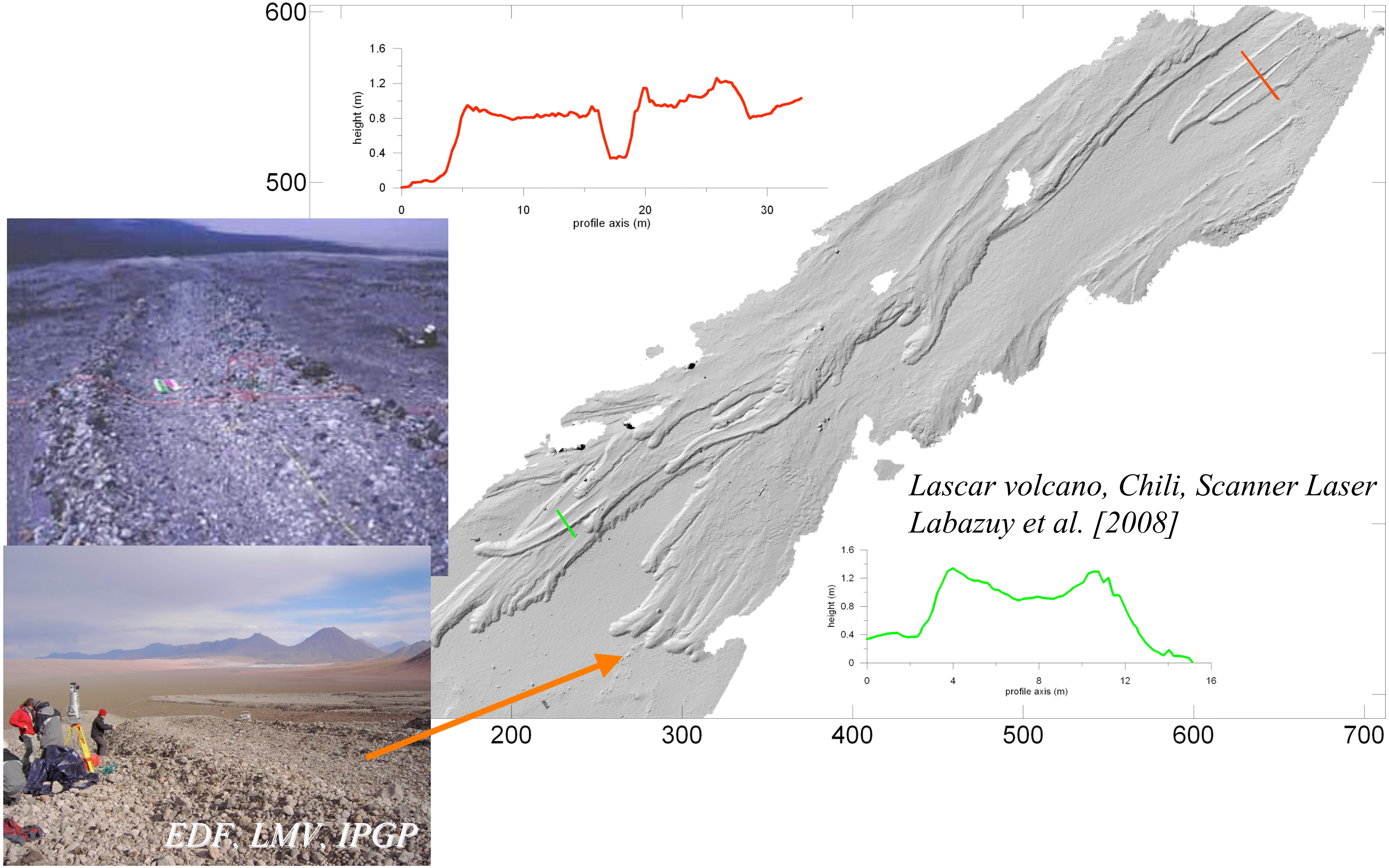


Numerical simulation, Lucas, Mangeney, Bouchut

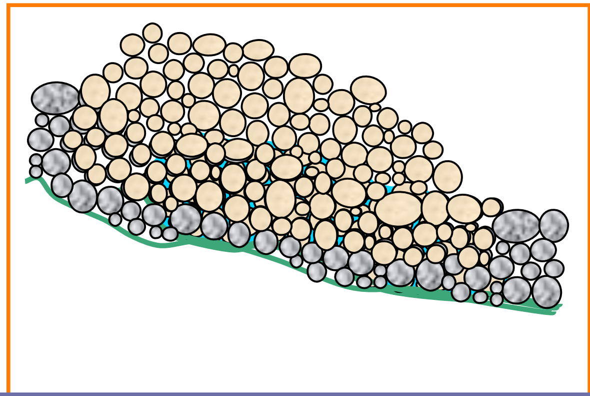
Nathalie Thomas, IUSTI

From morphometric observations to emplacement dynamics

- The levee/channel morphology of self-channelling flows on the Earth, on Mars …



How does it form ?



Erosion/deposition ?

Role of water ?

Numerical modelling of dry granular flows

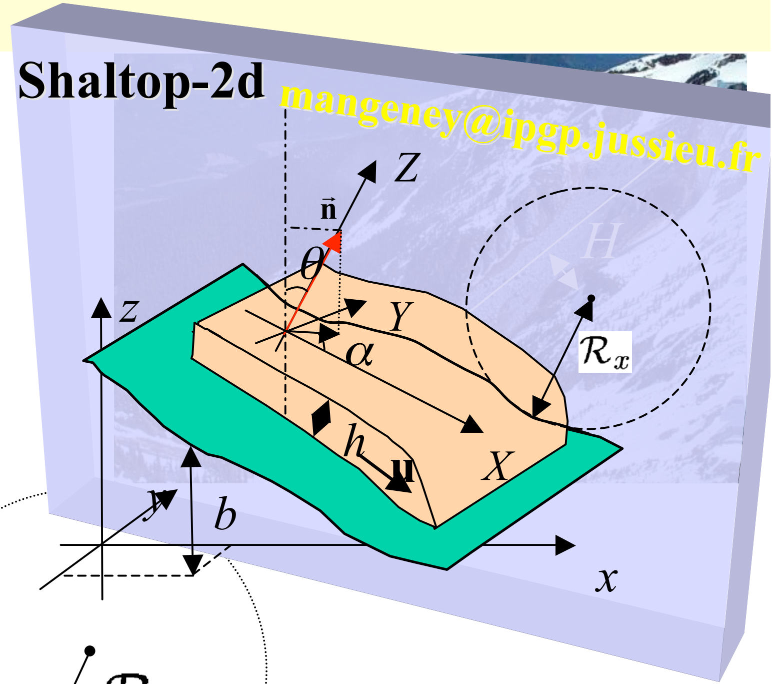
over complex topography?

Thin Layer Approximation

- Flow on **complex natural topography**

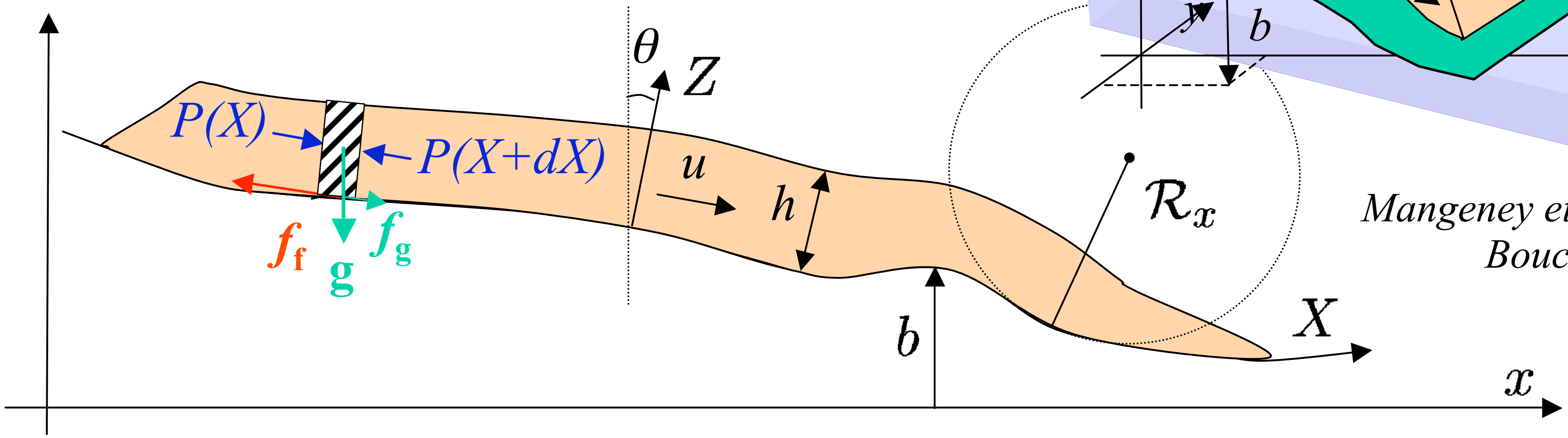
$\Downarrow$ small **Aspect ratio**

high computational cost $\Rightarrow$ $a = \dfrac{H}{L} << 1$



Mangeney et al. [2007]
Bouchut [2004]

- Depth-averaged thin layer model model



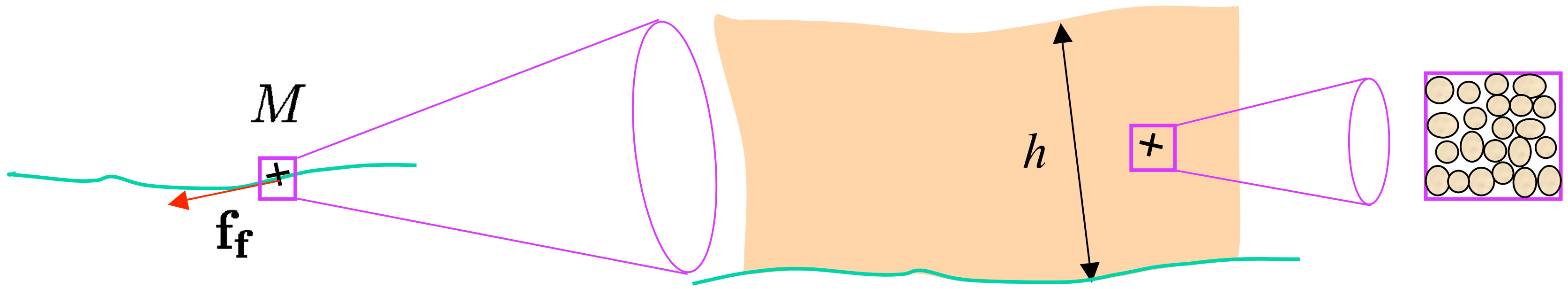
$$\underbrace{\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial X}}_{\text{inertia}} = \underbrace{\gamma_X g}_{\text{gravity}} \underbrace{- K\frac{\partial}{\partial X}(g\gamma_Z h)}_{\text{pressure gradient}} \underbrace{- \mu\left(g\gamma_Z + \frac{u^2}{\mathcal{R}_x}\right)\frac{u}{|u|}}_{\text{Coulomb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

Coulomb friction : $\mu = \tan\delta$

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

[*Savage and Hutter,* 1989]

Friction force : from grain to averaged media behavior



Averaged scale **?** **Local** scale **?** **Grain** scale

Constitutive relation at the **local** scale : existence and formulation ?

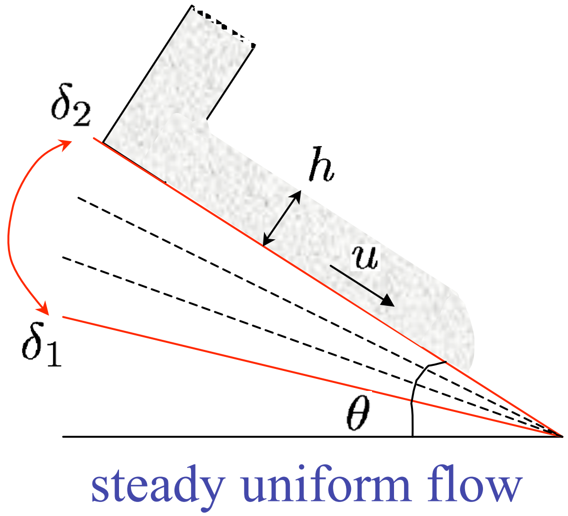
$\Downarrow$

Continuum equations for granular flows **are not well established**

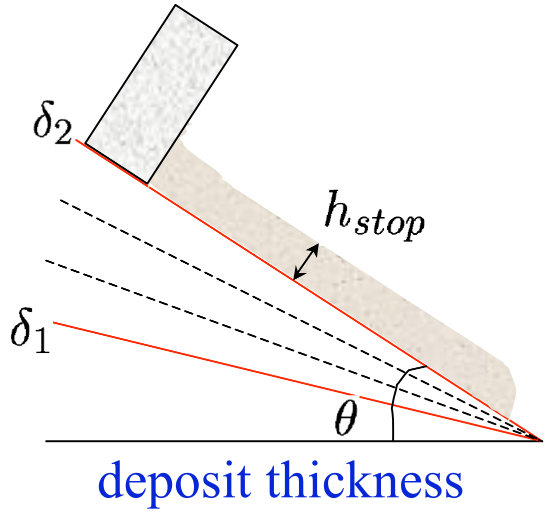
Empirical relation deduced from experiments

Scaling law from experiments of **steady uniform flows over inclined plane**

Pouliquen [1999]

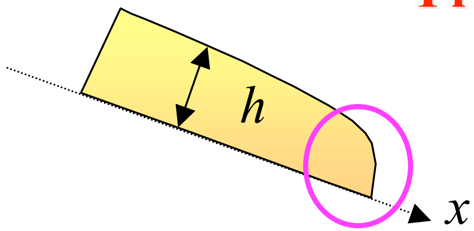


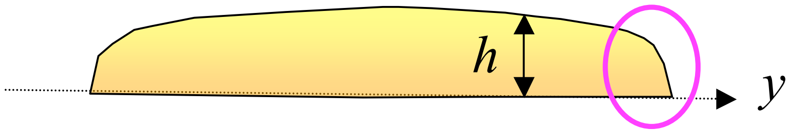
+



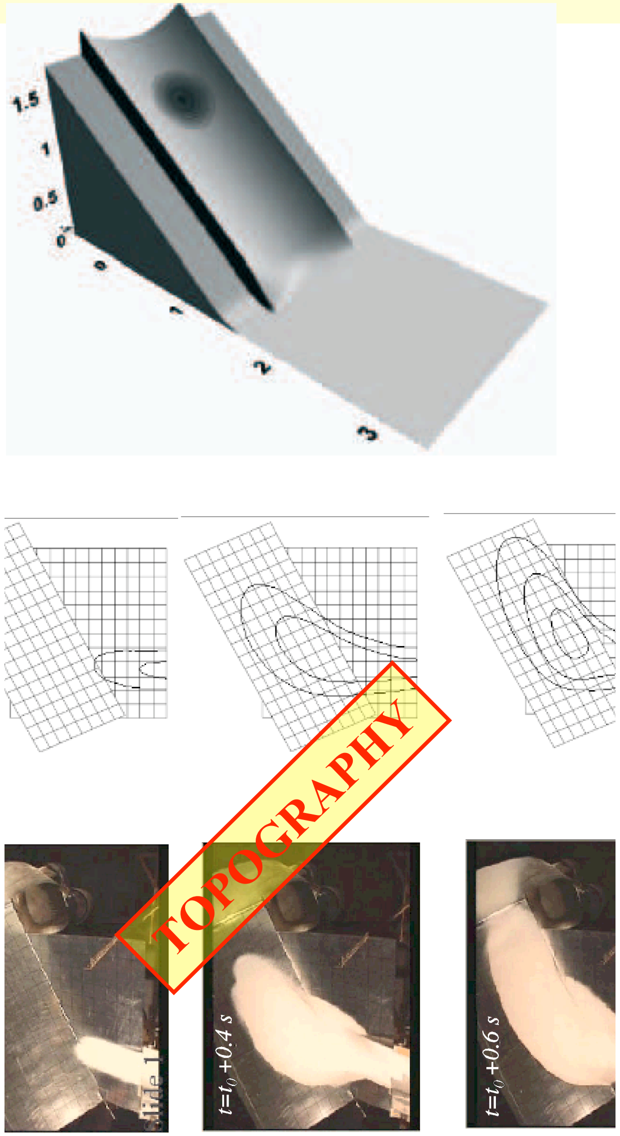
$$\mu(Fr, h) = \tan\delta_1 + (\tan\delta_2 - \tan\delta_1)\exp\left(-\frac{\beta}{Fr}\frac{h}{d}\right) \qquad Fr = \frac{u}{\sqrt{gh}}$$

Friction f_f ↗ as the thickness ↘

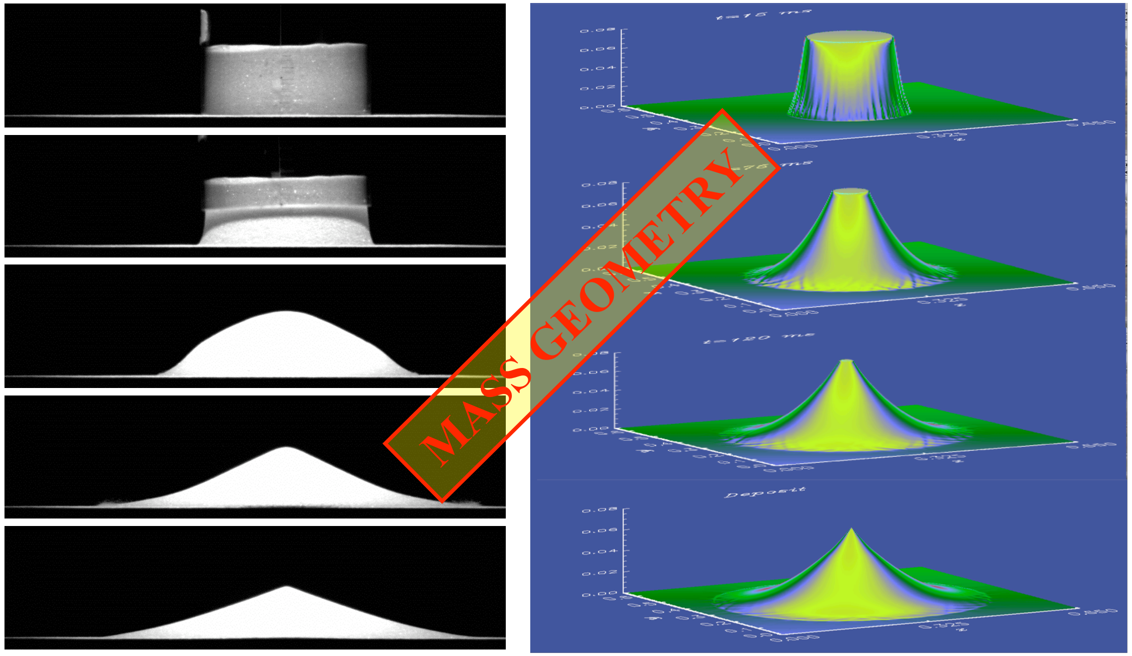




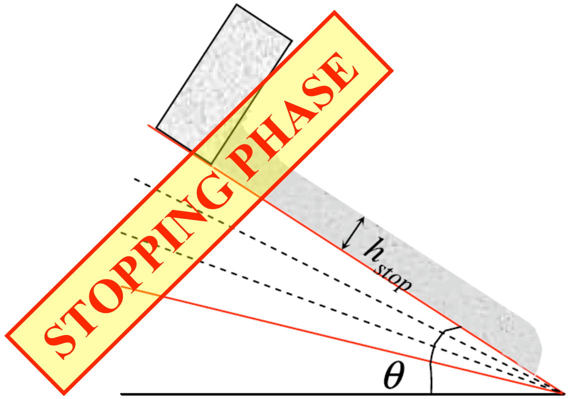
Simulation of laboratory experiments



Pirulli, Bristeau, Mangeney, Scavia [2006]



Mangeney et al. [2005]

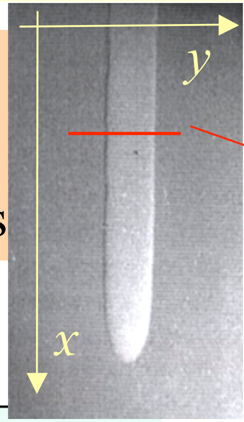


Mangeney, Vilotte, Bristeau, Perthame et al. [2003]

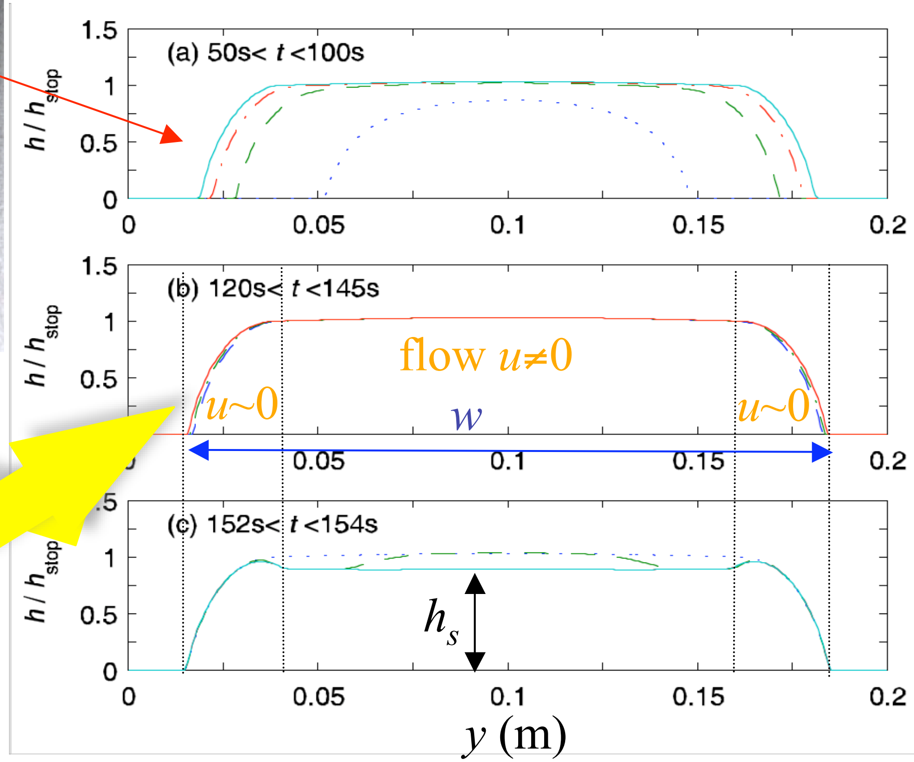
Simulation of self-channeling flows

Qualitative agreement
between
experimental and numerical results

COMPLEX FLOW

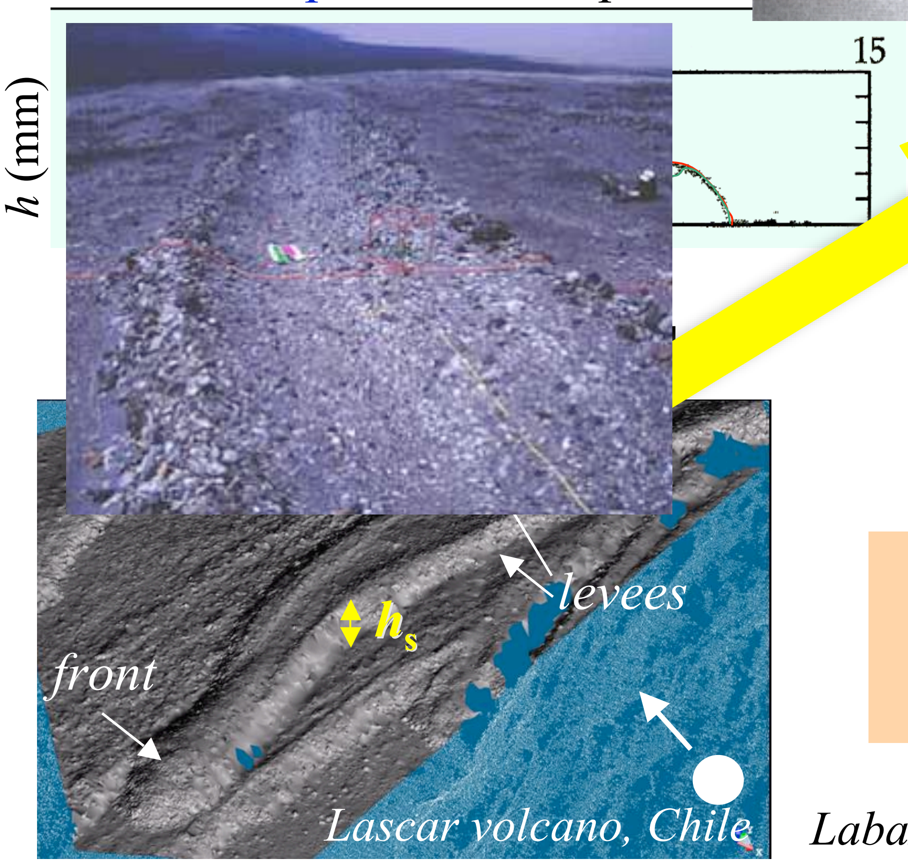


Numerical simulation



Mangeney et al. [2007]

Experimental deposit

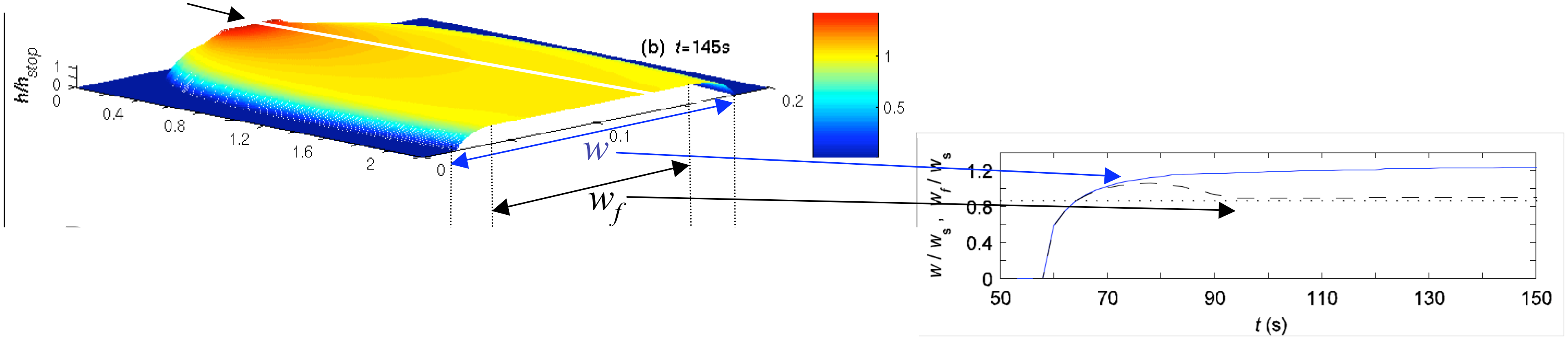


Polydispersity and mixture concepts are not needed to explain
self-channeling flows and levee formation

Labazuy, Kelfoun, Mangeney et al. [2008]

Relation between dynamics and deposits

Input flux Q_0 *Steady regime*



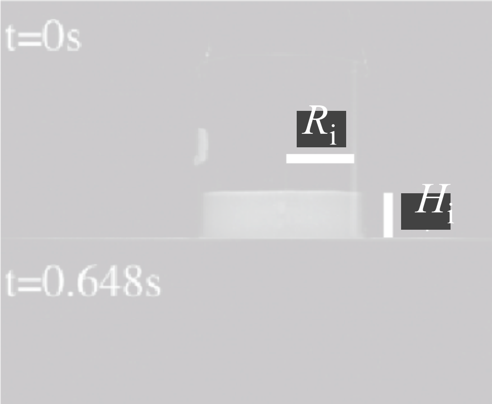
Scaling laws for mean velocity u_f and thickness h_f

$$\frac{w_f}{w_s} = \left(\frac{h_f}{h_{stop}}\right)^{-5/2}, \qquad u_f = \gamma h_f^{3/2}$$

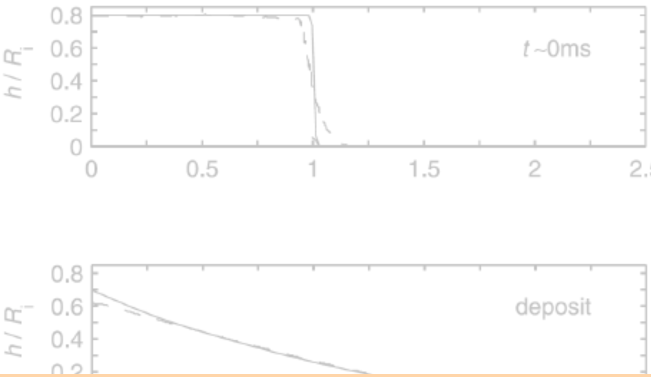
Measurement of w_c **and** h_c → first order estimation of the dynamics (h_f, u_f)

Limits of the thin layer approximation

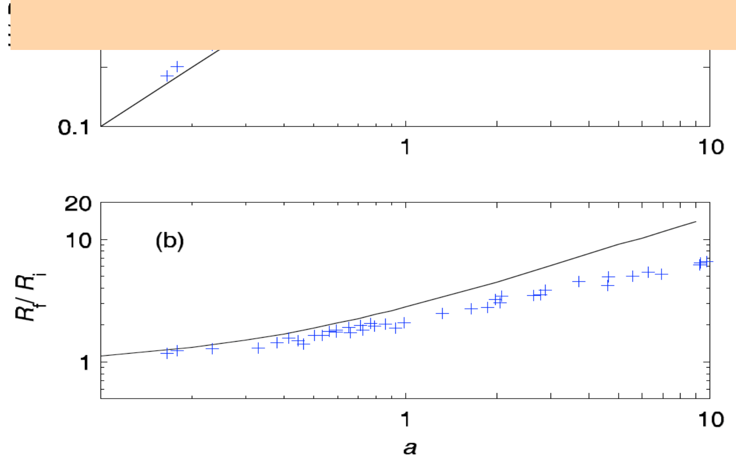
Initial aspect ratio: $a = H_i / R_i$

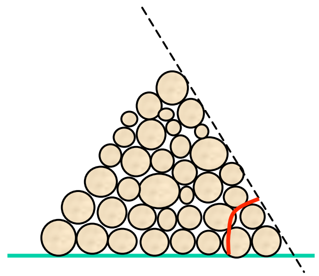


a=0.8



Shaltop-2d well match dry granular collapse in the laboratory
if $a < 1$
which is generally the case for natural landslides !





static friction angle

Summary of the experiment simulation

• Simulations with **friction angle ~ typical friction angle for the granular material** roughly reproduce:

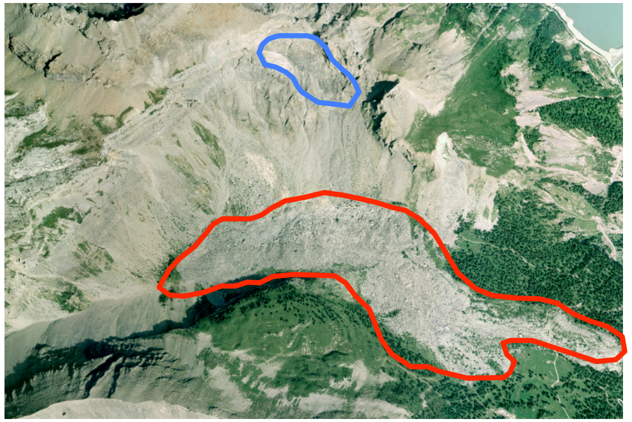
- mean behavior of the flow
- mean shape of the deposit
- some morphological structures

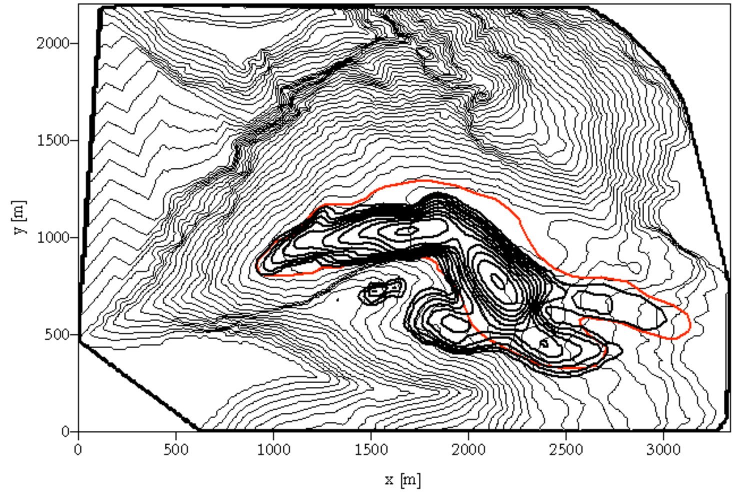
What about natural avalanches ?

Simulation of natural gravitational flows

• **Operational codes** : Six des Eaux Froides landslide, Switzerland, 1946 [*Pirulli and Mangeney,* 2006]

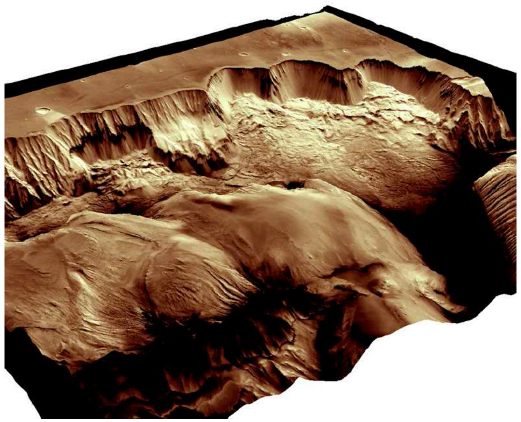
$t = 70$ s friction angle $\delta = 17^o$

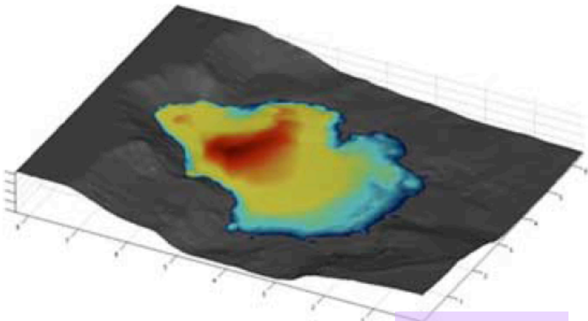




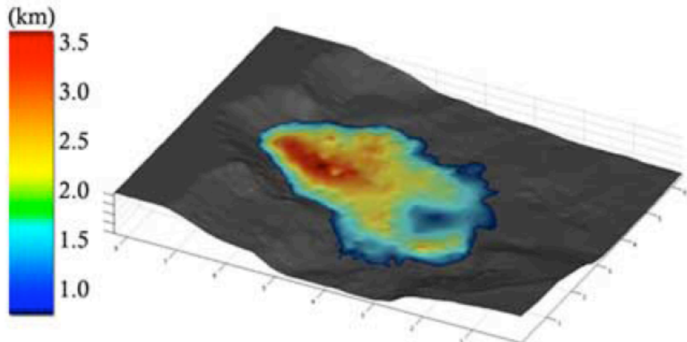
Good news: The calculated deposit area well match the observations

• Ophir Chasma, Valles Marineris, Mars [*Lucas and Mangeney*, 2007]





Simulation using $\delta = 10^o$.



Martian observation MOLA DTM.

Prediction?

- **Small friction angles** δ compared to typical of natural materials! $\theta_r \sim 35^\circ$

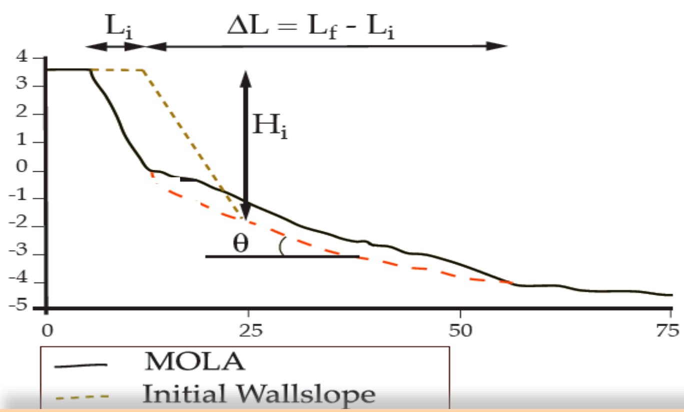
$\mu = \tan\delta$: **empirical description of the mean dissipation**

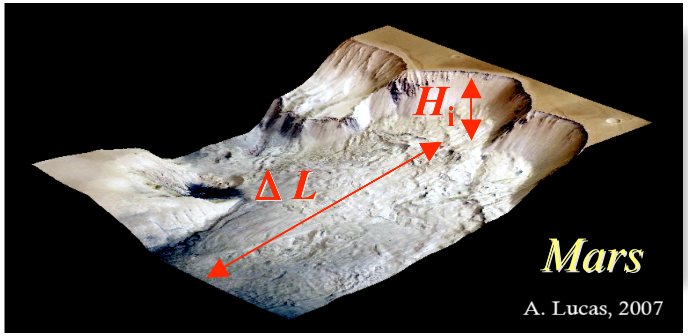
- **Quite bad news** : High variability of **adjusted friction angle** for natural flows

Landslide	Volume	Basal friction angle
Fei Tsui landslide, Hong-Kong, 1995	$V = 1.4\times10^4$ m^3	$\delta = 26^\circ$
Shum Wan landslide, Hong-Kong, 1995	$V = 2.6\times10^4$ m^3	$\delta = 18^\circ$
Six des Eaux Froides, Switzerland, 1946	$V = 5\times10^6$ m^3	$\delta = 17^\circ$
Frank, Canada, 1903	$V = 3\times10^7$ m^3	$\delta = 14^\circ$
Boxing Day, Montserrat, 1997	$V = 5\times10^7$ m^3	$\delta = 15^\circ$
Ophir Chasma, Valles Marineris, Mars	$V = 5\times10^{12}$ m^3	$\delta = 9.8^\circ$
Candor Chasma, Valles Marineris, Mars	$V = 2.3\times10^{11}$ m^3	$\delta = 9.9^\circ$
Ganges Chasma, Valles Marineris, Mars	$V = 1\times10^{12}$ m^3	$\delta = 9.4^\circ$

Useful tool for risk assessment using calibration on past events in the same context!

Mobility of experimental and natural flows

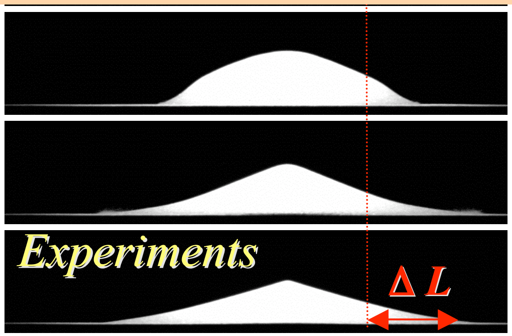


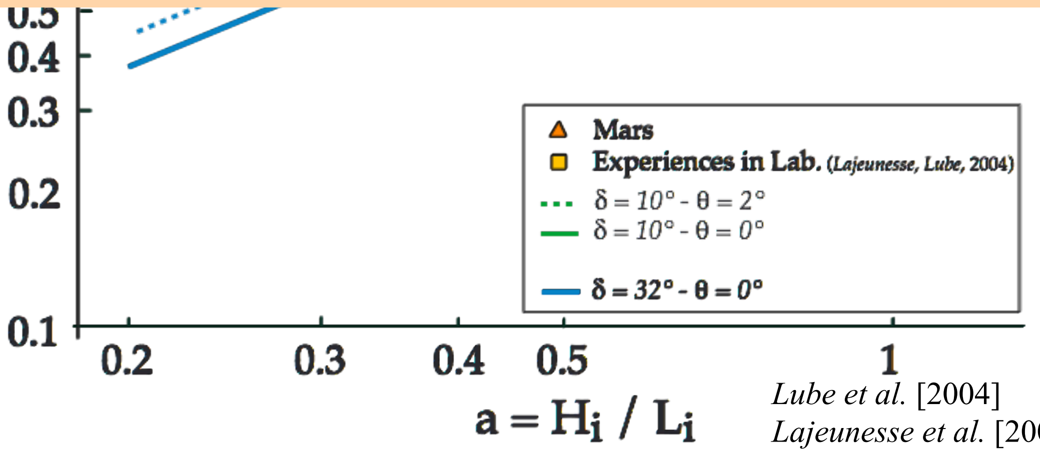


Very low friction ⇒ mechanical behavior of

Martian landslides ≠ Experimental dry granular flows

Topography effects ?

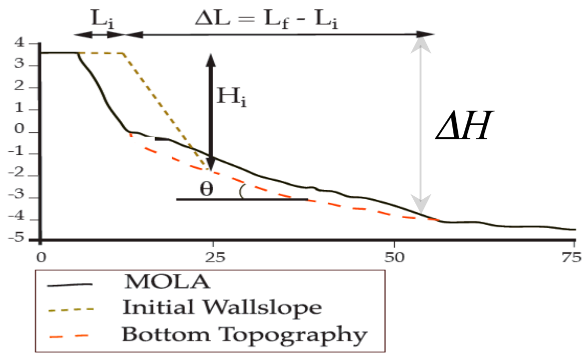




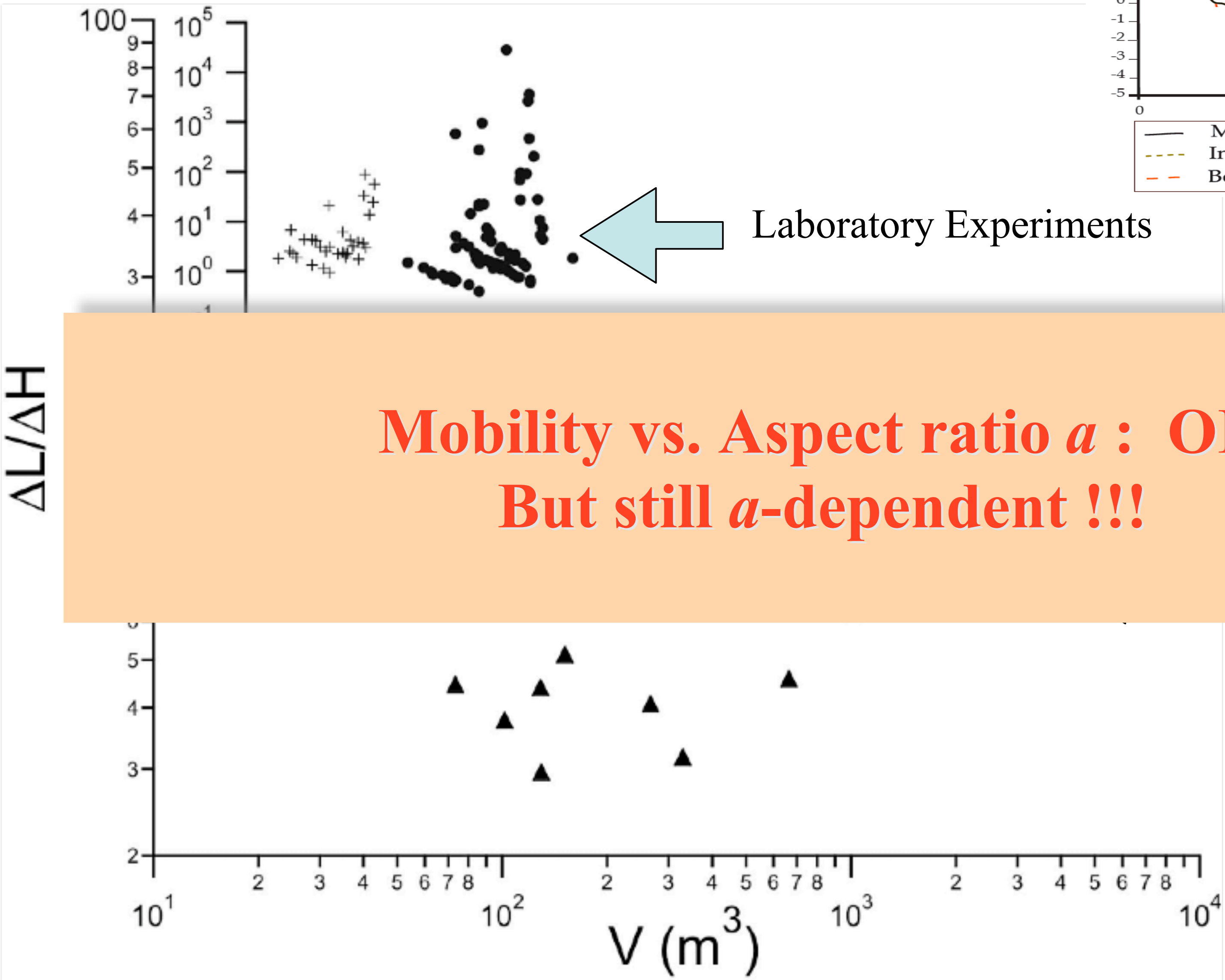
Lube et al. [2004]
Lajeunesse et al. [2006]
Lucas and Mangeney [2007]

How to define the mobility of gravitational flows ?

Initial aspect ratio: $a = H_i / L_i$



Lucas and Mangeney [2007]

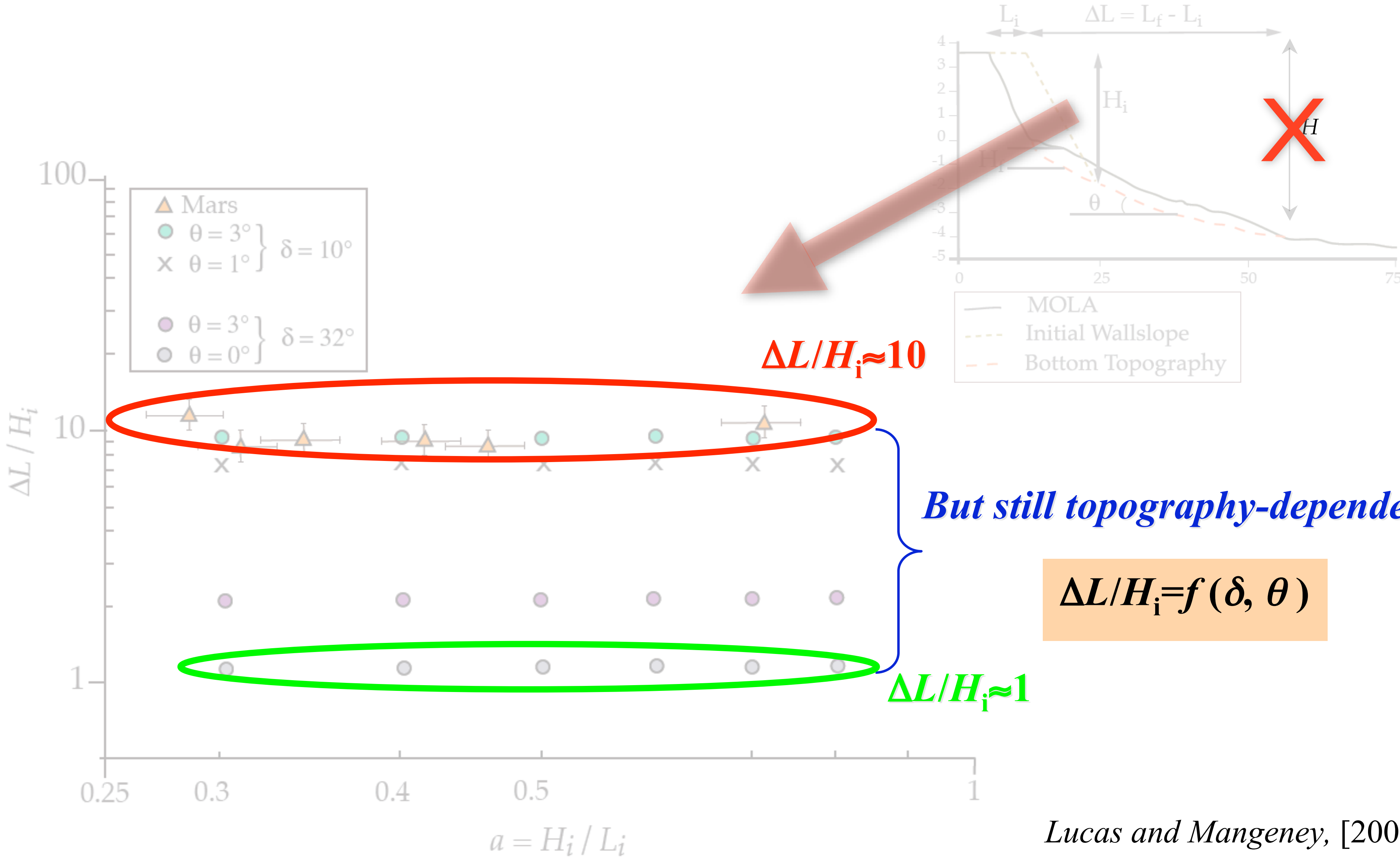


Mobility vs. Aspect ratio *a* : OK
But still *a*-dependent !!!

Lajeunesse et al. [2006]

A new mobility…

New mobility vs. initial aspect ratio is relevant !



$\Delta L/H_i \approx 10$

But still topography-dependent

$\Delta L/H_i = f(\delta, \theta)$

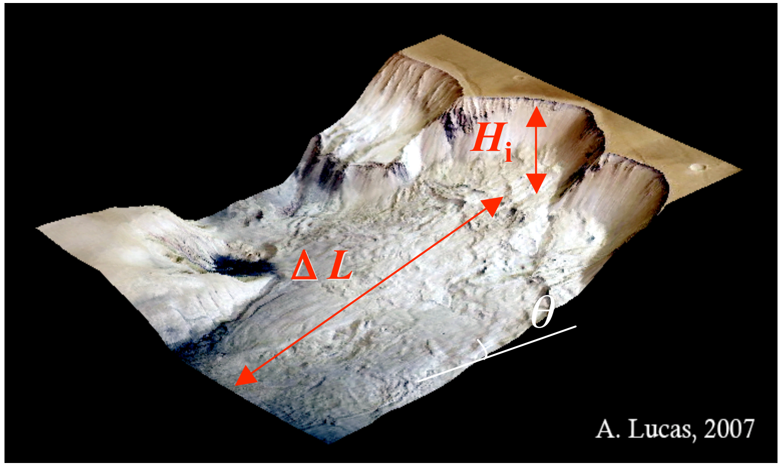
$\Delta L/H_i \approx 1$

Lucas and Mangeney, [2007]

An "intrinsic" Mobility

$$m'_e = f'(\delta, \cancel{\theta}) = 1/(\text{mean dissipation})$$

New mobility calculated from **analytical solution** [*Mangeney et al*., 2000]



$$m'_e = \frac{1}{\tan\delta} = \frac{1}{\tan\theta + \alpha\frac{H_i}{\Delta L}}$$

Friction coefficient
≡ mean dissipation

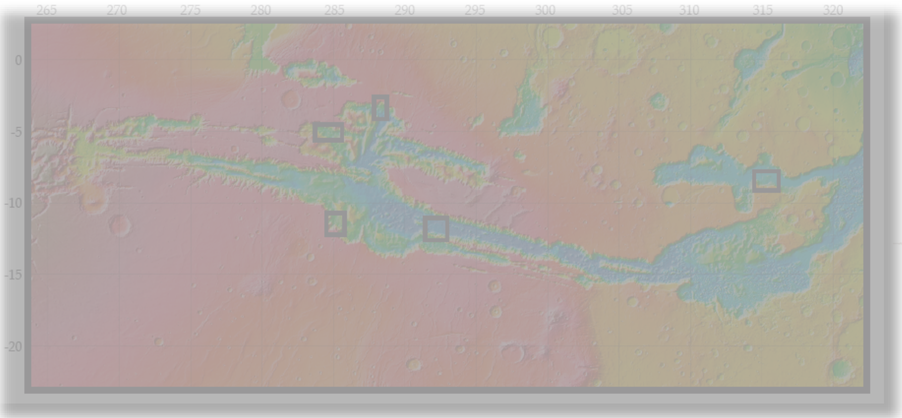
Topography

Morphometry

field measurements give the friction coefficient, i. e. **the effective dissipation**

Lucas and Mangeney [2007]

New mobility : survey at the field scale



A few landslides in Valles Marineris

Geomorphic survey using Imagery (THEMIS, HRSC, MOC, HiRISE) and Topography (MOLA, HRSC)

Using this "measured" friction angle, what about 3D deposit??!

$$\boxed{m'_e =} \quad \boxed{\frac{1}{\tan\theta + \alpha \frac{H_i}{\Delta L}}}$$

Landslides	Mobility (m'_e)
Ophir	5.8
Candor	5.6
Ganges	6
Coprates	7.7
Melas	6.9

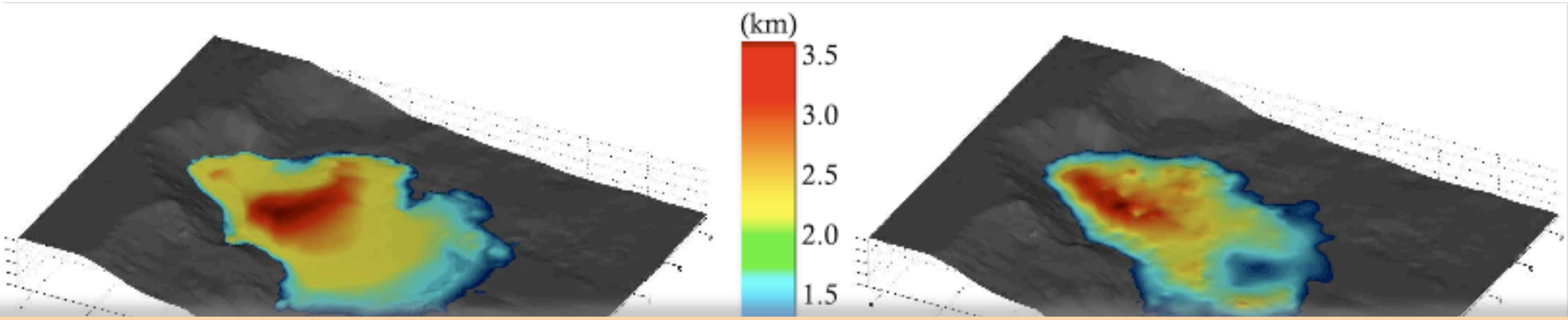
Tab 1 – Mobility *m'e* and angle of friction δ calculated for a few landslides on Mars.

~ the same δ !!

3D Numerical simulation of Martian Landslides

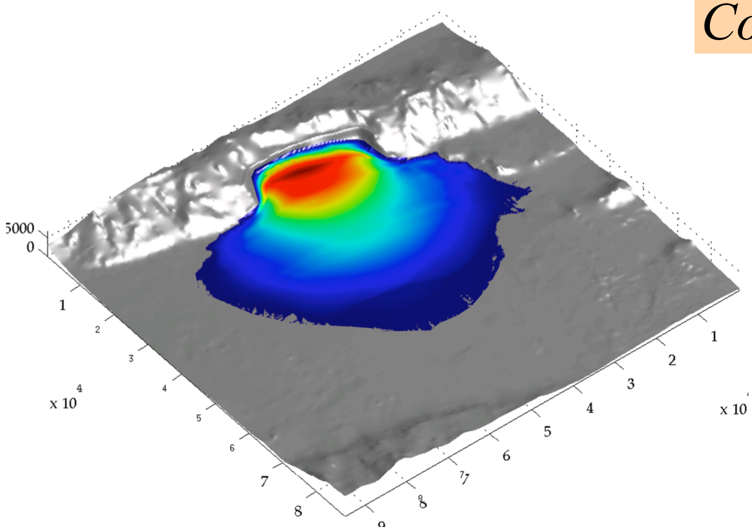
Numerical simulation | Observation

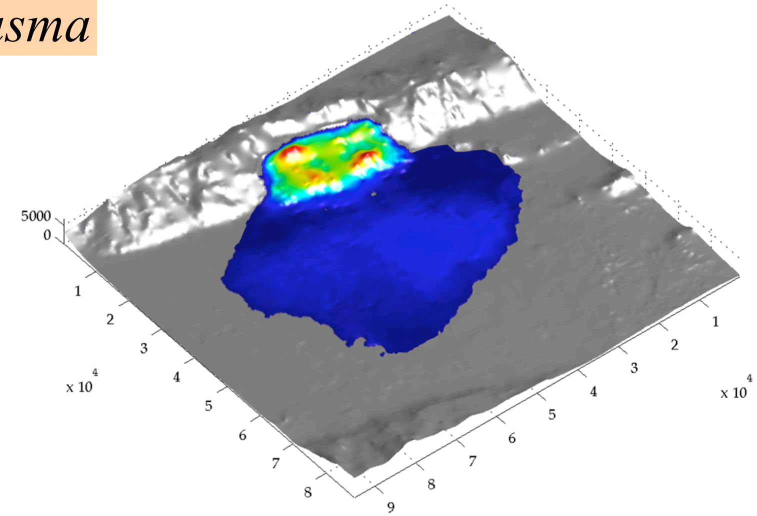
Ophir Chasma



Predictive power of actual empirical models

Coprates Chasma



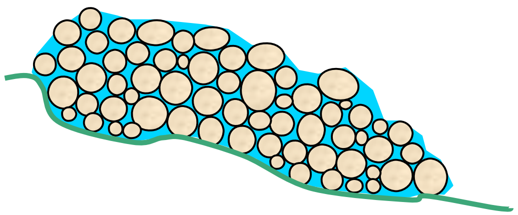


Lucas and Mangeney, [2008]

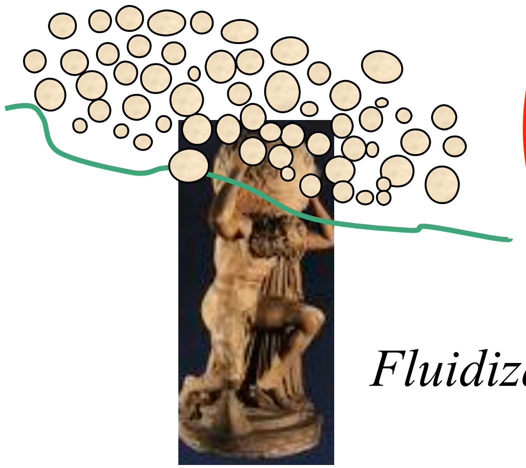
High mobility of natural gravitational flows
can not be explained by
dry granular flows over a rigid bed

Significant **physical processes**
are missing in the laboratory

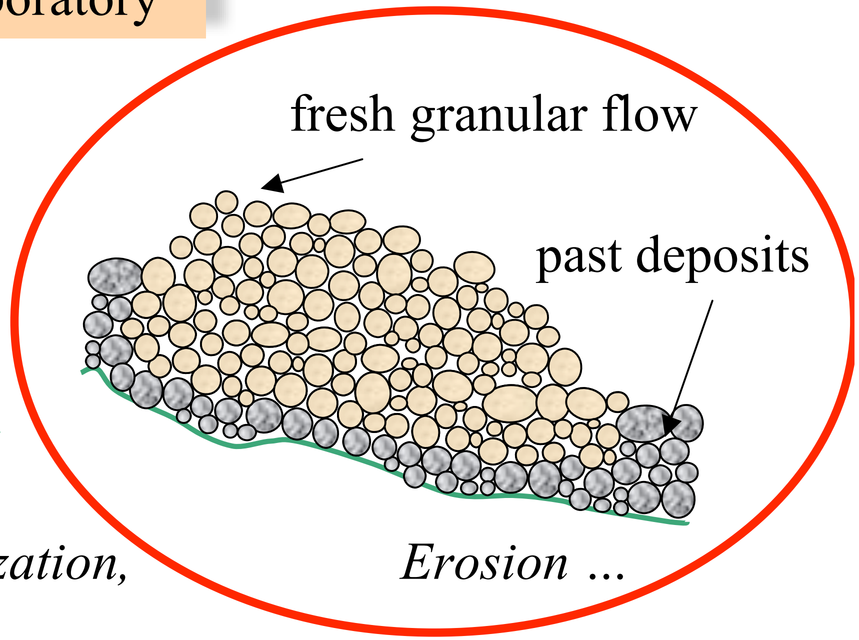
???



Fluid phase,



Fluidization,

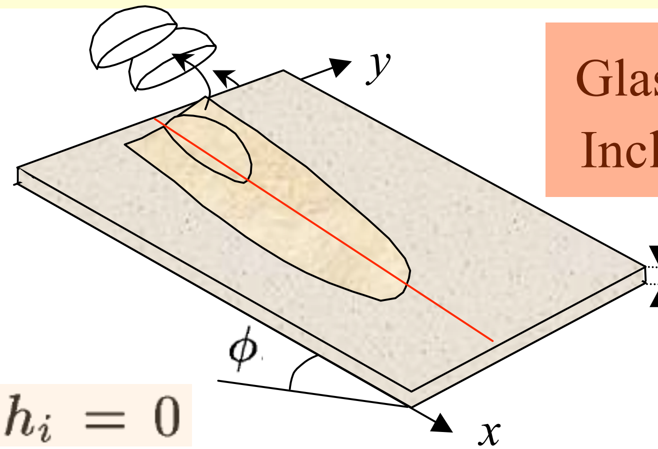


Erosion …

Laboratory experiments on granular flows

Glass beads $d = 0.5$ mm Initial thickness $h_0 = 42\,d$

Inclination angle $\phi = 23°$ [*Pouliquen and Forterre*, 2002]

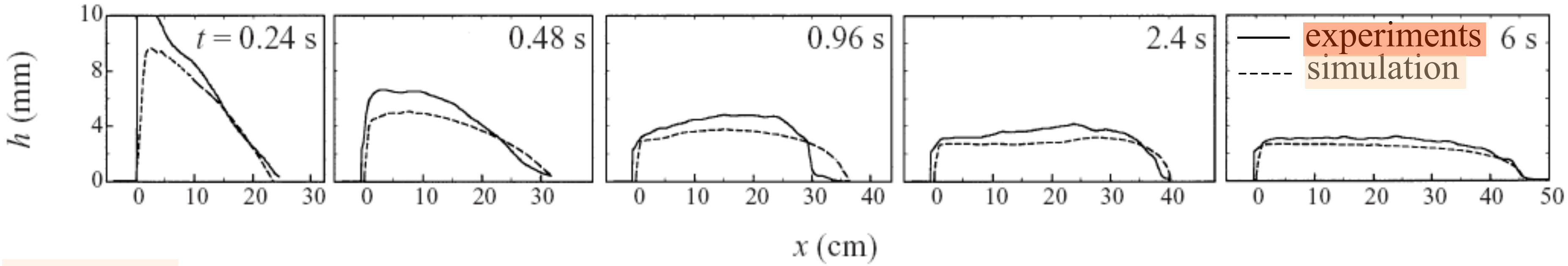


$h_i \ll h_0$

Simulation using thin-layer model

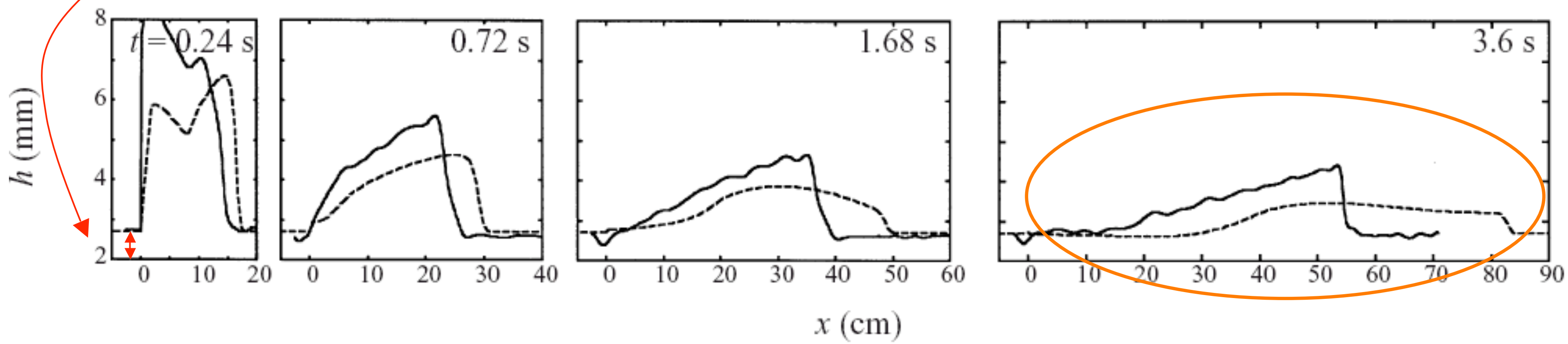
$h_i = 0$

Decelerating avalanche with deposit

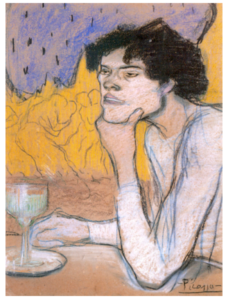


$h_i = h_s$: thickness of the deposit for granular flow over a rigid bed

Surge wave



The partial fluidization theory



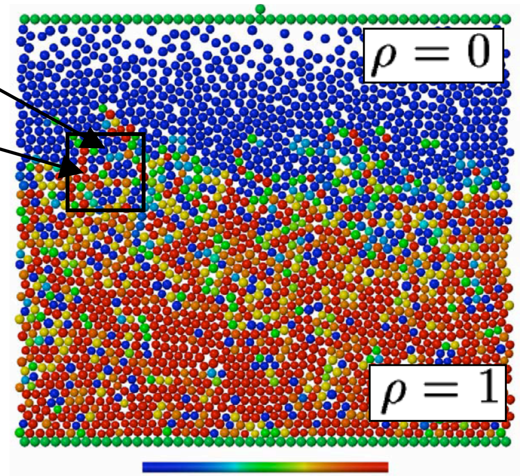
- Main fundamental problem:

σ_{ij} **???** **constitutive relation valid for flowing and static grains**

- **The partial fluidization model** faces the challenge: [*Aranson and Tsimring*, 2002]

$$\sigma_{ij} = \sigma^f_{ij} + \sigma^s_{ij}$$

$$\begin{cases} \sigma^f_{ij} & \text{- flowing part : rheology of flowing grains} \\ \sigma^s_{ij} & \text{- static part} \end{cases}$$



Discrete element simulations, [*Volfson et al.*, 2003]

- **The order parameter** $\rho = \dfrac{\Sigma \text{ static contacts}}{\Sigma \text{ contacts}}$

ρ characterizes the state of the granular matter

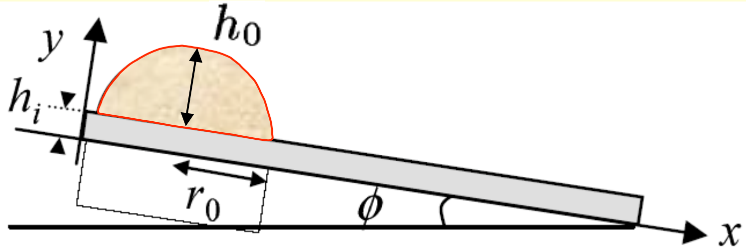
$$\sigma^f_{xy} = q(\rho)\sigma_{xy}$$

- Well known **theory of phase transition** (Ginzburg-Landau equation)

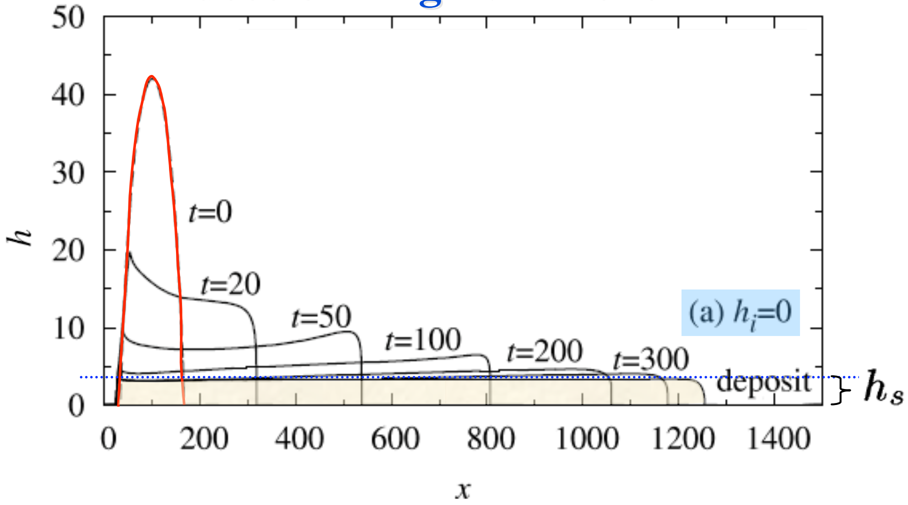
Numerical modeling : from decelerating avalanches to surge waves

- 2D numerical simulation

[*Mangeney et al.*, 2007]

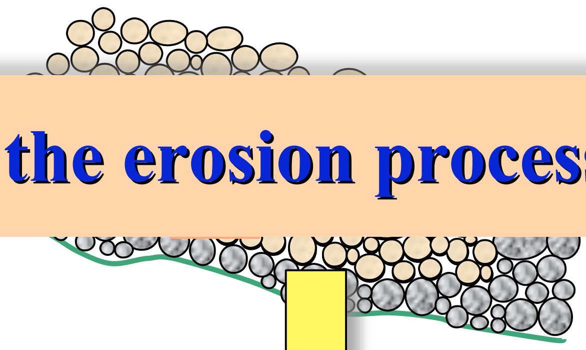


decelerating avalanche



Impact of erosion on avalanche mobility

• The erodible bed is a source of potential energy E_p ⟶ flowing mass E_k

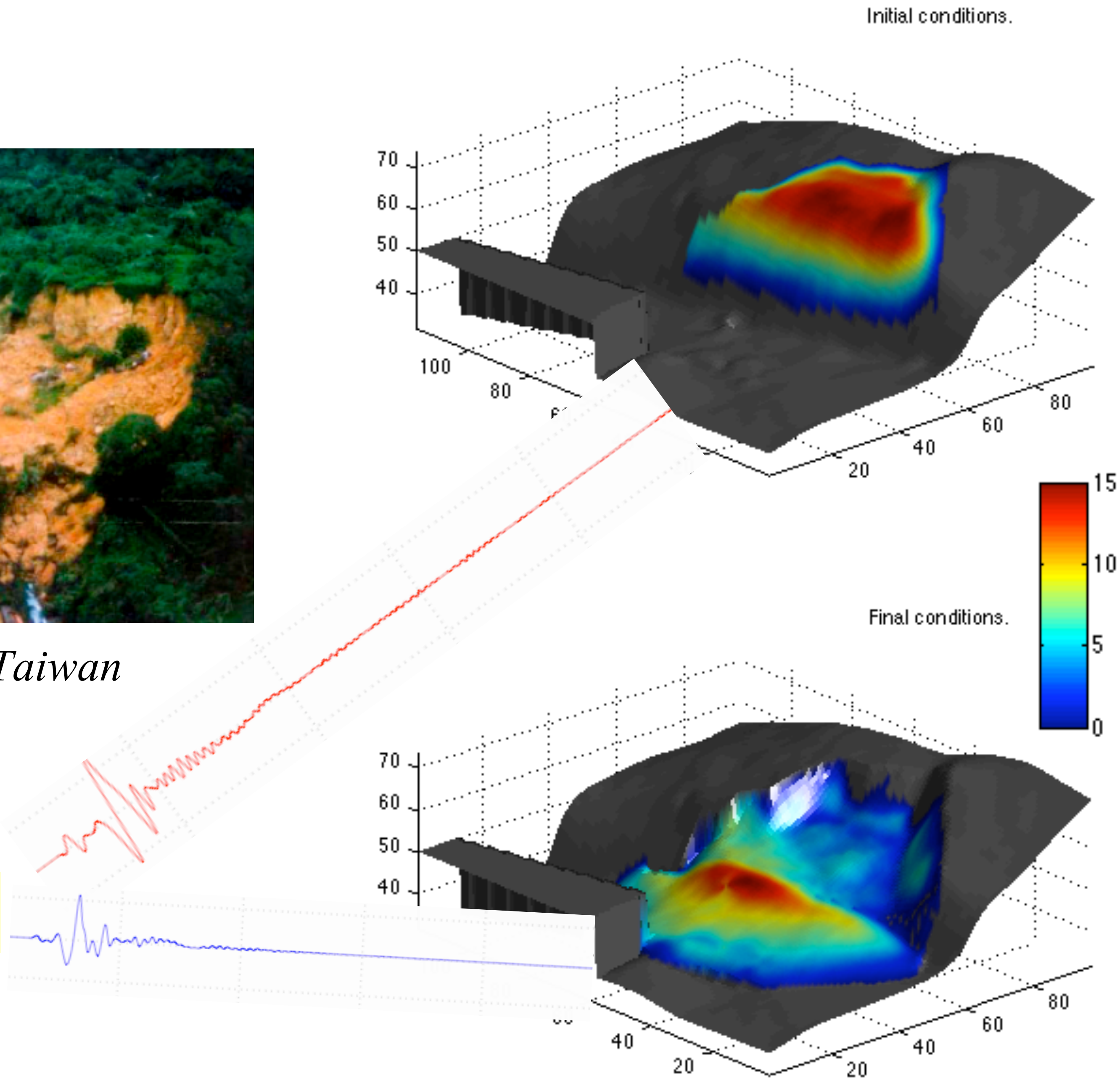


No signature of the erosion process on the deposit !

Data on the dynamics ??!

Dynamic properties of natural gravitational flows ?

Landslide in Taiwan

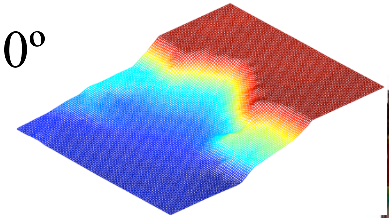


Seismology…

An extreme case…

Simulation of the landslide

Friction angle $\delta = 30°$



⇓

Simulation of the generated seismic waves

Pascal Favreau

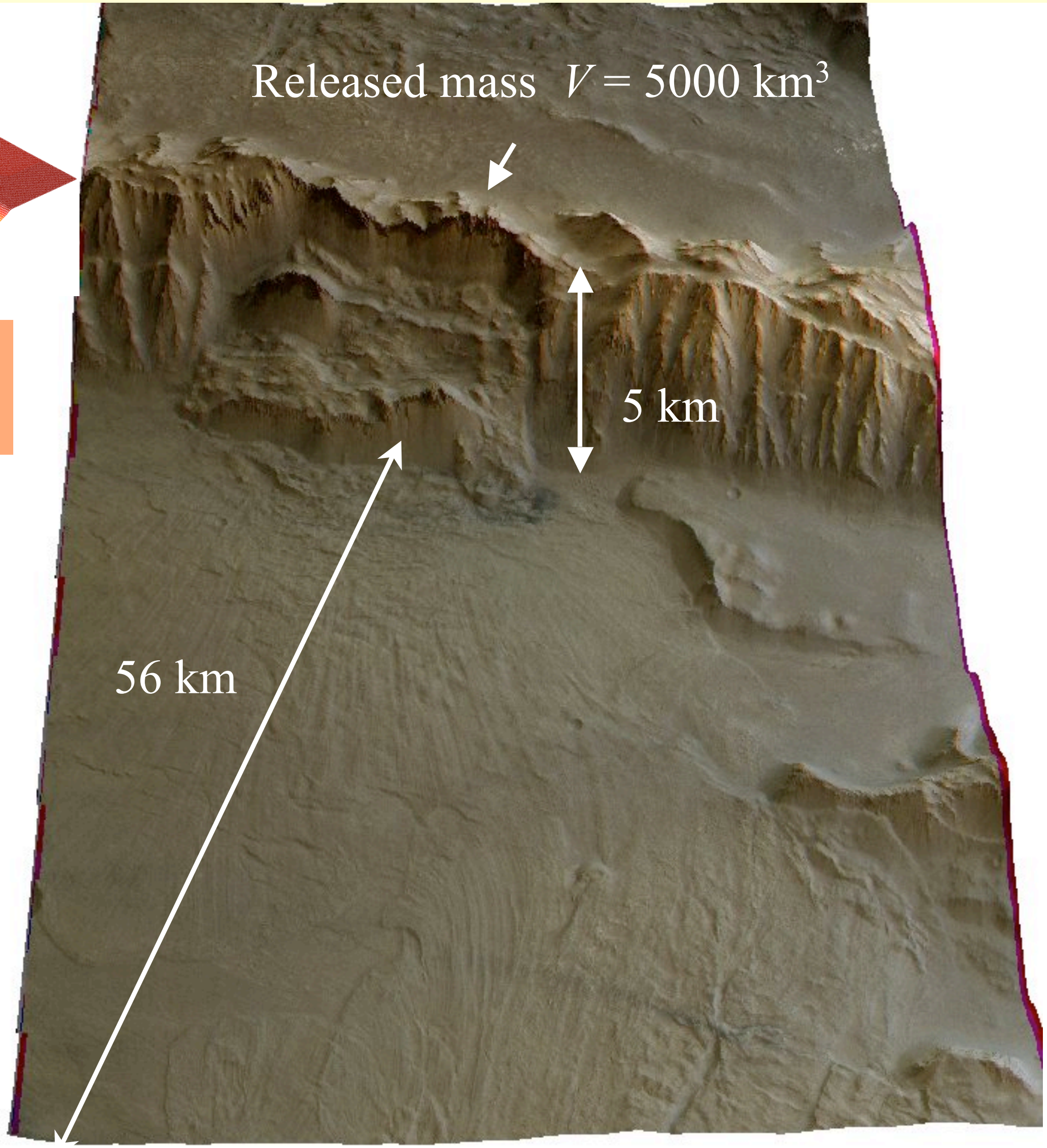
• Discharge and tangential stress

film_gliss_terrain_mars_force_25t.mpeg

• Discharge and normal stress

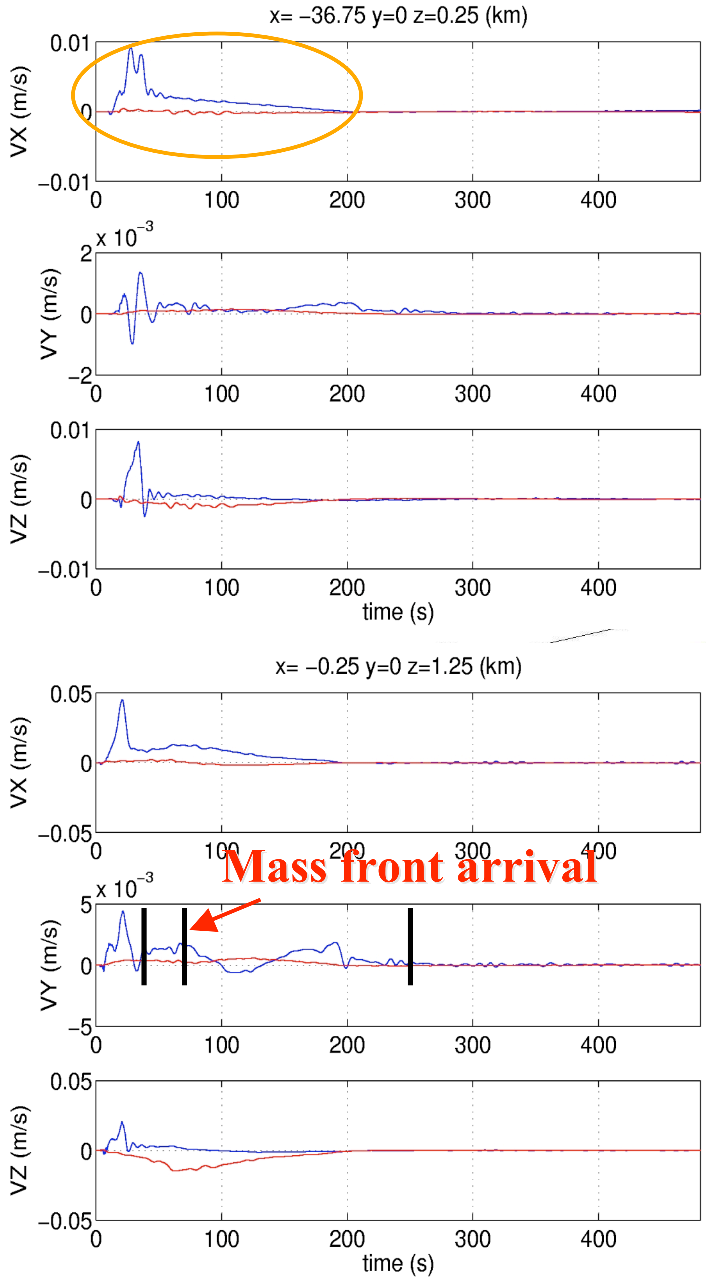
film_gliss_terrain_mars_force_25n.mpeg

Favreau, Mangeney, Lucas,…



Coprates Chasma, Valles Marineris, Mars

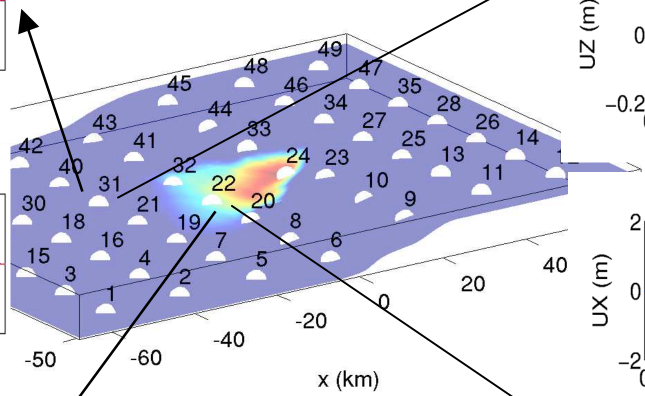
Synthetic waveforms from normal (red) and tangential (blue) forces

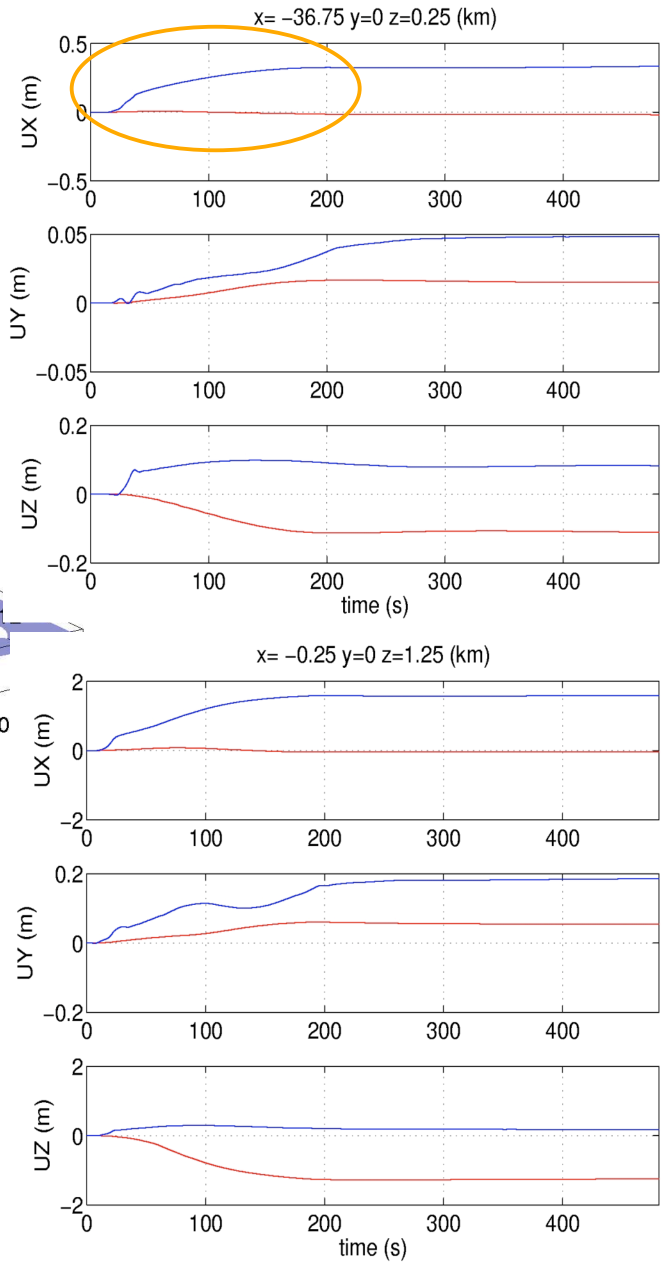


$\tau_{xz} \Rightarrow$ Short periods

$\sigma_{zz} \Rightarrow$ Low frequencies

Comparable static displacement





Conclusion

Numerical models: **empirical tool to study the mobility** of natural flows

once calibrated on past events

prediction in the same geological context

Numerical modeling helps « reading » the deposit's morphology

insight into **emplacement dynamics** → water on Mars?...

Operational software for risk assessment (**mangeney@ipgp.jussieu.fr**)

- More **physics** in the models: fluid/solid mixture model, erosion/deposition …
- More data on the dynamics : **seismology**
- Detailed analysis of the **deposit morphology** in various contexts