23-26th November 2021, IMPT, Lyon, France

Detection, dynamics and impact of landslides

Anne Mangeney[1,1']

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

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

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

Anne Mangeney

- **Background**

Master 1 in theoretical Physics, Paris VI

Master 2, Oceanography, Meteorology, Environment, Paris VI

- **PhD**

Modelling of anisotropic ice flow in ice-sheets (LGGE, Grenoble)

- **Post-doc**

Numerical simulation of tsunami waves (CEA, Bruyeres-le-Chatel)

- **Present situation**

Full professor, IPGP, University of Paris, **Seismology Group**

Associate researcher, Jacques-Louis Lions Lab., Paris (2021-2017),

Member of Institut Universitaire de France (since 2021)

Head of the Master Natural Hazards, IPGP

President of the CNRS section 18 (Earth and Telluric Planets)

Member of the Natural Hazard Prevention committee (Minister)

- **International connections**

Sabbatical year Inst. for Nonlinear Science, UC San Diego, 2006

Visiting Professor Seismolab, Caltech, USA, 2012

- **Achievements** *4 children*

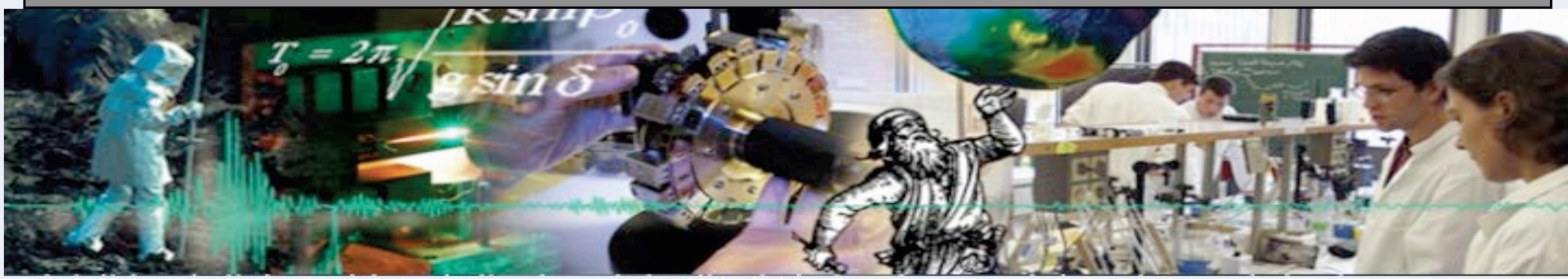
INSTITUT
de PHYSIQUE
du GLOBE
de PARIS

IPGP
INSTITUT DE PHYSIQUE DU GLOBE DE PARIS

Université de Paris

Trois missions de l'IPGP : recherche, observation des phénomènes naturels, enseignement et diffusion des connaissances en sciences de la Terre, des planètes et de l'environnement

1. Recherche	2. Observations	3. Formations
UMR 7154 IPGP	*UMS 3454 IPGP*	*DFED IPGP*



Le projet de tutelle secondaire IRD concerne l'UMR 7154 mais l'IPGP est organisé de telle sorte que tous les membres de l'UMR ont accès aux moyens de l'UMS 3454 et aux activités d'enseignement. Le directeur du grand établissement IPGP est directeur de l'UMR 7154, de l'UMS 3454 et des Formations (avec un directeur adjoint pour chaque entité)

Université de Paris

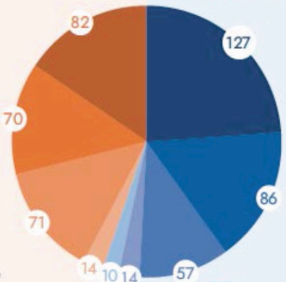
531
personnels en 2020 staff in 2020

237
non permanents non-permanent staff

294
permanents permanent staff

127 personnels IPGP IPGP staff
- **1 directeur** director
- **1 directeur général des services** general director of services
- **9 professeurs des universités** professors
- **4 maîtres de conférences** senior lecturers
- **19 physiciens corps des CNAP** physicists from CNAP
- **19 physiciens-adjoints CNAP** deputy physicists CNAP
- **74 BIATSS** engineers, technicians, administrative staff

82 doctorants
PhD candidates



70 post-doctorants
post-doctoral fellows

86 personnels CNRS CNRS staff
- **18 directeurs de recherche** senior researchers
- **20 chargés de recherche** researchers
- **48 ITA** engineers, technicians, administrative staff

71 BIATSS
engineers, technicians, administrative staff

57 personnels Université de Paris
Université de Paris staff
- **43 enseignants-chercheurs** professors
  - **dont 17 professeurs**
  - **26 maîtres de conférences** senior lecturers
- **14 BIATSS** engineers, technicians, administrative staff

14 ITA
engineers, technicians, administrative staff

14 chercheurs IGN IGN researchers
- **2 directeurs de recherche** senior researchers
- **4 chargés de recherche** researchers
- **2 assimilés directeurs de recherche** assimilated senior researchers
- **4 assimilés chargés de recherche** assimilated researchers
- **1 enseignant-chercheur** professor
- **1 doctorante (poste ingénieur)** PhD candidate (technician position)

10 personnels Université de La Réunion University of Reunion Island staff
- **2 professeurs** professors
- **5 maîtres de conférences** senior lecturers
- **3 BIATSS** engineers, technicians, administrative staff

Organisation
- 1 UMR unique (IPGP, UP, CNRS, IGN, U Réunion)
- 1 UMS (IPGP, CNRS)
- 17 équipes de recherche (2 aux grands moulins)

Répartition des personnels permanents

• IPGP	43,2 %
• CNRS	29,3 %
• Université de Paris	19,4 %
• IGN	4,8 %
• Université Réunion	3,4 %

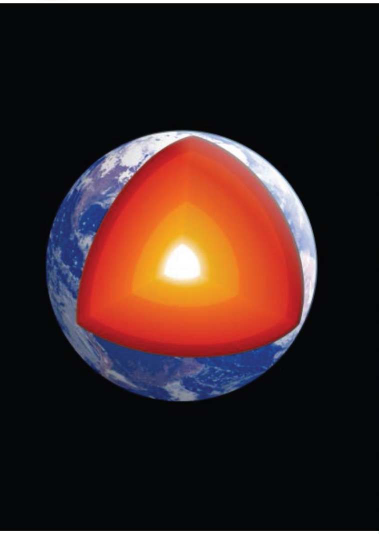
Budget consolidé 2020 : 45 M€ (Subvention pour charge de service public : 3,7 M€)

Formations
- 180 L, 125 M, 100 PhD
- licence ST, double licence ASTER, bachelor ScPo-IPGP UP, CPES Janson de Sailly-IPGP/UP, Licence pro gestion et traitement des déchets, licence pro méthodes d'exploration et géophysique appliquée
- master ST, master Génie de l'environnement et industrie
- EUR Earth-Planets-Universe dans Smarts'UP (+ Labex UnivEarthS)

IPGP INSTITUT DE PHYSIQUE DU GLOBE DE PARIS | Université de Paris

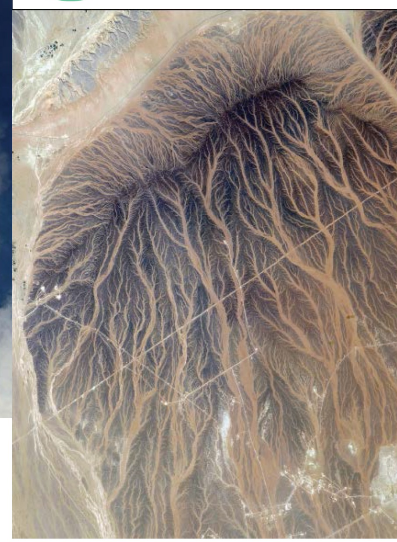
4 grandes thématiques de recherche qui regroupent les travaux des 17 équipes de recherche et des observatoires

Intérieurs de la Terre et des planètes

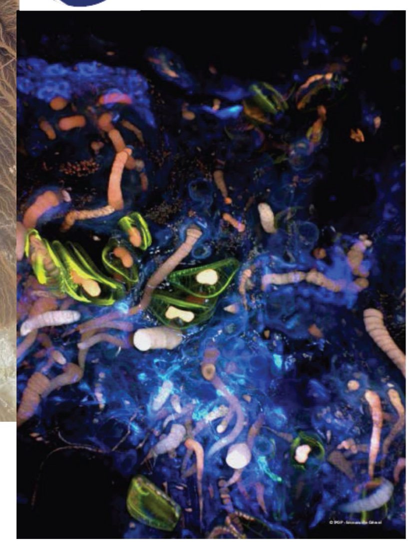


Risques naturels

Système Terre



Origines



IPGP INSTITUT DE PHYSIQUE DU GLOBE DE PARIS

Université de Paris

Réseau des observatoires et stations de l'IPGP

Network of the IPGP observatories and stations

+ Pôle de données CNES-CNRS Terre solide Form@ter
+ IR OZCAR

Outline

I – Introduction : Natural landslides and their simulation

- Ia – Geophysics and mathematics
- Ib – Complexity and variability of natural landslides
- Ic – Examples of landslide simulations for hazard assessment
- Id – Challenges in geophysics and landslide modelling

II – Thin layer depth-averaged models for field-scale simulation

- IIa – Thin layer approximation for granular flows
- IIb – Accounting for complex topography
- IIc – Need of two different reference frames for landslide tsunamis
- IId – Application to real landslides : unexplained high mobility

III – Back to lab-scale experiments and simulation

- IIIa – Granular column collapse on rigid and erodible beds
- IIIb – μ(I) rheology in 2D models, comparison with other models (DEM, thin-layer)
- IIIc – Static-flowing interface (erosion/deposition)
- IIId – Grain-fluid mixture model

IV – Landslide detection/characterization from generated seismic waves

- IVa – Inversion/simulation of low frequency landslide forces
- IVb – Insight from high frequency data through lab-experiments
- IVc – Monitoring landslide activity in link with volcanic activity
- IVd – Similar approach for glacial earthquakes and ice-mass loss quantification

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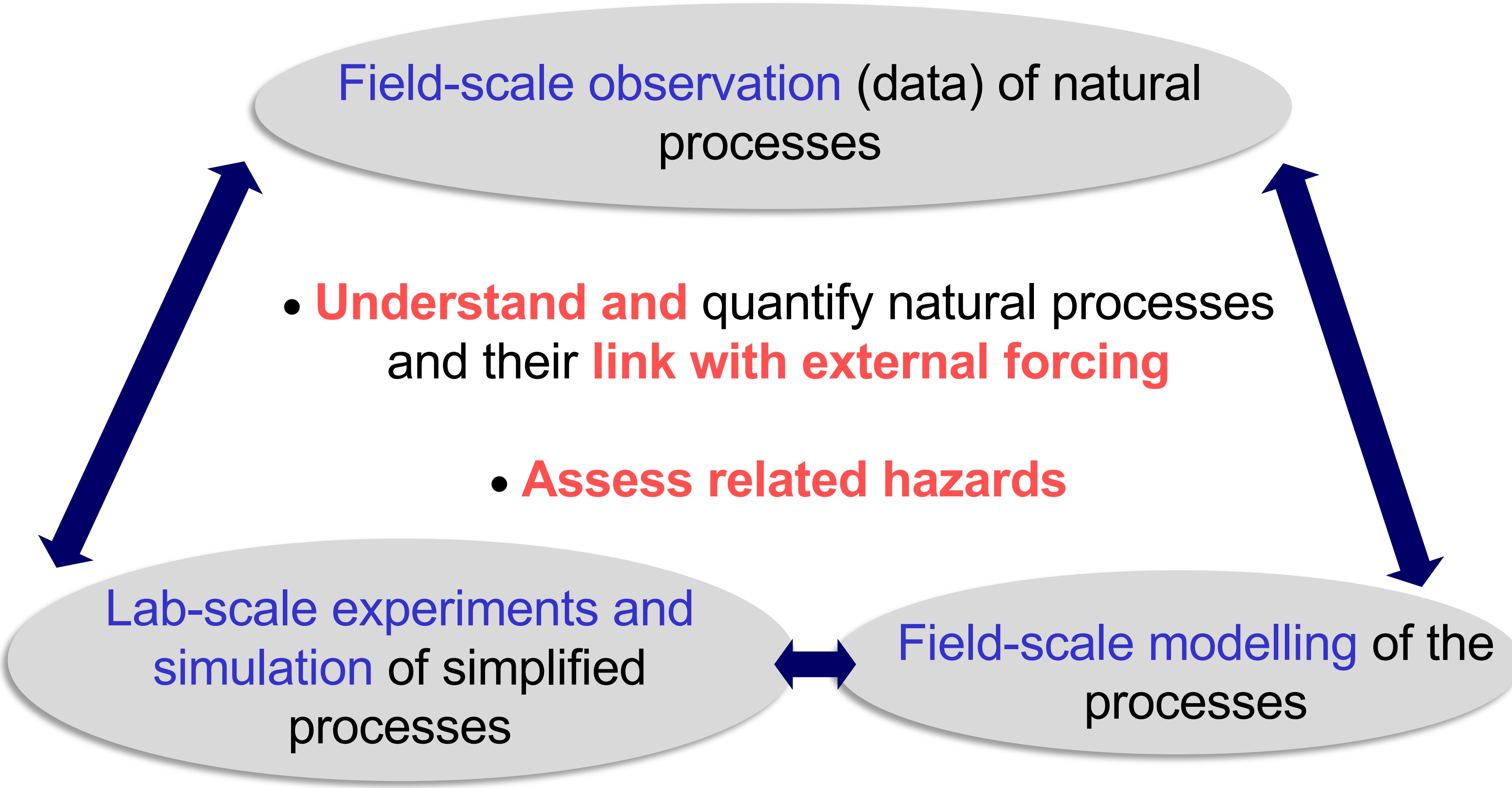
Key elements to address geophysical problems



Strong need of mathematical modelling, numerical methods, data analysis, signal processing, Machine Learning, statistics, surrogate models, uncertainty quantification, data assimilation, etc.

Basic ingredients for geophysics-mathematics link

Specialists in geophysics ⟺ Specialists in mathematics

➡ Mathematical challenges will naturally occur

*Solve 'geophysical' problems **WITH** geophysicists*

I will not give any recipies or equations to solve, etc. but

I will illustrate this type of geophisics/mathematics interaction

➡ 'mathematical' concessions

erc
European Research Council
Established by the European Commission

Synergy submitted

You have to create your own challenge by taking risks due to the necessity of:

- accounting for the **natural complexity** of the processes and
- simplifying the problem enough to **solve it numerically**

Make things as simple as possible, but not simpler. A. Einstein

Natural processes described by these equations

Mass and momentum conservation:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \mathbf{u}) = 0$$

f=ρg

$$\frac{\partial (\rho \mathbf{u})}{\partial t} = -\mathbf{u}\nabla.(\rho \mathbf{u}) - \rho \mathbf{u}.\nabla \mathbf{u} + \mathrm{div}\,\sigma + \mathbf{f}$$

with different initial and boundary considitons and rheological laws

- Natural flows are rich et complex, strong uncertainties on the rheology and associated parameters

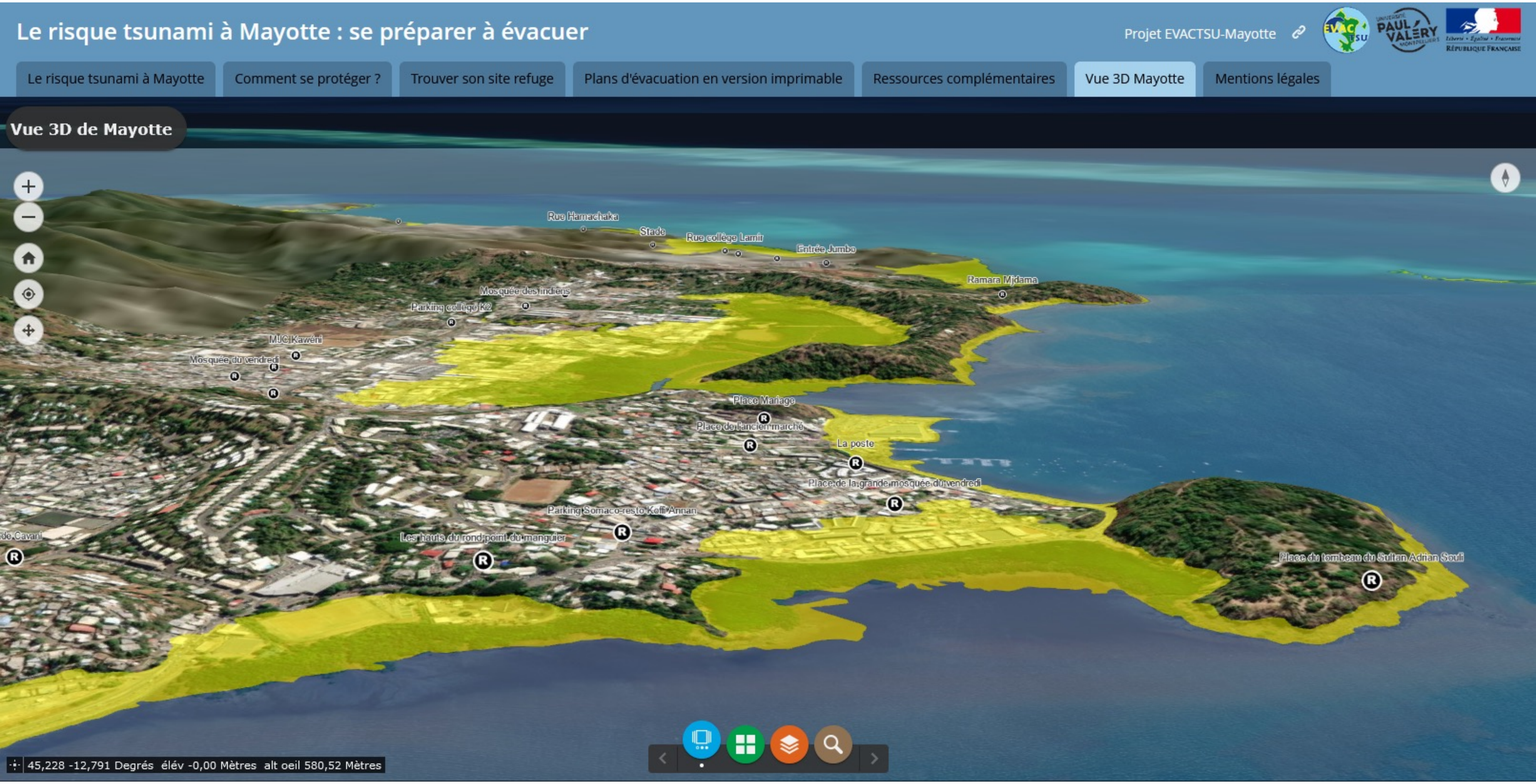
- The flows strongly depend on the complex boundary conditions (topography, etc.)

- Approximations based on physical considerations have to be performed for application to real processes....

For hazard assessment

The 2 November 2021 landslide at Mallama in Colombia, which killed 17 people. Image via the Gobernacion de Nariño. (from Landslides Blog D. Petley)

For hazard assessment



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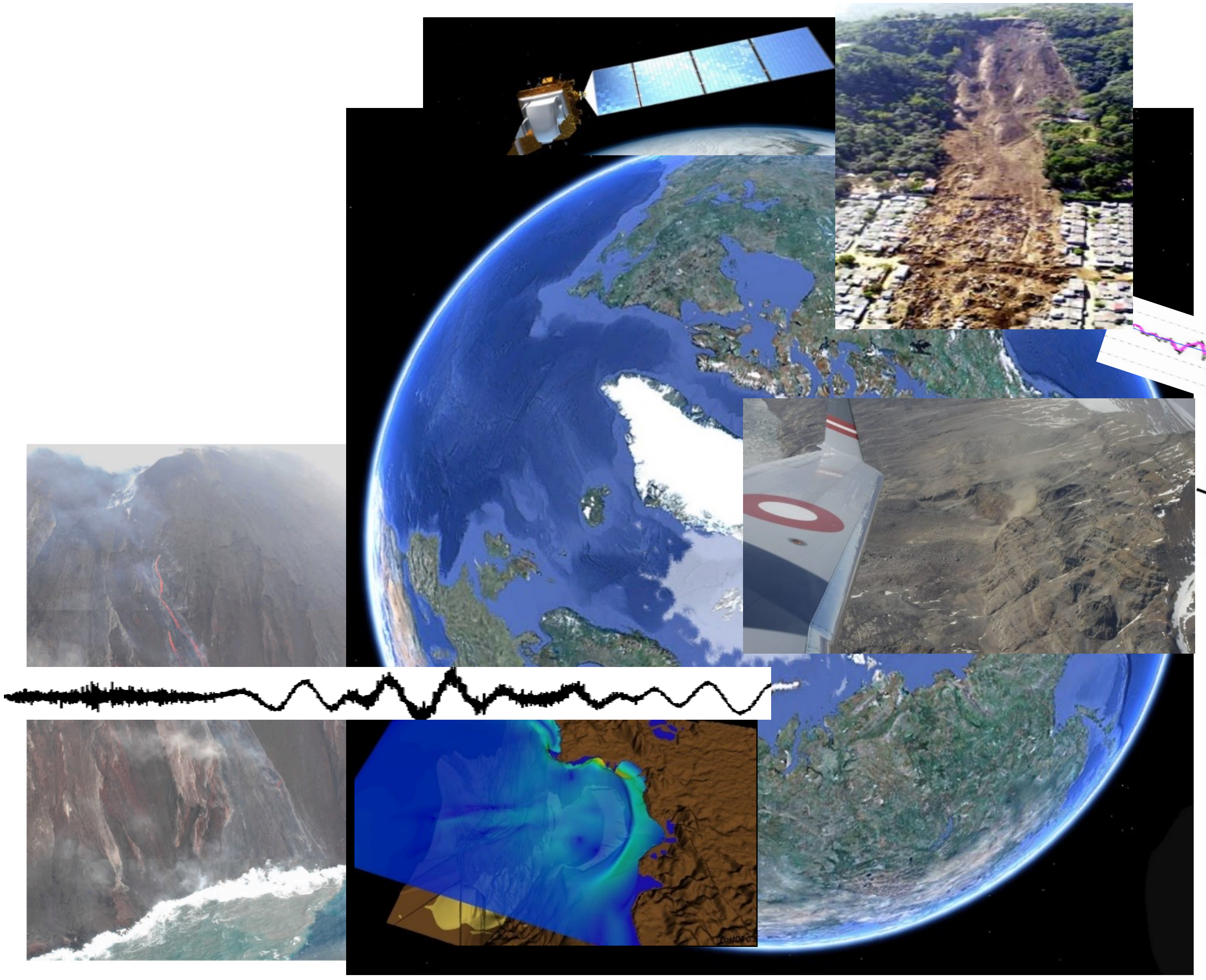
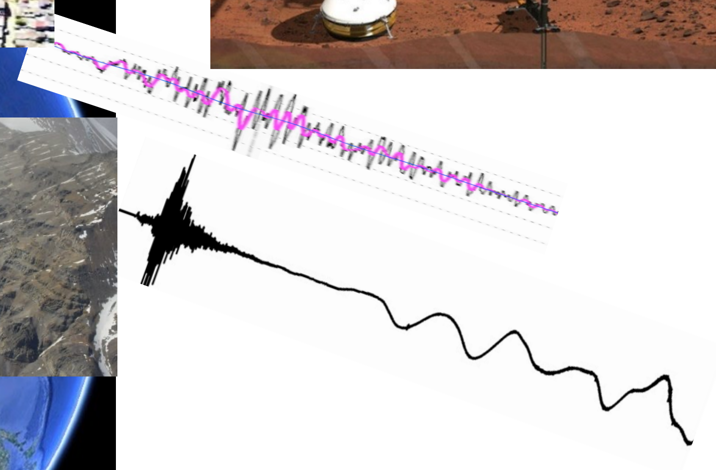
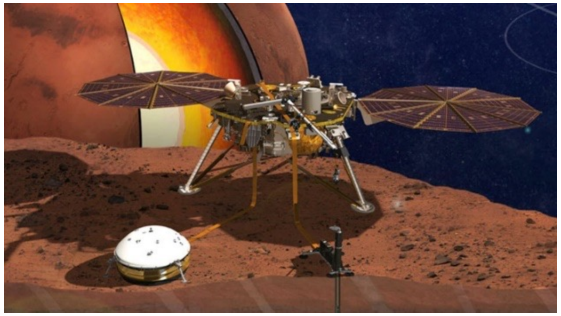
Landslides

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





Mars (InSight)

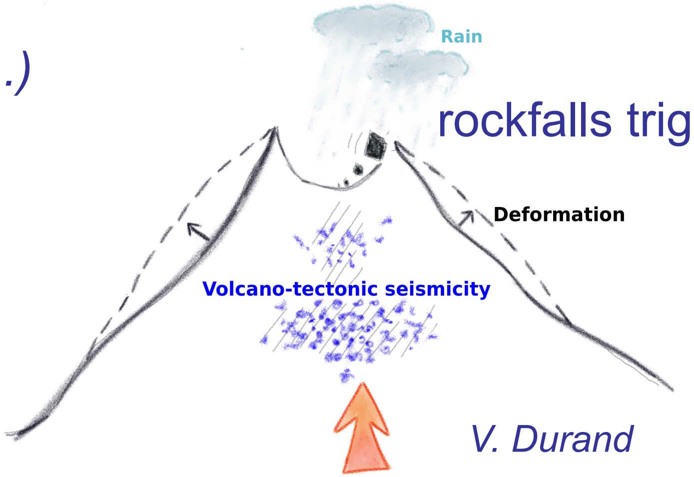


Broad objectives

• Destabilization: understand and quantify landslide occurrence/properties in link with external forcing

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

rockfalls triggering



V. Durand

• Predict **velocity and runout extent**

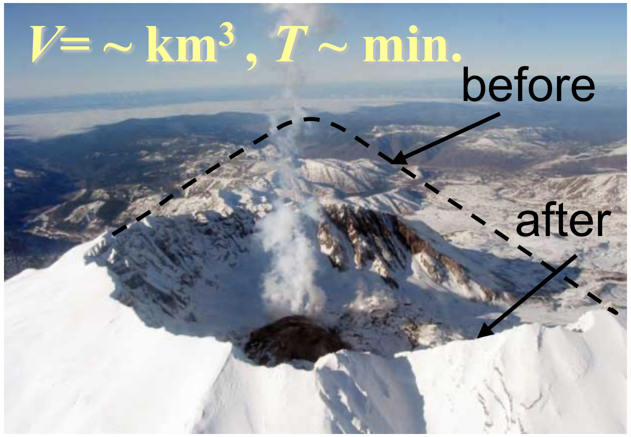
explain and quantify the high mobility of natural landslides …

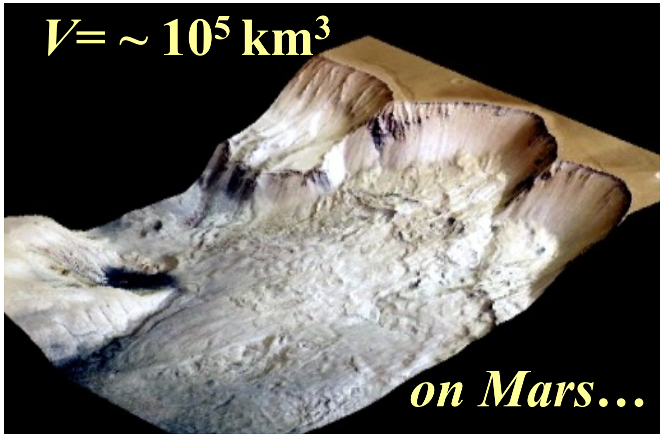
Lack of field measurements of their dynamics

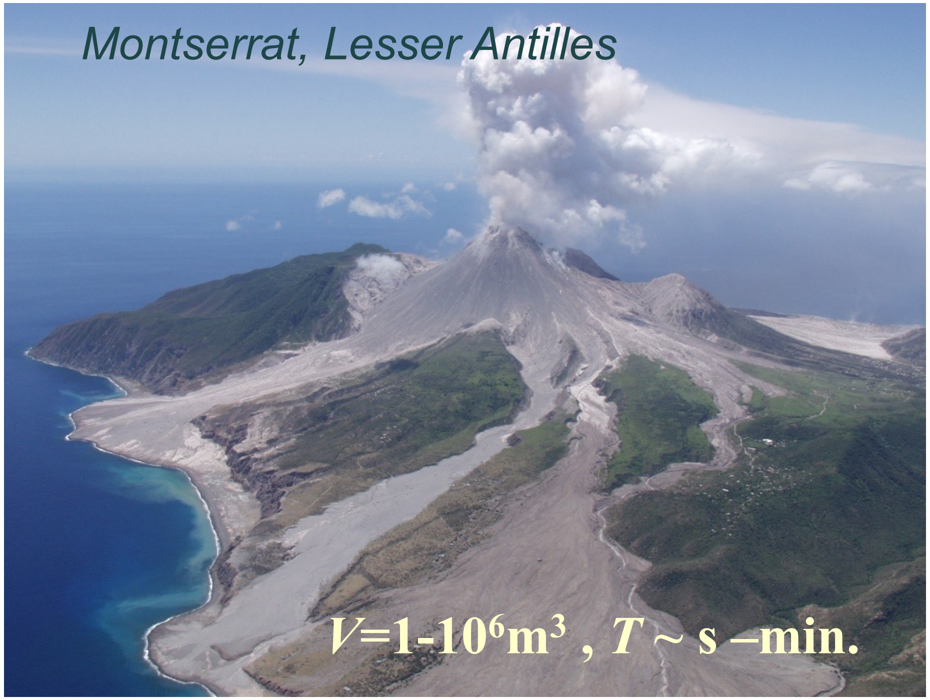
Mechanics and modelling of complex granular flows

Montserrat Island

Large variety of natural flows





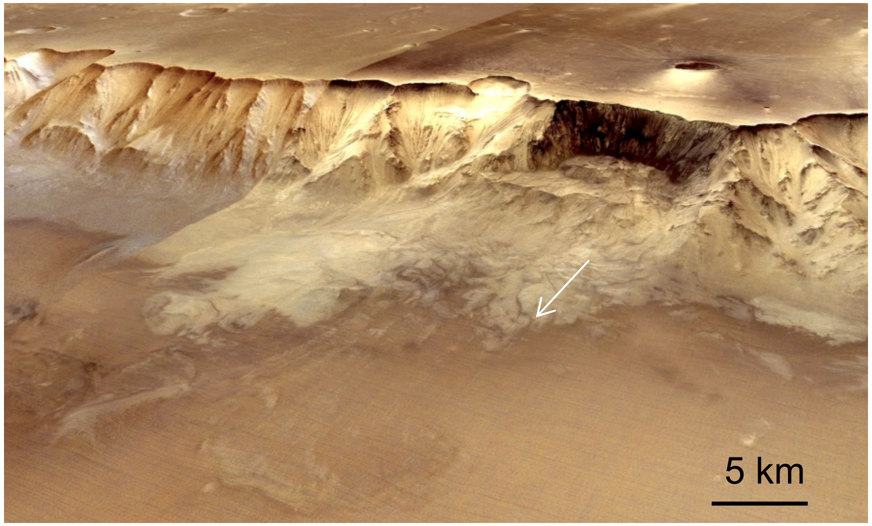


Volume scale : m^3 → 10^5 km^3

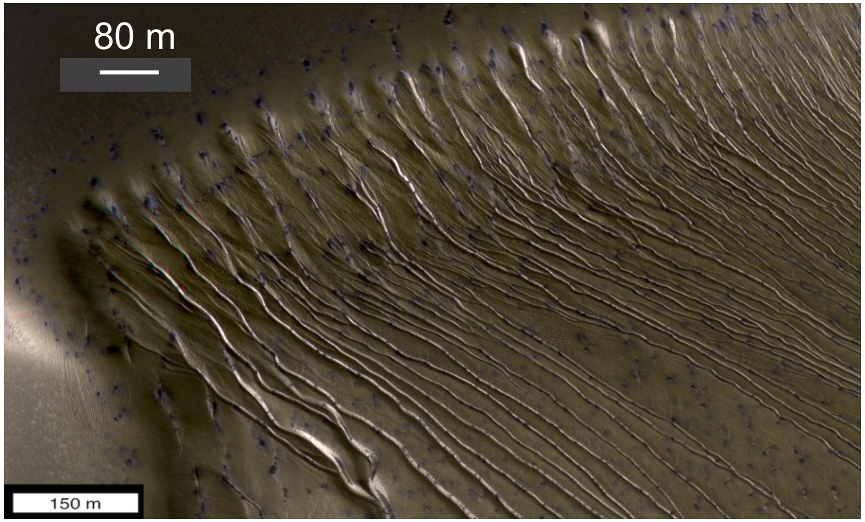
Time scale : second → year

≠ Sources, ≠ Topographies

On other planets



Ganges Chasma landslide,Valles Marineris, Mars



Gullies, mega-dune of Russell crater, Mars

Very different rheological laws

Mostly dry granular flows

La Réunion

Douvre, France

« Dry » granular flows

Snow avalanche : role of air

Significant erosion

High variability of snow behavior including thermal effects

Pyroclastic flows: role of gas

Debris avalanches
+ pyroclastic flows

Soufrière Hills, Montserrat

1995-2014

Significant erosion

Photo by C. Oppenheimer

Photo by R. Carniel and M. Fulle

Debris flows : role of water

Debris avalanches may transform into debris flows by entering rivers

Debris flows

Debris flows, Alps

Debris flows, Iceland

Strong role of water
Significant erosion

Mud flows : strong role of water and fine particles

(Photo H. Hubl, Vienna)

QUINDICI, Italy

very rapid to extremely rapid flow of saturated debris in a channel, involving significantly greater water content relative to the source material

Several possible classifications…

Table 1. Main types of geophysical flows and typical ranges of values of most relevant parameters.

Flow type	Setting, ambient fluid	Interstitial fluid	Particle size (m)	Particle density (kg m^{-3})	Particle volume fraction	Volume (m^3)
Subaerial landslides, rockfalls, rock or debris avalanches	Subaerial, extraterrestrial[a]	Air, none, small water content	10^{-3}–10^{1}	~2000–3000	~0.4–0.7	10^{0}–10^{10} 10^{9}–10^{13}[a]
Submarine landslides	Subaqueous	Water	—	—	—	10^{0}–10^{13}
Turbidity currents	Subaqueous	Water	10^{-4}–10^{-1}	~1500–2500	~0.001–0.1	10^{6}–10^{10}
Snow avalanches (dense, powder[c])	Subaerial	Air (water)	10^{-4}–10^{-1}	~100–1000	~0.1–0.4[b] ~0.001–0.01[c]	10^{4}–10^{6}
Pyroclastic density currents (dense[d], dilute[e])	Subaerial, subaqueous, extraterrestrial	Volcanic gases, air	10^{-6}–10^{0}	~500–3000	~0.1–0.5[d] ~0.001–0.01[e]	10^{4}–10^{8}
Debris flows, lahars	Subaerial, extraterrestrial	Water	10^{-4}–10^{0}	~2000–3000	~0.2–0.8	10^{4}–10^{9}

Flow type	Velocity (m s^{-1})	Thickness (m)	Runout distance (km)
Subaerial landslides, rockfalls, rock or debris avalanches	10^{-1}–10^{2}	10^{-1}–10^{2}	10^{0}–10^{1} 10^{1}–10^{2}
Submarine landslides	—	10^{-1}–10^{2}	10^{1}–10^{2}
Turbidity currents	10^{0}–10^{1}	10^{1}–10^{2}	10^{1}– 10^{3}
Snow avalanches (dense, powder[c])	10^{1}–10^{2}	10^{0}–10^{1}	10^{-1}–10^{0}
Pyroclastic density currents (dense[d], dilute[e])	10^{0}–10^{1}[d] 10^{1}–10^{2}[e]	10^{0}–10^{2}	10^{0}–10^{2}
Debris flows, lahars	10^{0}–10^{1}	10^{0}–10^{1}	10^{0}–10^{2}

See Delannay et al., 2017 for a review

Flow classification depending on the different regimes

Dimensionless numbers

defined as the ratio of relaxation time under load to shear time

$$I = I_{\mathrm{pi}} = \sqrt{\rho_{\mathrm{p}}\dot{\gamma}^2 d^2 / P_{\mathrm{p}}}$$

Particle inertia dominated regime (inertial number)

$$I = I_{\mathrm{v}} = \frac{\eta_{\mathrm{f}}\dot{\gamma}}{P_{\mathrm{p}}}$$

Viscous resistance dominated regime (viscous number)

$$I = I_{\mathrm{fi}} = \sqrt{\rho_{\mathrm{f}}\dot{\gamma}^2 d^2 / P_{\mathrm{p}}}$$

Fluid inertia dominated regimes

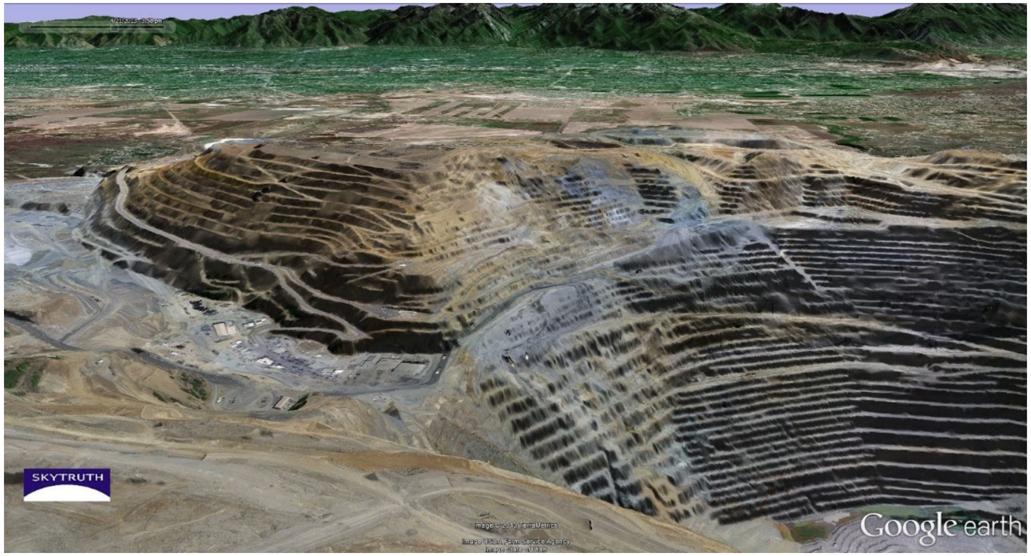
Savage number : ratio of the inertial grain shear stress to the weight of flowing layer per unit surface

$$N_{\mathrm{Sav}} = \frac{\rho_{\mathrm{p}}\dot{\gamma}^2 d^2}{(\rho_{\mathrm{p}} - \rho_{\mathrm{f}})gH}$$

Bagnold number: ratio of inertial grain shear stress to viscous shear stress

$$N_{\mathrm{Bag}} = \frac{\phi\rho_{\mathrm{p}}\dot{\gamma}^2 d^2}{(1-\phi)\eta_{\mathrm{f}}\dot{\gamma}} \qquad N_{\mathrm{Bag}} \sim I_{\mathrm{pi}}^2 / I_{\mathrm{v}}$$

Complex initial conditions : several sub-events



Bingham Canyon Mine
Utah,
Avril 2013
65 Mm^3

Two landslides one after the other

Retrogressive landslides

Complex initial conditions

9th October 2021 – Dolomites, Italy

Induced hazards

➡ Volcanic eruption

➡ Tsunamis

➡ Lahars

Volcanic flank collapse

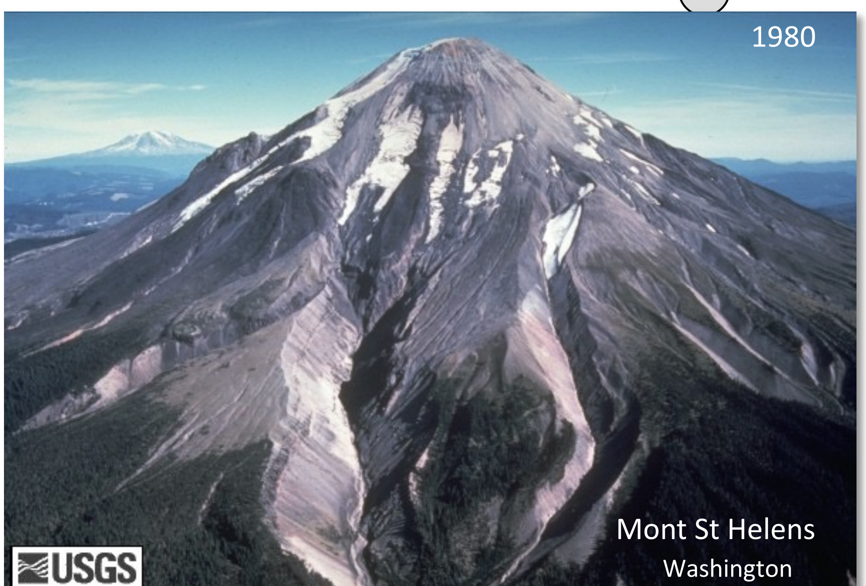
History of volcanic domes: phases of construction/destruction

Construction …
Products from eruptions

+

Destruction …
-Slow (erosion)
-catastrophic
(flanck collapse)

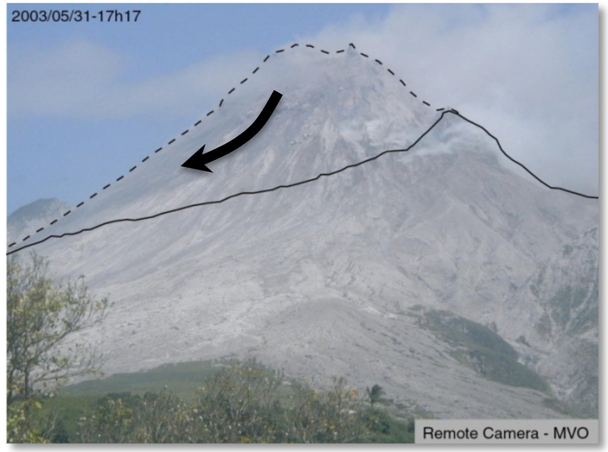
A. Le Friand

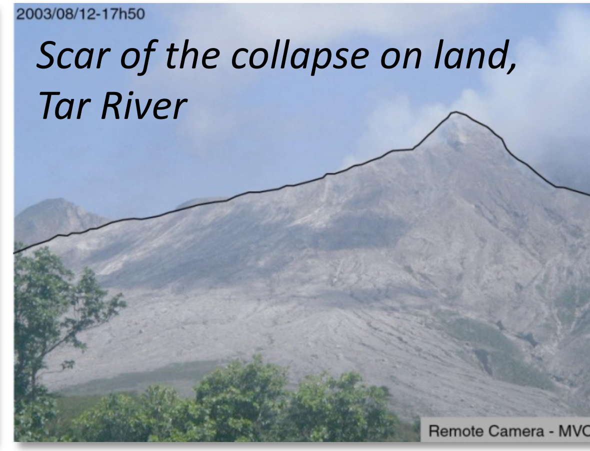


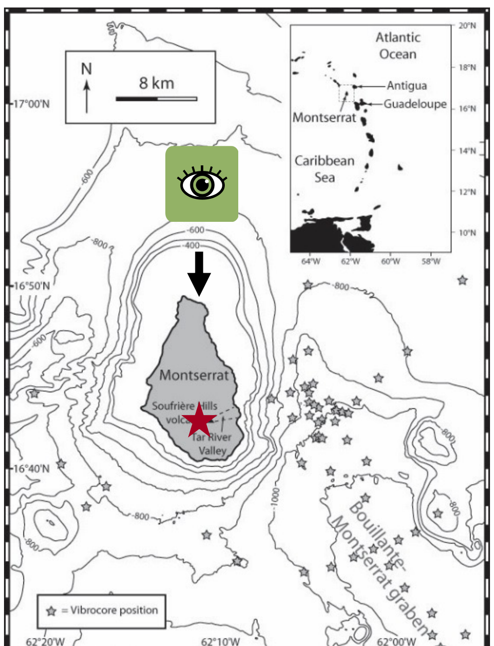
Volcanic flank collapse

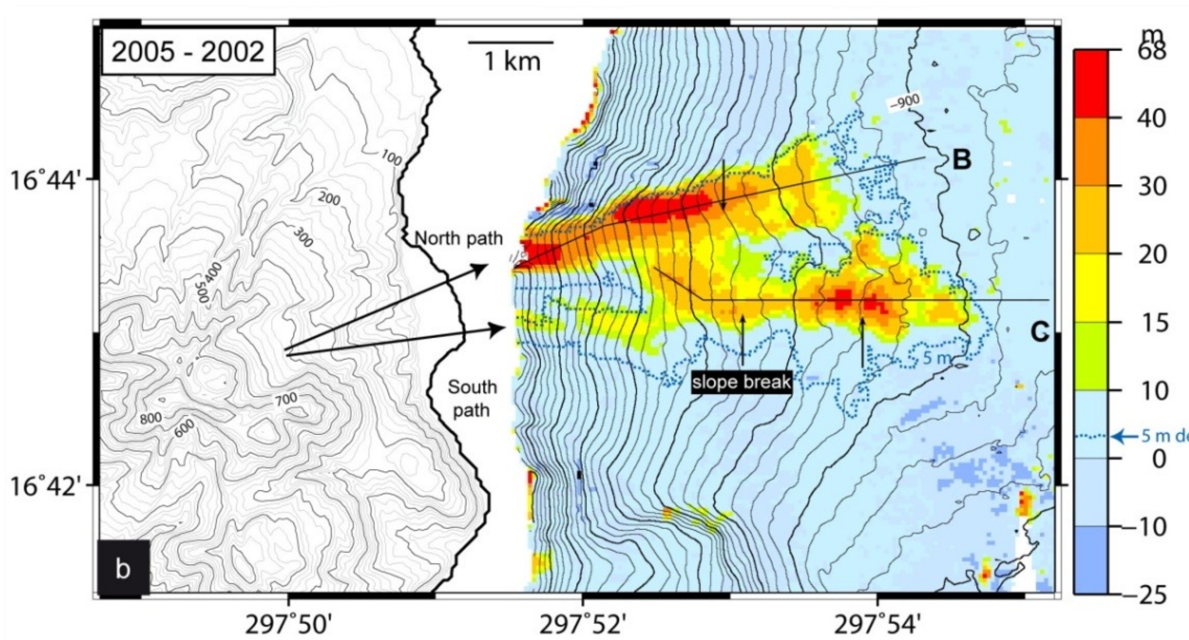
12 July 2003 :

Soufrière Hills volcano, Montserrat (~200 Mm^3) reaching the sea and generating a tsunami









Le Friant et al., 2009

All these processes are simulated in field conditions

Advanced numerical models are now used accounting for complex topographies, a free surface, complex initial conditions, complex rheological laws, etc.

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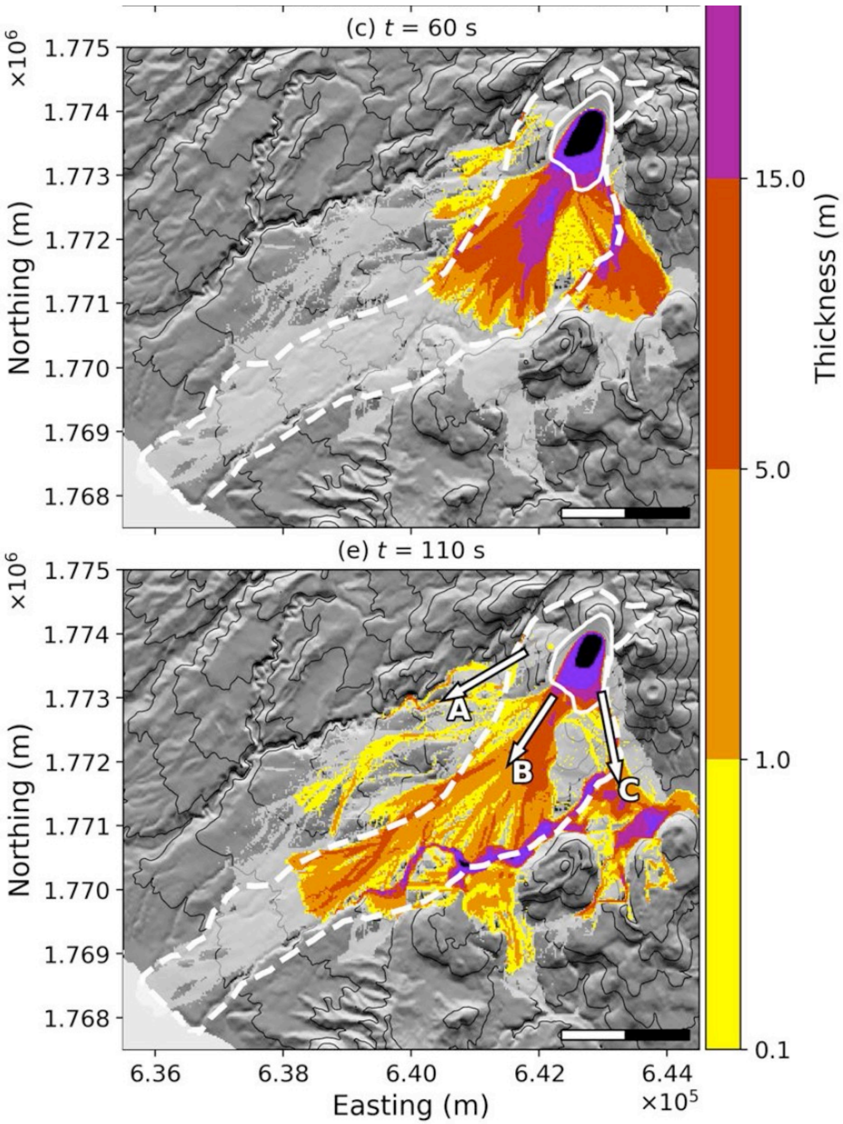
Beyond simple models



Past debris avalanche in Guadeloupe

First order role of:

- topography: channelling, overflows

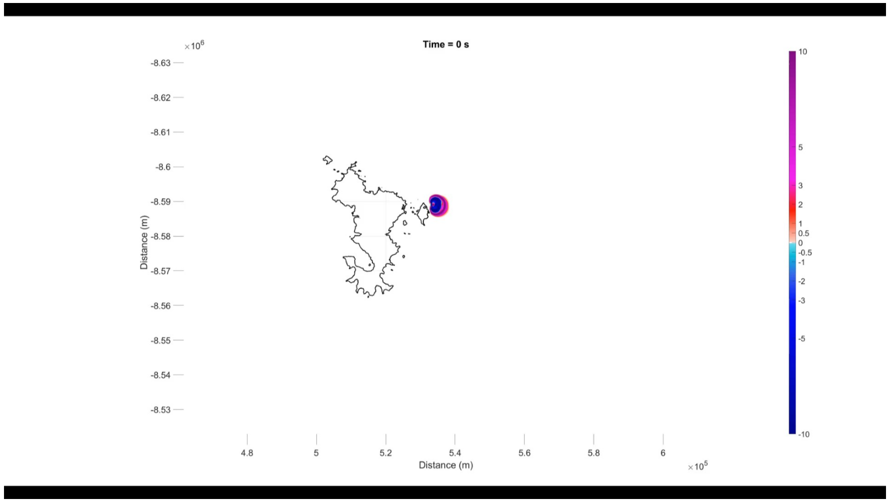
Fine description of the topography:
High numerical cost

- rheological behaviour: friction law, role of fluids, etc.

Very complex behaviour:
Strong non-linearities

Peruzzetto et al., 2019, 2021

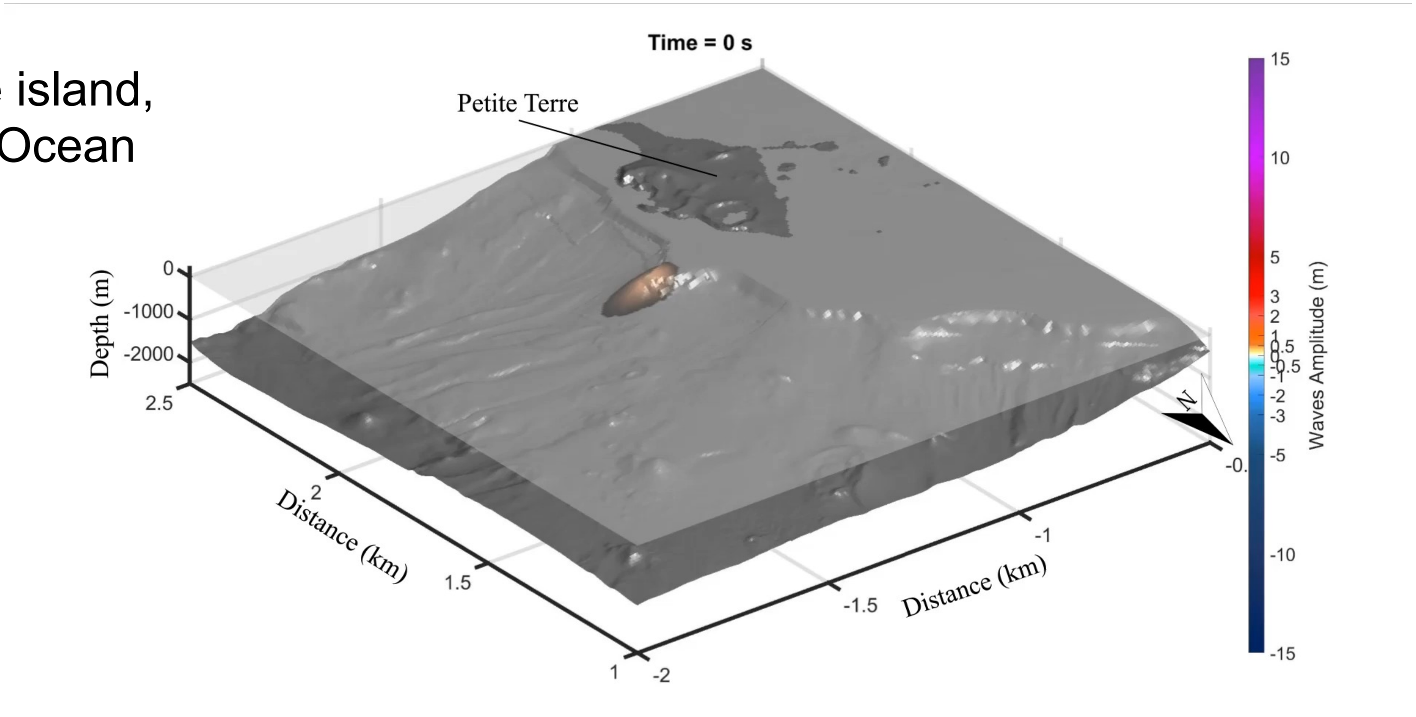
Beyond simple models



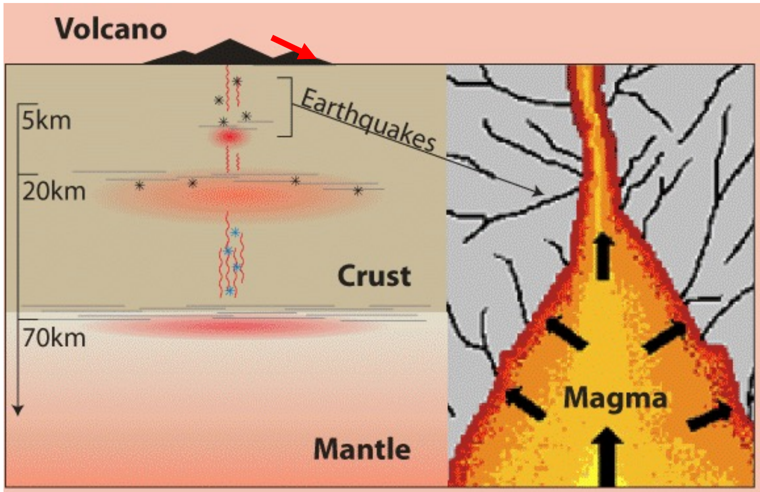
Coupled simulation of submarine avalanche and water waves

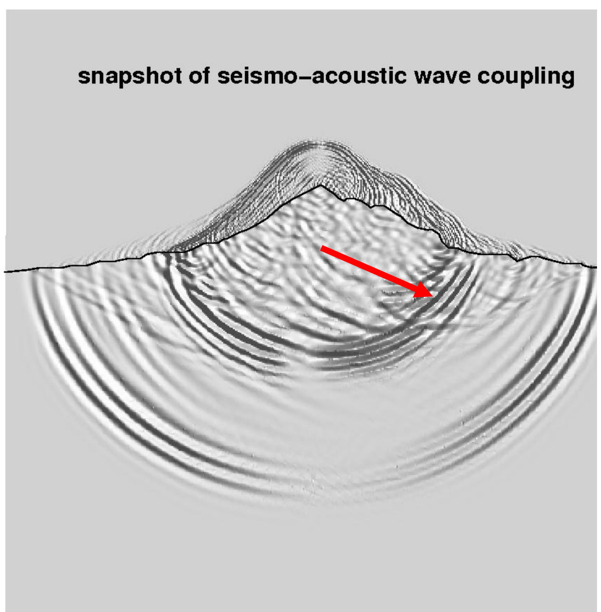
Poulain et al., 2021, Macias et al., 2021

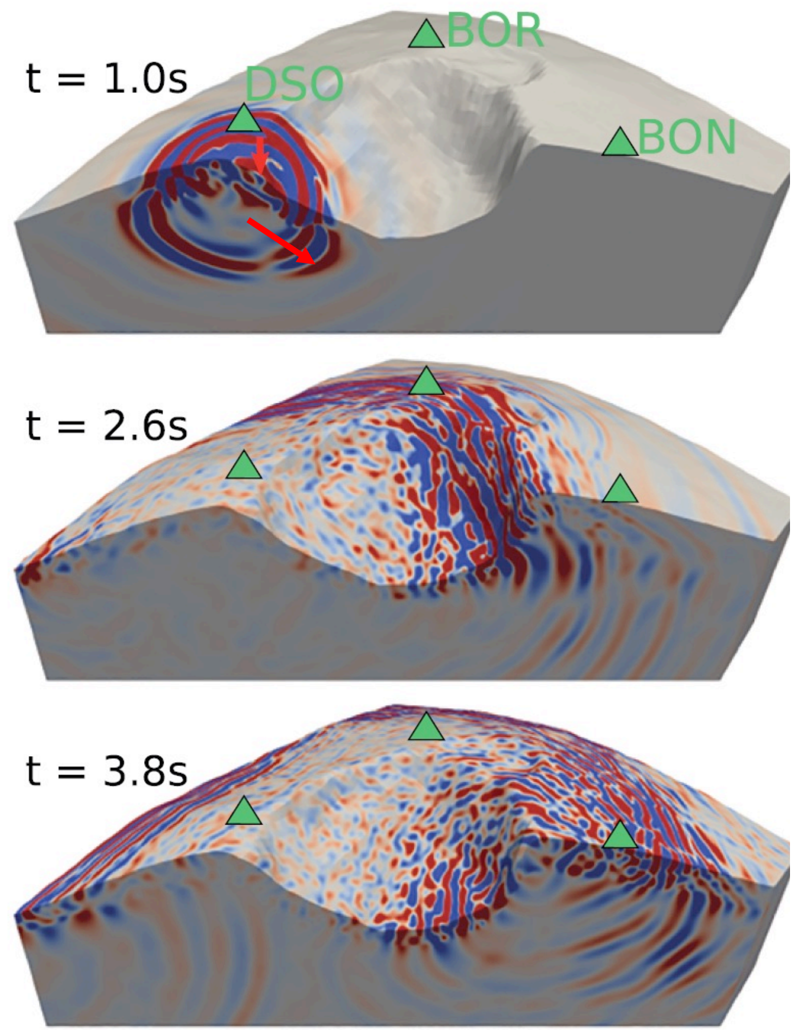
Mayotte island, Indian Ocean



Link with seismology, volcanology, climatology, ocean and atmosphere…







Kuehnert et al., 2020, 2021

Complex numerical models for hazard assessment

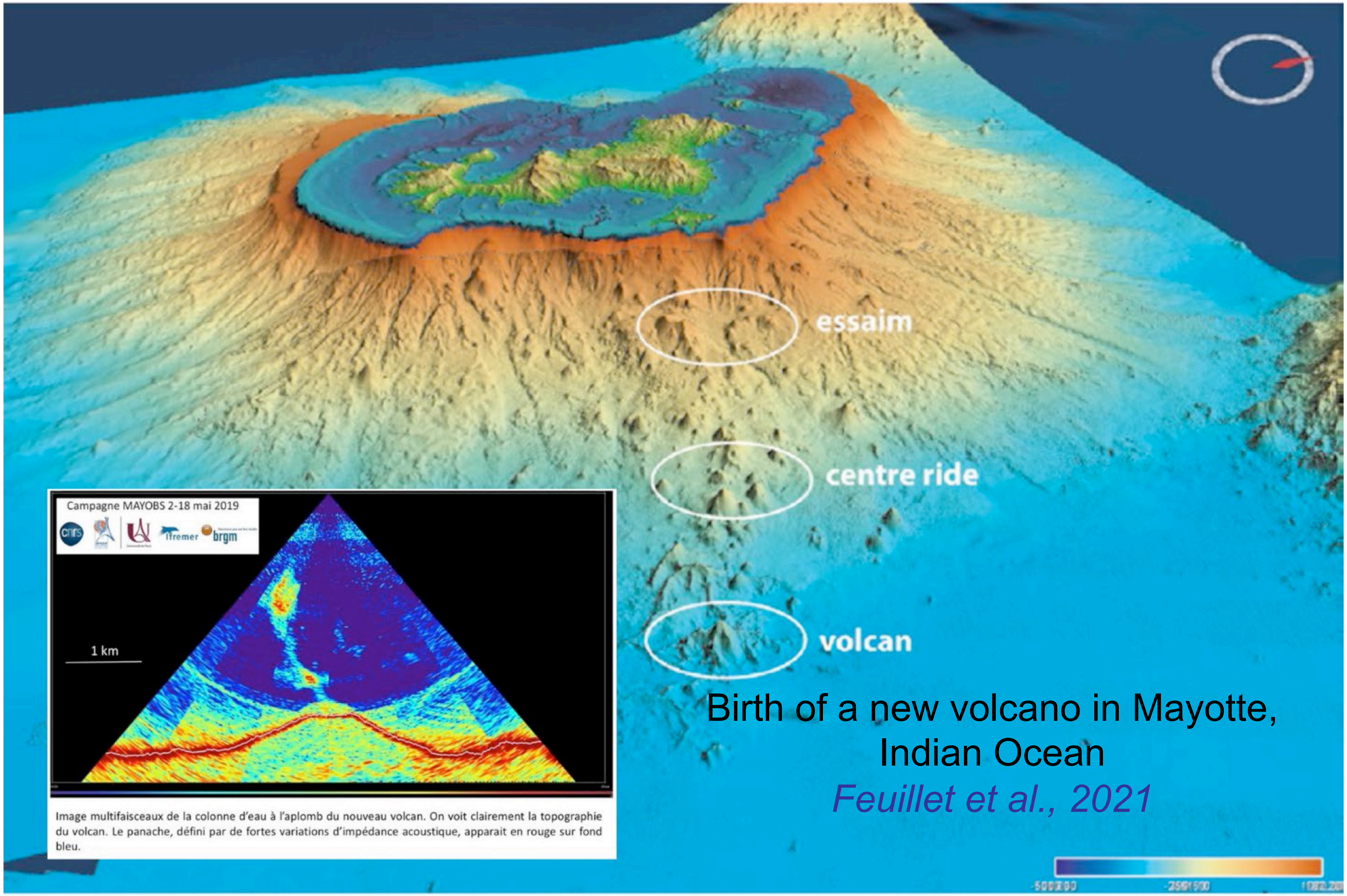
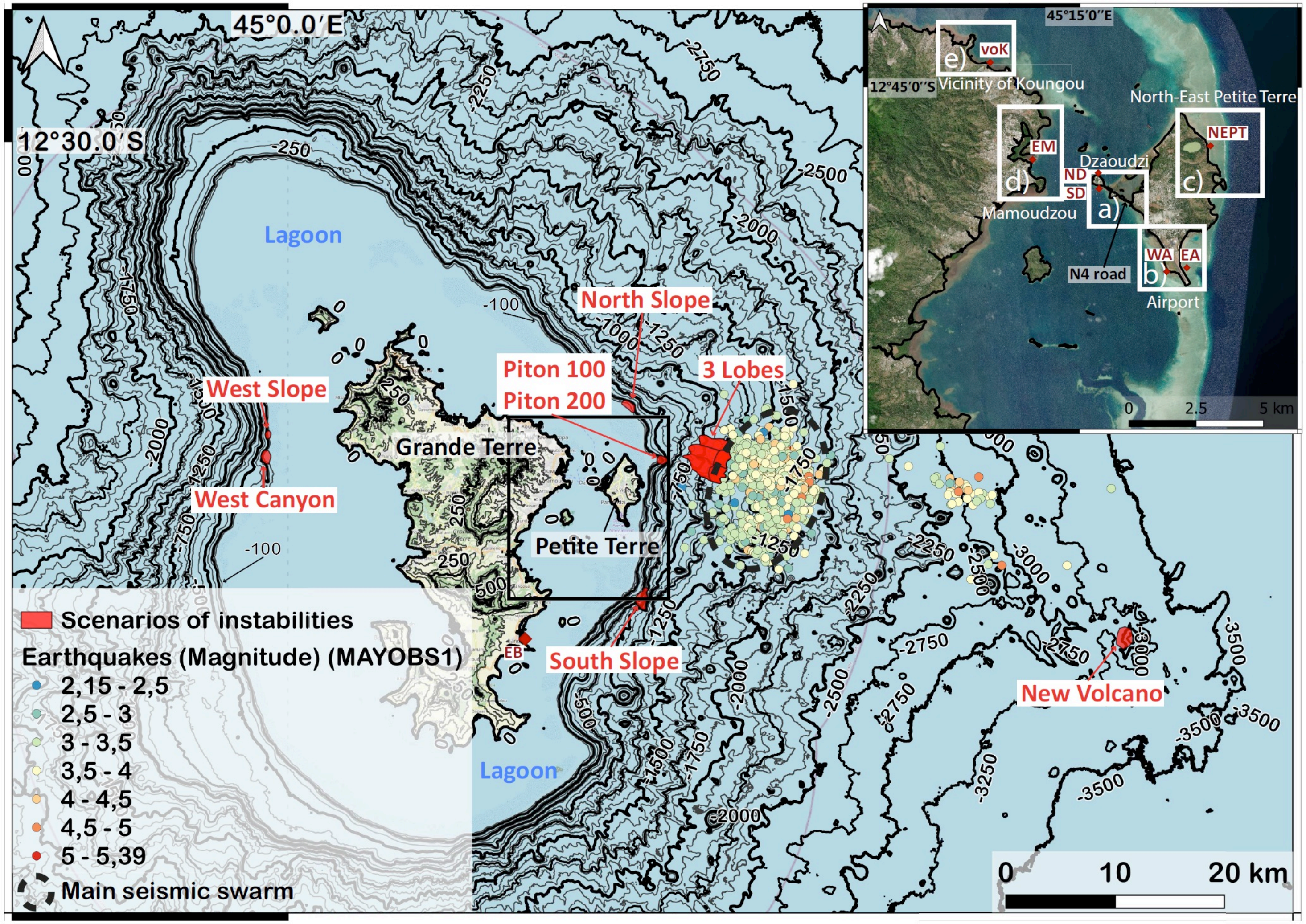


Figure 1 : Les nouveaux sites éruptif et sismiques de Mayotte et les pentes tsunamigènes du talus récifal (source REVOSIMA).

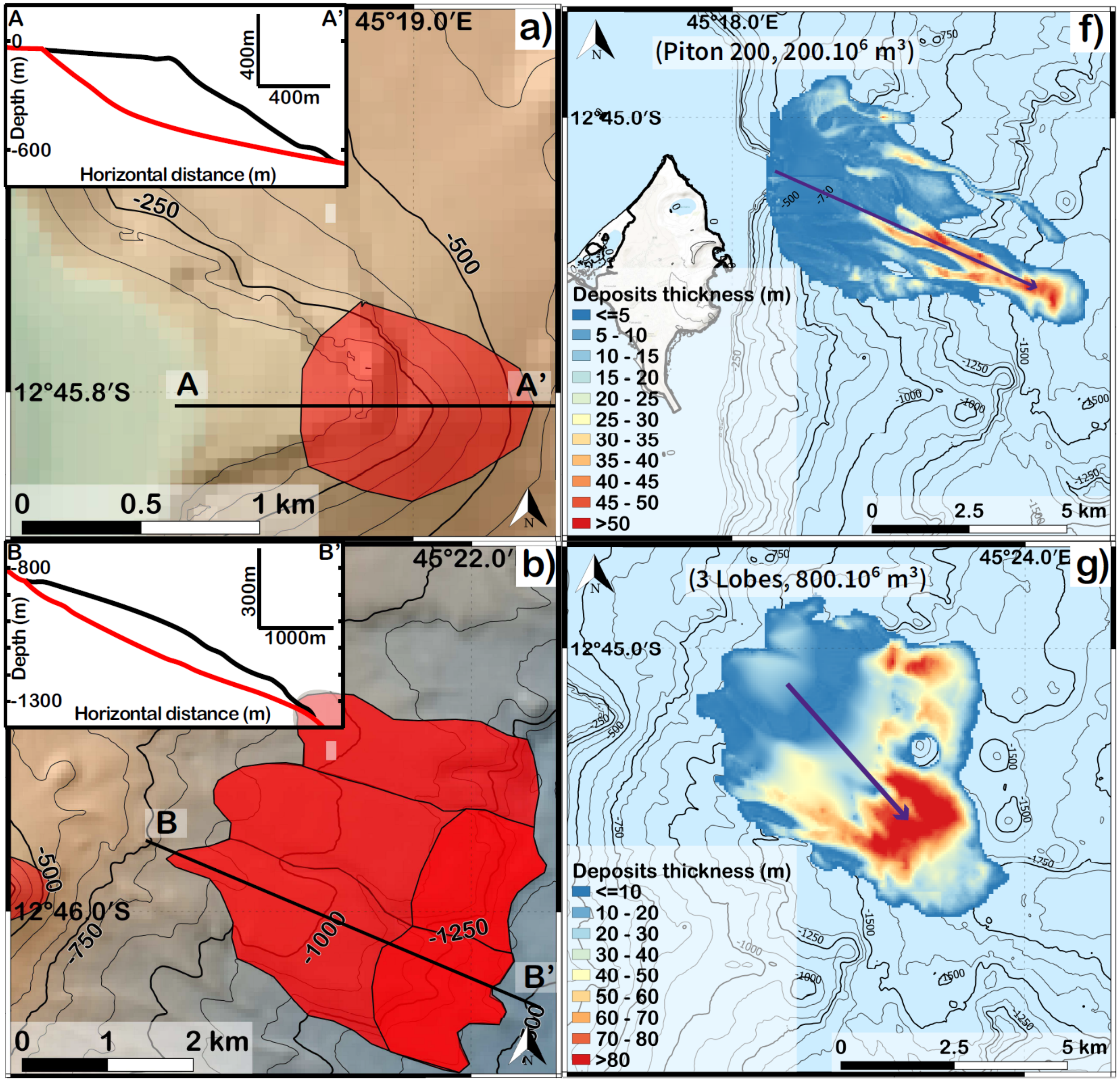
Tsunamis hazard due potential submarine landslides

Seismic activity + high submarine slopes

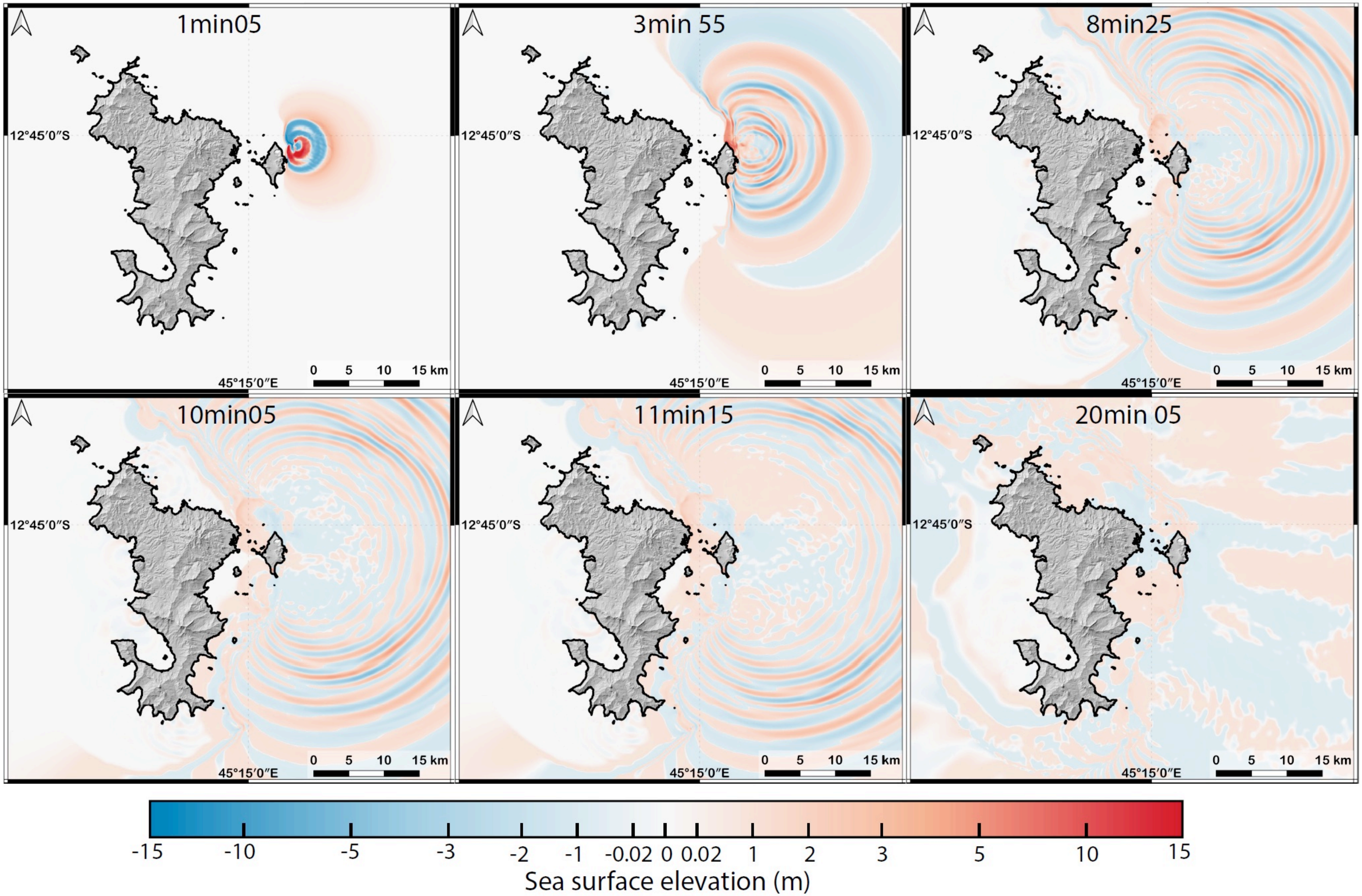


IPGP – BRGM – French Minister, local actors of hazards, *Poulain et al., 2021*

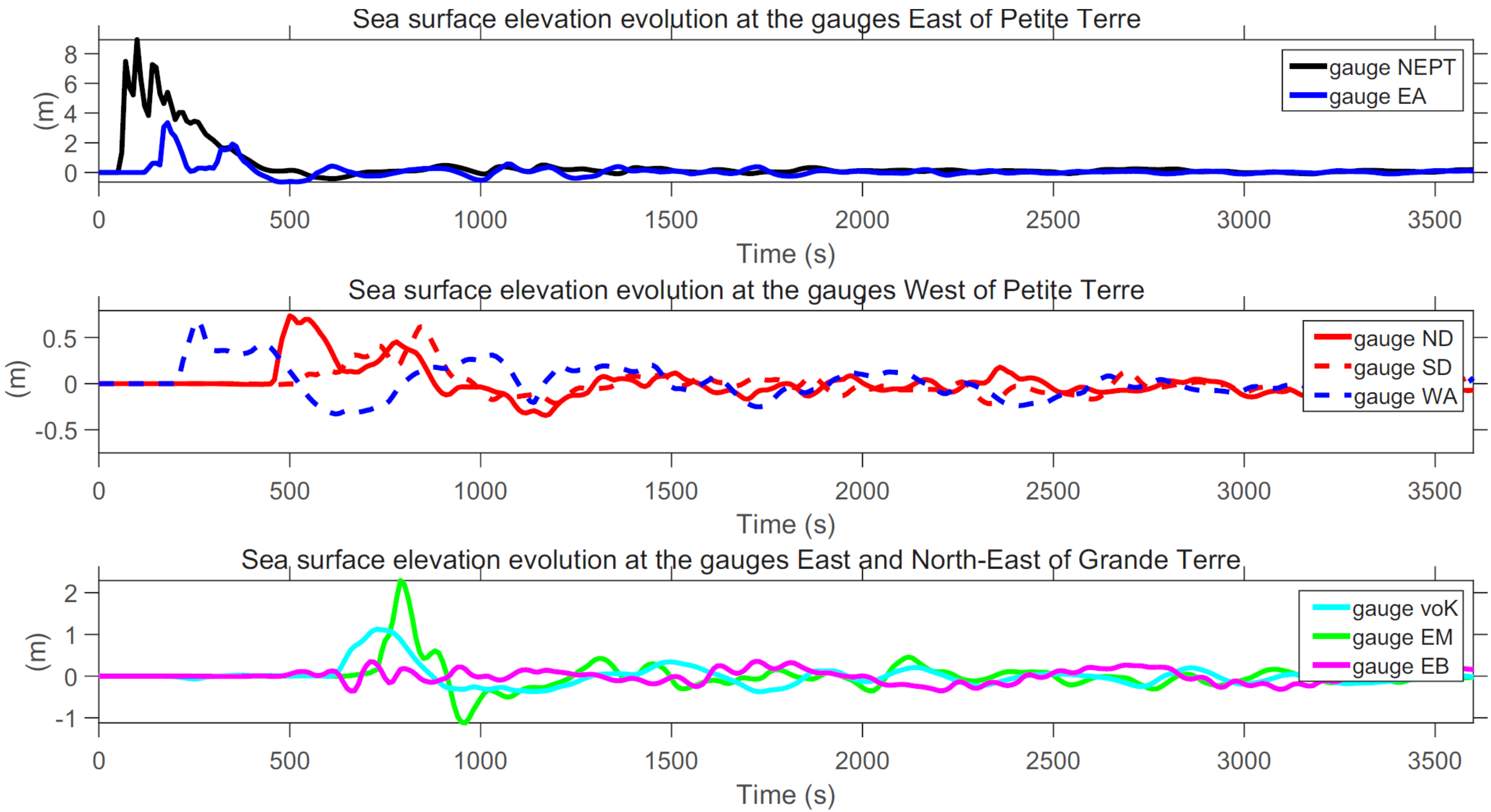
Potential landslide scenarios



Propagation of water waves

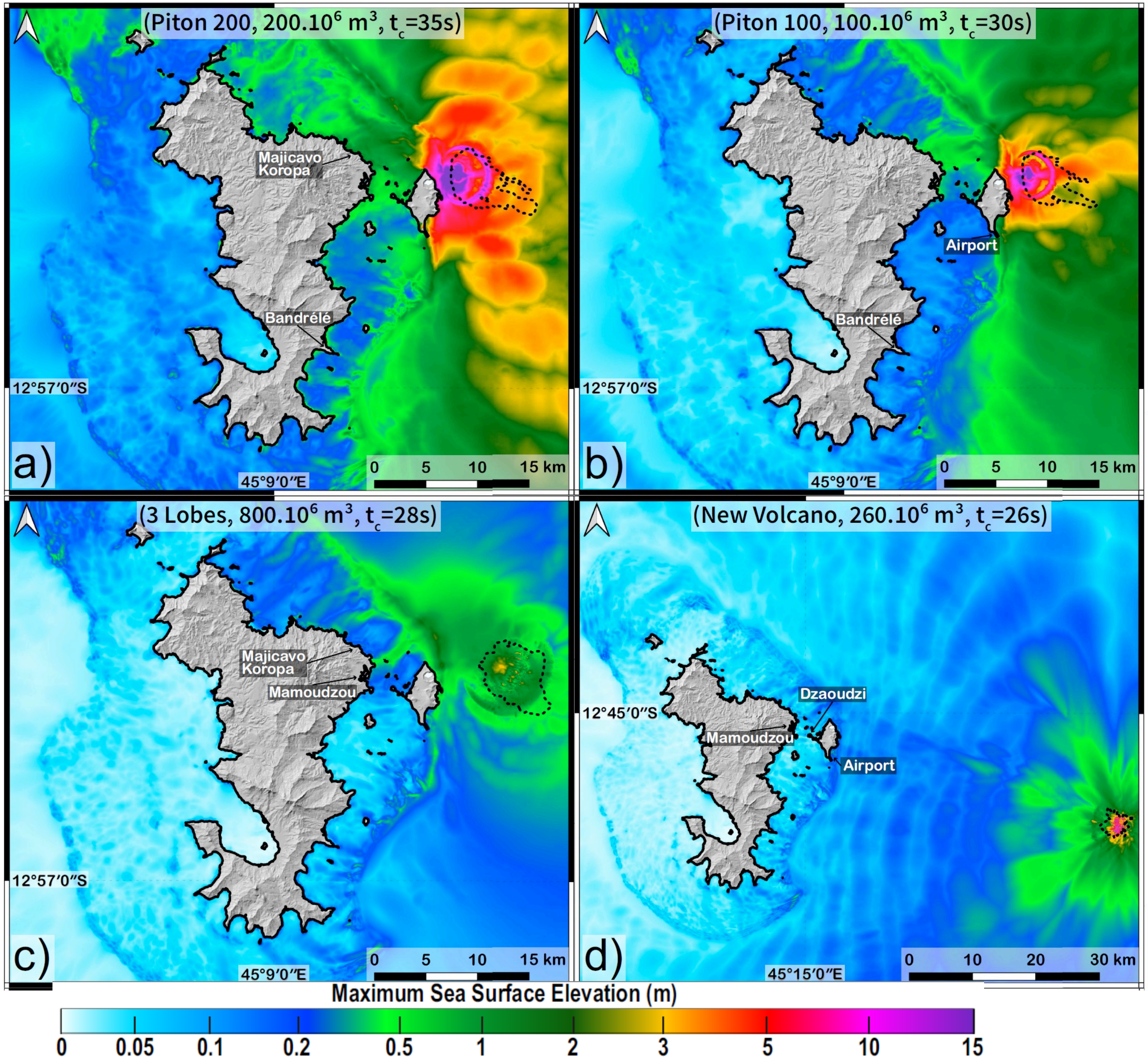


Arrival time and shape of the wave at the coast

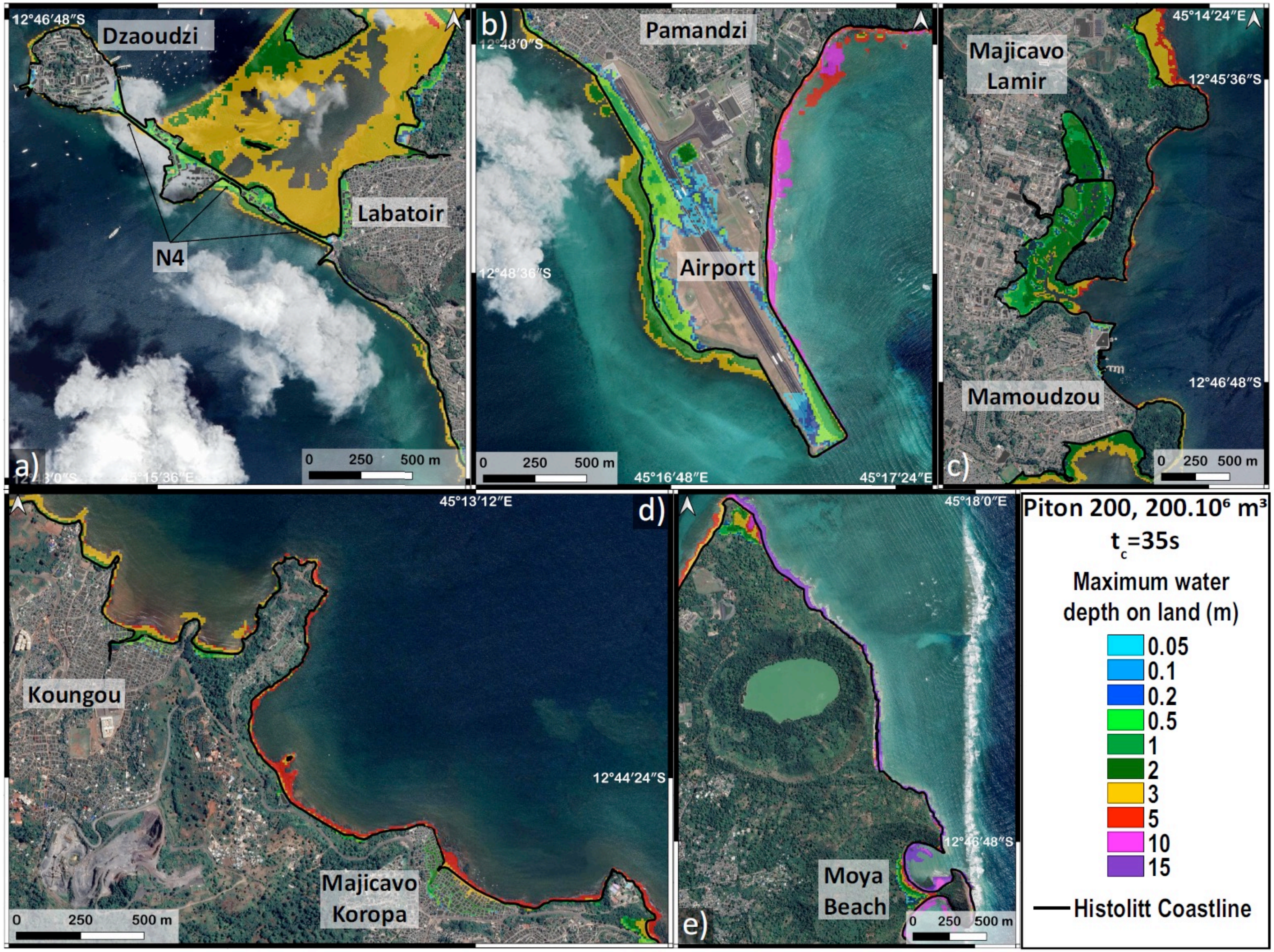


Poulain et al., 2021

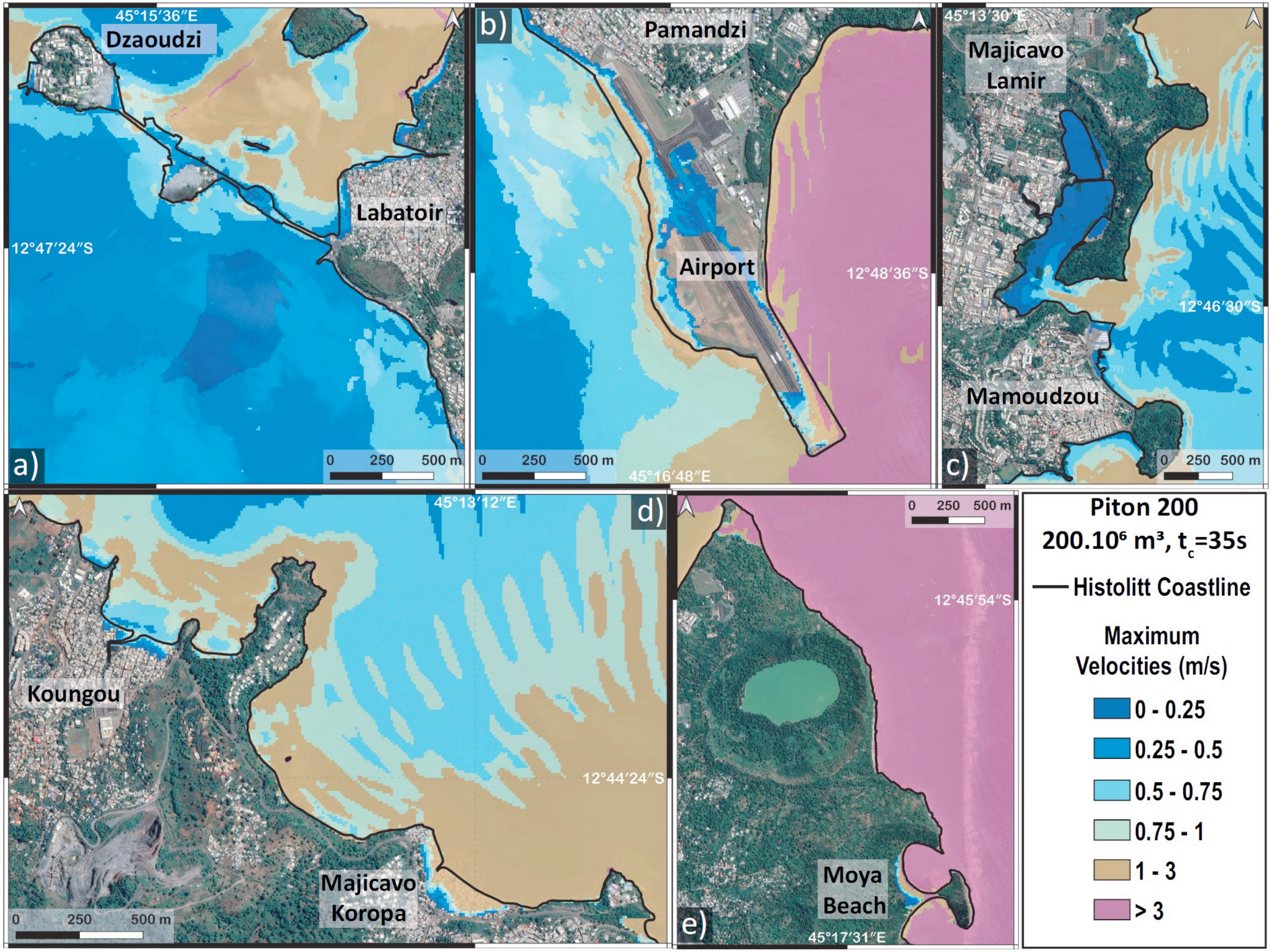
Numerical simulation of water surelevation



Maximum water detph during the simulation



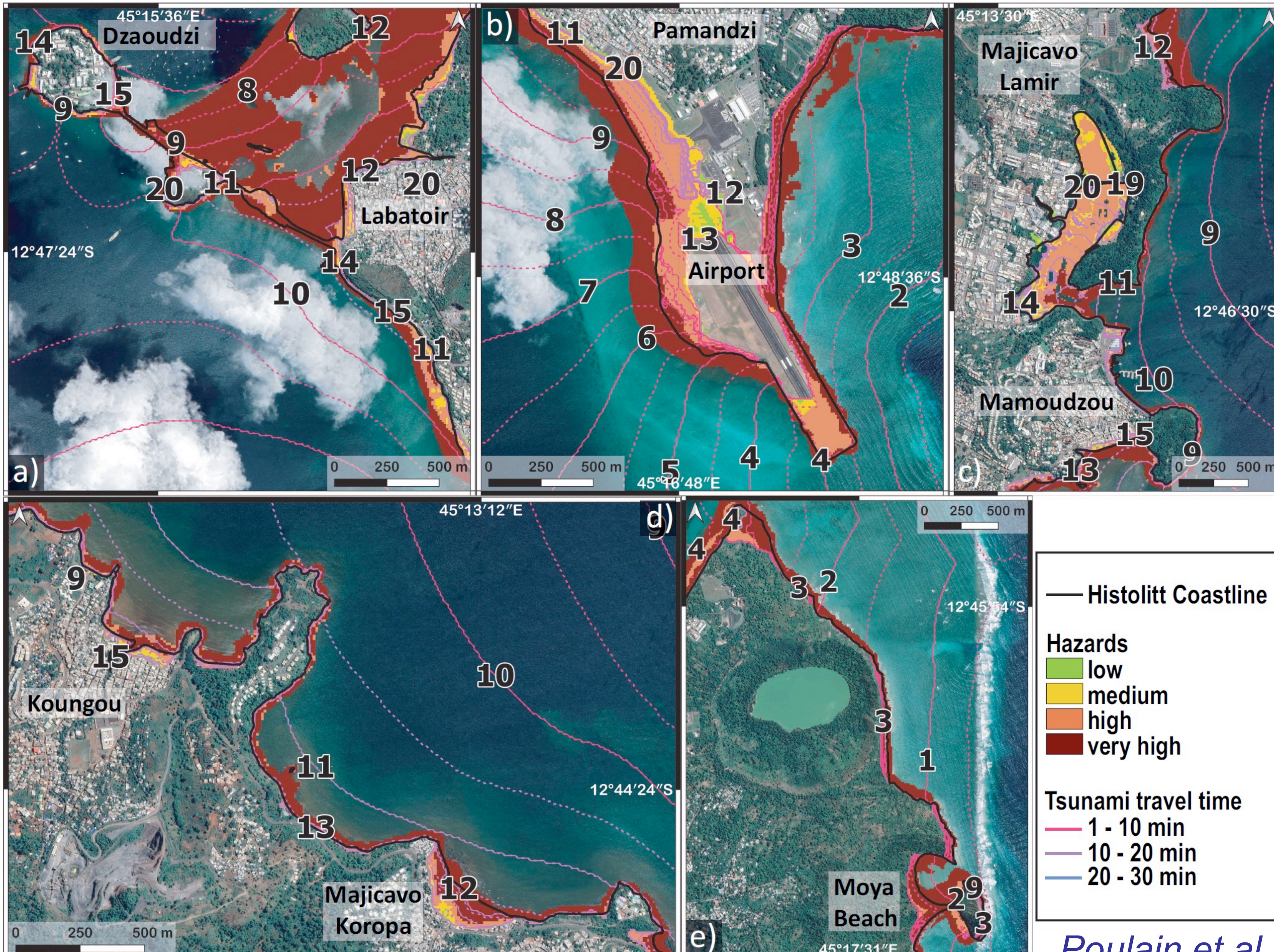
Maximum water velocity during the simulation



Poulain et al., 2021

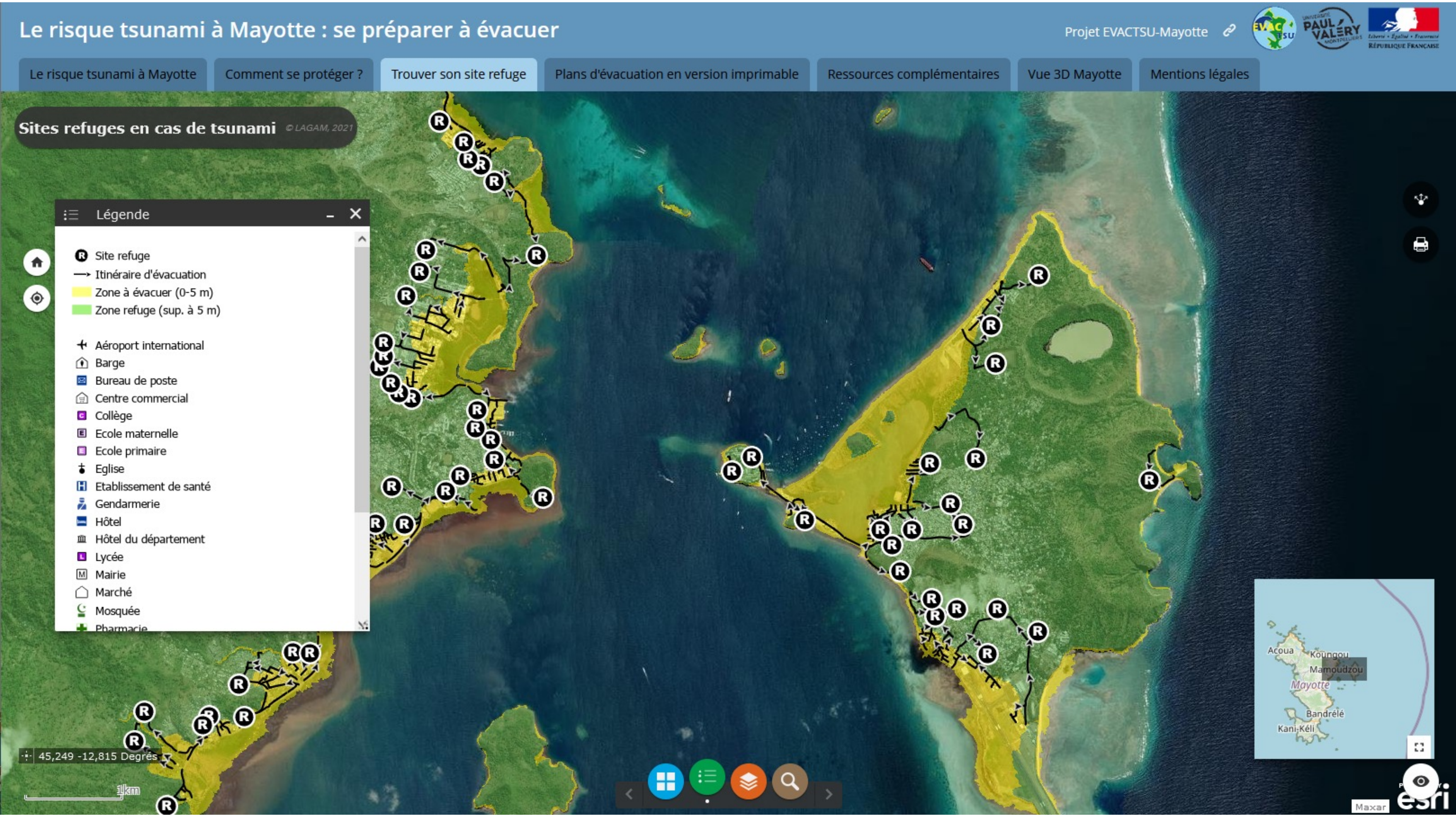
Hazard maps

BRGM-IPGP



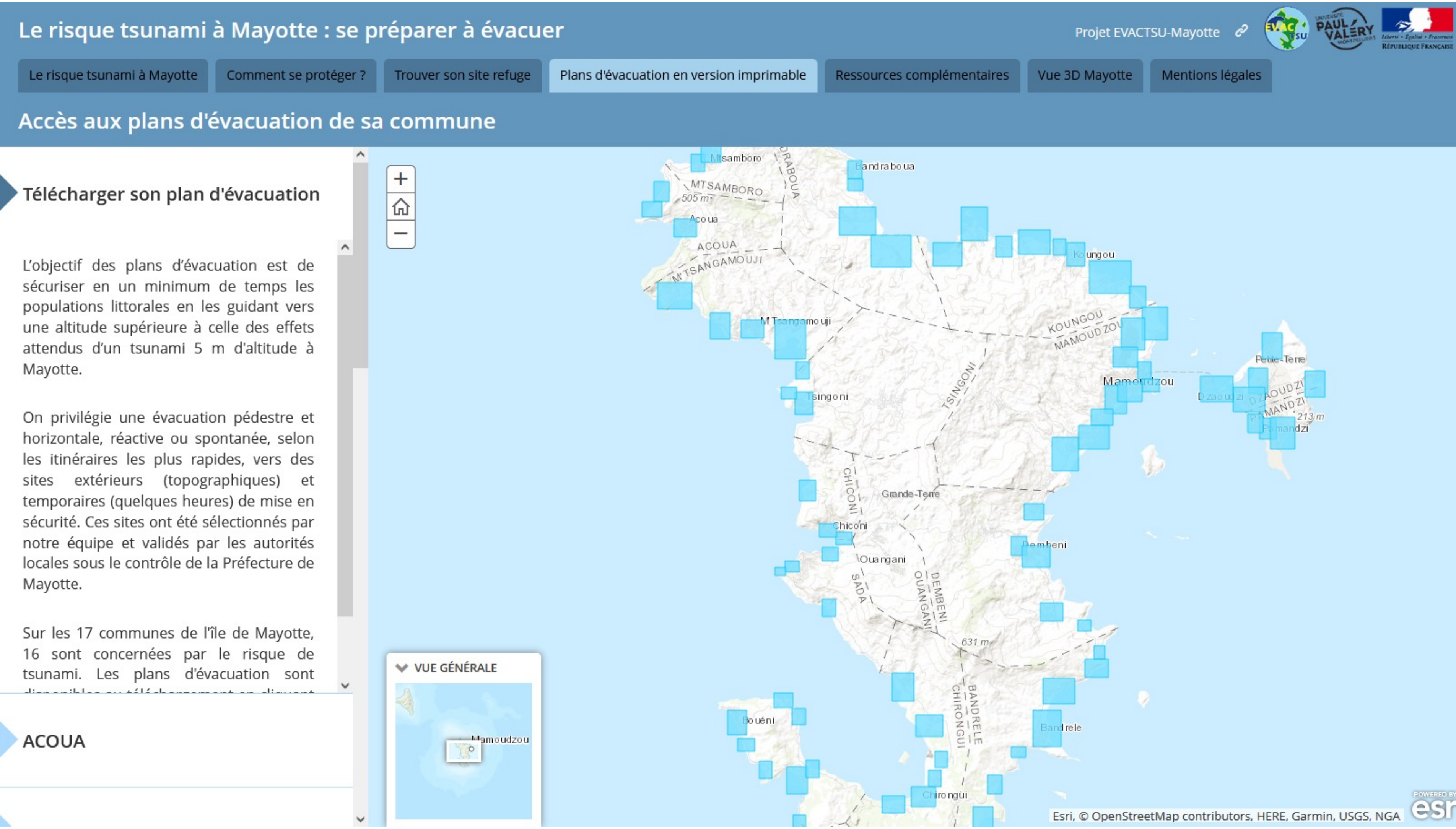
Poulain et al., 2021

Evacuation plans and refuges for population



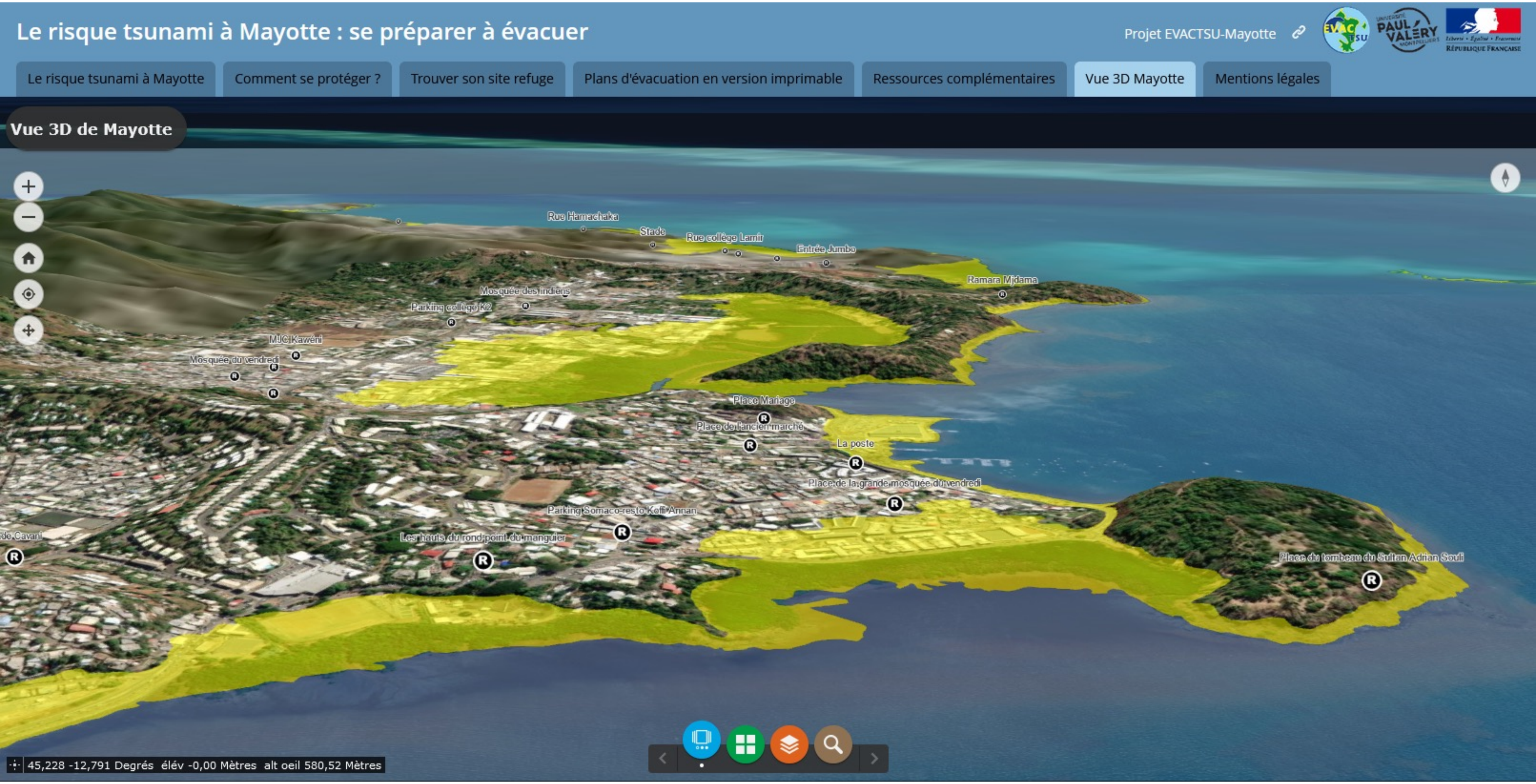
Leone et al., 2021

Evacuation plans and refuges for population



Leone et al., 2021

Evacuation plans and refuges for population



Leone et al., 2021

Outline

I – Introduction : Natural landslides and their simulation

Ia – Geophysics and mathematics

Ib – Complexity and variability of natural landslides

Ic – Examples of landslide simulations for hazard assessment

Id – Challenges in geophysics and landslide modelling

Main questions in geophysics

• How to detect geophysical flows and to assess their related hazards and indirect impact (tsunamis, etc)?

• What is the contribution of gravitational flows in erosion processes and relief evolution at the surface of the Earth and other planets?

• How are gravitational flows related to external forcing? Could they provide indicators or precursors of these forcing processes?

• What physical processes may be at the origin of the high mobility of large landslides?

• How to quantify and model erosion/deposition processes, solid/fluid interaction, polydispersity and fragmentation at the natural scale?

• How to retrieve the mechanisms of propagation and the characteristics of the flows from their deposit and/or from the generated seismic or geophysical signal?

Review paper: *Delannay, Valance, Mangeney, Roche, Richard, 2017*

Current challenges for landslide modelling

Improve the models, beyond simple approaches, to :

- Better describe essential elements of natural rheological behavior and complexity (role of fluids, erosion/deposition processes, material properties, etc.)
- Decrease the computational cost by developping physically and mathematically relevant approximations for field-scale simulations but still describe complex topography effects
- Build stable numerical models

in order to :

- Simulate the flow dynamics and deposit and associated hazard
- Extract relevant information on landslides from field measurements

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- Id – Challenges in geophysics and landslide modelling

II – Thin layer depth-averaged models for field-scale simulation

- IIa – Thin layer approximation for granular flows
- IIb – Accounting for complex topography
- IIc – Need of two different reference frames for landslide tsunamis
- IId – Application to real landslides : unexplained high mobility

III – Back to lab-scale experiments and simulation

- IIIa – Granular column collapse on rigid and erodible beds
- IIIb – μ(I) rheology in 2D models, comparison with other models (DEM, thin-layer)
- IIIc – Static-flowing interface (erosion/deposition)
- IIId – Grain-fluid mixture model

IV – Landslide detection/characterization from generated seismic waves

- IVa – Inversion/simulation of low frequency landslide forces
- IVb – Insight from high frequency data through lab-experiments
- IVc – Monitoring landslide activity in link with volcanic activity
- IVd – Similar approach for glacial earthquakes and ice-mass loss quantification

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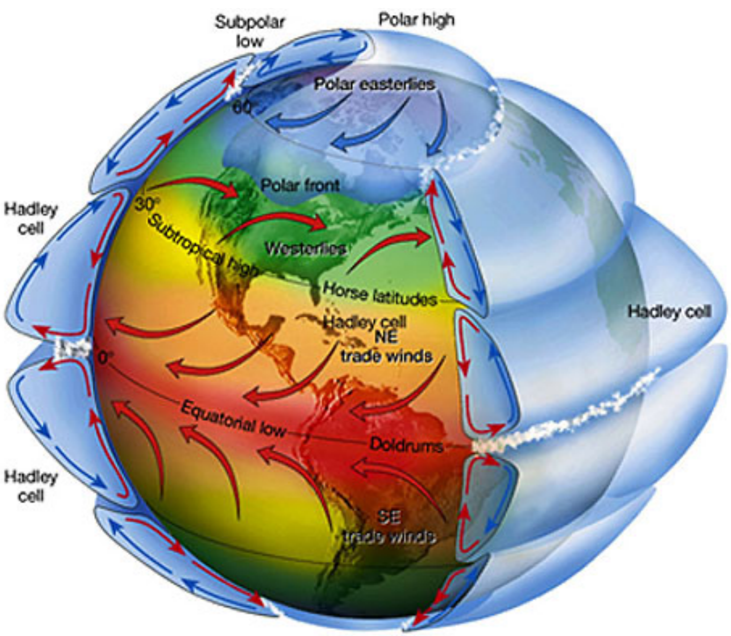
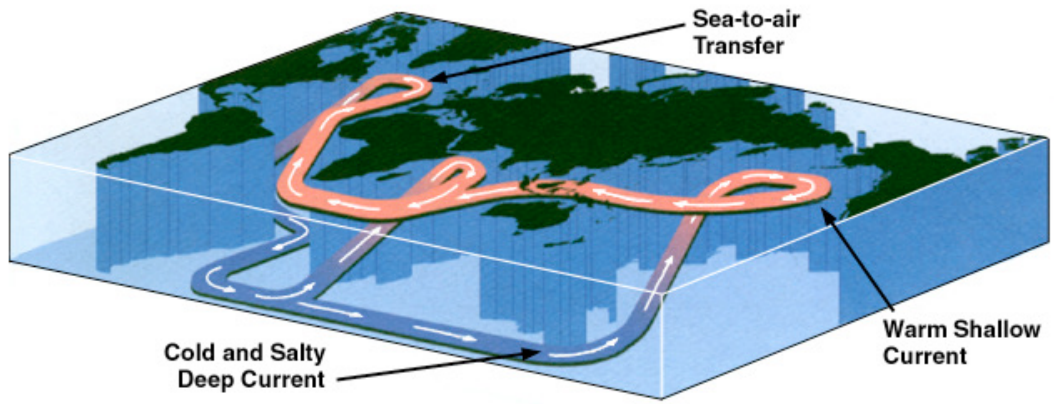
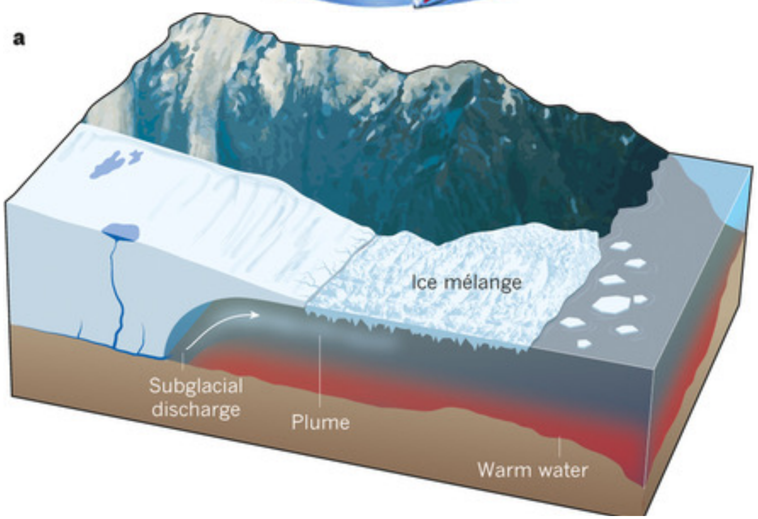
Thin layer approximation







Role of topography, Earth sphericity, etc.

Shallow natural gravitational flows

rivers

Lava flows

Strong thermal effects

Glaciers

viscosity

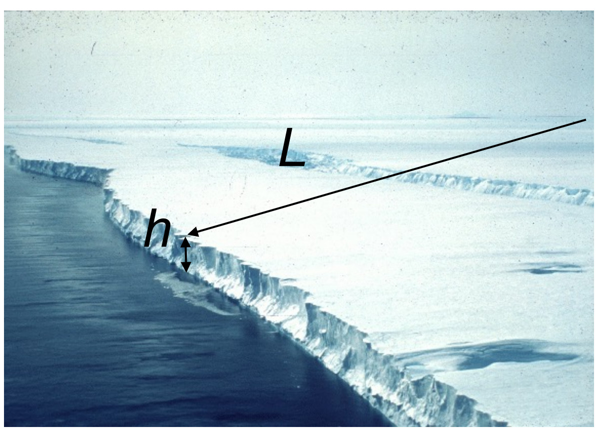
Shallow flows

Debris avalanche

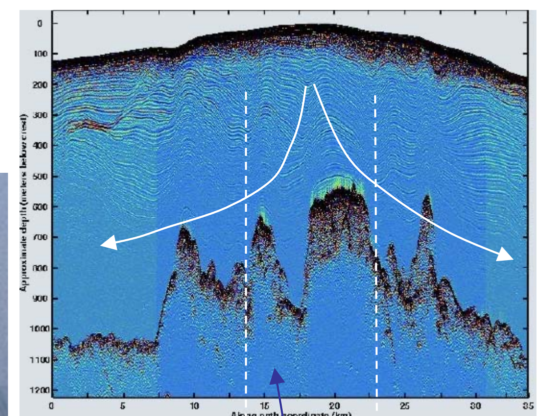
Rivers

Lava flow

$$a = \frac{h}{L} << 1$$



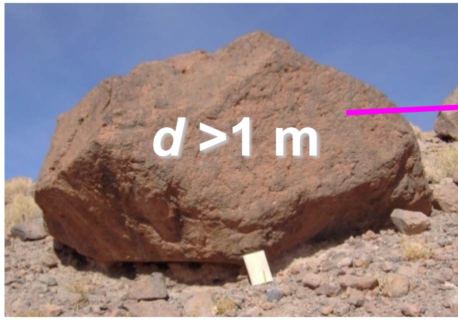
Ice sheet flow



$a \sim 1$

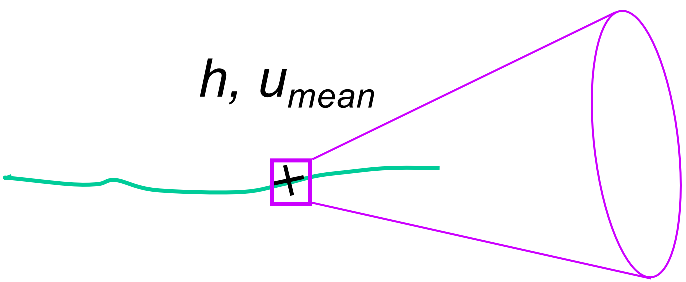
Numerical modelling of landslides

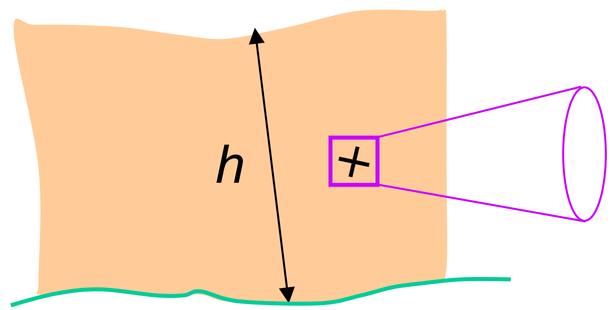
- Natural materials

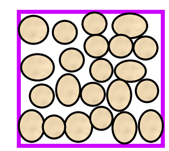


- Modeling

2D thin layer model | **3D continuum** model | **Discrete element** model





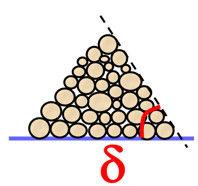


Mean scale

Reasonable computational cost

Empirical flow law …

$\mu = \tan\delta$



Local scale

High computational cost

Local flow law

Grain scale

High computational cost

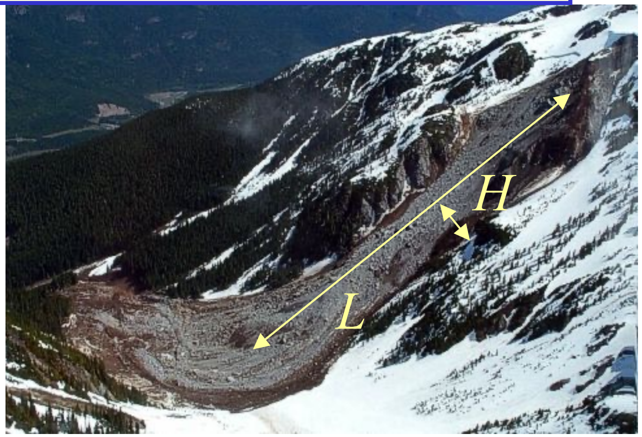
Particle size distribution ???

Thin layer approximation on 2D topography

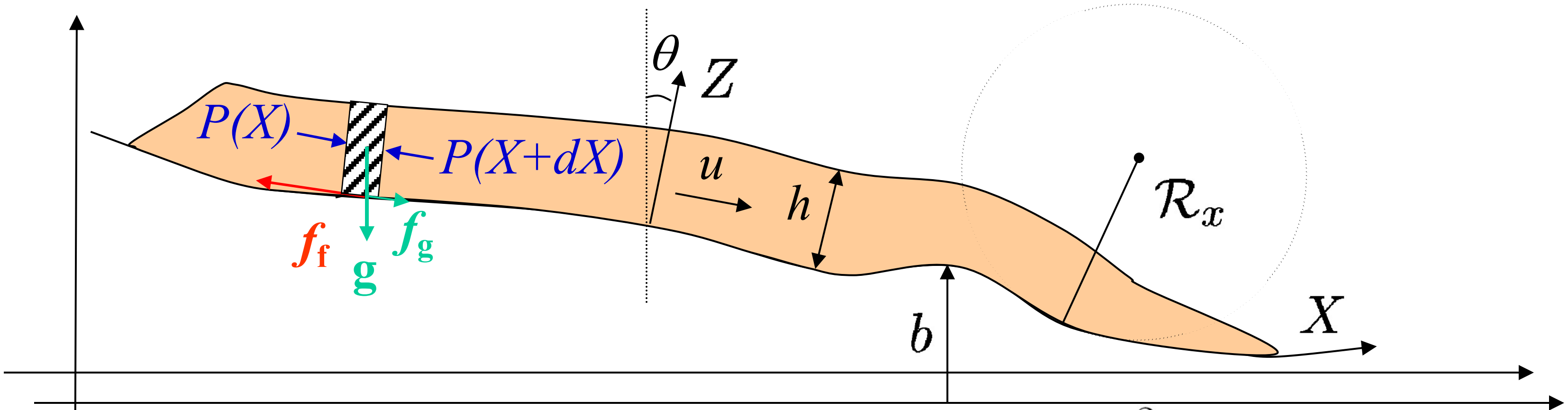
- Flow on **complex natural topography**

  high computational cost

  approximation: small **aspect ratio** $a = \frac{H}{L} \ll 1$



- Depth-averaged thin layer model



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

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

Savage and Hutter, 1989

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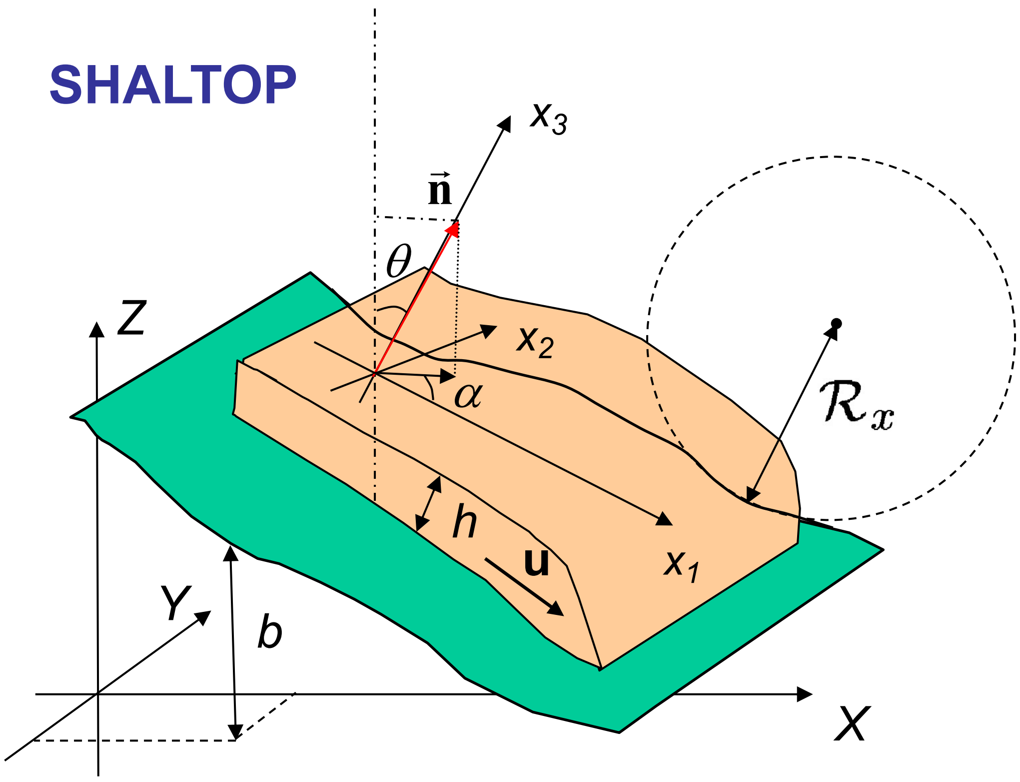
Thin layer approximation on 3D topography

- **Full curvature tensor**

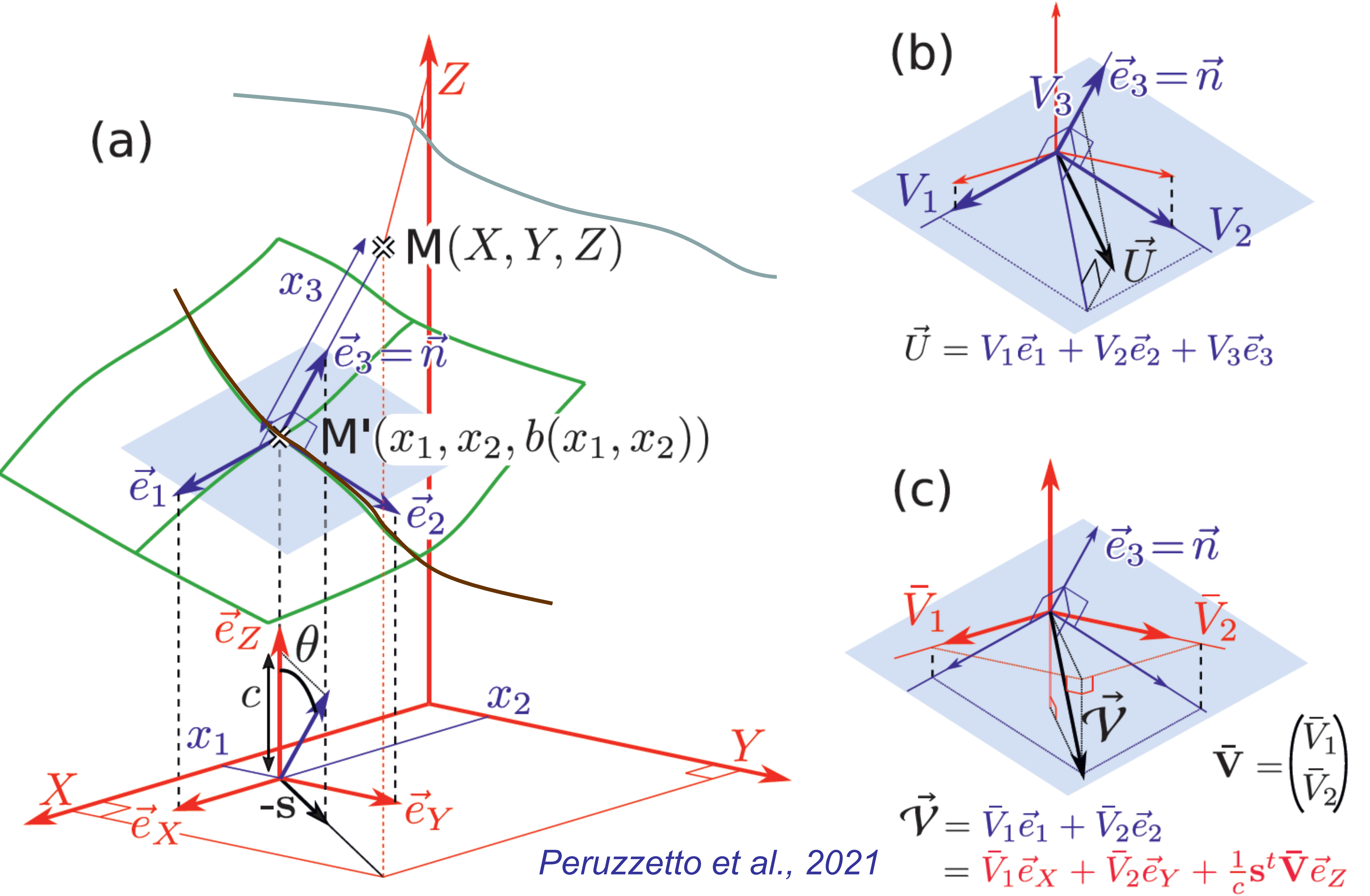
$$\mathcal{H} = c^3 \; \partial^2_{\mathbf{xx}} b$$

First equations including these « centrifugal » forces



Bouchut, Mangeney-Castelnau, Perthame, Vilotte, 2003, Bouchut and Westdickenberg 2004, Mangeney et al. 2007

Change of coordinate systems



Peruzzetto et al., 2021

SHALTOP equations in a Cartesian reference frame

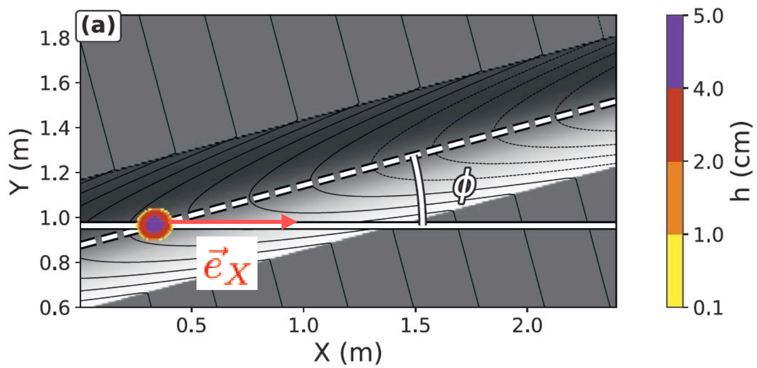
- Momentum conservation equation in the Cartesian reference frame

$$\vec{\mathcal{V}} = \bar{V}_1\vec{e}_X + \bar{V}_2\vec{e}_Y + \frac{1}{c}\mathbf{s}^t\bar{\mathbf{V}}\vec{e}_Z \qquad \text{with} \qquad \bar{\mathbf{V}} = (\bar{V}_1, \bar{V}_2)$$

$$\partial_t\bar{\mathbf{V}} + (\bar{\mathbf{V}}\nabla_{\mathbf{x}})\bar{\mathbf{V}} + (I_2 - \mathbf{s}\mathbf{s}^t)\nabla_{\mathbf{x}}\big(g(hc+b)\big)$$
$$= \underbrace{-c\Big(\bar{\mathbf{V}}^t(\partial^2_{\mathbf{xx}}b)\bar{\mathbf{V}}\Big)\mathbf{s}}_{F_H} - \frac{\mu g c\bar{\mathbf{V}}}{\sqrt{\bar{\mathbf{V}}^{\,2} + \left(\frac{1}{c}\mathbf{s}^t\bar{\mathbf{V}}\right)^2}}\Bigg(1 + \underbrace{\frac{\bar{\mathbf{V}}^t(\partial^2_{\mathbf{xx}}b)\bar{\mathbf{V}}}{g}}_{F_\mu}\Bigg)_+$$

Curvature terms

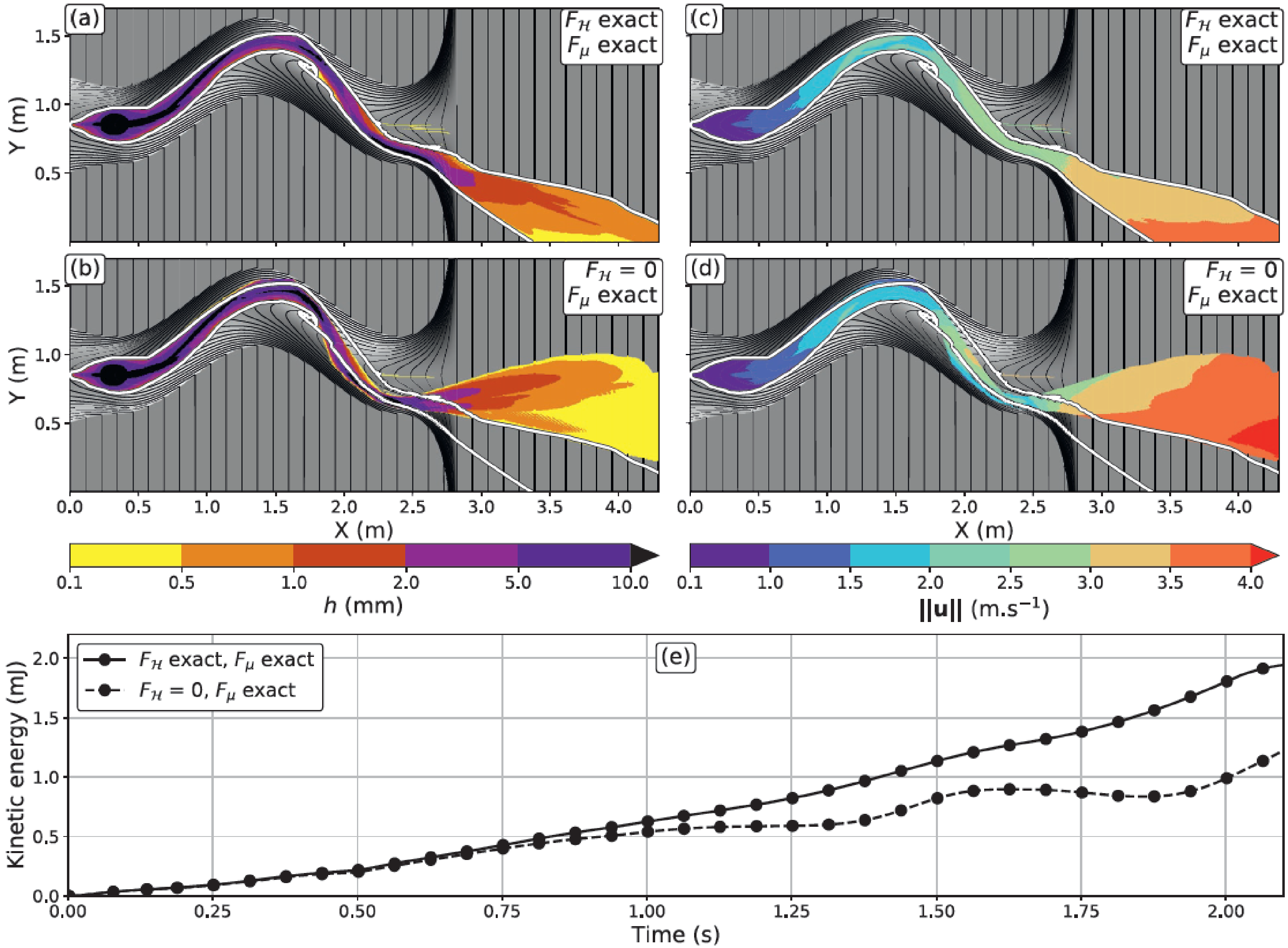
// Luca et al. (2009)



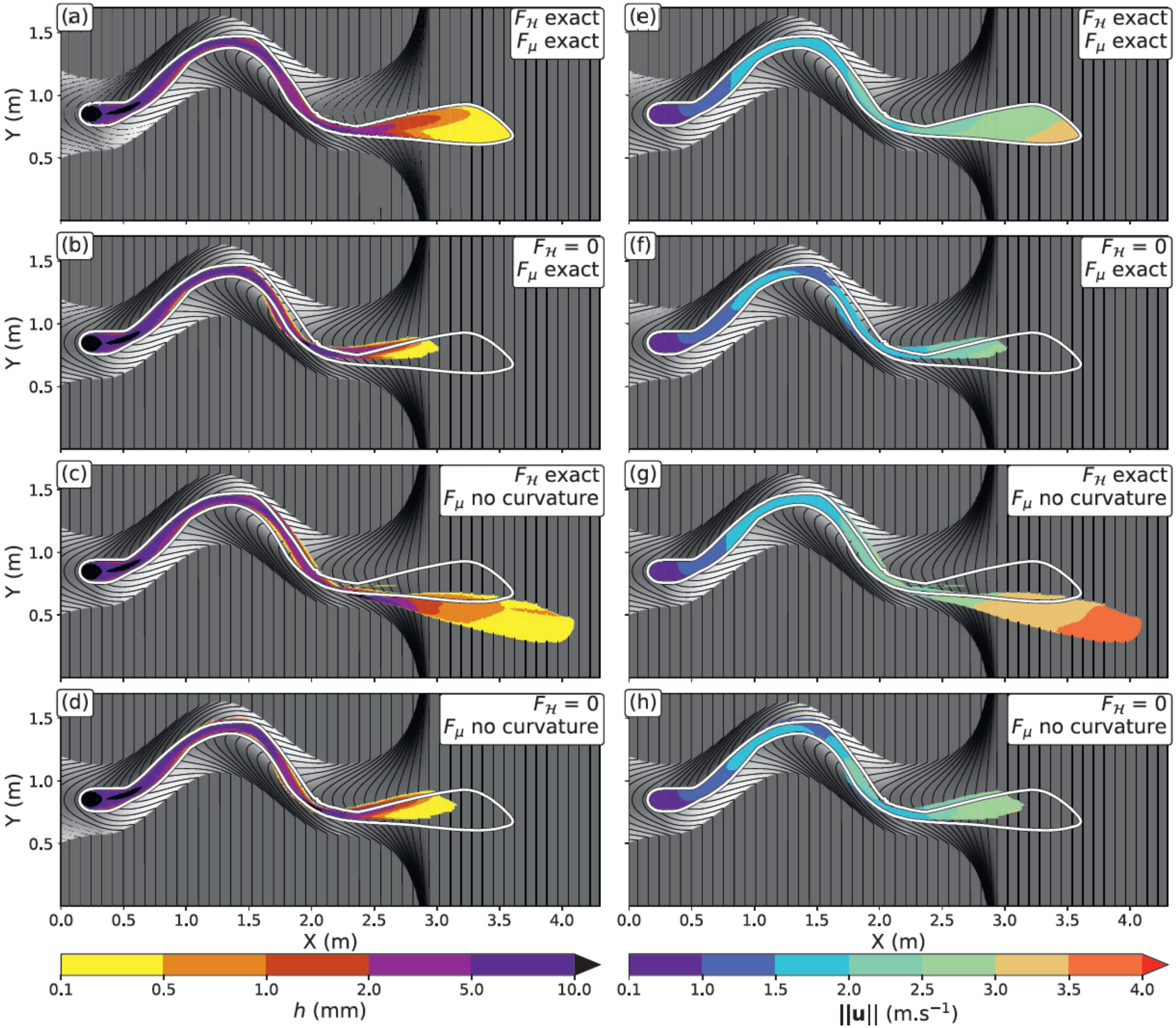
Invariant by rotation of the reference frame contrary to other approaches

Peruzzetto et al. (2021)

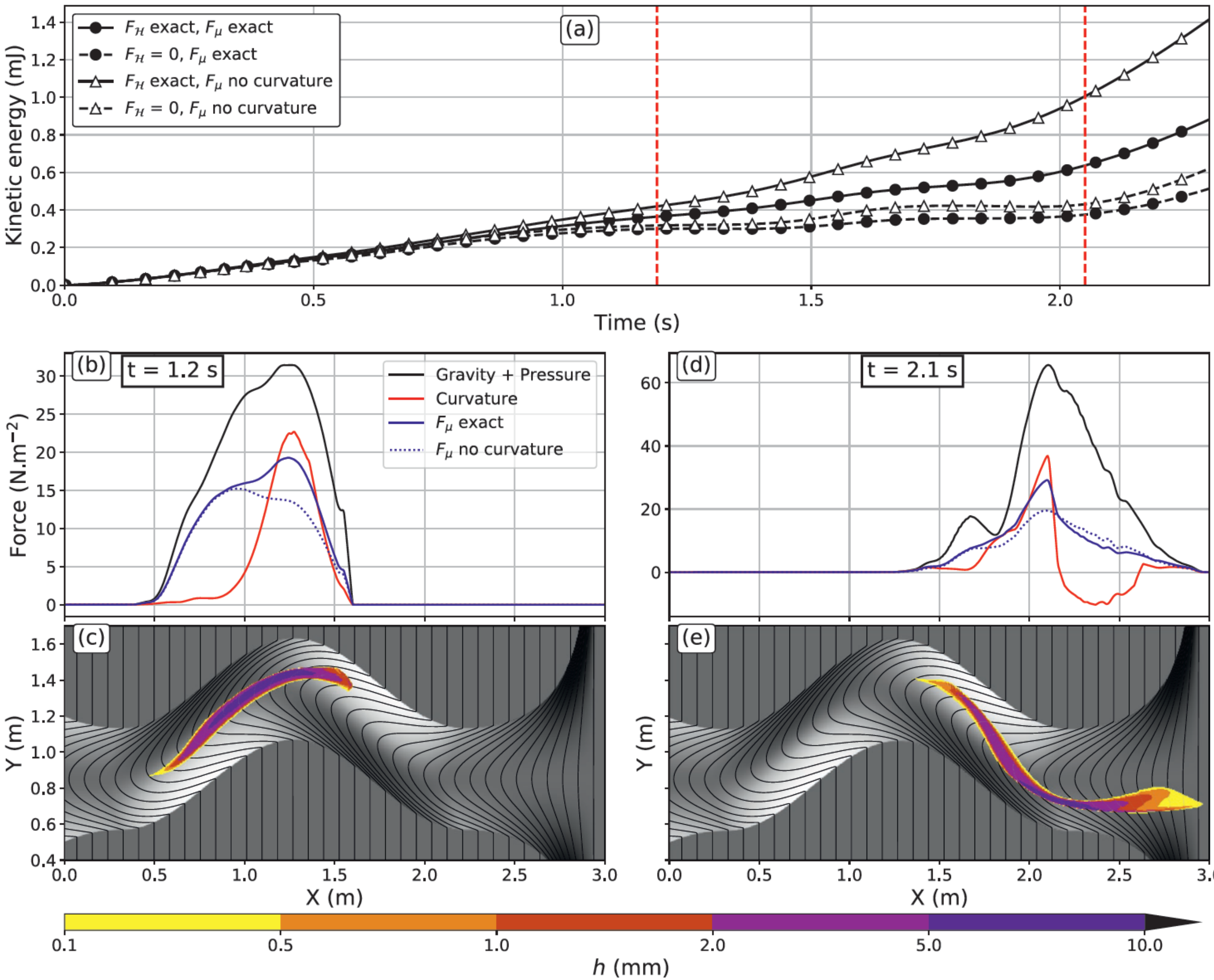
Curvature effects on simplified topographies



Friction angle δ =0°, slope angle θ =10° Strong effect for river or water flow simulations

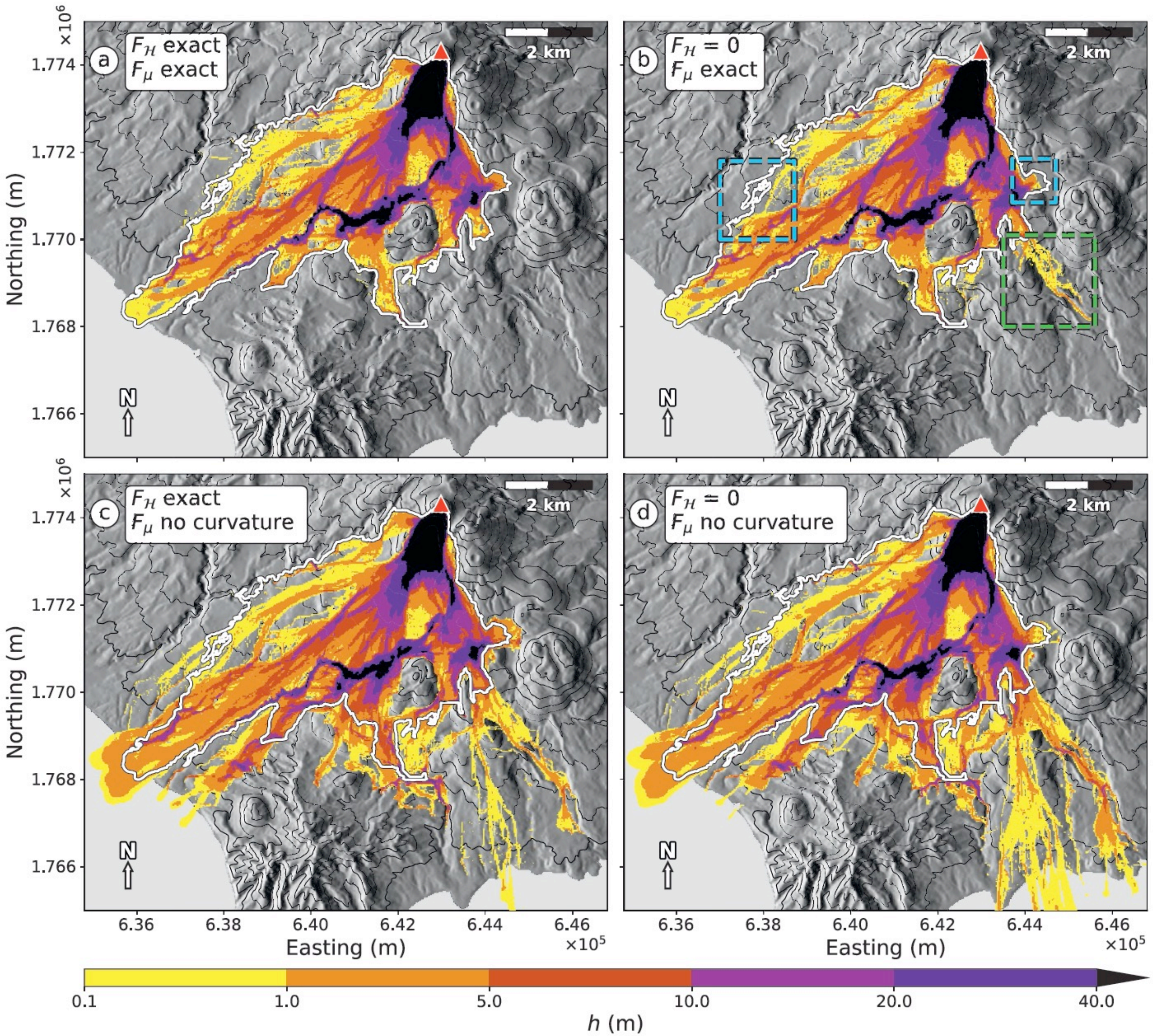


Friction angle $\delta = 15°$, slope angle $\theta = 25°$

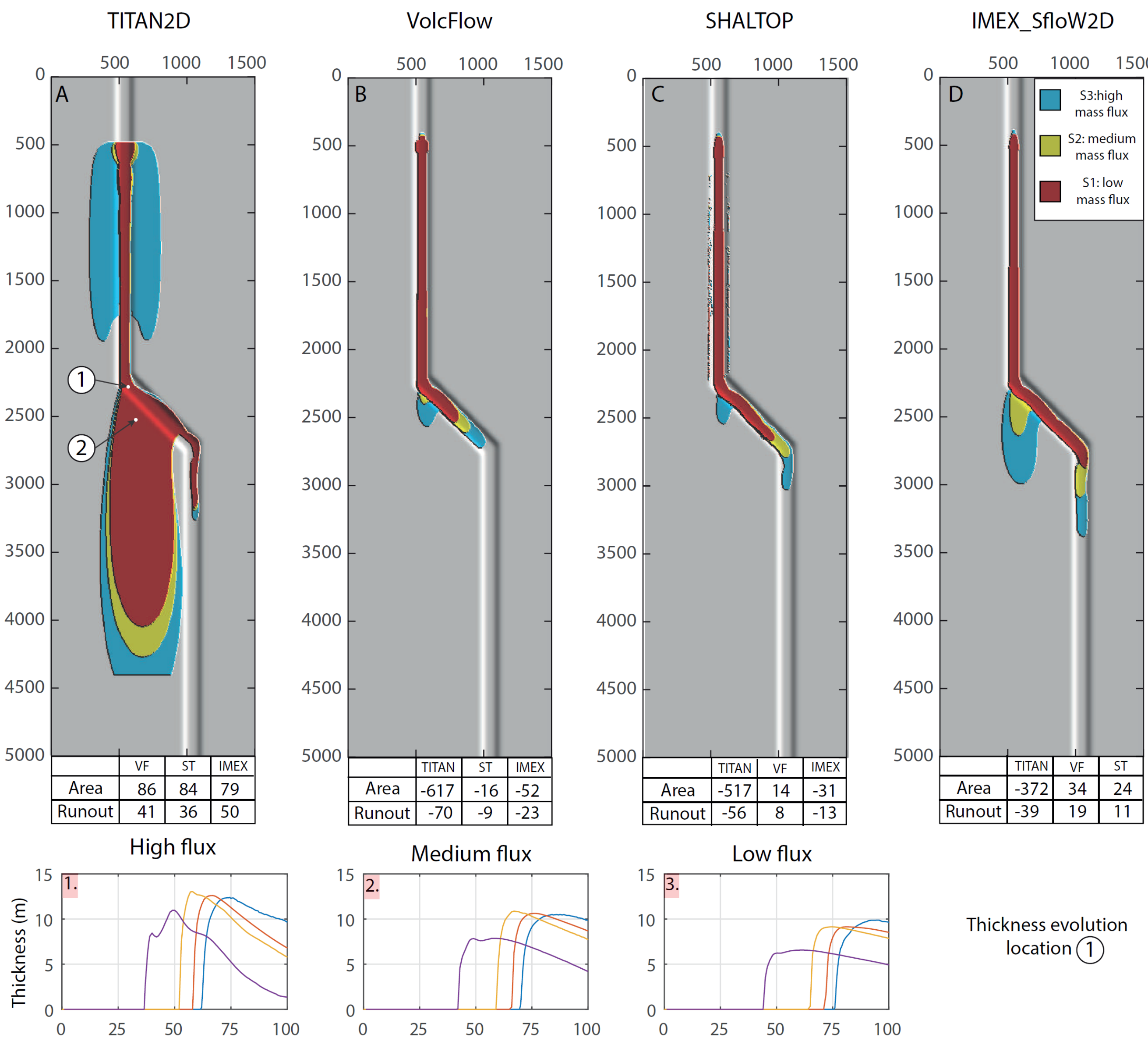


Friction angle δ =15°, slope angle θ =25°

Curvature effects on complex natural topographies



Model benchmark exercice



A	VF	ST	IMEX
Area	86	84	79
Runout	41	36	50

B	TITAN	ST	IMEX
Area	-617	-16	-52
Runout	-70	-9	-23

C	TITAN	VF	IMEX
Area	-517	14	-31
Runout	-56	8	-13

D	TITAN	VF	ST
Area	-372	34	24
Runout	-39	19	11

Gueugneau et al., 2021

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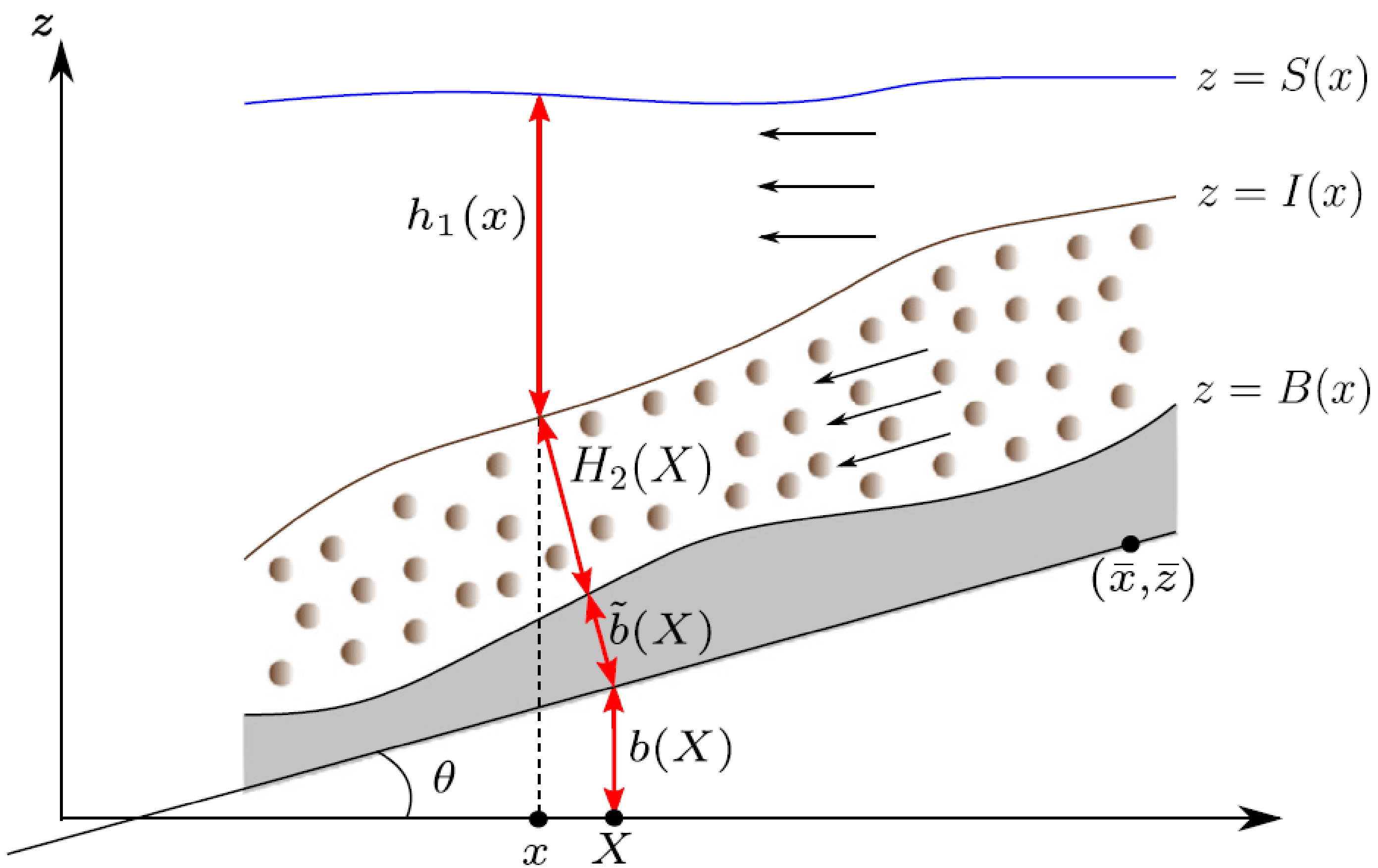
Two different integration directions for landslides and tsunami

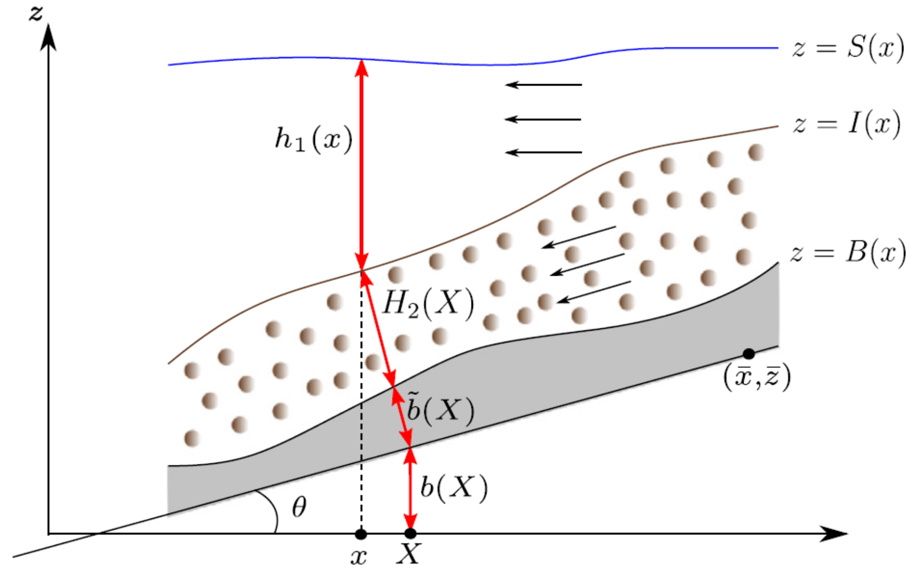
For a review see *Yavari-Ramshe & Ataie-Ashtiani (2016)*



Delgado-Sanchez, Bouchut, Fernandez-Nieto, Mangeney, Narbona-Reina (2021)

Two different directions for landslides and tsunami

$$(X,t) \mapsto (x,t) = (X - (\tilde{b}(X) + H_2(X,t))\sin\theta, t)$$



$$H_1(X,t) = h_1\big(X - (\tilde{b}(X) + H_2(X,t))\sin\theta, t\big),$$
$$U_1(X,t) = u_1\big(X - (\tilde{b}(X) + H_2(X,t))\sin\theta, t\big)$$

$$\mathcal{J} := \det(\nabla_{(X,t)}(x,t)) = 1 - \partial_X(\tilde{b} + H_2)\sin\theta$$

$$A := \nabla_{(X,t)}(x,t) = \begin{pmatrix} 1 - \partial_X(\tilde{b} + H_2)\sin\theta & -\partial_t H_2 \sin\theta \\ 0 & 1 \end{pmatrix}$$

$$\begin{cases} \partial_t(H_1\mathcal{J}) + \partial_X(H_1(U_1 + \partial_t H_2 \sin\theta)) = 0, \\ \partial_t(H_1U_1\mathcal{J}) + \partial_X\left(H_1U_1(U_1 + \partial_t H_2\sin\theta) + g\dfrac{H_1^2}{2}\right) = -gH_1\partial_X(b + (\tilde{b} + H_2)\cos\theta) - \mathcal{J}\gamma(\mathcal{J}U_1\cos\theta - U_2), \\ \partial_t H_2 + \cos\theta\,\partial_X(H_2U_2) = 0, \\ \partial_t(H_2U_2) + \cos\theta\,\partial_X\left(H_2U_2^2 + g\dfrac{H_2^2}{2}\cos\theta\right) = \\ \qquad = -gH_2\cos\theta\,\partial_X(b + \tilde{b}\cos\theta + rH_1) - g\,\mathrm{sgn}(U_2)H_2\cos\theta(1-r)\mu + r\gamma(\mathcal{J}U_1\cos\theta - U_2). \end{cases}$$

Friction between water and avalanche layers

Numerical method to solve these equations

Essential step for application in geophysics !

$$W = (\mathcal{H}_1, \mathcal{Q}_1, H_2, Q_2)^T = (H_1\mathcal{J},\ H_1\mathcal{J}U_1,\ H_2,\ H_2U_2)^T$$

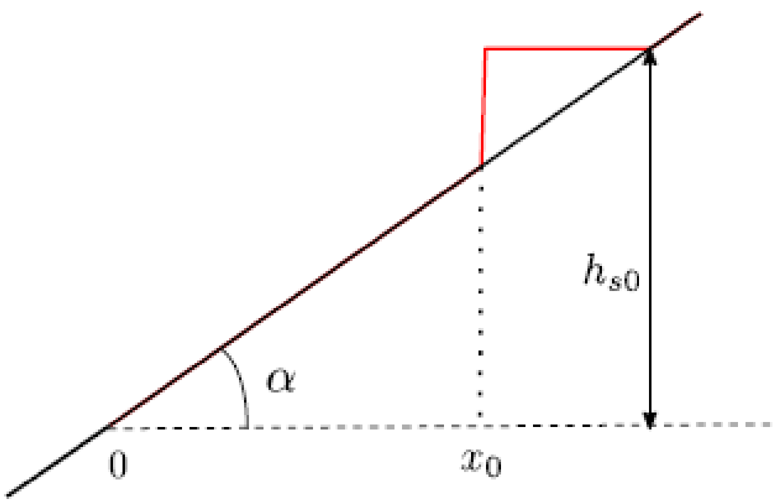
$$W_i^{n+1} = W_i^n - \frac{\Delta t}{\Delta x}(\tilde{\mathcal{F}}^n_{i+1/2} - \tilde{\mathcal{F}}^n_{i-1/2}) - \frac{\Delta t}{\Delta x}\mathcal{S}_i^n$$

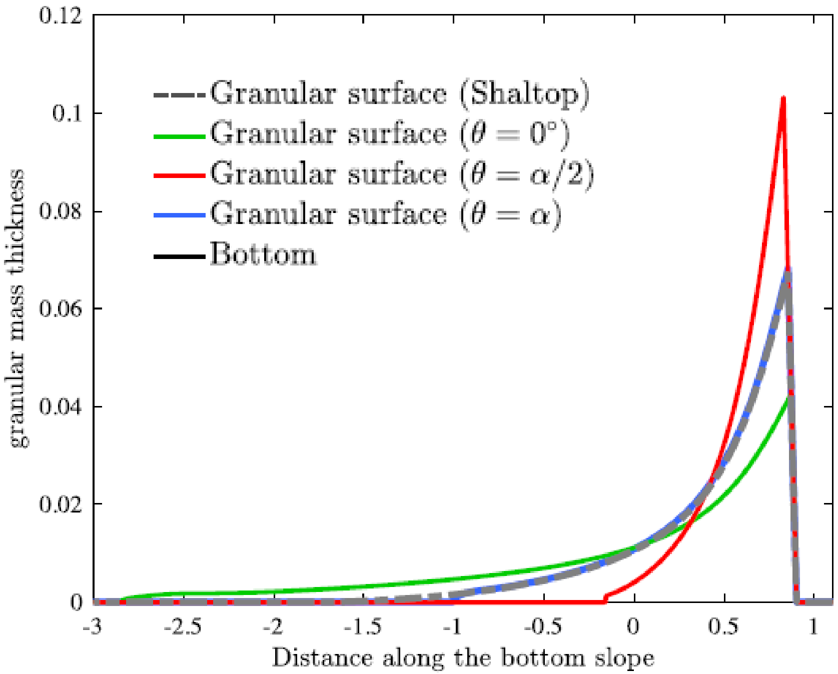
$$\begin{aligned}\tilde{\mathcal{F}}_{i+1/2} &= \frac{1}{2}\Big(\mathcal{F}(W^+_{i+1/2}) + \mathcal{F}(W^-_{i+1/2})\Big) \\ &\quad - \frac{1}{2}\Big(\alpha_{0,i+1/2}(W^+_{i+1/2} - W^-_{i+1/2}) + \alpha_{1,i+1/2}\big(\mathcal{F}(W^+_{i+1/2}) - \mathcal{F}\big(W^-_{i+1/2}\big) + \mathcal{S}_{i+1/2}\big)\Big)\end{aligned}$$

Hydrostatic reconstruction of the variables

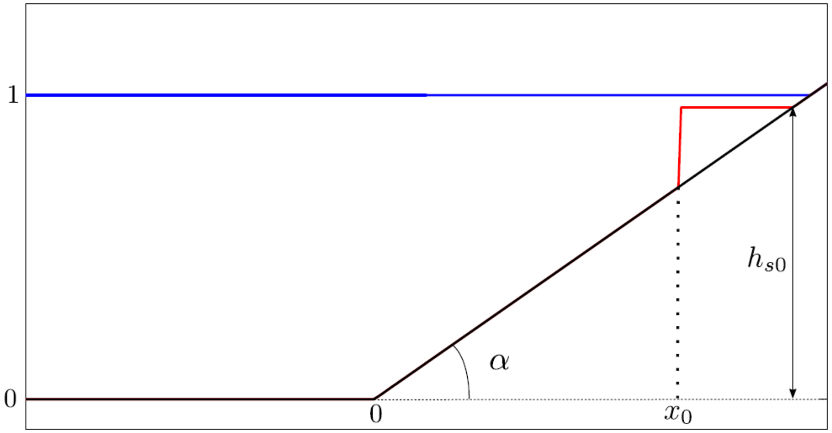
$$W^\pm_{i+1/2} = (\mathcal{H}^\pm_{1,i+1/2}, \mathcal{Q}^\pm_{1,i+1/2}, H^\pm_{2,i+1/2}, Q^\pm_{2,i+1/2})^T$$

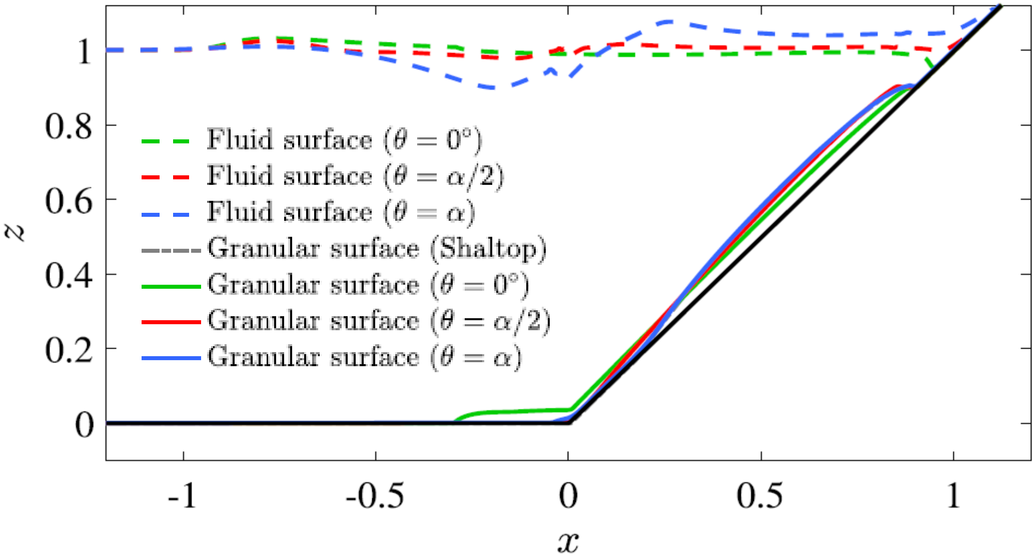
Quantification of the error in reference choice





α = 45°





Delgado-Sanchez et al. (2021)

Introduce curvature effects …..

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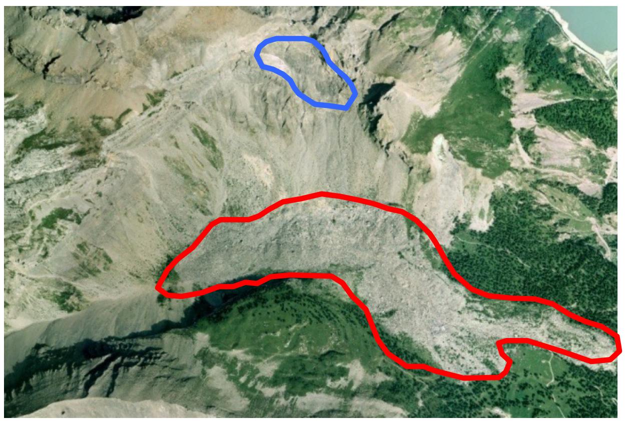
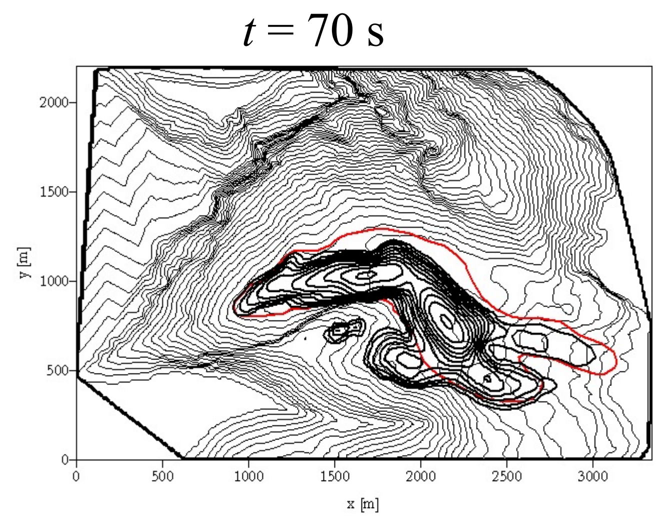
Simulation of natural flows

Simulation of observed deposits (Switzerland)

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





Calibrated friction angle : δ=17°

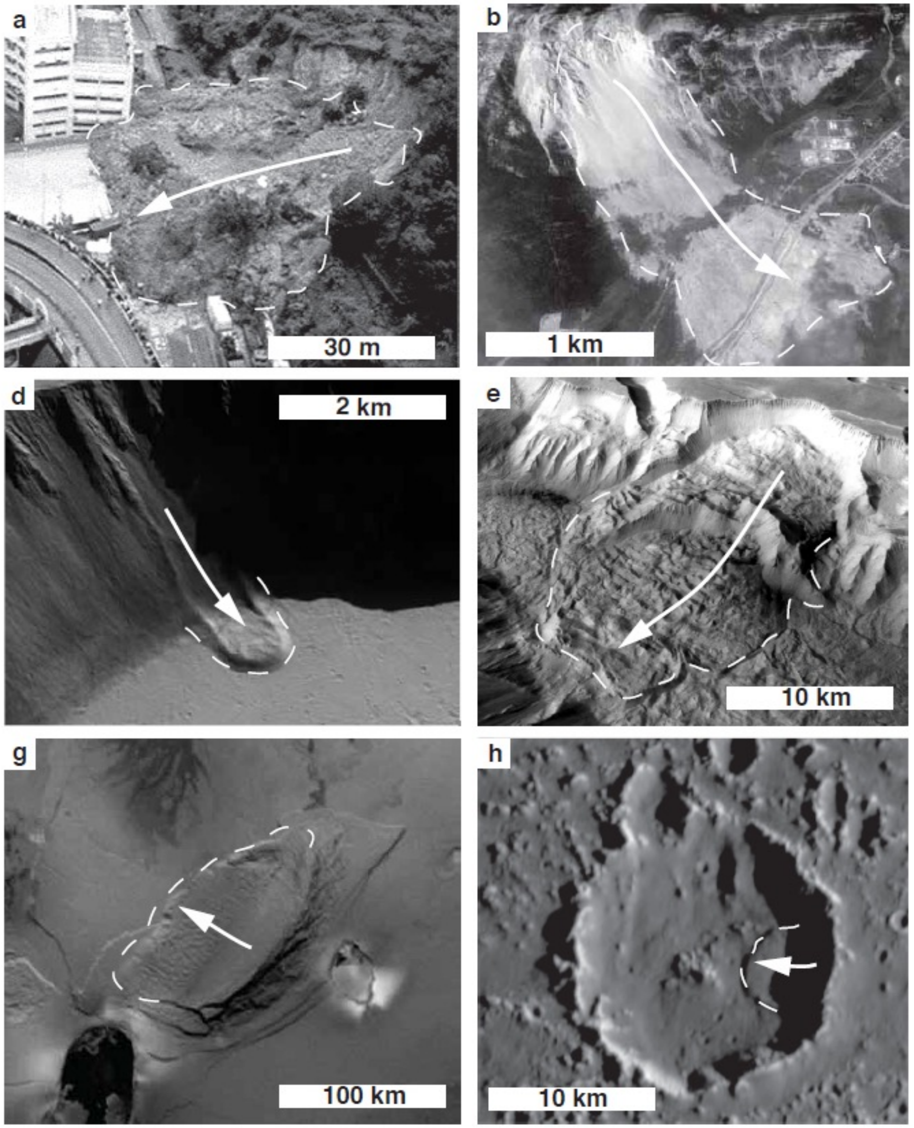
Small compared to friction angles of natural materials ! $\theta_r \sim 35^\circ$

Origin of the high mobility of natural flows ?

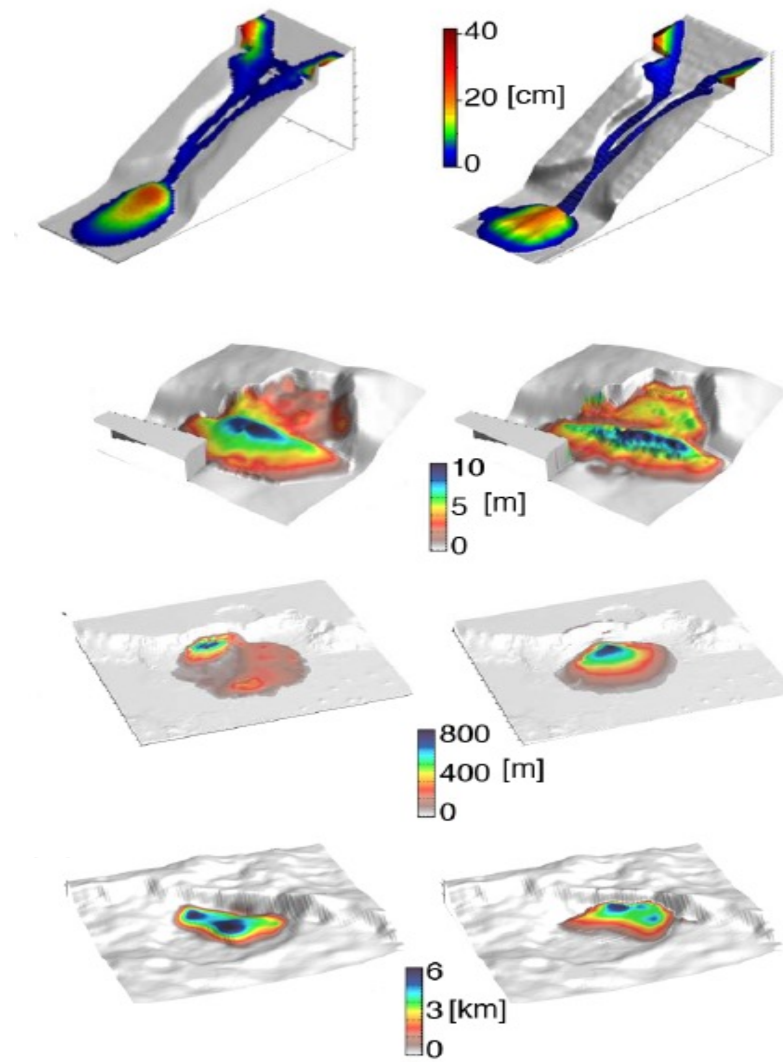
Pirulli and Mangeney, 2008

Simulation of a large variety of natural flows

Simulation with empirical friction coefficient



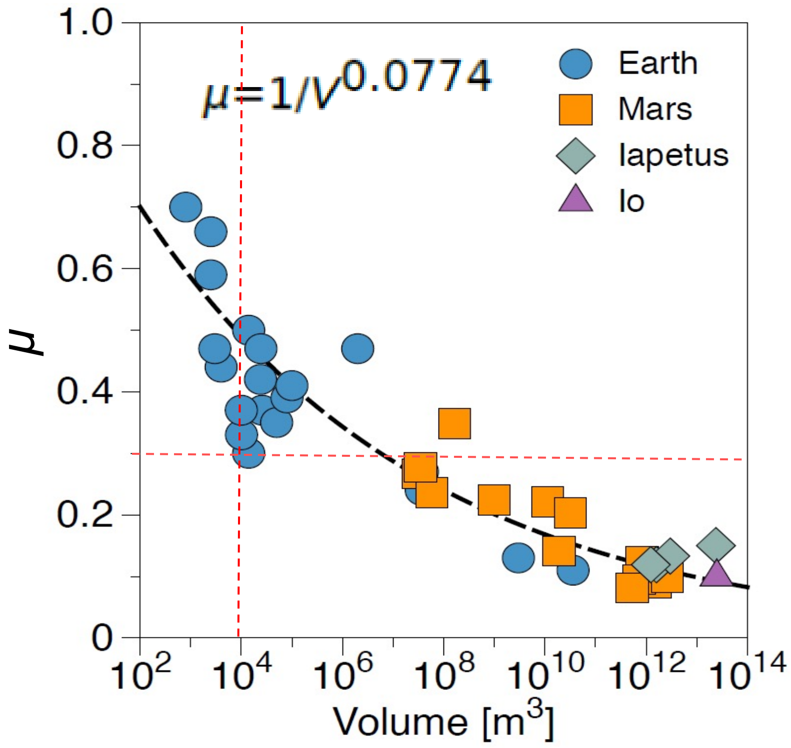
Observed deposit Simulation



Lucas, Mangeney, Ampuero, Nature Communications, 2014

Empirical friction laws based on deposit data

Friction coefficient $\mu = \tan \delta$

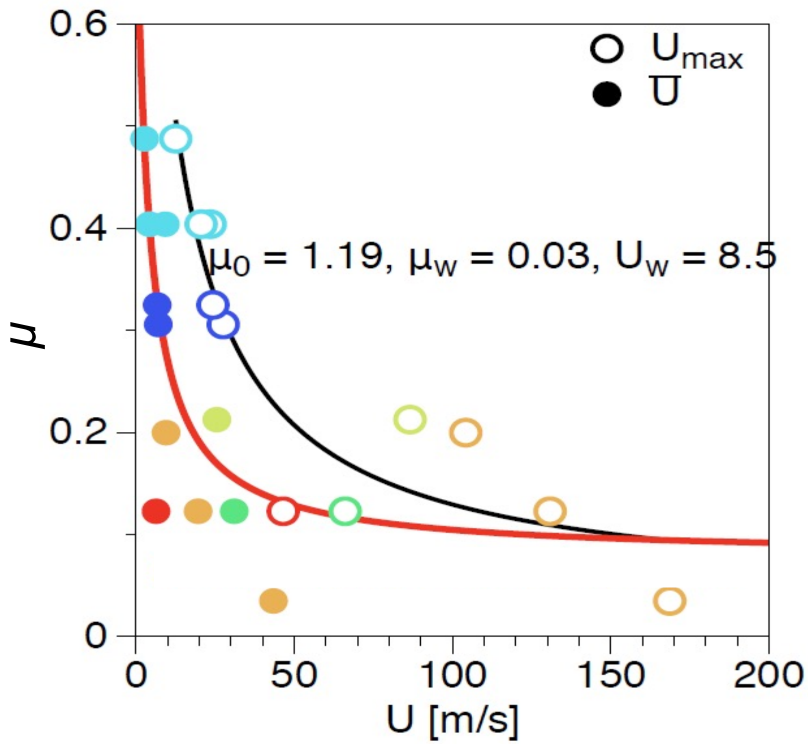


Physical origin ?

Lucas, Mangeney, Ampuero, Nature Communications, 2014

Empirical friction weakening with velocity

Friction coefficient $\mu = \tan\delta$

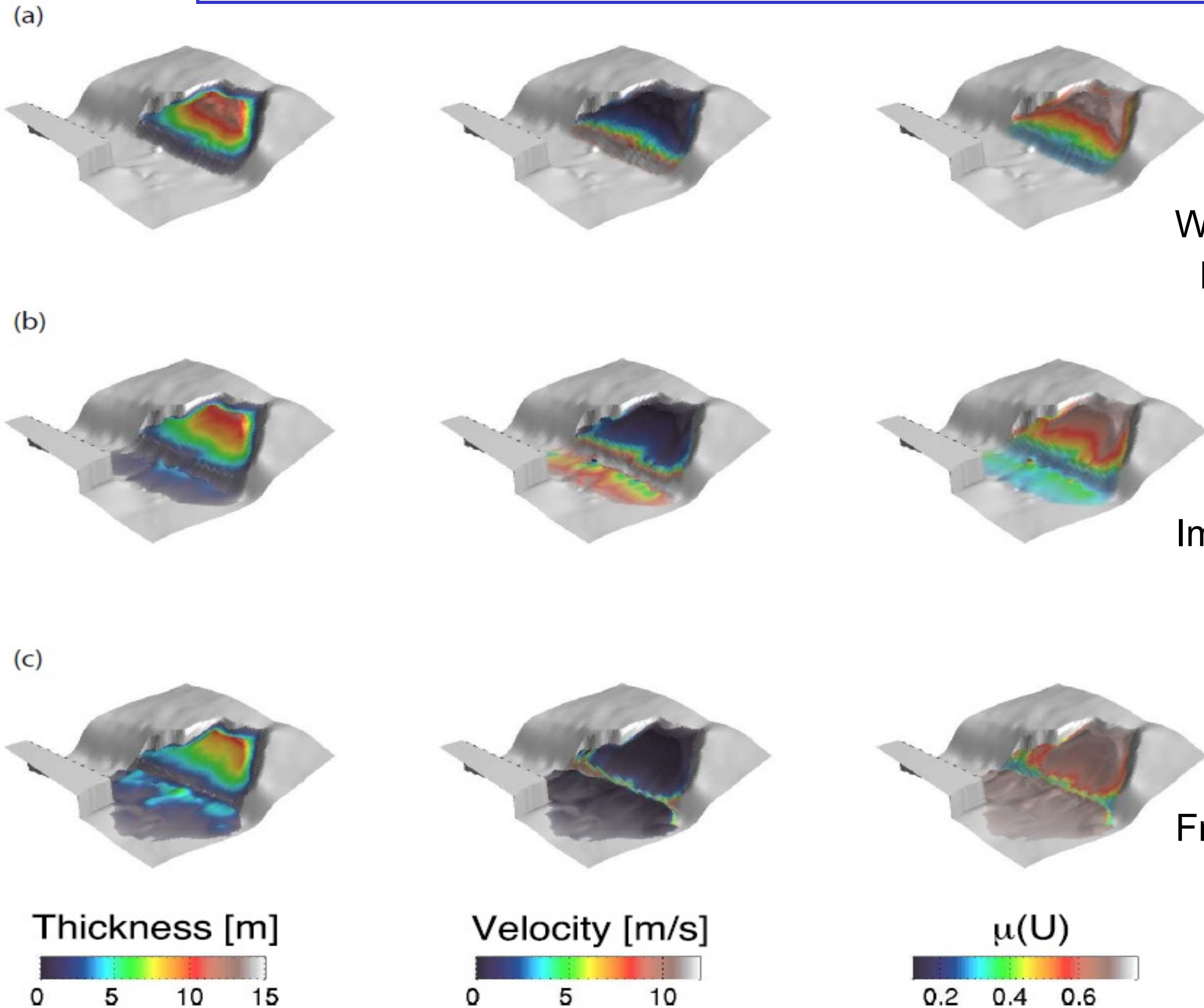


$$\mu(U) = \frac{\mu_o - \mu_w}{(1 + \|U\|/U_w)} + \mu_w$$

$$\mu_o = 0.84,\ \mu_w = 0.11,\ U_w = 4\ \mathrm{m.s}^{-1}$$

Lucas, Mangeney, Ampuero, Nature Communications, 2014

Reproduce small to large landslides

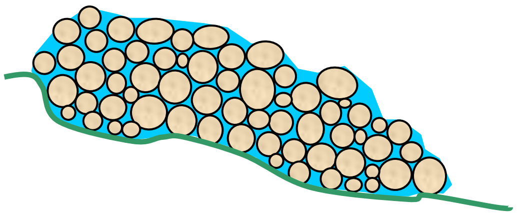


With the same parameters

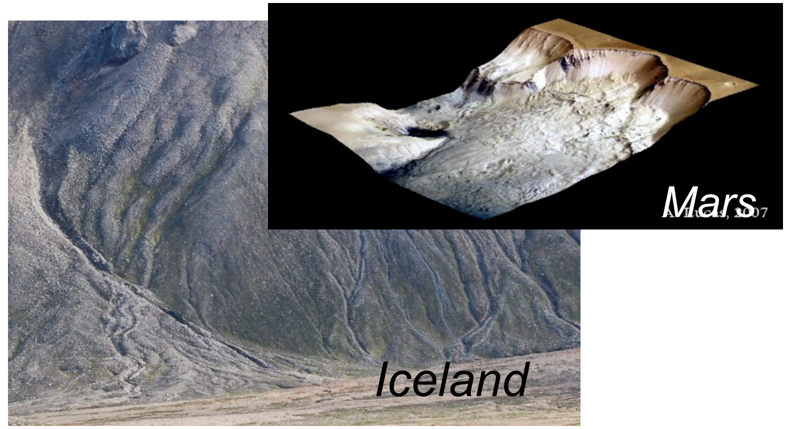
Improve deposit morphology

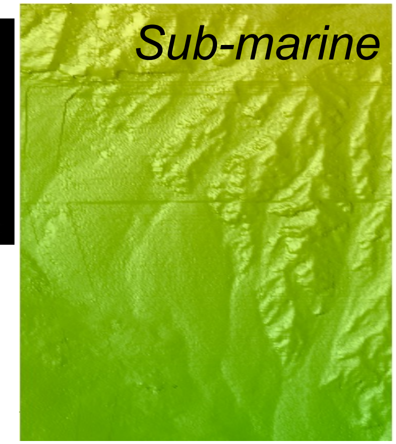
Friction coefficient $0.1 < \mu < 0.8$

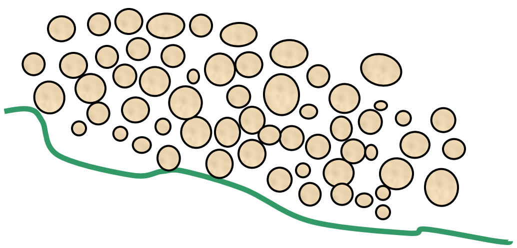
Different physical processes



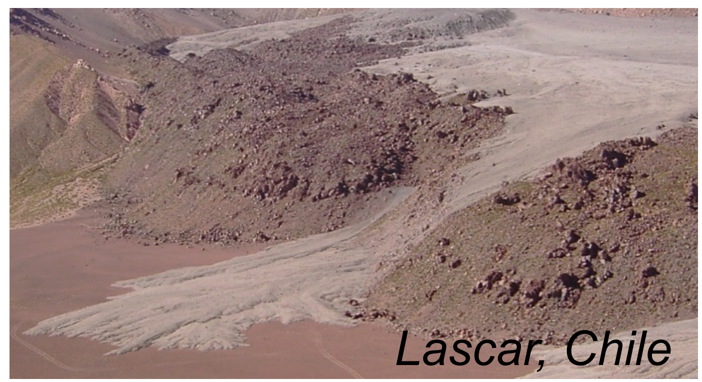
Fluid phase (water, mud)



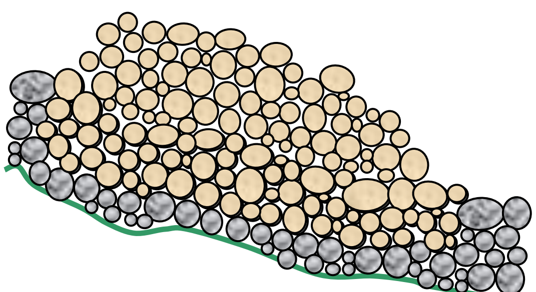




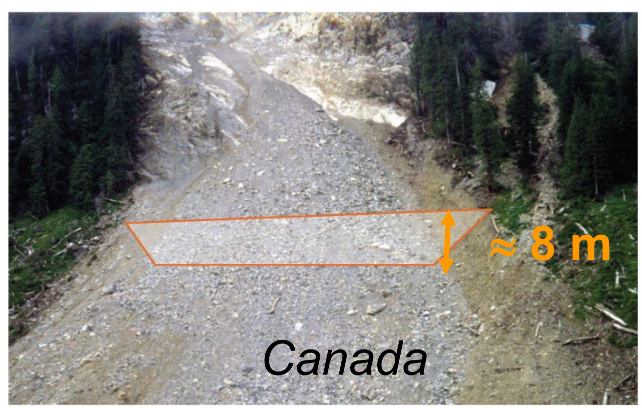
Fluidization (gas, air)



// snow avalanche



Erosion



// rivers, glaciers