Quel lien génétique entre écoulements et formes de paysages soumis à des changements de phase en ablation?

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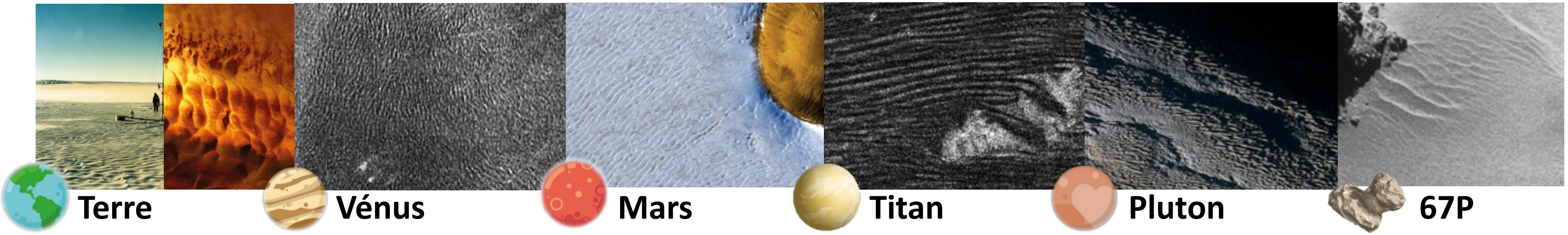
Introduction

Bedforms

motifs réguliers, périodiques qui se créent sous l'influence du milieu et du climat

=

Surfaces planétaires



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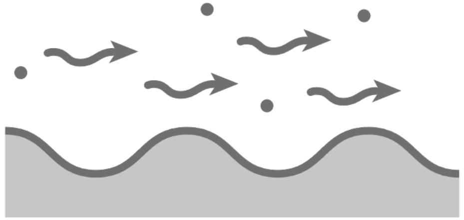
Écoulements



transport

gaz

liquides

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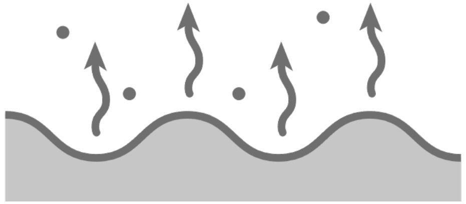
Transferts de matière

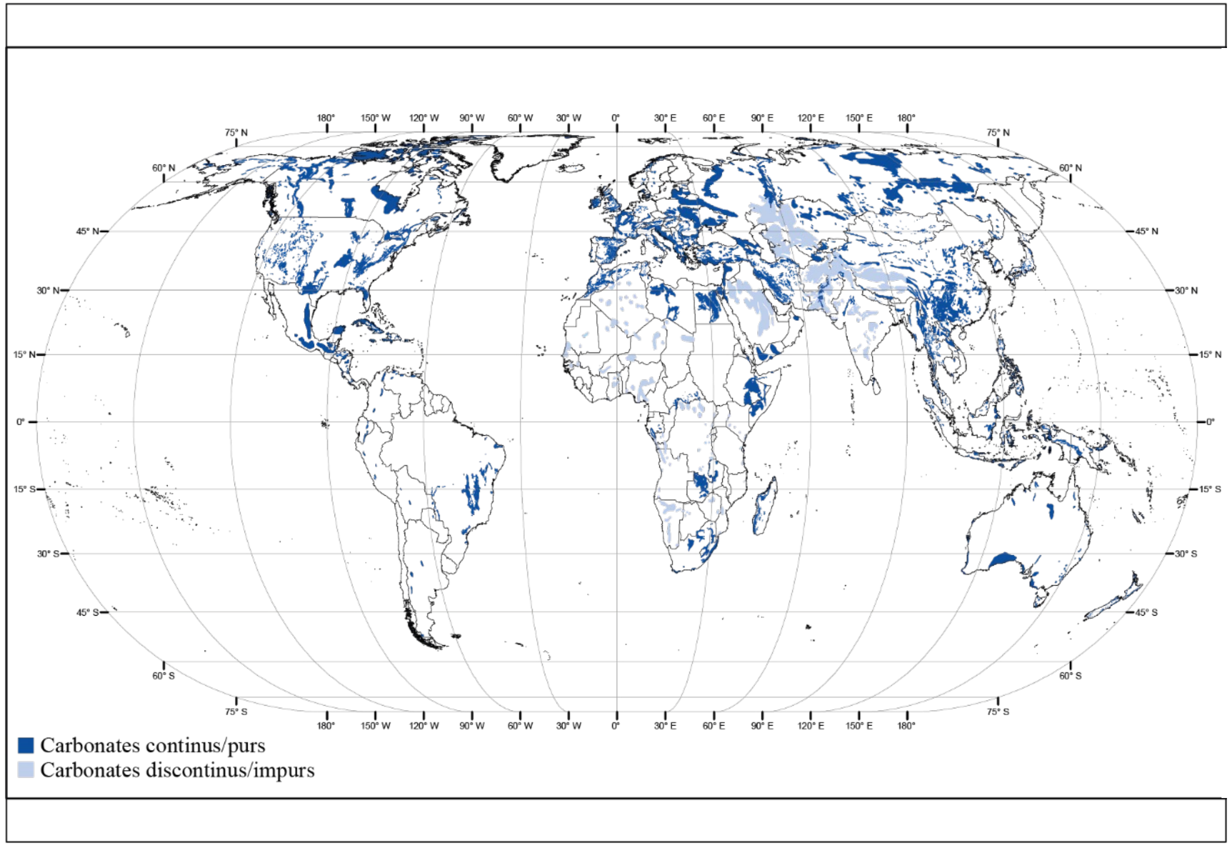


ablation

sublimation

fusion/dissolution

Chemical phase change : dissolution

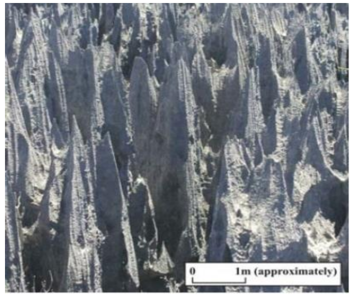


limestone $CaCO_3 + CO_2 + H_2O \Longleftrightarrow Ca^{2+} + 2HCO_3{}^-$

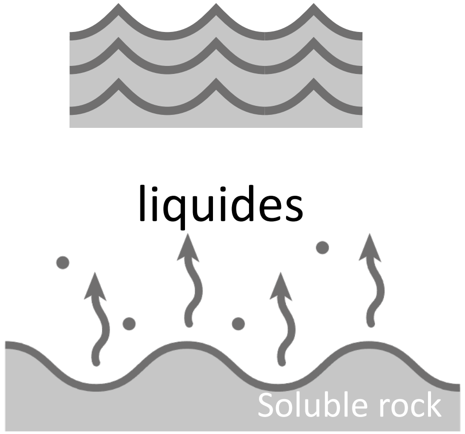
Chemical **Erosion** of rocks by dissolution when they are submitted to a water flow (rain, seepage …). Minerals often transported under an ionic form.
In general, combination of mechanical and chemical erosion.
Alteration or weathering: the rock is weakened chemically in a first step, then fragments are transported by the flow.

- ***Flutes*** in Limestone Cave

- Limestone Forest
Tsingy,
Malaysia and Madagascar
Very sharp topography (pinnacles), under action of tropical rainfalls.

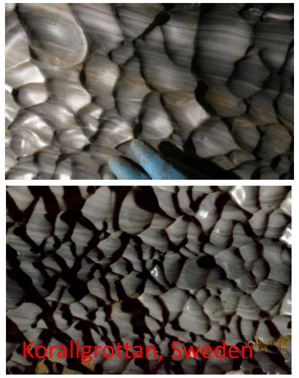


M. Veress, G. Tóth, Z. Zentai, R. Schläffer, **Carpathian Journal of Earth and Environmental Sciences**, **4**(1), 95 (2009) The Ankarana Tsingy and its development



ablation

Scallop patterns at a smaller scale

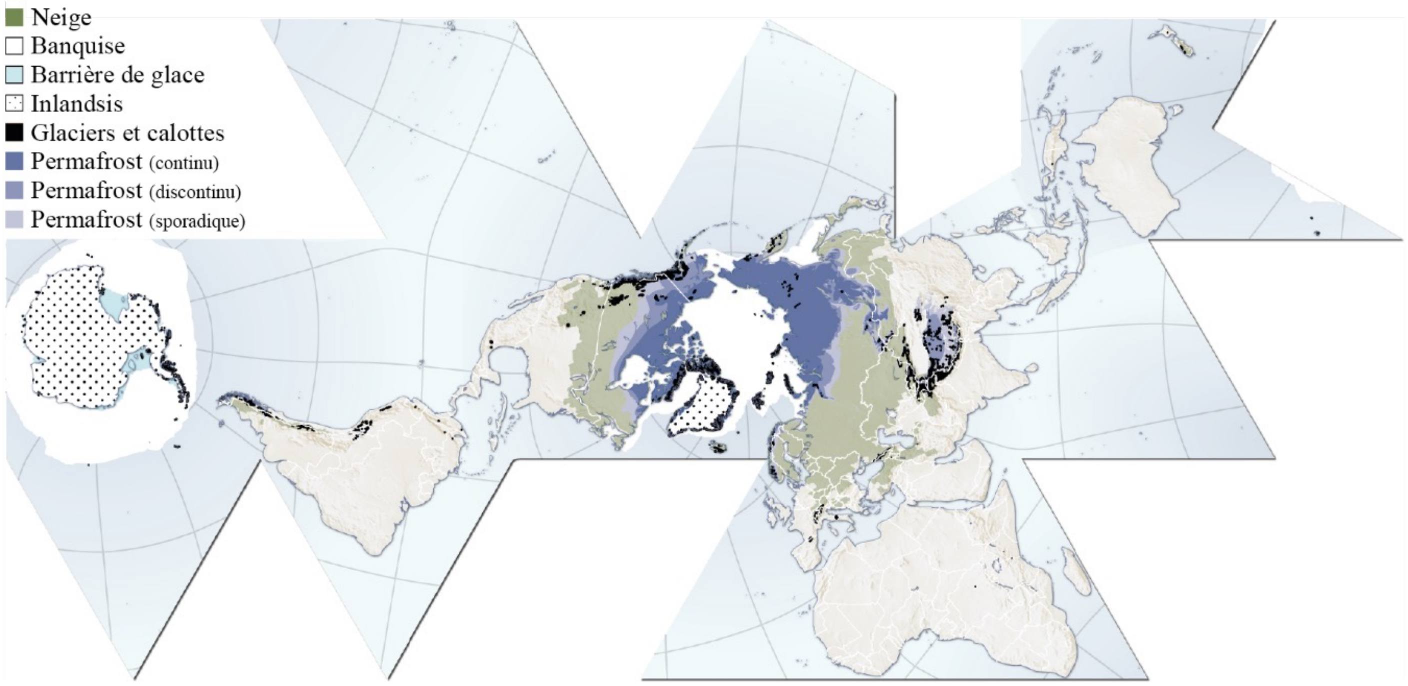


- **Limestone. Karst**. Groundwater flow

Producing an underground network.
Digging of caves by dissolution.
But at a smaller scale: characteristic shapes
Speleothems : stalactites …

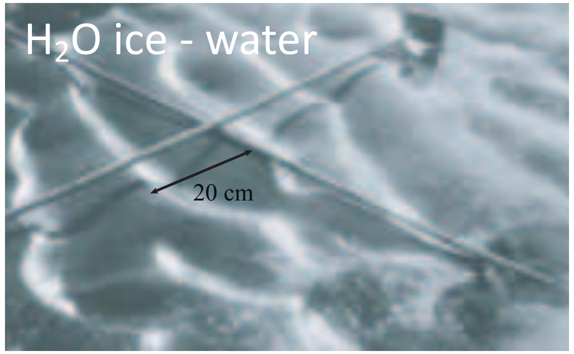
- Ondulation patterns on cave walls shaped by erosion: Scallops patterns

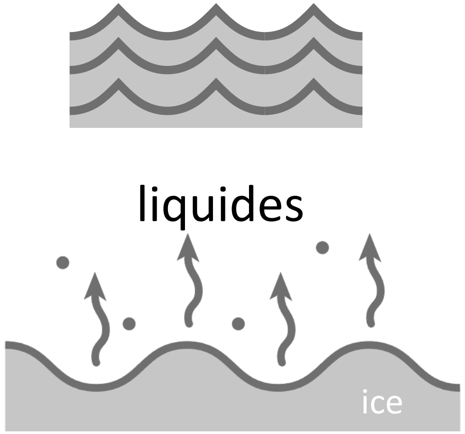
Physical phase change : fusion



Physical **Erosion** of ice by melting when they are submitted to a water flow (thin-film meltwater, shallow water or deep flow).
Melting temperature is determined by the Clapeyron relation but could depend on the liquidus/solidus if the substance is not pure.
The melting rate is determined by the thermal energy flux input.

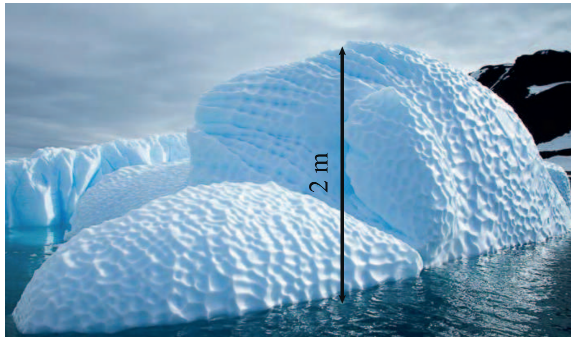
- Melting, Rivière St-Croix ice **ripples**, Wisconsin, USA





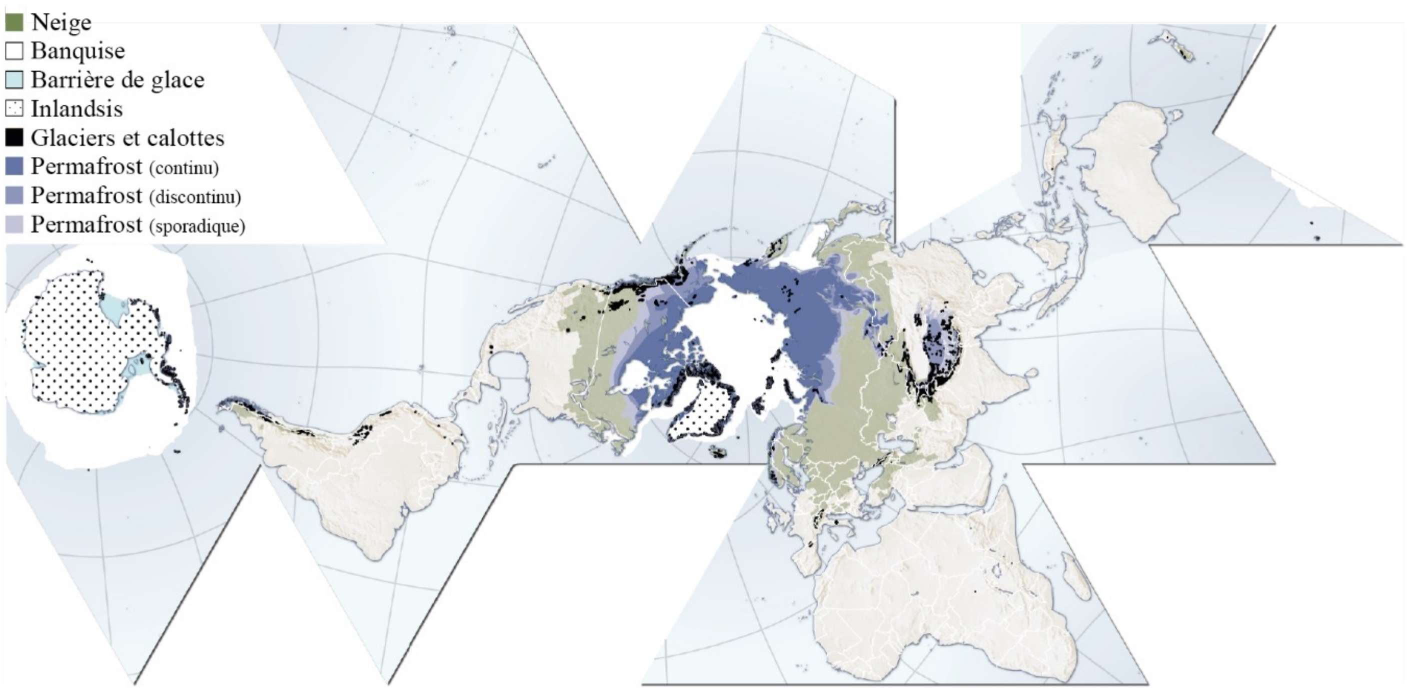
ablation

- ice **pinacles**, and **dirt cones**

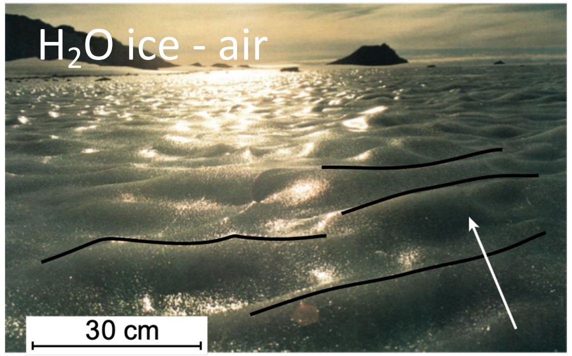


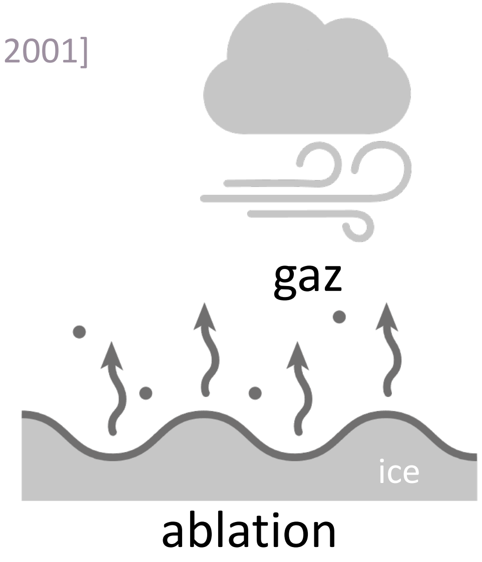
- Icy **Scallops** formed by fusion on an overturned iceberg, Paulet Island, Antarctique.

Physical phase change : sublimation on Earth



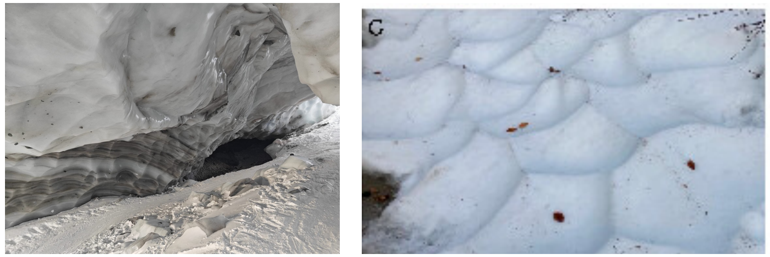
- Sublimating blue ice areas, [Bintanja, 2001] sublimation **waves**, Antarctica.





- ice **penitentes**

- Icy **scallops** and **flutes** formed by sublimation on ice tunnel walls, French Alpes and **sharp polygonal depression** on snow.



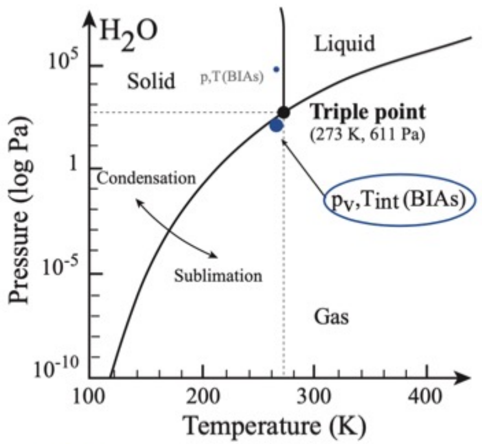
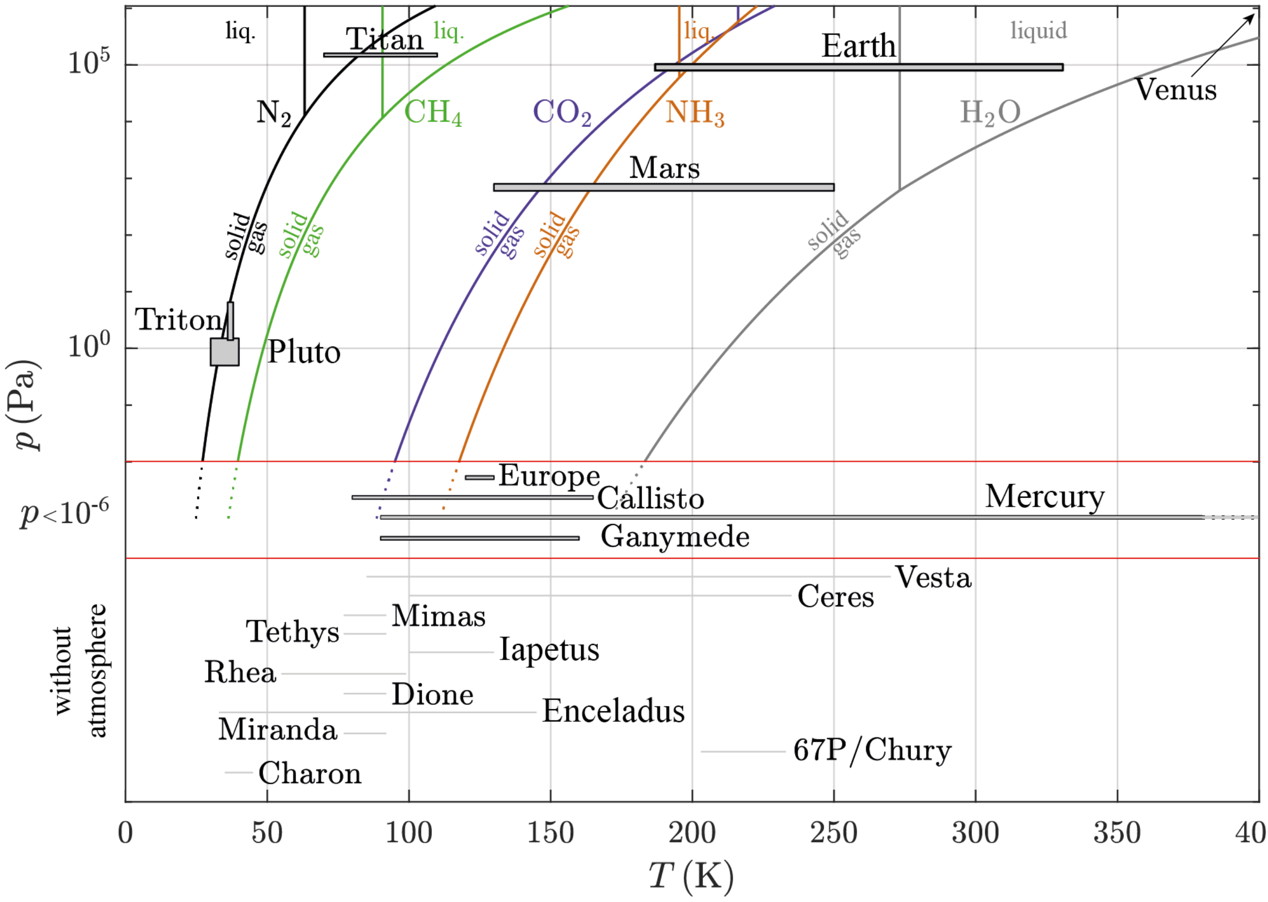


FIGURE – Phase diagram of H_2O

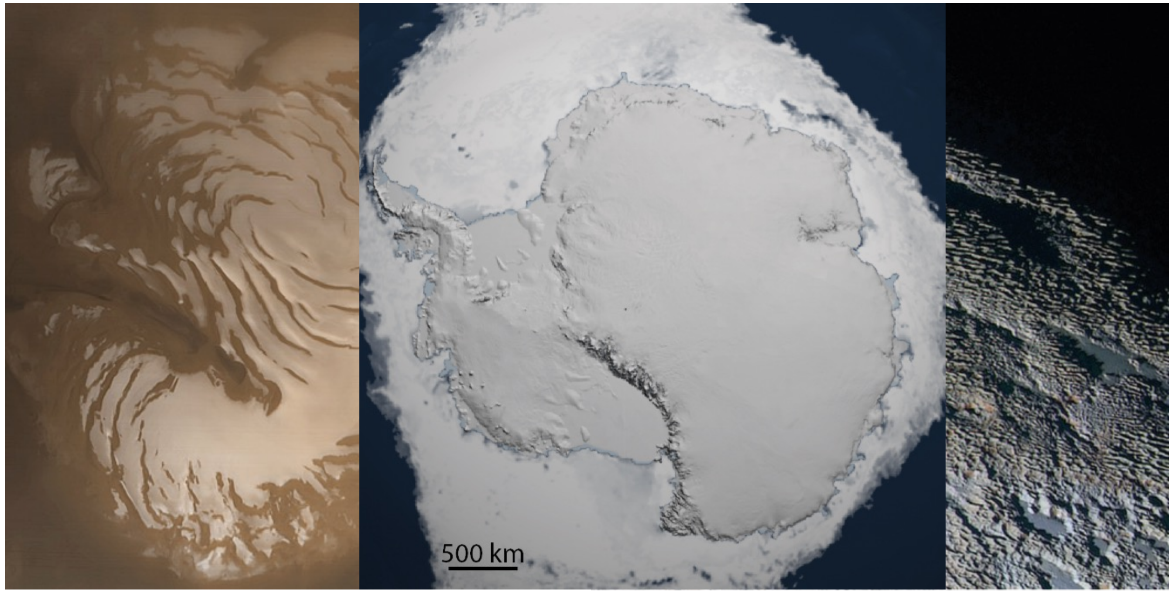
Physical **Erosion** of ice by sublimation when vapor ice diffuse in a carrier flow. Saturated pressure is determined by the Clapeyron relation. The ablation rate is determined by the difference between the vapor pressure and the saturated pressure.

Physical phase change : sublimation on planetary surfaces

→ Large occurrence of volatile ices in the Solar System



- On other planets and icy bodies: more effective
- On Earth: minor role except in Antarctica



Martian North Polar Cap *Bladed Terrain Deposits, Pluto*

[Howard, 2000 ; Smith et al, 2011] **[Moore et al (2017)]**

→ **Sublimation as landforms-shaping processes at <u>different scales on planetary bodies</u>**

Quel lien génétique entre la diversité des motifs et les écoulements ?

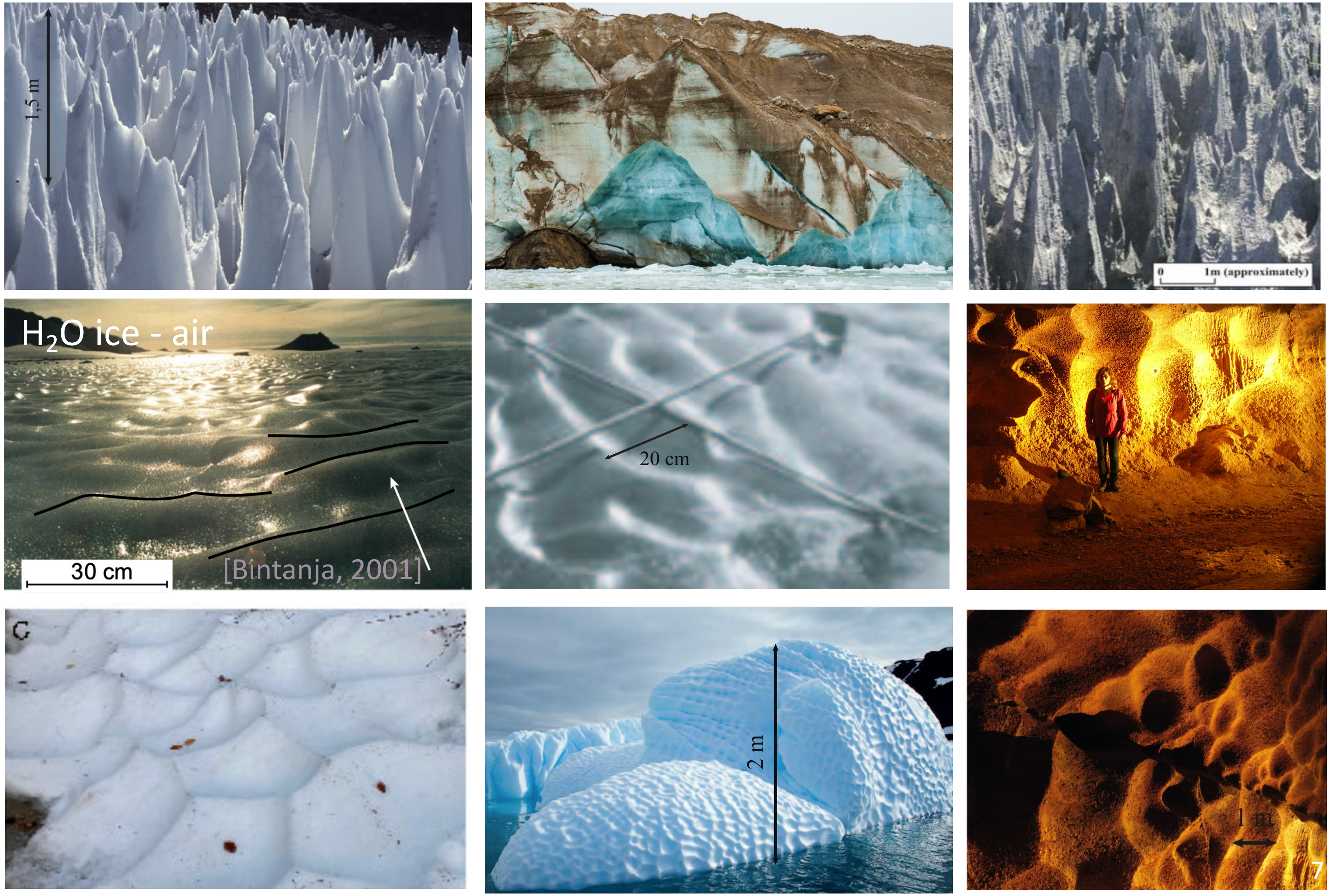
→ **Identifier et comprendre les *bedforms* solides pour en faire un outil de prédiction**

Diversité de

- formes et orientations
- dimensions
- environnements
- substrats
- types d'écoulement
- types de transfert

→ **Étudier leurs formes**

→ **Relier leurs caractéristiques morphologiques à celles de l'écoulement**



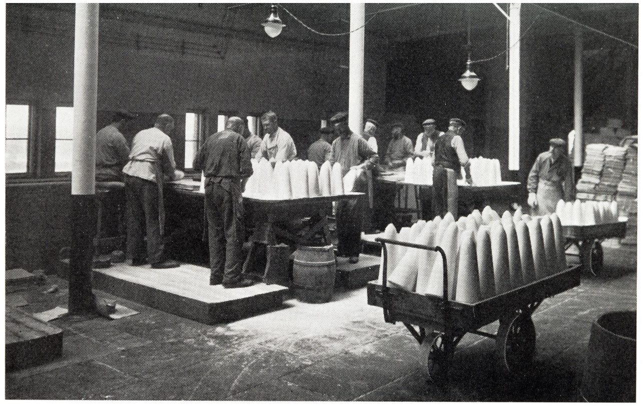
sublimation *fusion* *dissolution*

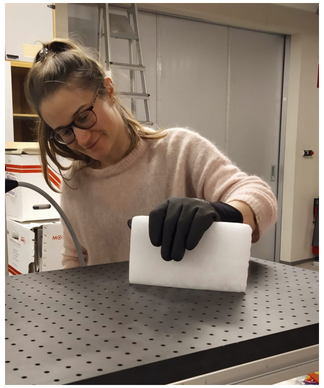
[Bintanja, 2001]

Quel lien génétique entre la diversité des motifs et les écoulements ?

→ **Dissolution, melting and sublimating patterns in experiments**

- Experiments usually consist of simply following
  the dissolution of a block of sugar (glucose, sucrose, or a mixture), salt (NaCl), or plaster,
  the melting of an icy block in a tank of water,
  the sublimation of a block of CO2 ice.





- We propose to classify experiments as a function of the external forcing and boundary conditions

→ **Do they modify the coupling processes that drive pattern formation ?**

Quel lien génétique entre la diversité des motifs et les écoulements ?

⟶ **External forcing and boundary conditions**

1. Buoyancy driven flow

- ⇒ Stable density stratification
- ⇒ Unstable density stratification

2. Externally driven flow

- ⇒ Deep flow
- ⇒ Free surface flow

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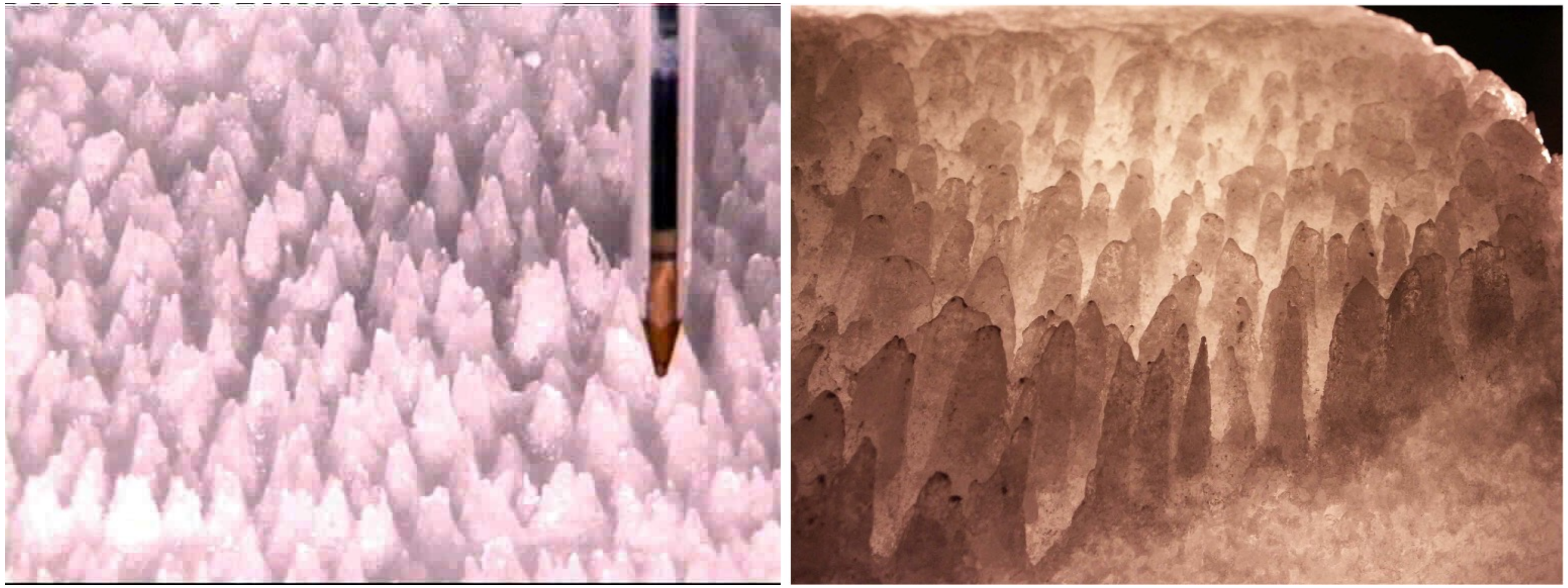
Boundary conditions: pattern formation stimulated by radiation

Penitentes in the field



Penitentes in a laboratory scale experiment (from Bergeron *et al.* [165])

=> self-illumination of the surface-a scale-free process-
+ modulation in albedo
BUT primarily controlled by vapor diffusion and heat conduction.

- $\Rightarrow$ No formation over -4°C
- $\Rightarrow$ Need of sufficient differential concentration ($p_{H2O} - p_{sat}$)
- $\Rightarrow$ No formation with wind greater than 2.5 m/s

=> Aerodynamic mixing of vapor above the ice surface ?

Scaling law suggested by [Claudin et al., 2015]

$$\lambda \simeq 2\pi \frac{\mathcal{P}^{2/3}}{\Omega^{1/3}} \ell \qquad \ell = 5 \frac{\nu}{u_*} \qquad \mathcal{P} = \frac{\kappa_s}{\rho'_{\mathrm{sat}} D \Delta H_{\mathrm{sub}}}$$

=> Buoyancy-driven vapor flow ?

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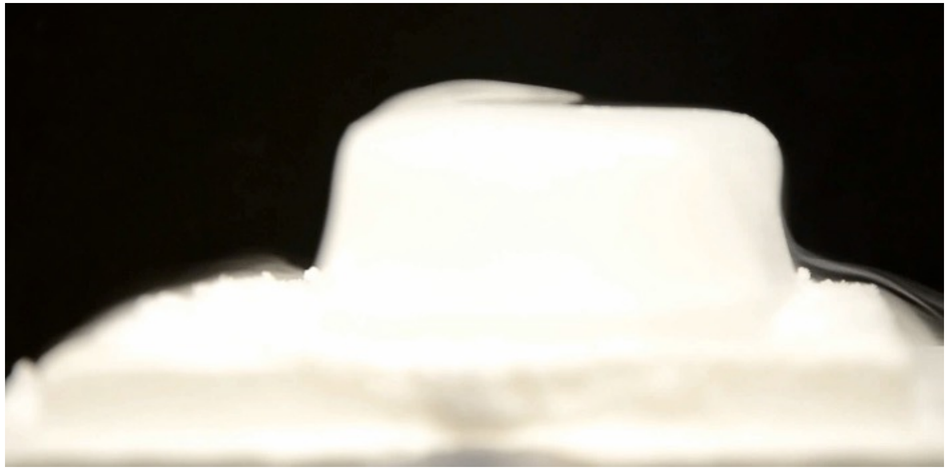

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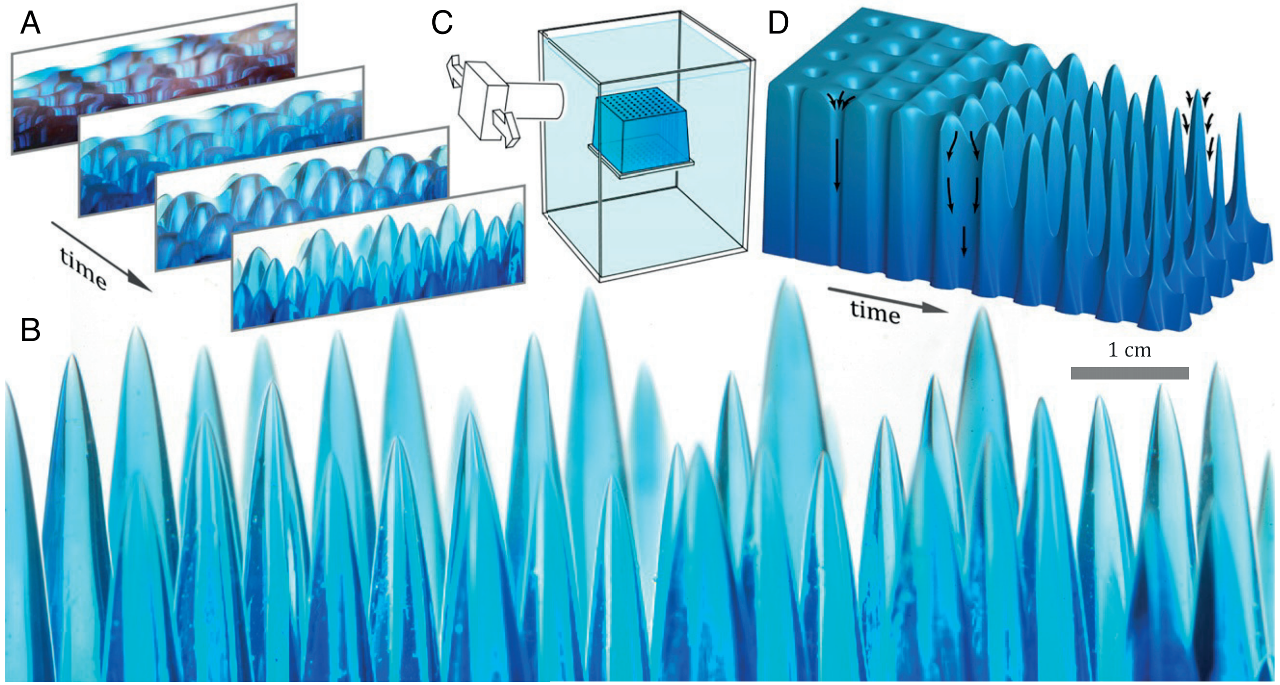
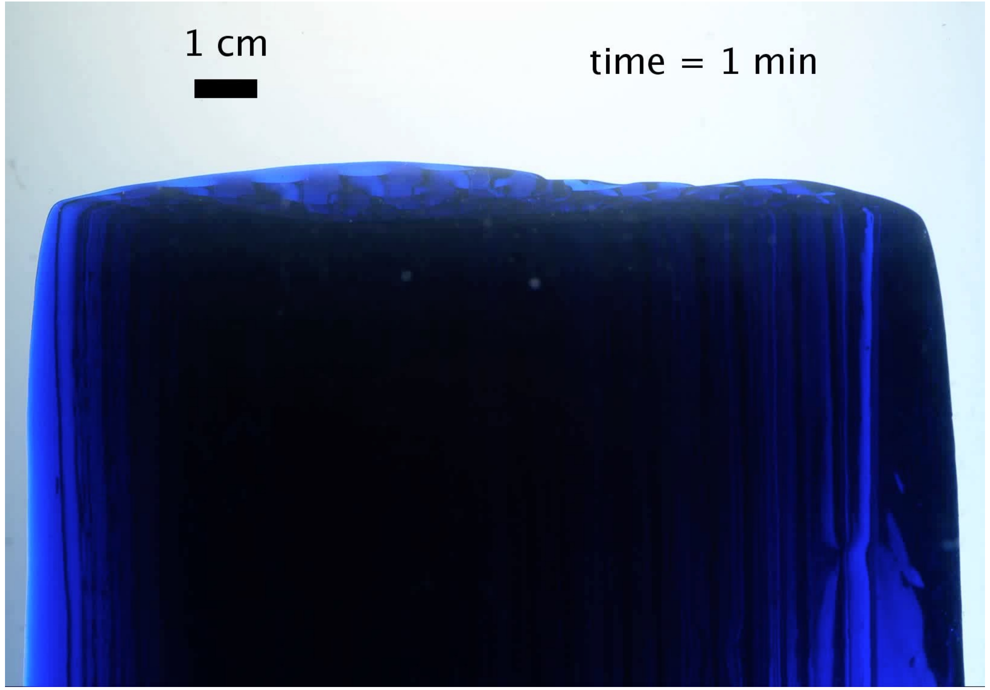
Stable density stratification: dissolution of candy cone in quiescent water

Bed-of-nails morphology from dissolution of a porous solid: Experimental schematic and interpretive schematic showing shape progression and expected flow structure.

[Huang *et al.*, PNAS, 2020]

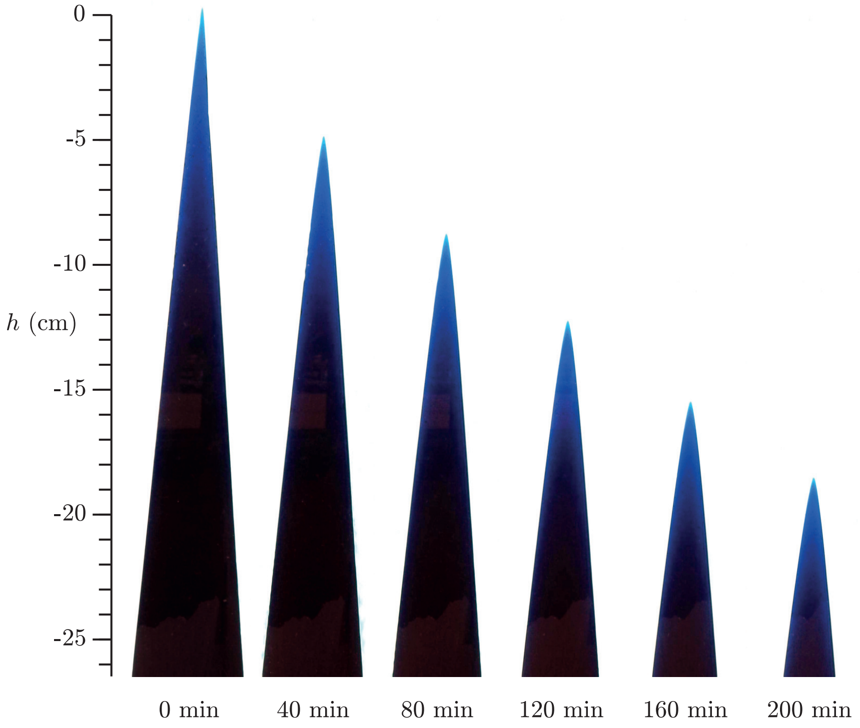




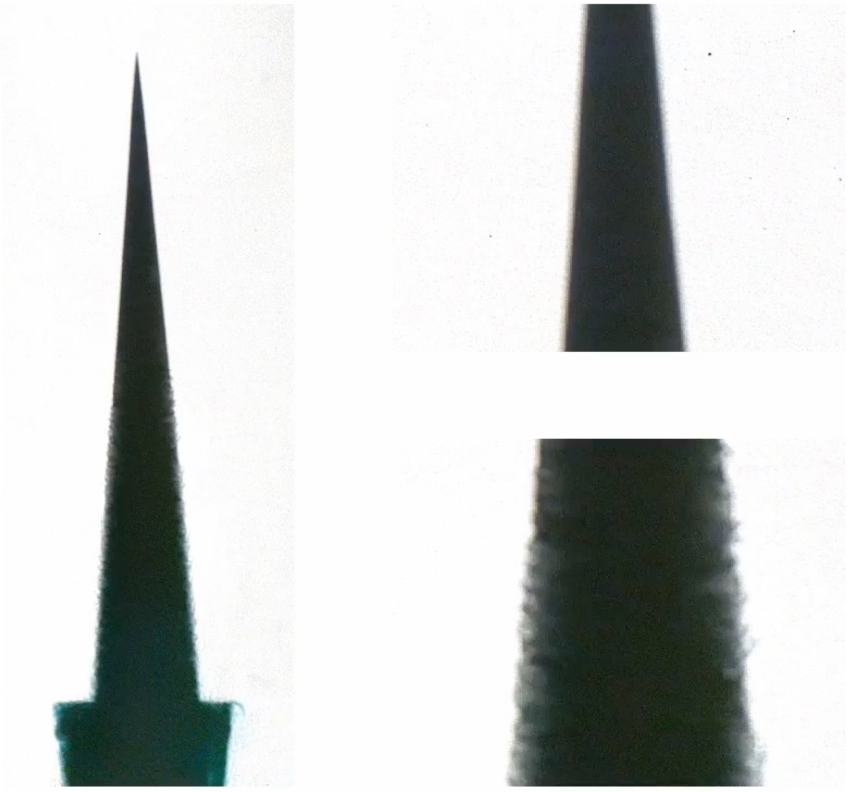
A block seeded with vertical pores dissolves and form an array of sharp pinnacles

- Temporal progression: The openings widen and develop into rounded hills, which then steepen into pillars.
- The pillars sharpen to form an array of pinnacles.

Stable density stratification: dissolution of candy cone in quiescent water

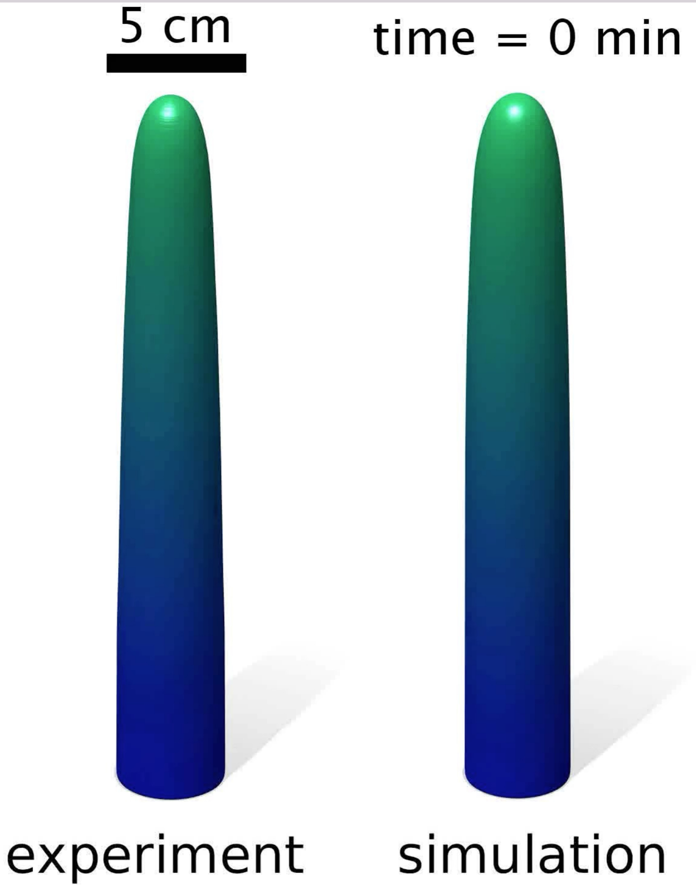


Dissolution of a candy cone at 40 min intervals, illustrating the descent of the tip.
The candy cone slowly blunts with time and receding velocity slowly decreases with time.



[Pegler & Davies Wykes, JFM, 2020]

Shadowgraph image of dissolving candy cone.
=> laminar & turbulent regions.



[Huang *et al.*, PNAS, 2020]

=> Evolution from cone to tip singularities.

These 2 experiments show that an initial upright cylinder sharpens with time while receding (right) whereas an initial cone blunts with time (left) **=> the erosion dynamics depends on the initial shape.**

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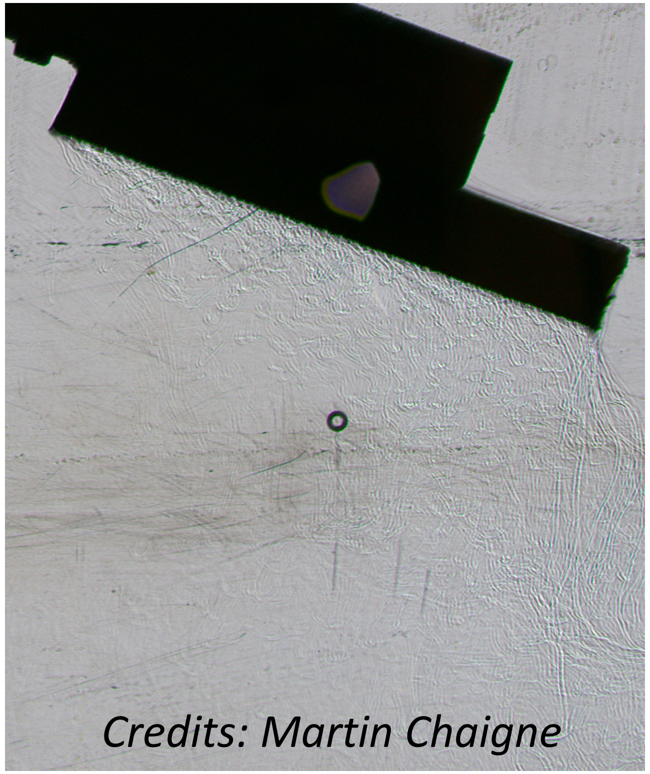
⟶ **External forcing and boundary conditions**

1. Buoyancy driven flow

⇒ Stable density stratification

⇒ Unstable density stratification



Credits: Martin Chaigne

2. Externally driven flow

⇒ Deep flow

⇒ Free surface flow

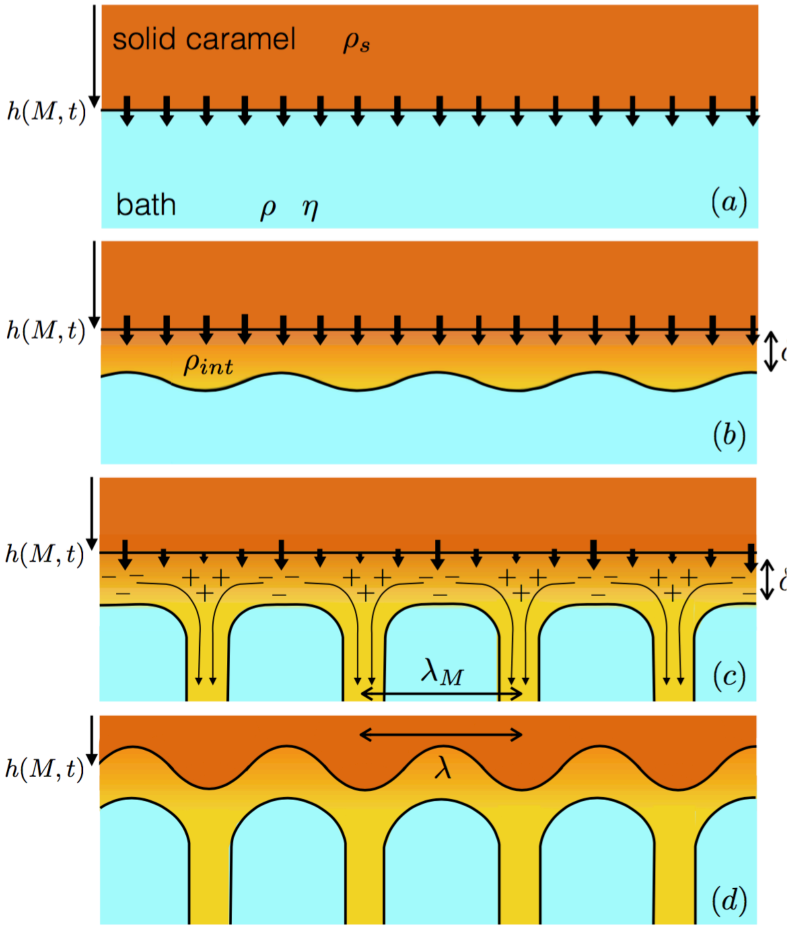
Unstable density stratification: a solutal Rayleigh-Bénard instability

Rayleigh-Taylor instability of a thin film
After Brown, Physics of fluid A,1989 –
Kerr and Lister, JFM, 1989

The film is unstable when the gravity overcomes the diffusion to transport the dissolved concentration

Because the solute front diffuses, the base state depends on time

It can also be seen as a Rayleigh-Taylor instability of a thin film whose thickness depends on a balance between gravity and diffusion

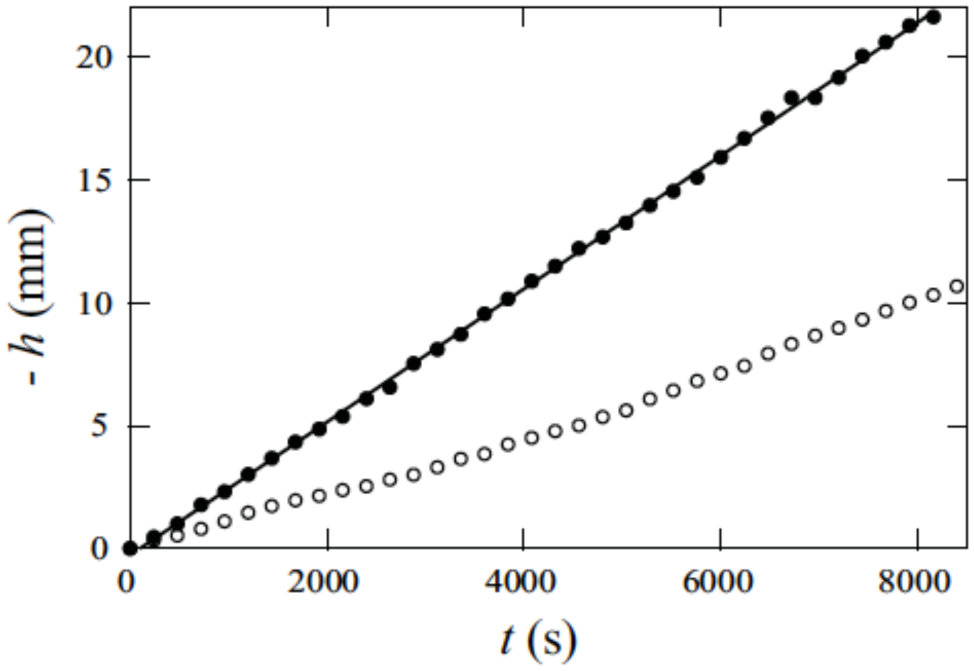


Sketch of the first steps of the solutal Rayleigh-Bénard instability in a transverse plane and its imprint on the block (from Cohen *et al. 2020)*

Unstable density stratification: scalloped patterns

Receding velocity

Caramel block (6 cm) in water, θ = 60°



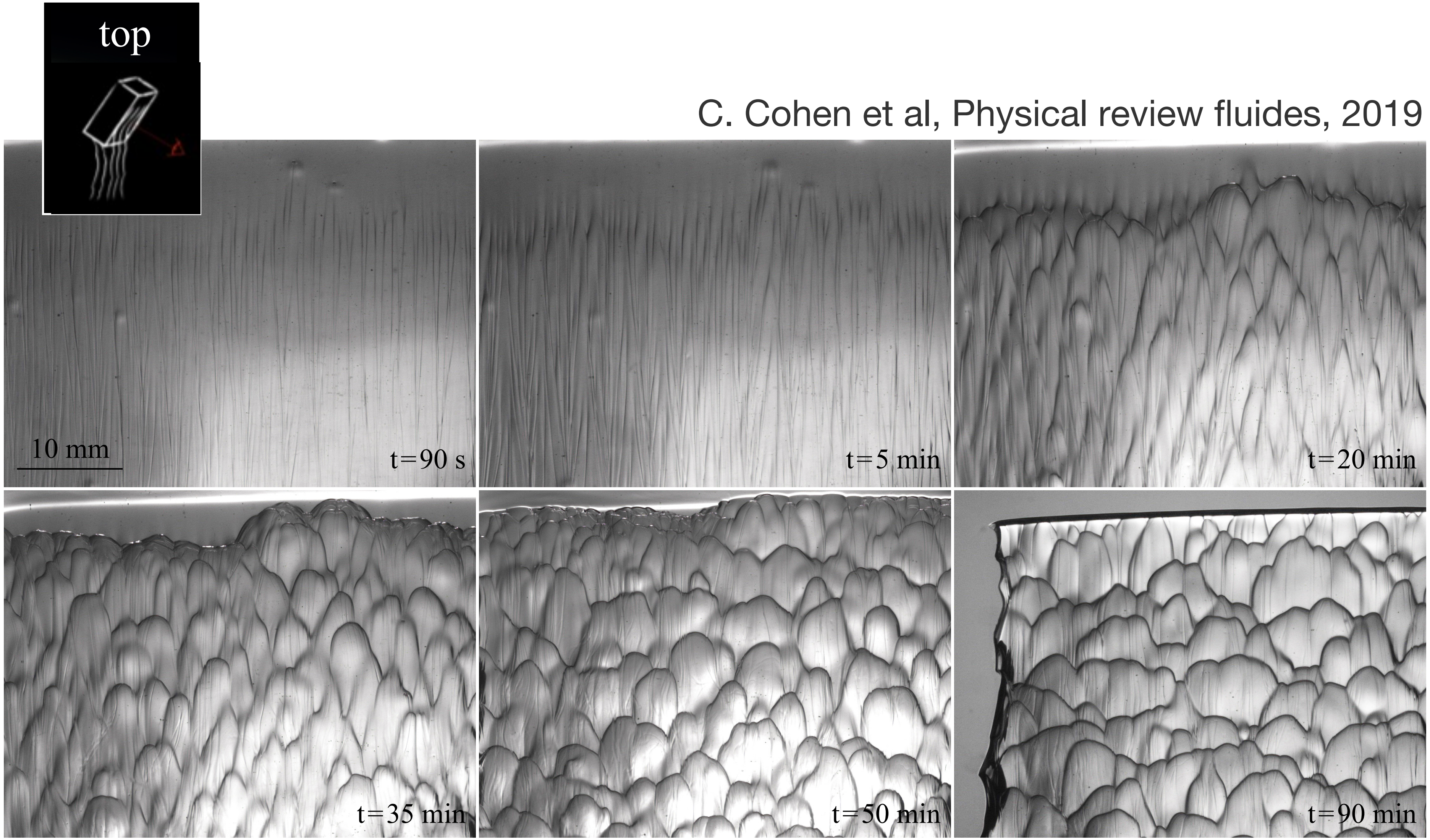
● Bottom interface $\dot{h} = -2,8.10^{-3}$ mm/s

○ Upper interface

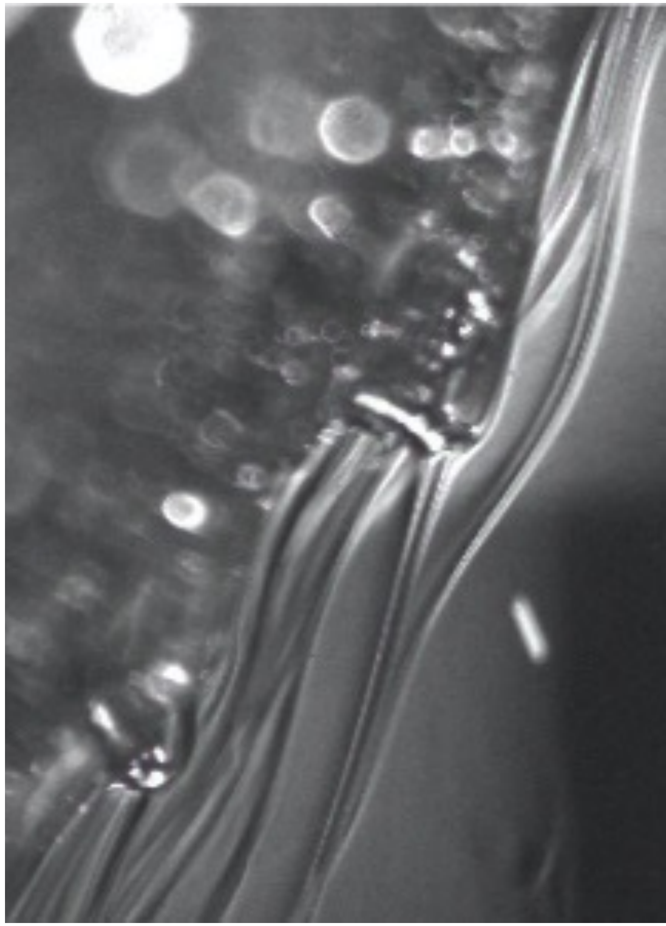
side view 120 x

Cohen, C., Berhanu, M., Derr, J., & Du Pont, S. C. (2020). Buoyancy-driven dissolution of inclined blocks: Erosion rate and pattern formation. *Physical Review Fluids*, *5*(5), 053802.

Unstable density stratification: dissolution pattern



C. Cohen et al, Physical review fluides, 2019



Patterns observed underneath an inclined block of solid caramel dissolving in water, $\theta = 60°$.

Black lines depict the sharp slopes. After a few seconds: λ=0,4mm. After 1 hour 7,6 x 6,3 mm, $v \approx 3.10-3$ mm/s

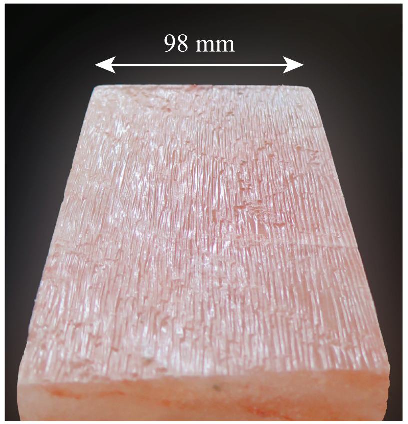
Fingerprints of flows on planetary surfaces subject to phase changes

S.Carpy, LPG, Nantes Université

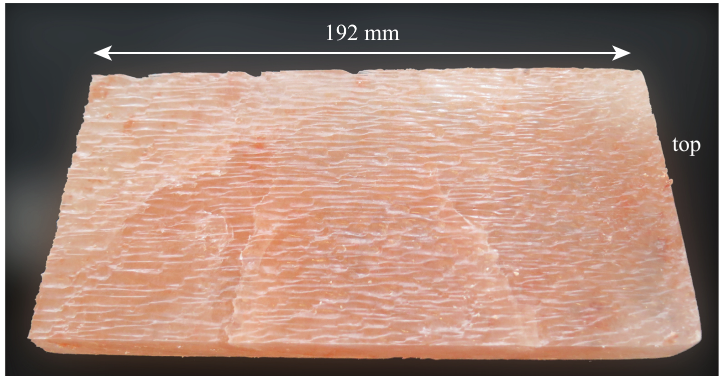
Unstable density stratification: scalloped patterns

a) 5 min.

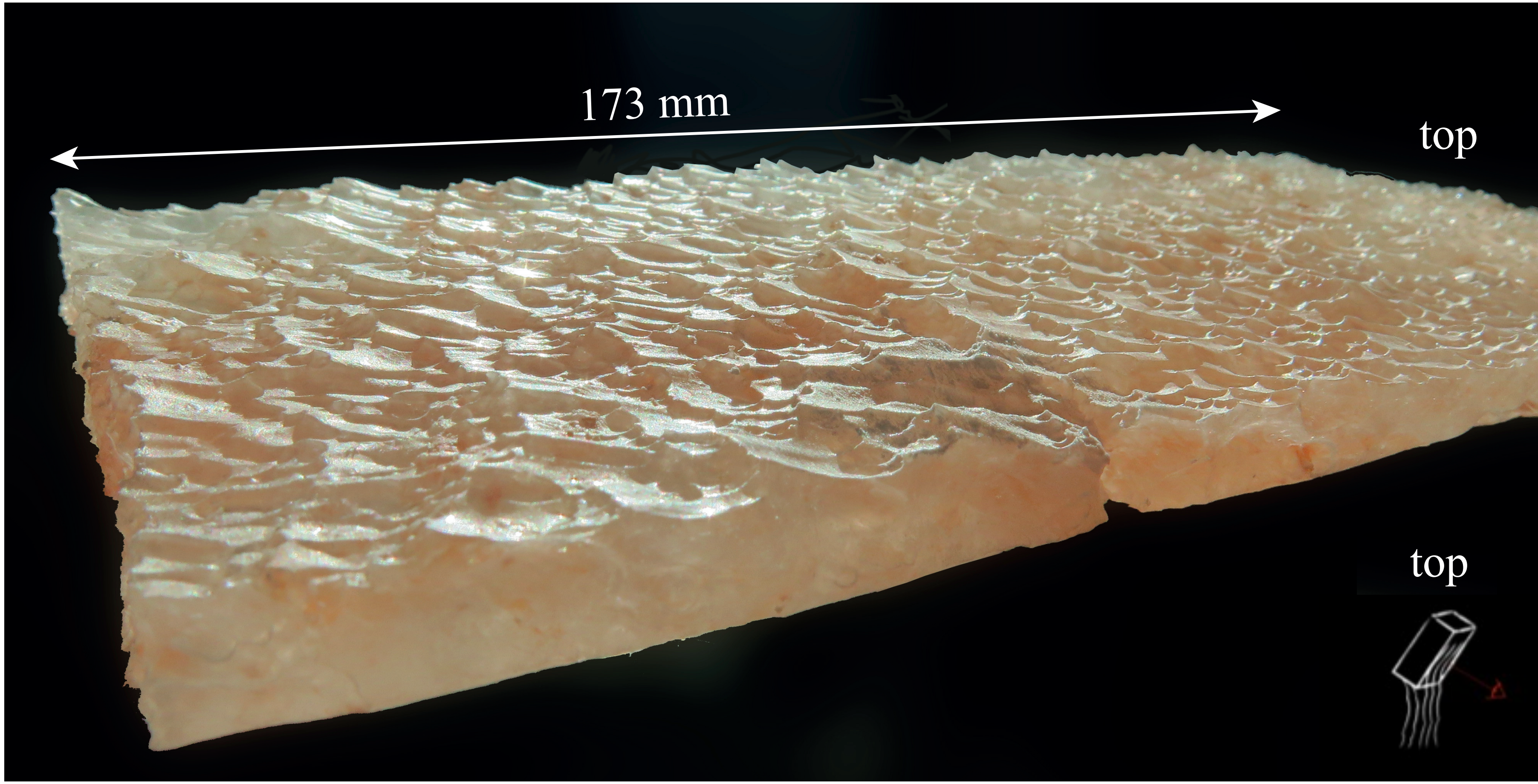
b) 10min.

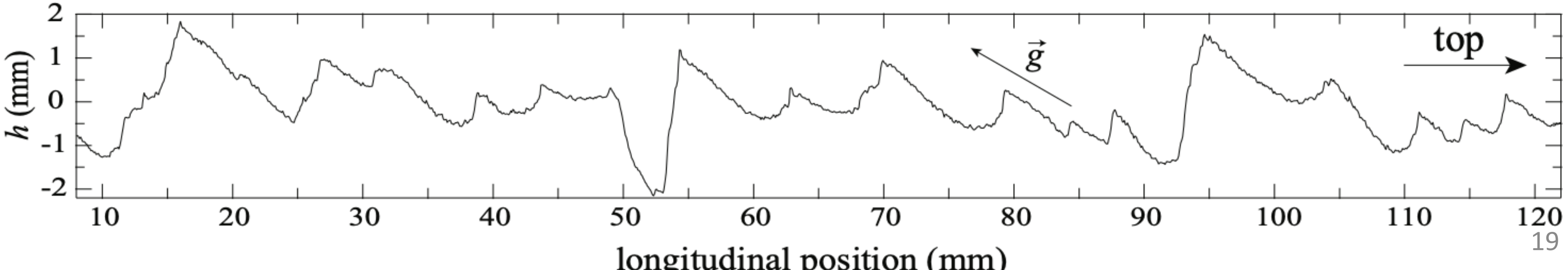


c) 20 min.



d) after 1 hour



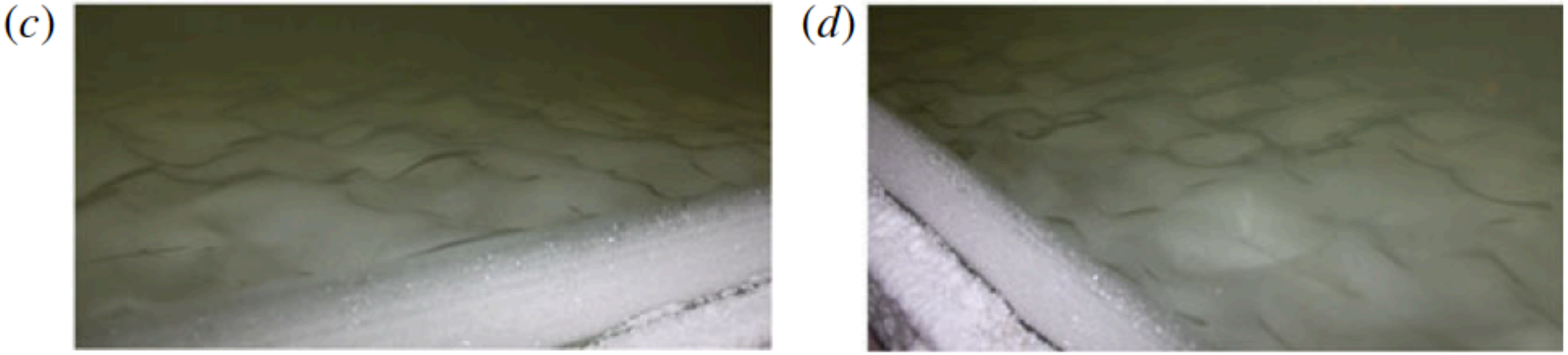


Pattern on block of salt

Salt block, water, θ = 60°

Unstable density stratification: experiments of Rayleigh-Bénard convection with a melting boundary

Ice scallops in the lab



(Bushuk et al.,
Journal of Fluid Mechanics, 2019)

Wavelength barely changes
from initiation to steady state

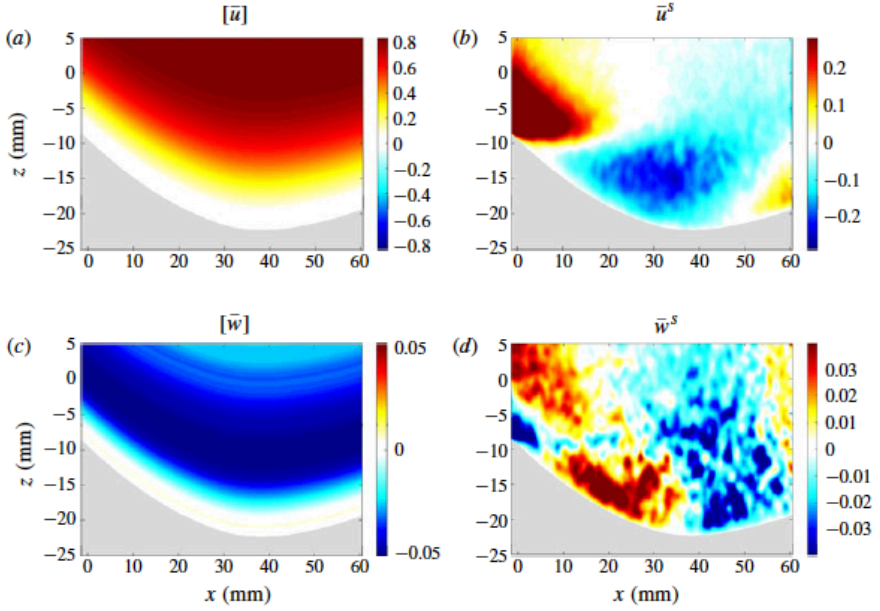


FIGURE 7. Decomposition of the time-mean scallop flow into an along-flow mean, ($[\bar{u}]$, $[\bar{w}]$), and a standing eddy component, ($\bar{u}^S$, $\bar{w}^S$). These data are from experiment 3.

Scallops in cave:

$$\mathrm{Re}_* = \frac{U\lambda}{\nu} \approx 22500$$

(Curl, Trans. Cave Res. Group,1966)

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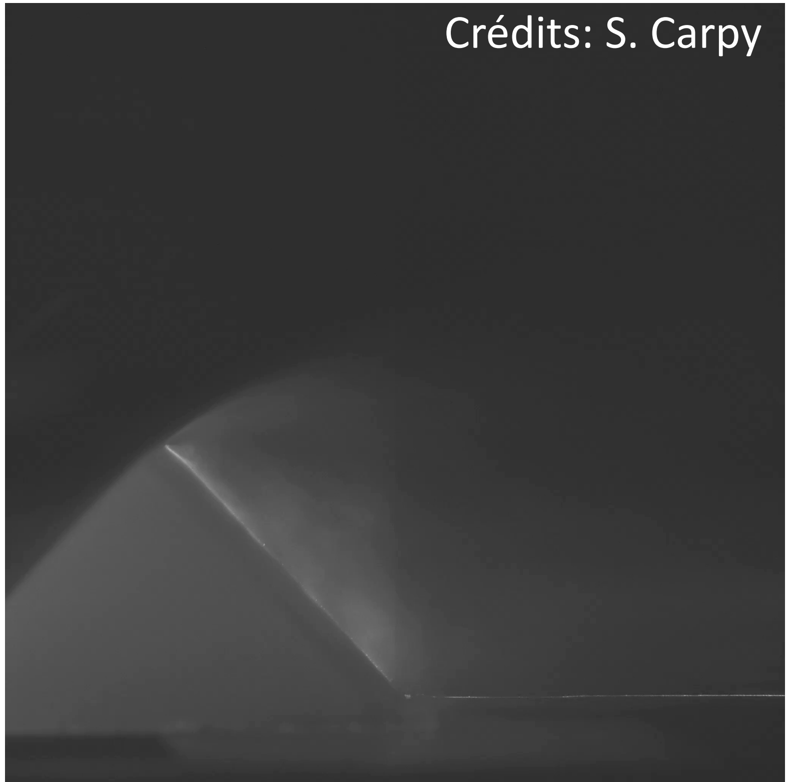

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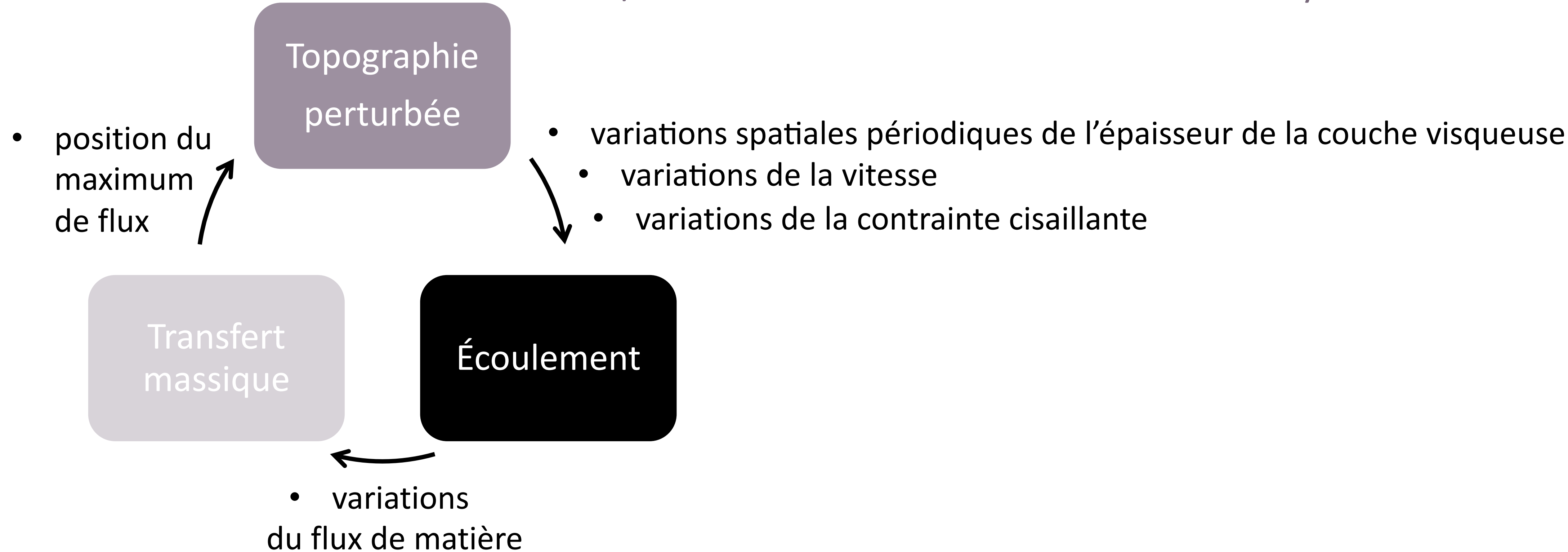
Modelling

[Bordiec, Carpy *et al.*, Earth Sciences Review, 2020]

- Can the combined effects of winds and sublimation/condensation lead to the formation of wavy bedforms ?



Topographie perturbée

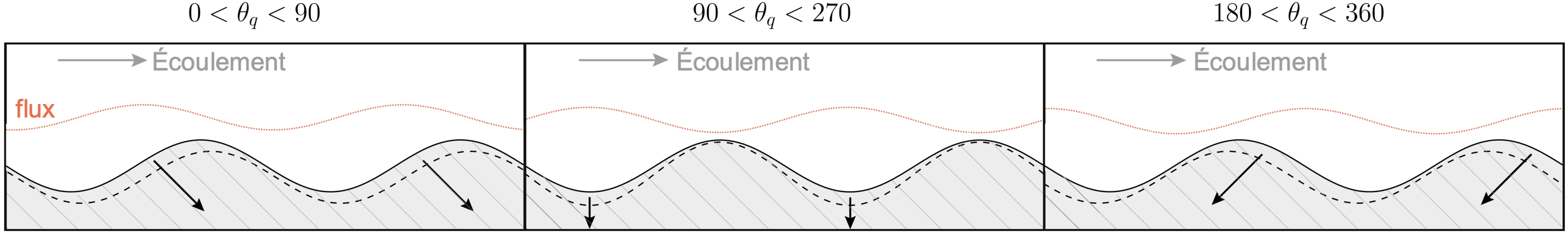
- variations spatiales périodiques de l’épaisseur de la couche visqueuse
  - variations de la vitesse
    - variations de la contrainte cisaillante

Écoulement

- variations du flux de matière

Transfert massique

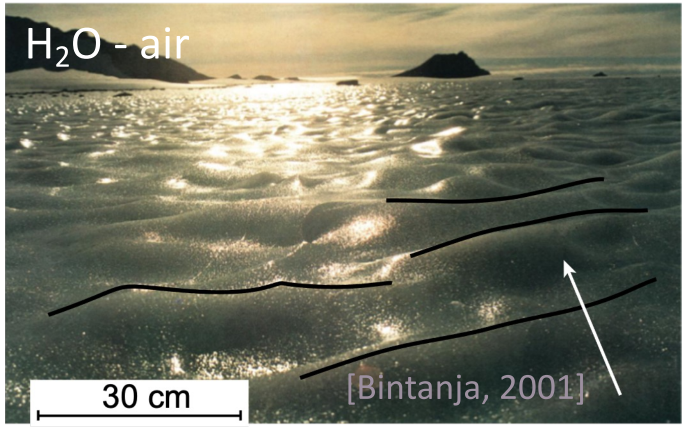
- position du maximum de flux



Terrestrial natural exemples : ice caves in Austria

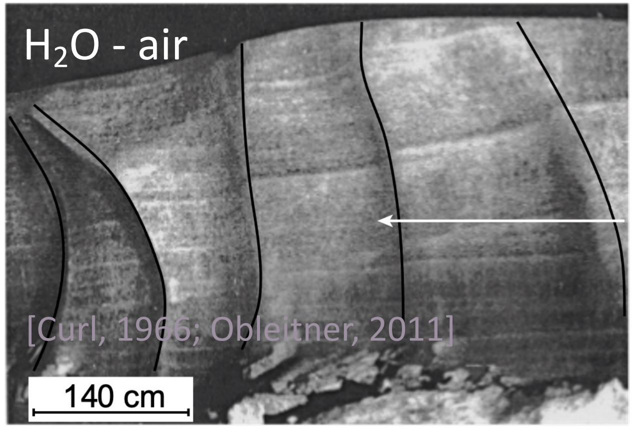
[Bordiec, Carpy *et al.*, Earth Sciences Review, 2020]

- Zone de Glace Bleue (ZGB) de *Svea,* Antarctique



[Bintanja, 2001]

- Grotte de glace *Eisriesenwelt,* Autriche



[Curl, 1966; Obleitner, 2011]

Environnement

Svea :

- ○ $T_{\text{int}} \sim 266\ \text{K}$
- ○ Humidité $RH = 30 - 50\%$
- ○ **Vents turbulents (vitesse $\boldsymbol{U \sim 2,4\ \text{m.s}^{-1}}$)**

→ **Sublimation annuelle nette**

Eisriesenwelt :

- ○ $T_{\text{int}} \sim 272\ \text{K}$
- ○ Humidité $RH = 97\%$
- ○ **Vents turbulents (vitesse $\boldsymbol{U \sim 0,2\ \text{m.s}^{-1}}$)**

→ **Sublimation (hiver)**

Morpho.
Cinétique

- ○ $\lambda \sim 22\ \text{cm et } 2\zeta_0 \sim 1 - 2\ \text{cm}$
- ○ $v \sim 1{,}5\ \text{cm.mois}^{-1}$ dans le sens du vent

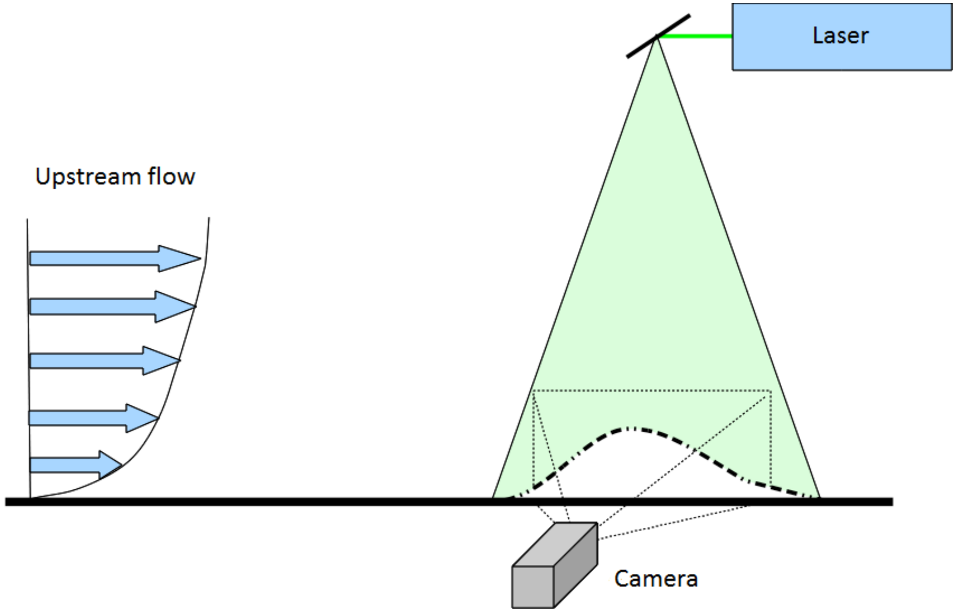
- ○ $\lambda \sim 1{,}4\ \text{m et } 2\zeta_0 \sim 0{,}3\ \text{m}$
- ○ v mentionnée mais non mesurée

Wind tunnel experiment : sublimation of CO_2 ice

[Bordiec, Carpy *et al.*, Earth Sciences Review, 2020]

L'action couplée du vent et de la sublimation /condensation peut-elle jouer un rôle géomorphologique ?

Soufflerie atmosphérique [LHEEA] (section = 2m x 2m, longueur = 20m)



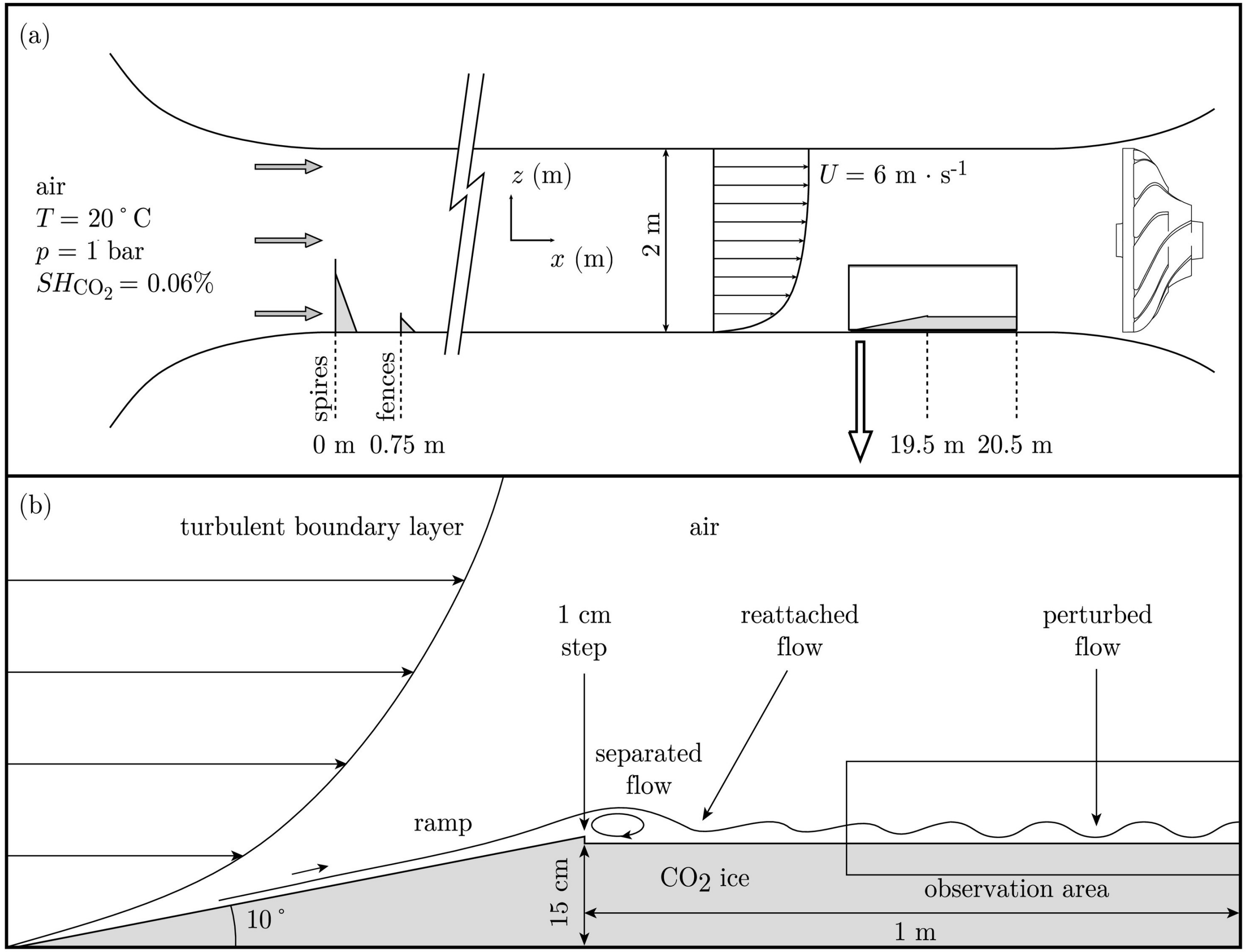
Principe du dispositif expérimental

Glace de CO_2 → Sublimation aux conditions de pression et température terrestres (T [1 bar] ≈ - 75°C)

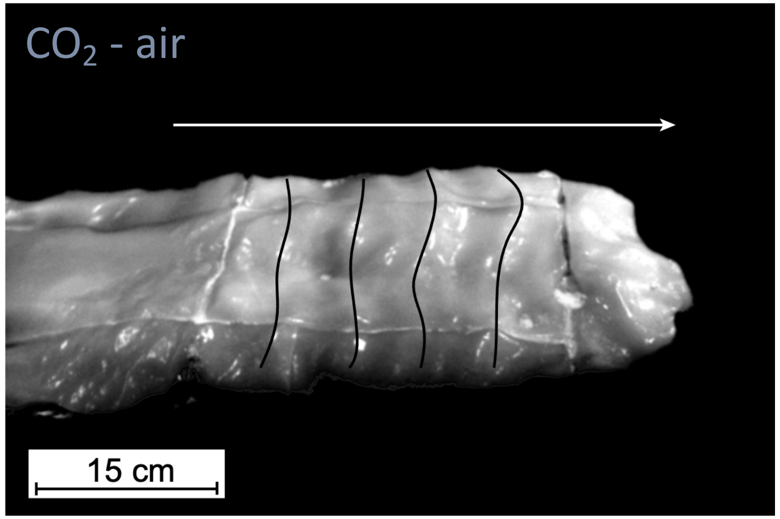
Wind tunnel experiment : sublimation of CO_2 ice

[Bordiec, Carpy *et al.*, Earth Sciences Review, 2020]

- Could analogical experiments be reproduced in a controlled environement ?



Atmospheric wind tunnel 2x2x20 m (LHEEA, Nantes)



Lab. Experiments on CO2
[Herny, 2014]

Environnement

Tint ~198K
Humidity RH = 20%
Turbulent winds ~6 m/s
-> net sublimation

kinetics

λ ~6.5 cm and $2\zeta_0$ ~1 cm
v ~ not observed

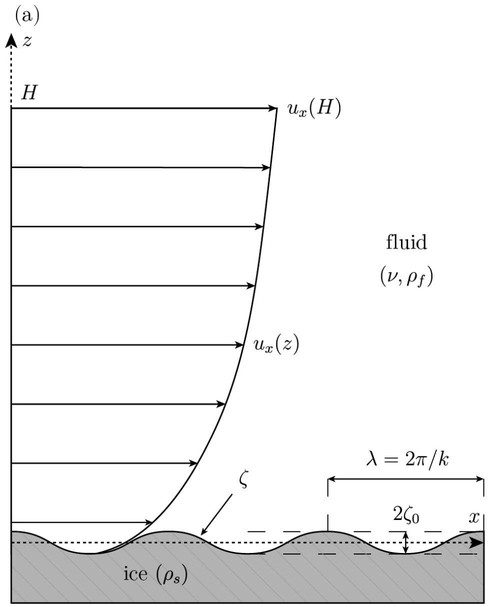
Fingerprints of flows on planetary surfaces subject to phase changes

S.Carpy, LPG, Nantes Université

Modelling

[Bordiec, Carpy *et al.*, Earth Sciences Review, 2020]

- Can the combined effects of winds and sublimation/condensation lead to the formation of solid bedforms ?



- Flow dynamics (Navier-Stokes) $\partial_i u_i = 0$

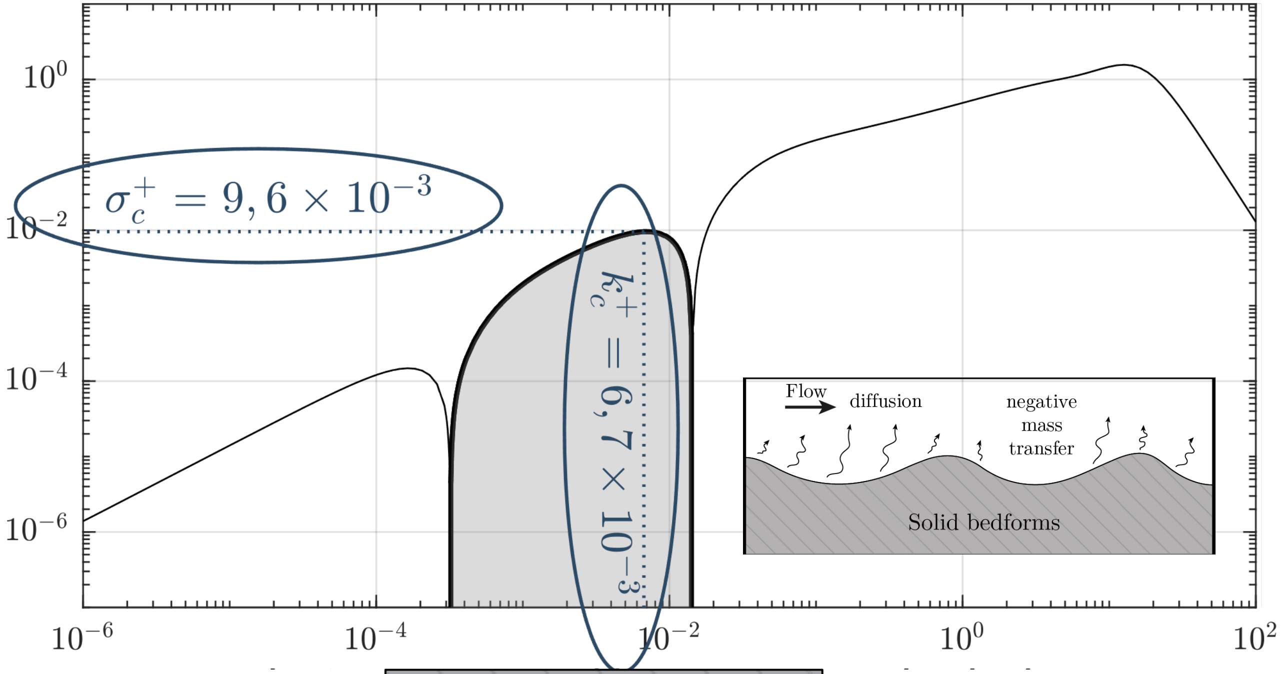
$$\rho_f\Big(\partial_t u_i + u_j \partial_j u_i\Big) = \partial_j\Big(-p\delta_{ij} + \mu\big(\partial_j u_i + \partial_i u_j\big)\Big)$$

- Mass transfer (advection-diffusion) $\partial_t c + u_i \partial_i c + \partial_i q_i = 0$

$$q_i = -D\partial_i c$$

- Turbulence modeling
  - Statistical turbulence modeling (RANS method)
  - Eddy viscosity type of closure + Modified mixing length **[Loyd, 1970; Hanratty, 1981]**

- Temporal stability of the system subject to small disturbances ($k\zeta_0$) as in **[Claudin, 2017]** $\zeta(x,t) = \zeta_0 e^{\sigma t}\Re\big(e^{i(kx+\omega t)}\big)$



$$\lambda = \frac{\nu}{u_*}\frac{2\pi}{6.7 \times 10^{-3}}$$

[Bordiec et al, 2020]

Wind+mass transfert produce bedforms

- Can the combined effects of winds and sublimation/condensation lead to the formation of solid bedforms ?

Relation de dispersion

→ Objectif : évolution temporelle du profil topographique

$$\zeta(x,t) = \zeta_0 e^{\sigma t}\Re\left(e^{i(kx+\omega t)}\right)$$

σ taux de croissance associé à k et à la pulsation ω

↓

Relation de dispersion : $D(k,\omega,\sigma) = 0$

- Profil
  $\zeta(x,t) = \zeta_0 e^{\sigma t}\Re\left(e^{i(kx+\omega t)}\right)$
- Décomposition du flux
  $q_z = q^0\left[1 - Qk\zeta\right]$
- Évolution de l'interface
  $\rho_s \dfrac{d\zeta}{dt} = \pm q_z(\zeta) + q^0$

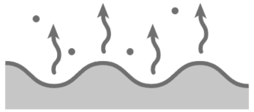
Relation de dispersion

$$\sigma + i\omega = \pm\frac{q^0}{\rho_s}kQ(0)$$

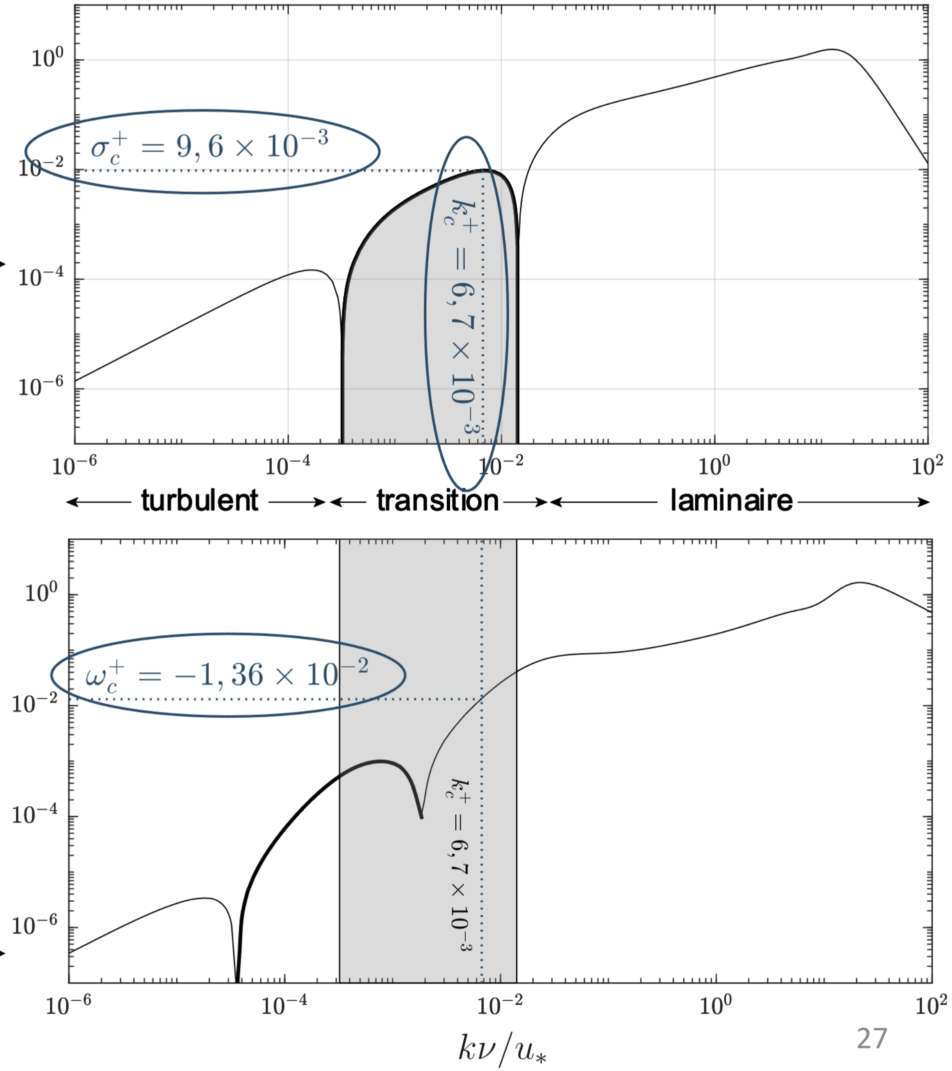
$$\sigma = \pm\frac{q^0}{\rho_s}k|Q(0)|\cos\theta_q \qquad \sigma^+ = \pm\sigma\frac{\rho_s}{q^0}\frac{\nu}{u_*}$$

$$\omega = \pm\frac{q^0}{\rho_s}k|Q(0)|\sin\theta_q \qquad \omega^+ = \pm\omega\frac{\rho_s}{q^0}\frac{\nu}{u_*}$$

En ablation



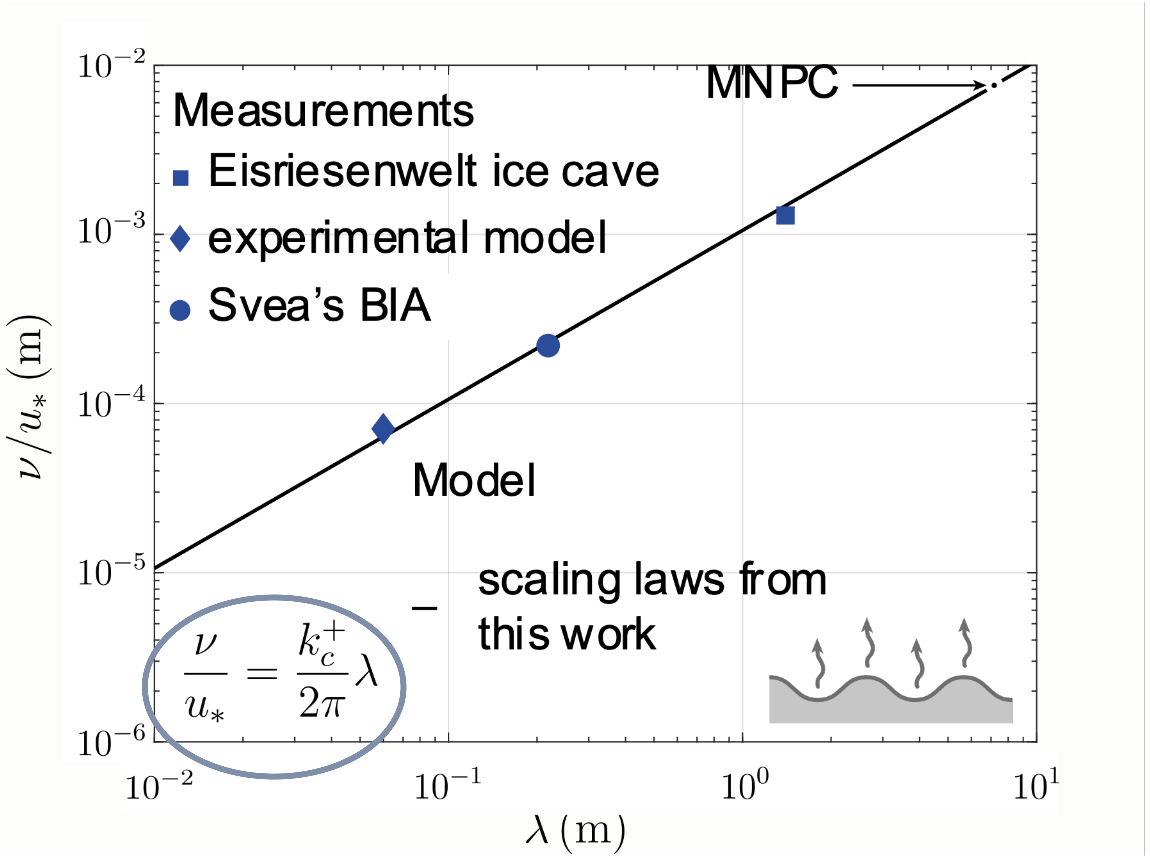
Pour $Sc = 1$



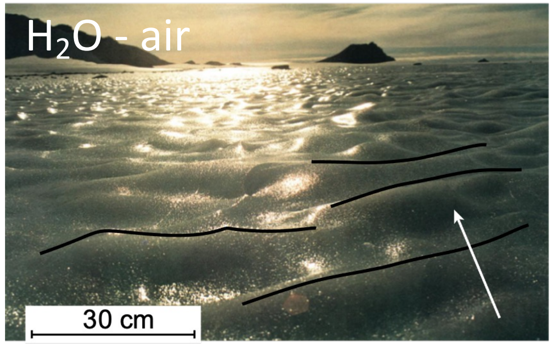
Validation of the first scaling law

[Bordiec, Carpy *et al.*, Earth Sciences Review, 2020]

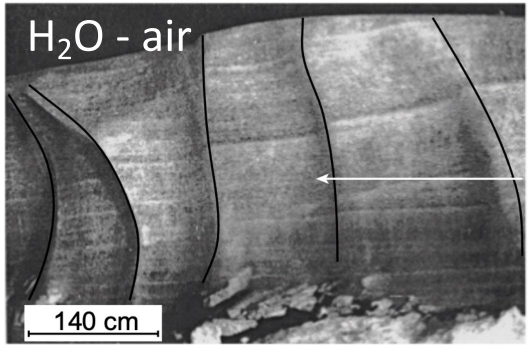
- Could we use solid bedform as geomorphic markers ?

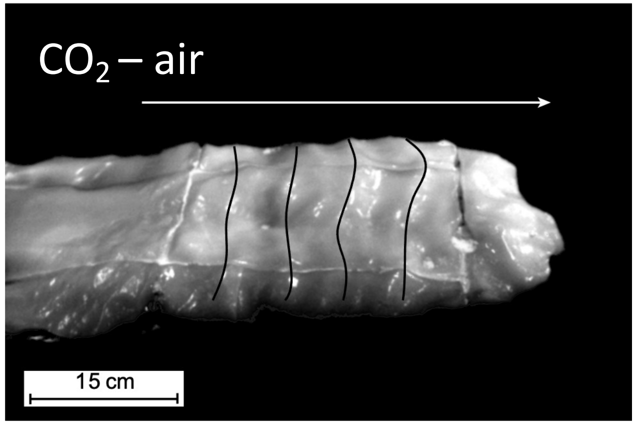


Blue Ice Areas (Antarctica)
[Bintanja, 2001]



Ice cave (Eisriesenwelt, Austria)
[Obleitner, 2011]





Lab. Experiments on CO2
[Herny, 2014]

Differences

- Scales (wavelength, amplitude)
- Ice-atmosphere compositions

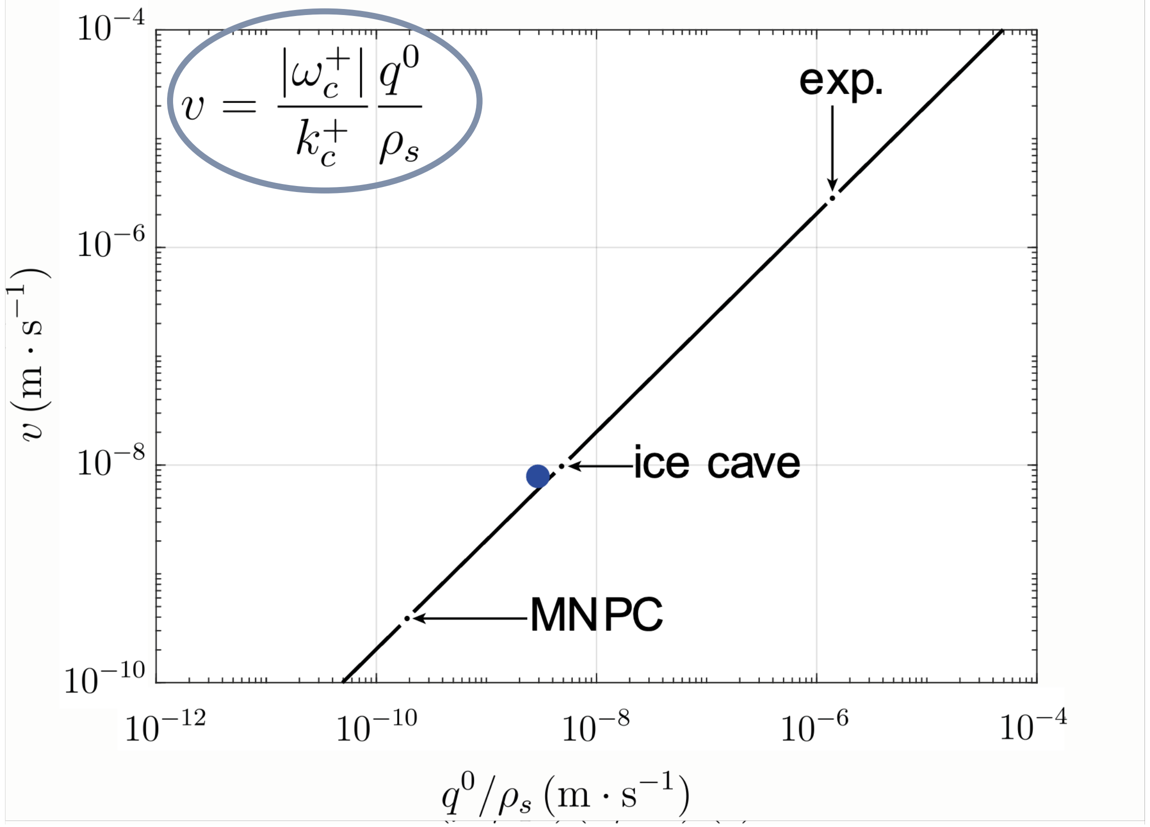
Similitudes

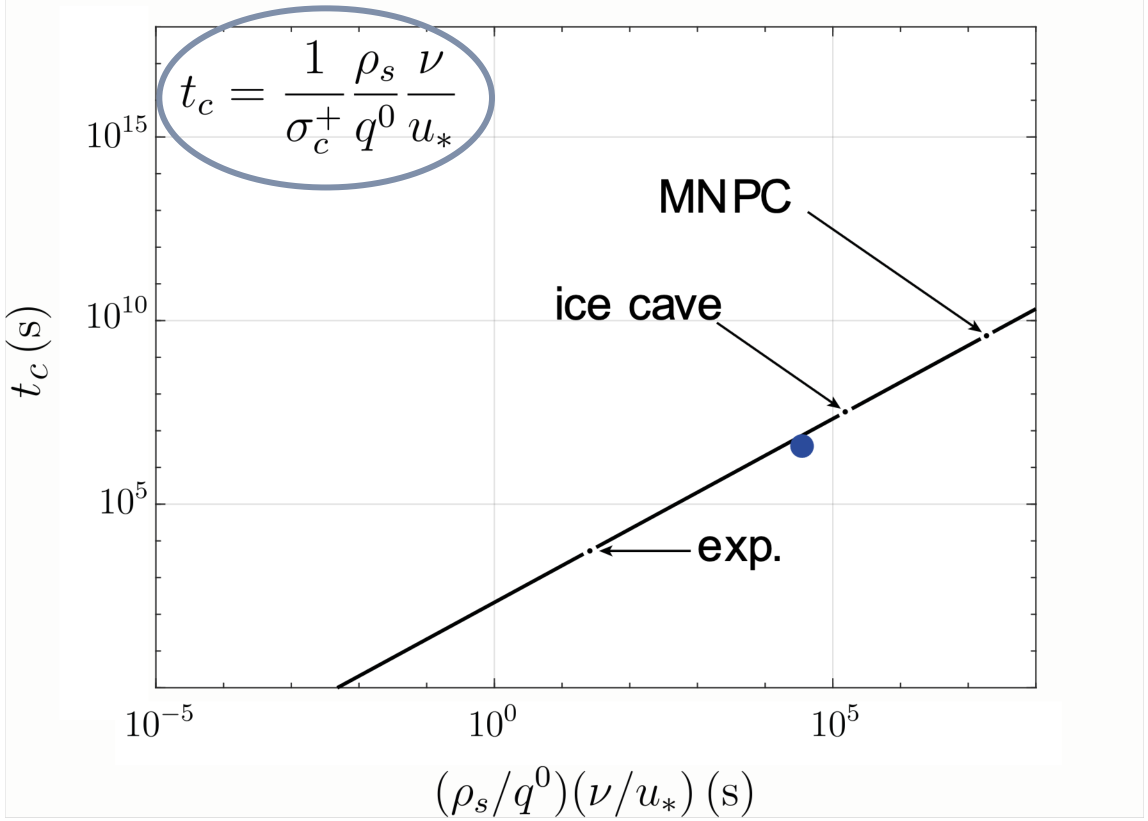
- Turbulent boundary layer of « infinite » height
- Surface temperatures lower than triple point
- $p_v < p_{sat}$ $(RH < 100\%)$
- Net ablation areas from surface energy balance

Validation of the second and first scaling law

[Bordiec, Carpy *et al.*, Earth Sciences Review, 2020]

- Could we use solid bedform as geomorphic markers ?





Model

– scaling laws from this work

Measurements

■ Eisriesenwelt ice cave

♦ experimental model

● Svea's BIA

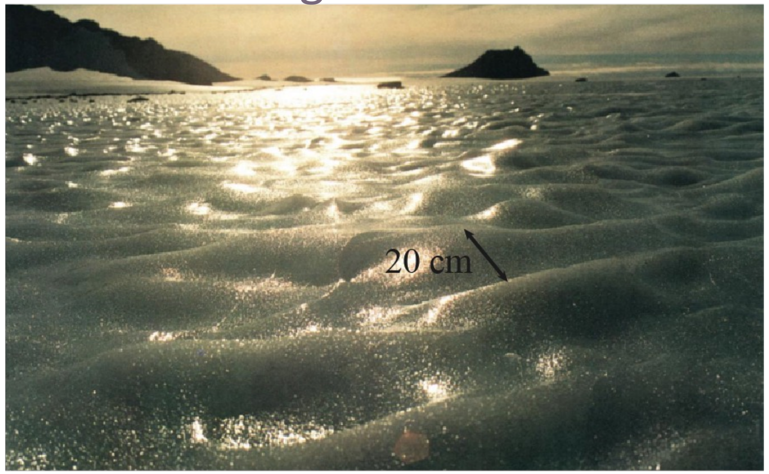
- Sublimation waves migrate downwind
- Migration velocity depends only on the sublimation rate

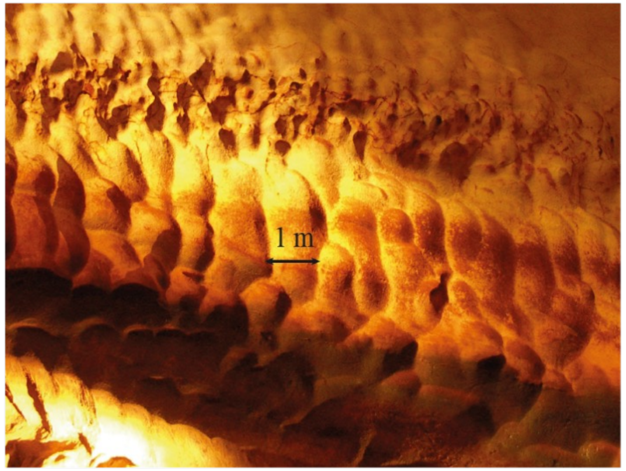
- A powerful tool to evaluate time scale of sublimation wave landscapes

Dissolution waves

[Carpy *et al.*, Frontiers, 2023]

- Are dissolution waves anaolgues to sublmimation waves?

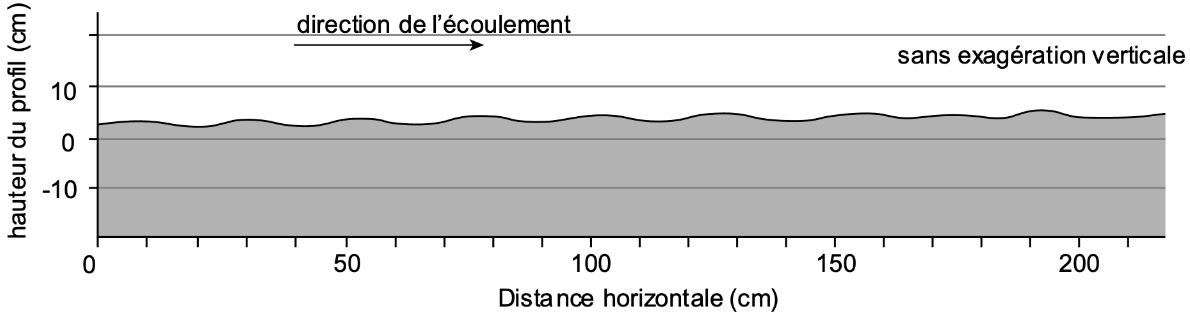




Forme : globalement 2D

→ crêtes parallèles et régulièrement espacées

Orientation : ⊥ à l'écoulement (asymétrie entre l'amont et l'aval)



→ Forme périodique identifiable : sinusoïde

Type/sens du transfert : sublimation/dissolution

→ **Environnements divers**

→ **Caractéristiques morphologiques et cinétiques variables**

Dissolution waves

[Carpy *et al.*, Frontiers, 2023]

- Are dissolution waves anaolgues to sublimation waves?

Exemple naturel

- Grotte de Saint-Marcel d'Ardèche

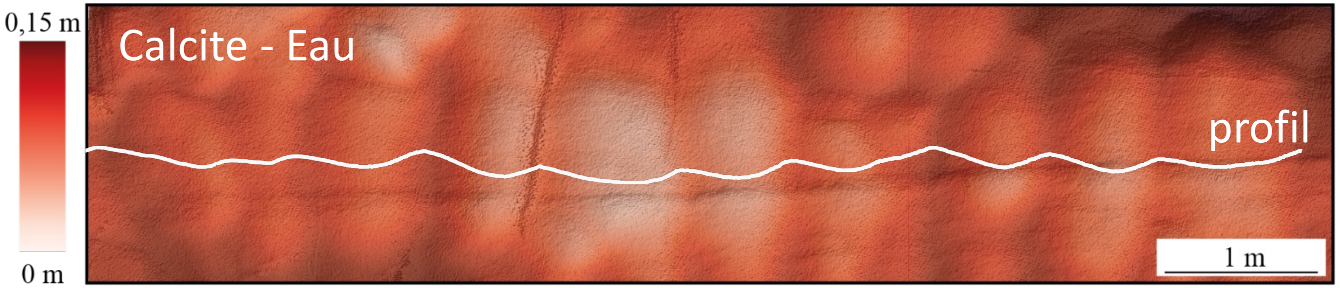
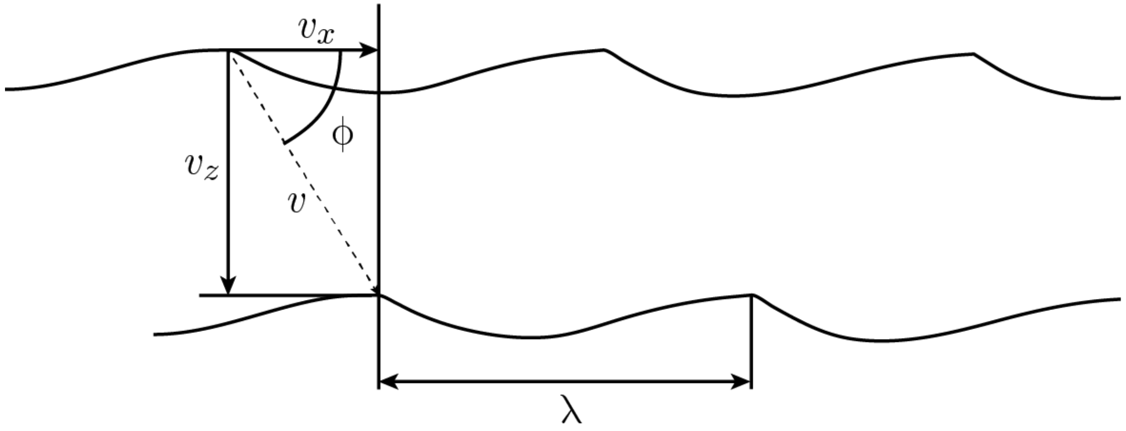


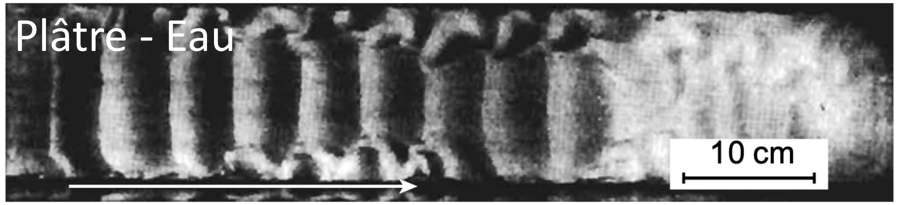
Image raster par interpolation de points LIDAR



Angle de propagation ϕ entre la migration et l'ablation ~60° à 65°

Exemple expérimental

- Dissolution du plâtre (4 exp.)
  [Blumberg and Curl, 1974]



- Concentration $c \sim 0{,}1\ s$
- **Écoulements turbulents (vitesse $\boldsymbol{U \sim 1\ \mathrm{m.s^{-1}}}$)**

⟶ **Dissolution nette**

- $\lambda \sim 2$ à 5 cm et $2\zeta_0 \sim 2$ à 6 mm
- $v_x \sim 4$ à $12\ \mathrm{cm.h^{-1}}$ dans le sens de l'écoulement

Modelling taking into account the Schmidt number

[Carpy *et al.,* Frontiers, 2023]

- Can we explain the similarity thanks to modelling ?

Relation de dispersion

⟶ Objectif : évolution temporelle du profil topographique

$$\zeta(x,t) = \zeta_0 e^{\sigma t}\Re\big(e^{i(kx+\omega t)}\big)$$

σ taux de croissance associé à k et à la pulsation ω

↓

Relation de dispersion : $D(k,\omega,\sigma) = 0$

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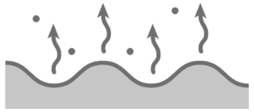
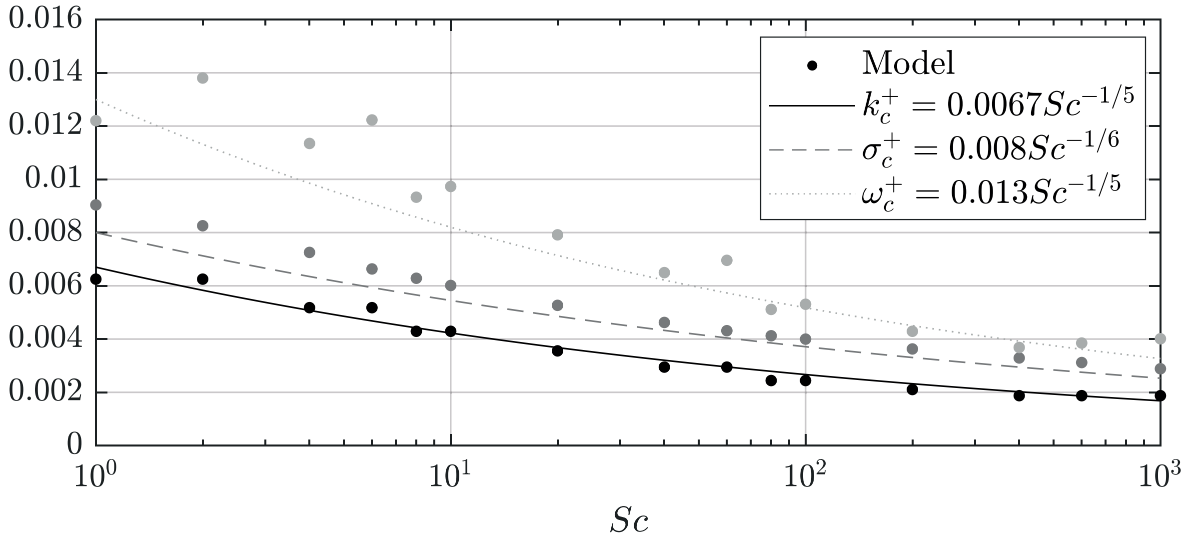
$$\omega = \pm\frac{q^0}{\rho_s} k|Q(0)|\sin\theta_q \qquad \omega^+ = \pm\omega\frac{\rho_s}{q^0}\frac{\nu}{u_*}$$

En ablation

Pour Sc variable



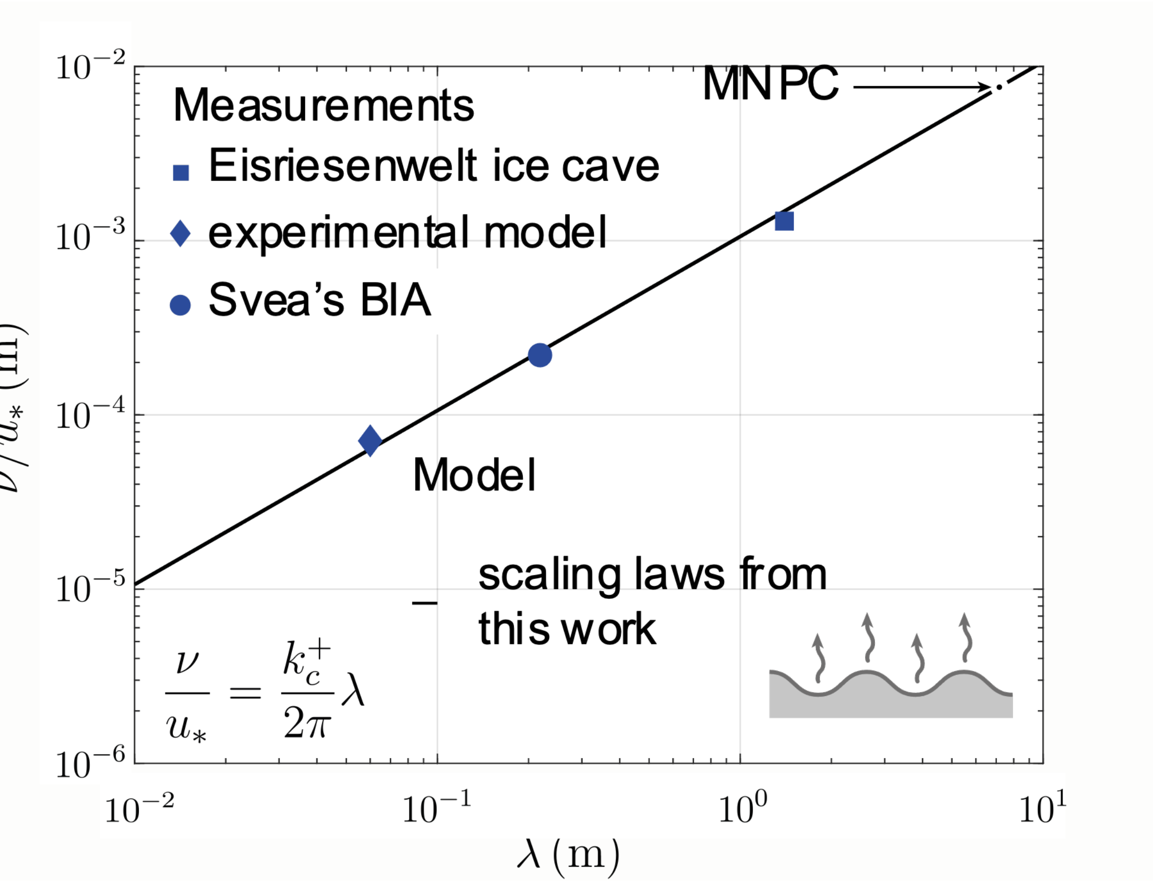


$k\nu/u_*$

Validation of the first scaling law with sublimation and dissolution waves

[Carpy *et al.*, Frontiers, 2023]

- Could we use solid bedform as geomorphic markers ?



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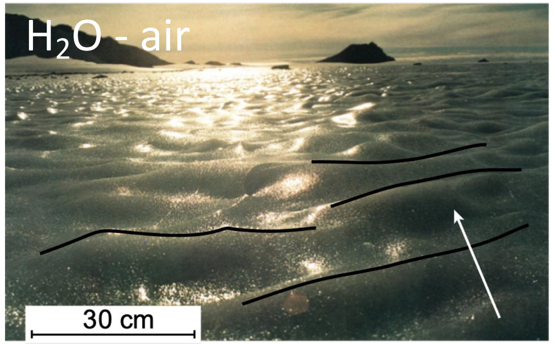
[Bintanja, 2001]



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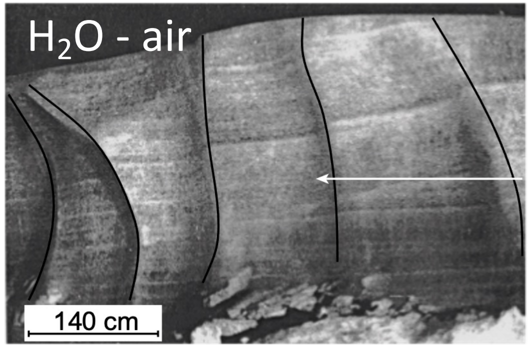
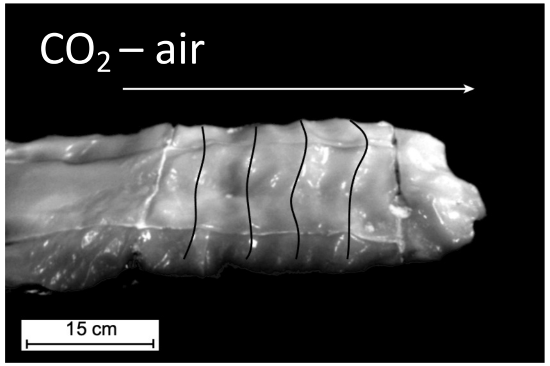
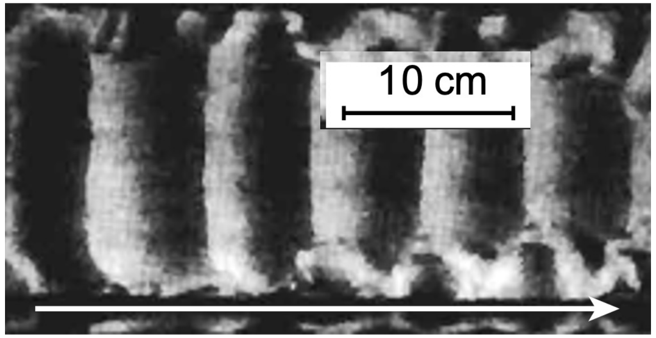




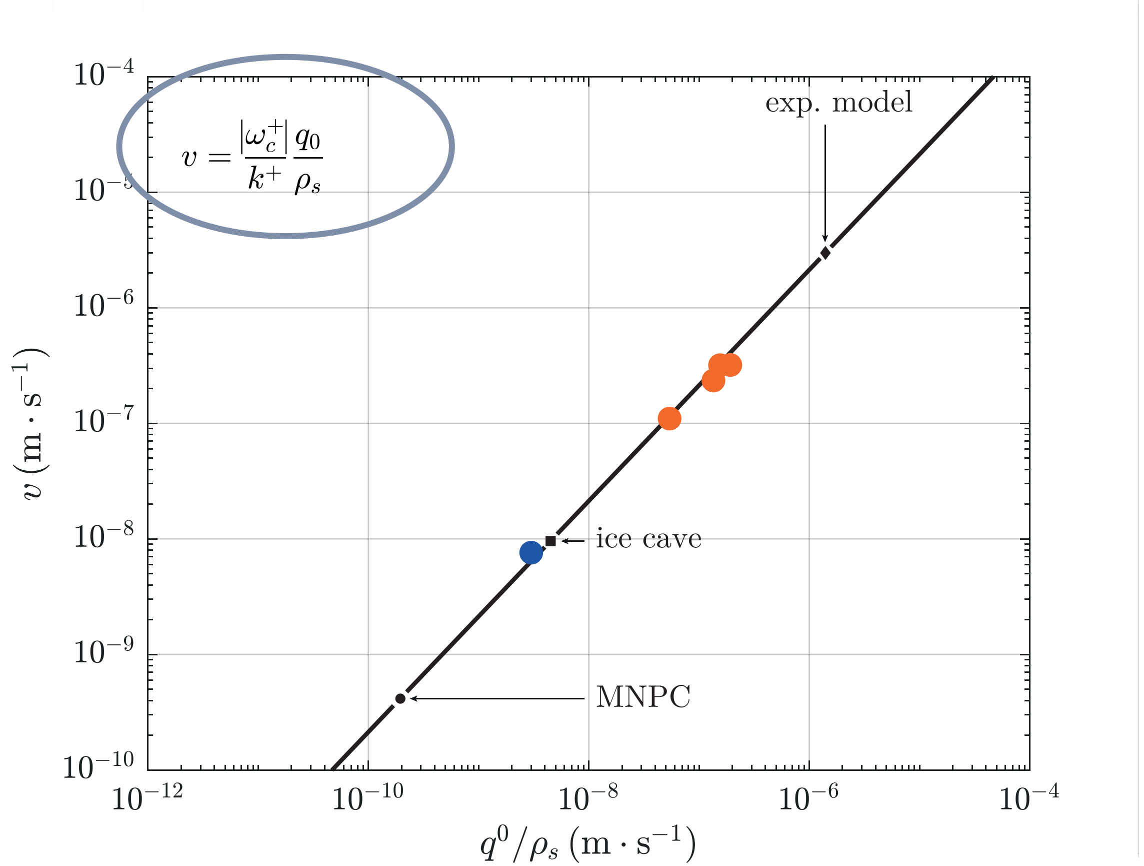
Lab. Experiments on CO2
[Herny, 2014]

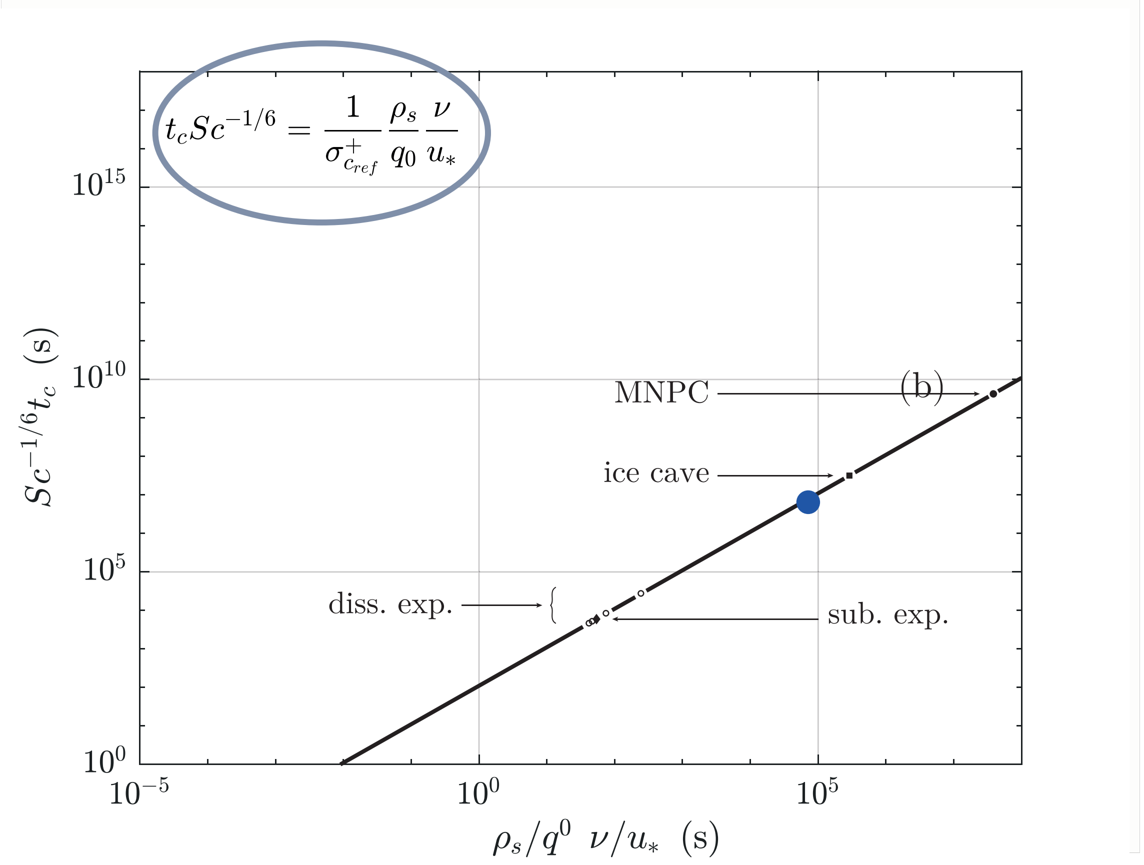


Lab. Experiments on plaster
[Blumberg & Curl, 2014]

Validation of the second and first scaling law and prediction for martian sublimation waves

[Carpy *et al.*, Frontiers, 2023]





Model

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♦ experimental model

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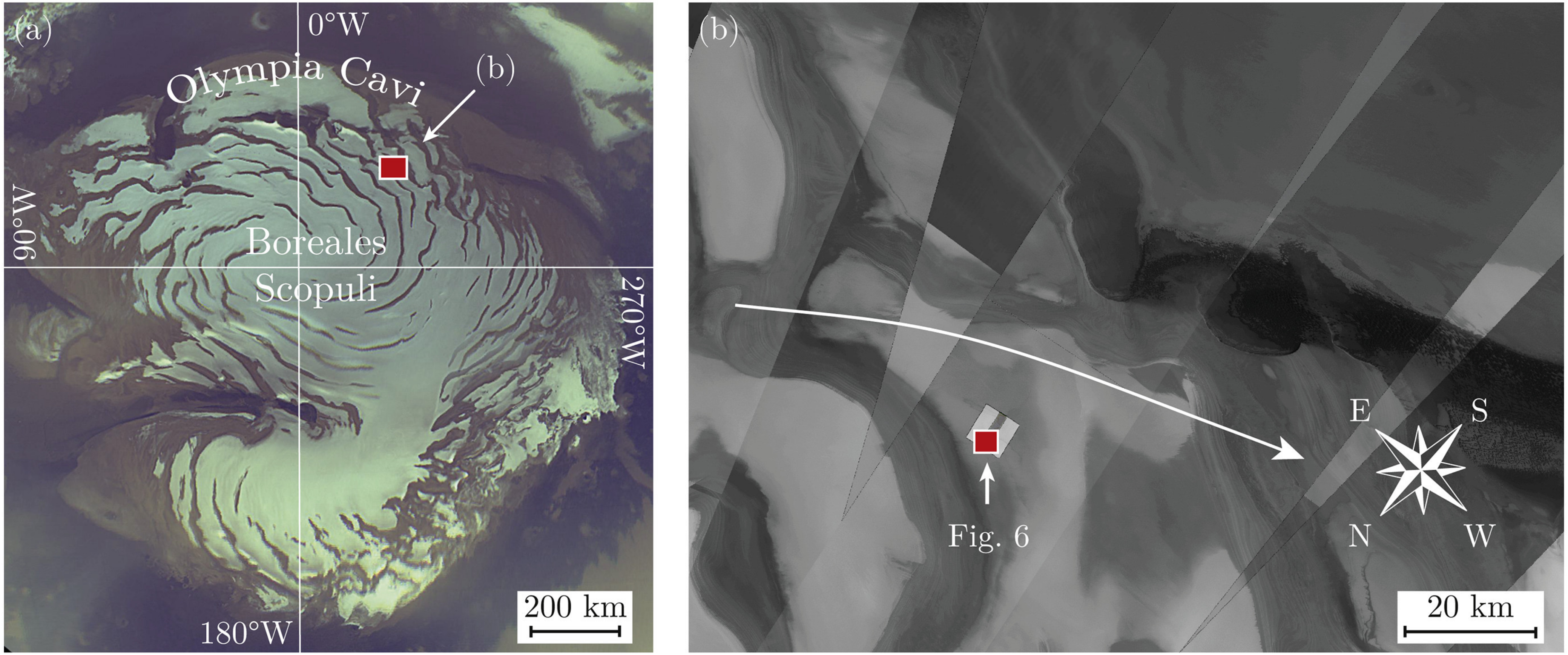
- A powerful tool to evaluate time scale of sublimation wave landscapes

Predictions for the martian North polar cap

[Carpy *et al.*, Frontiers, 2023]



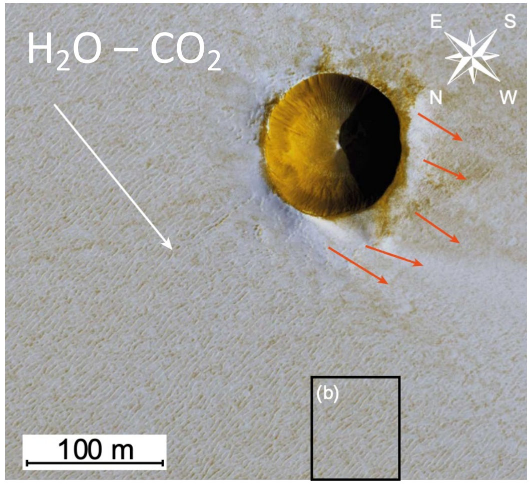
- Between two spirals at 82°N, 120° E
- Dominant winds orientation from mesoscale simulations [Massé et al, 2012]

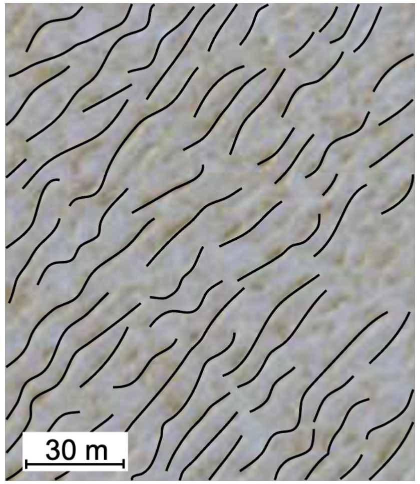
Predictions for the martian North polar cap

[Carpy *et al.*, Frontiers, 2023]

Exemples naturels planétaires

- Calotte Polaire Nord de Mars (CPNM)



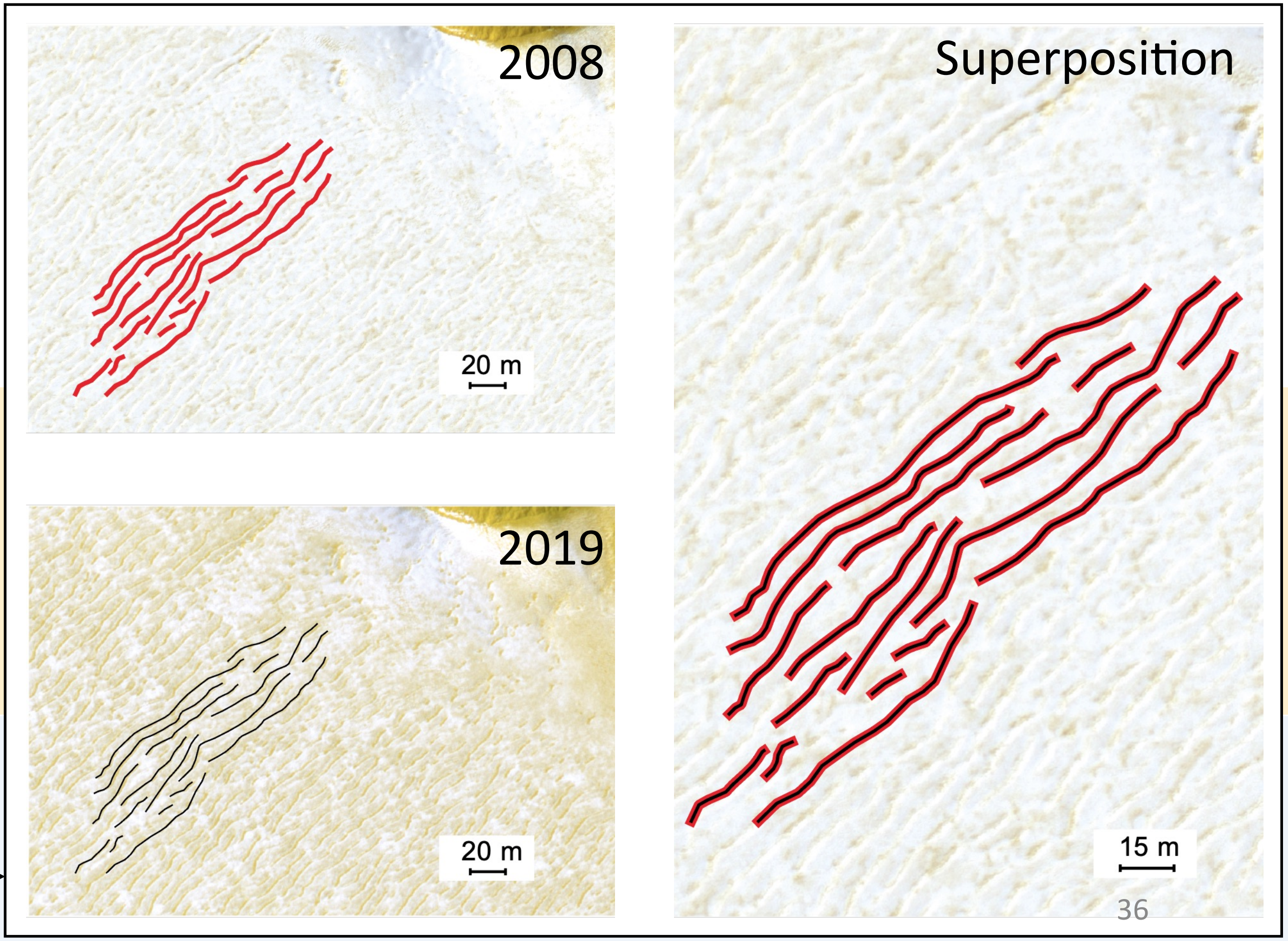


Environnement

- ○ $T_{\text{int}} \sim 220\ \text{K}$
- ○ Humidité relative $RH = 25\%$
- ○ **Vents turbulents (vitesse $\boldsymbol{U \sim 2,5\ \text{m.s}^{-1}}$)**
- → **Sublimation de H_2O (printemps-été)**

Morpho. Cinétique

- ○ $\lambda \sim 7\ \text{m et } 2\zeta_0 \sim 0,4\ \text{m}$
- ○ v non observée

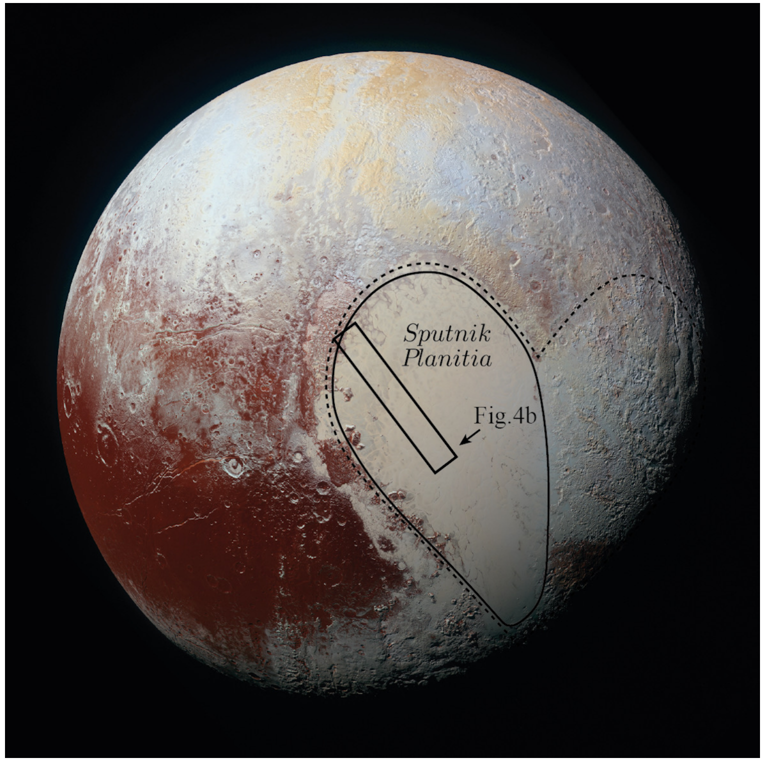


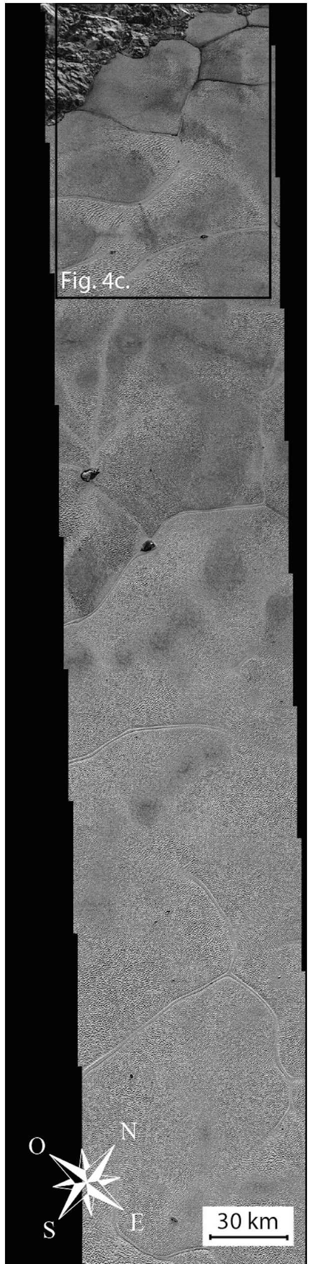
Predictions for the Sputnik Planitia, Pluto

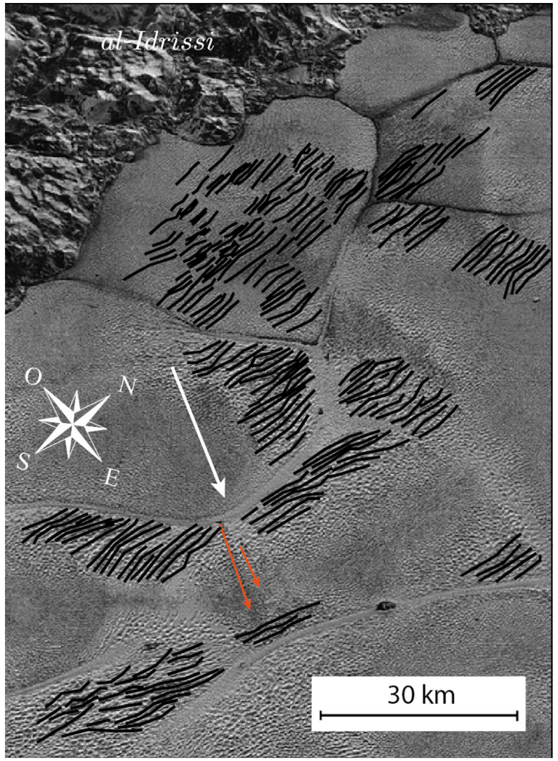
[Carpy *et al.,* Frontiers, 2023]

Exemples naturels planétaires

- Sputnik Planitia (Pluton)







Quel lien génétique entre la diversité des motifs et les écoulements ?

→ **External forcing and boundary conditions**

1. Buoyancy driven flow
   - ⇒ Stable density stratification
   - ⇒ Unstable density stratification

2. Externally driven flow
   - ⇒ Deep flow
   - ⇒ Free surface flow

→ **Evolution in sharp tips and crest by normal ablation**

Sharp scallops on marble limestone from the Korallgrottan cave, Sweden.

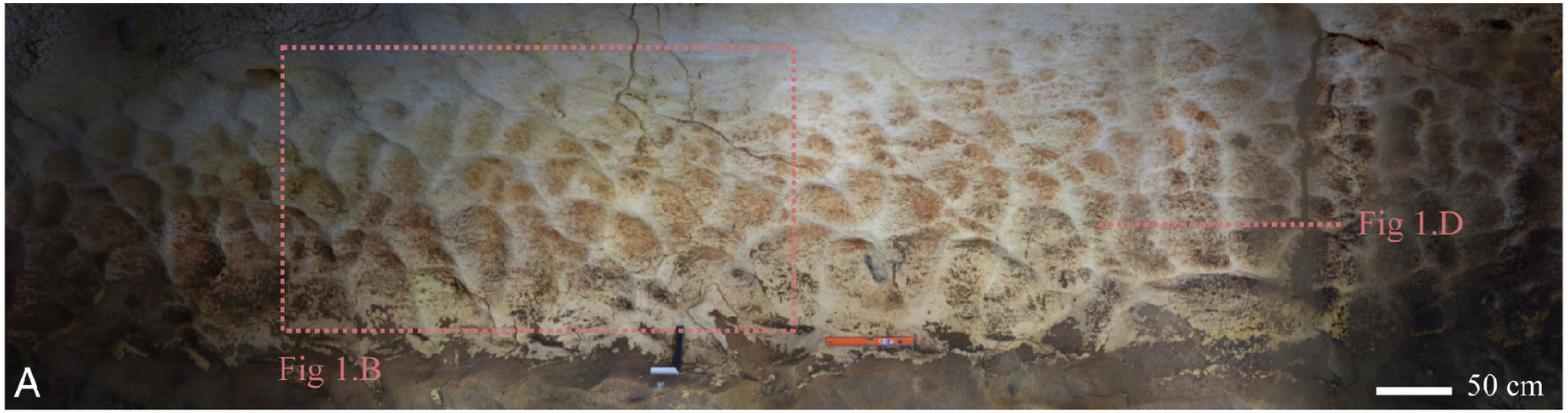
Ice scallops on the immersed surface of an iceberg.

Suncups formed by sublimation of snow in Vercors, France.

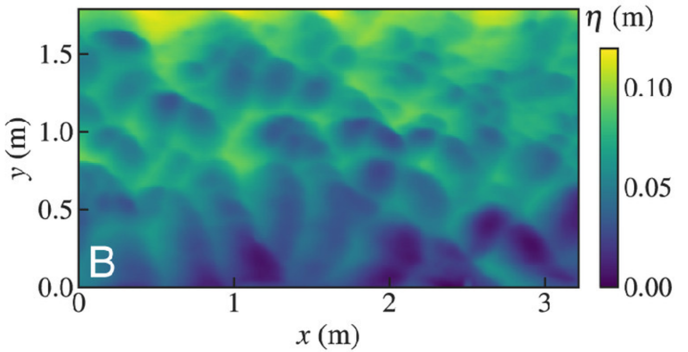
Scallop patterns on the Murnpeowie Meteorite, South Australian Museum, Adelaide.

Emergence of singular shape: characterization of singularities in the field

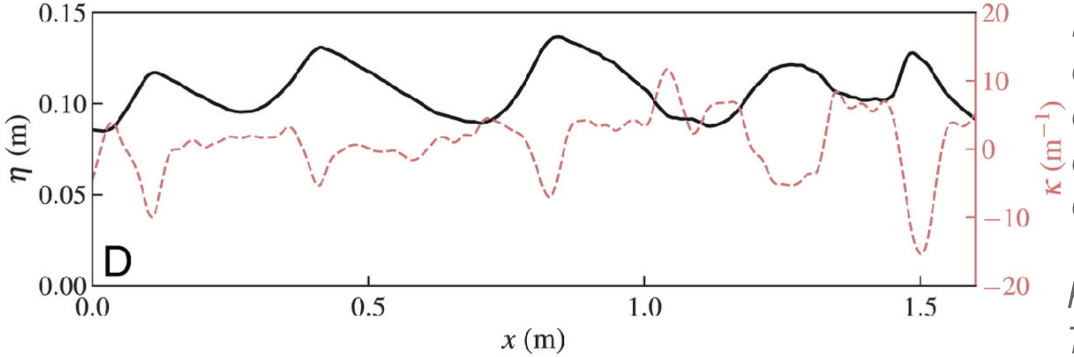
[Chaigne, Carpy *et al.*, PNAS, 2023]



Orthophotograph of a vertical wall of the cave, approximately 2 m high and 10 m long, covered by scallops



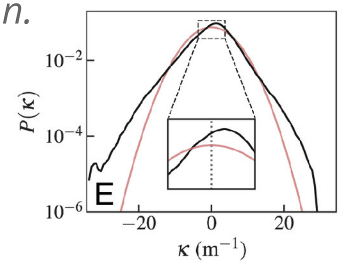
3D reconstruction of a portion of the wall using photogrammetry.

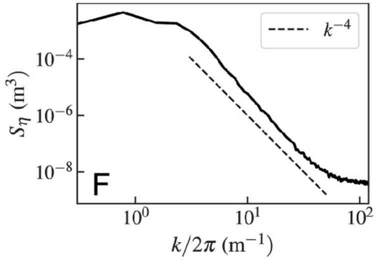


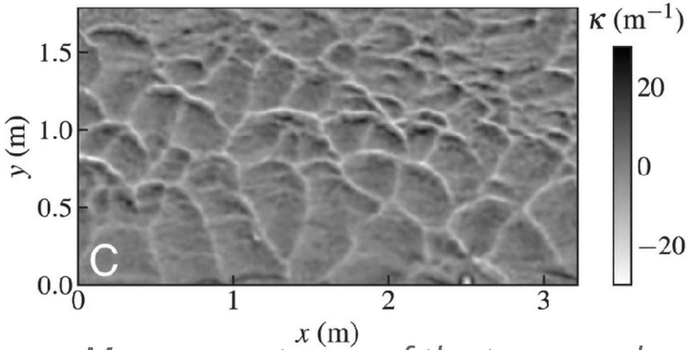
Longitudinal cross-section at the location of the pink dotted line on the orthophotograph (black solid line) and corresponding mean curvature (pink dashed line).

Power Spectral Density of the topography. The black dashed line corresponds to a power law in k−4.

Normalized mean curvature distribution. The solid pink line indicates Gaussian distribution with zero mean and same SD. Inset: Shape of the distribution around zero revealing a shift toward positive values.







Mean curvature κ of the topography for the same portion of the wall. Lines with highly negative curvature indicate the location of crests.

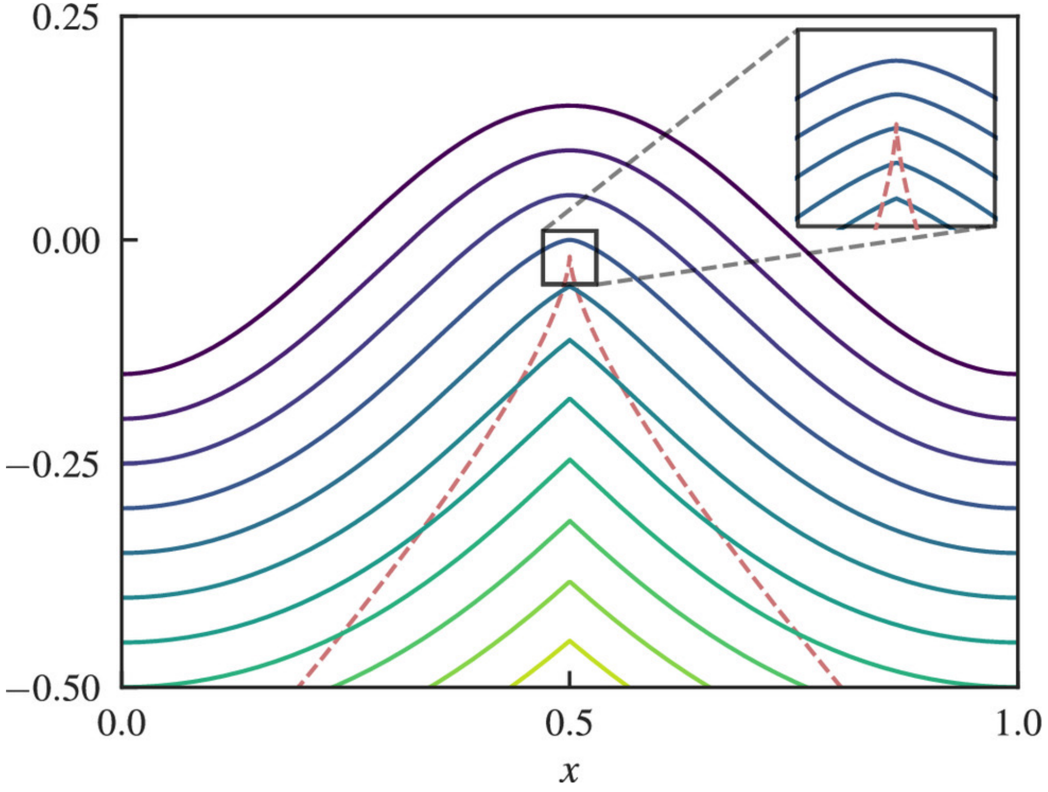
=> We identify indicators of the presence of crests :

- an asymetric mean curvature distribution P(κ)
- a characteristic exponent in the Fourier Spectrum S_η

Emergence of singular shape: normal ablation model

[Chaigne, Carpy *et al.*, PNAS, 2023]

Normal Ablation Model of a sinusoid with uniform dissolution rate.



From top to bottom, Successive interfaces resulting from the normal ablation, for selected steps. Pink dotted line: Evolute curve of the initial sinusoid shape, i.e., locus of its centers of curvature.

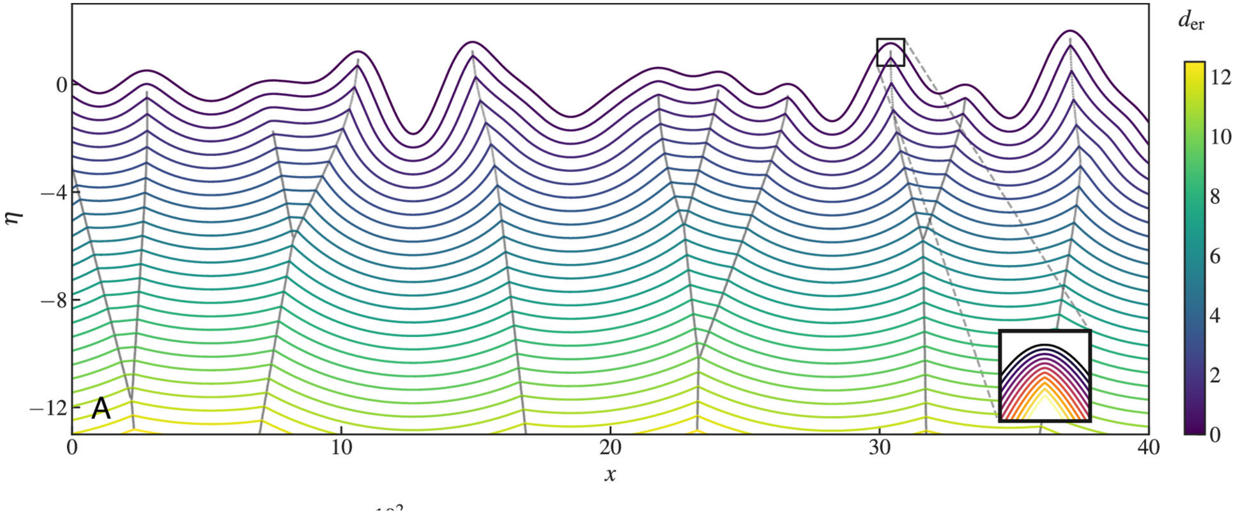
=> A tip (where the curvature diverges) appears when the interface crosses the evolute.

$$-\rho_s\,\mathbf{v_d} = \alpha(c_{\mathrm{sat}} - c_{\mathrm{i}})\,\mathbf{n}$$

$$\rho_s\,\mathbf{v_d}\left(1-\frac{c_{\mathrm{i}}}{\rho_{\mathrm{i}}}\right) = D\,(\nabla c|_{\mathrm{i}}\cdot\mathbf{n})\,\mathbf{n}\,,$$

- In erosion by dissolution, the **erosion velocity** depends on the local concentration, but is always **normal** to the interface. This may be sufficient to explain the appearance of spikes.

- For example, a curve having curvature variations and undergoing a normal ablation process evolves in finite time to exhibit singularities.



Normal ablation of a random interface with a uniform dissolution rate.

Emergence of singular shape: heterogenous dissolution of an interface

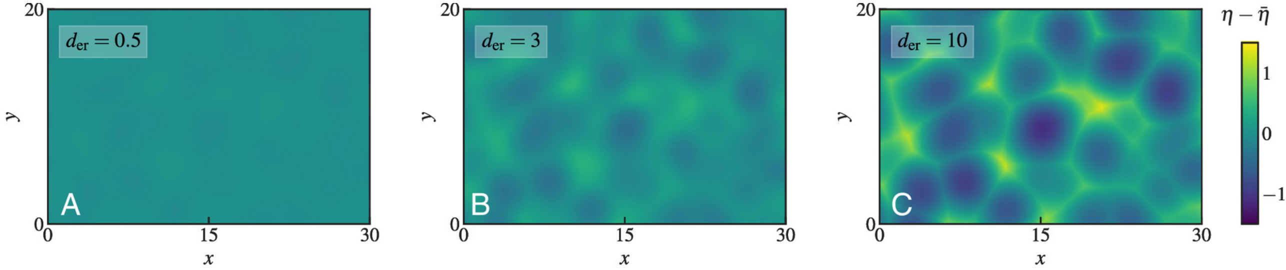
[Chaigne, Carpy *et al.*, PNAS, 2023]

Heterogeneous Dissolution Rate for a 2D Interface.

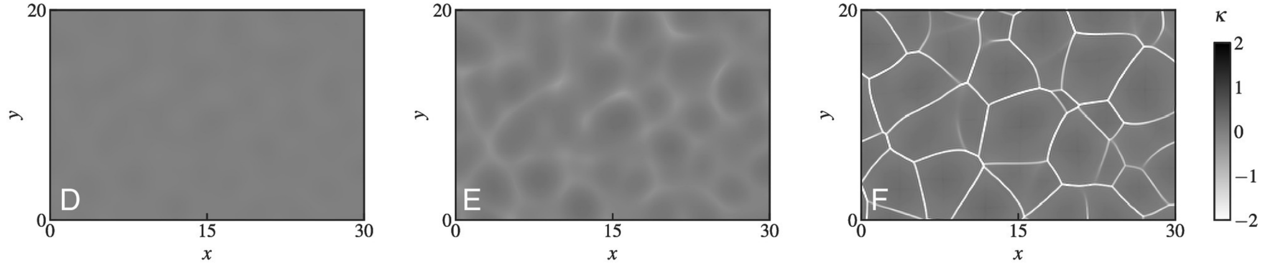
- We start from a flat interface and impose a heterogeneous erosion rate varying on a given typical wavelength. Each point of the interface is then propagated in the direction of its normal in proportion to the local erosion rate, and the process is repeated.

- A **cellular pattern** of concavities, surrounded by **sharp crests** organized into a connected network, progressively appears.

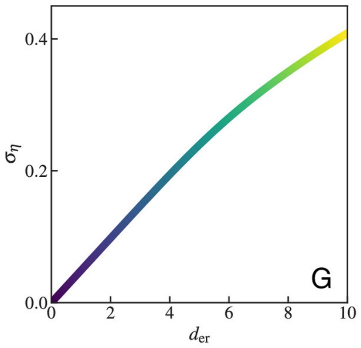
- We recover the indicators of crests identified on natural shapes.



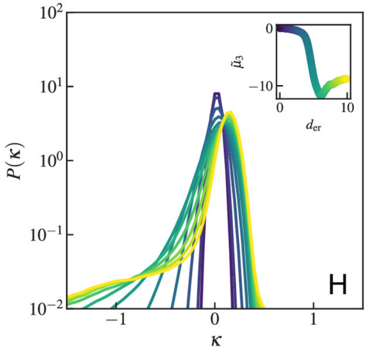
Topography of the surface at three different moments



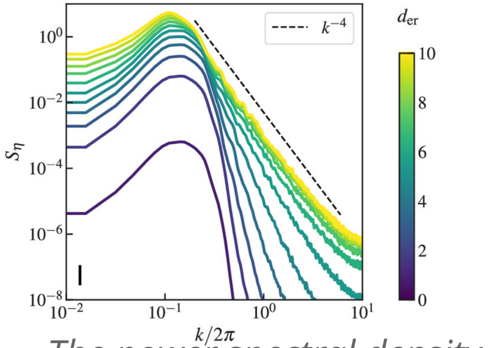
Corresponding mean curvature field.



SD of the topography versus erosion length.



Distribution of the mean curvature.

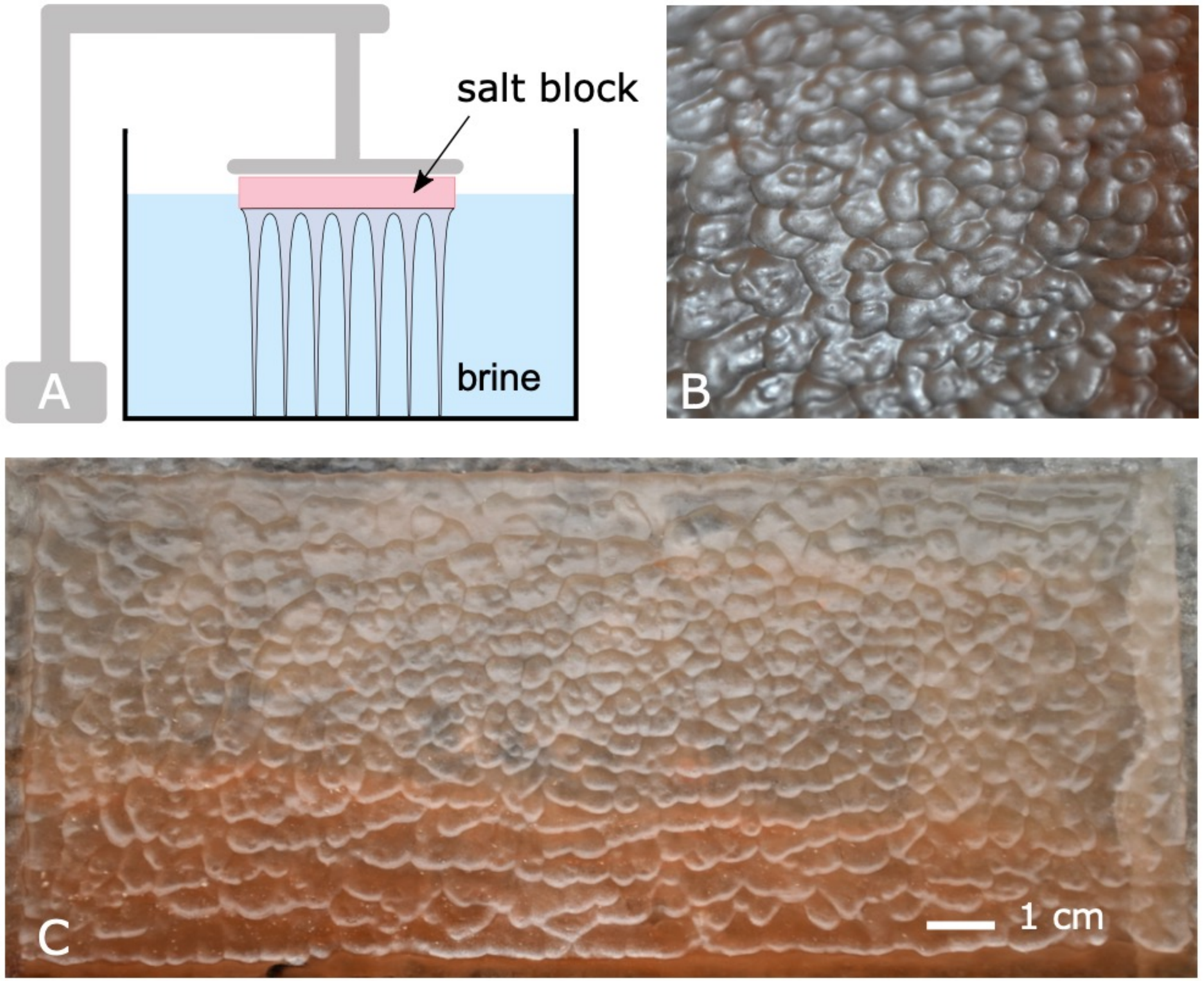


The power spectral density of the topography collapses at small wavelengths on a characteristic power law in k−4.

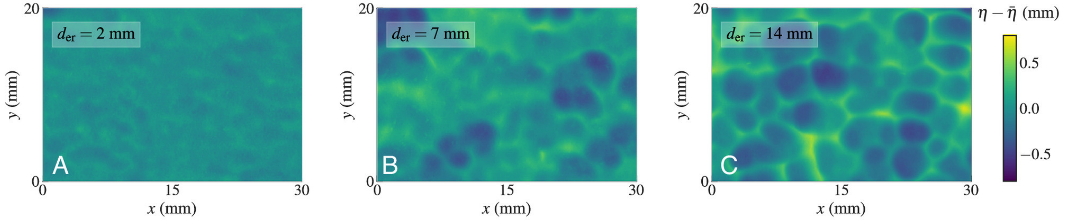
Emergence of singular shape: comparaison to solutal convection experiments

[Chaigne, Carpy *et al.*, PNAS, 2023]

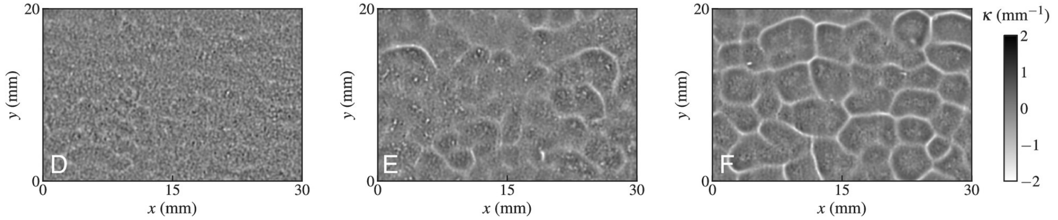
after 220 hours of dissolution



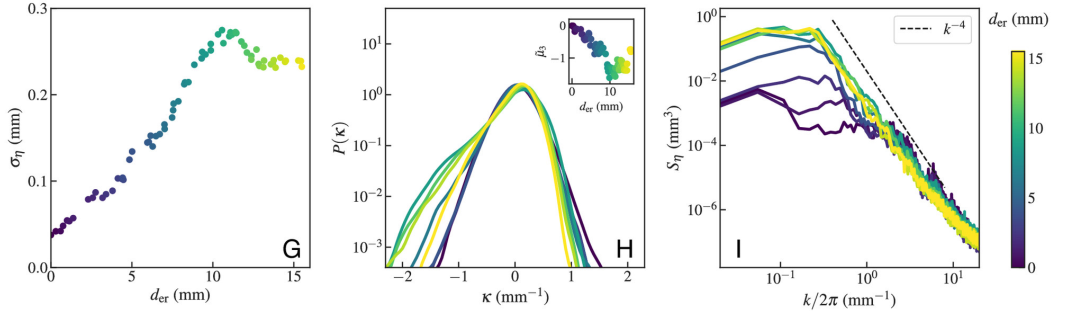
Scallops emerge on the bottom surface of the block.



Topography of the surface at three different moments



Corresponding mean curvature field.



SD of the topography versus erosion length.

Distribution of the mean curvature.

The power spectral density of the topography collapses at small wavelengths on a characteristic power law in k−4.

=> **Scallops formation result from a geometric effect**

Quel lien génétique entre la diversité des motifs et les écoulements ?

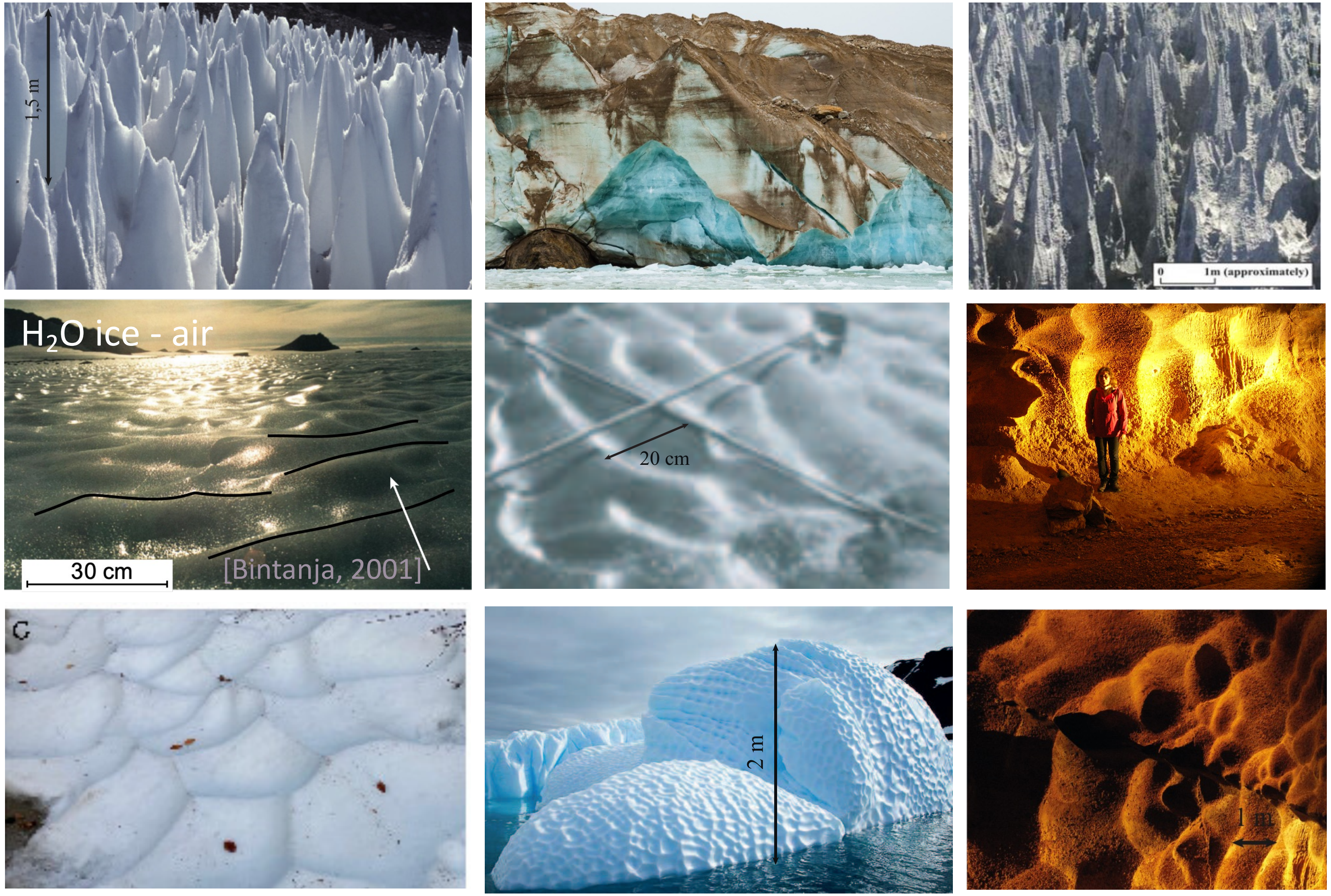
Conclusion

- ✓ Review the formation of patterns engraved in the solid substrate by surface flows in real geological environments, whether on Earth or on other planets.
- ✓ Demonstrate the relevance of lab-scale experiments for the understanding of flow and phase-change driven geo-scale pattern formation mechanisms
- ✓ Carpy et al, 2024, accepted, CRAS

Perspectives

- ☐ based on the governing coupling boundary conditions at the fluid/solid interface where the phase change happens, knowing the driving mecanims

=> modelling of phase change with jump at the interface (Carpy & Mathis, 2019) with flow motion ?



sublimation fusion dissolution