Morphology of scallop patterns in erosion by dissolution

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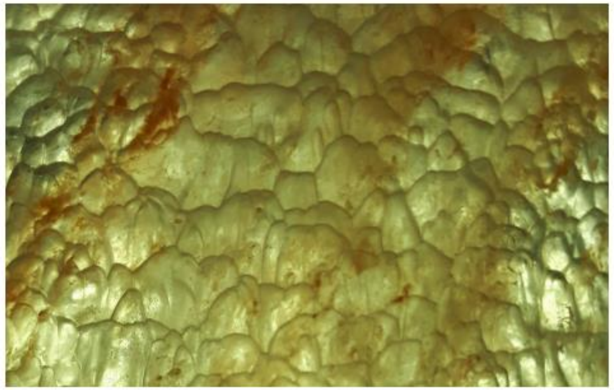
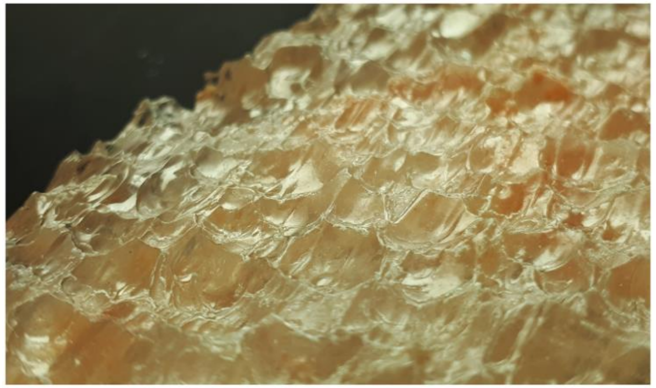




EGU 2020. NP1.1. Mathematics of Planet Earth. May 4th 2020

Erosion by dissolution

- Chemical Erosion of rocks by dissolution when they are submitted to a water flow: rain, seepage … Dissolved minerals often transported under a solute form. Dominant erosion process for soluble minerals: limestone, gypsum, salt.

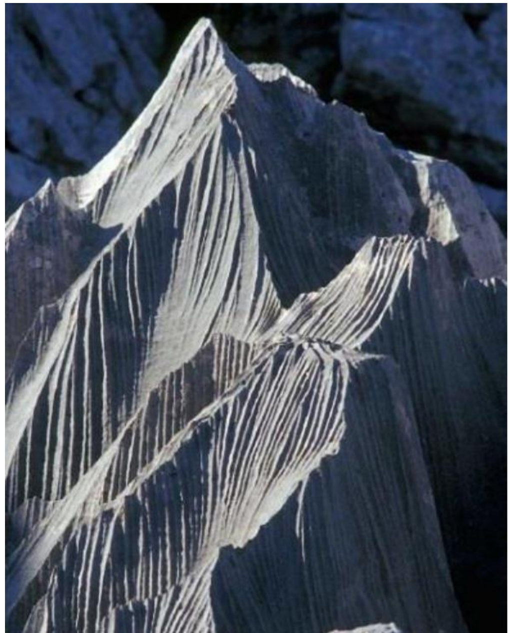
- Erosion rate and shape of dissolved surface is often controlled by the solute transport. Hydrodynamics mechanisms. Application in geomorphology at various scales...

Limestone pavement French Alps

Salt, Vale de la Luna, Chile

Tsingy of Bemaraha , Madagascar, Credit Wikipedia

Rillenkarren, limestone Slovenia, Credit Marko Simic



Scallops created by a turbulent flow

- Specific dissolution patterns: assemblage of saucer shapes depression with sharp edges.
  Main occurrence cave limestone wall subjected to a turbulent water flow

Grotte des Puits, Moselle, France
Losson & Quinif **Karstologia** 2001, no. 37, p. 29 (2004)

British Columbia
https://www.geocaching.com/geocache/GC2AGFY_scallop-cave

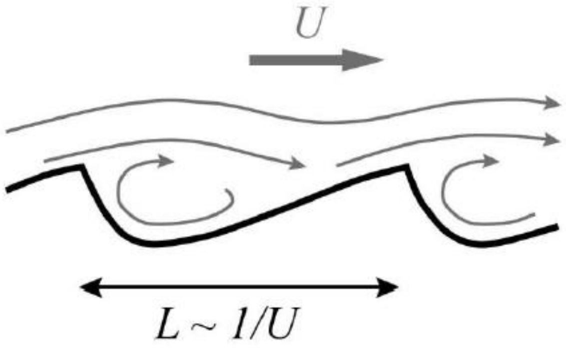
Korallgrottan, Sweden
Johannes Lundberg

Analog mechanism for ice melting in turbulent flows
Bushuk et al. **J. Fluid Mech** 873 942 (2019)

- Scallops formation, experiments on gypsum, Blumberg & Curl **JFM 1974**,

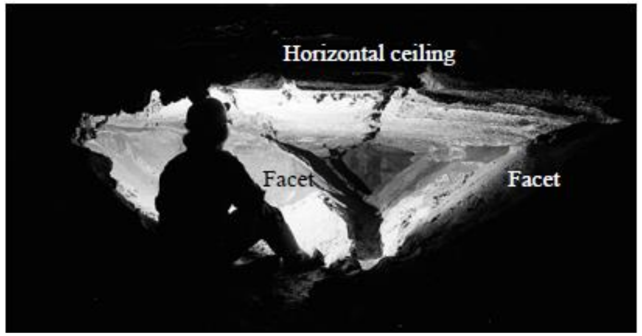
At high Re, L~1/U.
Interaction of the turbulent boundary layer with the topography.

Recent theoretical paper: P. Claudin, O. Durán and B. Andreotti
J. Fluid Mech. 832, R2 (2017) “Dissolution instability and roughening transition”



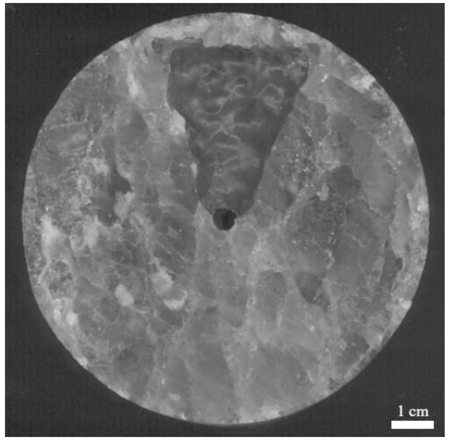
Scallops created by solutal convection

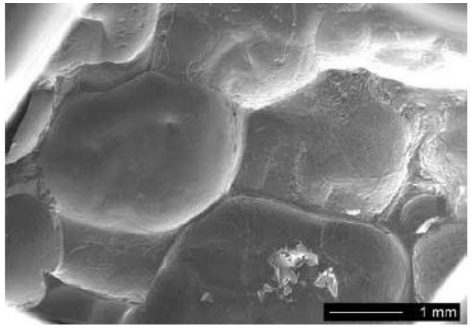
- Dissolution cavities filled with water without external flow.
  Soluble mineral: limestone, gypsum, salt
  Fluid charged in solute is denser and induces a convection flow.
- Ceilings: scallop pattern, solution cups

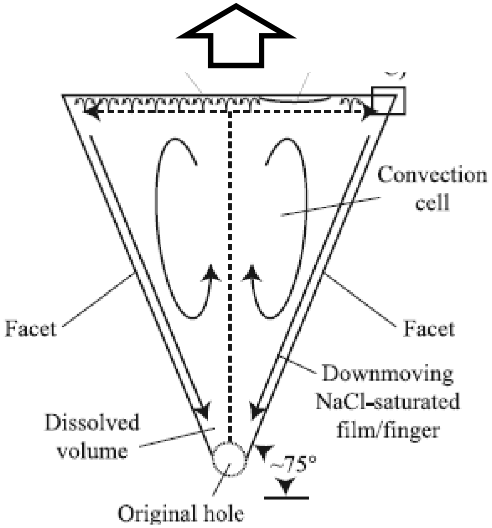


Segeberger gypsum cave, Germany (from Reinboth, 1992). Triangular shape.

Solution pits of the Heimkehle gypsum cave, Germany (photo by S. Kempe).

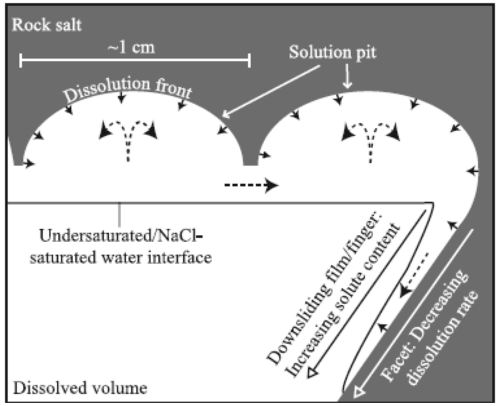






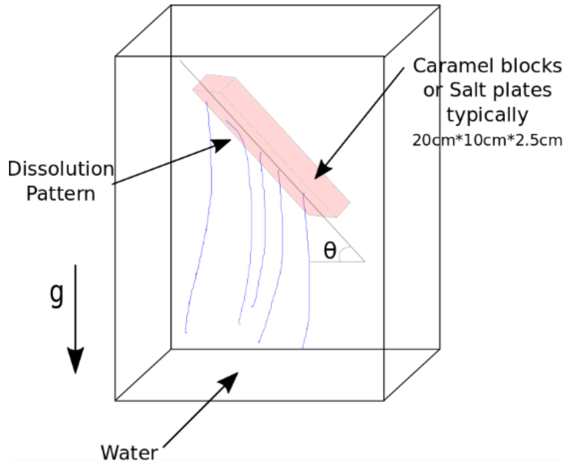
Experiments in salt
Ceiling with solution cups
Gechter **Water Resources Research** 44, W11409 (2008)

Convection cupolas.
Left: large wall convection niches, Kraus-Höhle, Austria (photo: Ph. Audra).
Right: ceiling cupolas,
Grotte des Serpents, France (photo: Ph. Audra).
Credits: Audra et al. (2005)
MORPHOLOGICAL INDICATORS OF SPELEOGENESIS: HYPOGENIC SPELEOGENS



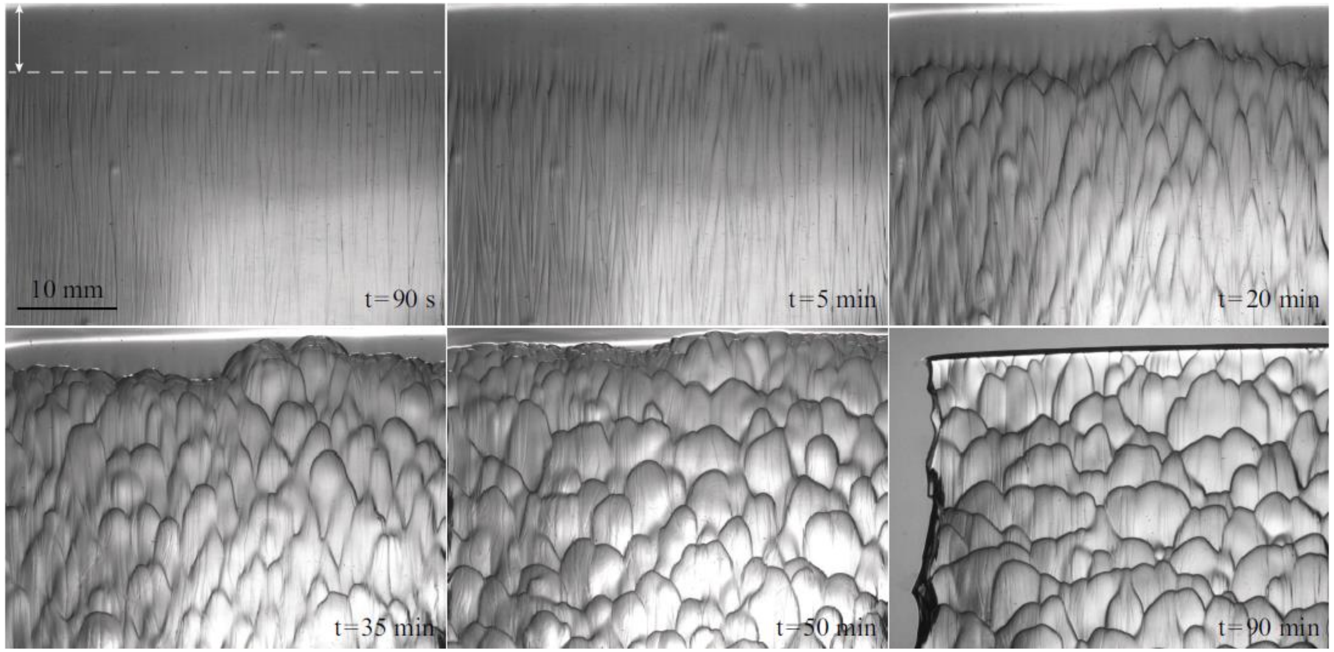
Solutal convection experiments at MSC

- Blocks of soluble material (mainly caramel and salt) in quiescent water



Cohen, Berhanu, Derr and Courrech du Pont, **Phys. Rev. Fluids** 1, 050508 (2016)
“Erosion patterns on dissolving and melting bodies”

Cohen, Berhanu, Derr and Courrech du Pont, accepted in **Phys. Rev. Fluids** (2020)
“Buoyancy driven dissolution of inclined blocks: Erosion rate and pattern formation”
Preprint: arXiv:2004.09898

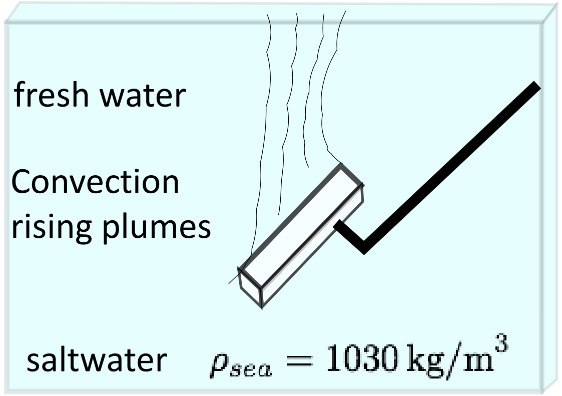


Transmission images for caramel. Pattern on the **bottom** face
Initial **longitudinal stripes**. Then, emergence of **scallops**.

- Initial wavelength of stripes and erosion rate are well predicted by scaling laws based on a solutal Rayleigh-Bénard instability.

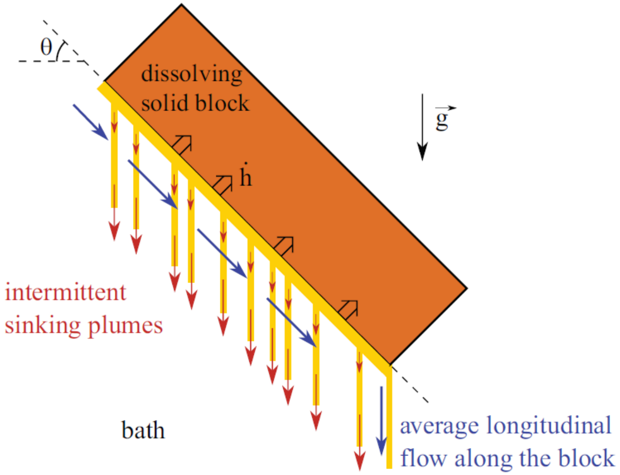
See also our numerical study
Philippi, Berhanu, Derr and Courrech du Pont,
Phys. Rev. Fluids 4, 103801 (2019)
“Solutal convection induced by dissolution”

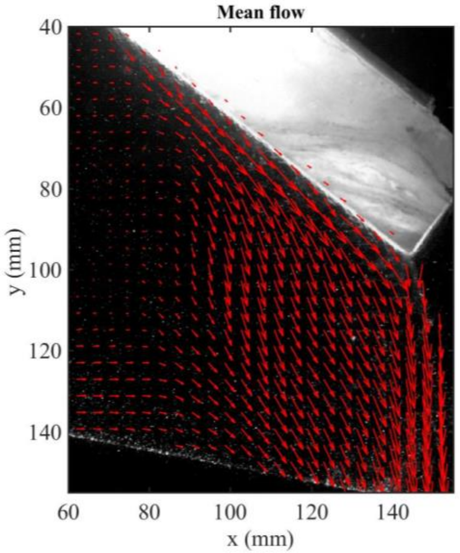
Analog mechanism for ice melting. Scallops



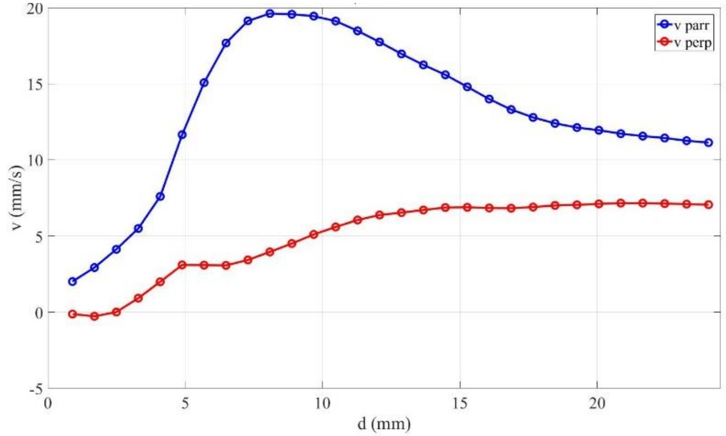
Solutal convection experiments at MSC

- Hydrodynamics: vertical sinking plumes + in average recirculation shearing flow.



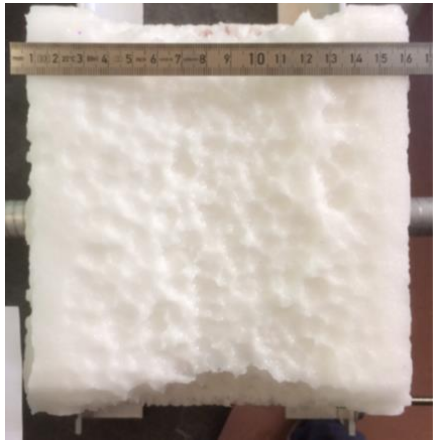


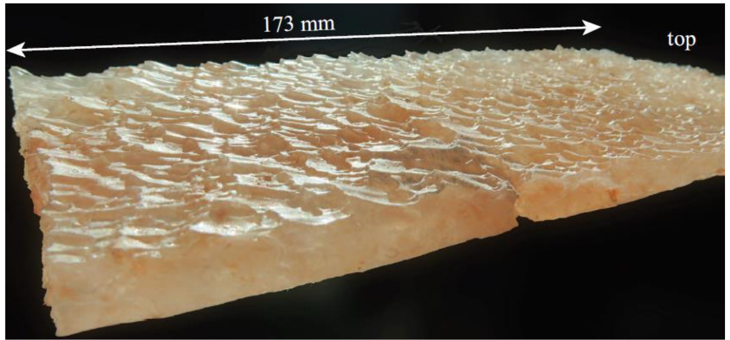
Typical velocity 1 cm/s for salt in fresh water.



- **Scallop** patterns

on salt block (granular salt conglomerates ~ 20*20*20 cm) and salt plates (pink salt of Himalaya 20*10*2.5 cm)



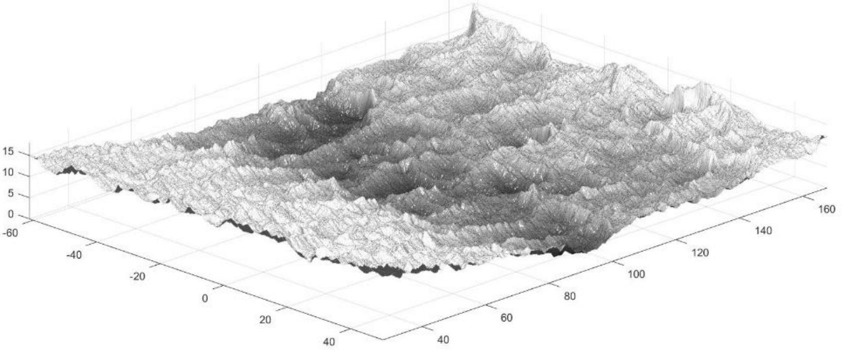


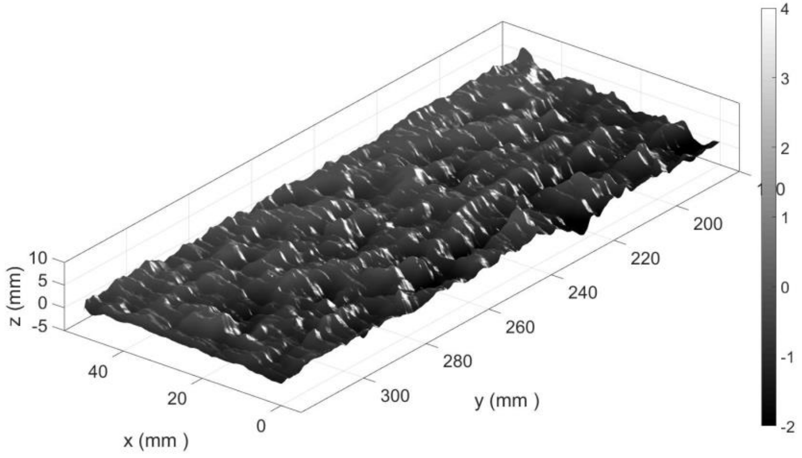
Morphology of scallops created from solutal convection

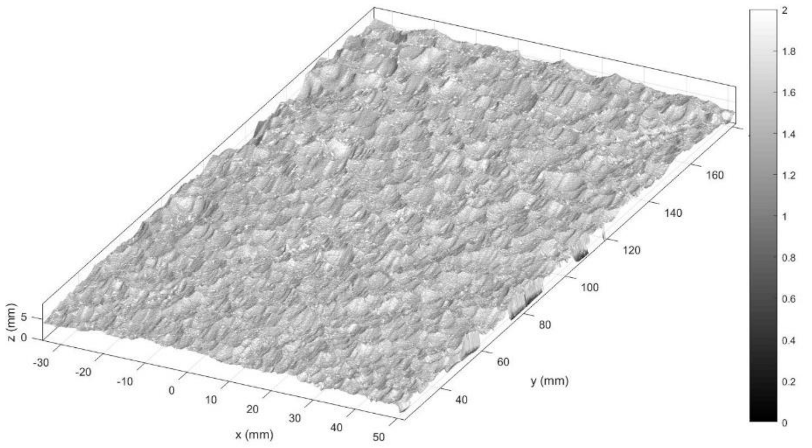
- For inclined blocks, scallops disordered pattern arising from the transversalization of a longitudinal pattern. Role of the flow ?
- For all scallop patterns: nearly round depressions, cups, saucer shape associated with sharp edges, spikes.
- General morphology for other ablation processes ?
- Here, characterization of scalloped surface obtained by solutal convection on salt surface.
  Laser scanner Micro-Epsilon 2900-100/BL
  3D shape reconstruction.

For example meteorites (Regmaglyptes) see Amin et al. PNAS 116 33 16180 (2019)

Murnpeowie Meteorite
Credits: James St. John







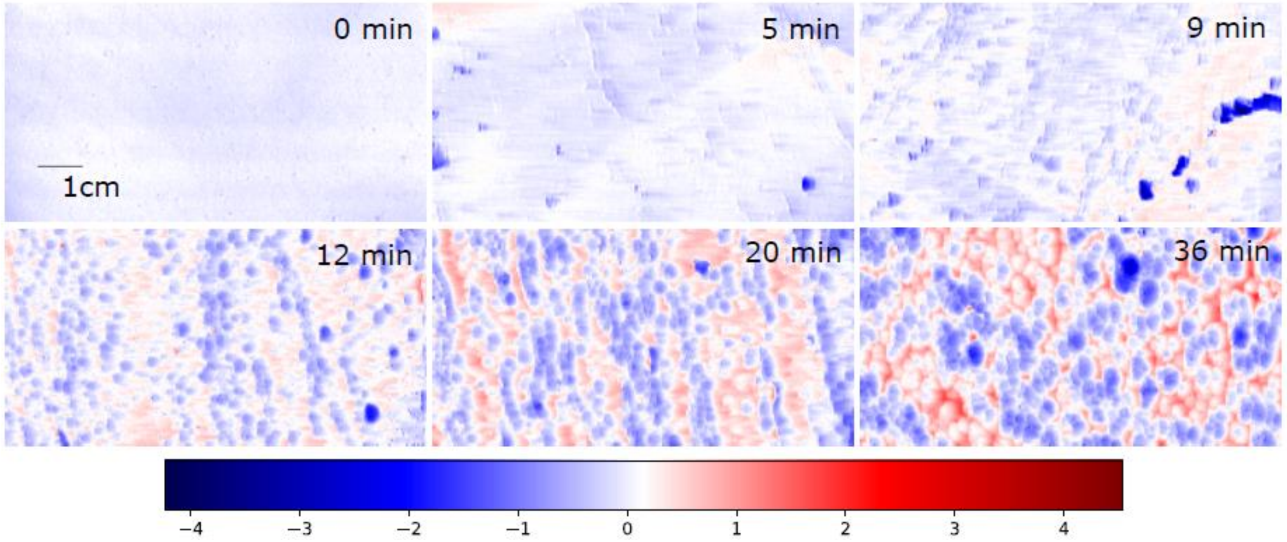
Growth of the rugosity

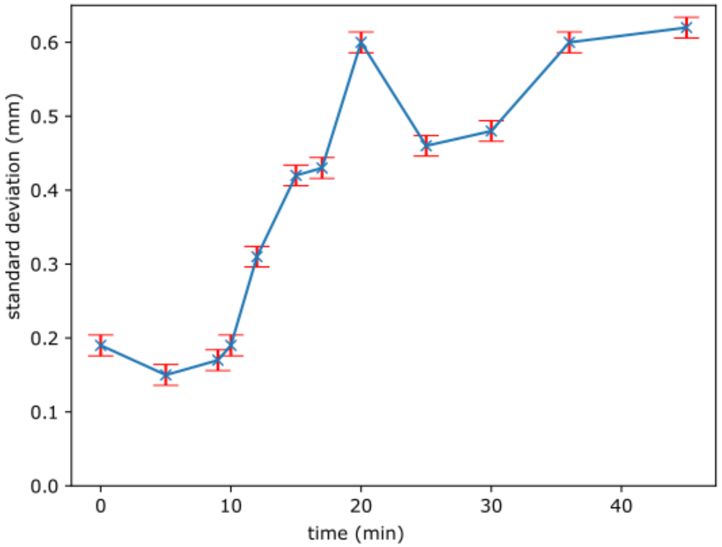
- Pink salt plate of Himalya.
  Independent experiments

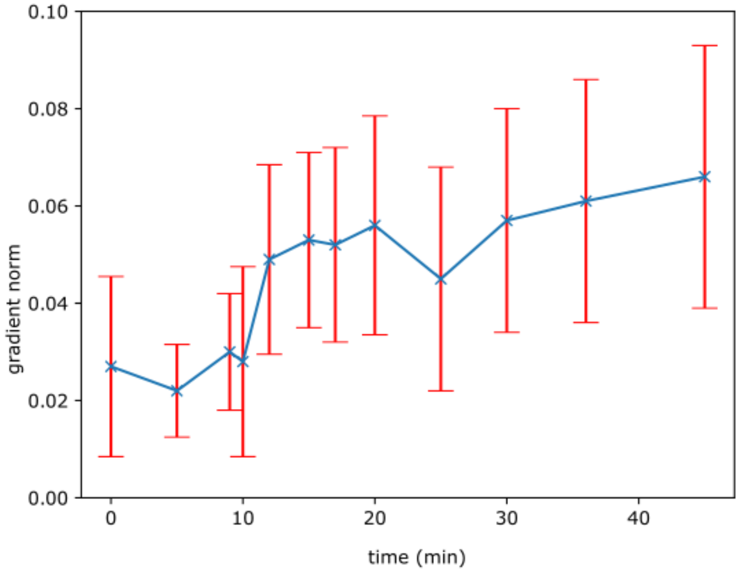
After 20 min

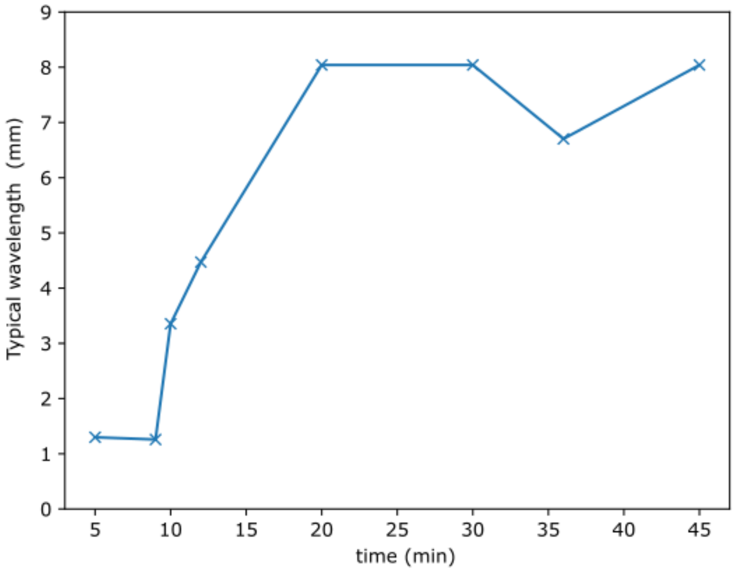
Colormap mm

exposure
time in water
Inclination
56.5°



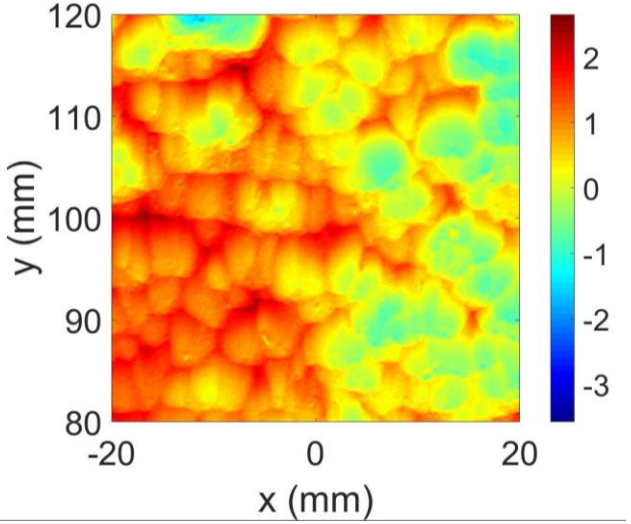




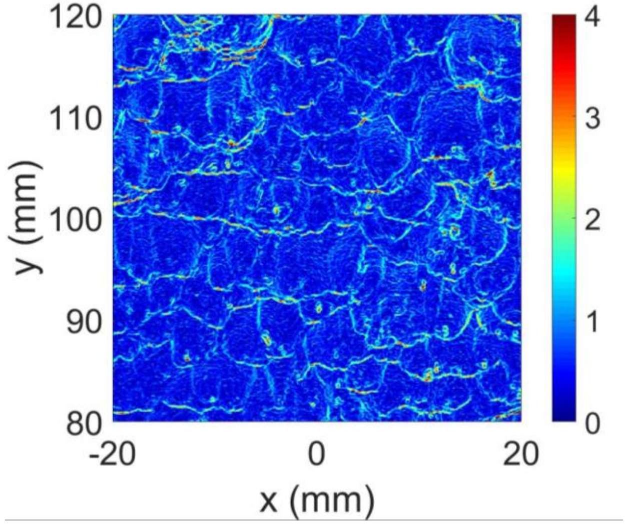


Small scale Shape

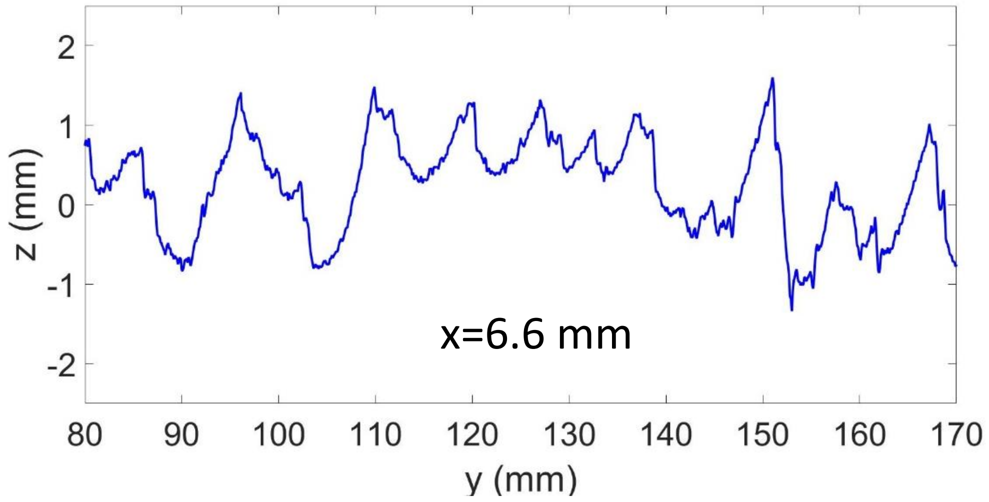
Elevation map Colorscale mm



Gradient



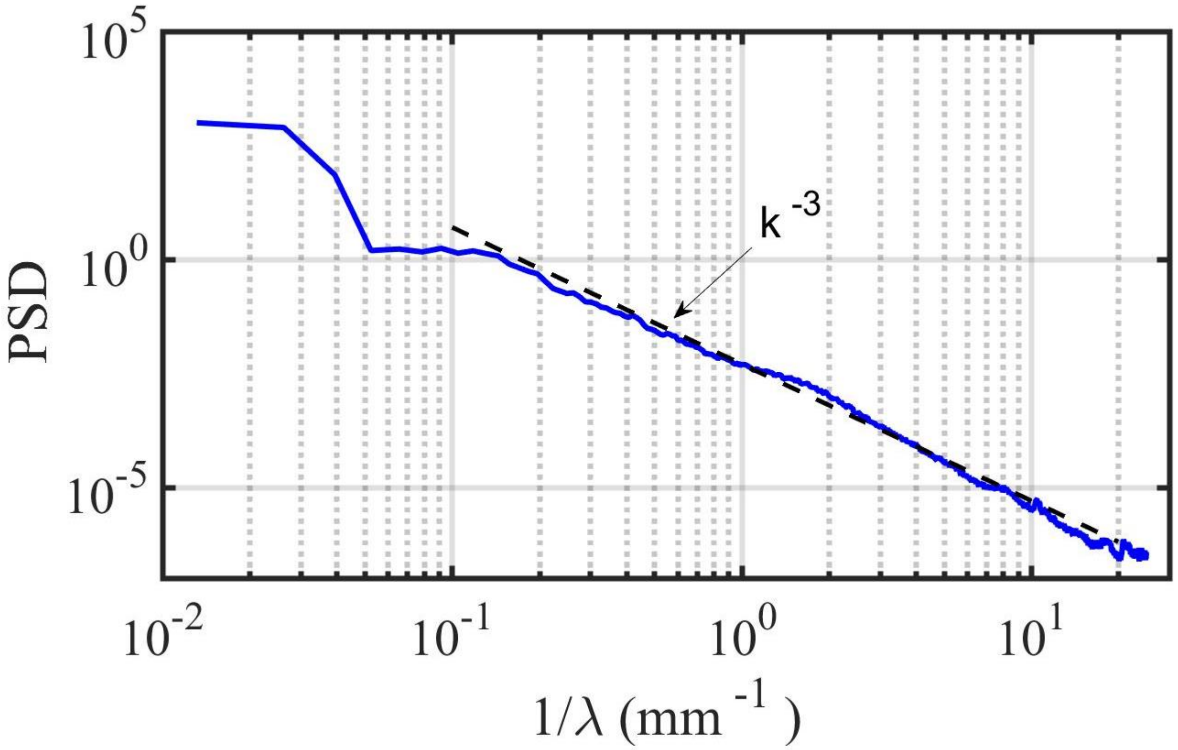
Longitudinal profile



- Experiment 36 min, inclination 56.5°

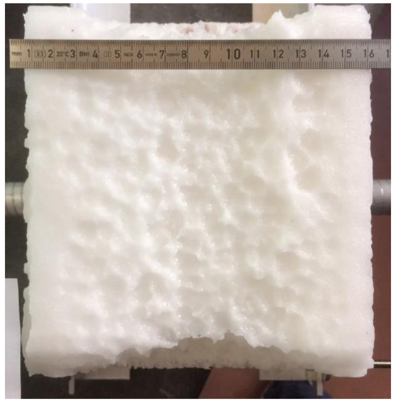
Sharp crests and depressions at small scale. Gradient map delimits the scallops, by underlining the crests positions.

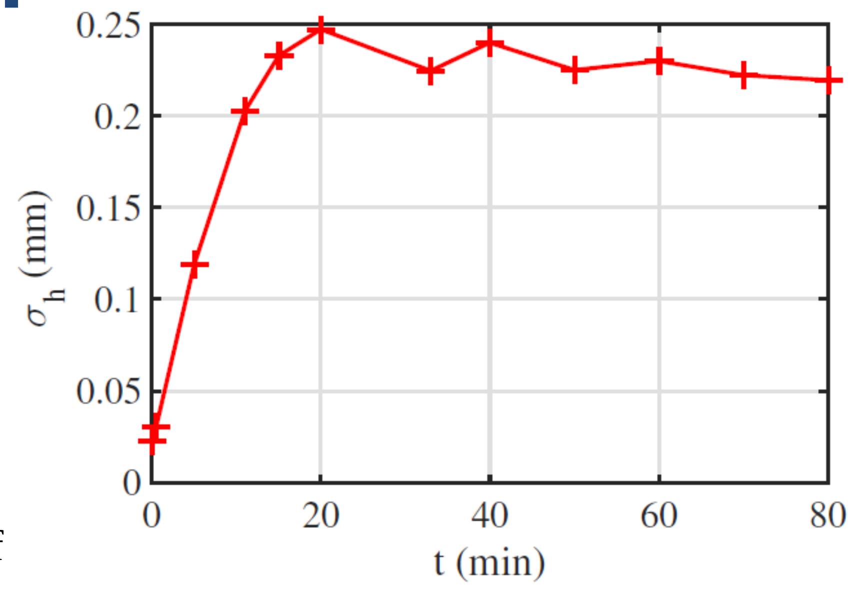
2D average power spectrum of the surface



Singularity power spectrum

● Experiments with large blocks. Inclination 40°.
Saturation of surface standard deviation (rugosity).





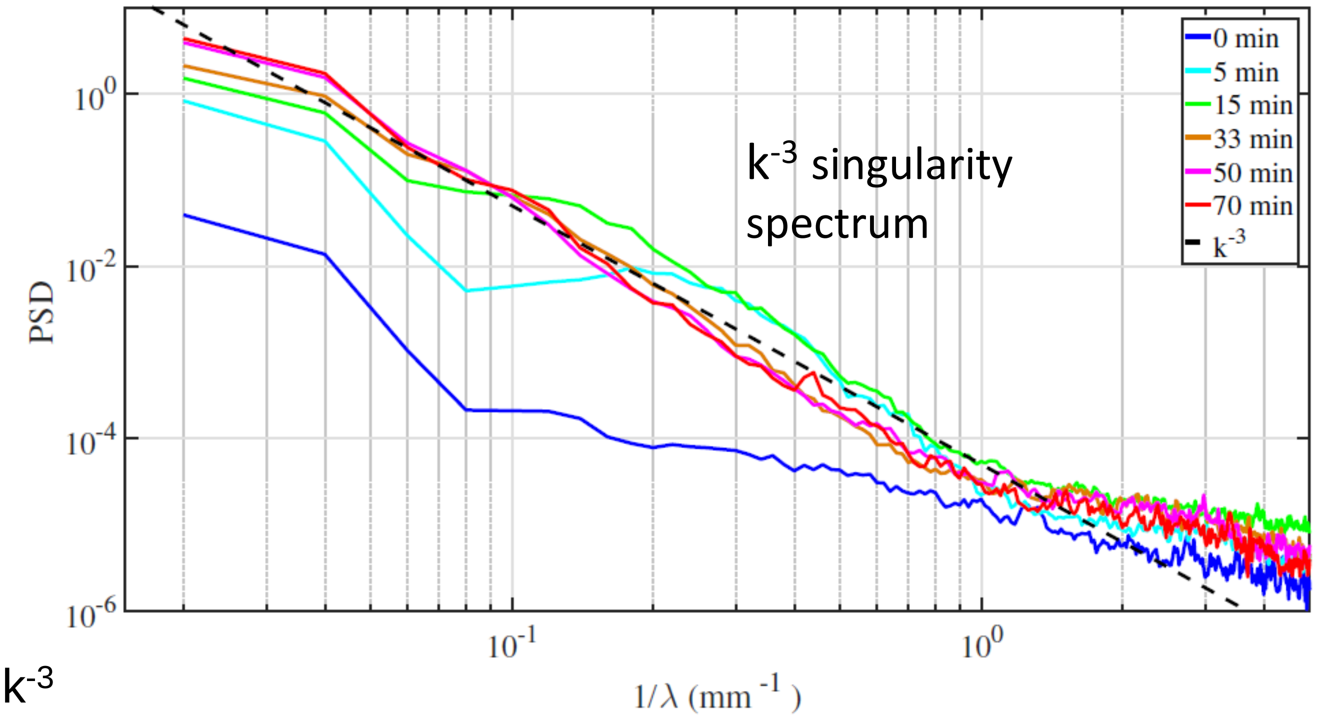
● Power spectrum of surface:
At long times power law in k^{-3} .
See Kuznetsov **JETP** 80 2 (2004)
"Turbulence Spectra Generated by Singularities"
Surface: Cusps, discontinuity second derivative (Dirac delta comb) + regular function f

$$\frac{\partial^2\eta}{\partial x^2} + \frac{\partial^2\eta}{\partial y^2} = \sum_i \Gamma_i\, \delta(\mathbf{r} - \mathbf{r_i}) + f(\mathbf{r})$$

Applying 2D spatial Fourier transform

$$k^2\,\tilde{\eta} \sim \sum \Gamma_i\, \mathrm{e}^{-\imath\,(k_x\,x + k_y\,y)} \quad \text{with} \quad k^2 = k_x^2 + k_y^2$$

$$\tilde{\eta} \sim k^{-2}$$



With hypothesis of isotropy,
angular averaged power spectrum.

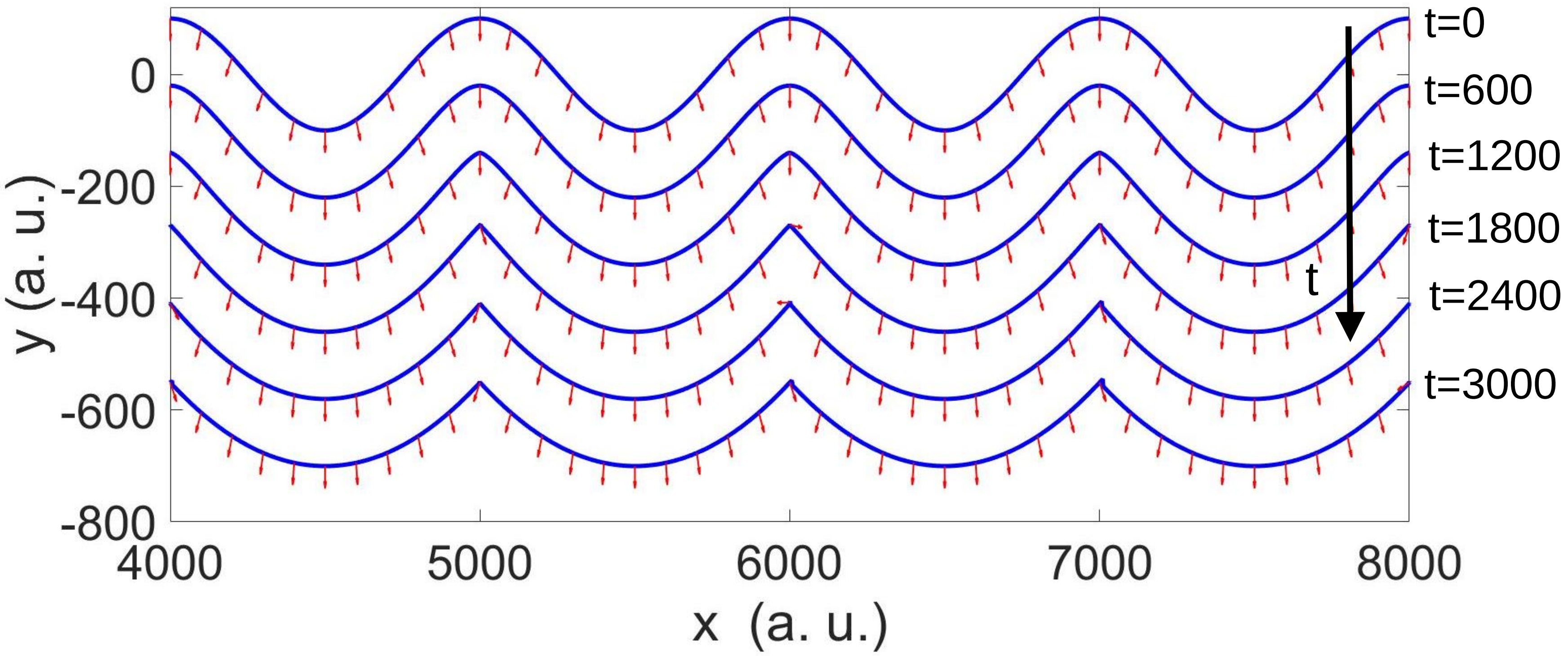
$$PSD = 2\,\pi\,k\,|\tilde{\eta}|^2 \sim k^{-3}$$

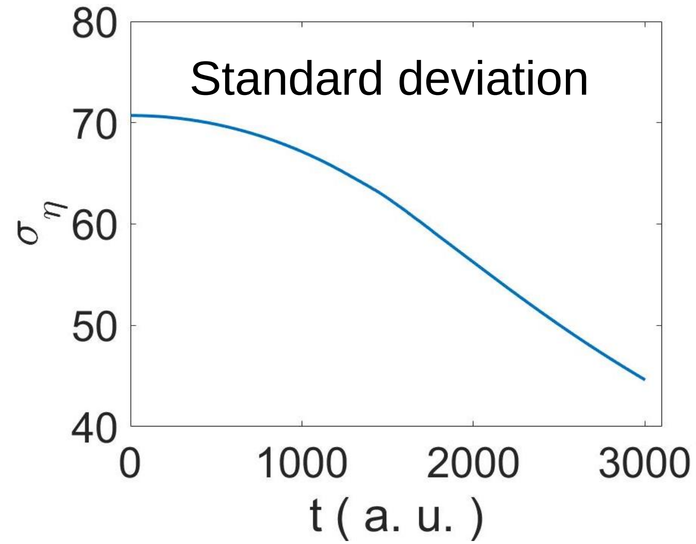
Surface dominated by point-like singularities ⇒ PSD in k^{-3}

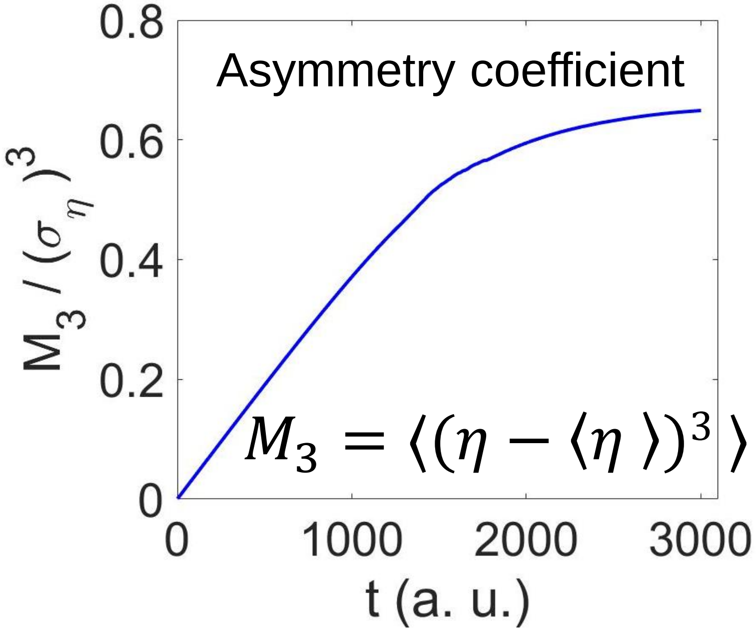
Emergence of singularities in finite time.

● Simple ablation model. Surface retracting with a constant velocity normal at its interface.
Case of a well stired liquid.

2D Example: Starting with a sine profile, evolution of η(x,t)







$$M_3 = \langle(\eta - \langle\eta\rangle)^3\rangle$$

● Stable wavelength. Profiles is deformed.
Cusp singularity. Profile becomes asymetrical.
But patterns amplitude decreases with time (non physical).

Conclusion

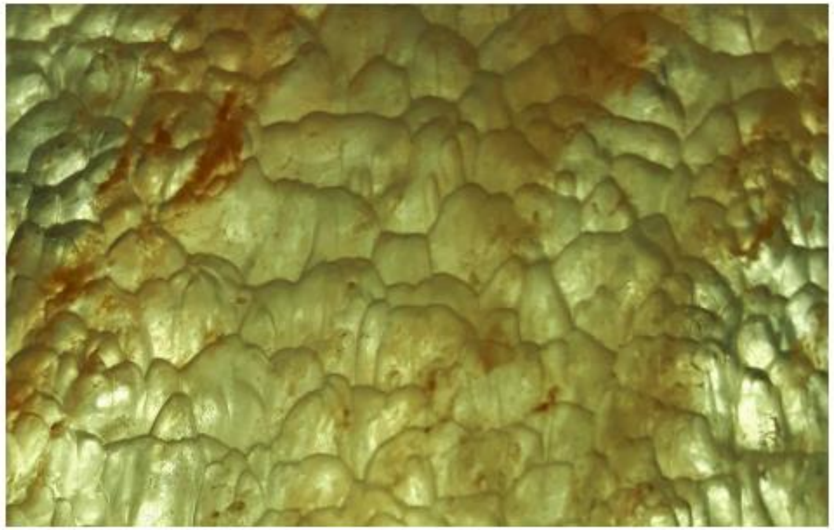
- Dissolution patterns, at small scale
  characterized by sharp shape:
  spikes, pits, scallops …

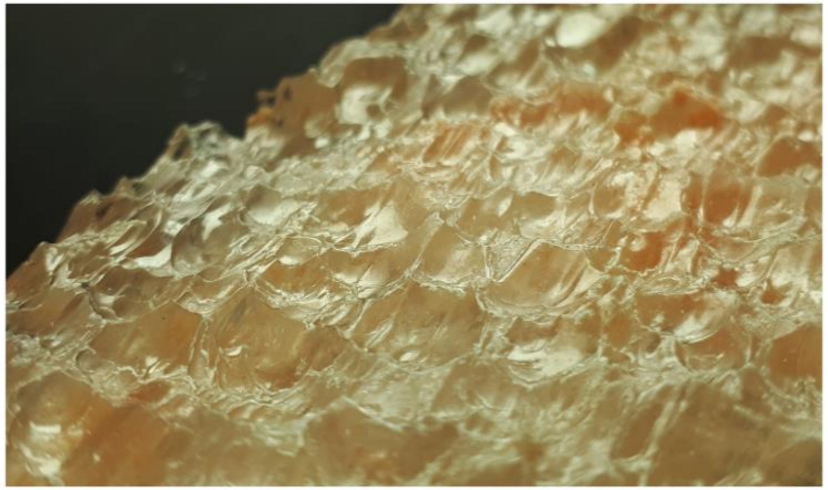
- Emergence of singularities in finite time by ablation model.
  Shape stability of a retracting surface. Mathematical problem.
  Regularization by the Mullins-Sekerka effect ?
  Dissolution velocity increases with the local curvature at the micron scale.

- Must be coupled to hydrodynamics models
  to explain the actual dissolution shapes

- Increase of the area of the solid/liquid interface.
  Important when dissolution controlled by the chemical kinetics,
  but likely does not change the erosion rate,
  when solute transport is the limiting mechanism.

- Need of numerical simulations at small scale
  to resolve the concentration boundary layer.





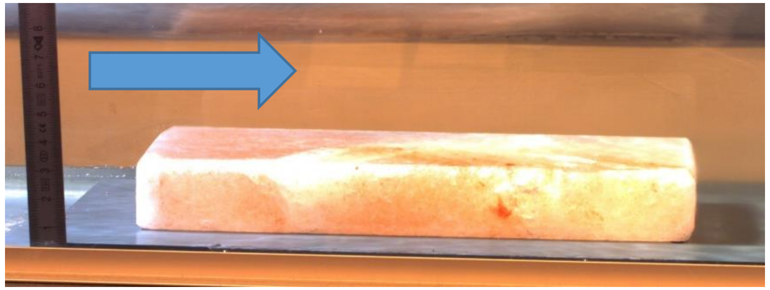
Perspectives

- Scallops created by a turbulent flow. Request a stream velocity of order 1m/s or more.

Preliminary experiments show a longitudinal pattern of flutes.
Formation of scallops by a transverse instability mechanism (see Claudin et al. JFM 2017)
may occur by the destabilization of a longitudinal pattern in agreement with experiments of Allen performed with gypsum.

- In agreement with experiments of Allen performed with gypsum.

Allen **J. Fluid Mech. 49, 1, 49 (1970).**
"Bed forms due to mass transfer in turbulent flows:
a kaleidoscope of phenomena"
Moulds of longitudinal ridges in the early stage of the instability
U ~ 0.3 m/s 193 h
Image width 28 cm



30 min U ≈ 0.2 m/s

Flutes λ ~ 5mm