Morphology of scallop patterns in erosion by dissolution

Michael Berhanu (CNRS researcher)

Raphael Dubourg, Arthur Walbecq, Cyril Ozouf (Interns)

Adrien Guerin, (Post-doctoral researcher)

Julien Derr, (Associate Professor)

Sylvain Courrech du Pont (Associate Professor)

MSC (Matière et Systèmes Complexes), CNRS, Paris Diderot, Université de Paris

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

- 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
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 Heimkehrle gypsum cave, Germany (photo by S. Kempe).


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”

- 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
“Solutal convection induced by dissolution”

Analog mechanism for ice melting. Scallops

Transmission images for caramel. Pattern on the bottom face
Initial longitudinal stripes. Then, emergence of scallops.
Solutal convection experiments at MSC

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

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

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

- 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

- $k^{-3}$
**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

\[
k^2 \tilde{\eta} \sim \sum_i \Gamma_i e^{-i(k_x x + k_y y)} \quad \text{with} \quad k^2 = k_x^2 + k_y^2
\]

\[
\tilde{\eta} \sim k^{-2}
\]

With hypothesis of isotropy,
angular averaged power spectrum.

\[
PSD = 2 \pi k |\tilde{\eta}|^2 \sim k^{-3}
\]

Surface dominated by point-like singularities $\Rightarrow$ 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 stirred liquid.

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

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

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

<table>
<thead>
<tr>
<th>$t$</th>
<th>$\sigma_\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>600</td>
<td>70</td>
</tr>
<tr>
<td>1200</td>
<td>60</td>
</tr>
<tr>
<td>1800</td>
<td>50</td>
</tr>
<tr>
<td>2400</td>
<td>40</td>
</tr>
<tr>
<td>3000</td>
<td>30</td>
</tr>
</tbody>
</table>
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.
Scallops created by a turbulent flow. Request a stream velocity of order 1 m/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.

Flutes $\lambda \sim 5$ mm

In agreement with experiments of Allen performed with gypsum.


“Bed forms due to mass transfer in turbulent flows: a kaleidoscope of phenomena”

Moulds of longitudinal ridges in the early stage of the instability $U \sim 0.3$ m/s 193 h

Image width 28 cm