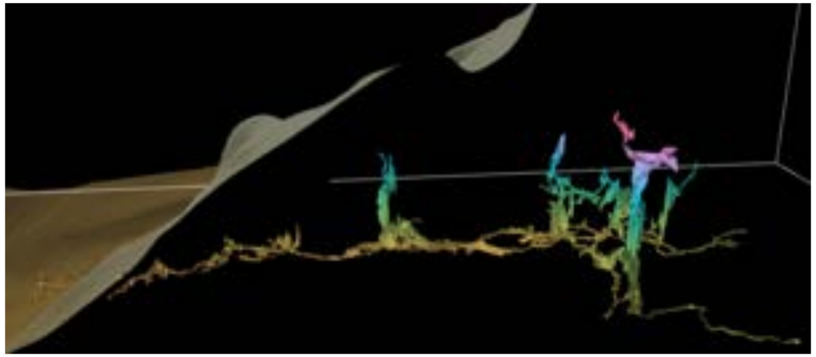
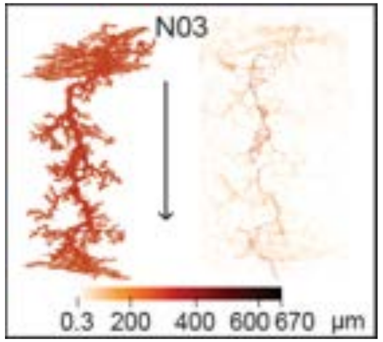
KASPER

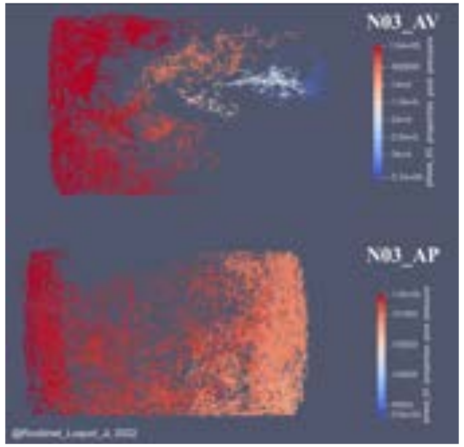
KArst system Self-organization for water resource Protection and vulnERability



Garrel karstic system from karst3D database (m-km)



X-ray tomography images and pore network models (cm)



Flow simulations on PNMs

Kick-off meeting, Montpellier, 2025-01-21

Context – Karst properties and vulnerability

Karst systems :

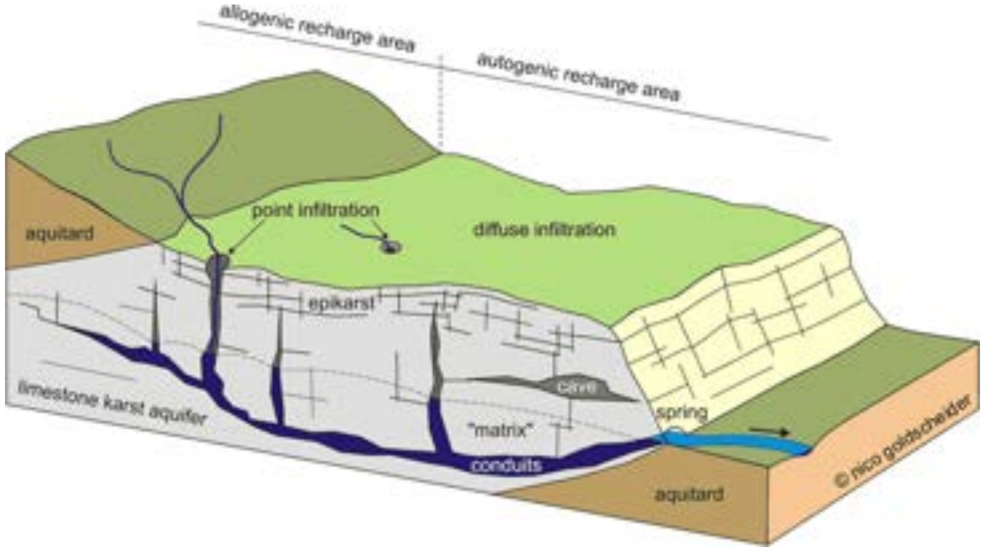
- water resource for one fourth of the worldwide population
- 30% of the surface area in France
- main perennial water resource of the Mediterranean basin

Properties of karst systems:

- highly permeable hierarchical conduits over significant extent

➢ recharge dynamics

➢ propagation of contaminants



Bloc diagramme schématique d'un karst binaire [Goldscheider & Drew, 2007]

Vulnerability of karst systems related to their heterogeneous properties and organization

➢ **Need to understand karst formation**

Context – Karst formation hypothesis

Traditional paradigm

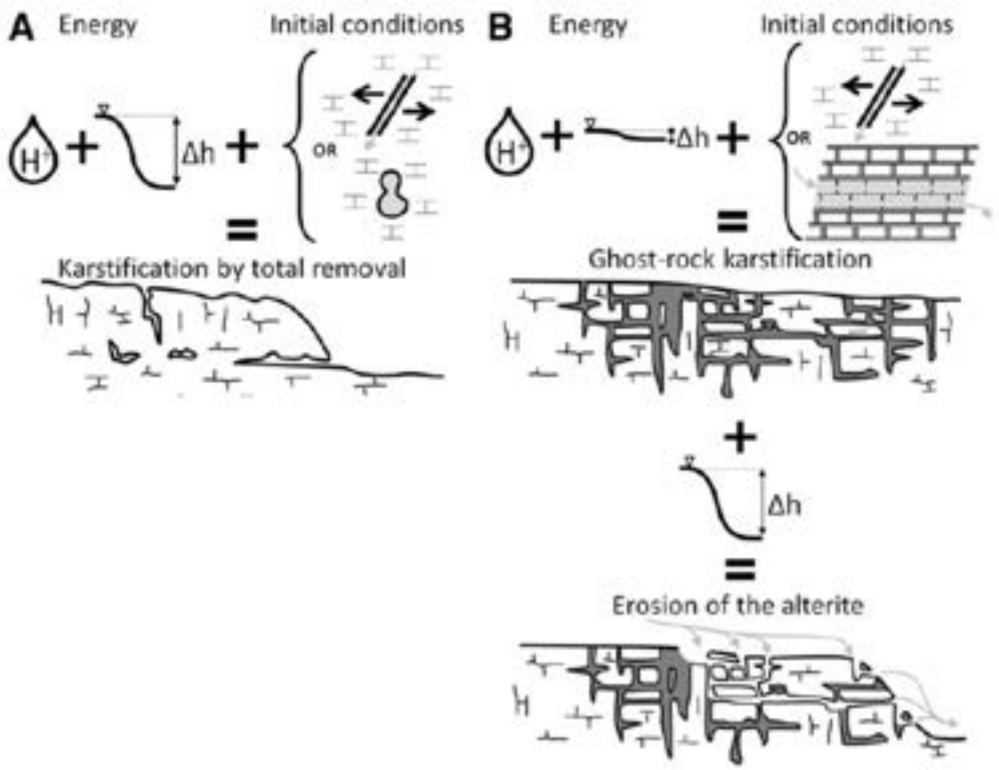
- Acidic rainwater circulates along open discontinuities
- Matter is dissolved and removed during its circulation
    - ➢ **Dissolution and erosion processes occur simultaneously**

➢ Fails explaining the genesis of numerous karstic systems

Ghost-rock karstification

- Phase1: chemical dissolution + low hydraulic gradients
    - ➢ Ghost-rock formation
- Phase 2: strong changes in hydrodynamic + mechanical erosion
    - ➢ Matter removal and pathways formation

➢ **Decoupled chemical and mechanical processes**



The thermodynamic concept of karstification [Dubois et al., 2014]

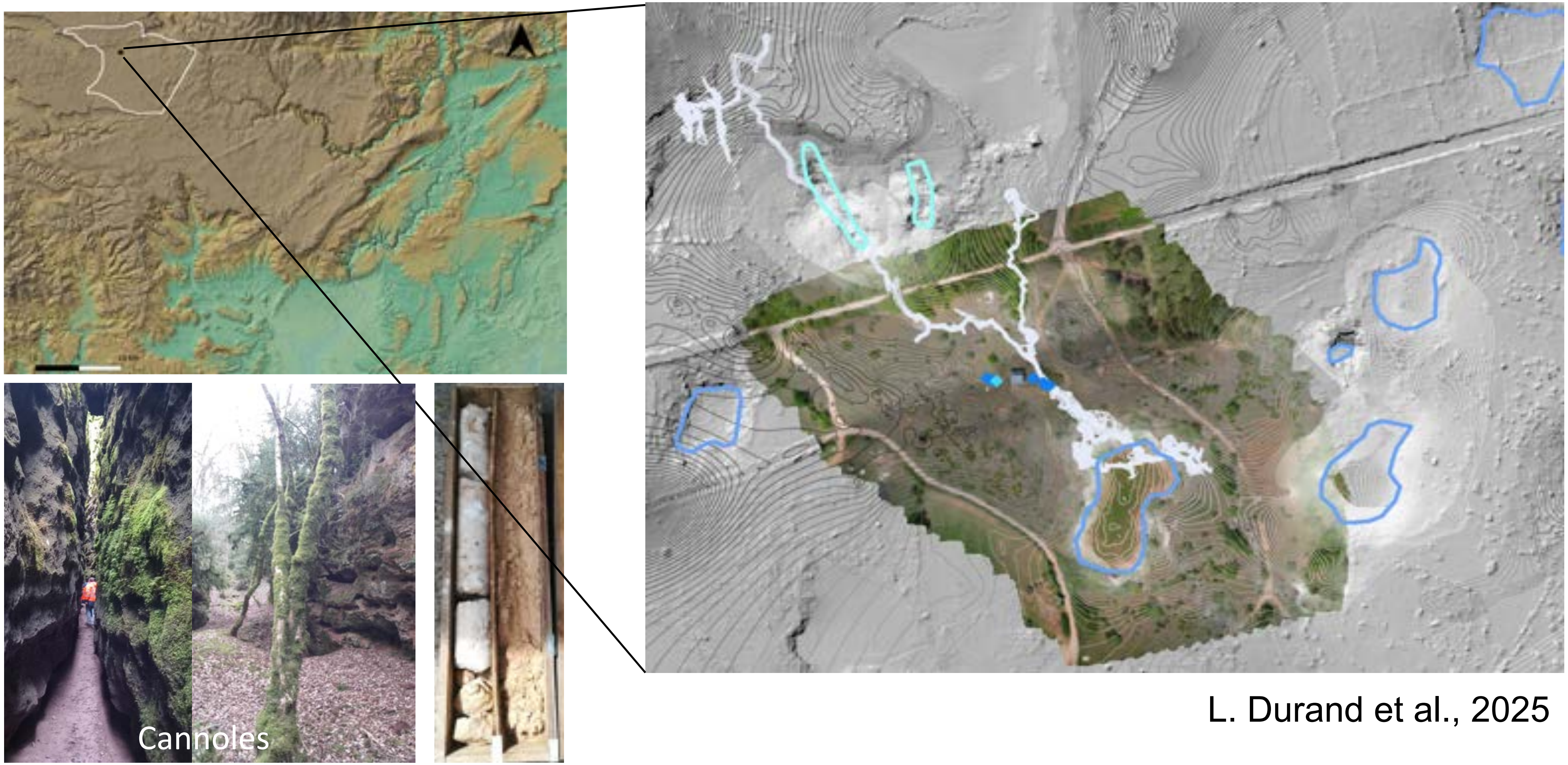
Objectives and methodology

➢ **Improve our understanding of karst system formation: traditional paradigm VS ghost-rock theory**

- Field-scale observations: Larzac site and karst3D database
- Laboratory-scale measurements: dissolution experiments under various conditions
- Modeling tools: from the laboratory to field scale

Field scale at the Larzac site

- Evidence of ghost-rock formation on the site



L. Durand et al., 2025

Preliminary work – Field scale at the Larzac site

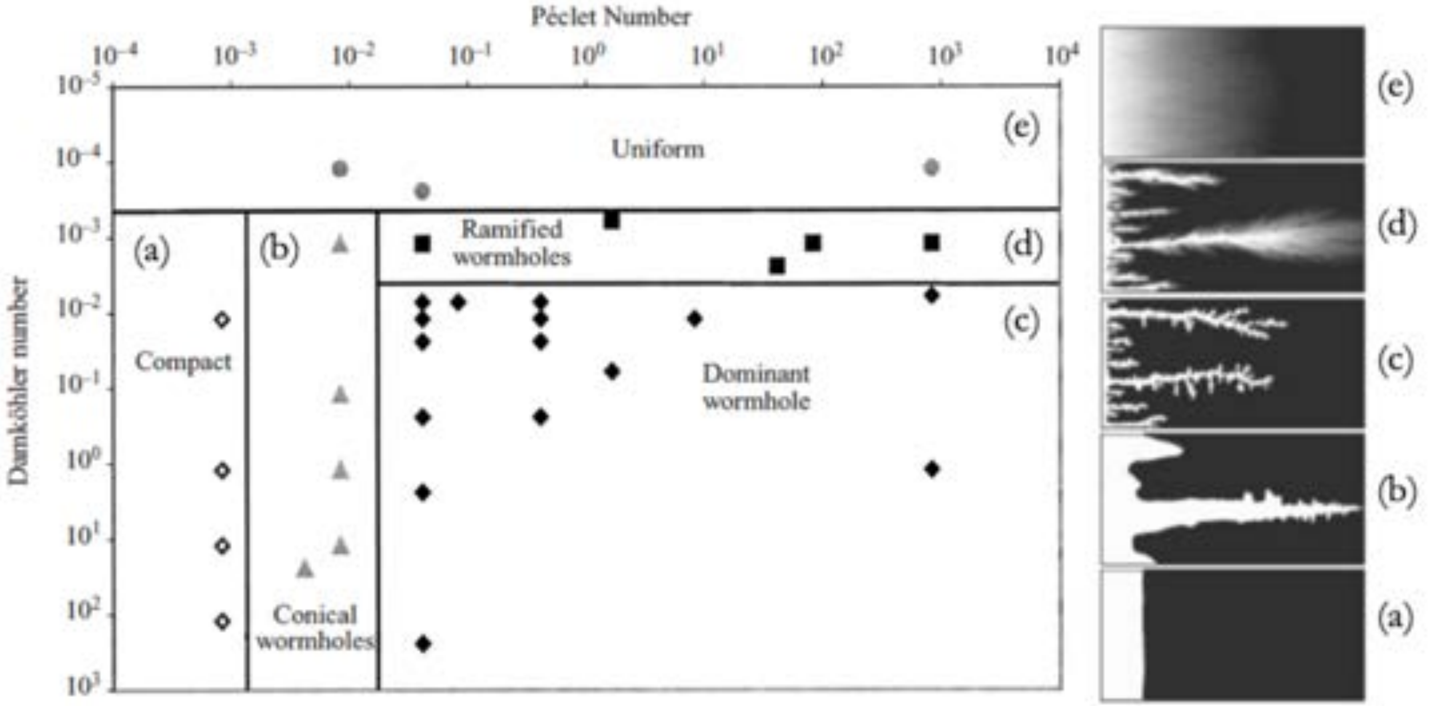
- Data available on the site: chemical measurements, geophysical imaging

L. Durand et al., 2025

Preliminary work – Laboratory experiments (in the literature)

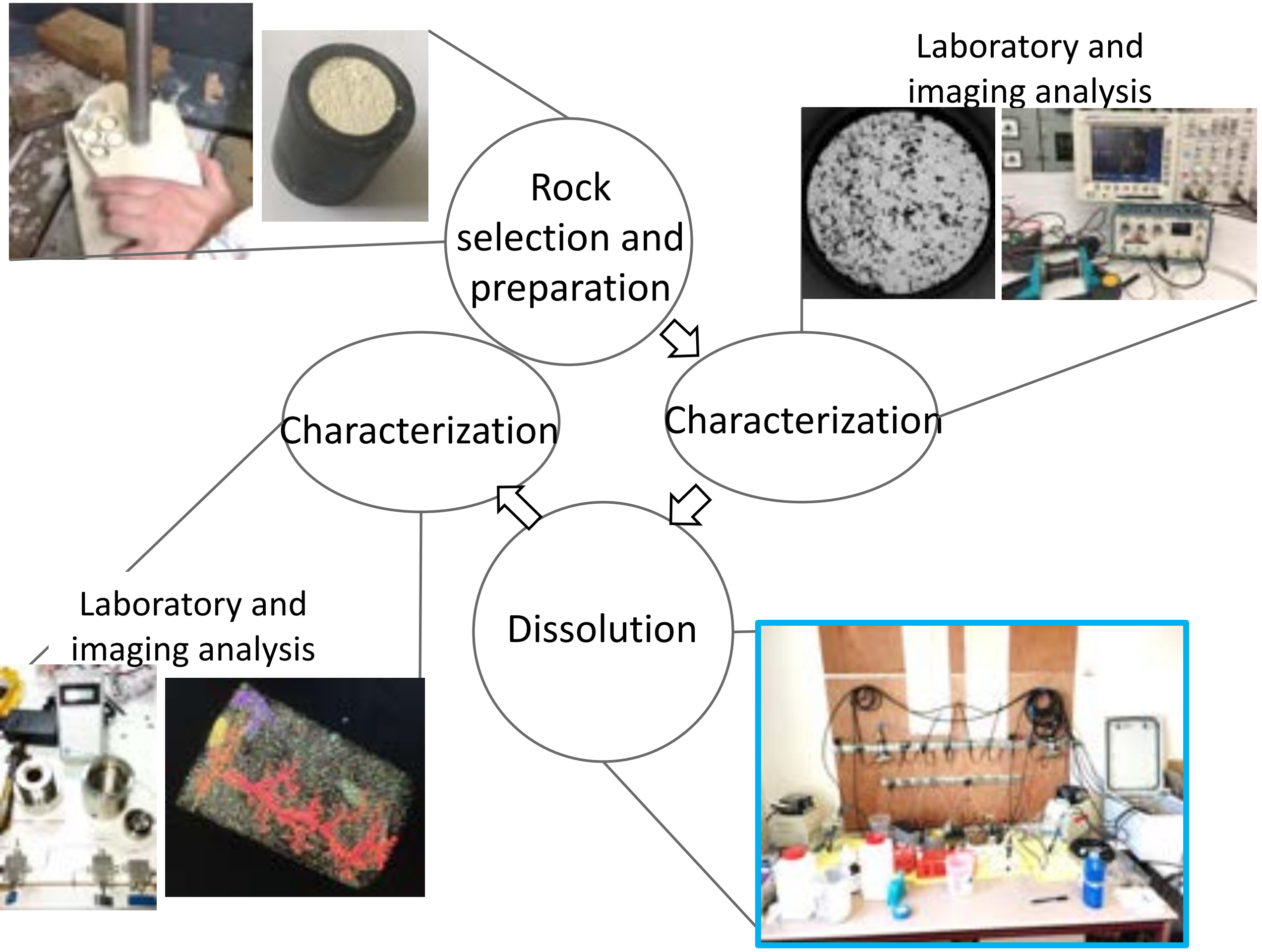
- Dissolution experiments on carbonate rocks
- Changes in chemical and structural properties
- Associated numerical simulations

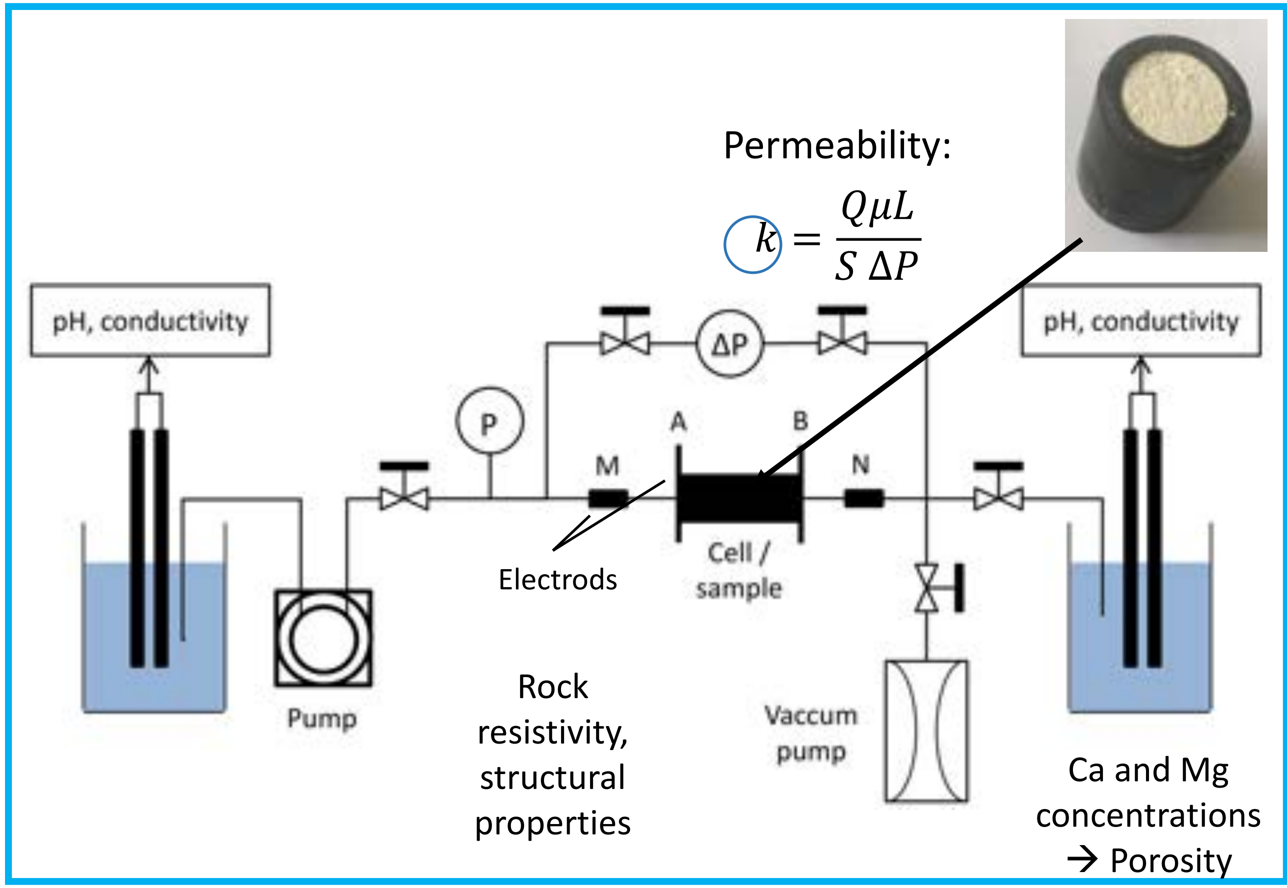
➢ Various dissolution regimes
➢ Driven by hydro-chemical conditions



Dissolution regimes from numerical simulations (modified from [Golfier et la., 2002])

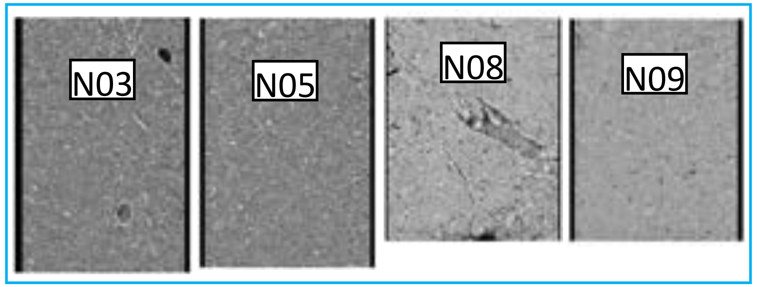
Preliminary work – Laboratory experiments (in the team)



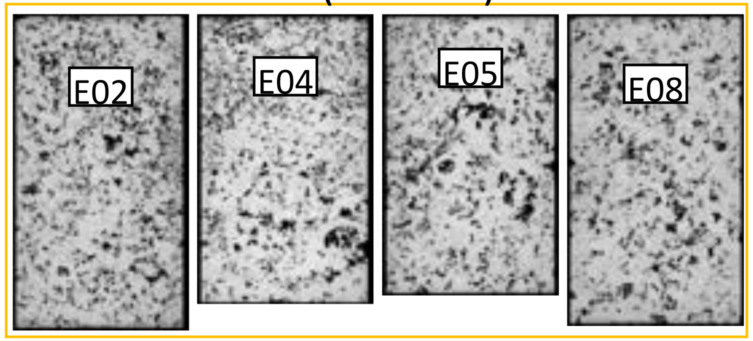


Preliminary work – Laboratory experiments (in the team)

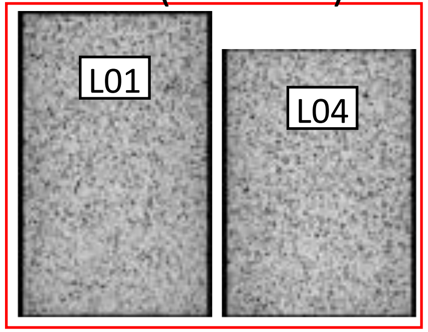
Normandie (craie)

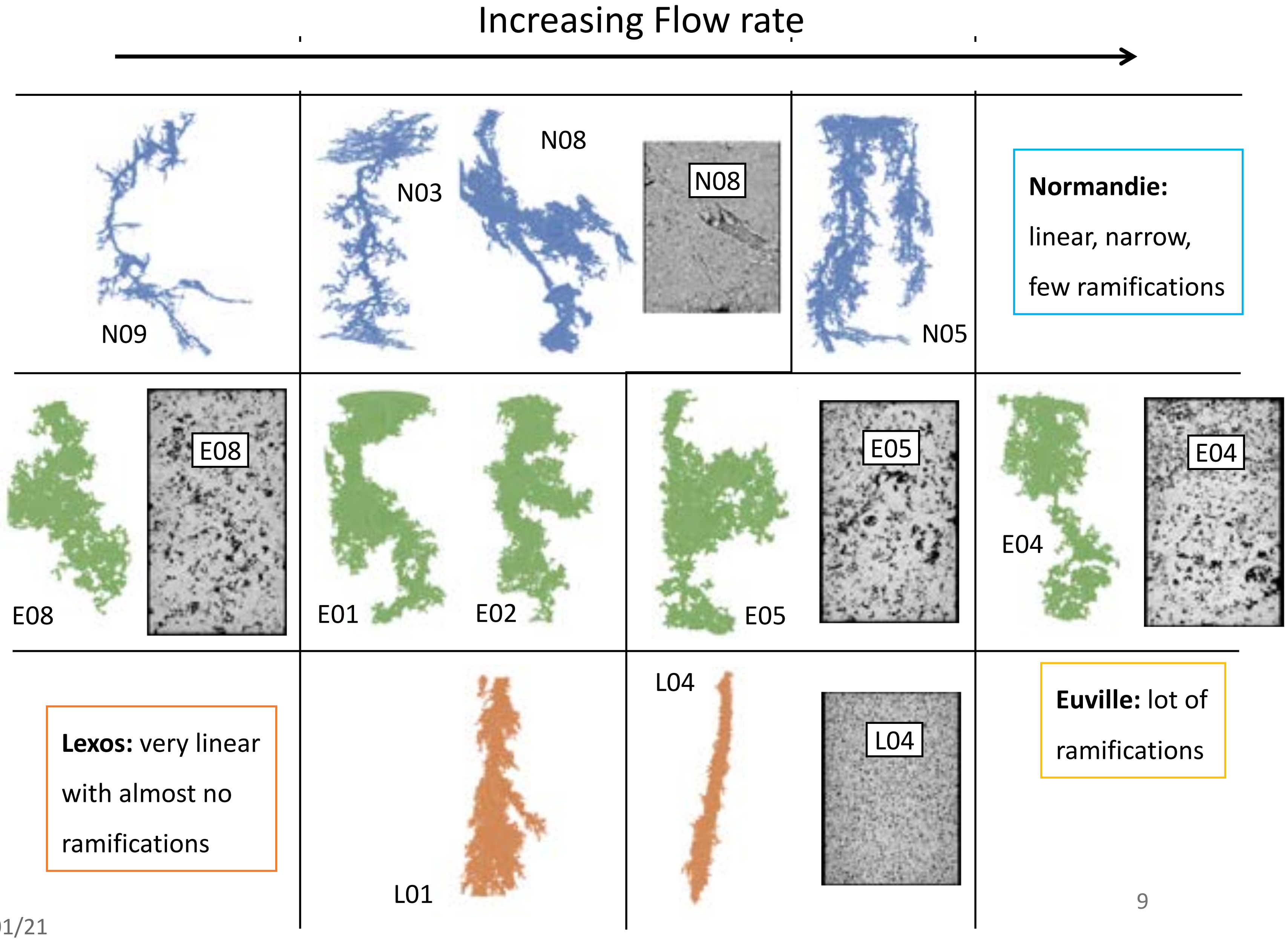


Euville (calcaire)



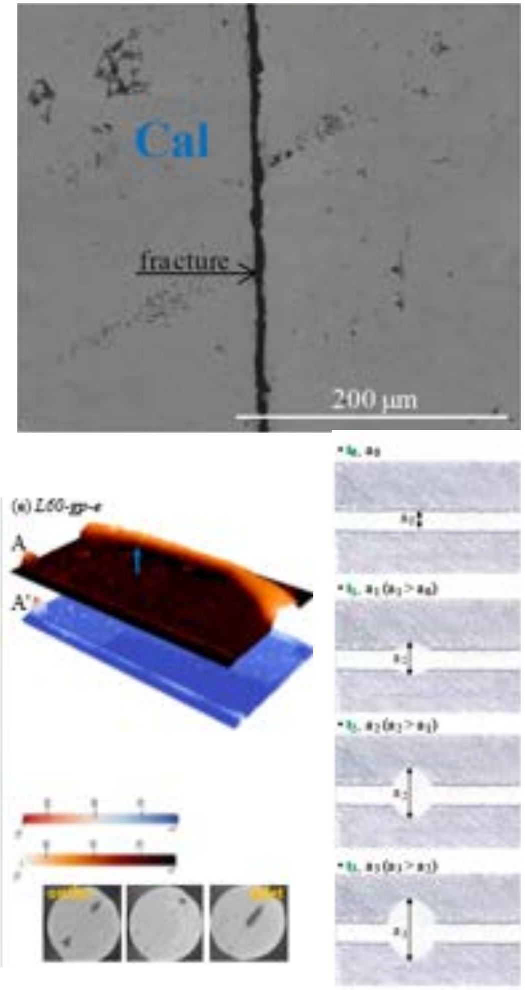
Lexos (dolomie)



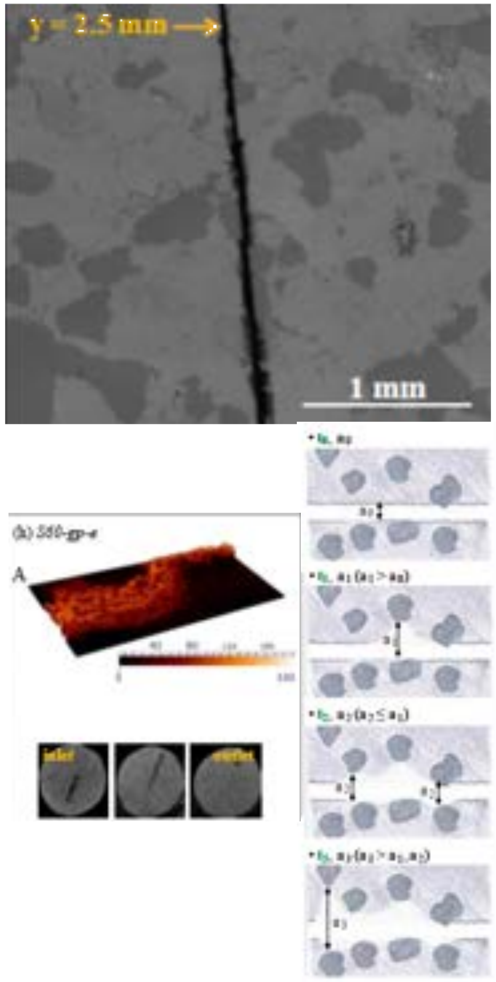


Preliminary work – Laboratory experiments (in the team)

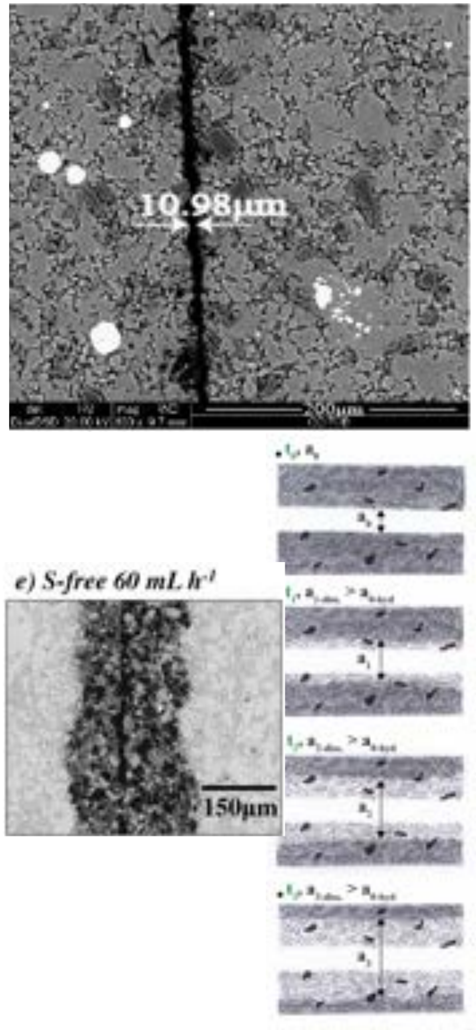
Limestone
(100% calcite)



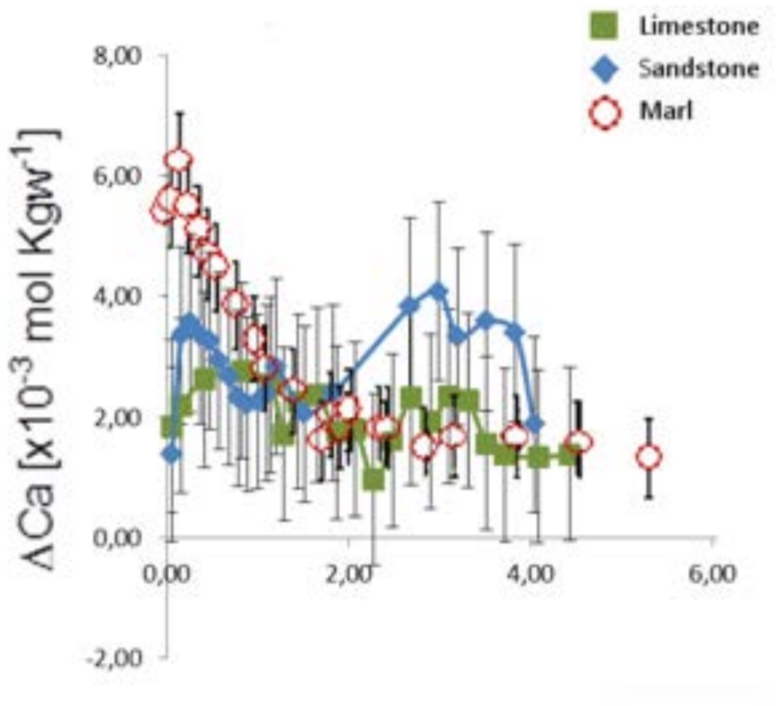
Sandstone
(67% calcite, 33% quartz)



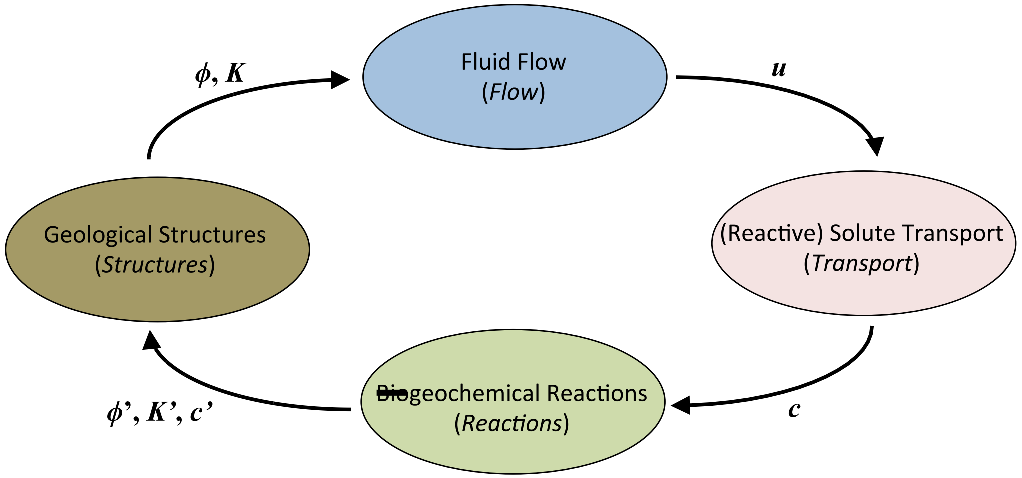
Marl
(70% calcite, 10% quartz, 18% clays, 2% oxides)



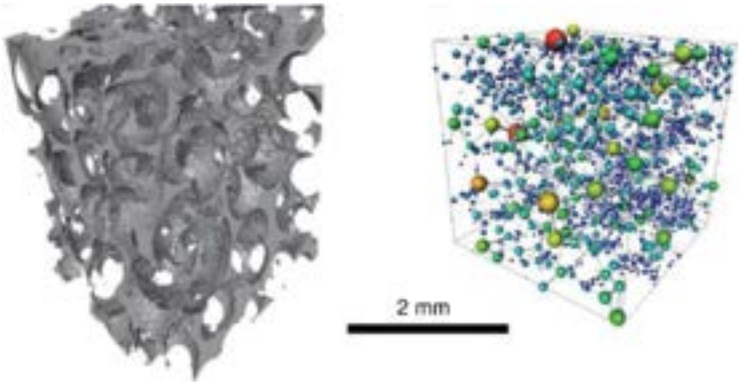
Dissolution rates
limestone < sandstone < marl



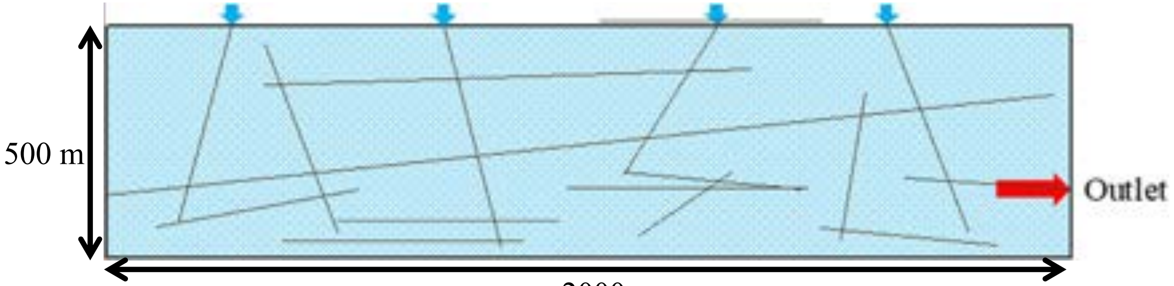
Preliminary work – Numerical modeling (in the literature)



Hydro-geochemical coupling



(a) Pore space image of carbonate. (b) Corresponding pore network model (PNM) [Blunt et al., 2013; Baqer and Chen, 2022]



Conceptual model of a fracture network in a carbonate aquifer [modified from Maqueda et al., 2023]

Chemical reactions of calcite-dissolution problems:

(i) Hydrolysis of acetic acid:

$$CH_3COOH_{(aq)} \leftrightarrow CH_3COO^-_{(aq)} + H^+_{(aq)} \quad (1)$$

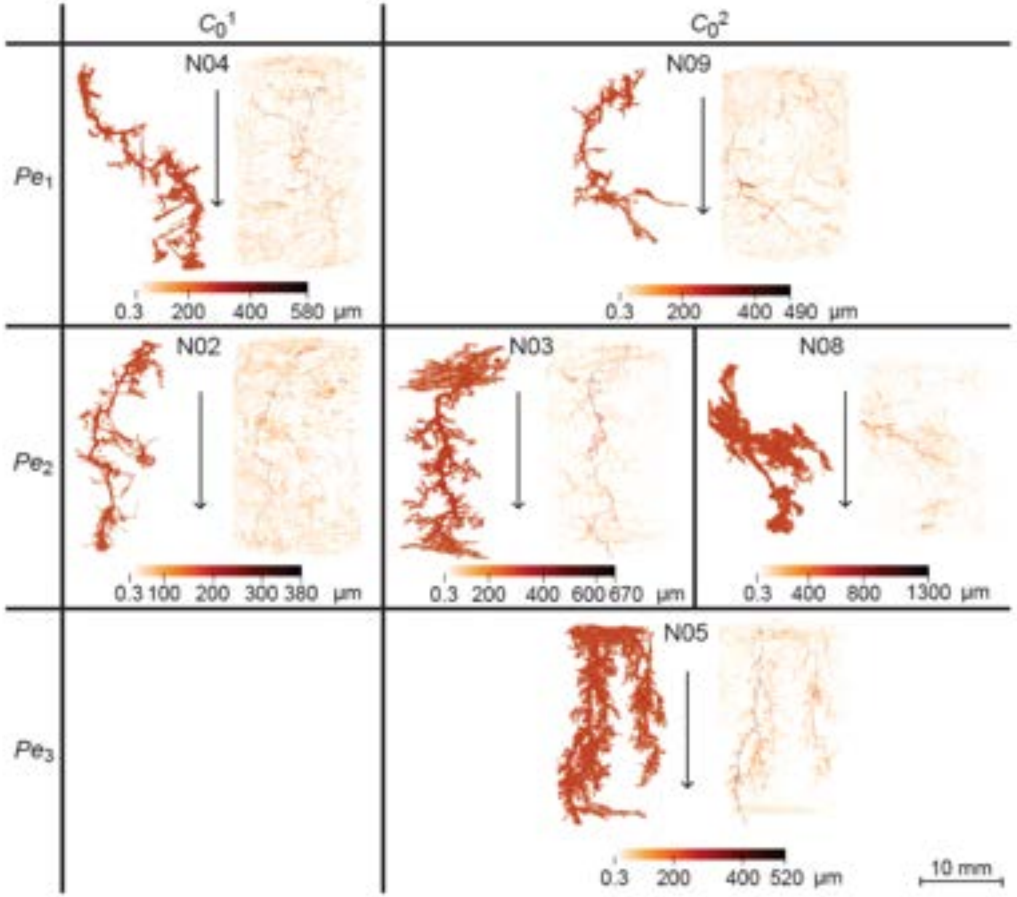
(ii) Kinetic of calcite dissolution:

$$CaCO_{3(s)} + H^+_{(aq)} \rightarrow Ca^{2+}_{(aq)} + HCO^-_{3(aq)} \quad (2)$$

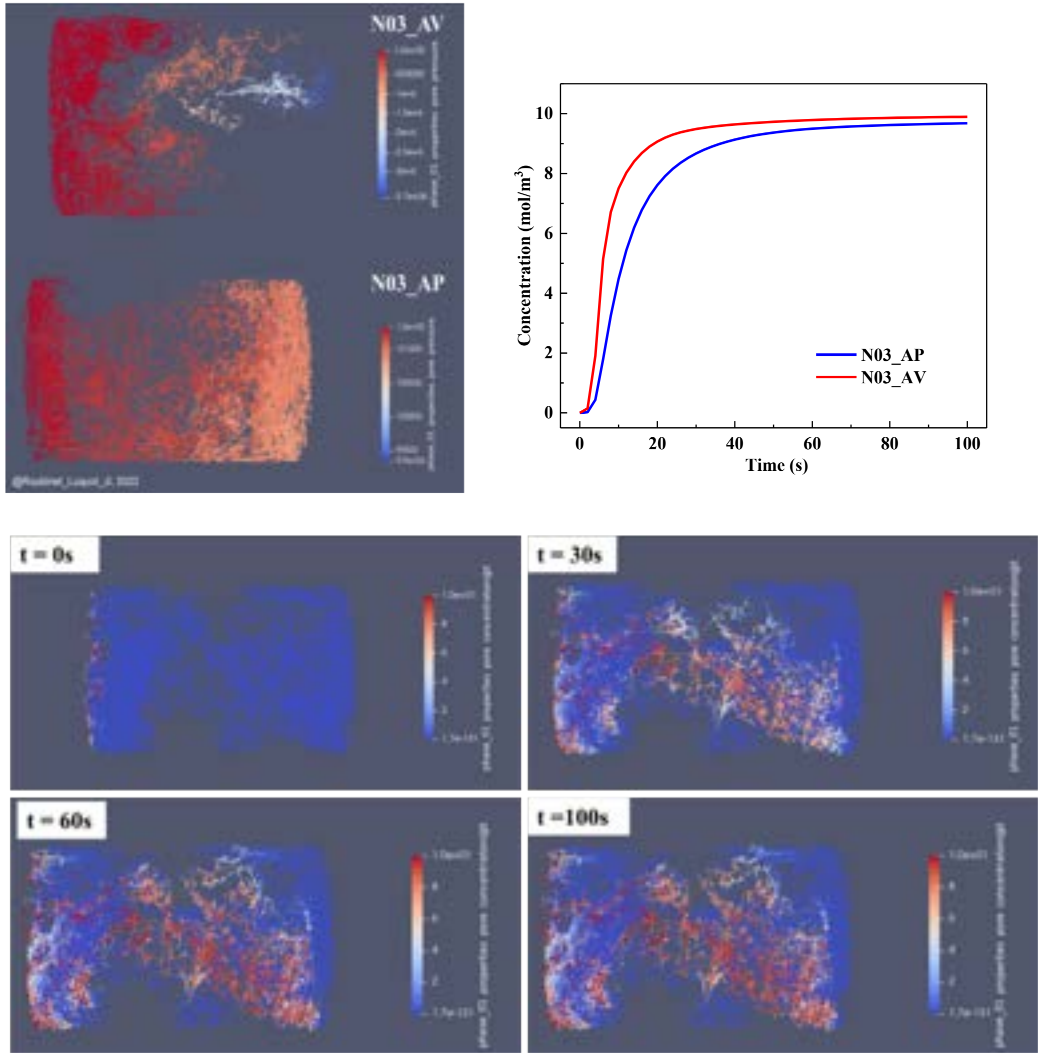
(iii) Equilibrium with carbon dioxide:

$$CO_{2(g)} + H_2O_{(l)} \leftrightarrow HCO^-_{3(aq)} + H^+_{(aq)} \quad (3)$$

Preliminary work – Numerical modeling (in the team)

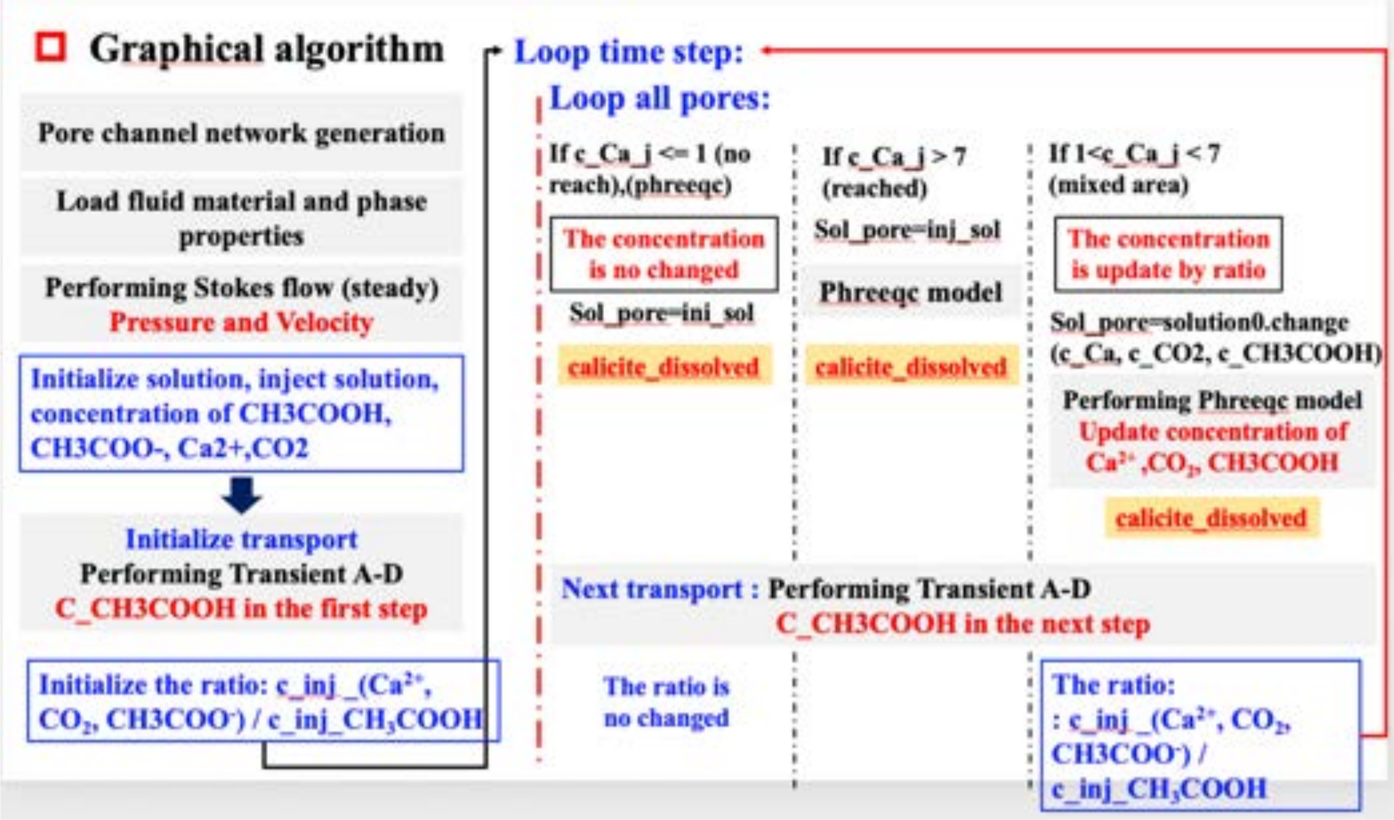


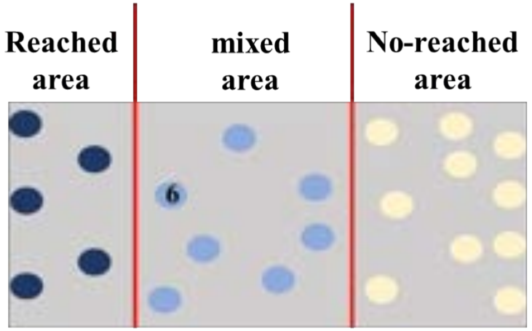
X-ray tomography images and PNMs of carbonate samples after dissolution experiments [Leger et al., 2022]



Flow and transport simulation for sample NO3 with OpenPNM software [Ji, 2023]

Preliminary work – Numerical modeling (in the team)





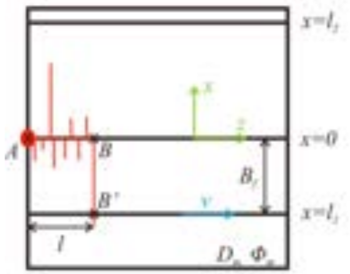
Assumption:

1. Reached area: The solution in pores is updated by injection solution in each time step.
2. No-reached area: The solution in pores is initial solution with no changed.
3. Mixed area: The concentration is update by the ratio.

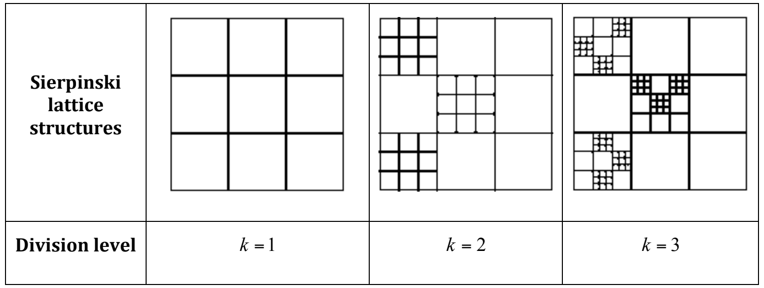
Reactive transport algorithm by coupling OpenPNM and PhreeqC [Ji, 2023]

➢ **Computational time and storage too heavy : continue the parallelization of the code + work on simplified PNMs**

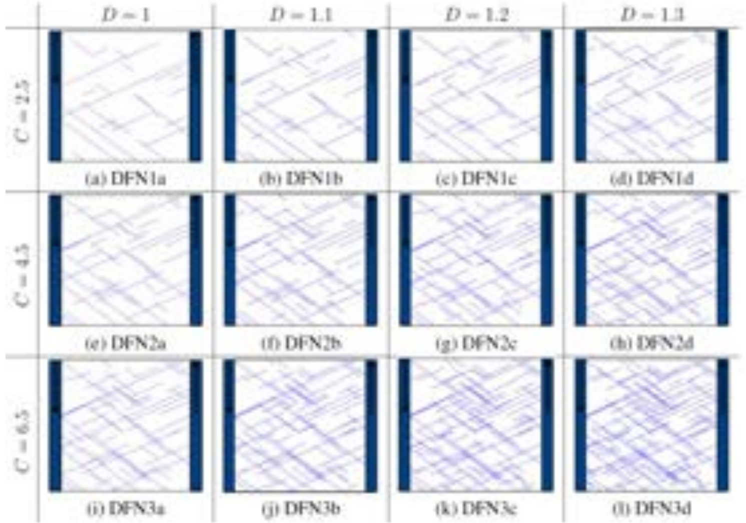
Preliminary work – Numerical modeling (in the team)



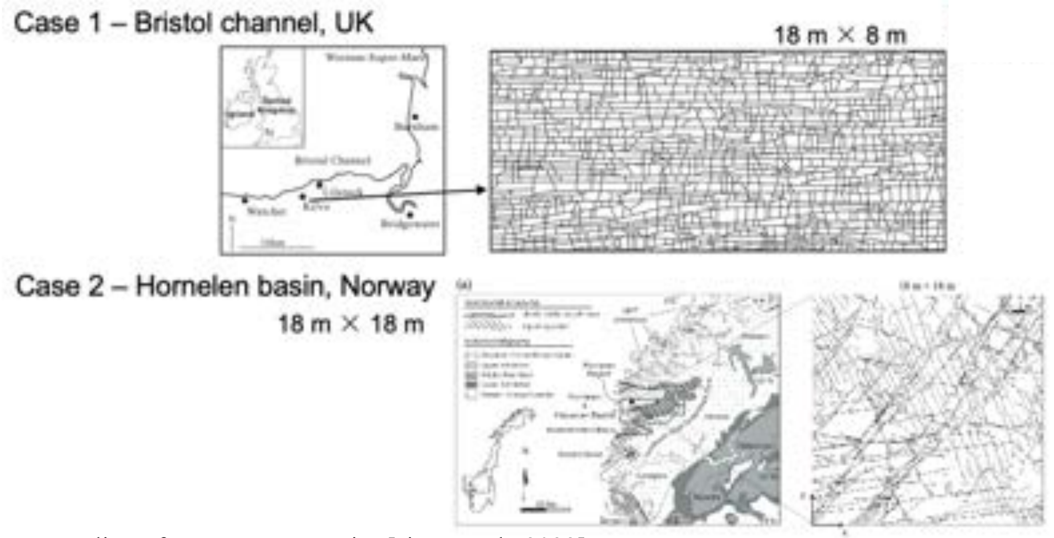
Particle-based method
[Roubinet et al., 2010]



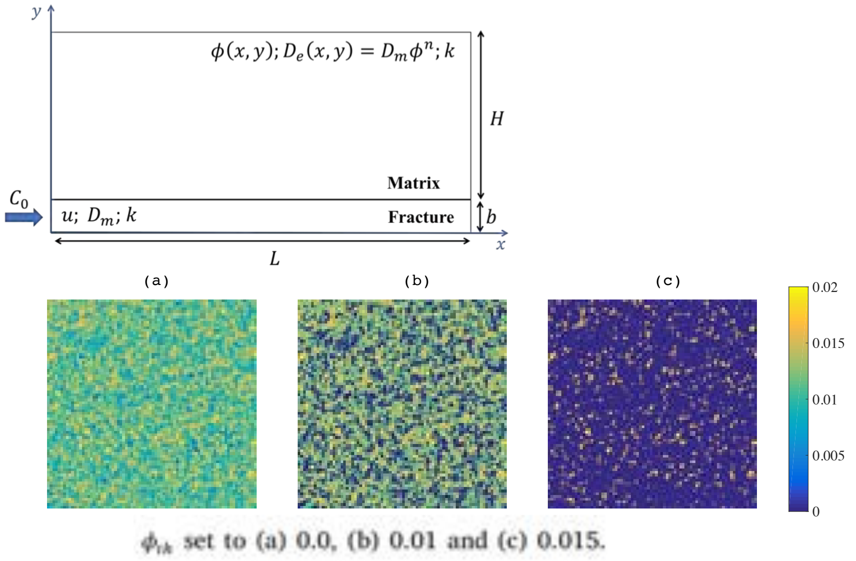
Solute transport simulations in Sierpinski lattice structures
[Roubinet et al., 2013]



Heat transport simulations in fractal models [Gisladottir et al., 2016]



Upscaling of transport properties [Jiang et al., 2022]



Reactive transport with heterogeneous matrix at the fracture-matrix scale [Roubinet et al., 2022]

Methodology and team

LABORATORY EXPERIMENTS (WP1)

- Reproduce ghost-rock formation
- Link rock properties/experimental conditions and formation concept

Linda Luquot
Sandra Van-Exter
Post-doc

Provide data for code implementation/validation →

← Complementary information to link properties and formation concept

NUMERICAL MODELING (WP2)

- Reproduce “traditional” laboratory experiments
- Link numerical method and formation concept
- Investigation of field-scale simulations

Delphine Roubinet
Gérard Lods
Master and PhD students

↔ Comparison of structures

Provide data for code implementation/validation

Complementary information to link properties and formation concept

FIELD-SCALE OBSERVATIONS (WP3)

- Comparison between lab-scale and field-scale structures
- Identification of different formation concept in karst3D database
- Field data for large-scale model

Cédric Champollion
Philippe Vernant
Research engineer

- ANR PRME: Projet de Recherche Mono-Equipe (Single team research project)

Methodology and team

Gantt chart

	2025		2026	2027	2028	
WP1 – Laboratory experiments	*WP1*					Reports
WP2 – Numerical models	*WP2a*	*a*	*WP2b*	*WP2c*	*WP2d*	
WP3 – Field work and database				*WP3*		

(green)	Master's internship	(blue)	PhD student
(grey)	Research engineer	(orange)	Post-doctoral research

Starting now: M2 internship with Pu Li –> laboratory experiment and numerical models
2025-09: PhD student
2026: post-doctoral position
2027: engineer position

Coming soon... website and logo ☺

https://anr-kasper.gm.umontpellier.fr

References

- Baqer, Y., Chen, X. (2022) A review on reactive transport model and porosity evolution in the porous media. Environmental Science and Pollution Research, 29, 47873–47901, 10.1007/s11356-022-20466-w.
- Blunt MJ, Bijeljic B, Dong H, Gharbi O, Iglauer S, Mostaghimi P, Paluszny A, Pentland C (2013) Pore-scale imaging and modelling. Adv Water Resour 51:197–216
- Golfier, F., Zarcone, C., Bazin, B., Lenormand, R., Lasseux, D., and Quintard, M. (2002) On the ability of a Darcy-scale model to capture wormhole formation during the dissolution of a porous medium, Journal of Fluid Mechanics, 457, pp.213
- Ji J., 2023, Visiting scholar report
- Leger, M., Roubinet, D., Jamet, M., Luquot, L. (2022) Impact of hydro-chemical conditions on structural and hydro-mechanical properties of chalk samples during dissolution experiments, Chemical Geology, 594, 120763
- Maqueda, A., Renard, P. & Filipponi, M. Karst conduit size distribution evolution using speleogenesis modelling. Environ Earth Sci 82, 360 (2023). 10.1007/s12665-023-11035-6.