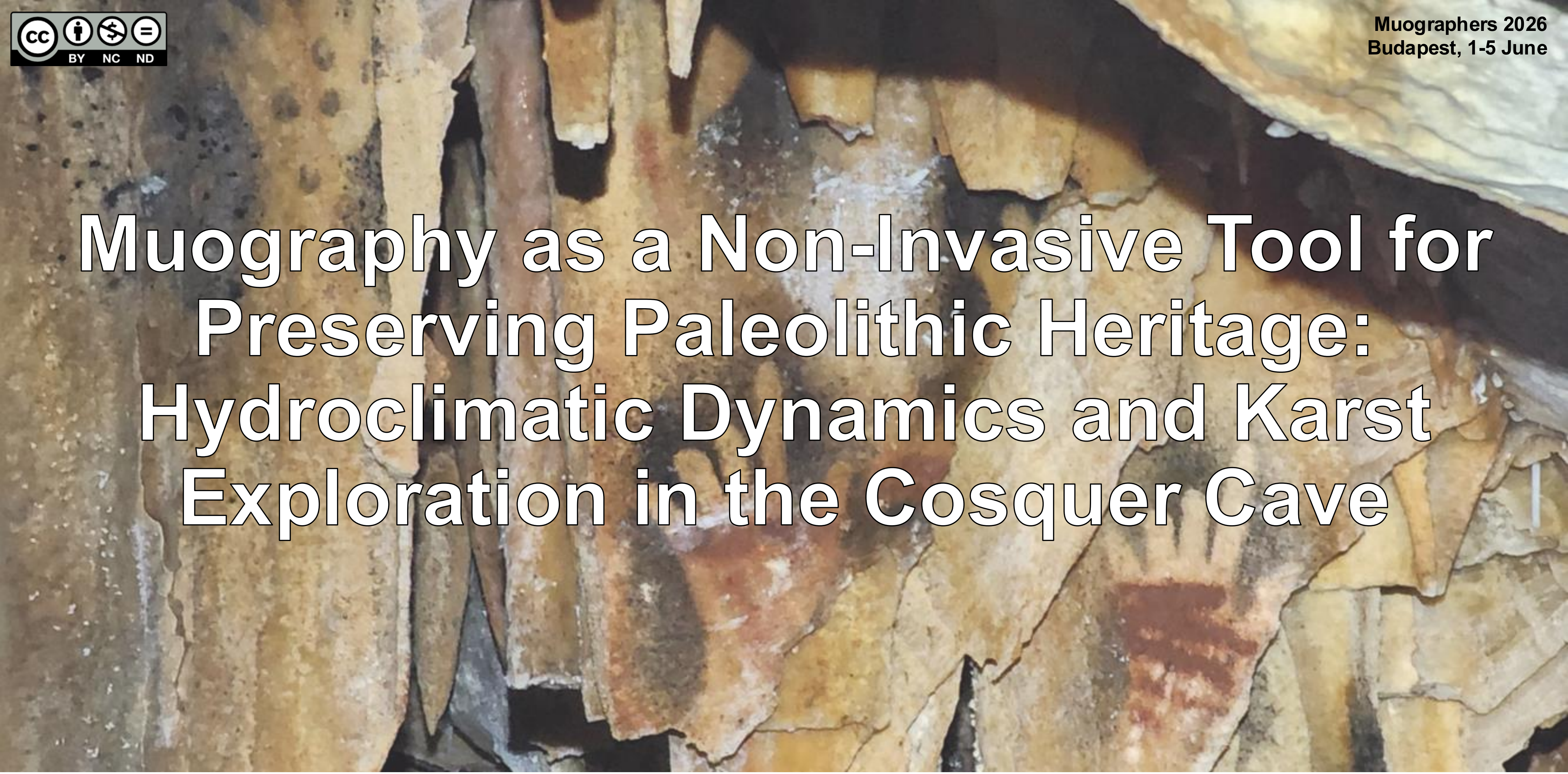
Muographers 2026
Budapest, 1-5 June



Muography as a Non-Invasive Tool for Preserving Paleolithic Heritage: Hydroclimatic Dynamics and Karst Exploration in the Cosquer Cave

LSBB · CNRS · Avignon Université · HUN-REN Wigner

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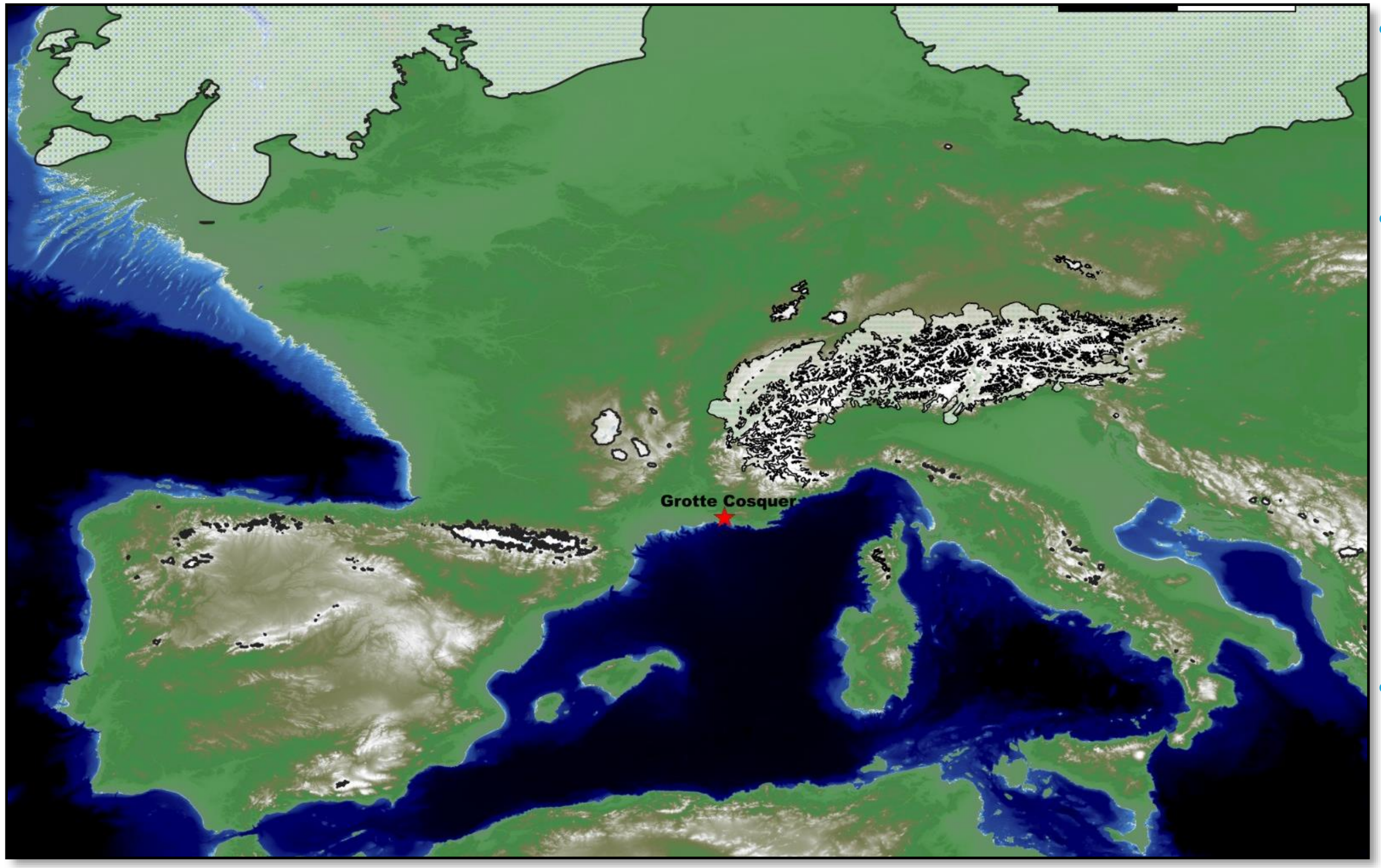
Paleolithic; a different world



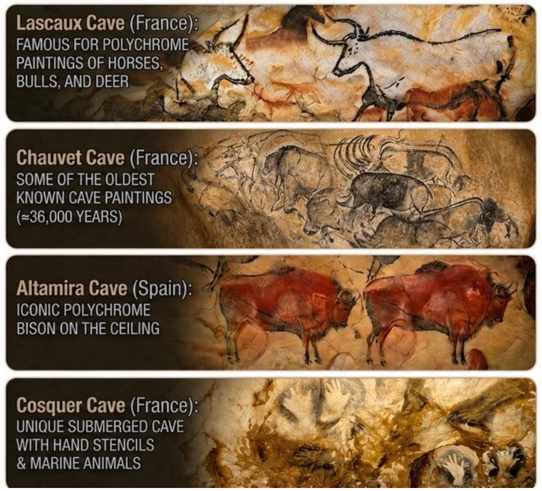
Topographic map of Europe ~33,000 BCE, showing sea level adjustments, and glacial cover.

- Fennoscandian Ice Sheet locked up massive volumes of water, resulting in an ice overburden of up to 3 km.
- This regression drove a 120-meter drop in global sea levels and the emergence of vast landmasses:
  - Doggerland: A fertile bridge connecting Britain to mainland Europe.
  - Mediterranean Shelves: Coastlines extended kilometers outward.
- Pleistocene fauna included extinct megafauna distributed along drastically shifted geographical ranges.
- Concentration of human presence in habitable lands.

A Different World, Different Minds

- Paleolithic **humans were primarily nomadic** or semi-nomadic hunter-gatherers, organized in small mobile groups that moved seasonally in response to resource availability.
- **Caves were used intermittently** as shelters, activity spaces, or symbolic sites, consistent with the presence of concentrated parietal artworks in specific underground locations.
- Paleolithic artistic production includes both **portable art and parietal art**, reflecting early symbolic and cognitive development in human societies.

Parietal art (caves)



Portable art (mobiliary)

Source: Generated by the author.

Ignacio Lázaro Roche
on behalf of the collaboration

A tragic serendipity

The four discoverers: Pascale Oriol, Cendrine Cosquer, Yann Gogan and Henri Cosquer.

The official history of the cave is marked by a fatal incident that forced its public reveal.

> "Disoriented by a dense cloud of particles, three divers from Grenoble lost their lives... forcing Henri Cosquer to declare the site two days later."

— Official Report, Maritime Affairs (September 3, 1991)

Mid 1980's
- First exploration of the entry gallery of the cave

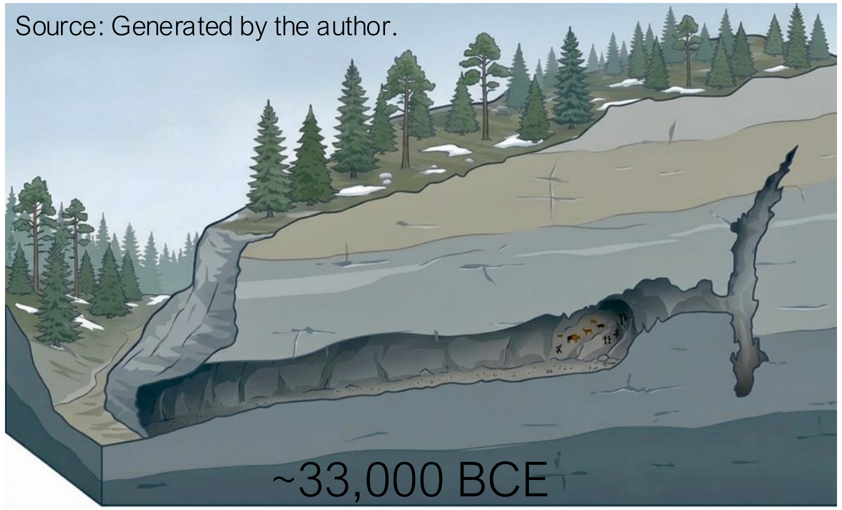
9th July 1991
- First discovery of parietal art at Hall 1

Summer 1991
- Cosquer starts privately exploring and documenting the cave

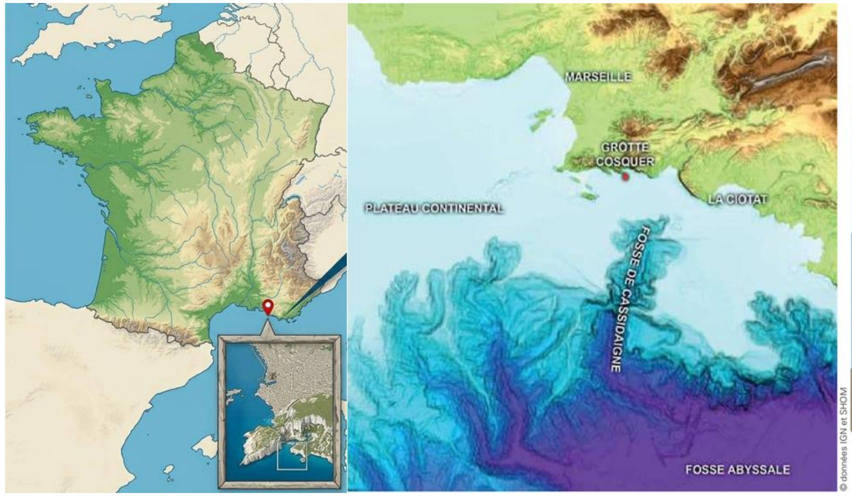
1st September
- 3 experienced cave divers die in the galleries

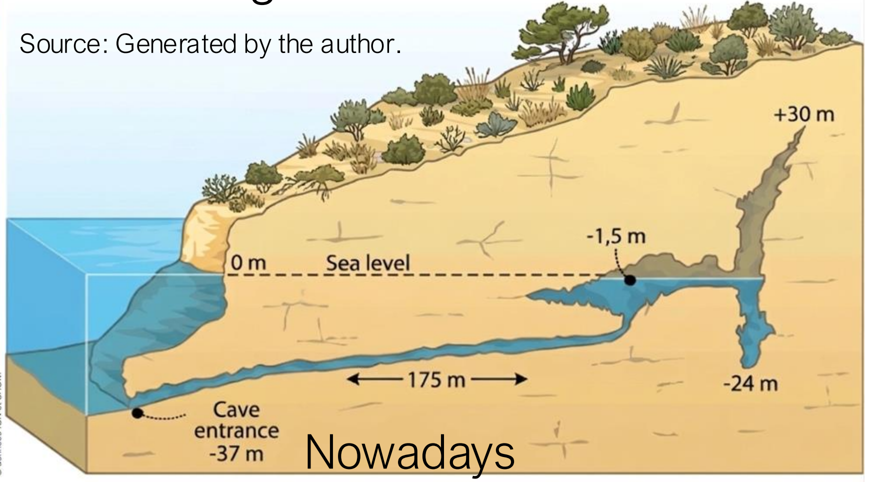
3rd September
- H. Cosquer makes public the existence of the cave.

Cosquer cave, a unique site



- Sea levels rose due to glacial melting.
- Cave entrance submerged ~12,000 to 8,000 years ago.
- **Natural isolation helped preserve the cave for millennia.**
- However, part of the parietal record has been **permanently lost** due to submersion.
- **Highly fragile environment** due to tidal variations (short term), rising water levels and modern climate change (long term).

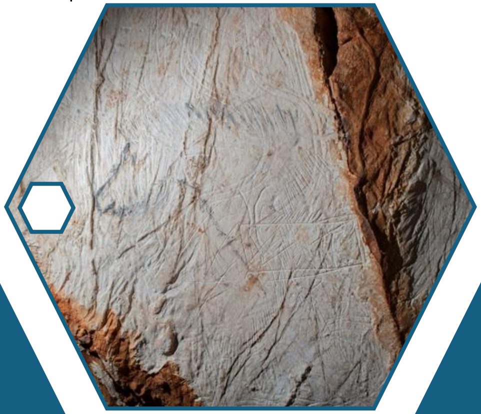




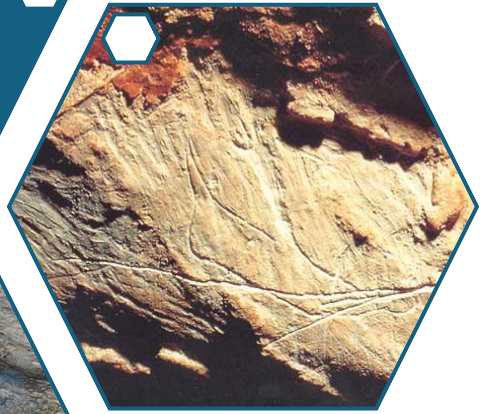
MONUMENT HISTORIQUE

Outstanding heritage

Source of images: https://archeologie.culture.gouv.fr/cosquer/fr/mediatheque

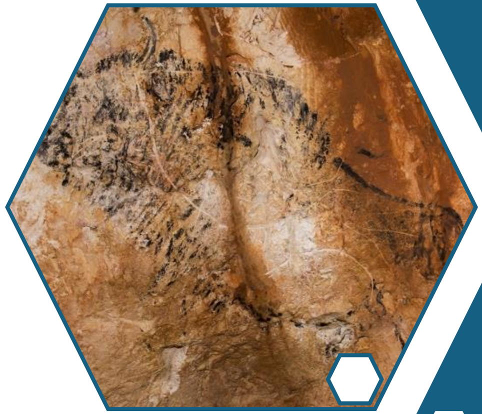


1 Human Representation: A single human figure, often referred to in literature as "The Killed Man".



Over 200 Geometric Signs.

65 Negative Hands: Stencils created primarily with red and black pigments.



8 Sexual Representations.

177 Animal Figures: A diverse range of fauna including both terrestrial species (horses, bison, ibex) and rare marine life (seals, auks)

Preservation: race against time

Photo : C. Montoya

Source: Generated by the author.

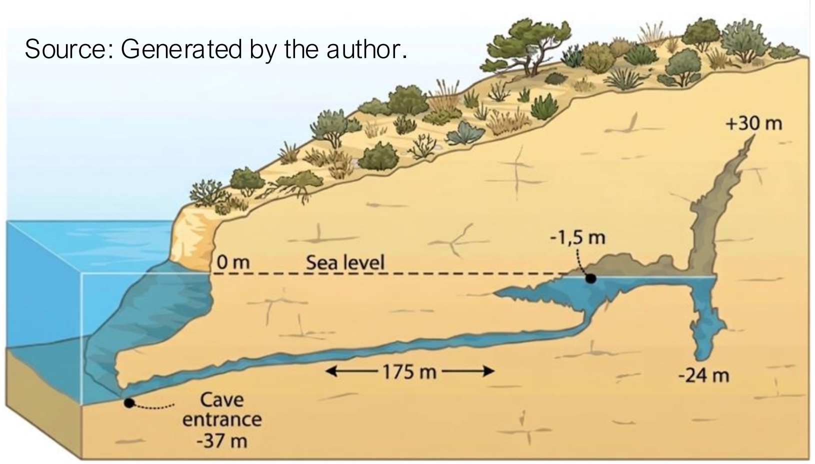


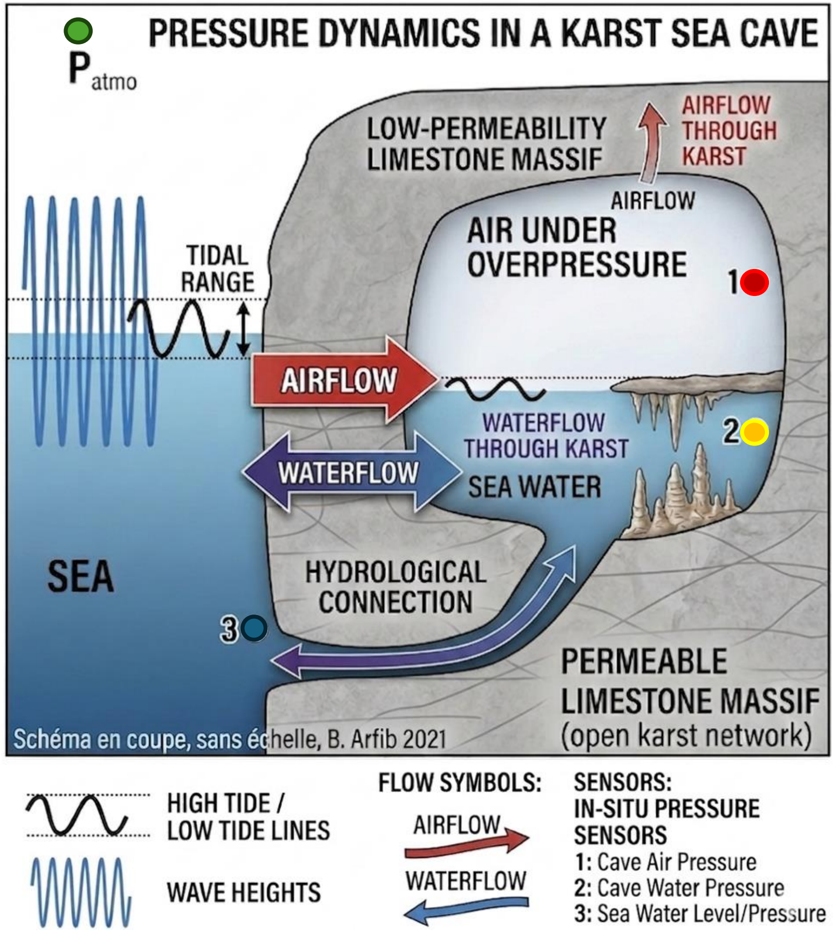
Photo : S. Touron

Environmental parameters monitored:

- Water level, pressure, conductivity, temperature, humidity, radon, rainfall, CO_2/O_2, …

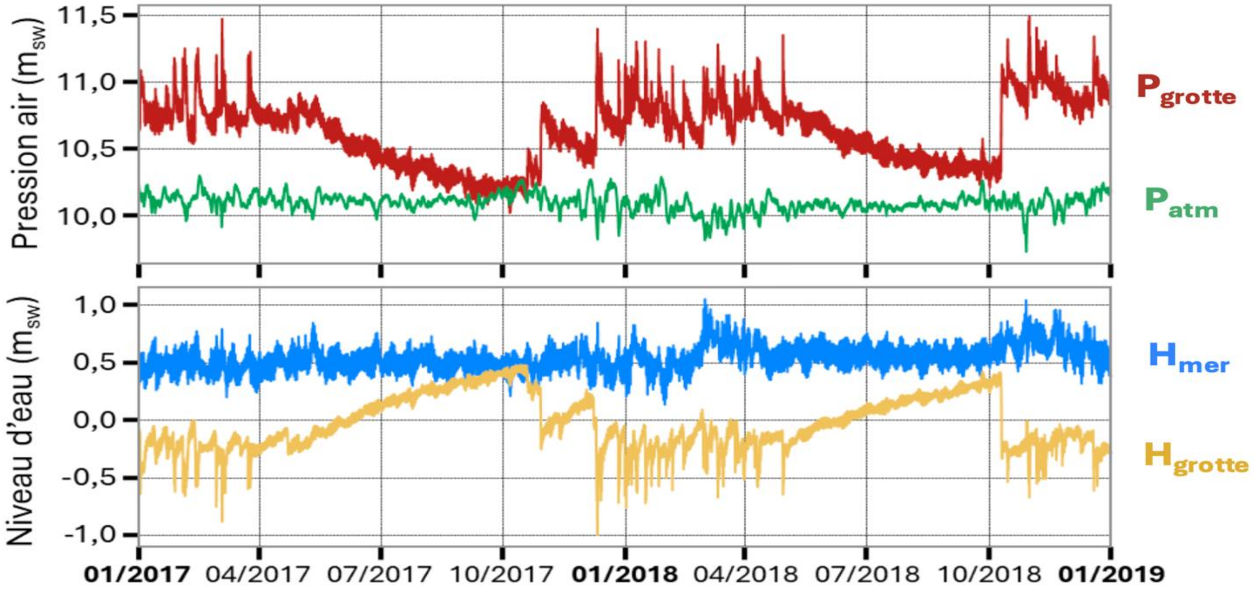
- The cave acts as a diving bell, the water level inside is slightly lower than outside.
- Strong water level variations.
- **Urgent preservation actions needed.**

Complex hydroclimatic behavior.



Source: Adapted by the author from : Bruno Arfib. Les variations si particulières du niveau d'eau dans la grotte Cosquer. Dossiers d'Archéologie, 2021, La grotte Cosquer, trente ans de recherches, 408. ⟨hal-03679590⟩

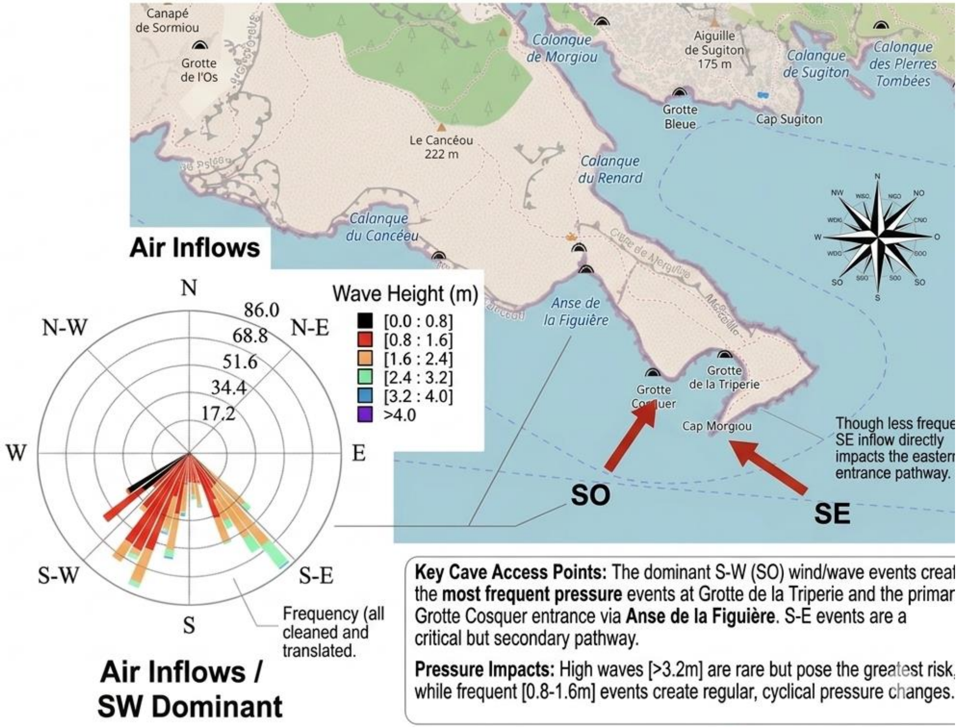
- A coastal karst cave connected to the sea can trap air under pressure. External forcing (waves, tides, atmospheric pressure) drives air circulation and water exchange through the system.
- Rapid, punctual pressurizations followed by slow pressure release.



Source: Hugo Pellet. La dynamique des écoulements d'air et d'eau dans un massif carbonaté karstique côtier et impact sur l'altération des parois : application à la grotte Cosquer et l'état de conservation de ses parois et de ses œuvres. Hydrologie. Aix Marseille Université, 2025. Français. ⟨tel-05105768⟩

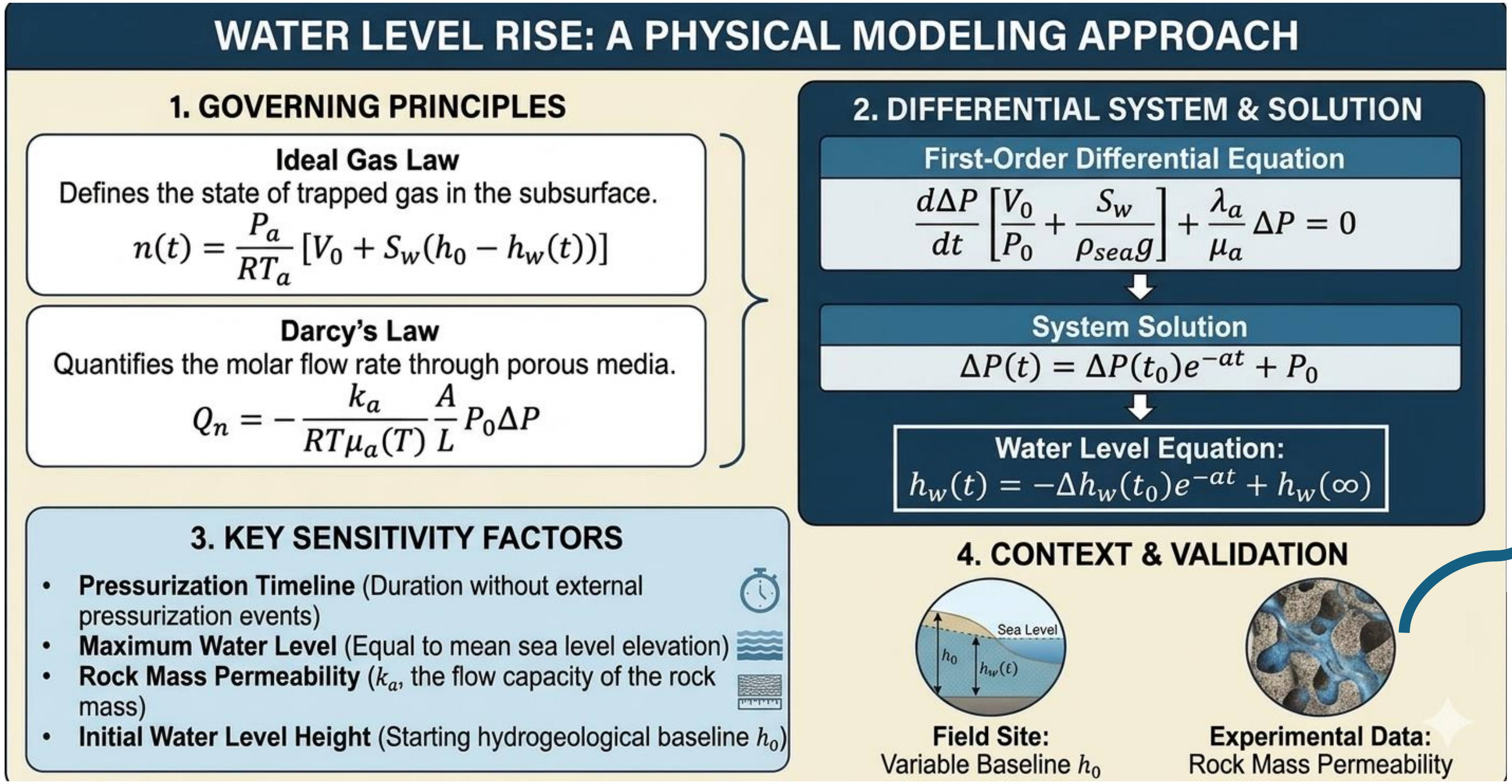
Analyzing the pressure build-up

Source: Adapted by the author from : Hugo Pellet, 2025. ⟨tel-05105768⟩

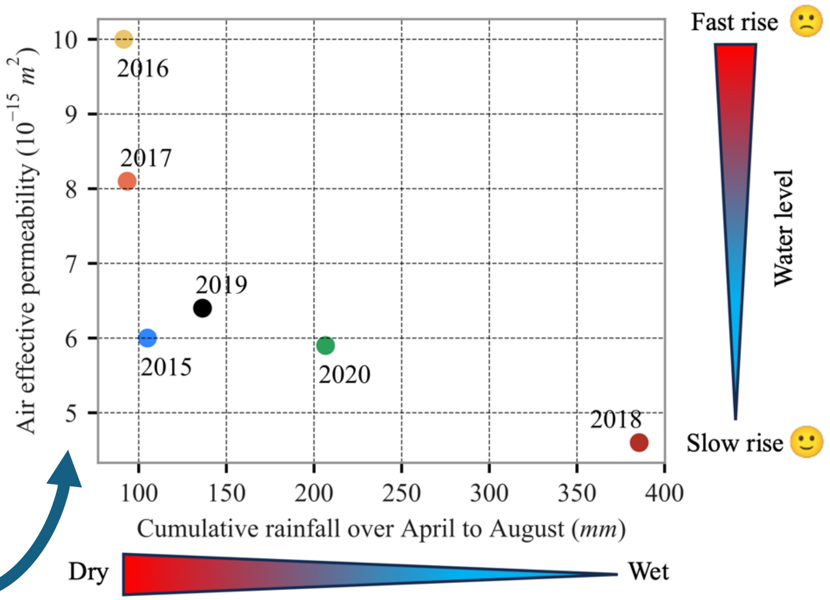


- Seasonal Patterns
  - Autumn/Winter: Rapid, frequent pressurization (storms)
  - Spring/Summer: Gradual pressure release (low permeability)
- Oceanographic Drivers
  - Wave height: > 0.8 m (90% of pressurization events)
  - Wave direction: SW waves (perpendicular to cliff) most effective
  - Sea level: High tide + storm waves increase air intrusion
- Cave System Factors
  - Submerged karst conduits: Control water/air exchange
  - Low-permeability limestone: Slow pressure dissipation

Unraveling the air discharge



Source: Adapted by the author from : Hugo Pellet, 2025. ⟨tel-05105768⟩ Legend in spare slides.

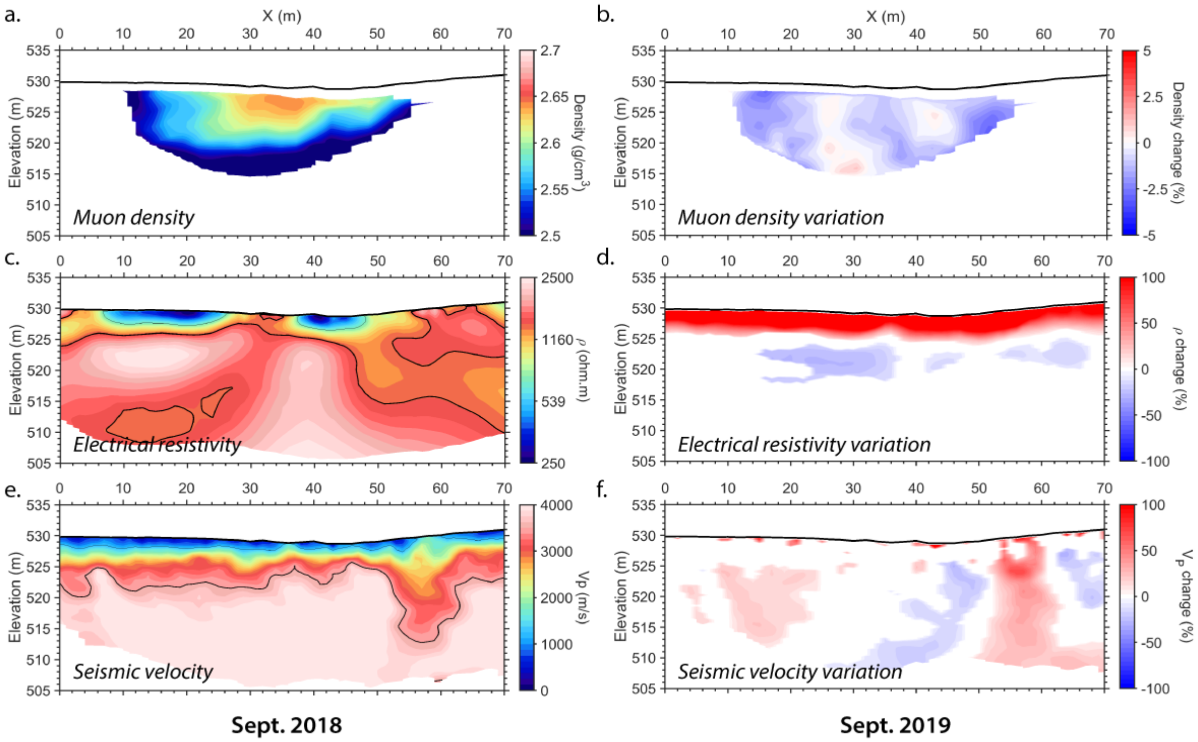


Mean air effective permeability (m^2) between July and August versus cumulative rainfall at Cassis from April to August (mm) for years 2015 to 2020 (for model A/L = 50 m)
Source: Hugo Pellet, 2025. ⟨tel-05105768⟩

- *Dry periods = higher air permeability = fast water rise.*
- *Rain periods = slow water rise when the soil is wet.*

Muography as a complementary tool

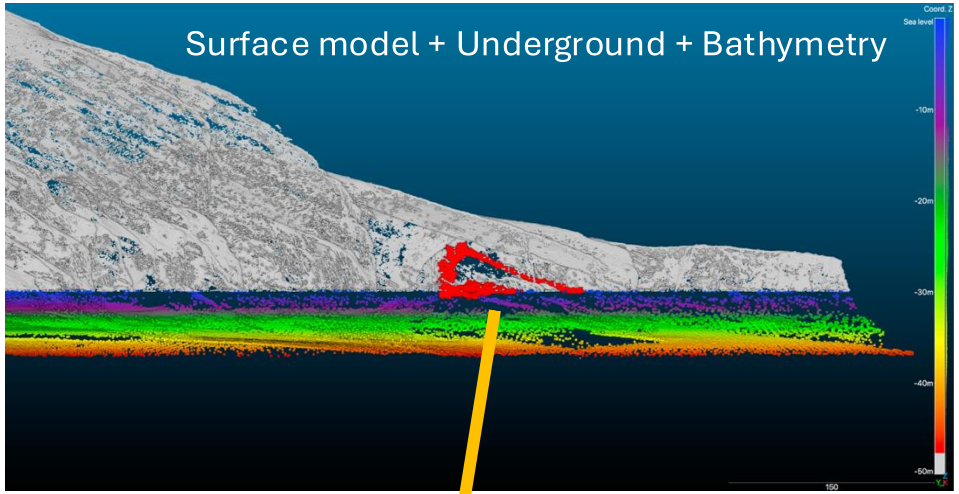
Groundwater comparative monitoring experiment at LSBB

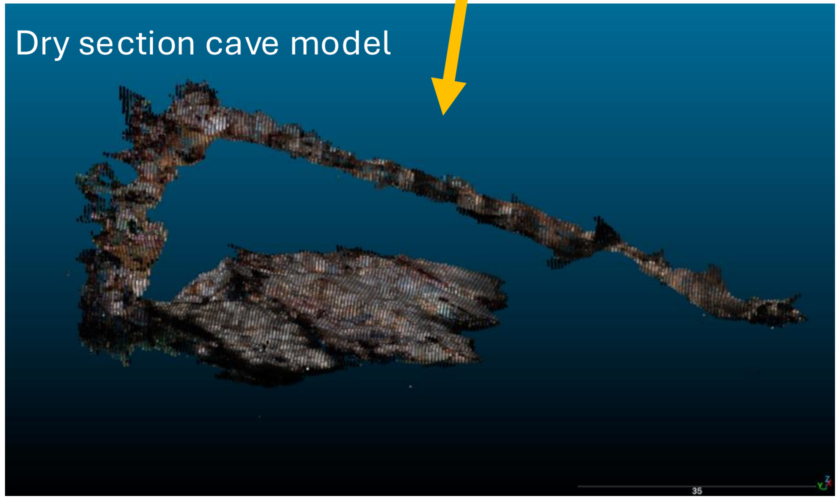


Muon density measured in T_0 (a) and density change in T_1 (b).
Electrical resistivity measured in T_0 (c) and electrical resistivity change in T_1 (d).
Seismic velocity measured in T_0 (e) and seismic velocity change in T_1 (f).
Source: I. Lázaro et al. Chapter 10 from Muography: Exploring Earth's Subsurface with Elementary Particles

- Soil permeability varies with humidity, and muon tomography has demonstrated sensitivity to density changes associated with groundwater dynamics in similar settings.
- This technique not only offers a powerful tool for monitoring karst systems like Cosquer Cave but also holds potential for detecting uncharted cavities.

Modeling the environment



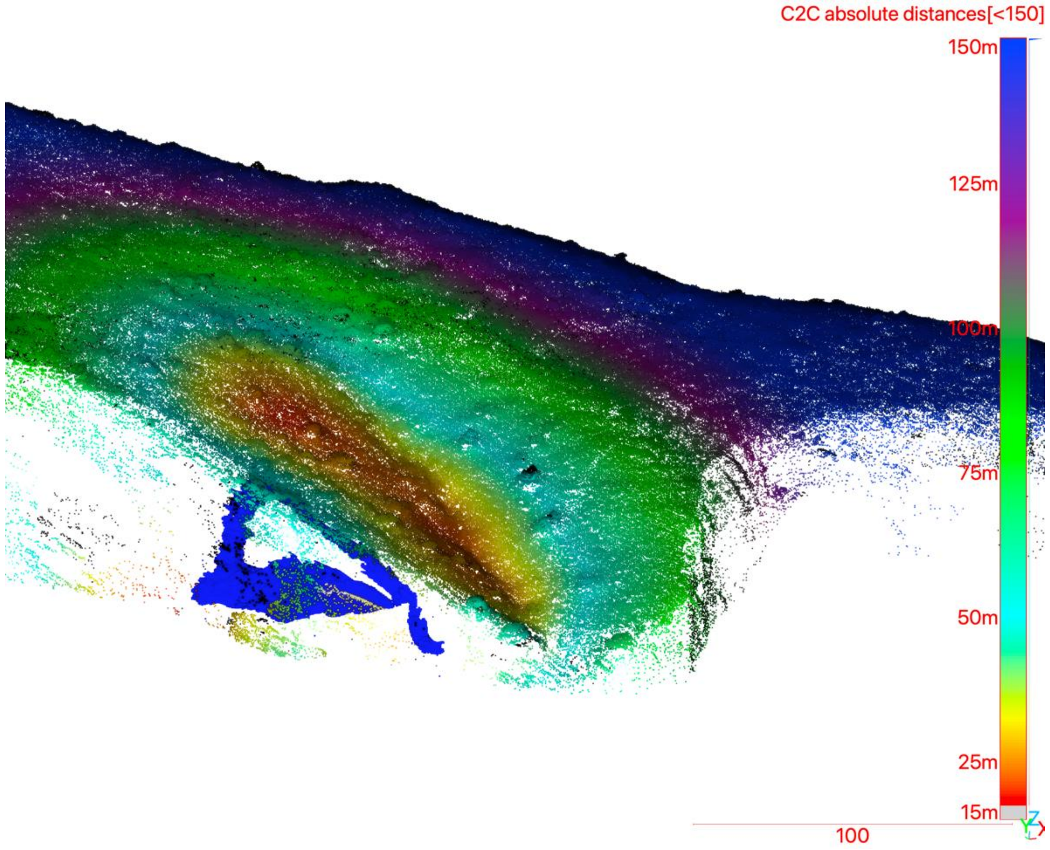


- The Cosquer consortium has produced a high-precision 3D model by means of LiDAR scanning and photogrammetry to enable detailed analysis of rock art and cave morphology for multidisciplinary research.
- Challenges include material deployment, flooded zones, and data ground/underground alignment.
- This model has been used to make a replica of the cave for the general public (800.000 visitors per year).

Source: Images by the author based on data provided by the Cosquer collaboration, IGN and SHOM.
Cf. Loic Jeanson, Caroline Font, Priscilia Barbuti, Valentin Grimaud, Stéphane Renault, et al.. La grotte Cosquer à Marseille : outils et méthodes numériques pour un objet d'étude complexe et difficilement accessible. JC3DSHS 2023 - Les Journées du Consortium 3D SHS, Nov 2023, Lyon, France. pp.29-39. ⟨hal-04479484v3⟩

Optimal topology for muography

Rock overburden.
Euclidean distance between the cave and the surface.

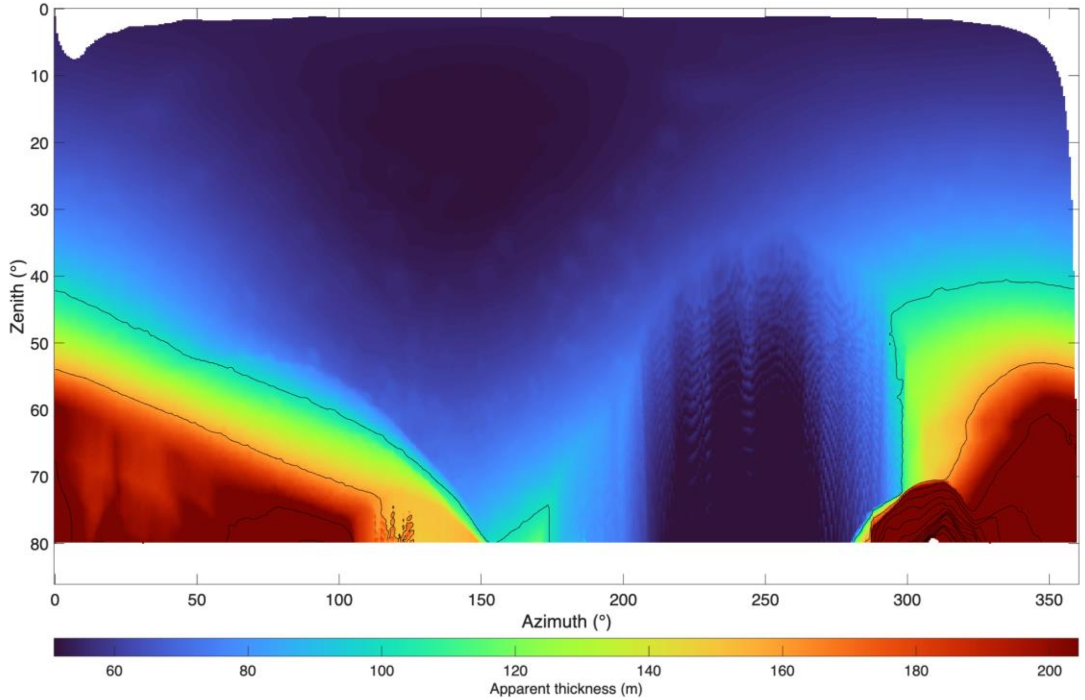


Source: Images by the author based on data provided by the Cosquer collaboration.

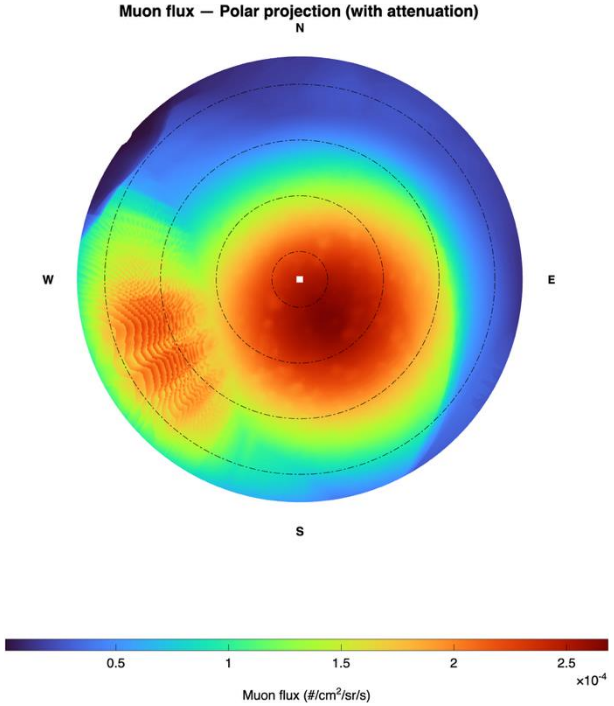
- The limestone massif (~50–100 m) is within the optimal thickness range.
  - Sufficient muon statistics with meaningful density contrast
  - Good sensitivity to medium-scale structures (~1–10 m)
  - Usable images in days to weeks
  - No heavy shielding required
- Constant density contrast: Air-filled caves vs. limestone.
  - Documented caves provide direct validation targets
  - Known voids anchor inversion parameters and help reduce systematic offsets
- Slow dynamic density variations: groundwater filtration.

Preliminary work

Contour map of the apparent rock thickness (m) as seen by the detector, presented as a function of zenith and azimuth angle.



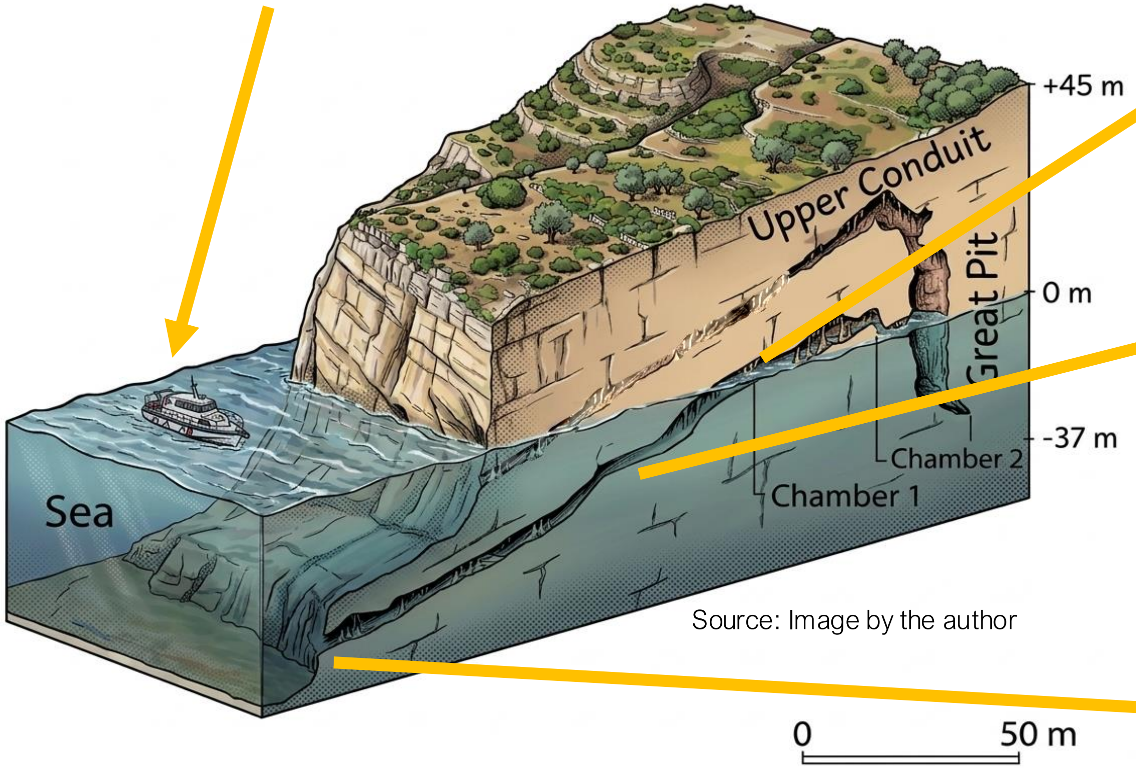
Polar projection of muon flux (μ/cm²/sr/s), incorporating attenuation, showing the relative muon intensity at different sky positions



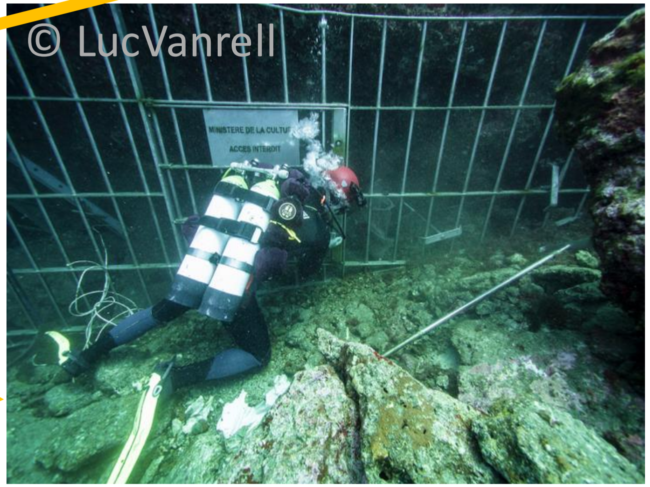
Source: Images by the author

This MATLAB-based simulation assumes a solid rock mass; integration of the actual cave geometry is ongoing in partnership with Valencia International University as part of a Master's thesis.

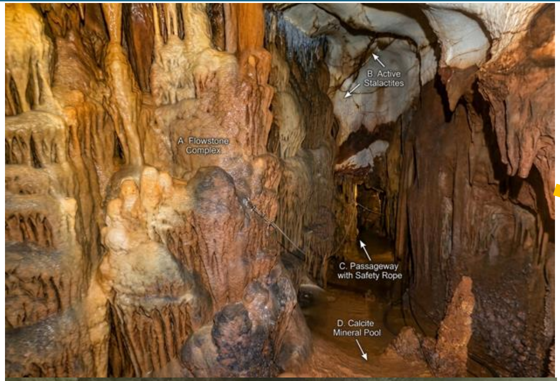
Challenging logistics : lower path



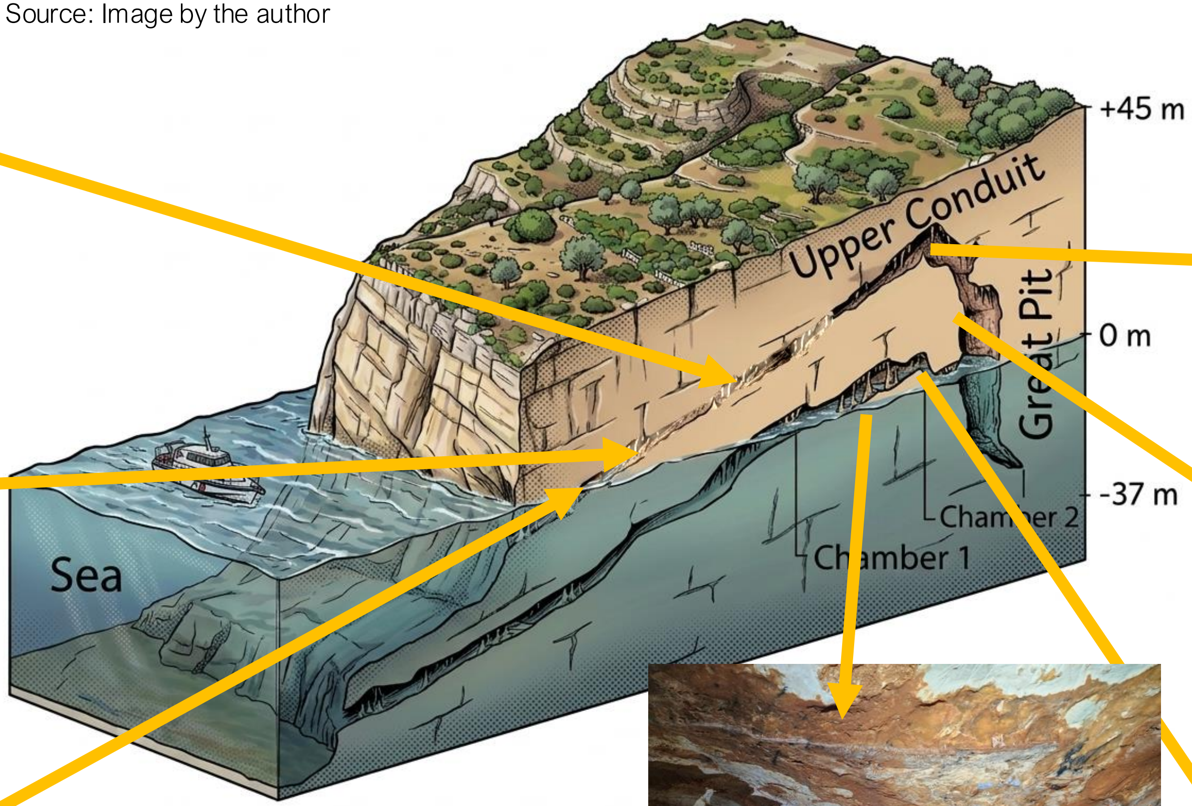
Source: Image by the author

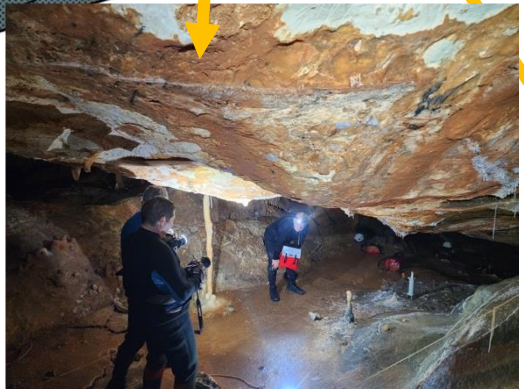


Challenging logistics : upper path



Source: Image by the author



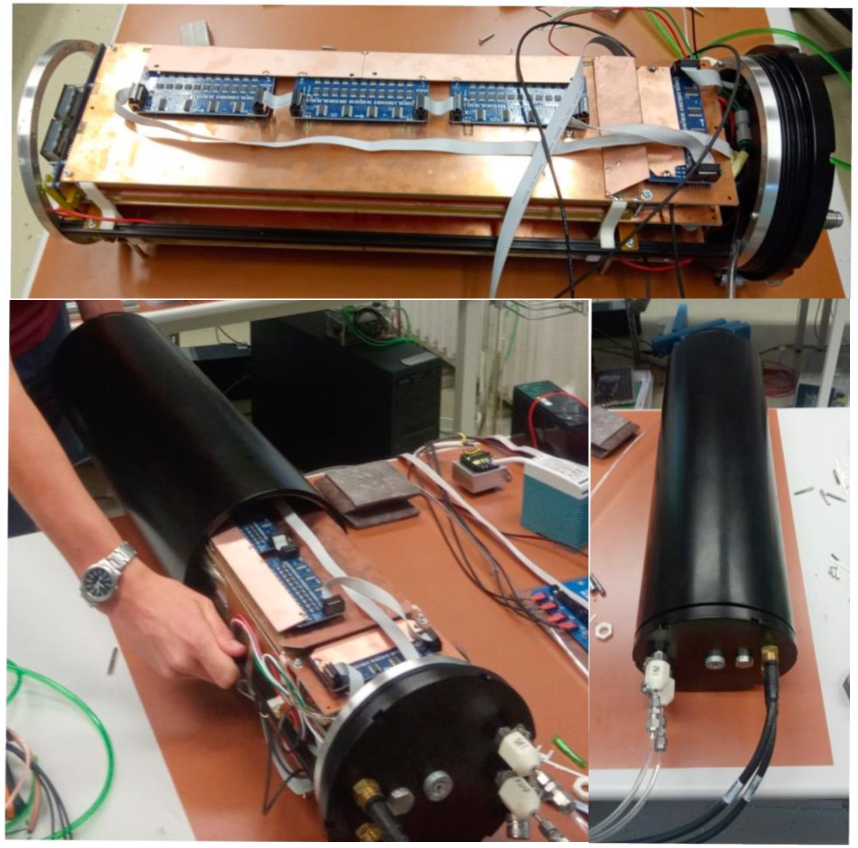


Logistical Constraints

- Regulatory approval: All scientific projects require prior authorization from the French Ministry of Culture
- Archaeological protection: Strict zoning to avoid any disturbance of pristine substrates and floor deposits
- Environmental preservation: All instrumentation must be passive and non-invasive (protected site)
- Power autonomy: Full autonomous operation required for entire deployment period
- Logistical constraints: Technical diving required to pass restricted passages (squeezes) at −37 m
- Temporal constraints: 1-month operational window per year (autumn campaign)
- Meteorological dependency: Access strictly weather- and stability-dependent
- Personnel qualifications: Certified advanced speleology and cave diving required to access

The technology

Sealed mode MWPC telescope for underwater muography
by Detector Physics Group HUN-REN Wigner Research Centre for Physics



- MWPC optimized for muon tracking.
- Gas mixture (Ar + CO_2 - 82:18) hermetically confined
- Multiple tracking layers aligned in a rigid geometry for precise 3D angular reconstruction of trajectories.
- Lightweight and modular form factor, specifically designed to be hand-carried through tight cave passages (squeezes) and restricted shafts.
- Watertight cylindrical vessels capable of withstanding hydrostatic high-pressure (-100m) and 100% relative humidity.
- Low power consumption.
- Environmental Resilience: High long-term baseline stability against ambient temperature fluctuations
- Passive Remote Sensing: Operates as a purely non-invasive receiver utilizing naturally occurring cosmic-ray muons, ensuring zero radiation emission or disruption to protected archaeological or geological sites.

Source: Images from Dezső Varga
https://indico.cern.ch/event/1632132/contributions/6926453/attachments/3225551/5748403/sealed_wigner_24feb2026.pdf

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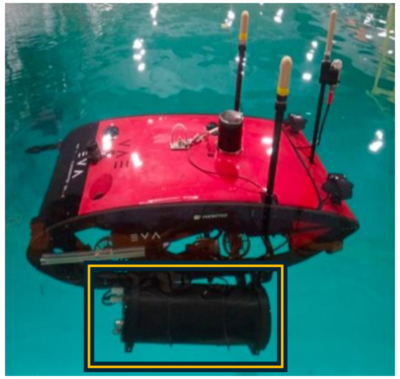

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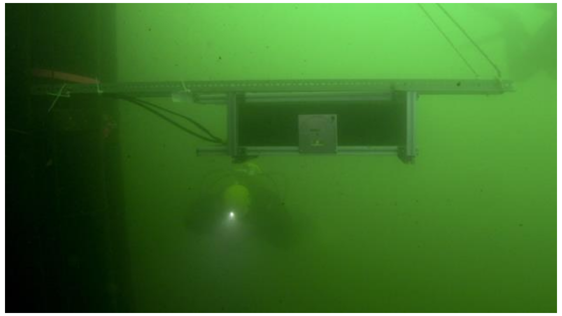
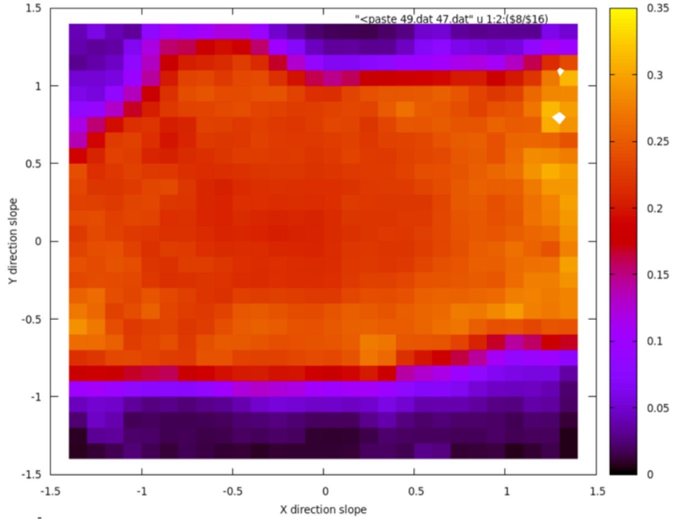


Detector at Hévíz thermal lake, Hungary
Source: Images from Gergő Hamar

- Possibility to deploy using a ROV, close to neutral buoyancy
- 4 days of autonomy from built-in battery
- Possibility to use supplementary external batteries.
- Sealed mode operation confirmed for 9 months.
- Tested at –13.8m for 2 weeks, currently at -27m
- Tested from -20ºC to 50ºC

More about the detector and its testing phase results :

Muography advancements in industrial extremes
Jun 4, 2026, 9:10 AM
20m
Talk
Civil Engineering an...
Civil Engineering and In...
Speaker
Gergo Hamar (HUN-REN Wigner RCP)



Muography image from the bottom of the lake (relative to open sky)

Conclusion and Strategic Outlook

- Cosquer Cave is a uniquely vulnerable site, where hydroclimatic forcing directly threatens art preservation.
  - Complex air–water coupling, producing transient pressurization.
  - Site conditions are highly favorable for muography, but very challenging deployment and operation

- Muon tomography offers a non-invasive, passive solution to:
  - Image the karst structure, detect hidden cavities and conduits
  - Track density changes linked to groundwater dynamics

- The sealed MWPC system supports deployment under extreme constraints, ensuring:
  - Autonomous operation & minimal environmental impact
  - High pressure resistance

- Fall 2026:
  - Muon flux simulations to optimize detector location
  - First experimental campaign
  - Objective: PoC of muography in coastal karst

- Goals:
  - Advance understanding of coastal karstic dynamics
  - Support short & long-term heritage conservation

Thank you for your attention

Background image: Great auk drawing from Cosquer cave.

Spare slides

Symbol	Parameters	Unit
Patm	Atmospheric pressure (outside the cave)	Pa or msw
Ps	Absolute pressure above the probe moored in the sea	Pa or msw
hs	Sea level above the probe	msw
Pa	Cave air pressure	Pa or msw
Pw	Cave absolute pressure above the probe moored in water	Pa or msw
hw	Cave water level above the probe	msw
hwl	Cave water level at low tide	msw
hwh	Cave water level at high tide	msw
Δhw	Tide range in cave	msw
Ta	Cave air temperature	°C or K
Tw	Cave water temperature	°C or K
Vl	Air-filled cave volume at low tide	m3
Vh	Air-filled cave volume at high tide	m3
V	Air-filled cave volume	m3
h0	Reference water level above the probe	msw
V0	Reference air-filled cave volume	m3
Sw	Surface of water bodies in the cave	m2
n	Cave air quantity	mol
Q	Volumetric airflow rate	m3 s-1
Qn	Molar flow rate	mol s-1
qn	Molar flux	mol m-2 s-1
L	Fracture length or limestone thickness	m
W	Fracture width	m
A	Cave cross-sectional area	m2
λa	Air intrinsic transmissivity	m3
ka	Air effective permeability	m2
b	Hydraulic aperture of a fracture	m
r	Radius of a pipe (equivalent to a karst conduit)	m
μ	Air dynamic viscosity	Pa s
R	Ideal gas constant	J K-1 mol-1
ρsea	Sea water density	kg m-3
g	Gravitational acceleration	m s-2
γ	Adiabatic index	-
P0	Standard pressure	Pa
T0	Standard temperature	K