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Multi-scale instrumentation for studying prebiotic chemistry in hydrothermal deep-sea vents conditions at lab scale

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Context

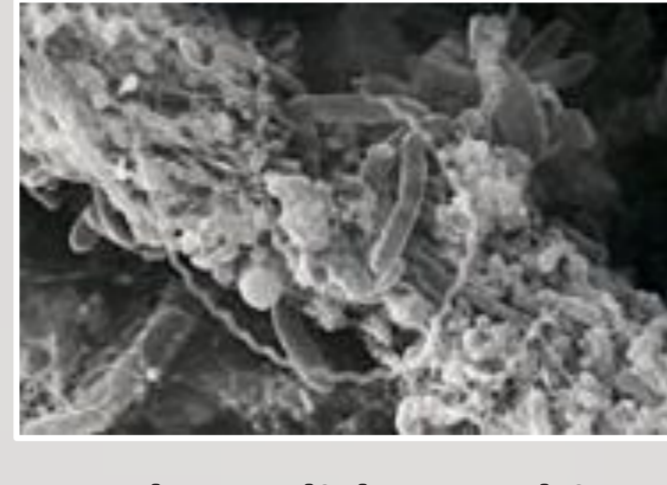
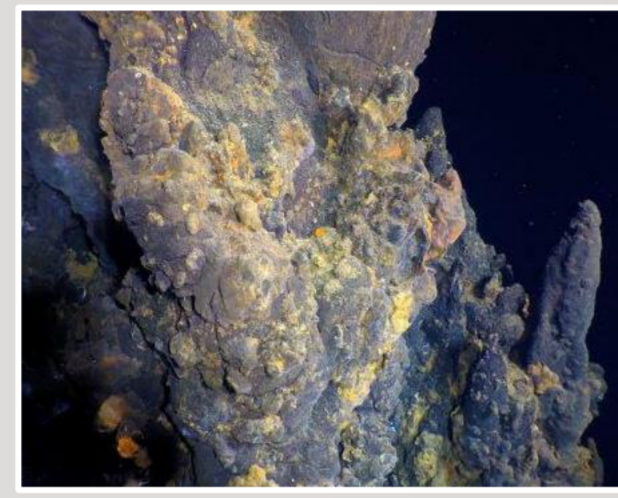
The exploration of seafloor hot springs on the Galapagos mid-ocean rift by the submarine Alvin in 1977, revealed that hydrothermal chimneys were homes of incredible ecosystems in which microorganisms could survive under conditions of extreme heat and pressure. Since then, it has been suggested that life's emergence could have been driven by the thermodynamic disequilibria that results from a mixture of water, gases and microporous minerals.

Oasis of life in the dark and cold deserts of the abysses



Peculiar ecosystems

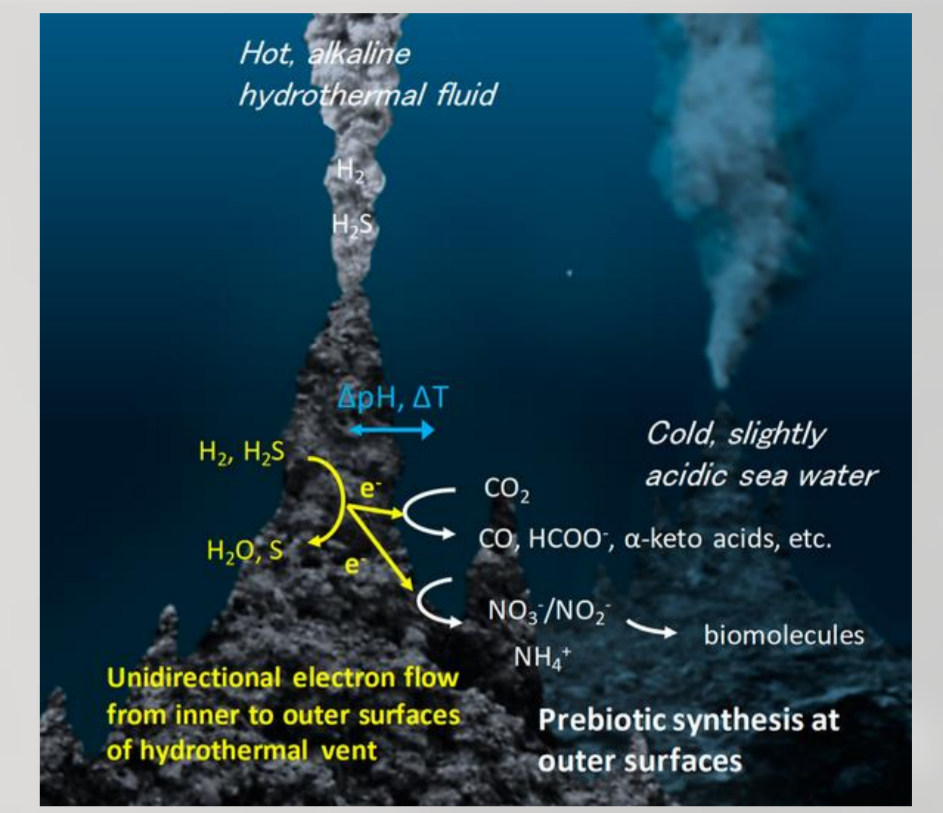
Complex dynamic geochemistry



Chemolithotrophic microbial life

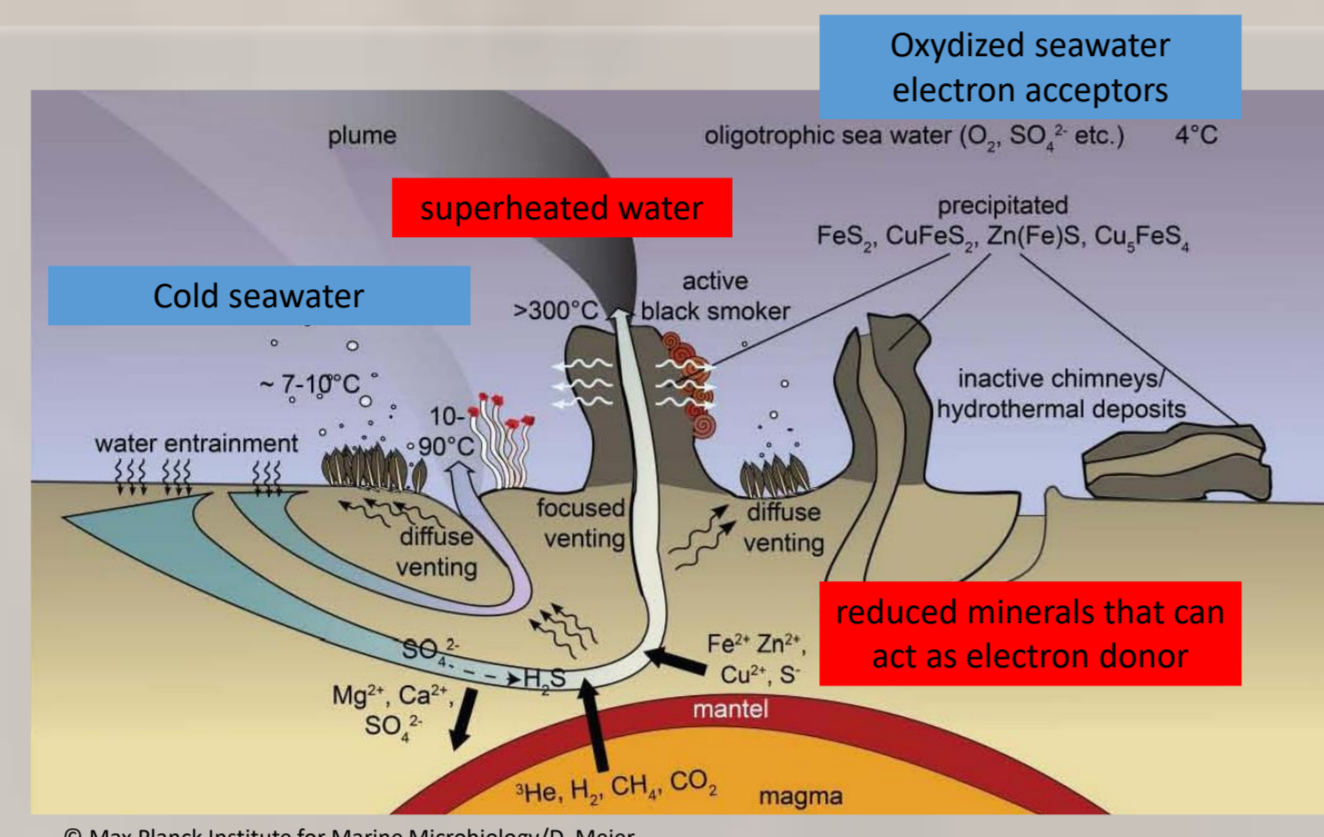
A cradle for the origins of life?

- Reductive environment
- High and continuous thermal energy
- Thermal cycles
- Porous media / confined environments
 - Adsorption on mineral surfaces / catalysis
 - Higher local concentrations
 - Chemicals gradients

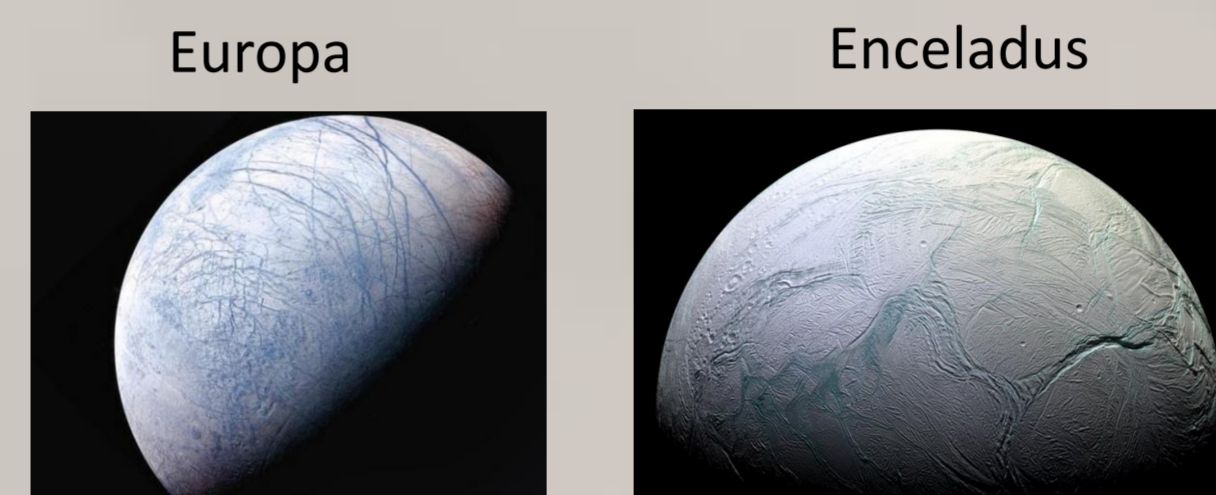


What are hydrothermal deep-sea vents ?

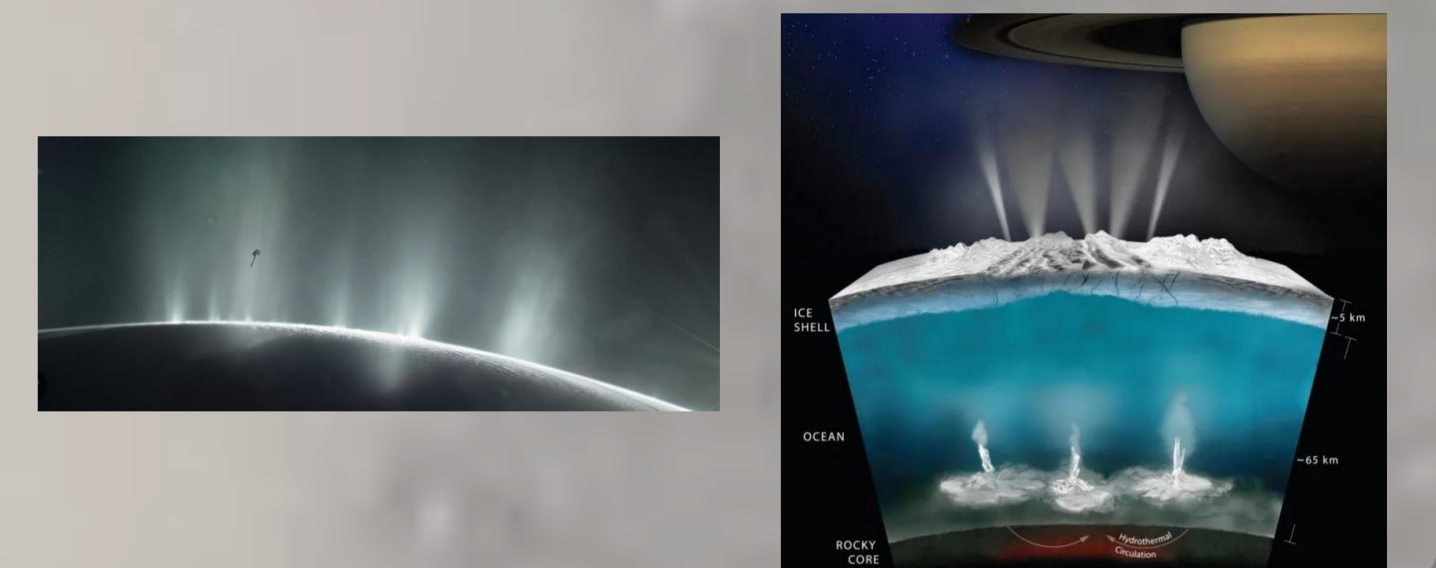
- No light → chemosynthesis (micro-/macroscopic life)
- Thermal gradients (cold to hot)
- Chemical gradients (oxidized to reduced)
- High pressure conditions (up to 50 MPa) - Prevent the water to boil



Ocean worlds – Icy Moons



Deep-sea Hydrothermalism thanks to tidal heating ?

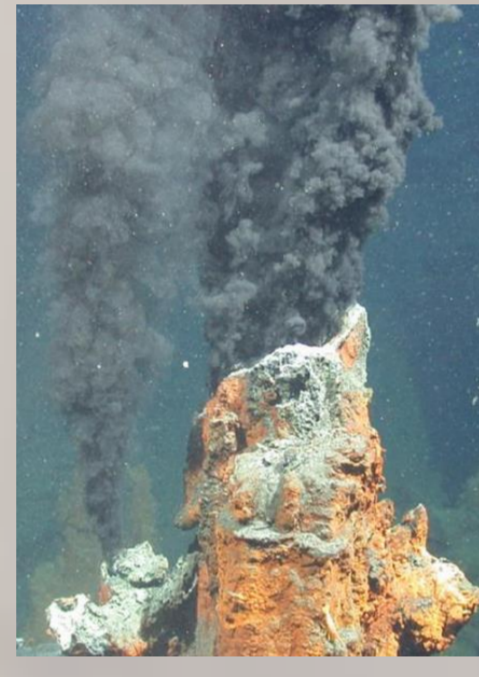


Black smokers

Precipitation of polymetallic sulfurs and anhydrites

Composition : sulfides of iron, copper, nickel, zinc...

- velocity : cm/s – m/s
- high temperature 300-450°C
- acidic pH ~3-5
- anoxic fluids, rich in silica (Si), carbon dioxide (CO_2), hydrogen sulfide (H_2S), methane (CH_4), dihydrogen (H_2) and transition metals (Fe, Mn, Zn Cu, Ni...)



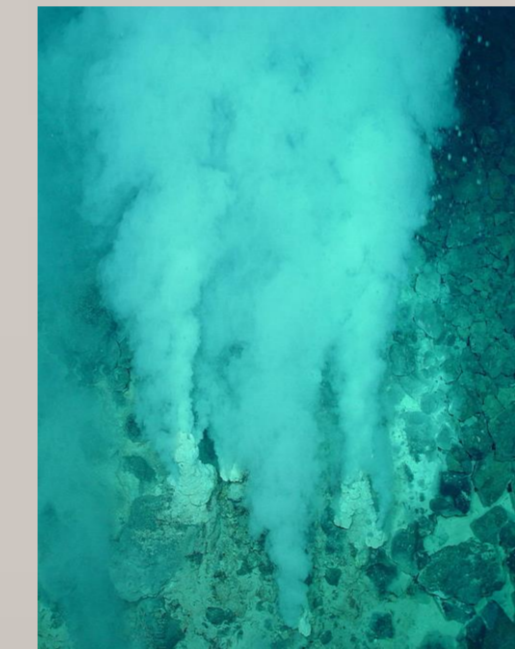
Black smoker, hydrothermal system Mid-Atlantic ridge

White smokers

Precipitation of silicate, carbonates and baryte

Composition : calcium carbonate (calcite, aragonite) ($CaCO_3$), brucite, ($Mg(OH)_2$),

- low temperature <100°C
- alkaline pH ~ 9 +
- mineralizing fluids: rich in calcium and form dominantly sulfate-rich (i.e., barite and anhydrite) and carbonate deposits, poor in hydrogen sulfide



White smokers of Lost City, Mid-Atlantic ridge

What about late hadean / early Archean smokers?

Analyses of ancient fossiliferous hydrothermal vent deposits suggest that these systems had closer characteristics with current white smokers.

Fluid:

- T : 150-200°C
- pH : 12 (NaOH)
- Salinity : ~20-35 g/l (NaCl and $MgSO_4$)
- up to 2,7 M CO_2 15-16 mM H_2

Ocean :

- ~3.8 Ga : 50-80°C
- 1.2x actual salinity
- CO_2 -rich but no O_2 !

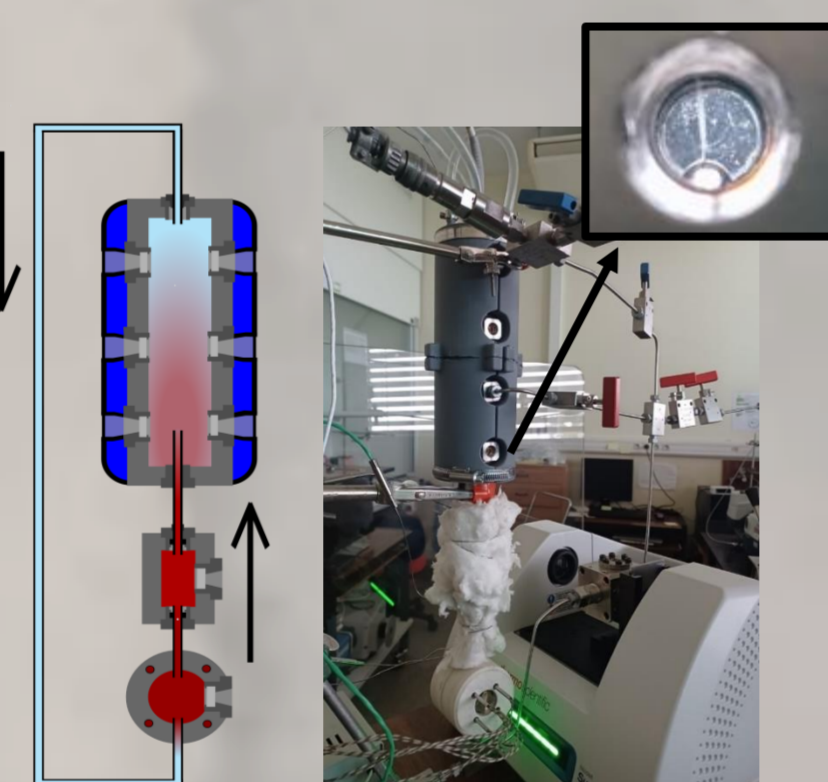
Experimental approaches for investigations at lab scale

The hydrothermal pump set-up

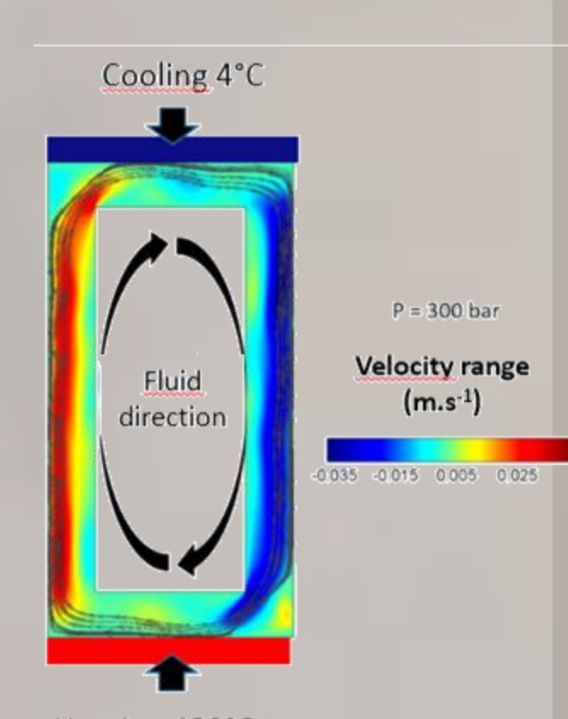
Recreating the hydrothermal pump at lab scale

Experimental set-up (300 bar):

- Three cells at different temperature equipped with transparent windows
 - Hydrothermal fluid cell (500°C)
 - Minerals-containing cell
 - Seawater cell (10°C)
- Connected with capillary tubing

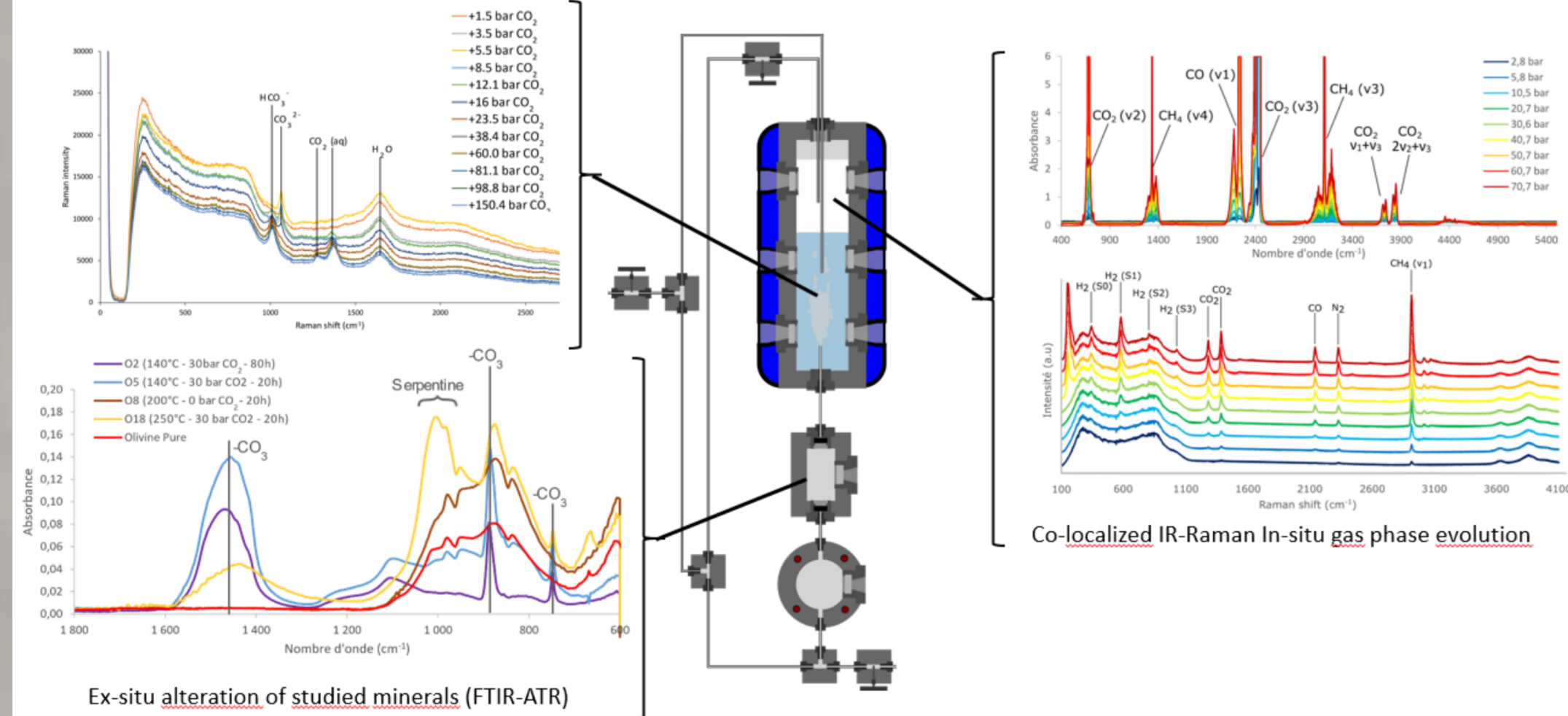


Numerical modelling



In situ FTIR and Raman analyses:

In-situ evolution of the carbonate chemistry in alkaline water



- Access to realistic multi-stage chemistries accounting for thermal and chemical gradients, fluid flow and model mineralogies

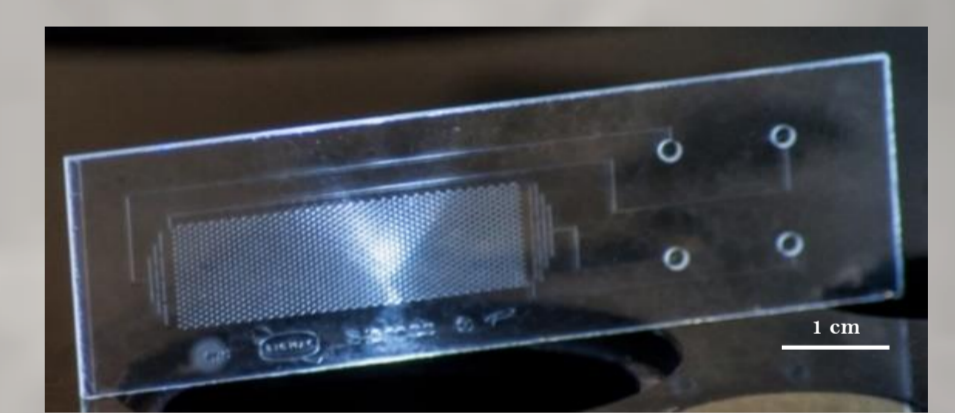
HP / HT Microfluidics: fast screening approaches and dynamic pore-scale view

- Fast screening (vs. autoclave batch modes)

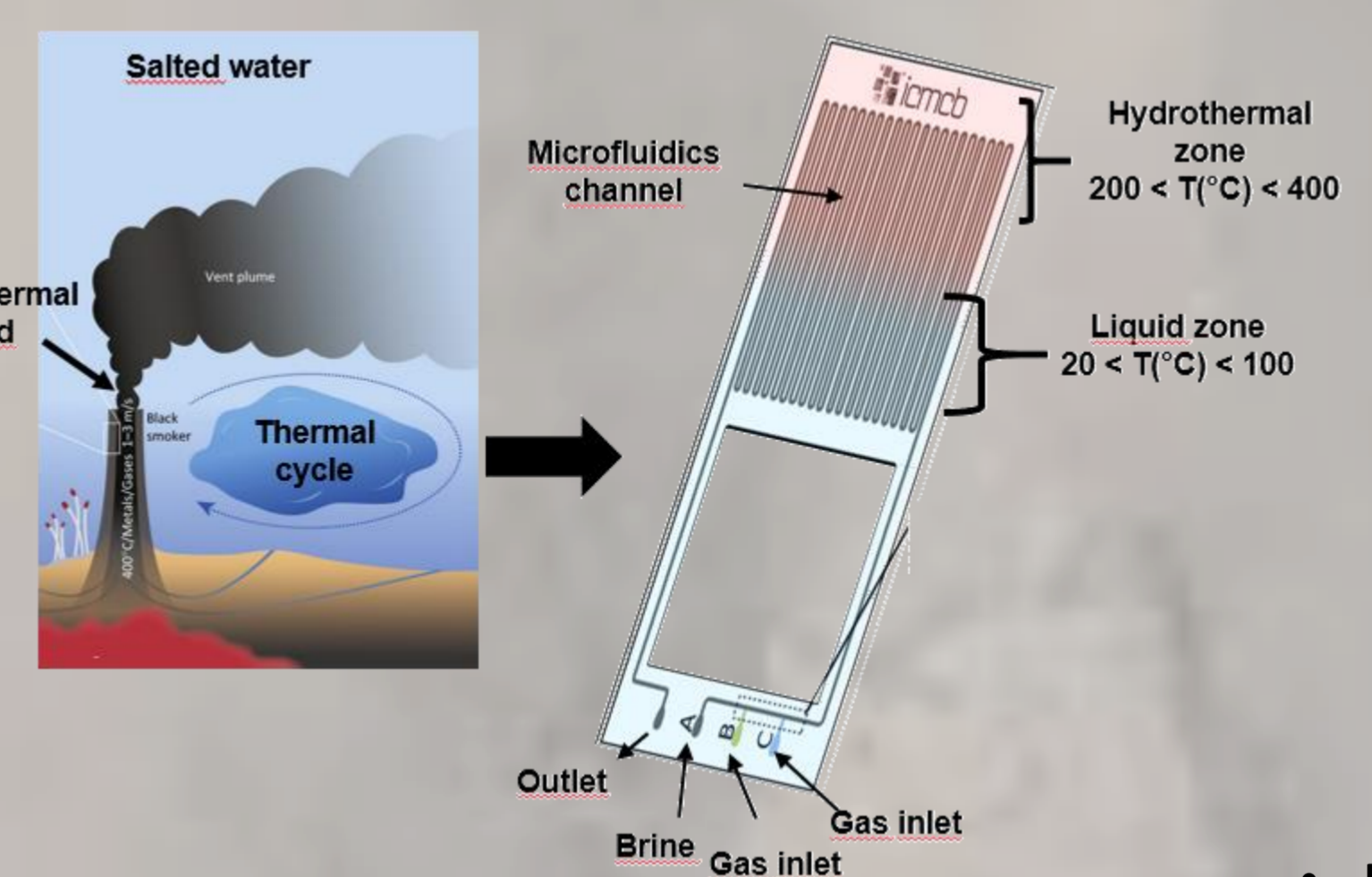
- Multiple On chip conditions (p, T, composition)
- Multi analyses within a single experiment



- In situ and online characterization (Live imaging & characterization of the process)
- Flexible design (porous media, microchannels, etc.) (vs. Capillaries and tubings)

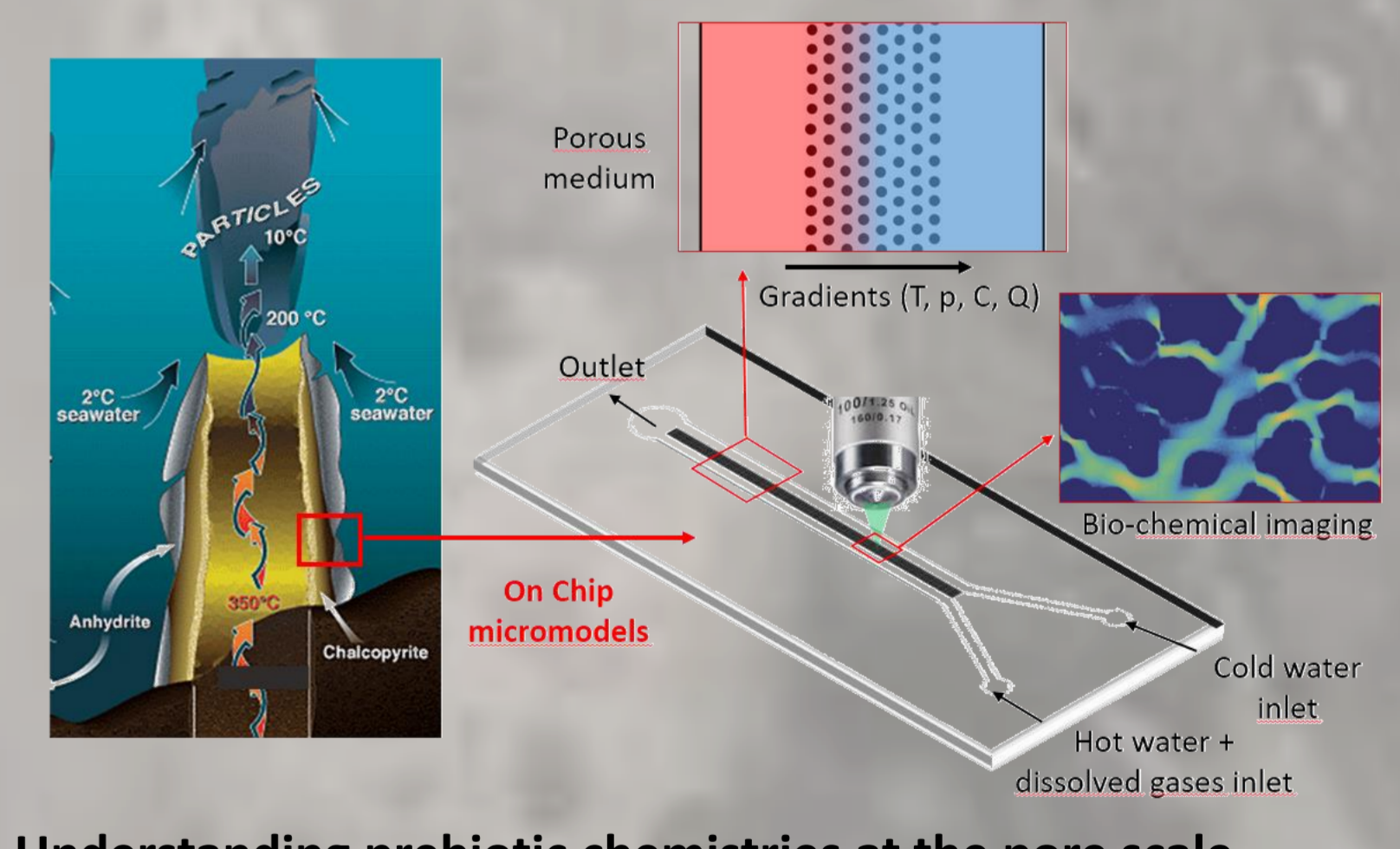


1- Speeding up discoveries on prebiotic chemistries



- Ultra-fast (ms – s) thermal cycles
- Fast screening capability

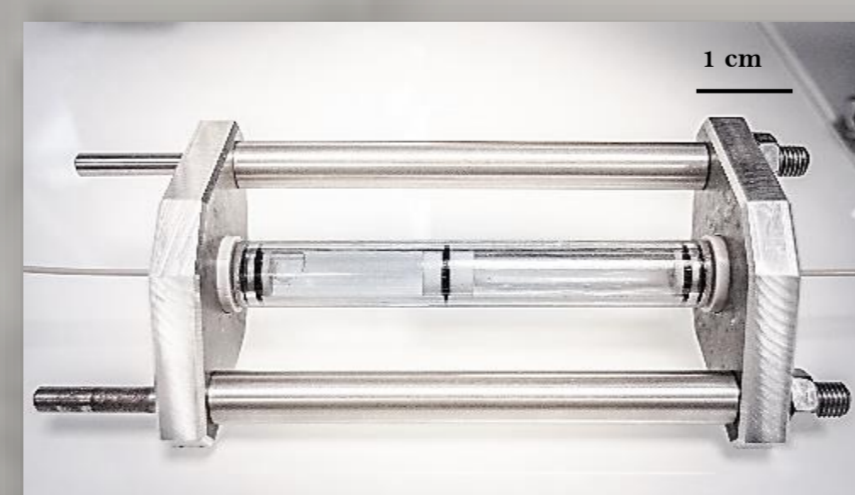
2- Hydrothermal vents on a chip



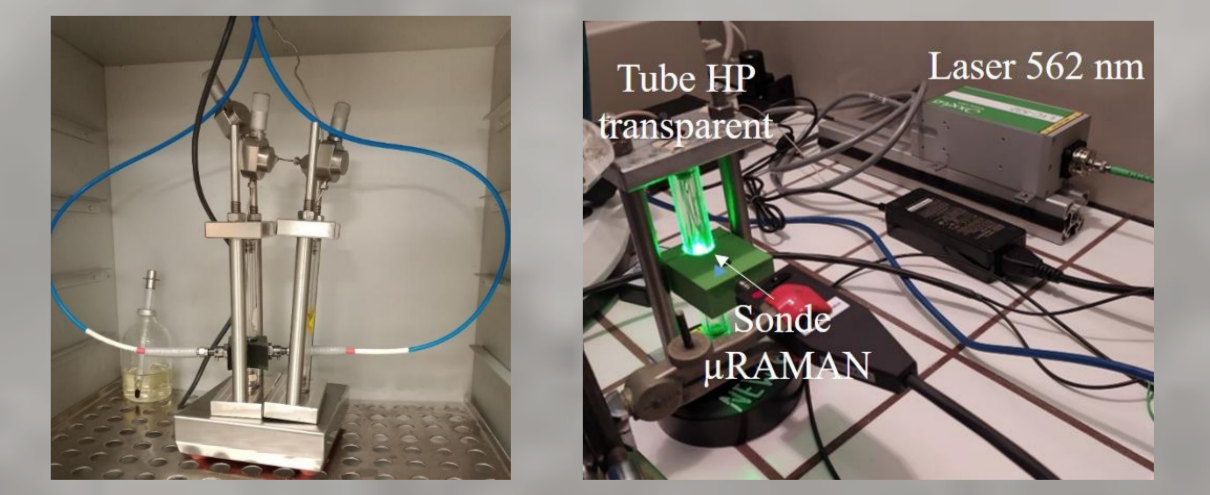
- Understanding prebiotic chemistries at the pore scale
- Taking into account thermo-hydrodynamics + geochemistry
- In situ real time monitoring + modelling

Millifluidic continuous process for prebiotic chemistry

- Sapphire transparent reactor (2 – 10 mL)
- Integration of minerals pack-bed
- Variation of residence time (flowrates), pressure (< 400 bar), temperature (< 250°C), mineral and fluid composition



- Continuous process for kinetics data acquisition
- Implementation of in situ probes (pH, Raman, UV-Vis)
- Combination with ex situ analysis (continuous monitoring with GC-MS)



Challenges and opportunities

- New experimental approaches for a better understanding of the hydrothermal vents characteristics
- The need for taking into account thermo-hydro-chemical combined processes for investigating deep-sea vents geo-(bio)chemistries
- Reactive minerals surfaces helps catalyzing chemistries / stabilizing reactive intermediate species

- Database generation of hydrothermal prebiotic chemistries → Towards AI predicting approaches?
- Establish the contribution of hydrothermal vents in the formation of prebiotic molecules
- Importance of confined micro-environment in porous media (concentrated species, reactivity of minerals surfaces, etc.)