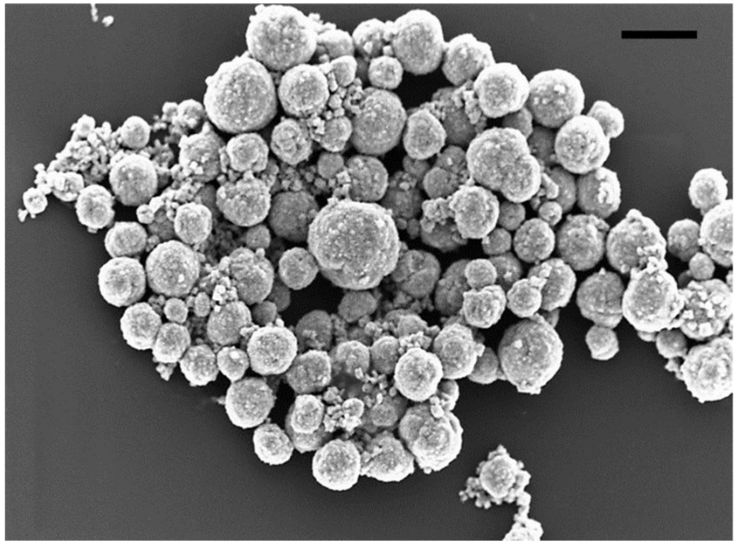
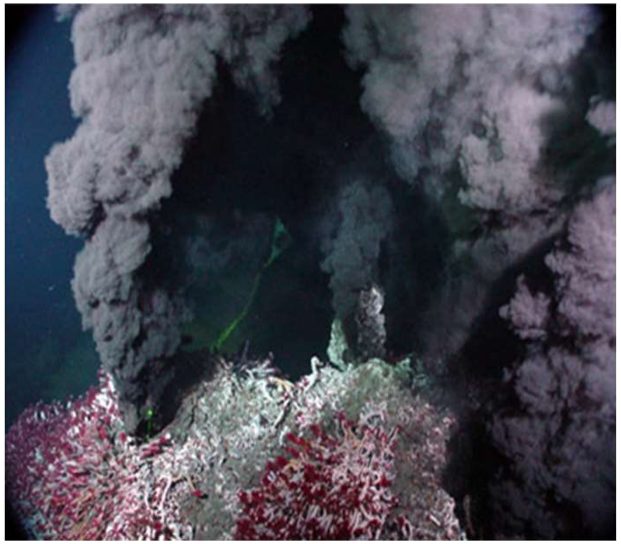
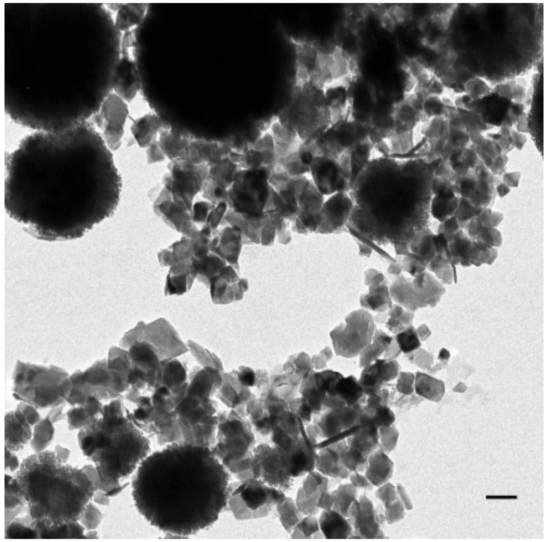
Topologie des archées

Aurore Gorlas 13/03/26

Biomineralization and iron sulfide production by hyperthermophilic archaea

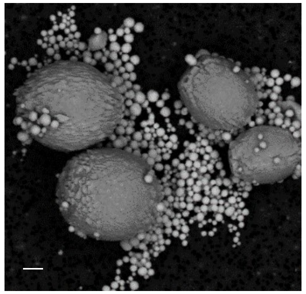




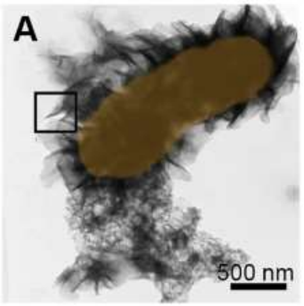


Biomineralization, a key process by which organism interact with their environment

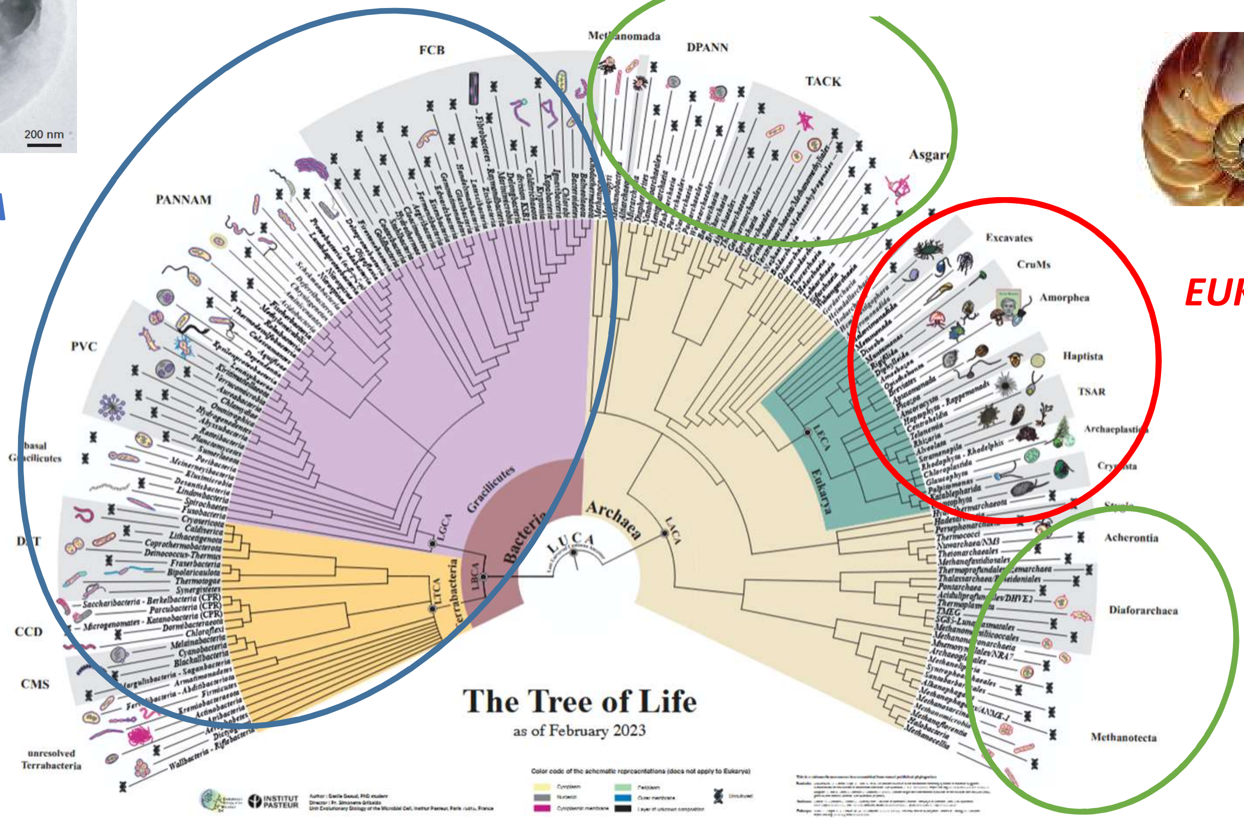
More recently
few examples



BACTERIA

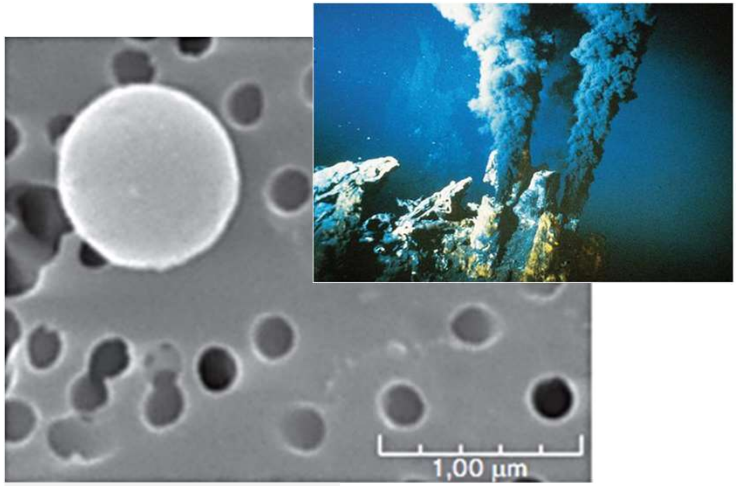


ARCHAEA

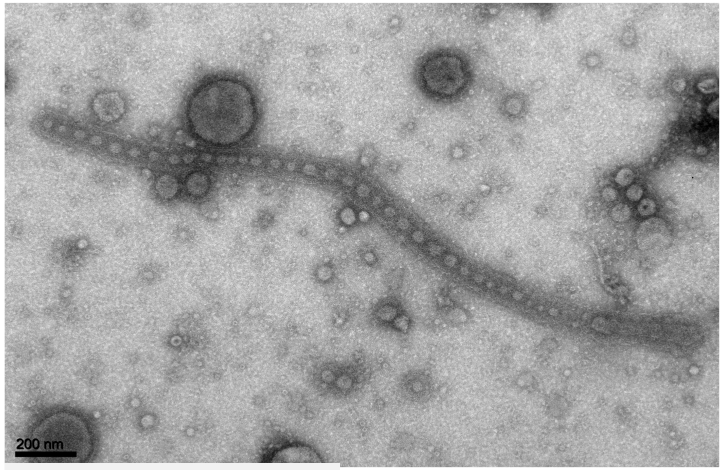


EUKARYA

Thermococcales, major inhabitants of the hot parts of hydrothermal sources

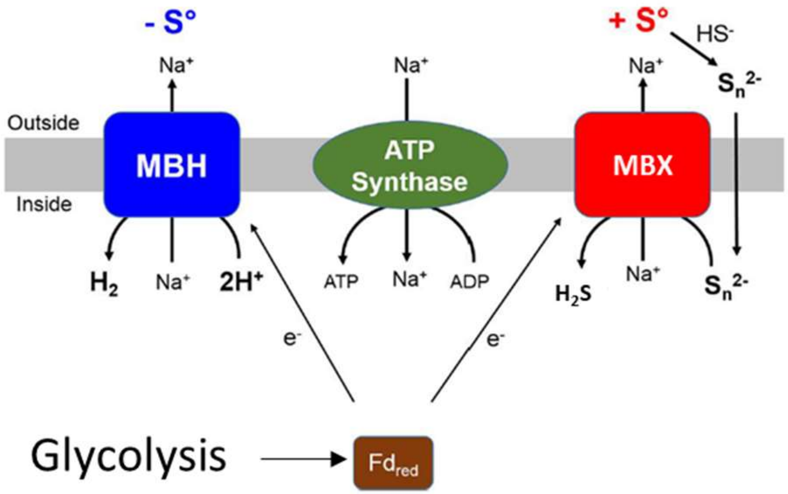


Gorlas et al., 2013



Gorlas et al., 2015

- *Archaea*
- Hyperthermophile (85°C)
- Strictly anaerobe
- Mainly heterotroph
- Vesicles and nanotubes producer
- Sulfur reducer



Two distinct pathways to produce ATP

Production of sulfur vesicles by Thermococcales

Contents lists available at ScienceDirect

Biochimie

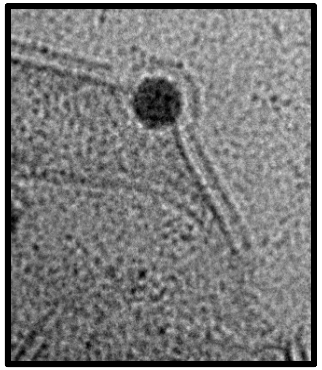
journal homepage: www.elsevier.com/locate/biochi

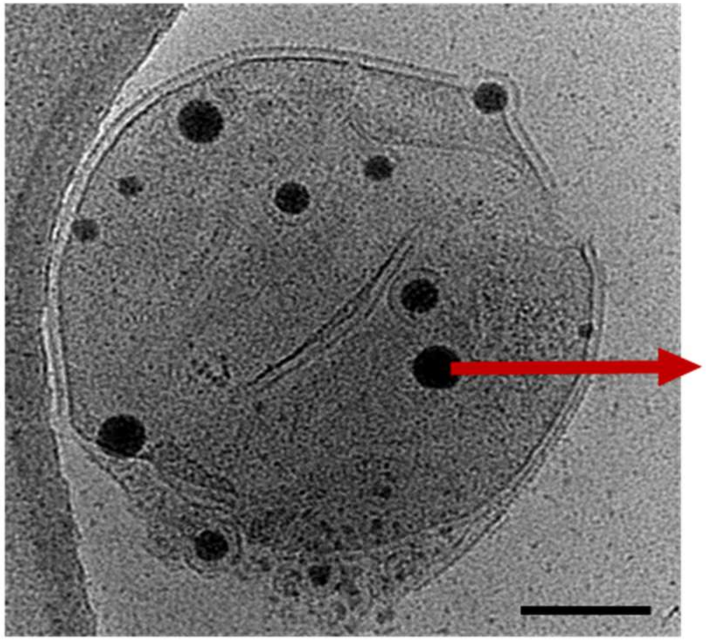
Research paper

Sulfur vesicles from *Thermococcales*: A possible role in sulfur detoxifying mechanisms

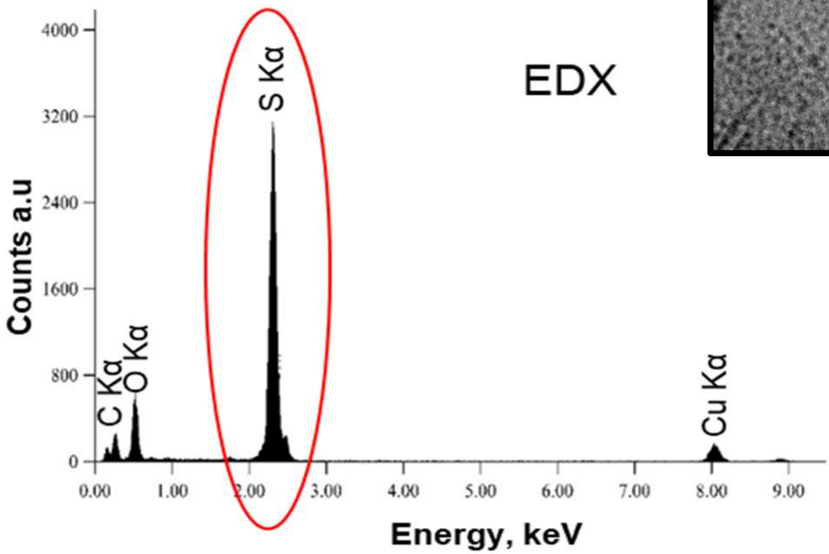
A. Gorlas [a,*], E. Marguet [a], S. Gill [a], C. Geslin [b], J.-M. Guigner [c], F. Guyot [c], P. Forterre [a,d]

With presence of S(0) in growth medium





Thermococcales cell

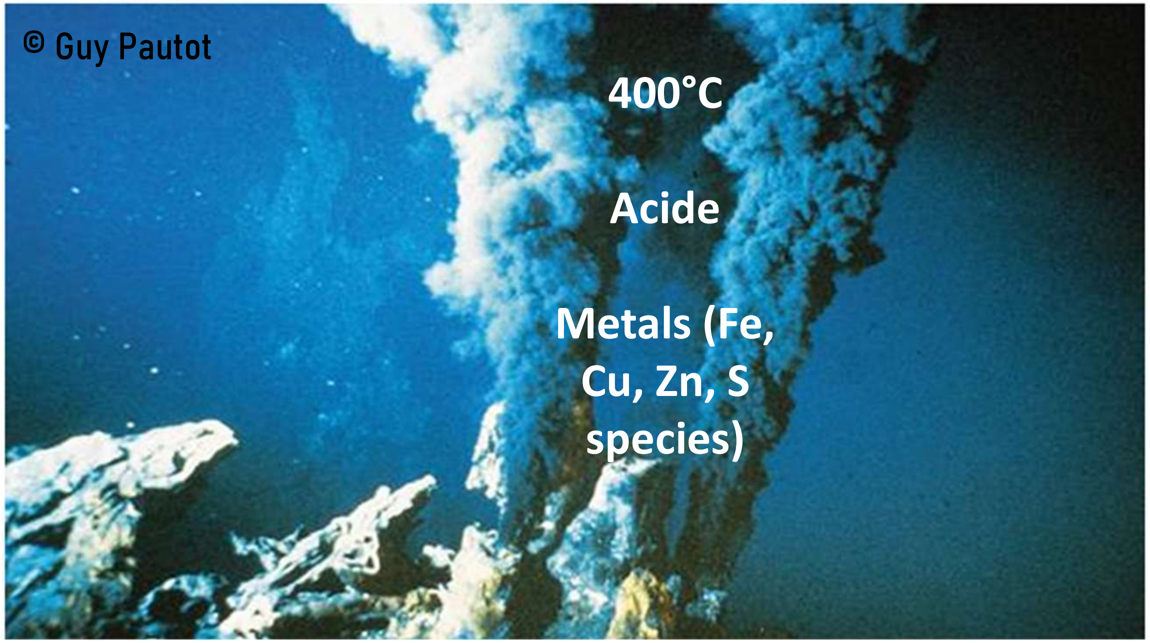


Sulfur transport

Gorlas et al., 2015

Hydrothermal vents, a site for microbe-mineral interactions

Hydrothermal deep-sea vent : an extreme environment for life



→ Strong physico-chemical gradients
Iron- and sulfur-rich systems
FeS_2 pyrite formation (> 200°C) (Rickard, 1997; Rickard & Luther, 2007)

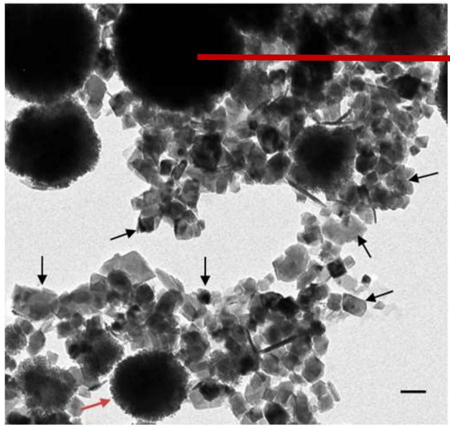
However at lower temperatures (< 150°C) FeS_2 are also produced by a still unknown mechanism which might involve the living compartments.

(Juniper & Fouquet, 1995; McCollom, 2007)

Biological induced mineralization by Thermococcales

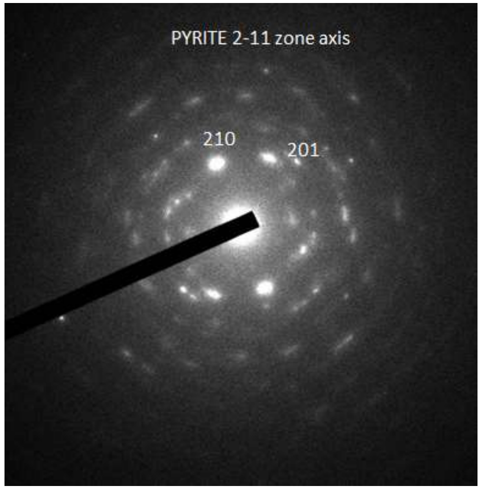
Rapid (<60 hours) formation of iron-sulfide minerals

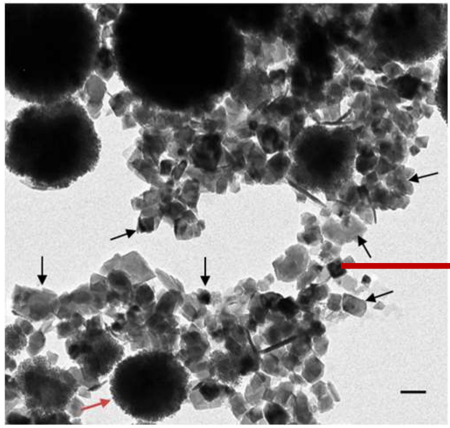
- Fe(II) mineralization medium
- Strict anoxia
- 85°C
- With **presence of S(0)** in growth medium



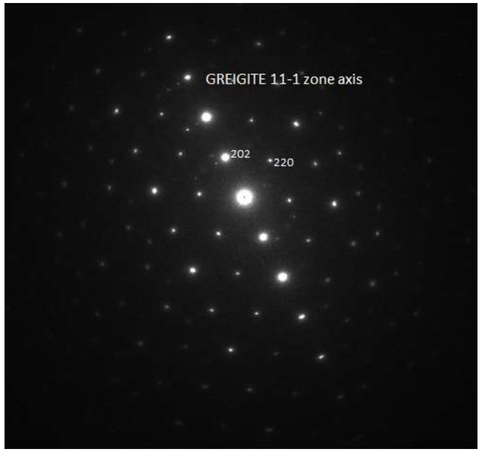
Pyrites (FeS_2) replacing former cells and vesicles of *Thermococcales*

Pyrite spherules





Extracellular Fe(II)Fe(III)$_2$S$_4$ greigite mineralization on EPS (Extracellular polymeric substance)



Gorlas *et al.*, 2018

Does this hyperthermophilic (i.e. >80°C) biosphere contribute significantly to the formation of minerals that build up the chimney and to the biogeochemistry of the hydrothermal system?

Physiological level:

Determine the **physiological and physico-chemical** conditions which **influence** and **control the rates of biominerals** produced

Genomic level:

Explore the **molecular mechanism of biomineralization**

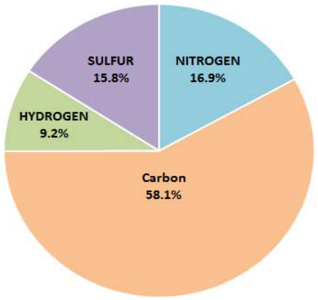
Ecological level:

Search for **biosignatures of hyperthermophiles** in black smokers

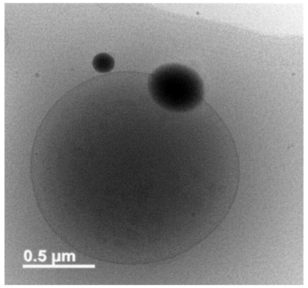
Thermococcales metabolism influences the production of iron-sulfide biominerals

In S(0) conditions (with Fe^{2+} solution at 5mM)

% intracellular of Carbon, Nitrogen, Hydrogen and Sulfur

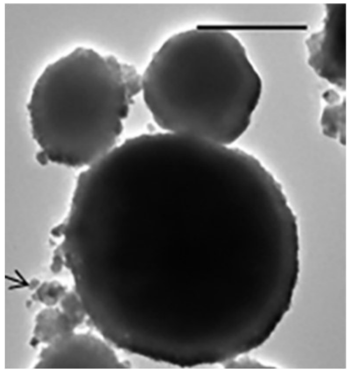


CHNS analyses



CryoEM

✓ Sulfur vesicles



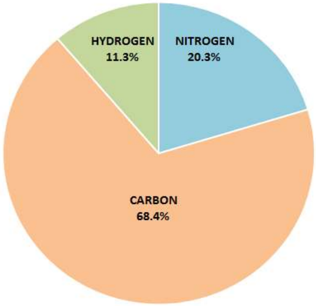
✓ Amorphous FeS

✓ Pyrite

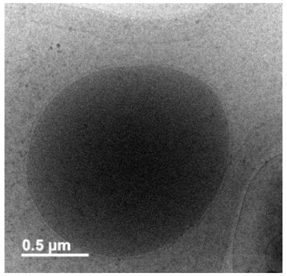
✓ Greigite

In L-cystine condition (with Fe^{2+} solution at 5mM)

% intracellular of Carbon, Nitrogen, Hydrogen and Sulfur

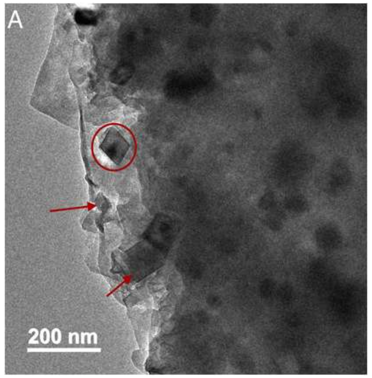


CHNS analyses



CryoEM

X No sulfur vesicles



✓ Amorphous FeS

X No pyrite

✓ Greigite

Essential role for intracellular sulfur and/or sulfur present in sulfur vesicles for pyrite formation

Gorlas *et al.*, 2022

Thermococcales metabolism influences the production of iron-sulfide biominerals

Pyrite formation, 2 major pathways

(Rickard, 1997; Rickard & Luther, 2007)

H_2S pathway :

$FeS + H_2S \rightarrow FeS_2 + H_2$

Polysulfide pathway :

$FeS + S_n^{2-} \rightarrow FeS_2 + S_{n-1}^{2-}$

In both S(0) and L-cystine conditions :

Production of H_2S

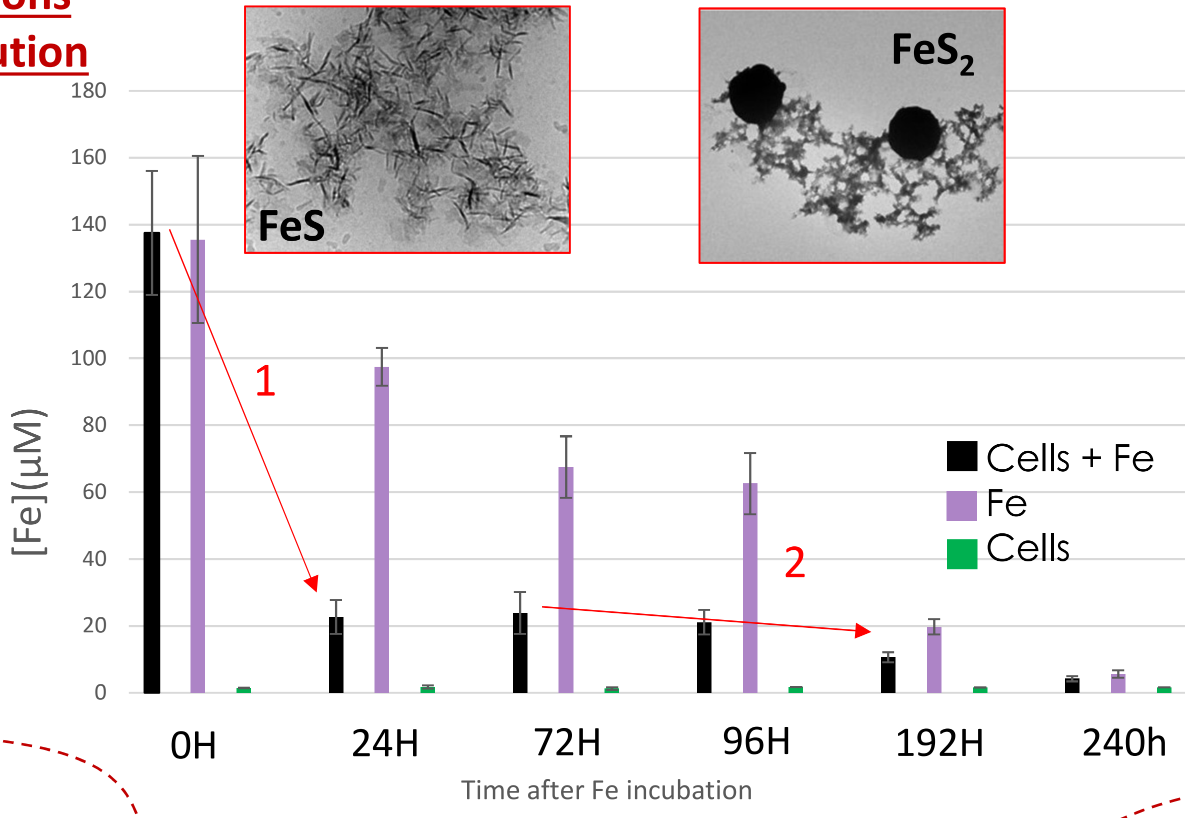
Sulfur intracellular and/or sulfur vesicles (source of polysulfides ?) act as precursor for pyrite formation

Gorlas et al., 2022; Truong et al., 2023; Mariotte et al., 2026

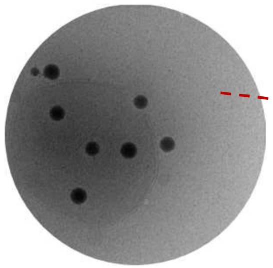
Pyrite production : successive precipitation phases

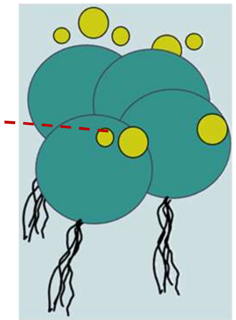
In S(0) conditions (with Fe^{2+} solution at 1mM)

Total dissolved iron measurement
MP-AES




Tom MARIOTTE



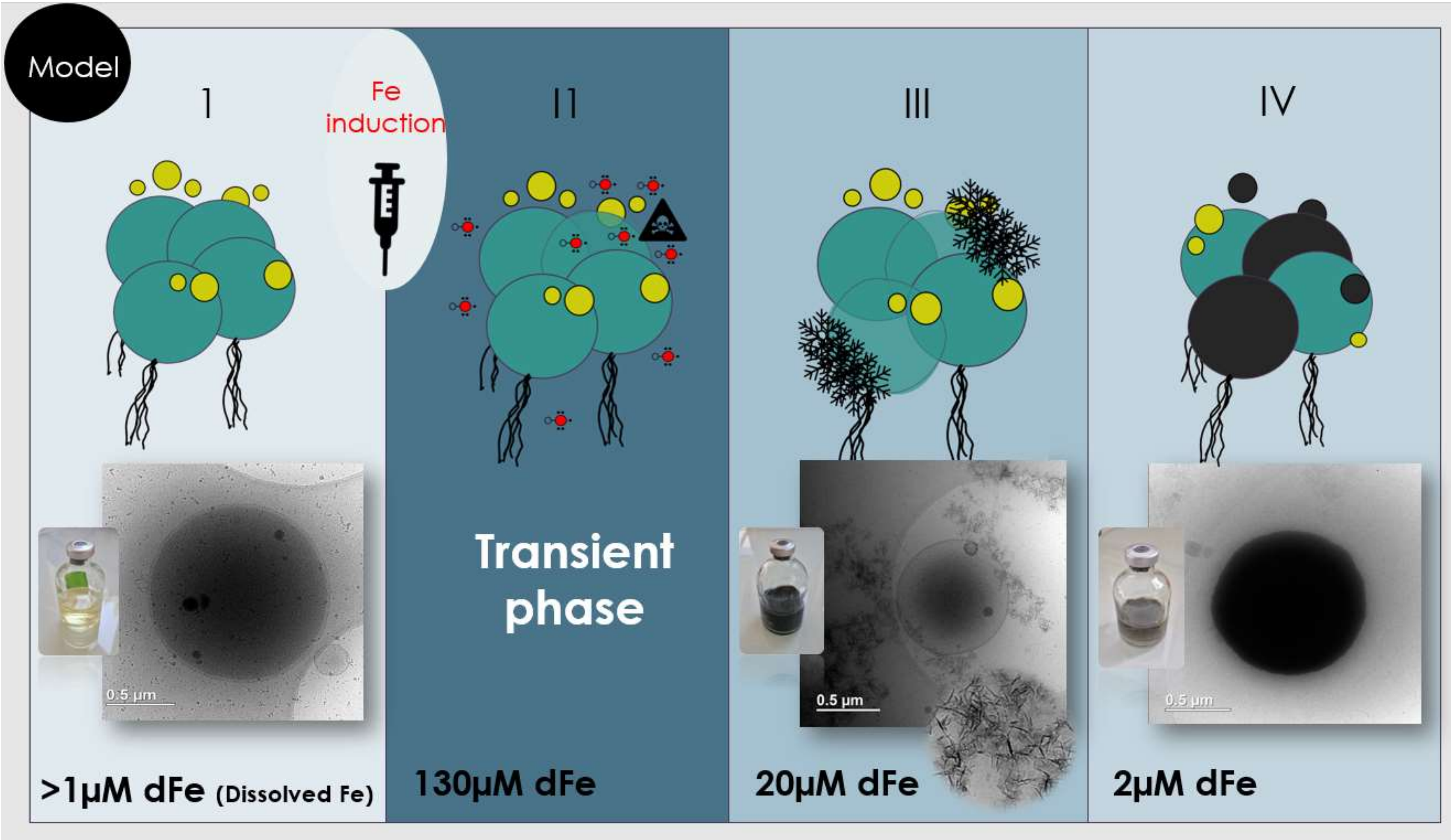


$Fe^{2+} + HS^{-} \rightarrow FeS + H^{+}$

$FeS + S_n^{2-} \rightarrow FeS_2 + S_{n-1}^{2-}$

Mariotte *et al.*, 2026

Pyrite production : successive precipitation phases



↘ chemical toxicity ↘ physical toxicity

Mariotte *et al.*, 2026

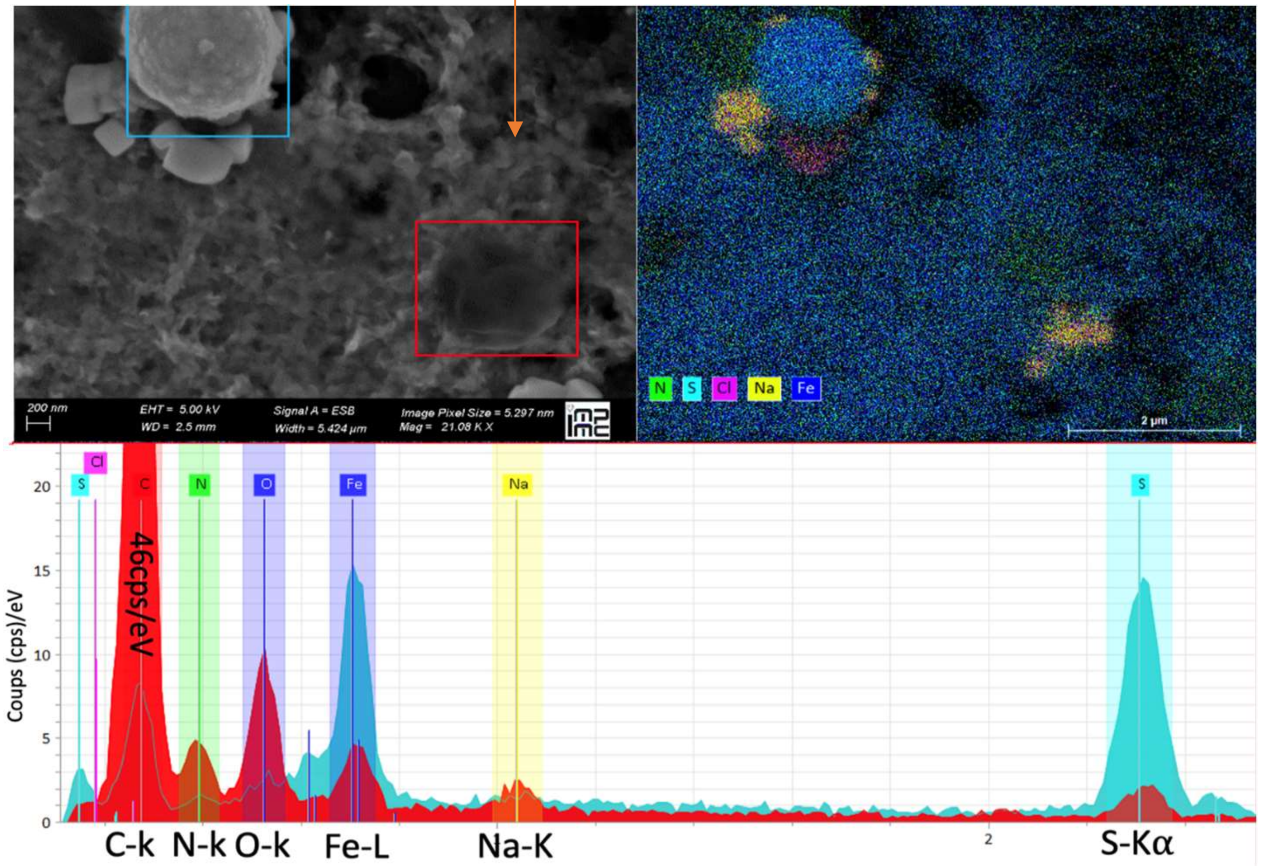
Population heterogeneity

In S(0) conditions (with Fe^{2+} solution at 1mM)

First pyrite after 72H of Fe induction

Mineralizing cells

Living cells



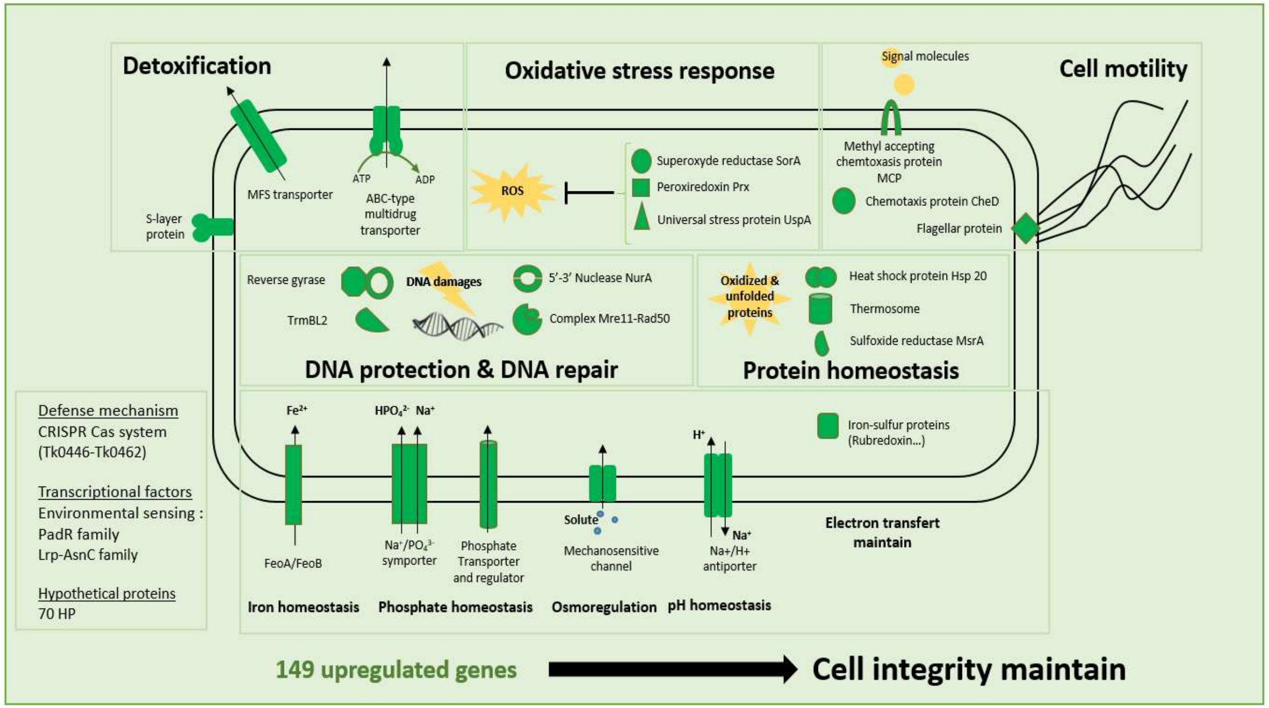
EDS analysis

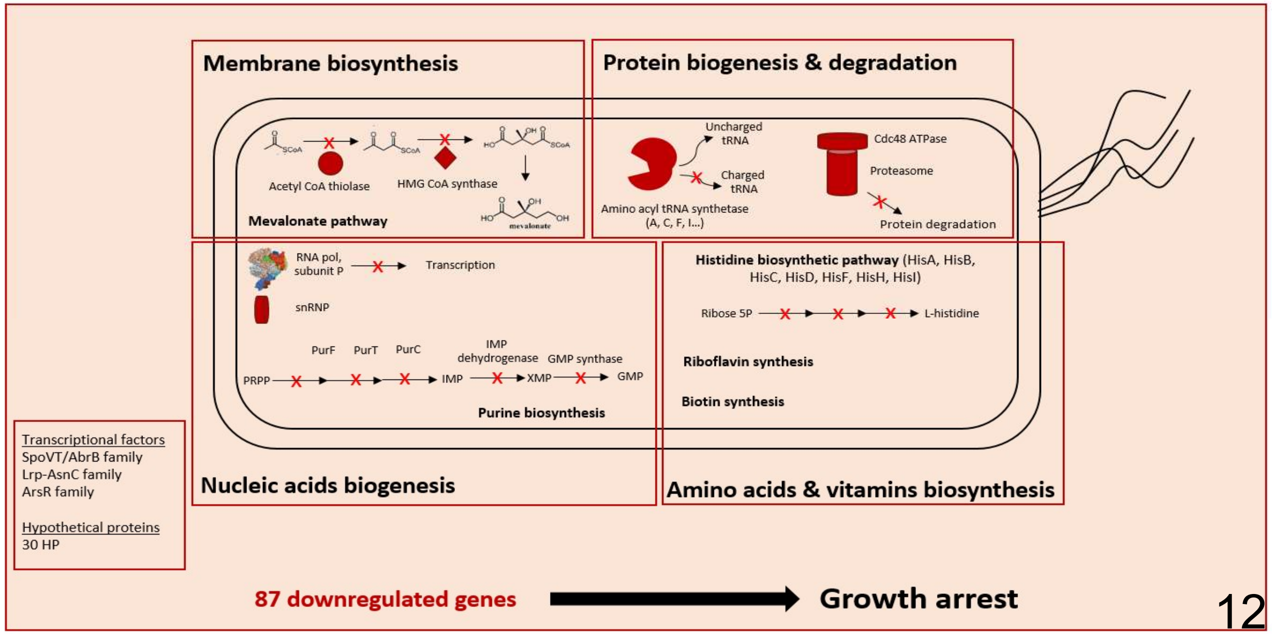
Mariotte *et al.*, 2026

In S(0) conditions (with Fe^{2+} solution at 1mM)

Transcriptomic analyses

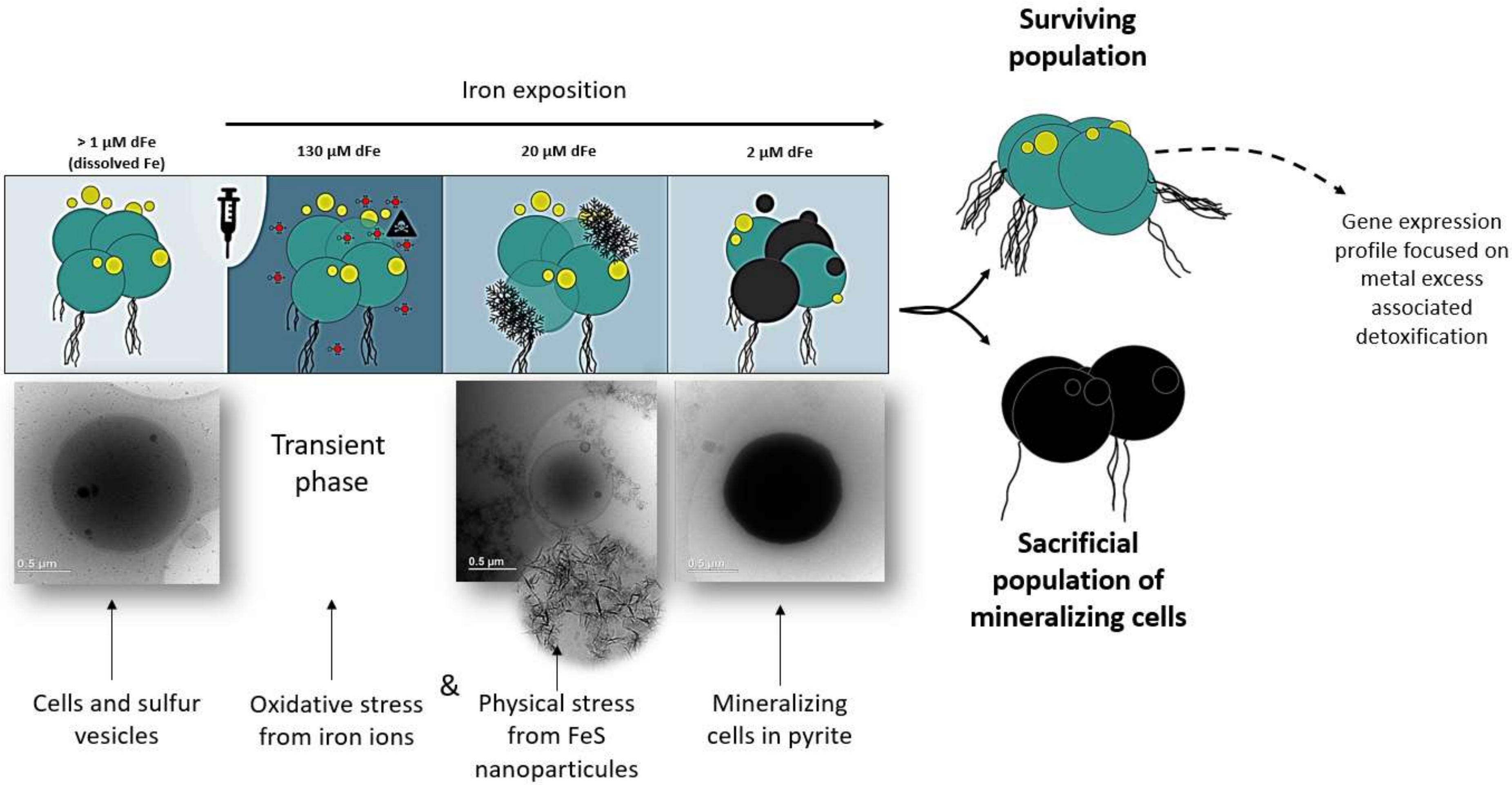
First pyrite after 72H of Fe induction





Mariotte *et al.*, 2026

Iron sulfides produced by Thermococcales: an iron detoxification mechanism

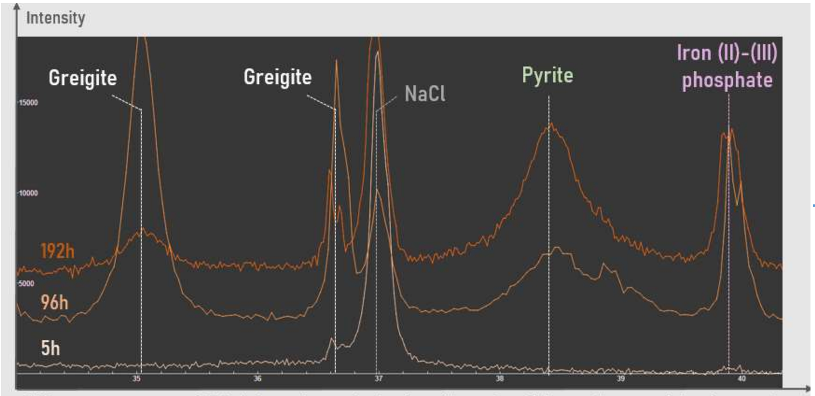


Mariotte *et al.*, 2026

Mineralogical characterization during mineralization process

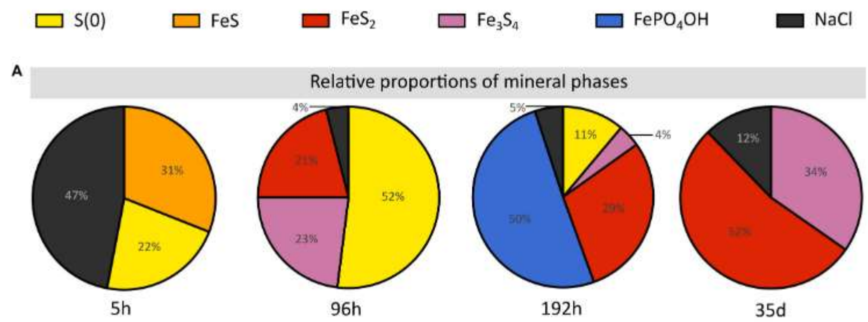
Chloé TRUONG

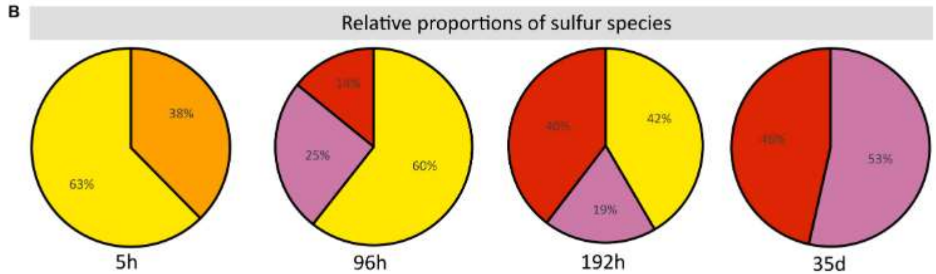
In S(0) conditions (with Fe^{2+} solution at 5mM)

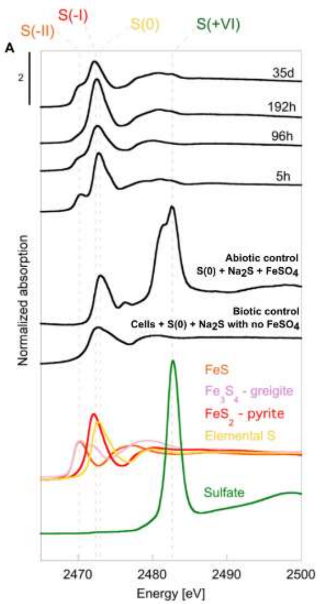


Diffractograms extract of *T. kodakarensis* samples incubated in a mineralizing medium containing elemental sulfur and Fe^{2+}, at 85 ° C . (2θ : 34 – 40°)

DRX analyses







XANES data

Phosphorus-iron-sulfur dynamics :

FeS (5h) < greigite-pyrite (96h) < pyrite - Iron II-III phosphate (192h) < greigite-pyrite (35d)

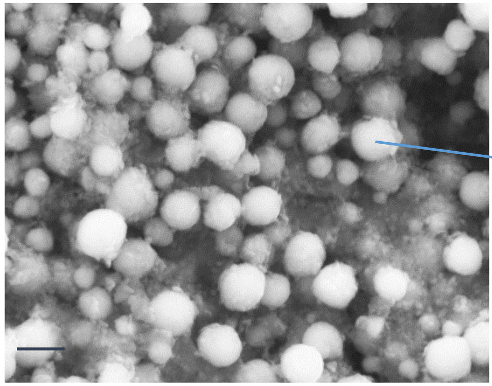
Sulfur redox swing from S(0) to S^{-2} (H_2S/FeS) and then to S^{-1} (FeS_2)

Iron redox evolution : Fe^{2+} in FeS and pyrite, Fe^{3+} in greigite and Iron II-III phosphate

Gorlas et al., 2022; Truong *et al.*, 2023

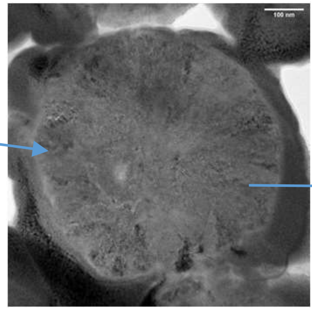
Characterization of biogenic pyrite spherules

In S(0) conditions (with Fe^{2+} solution at 5mM) – 96h

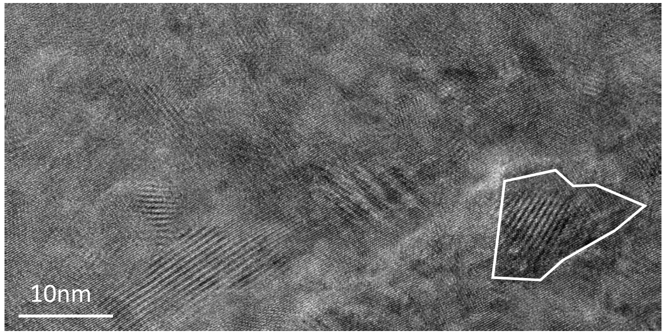


Pyrite spherules (200nm – 1µm)
Ultra-smooth surfaces

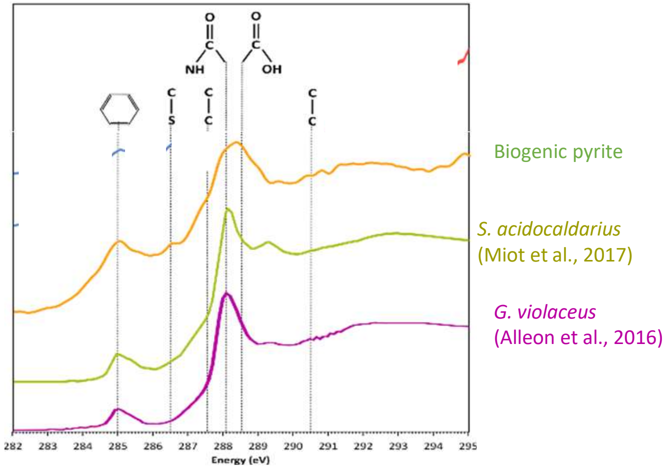
FIB section



Microtexture of pyrites



Polycrystalline pyrite
Small domains (15 nm)



XANES data

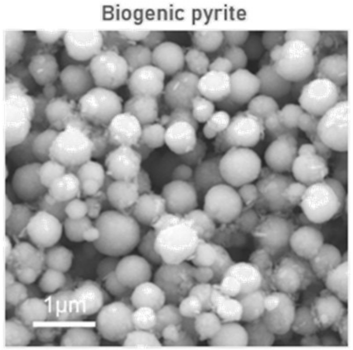
Presence of organic compounds trapped within the spherules

aromatic groups, amide groups and carboxylic groups…

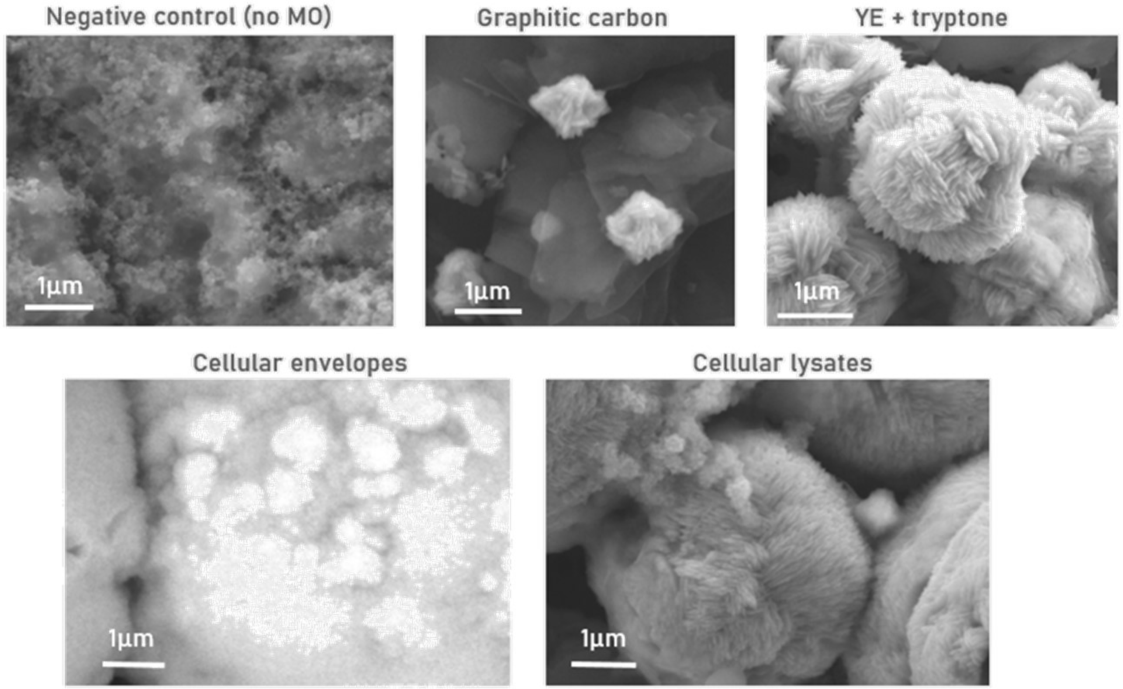
Truong *et al.*, 2023;
Truong *et al.*, 2024a

Abiotic syntheses of pyrite *VS* biogenic pyrite spherules

Chloé TRUONG



Pyrite spherules (200nm – 1µm)
Ultra-smooth surfaces
Polycrystalline pyrite
Crystallographic domains (15 nm)
Presence of organic compounds



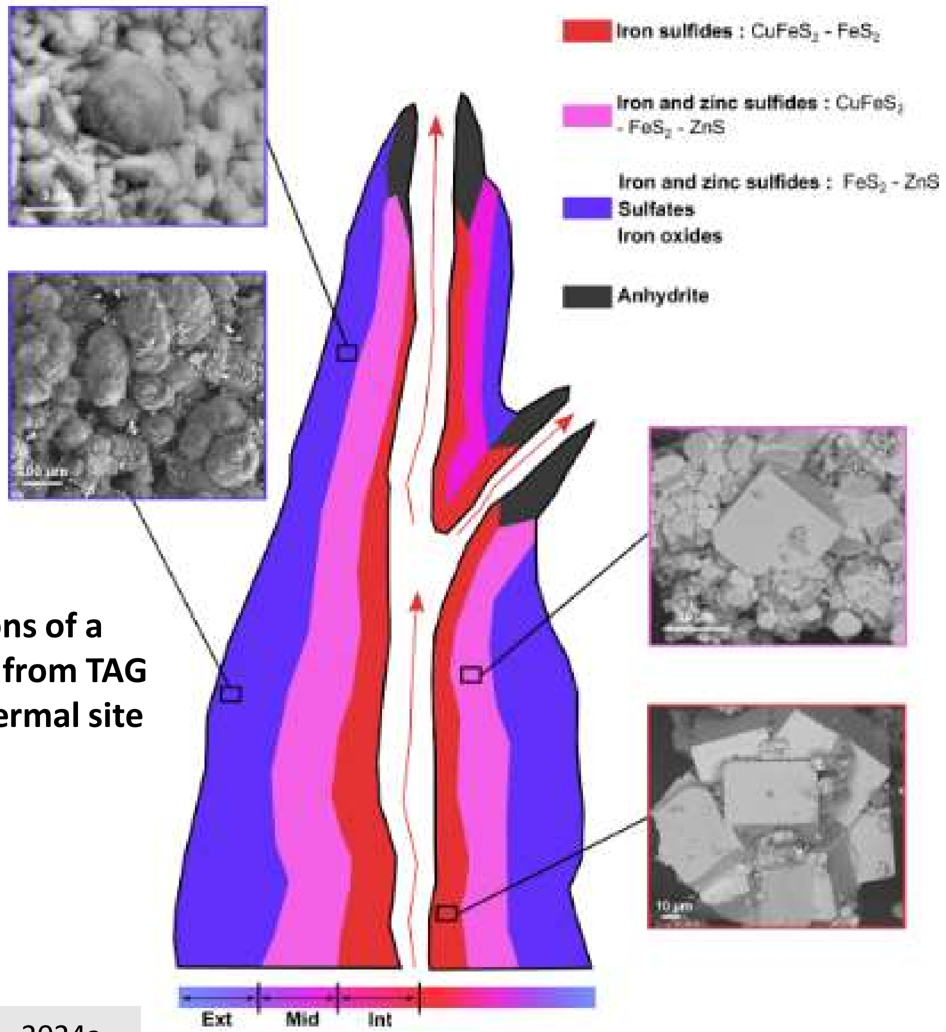
Negative control (no MO) – No pyrite (need MO)
Intracellular material – No pyrite (no reactive surface)

Graphitic carbon - sand-rose-like crystals, domains > 200 nm, no organic compounds
YE + tryptone - sand-rose-like crystals (5µm), domains > 100 nm, no organic compounds
Cellular envelopes – pyrite spehrules (10µm), domains > 50 nm, few organic compounds
Cellular lysates – pyrite spherules (2-10µm), domains < 10 nm, organic compounds

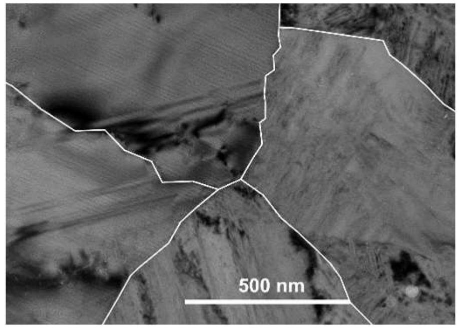
Truong *et al.*, 2024a
Truong *et al.*, 2024b

Biogenic pyrite spherules : biosignatures ?

Mineral biosignatures in black smokers ?



Sections of a chimney from TAG hydrothermal site



External portion contain pyrite spherules

2 – 5 µm in size

Mosaic disoriented domains of pyrite spherules

Domains > 100 nm

Presence of organic compounds

Greater similarity between pyrite spherules from cellular lysates and those from the TAG site

Truong *et al.*, 2024a
Truong *et al.*, 2024b

Biosignatures

Metabolism
Thermodynamic model

François
GUYOT

Sylvain
BERNARD

Metal stress response

Alexandre
GELABERT

Guillaume Morin

Pierre Le Pape

Biomineralization

ANDROMEDE

Thank you for your attention