Potential applications of biomining for in situ recovery

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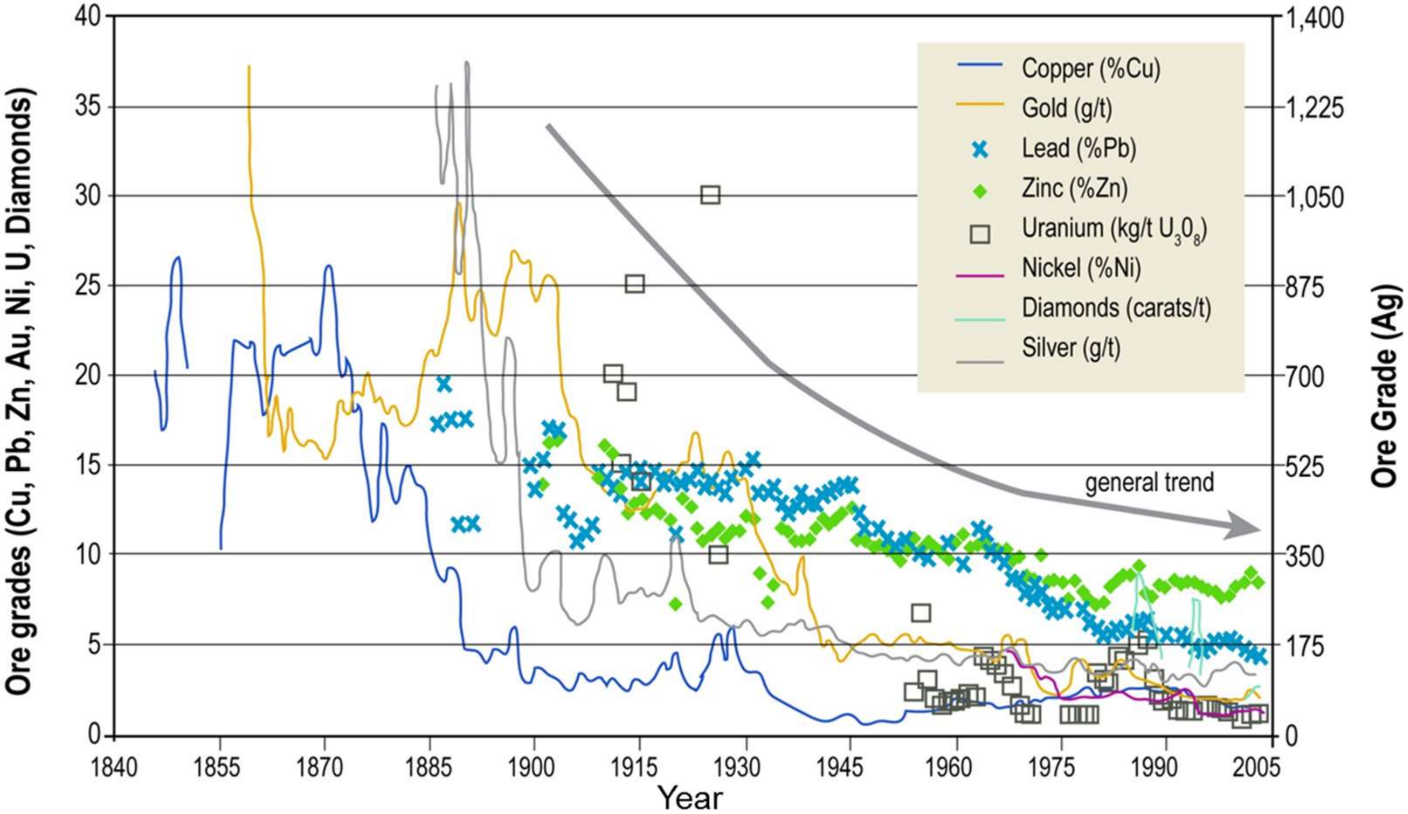
Declining ore grades



→ Motivation for biomining and *in situ* recovery

Mudd GM. 2009. The sustainability of mining in Australia: Key production trends and their environmental implications for the future. Research Report No RR5. Monash University and Mineral Policy Institute.

Principles of biomining and bioleaching

- **Biomining:** the use of microorganisms for extraction of metals from minerals and wastes and recovery of metals from leach liquors
  - **Bioleaching:** the use of microorganisms for the extraction of metals from minerals and wastes through redoxolysis, acidolysis and/or complexolysis
  - **Biorecovery:** the use of microorganisms for the recovering metals from leach liquors through bioprecipitation and/or biosorption

Bioleaching through redoxolysis

Biological process	Description	Electron donors and acceptors
Oxidative bioleaching	Fe^{2+} biooxidation for oxidative ferric leaching of sulfide minerals	Electron donor: Fe^{2+} Electron acceptors: O_2, NO_3^-
	Mn^{2+} oxidation to Mn^{4+} for use of MnO_2 as an oxidant for bioleaching sulfide minerals	Electron donor: Mn^{2+} Electron acceptor: O_2
Reductive bioleaching	Fe^{3+} bioreduction for reductive bioleaching of oxide minerals	Electron donors: organic compounds, H_2, reduced sulfur compounds Electron acceptor: Fe^{3+}
	Mn^{4+} bioreduction for reductive bioleaching of Mn ores	Electron donors: organic compounds Electron acceptor: Mn^{4+}

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Adapted from: Gumulya Y, Zea L, Kaksonen AH. 2022. *In situ* resource utilisation: the case for space biomining. Minerals Engineering 176: 107288.

Bioleaching through acidolysis

Biological process	Description	Electron donors and acceptors
Acidolysis with inorganic acid	Sulfur biooxidation to sulfuric acid for leaching acid-soluble minerals and wastes	Electron donors: reduced sulfur compounds Electron acceptors: O_2, Fe^{3+}
Acidolysis with organic acids	Biogenic organic acids production for leaching acid-soluble minerals and wastes	Electron donor: organic compounds Electron acceptor: O_2, none (fermentation)

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Bioleaching through complexolysis

Biological process	Description	Electron donors and acceptors
Complexo-lysis	Biogenic organic acids production for rare earth element leaching	Electron donors: organic compounds Electron acceptors: Fe^{3+}, O_2, none (fermentation)
	Biogenic cyanide production for gold leaching	Electron donors: organic compounds Electron acceptor: O_2
	Iodide (I^-) biooxidation to iodine (I_2) for gold leaching	Electron donor: I^- Electron acceptor: O_2

Contact, non-contact and collaborative bioleaching of sulfide minerals

Non-contact leaching

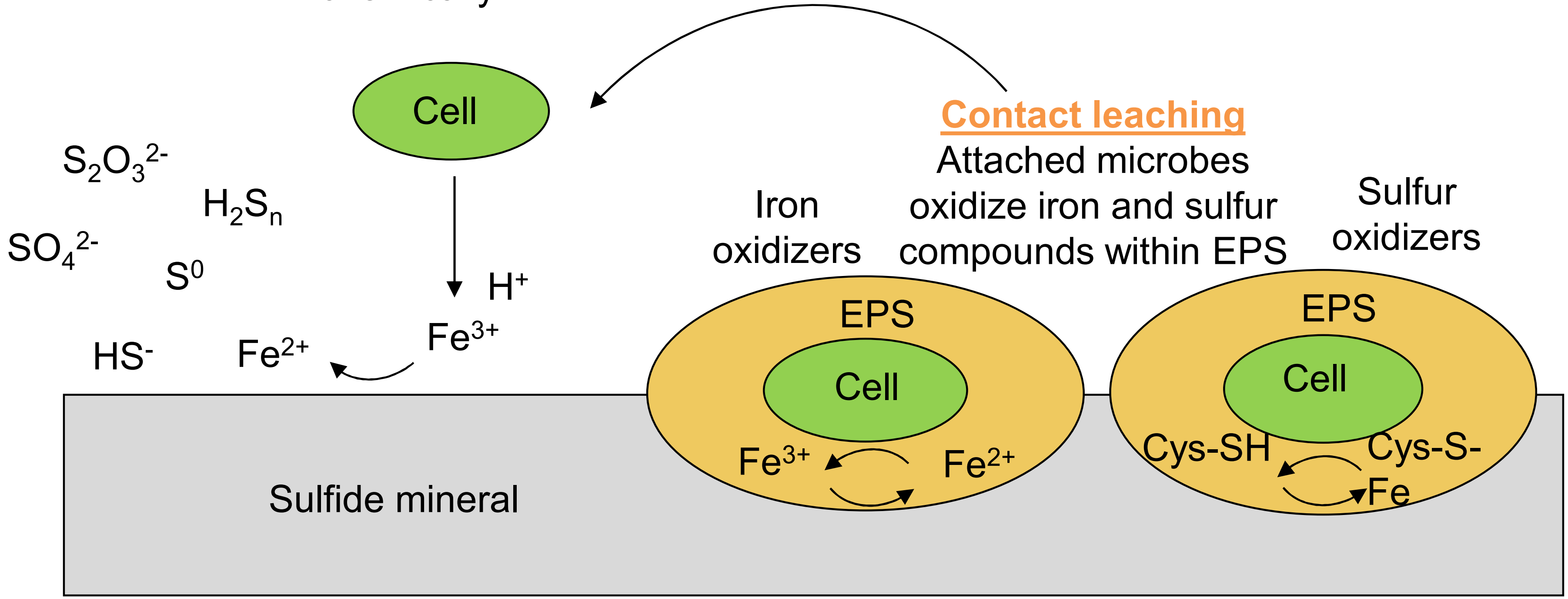
Planktonic microbes produce Fe^{3+} and/or H^+ which solubilize minerals chemically

Collaborative leaching

Attached cells release sulfur colloids for planktonic sulfur oxidizers

Contact leaching

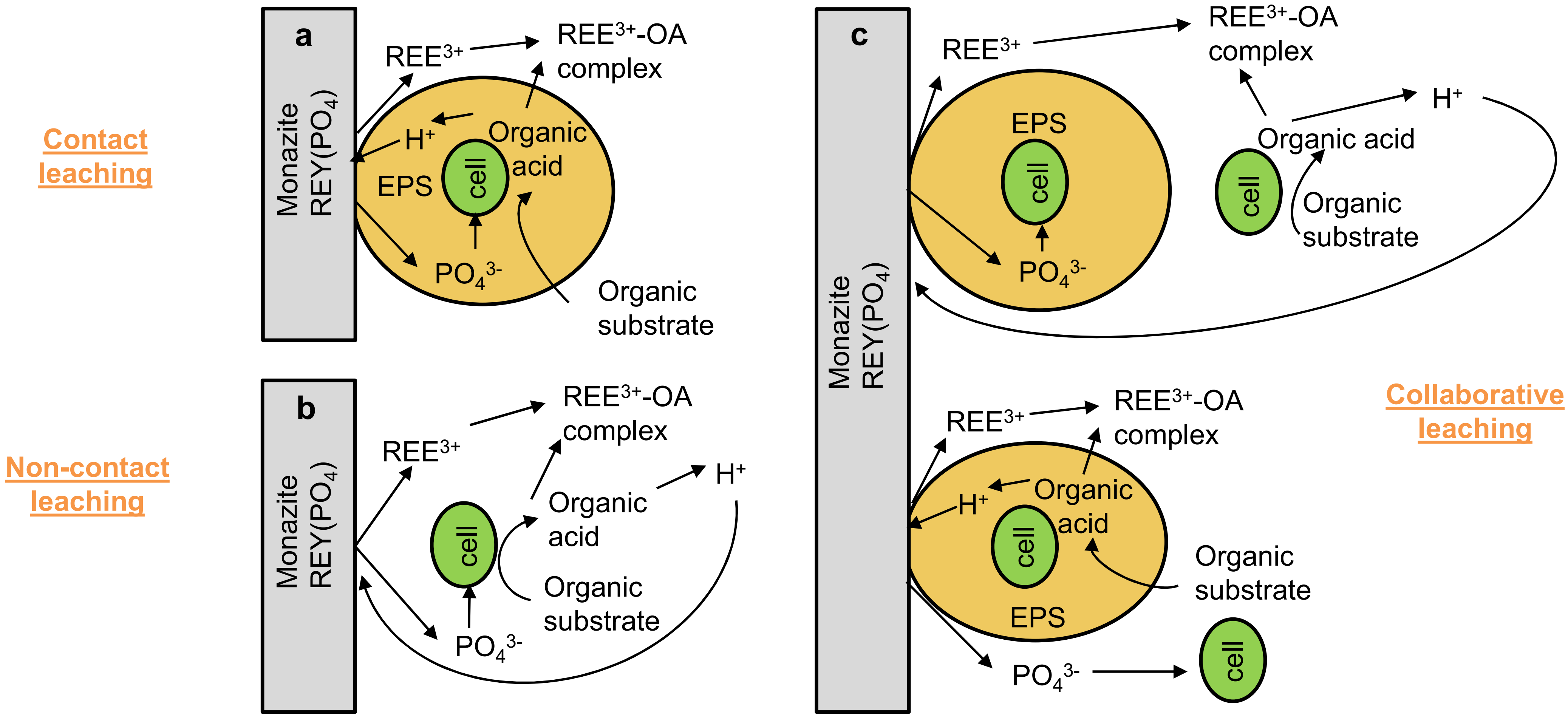
Attached microbes oxidize iron and sulfur compounds within EPS



EPS = exopolysaccharides

Rawlings DE. 2002. Heavy metal mining using microbes. Annual Reviews of Microbiology 56:65–91.

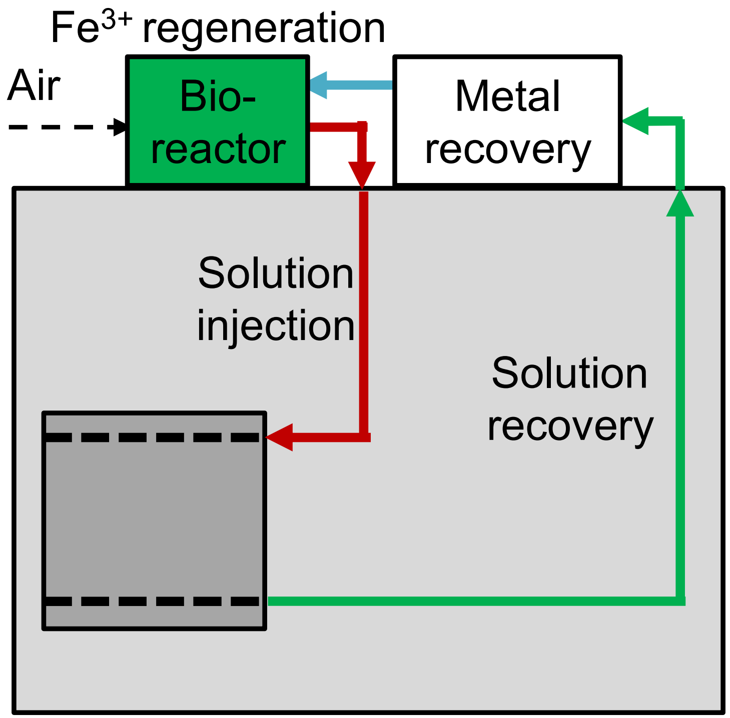
Contact, non-contact and collaborative bioleaching of rare earths from monazite



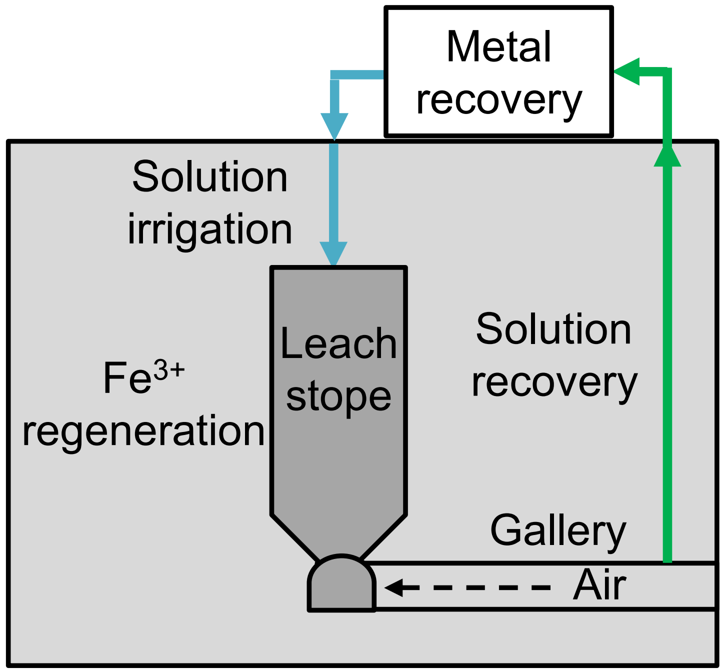
Adapted from: Fathollahzadeh H, Eksteen JJ, Kaksonen AH, Becker T, Watkin ELJ. 2018. Microbial contact enhances bioleaching of rare earth elements. Bioresource Technology Reports 3: 102-108.

In situ biomining of under saturated and unsaturated conditions

Saturated *in situ* biomining (biogenic lixiviant generation and leaching in separate unit processes)



Unsaturated *in situ* biomining (biogenic lixiviant generation and leaching in a single unit process)



Adapted from: Kaksonen and Pedersen 2023. Chapter 17: The Future of Biomining: Towards Sustainability in a Metal-demanding World. In: Bryan, Johnson, Roberto and Schlömann (eds.) *Biomining Technologies:* Bioprocessing Options for Extracting and Recovering Metals from Ores and Wastes. Springer-Verlag (Heidelberg, Germany). Pp. 295-314.

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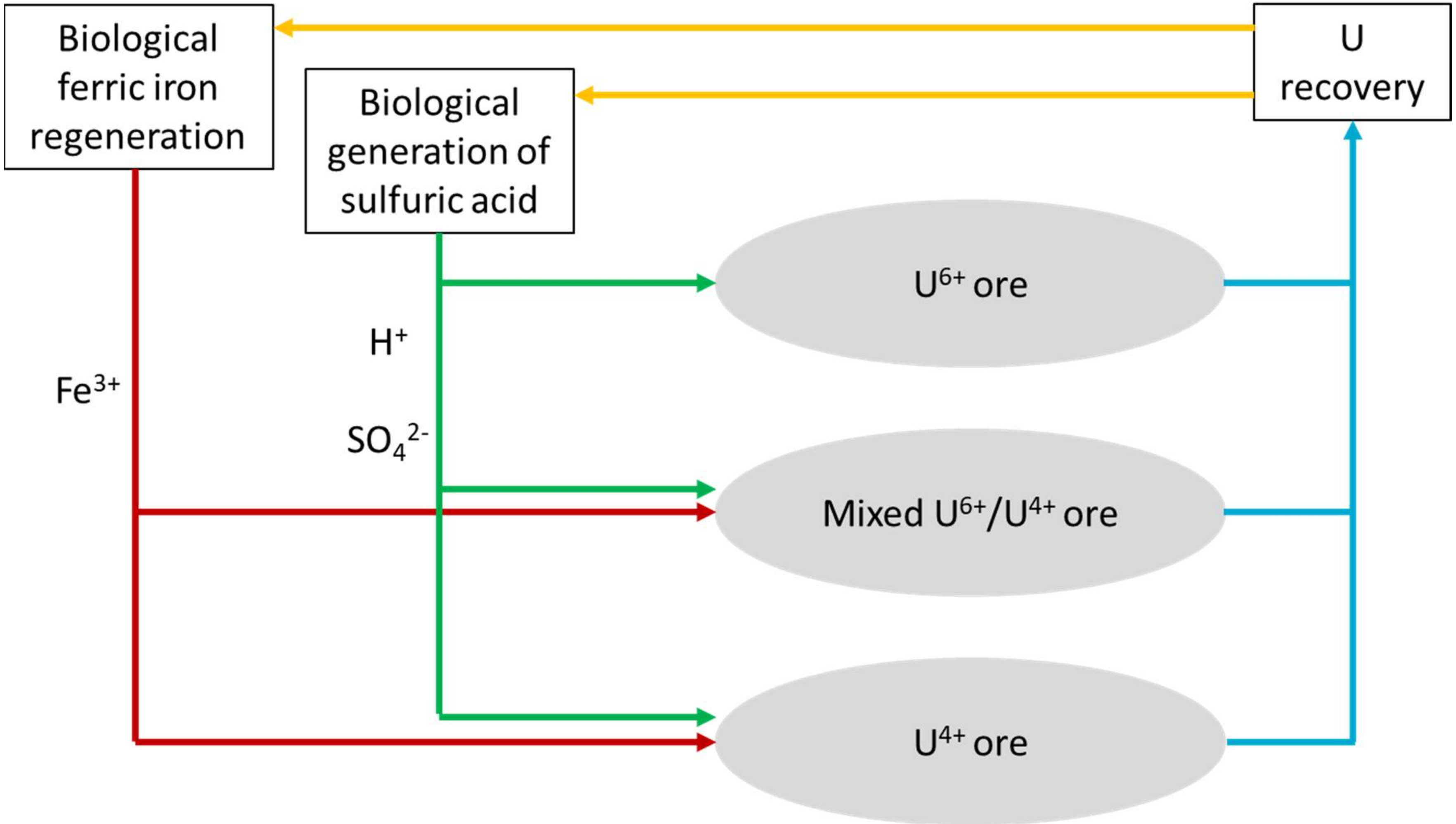
In situ bioleaching of uranium

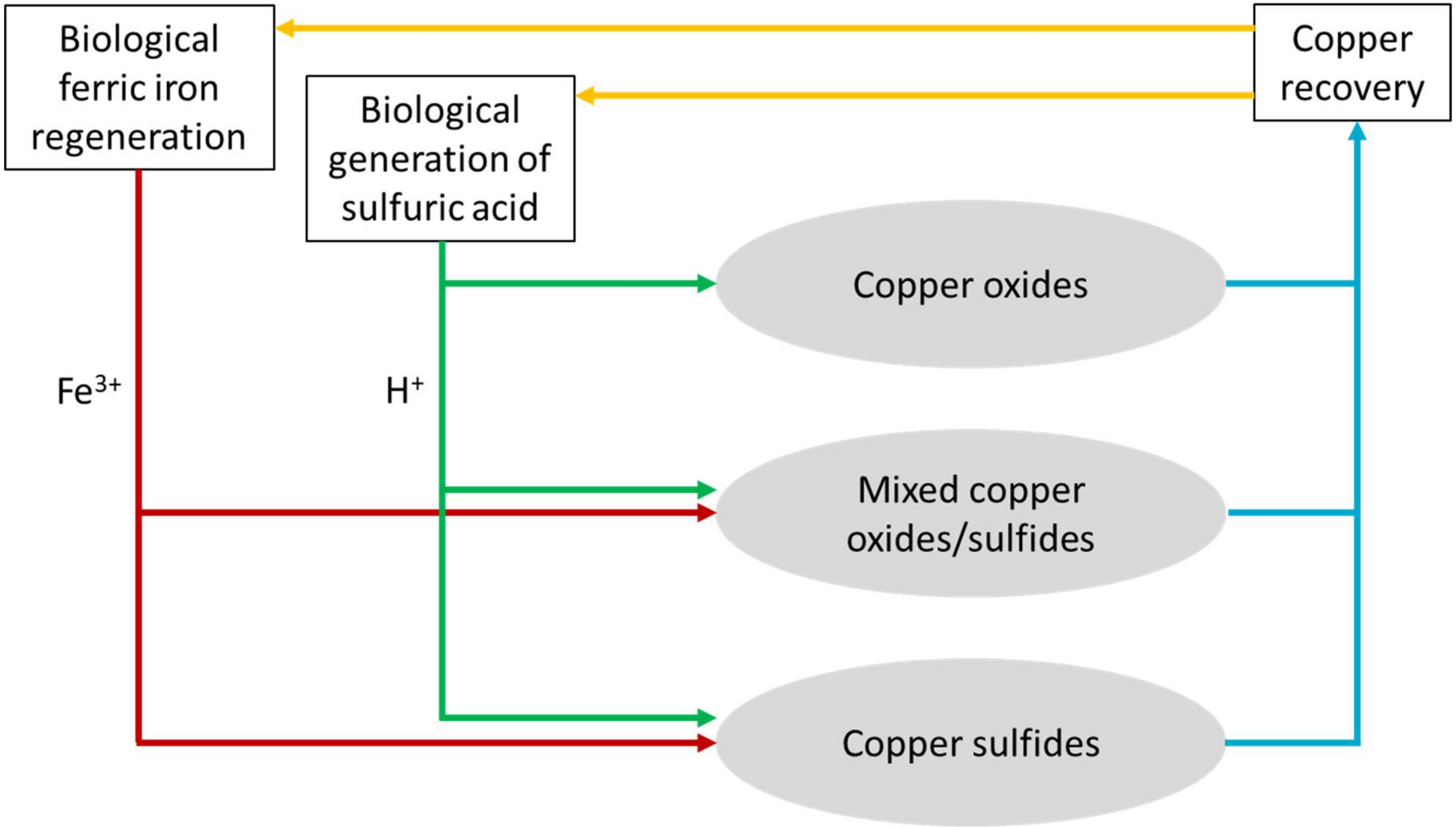


In situ stope bioleaching of uranium (Ontario, Canada)

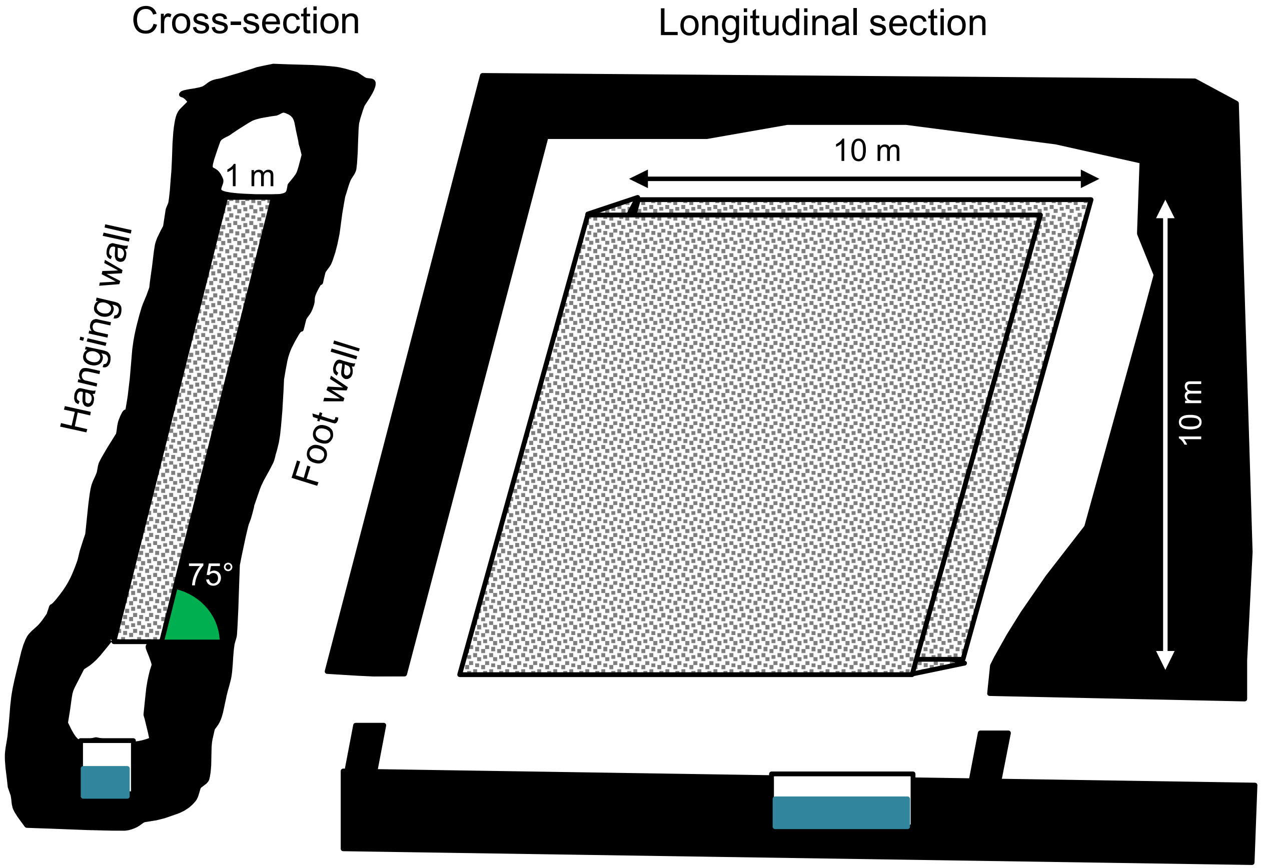
- **Stanrock Mine (1960s)**
  - Nutrient addition did not improve leaching
- **Agnew Lake Mine (late 1970s)**
  - Challenges with ore fracturing, and enabling sufficient contact between solution and minerals while containing the leach solution
- **Denison Mine (1980s and early 1990s)**
  - Ore was fractured and concrete bulkhead constructed across the opening of a horizontal shaft
  - Ore behind bulkhead was flooded with leach liquor in cycles and pregnant leach liquor drained after 3 weeks for U recovery
  - Bacteria and acidic ferric sulfate leaching improved yields compared to chemical acid leaching

Kaksonen AH, Lakaniemi A-M, Tuovinen OH. 2020. Journal of Cleaner Production 264: 121586

In situ bioleaching of copper



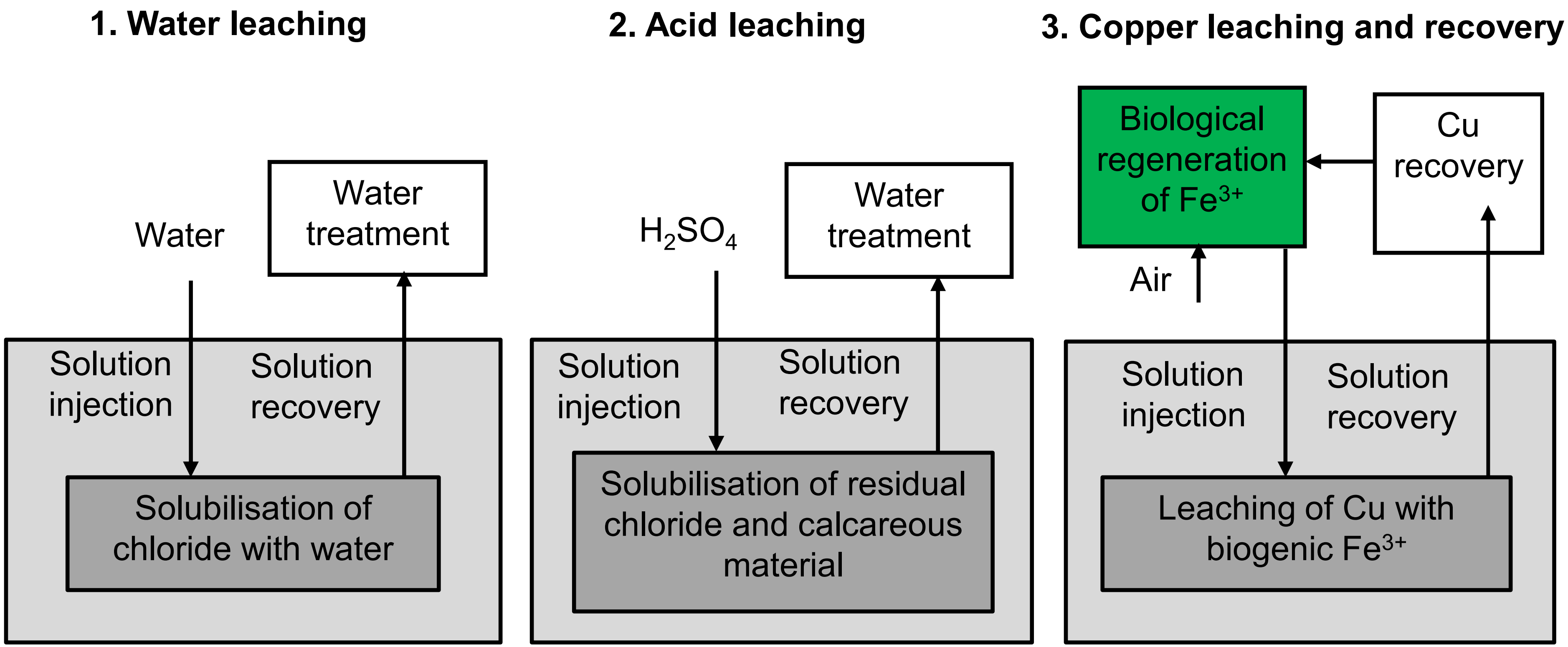
In situ stope bioleaching of Cu and Zn at Ilba Mine (Romania)



- Sulfidic ore: pyrite (FeS_2), chalcopyrite ($CuFeS_2$), covellite (CuS), bornite (Cu_5FeS_4), sphalerite (Zn,Fe)S, galena (PbS), marcasite (FeS_2)
- Ore blasted to <30 cm rocks
- 30% of ore removed → 70 m^3 ore leached in 10 m x 10 m x 1 m stope
- Inoculation with acidophilic Fe- and S-oxidisers
- Leach liquor aerated and circulated intermittently
- 10% Cu and 78% Zn leaching after 18 months
- Challenges with ore humidification and in winter access to energy for aeration and liquor circulation

Sand W, Hallmann R, Rohde K, Sobotke B, Wentzien S. 1993. Applied Microbiology and Biotechnology 40:421-426

In situ biomining of copper from a saline calcareous copper sulfide ore



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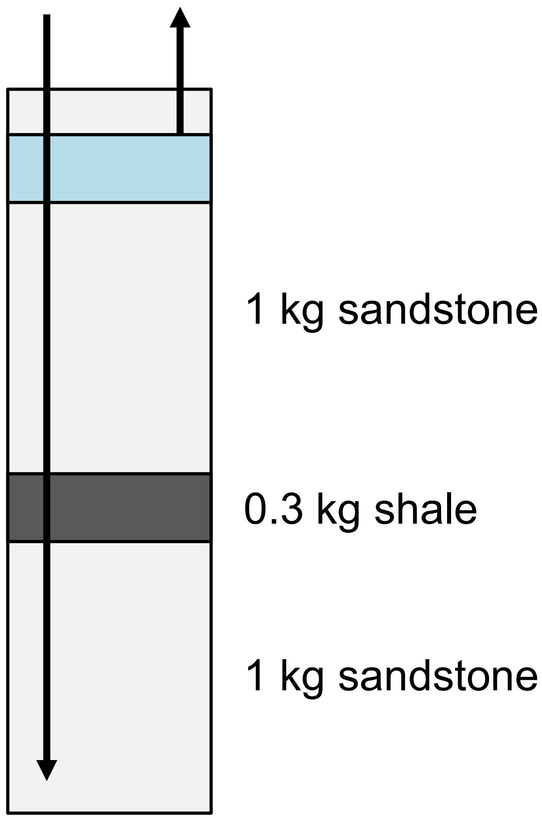
Lab-scale column study for evaluating *in situ* biomining of copper from a saline calcareous copper sulfide ore

- Kupferschiefer comprised of sandstone (2.98% Cu) and black shale (3.61% Cu), with Cu mainly in chalcocite (Cu_2S), bornite (Cu_5FeS_4),chalcopyrite ($CuFeS_2$),
- Lab-scale experiment with upflow columns and acidophilic iron- and sulfur-oxidisers
- Three steps:
  - 19 d water leaching
  - 3 d acid leaching (0.9 M sulfuric acid)
  - 40 d bioleaching (Cu removed with sulfide precipitation 7 time from bleed stream)
- Leaching yield: 59% Cu



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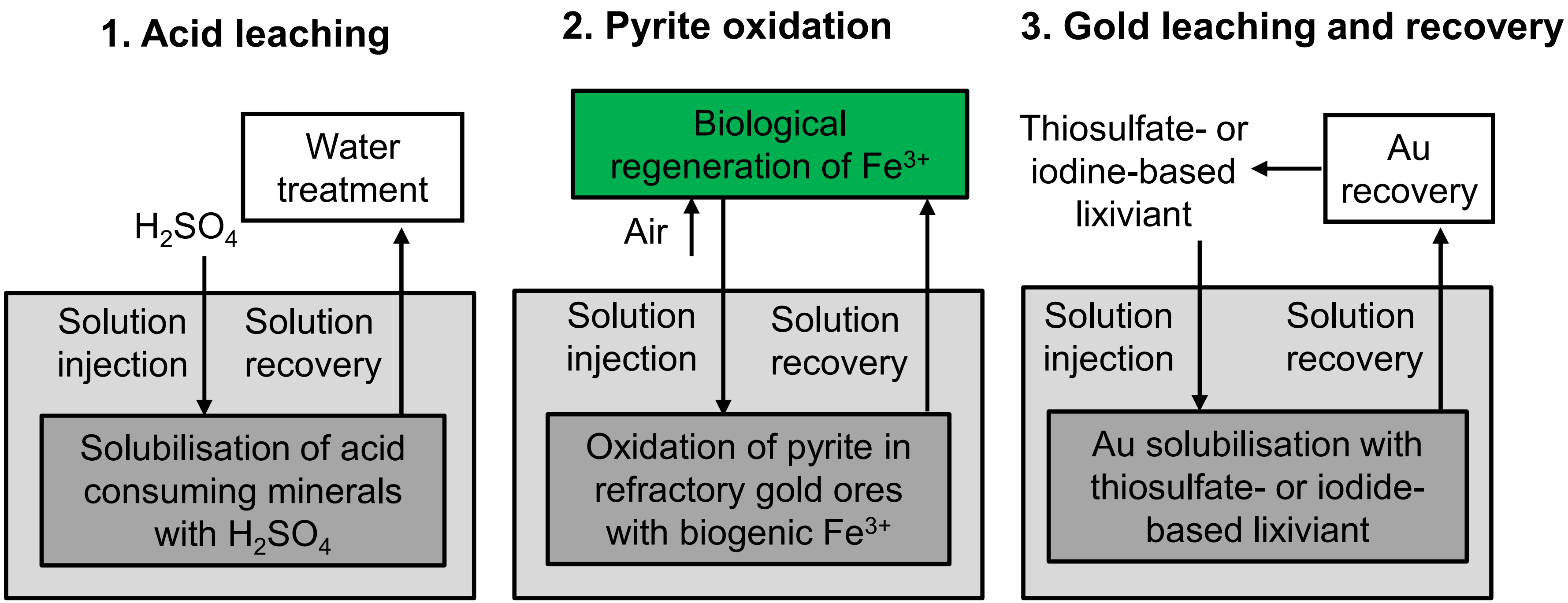
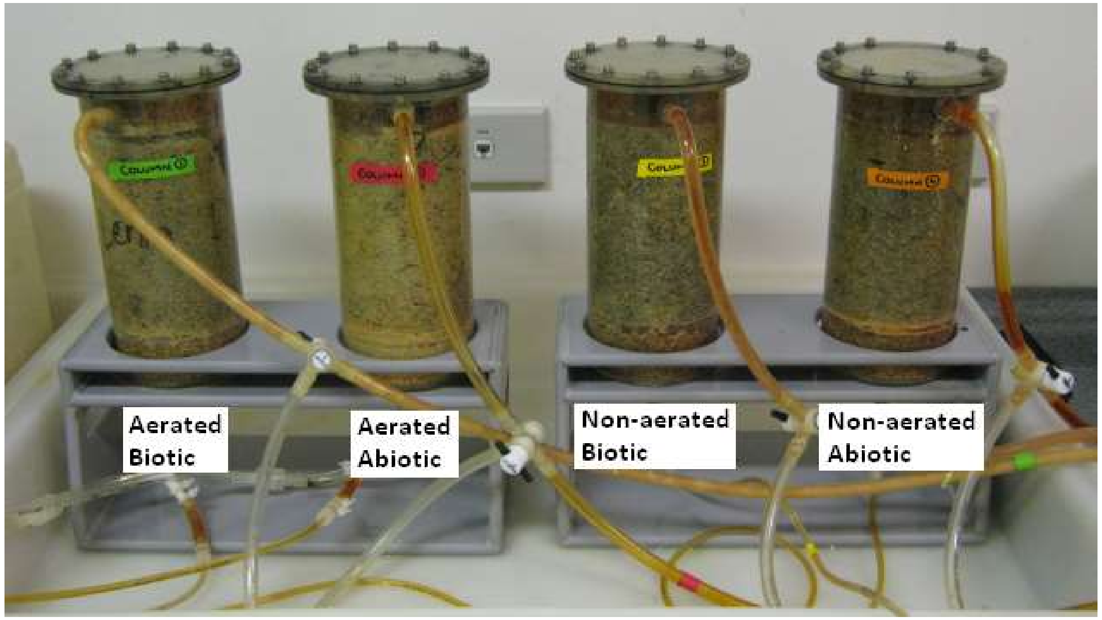
Pakostova E, Grail BM, Johnson DB. 2018. Bio-processing of a saline, calcareous copper sulfide ore by sequential leaching. Hydrometallurgy 179: 36-43.

In situ leaching of gold from refractory sulfidic deposit after biological pre-treatment



Adapted from: Kaksonen and Pedersen 2023. Chapter 17: The Future of Biomining: Towards Sustainability in a Metal-demanding World. In: Bryan, Johnson, Roberto and Schlömann (eds.) *Biomining Technologies:* Bioprocessing Options for Extracting and Recovering Metals from Ores and Wastes. Springer-Verlag (Heidelberg, Germany). Pp. 295-314.

Column study to evaluate *in situ* biooxidation of Au-bearing pyritic ores before gold leaching

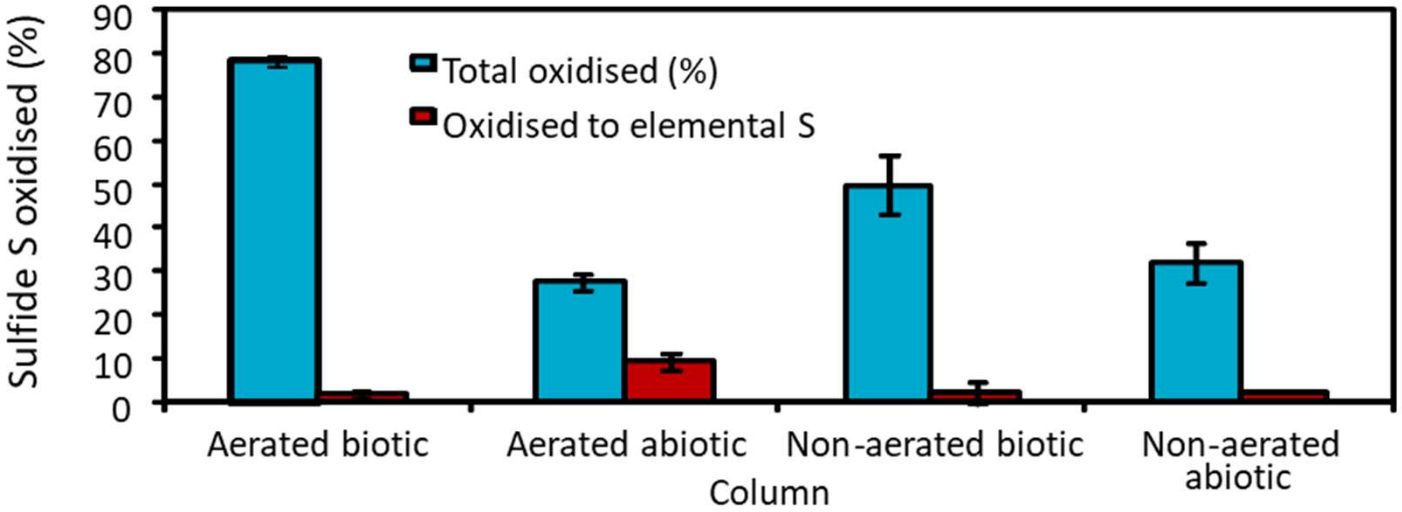


Upflow columns:
- 1.6 kg ore
- Particle size 1-4 mm
- S content 0.93%

- Ore washed with pH 1.5 distilled H_2O to decrease acid consumption
- Biologically generated ferric sulfate (26 g Fe^{2+} L^{-1} pH 1.7) pumped through 158 d
- Columns 1 and 2 aerated from the bottom at 0.6-0.8 L min^{-1}
- Thymol (0.4 g/L) added to abiotic (chemical control) column influents (2 and 4)

Kaksonen AH, Perrot F, Morris C, Rea S, Benvie B, Austin P, Hackl R. 2014. Evaluation of submerged bio-oxidation concept for refractory gold ores. Hydrometallurgy 141: 117-125.

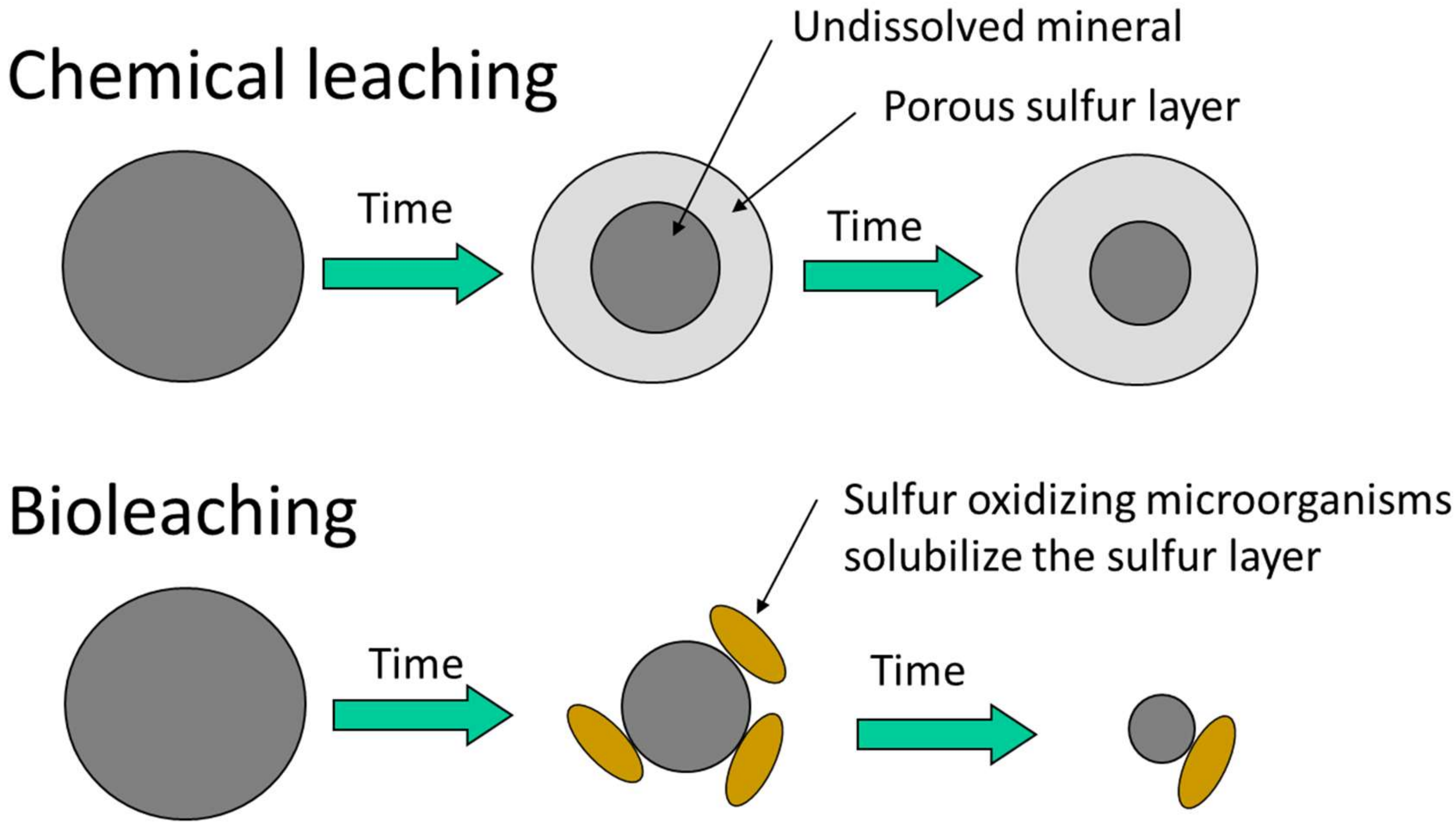
Key findings from the upflow column study



- Pyrite was oxidised under aerobic and anaerobic conditions using biologically generated ferric iron
- The simulated underground aeration and the presence of bioleaching microorganisms enhanced pyrite oxidation
- Microorganisms decreased the accumulation of S^0, the presence of which may decrease subsequent gold recovery

Kaksonen AH, Perrot F, Morris C, Rea S, Benvie B, Austin P, Hackl R. 2014. Evaluation of submerged bio-oxidation concept for refractory gold ores. Hydrometallurgy 141: 117-125.

Microbiological removal of passivating sulfur layers



Adapted from Crundwell FK. 2003. How do bacteria interact with minerals. Hydrometallurgy 71: 75-81.

Factors affecting bioleaching

Bioleaching

Mineralogical factors:
- Mineral composition
- Liberation
- Porosity/permeability

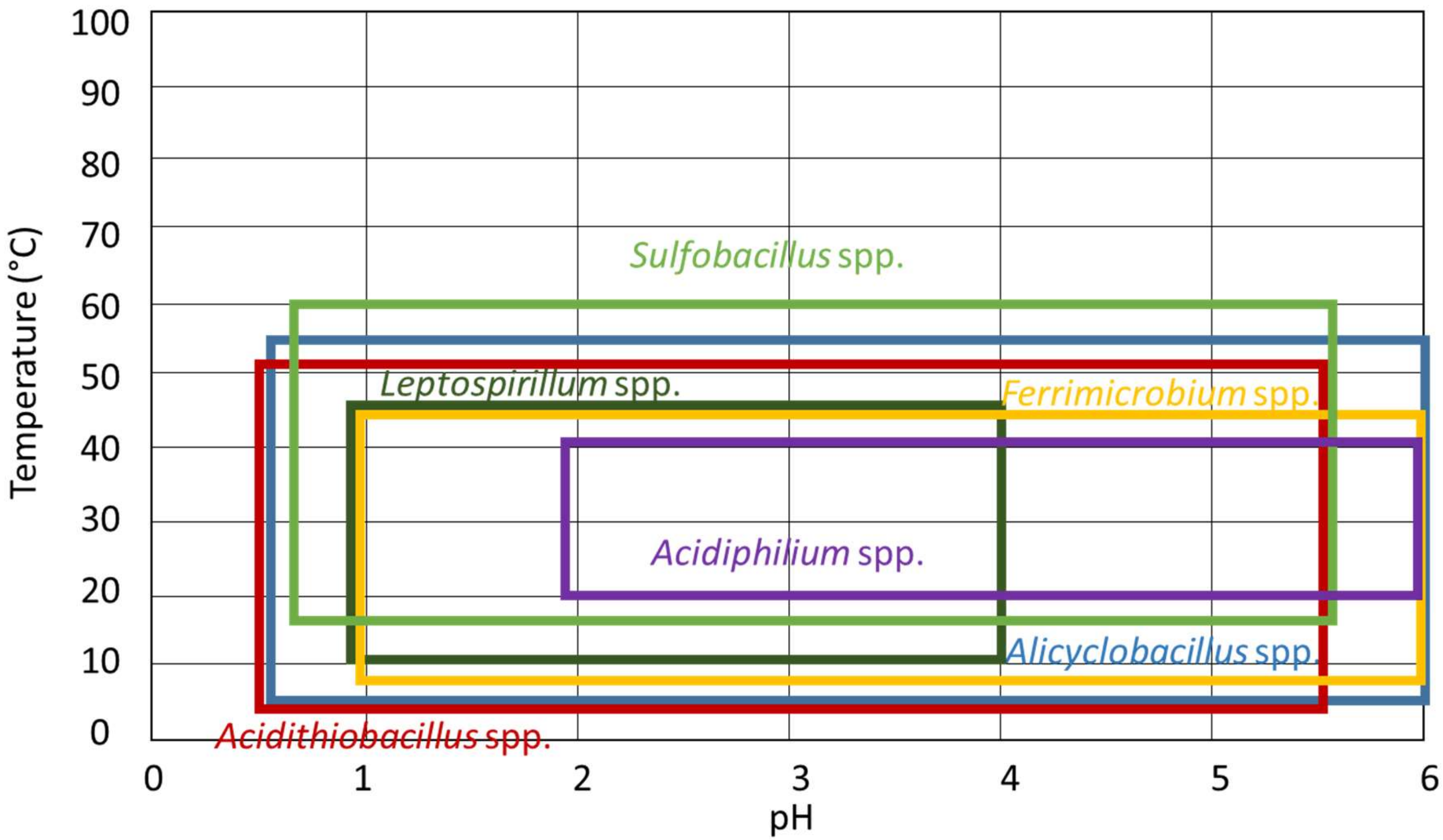
Physical-chemical factors:
- Temperature
- Pressure
- Solubility of gases (O_2, CO_2)
- pH
- Redox
- Fe^{2+}, Fe^{3+}
- Other metals

Process factors:
- Solid/liquid ratio
- Retention time

Microbiological factors:
- Strains
- Diversity
- Density
- Activity
- Distribution
- Substrate availability
- Tolerance

Kaksonen AH, Lakaniemi A-M, Tuovinen OH. 2020. Journal of Cleaner Production 264: 121586

Temperature and pH ranges of bioleaching bacteria



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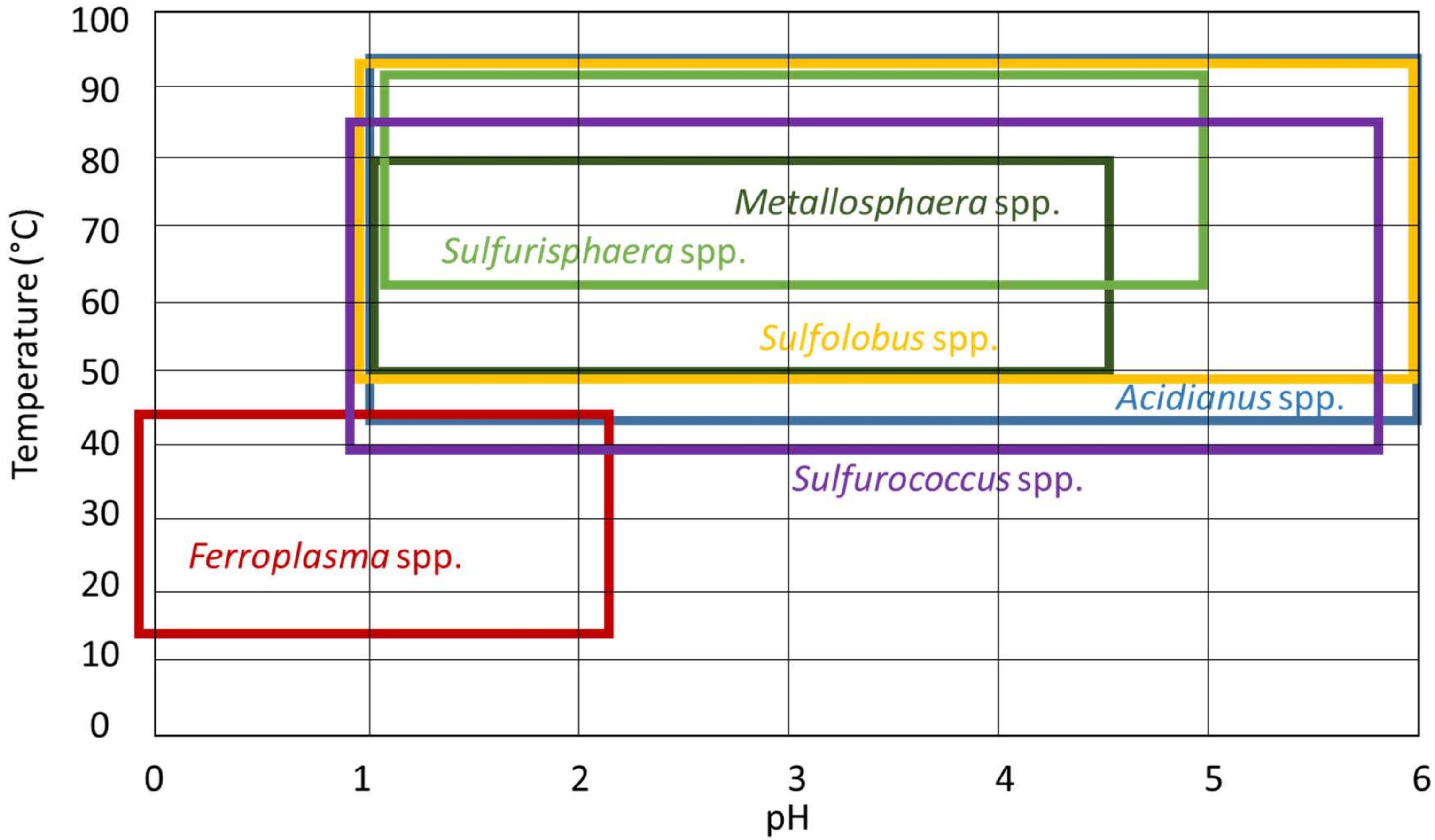
Temperature and pH ranges of bioleaching archaea



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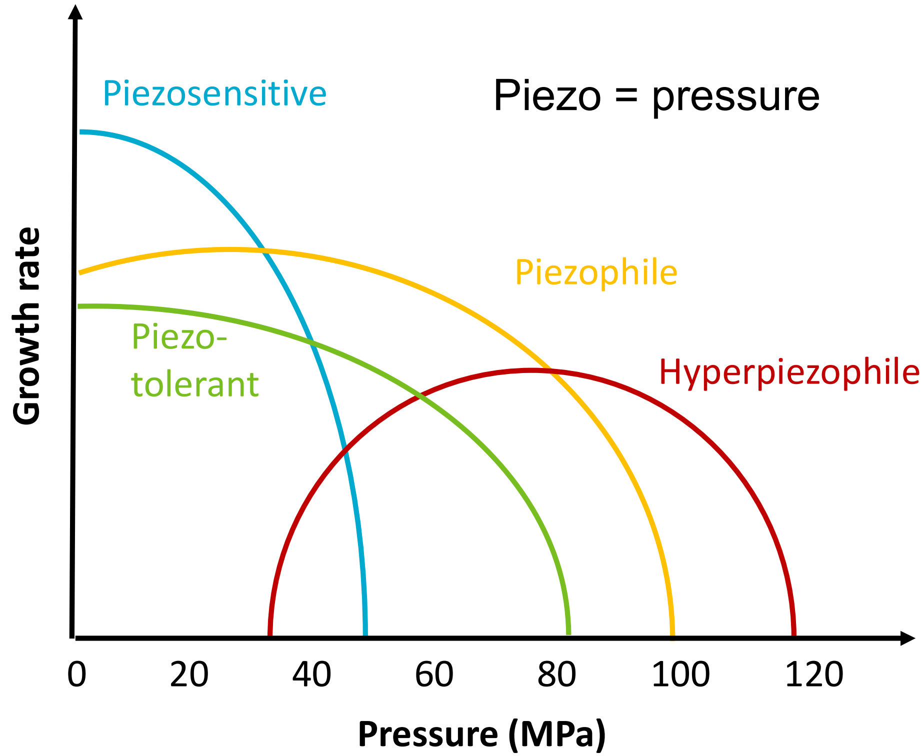
Pressure requirements for microorganisms



Adapted from:
Abe F, Horikoshi K. 2001. The biotechnological potential of piezophiles. Trends in Biotechnology 19(3): 102-8.
Fang J, Zhang L, Bazylinski DA. 2010. Deep-sea piezosphere and piezophiles: geomicrobiology and biogeochemistry. Trends in Microbiology 18: 413-422.

- Pressure increases in with increasing depth approximately 27.4 kPa km^{-1} in continental crust (Jones and Lineweaver, 2010b).
- Limit of liquid water on Earth at a depth of ~75 km (p = 3,000 MPa and T = 431 °C) → depth limit for hydrometallurgical ISR (Jones and Lineweaver, 2010a).
- *Acidithiobacillus ferrooxidans* is tolerant to hydrostatic pressure of 15.2 MPa (Hiskey 1994; Torma 1975)
- Active and viable *Escherichia coli* and *Shewanella odeinensis* detected at pressures of up to 1,060 MPa and 1,680 MPa, respectively, equivalent to depths of ~35 km and ~50 km below Earth's crust (Sharma et al., 2012)

Conclusions

- Bioleaching utilises acidolysis, redoxolysis, complexolysis
- Bioleaching mechanisms include contact, non-contact and collaborative bioleaching
- *In situ* bioleaching can be conducted under saturated or unsaturated conditions for a range of minerals and commodities
- Multiple factors impact biomining efficiency and can be optimised to improve leaching yields
- The application of biomining to ISR can enable resource extraction from low grade, complex and deep ore deposits, reduce passivation of mineral surfaces and environmental impacts of mining

Thank you

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