

Geochemical considerations for managing sulfide mine wastes

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All mine wastes are reactive...some more than others.

drainage pH

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14



Acidic (AMD, ARD)

- acidic pH
- moderate to high metals
(e.g., Fe, Cu, Ni, Zn, Pb, etc.)
- moderate to high sulfate
- low to no alkalinity

(Circum)Neutral (NMD, CND)

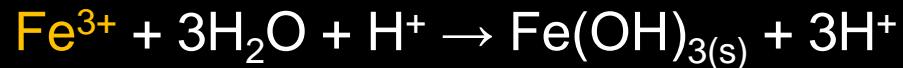
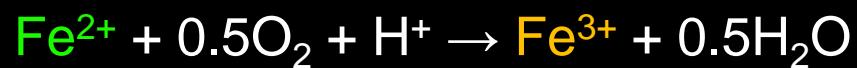
- mildly acidic to alkaline pH
- low to moderate metals
(e.g., Fe, Mn, Zn, As, Se, Sb, etc.)
- low to moderate sulfate
- low to moderate alkalinity

sulfide-mineral oxidation



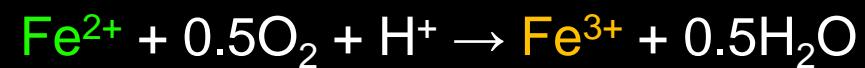
pH > ~5

direct oxidation (slow)



pH < ~5

indirect oxidation (fast)



Indirect sulfide-mineral oxidation is a microbial process.

circumneutral
pH

A. ferrooxidans

schwertmannite

(3)

Fe³⁺

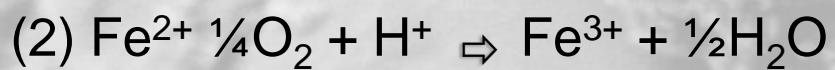
SO₄²⁻

Fe²⁺

(2) acidic
pH

(1)

Fe³⁺



1 μm

Weathering resistance

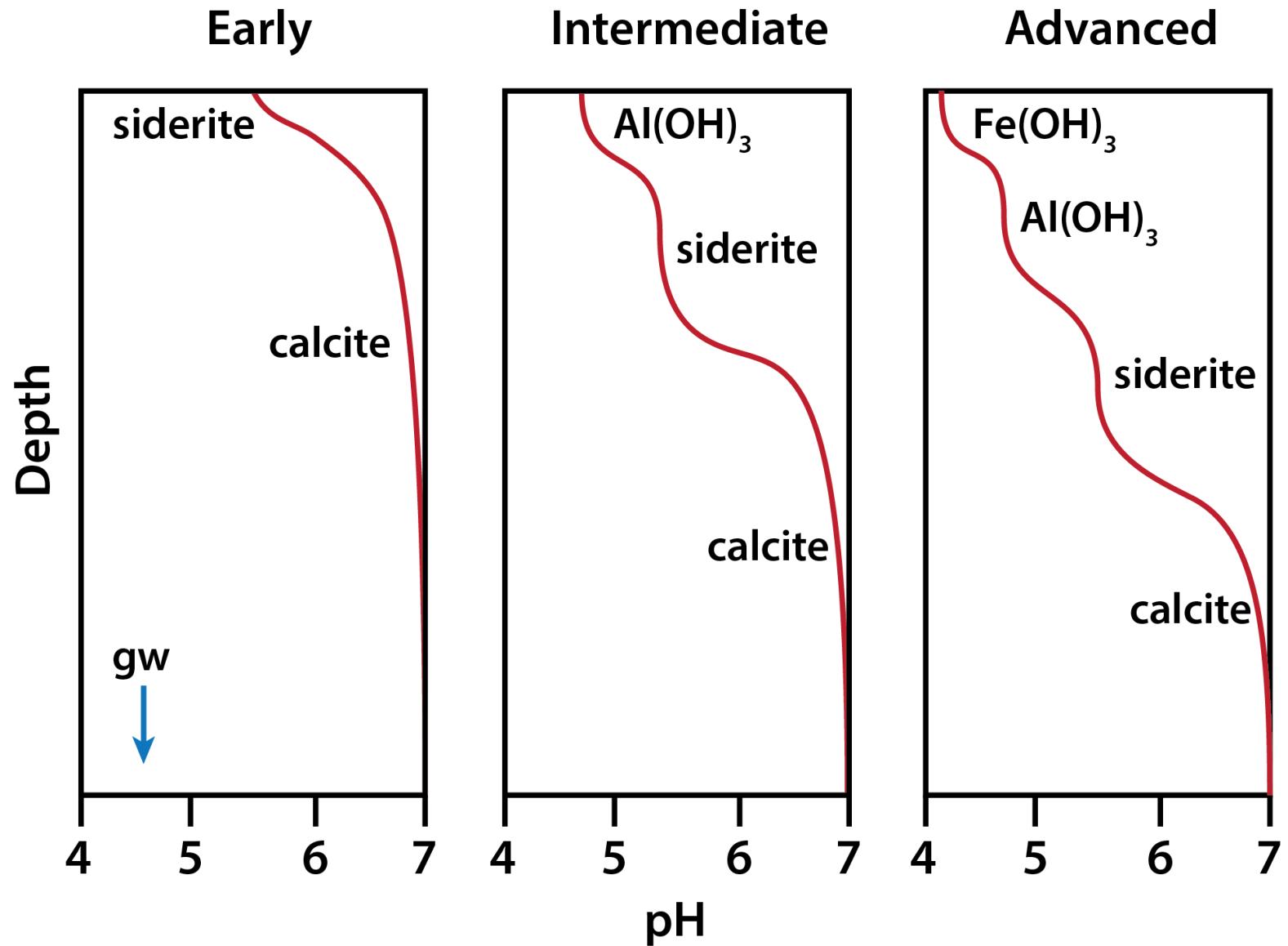
Mineral	Ideal Formula	Resistance
Pyrrhotite	$\text{Fe}_{(1-x)}\text{S}$	low
Galena	PbS	
Sphalerite	$(\text{Zn}, \text{Fe})\text{S}$	
Bornite	Cu_5FeS_4	
Pentlandite	$(\text{Fe}, \text{Ni})_9\text{S}_8$	
Arsenopyrite	FeAsS	
Marcasite	FeS_2	
Pyrite	FeS_2	
Chalcopyrite	CuFeS_2	
Magnetite	Fe_3O_4	
Molybdenite	MoS_2	high

Acid Neutralization

- mineral dissolution reactions neutralize acid generated *via* sulfide-mineral oxidation

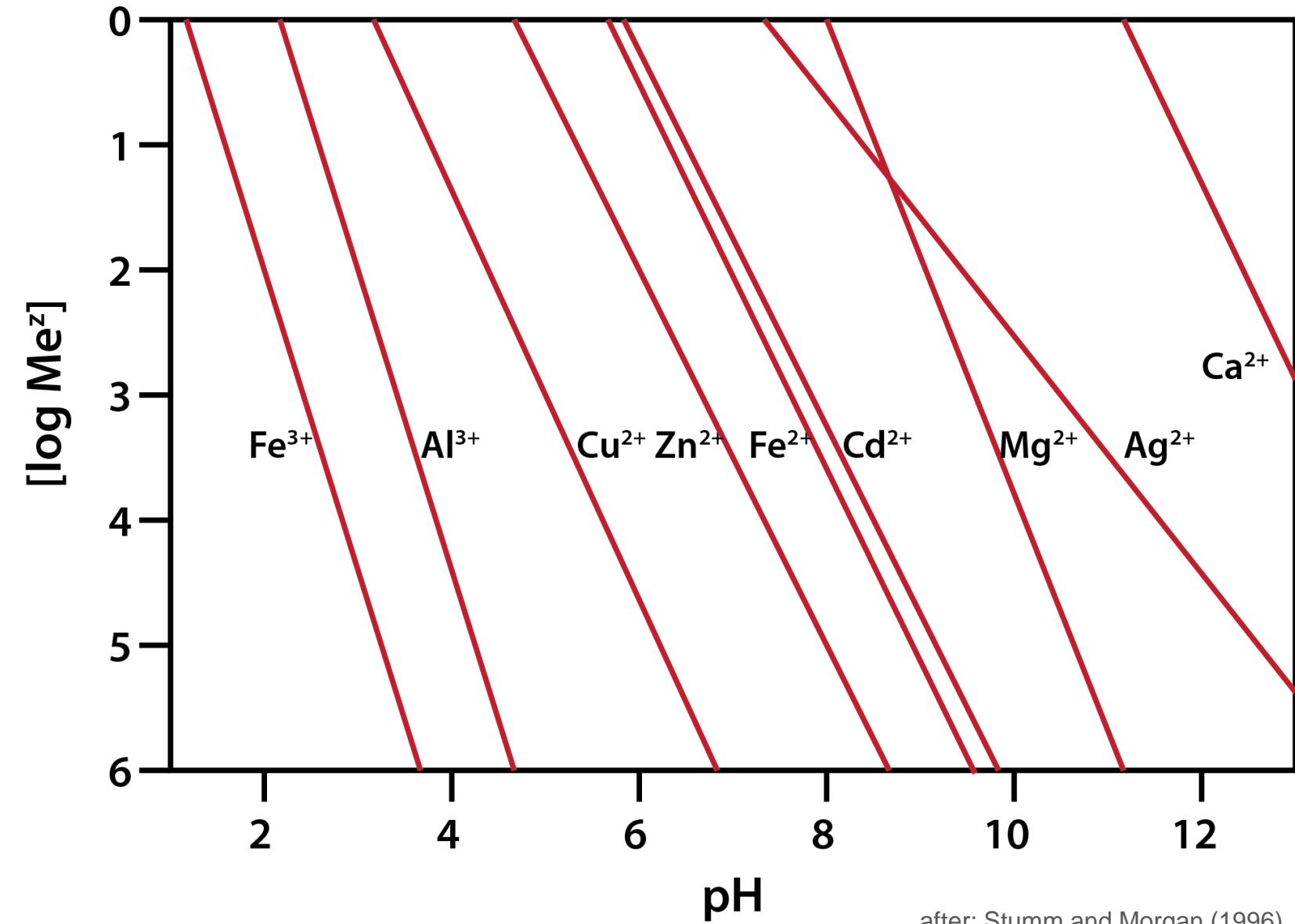
Mineral dissolution	pH range
calcite, dolomite	>6
siderite	4.5-6.0
Al(OH)_3	3.5-4.5
Fe(OH)_3	2.5-3.5
silicates (e.g. Ca-plagioclase)	< 2

Acid neutralization sequence

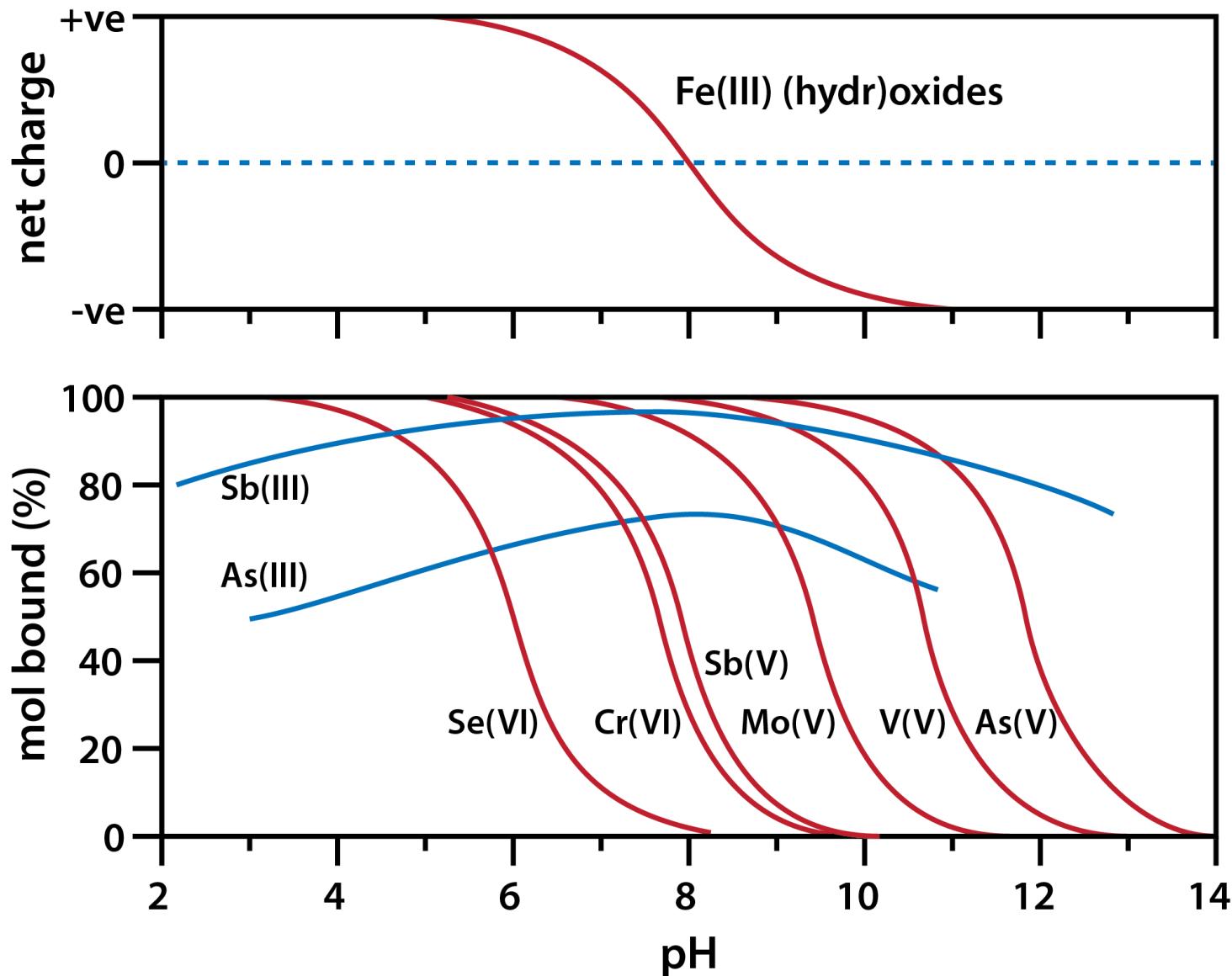


after: Blowes and Ptacek (1994)

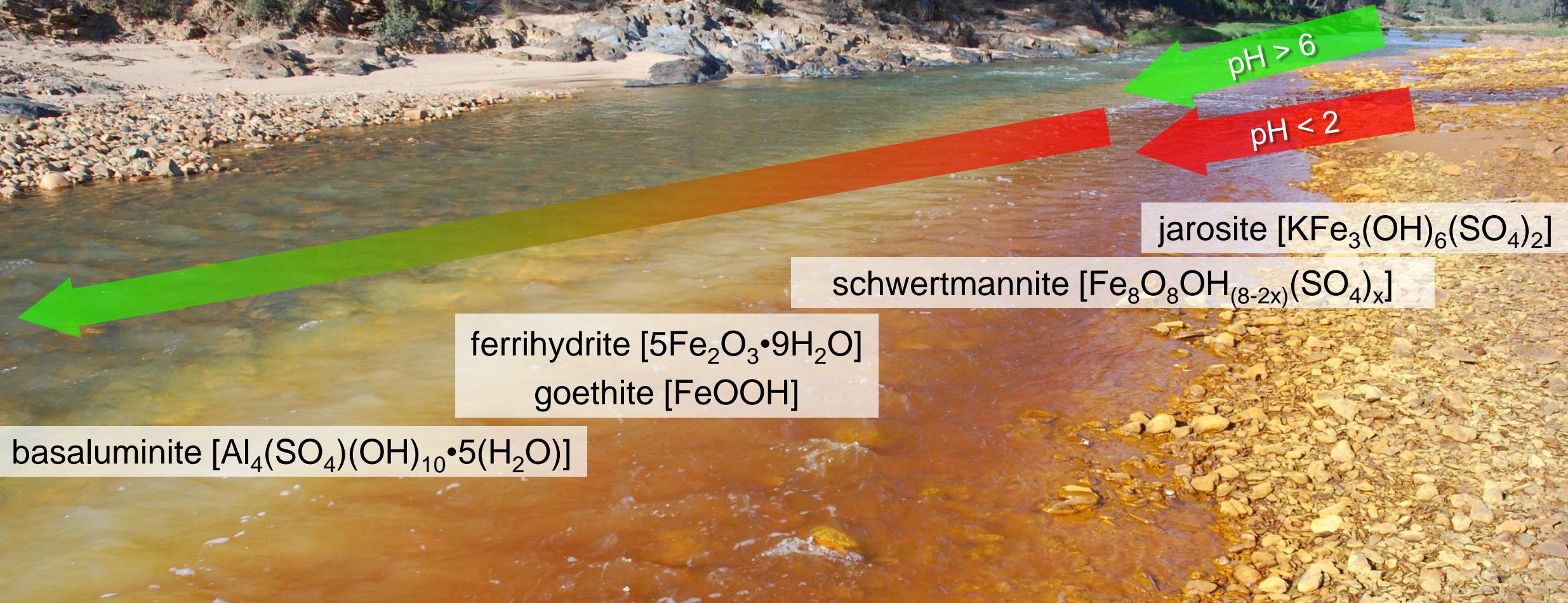
metal solubility vs. pH



metal sorption vs. pH

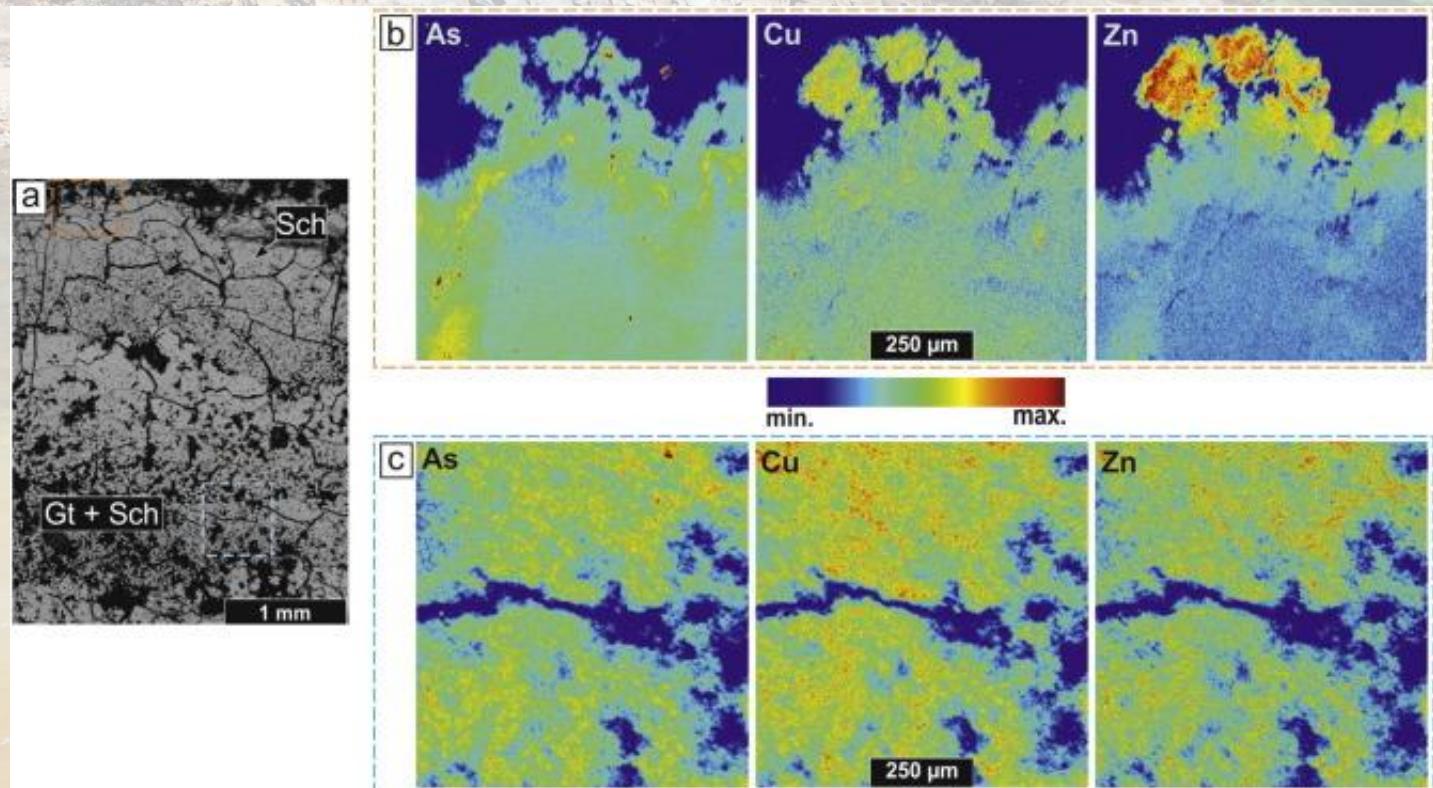


after Stumm and Morgan (1996), Dixit and Hering (2003), Leuz et al. (2006)



Secondary precipitates are ubiquitous...

schwertmannite



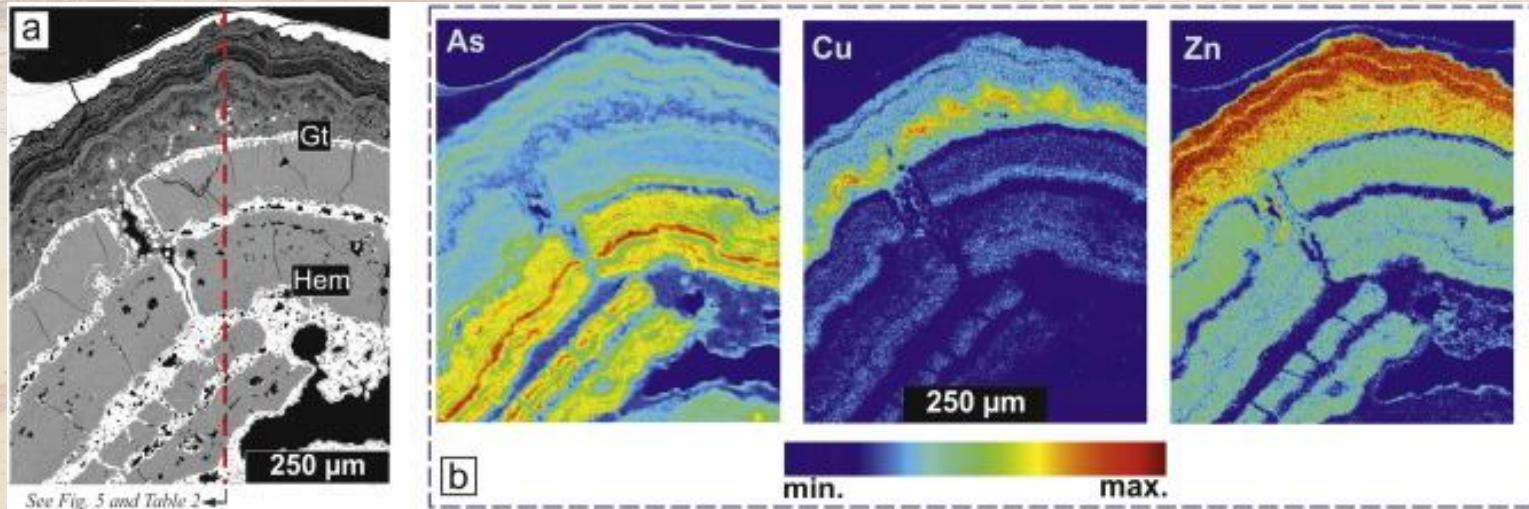
Cruz-Hernández et al. (2016)

...and are effective at sequestering metals...

...but are often metastable.

recrystallization

schwertmannite → goethite → hematite

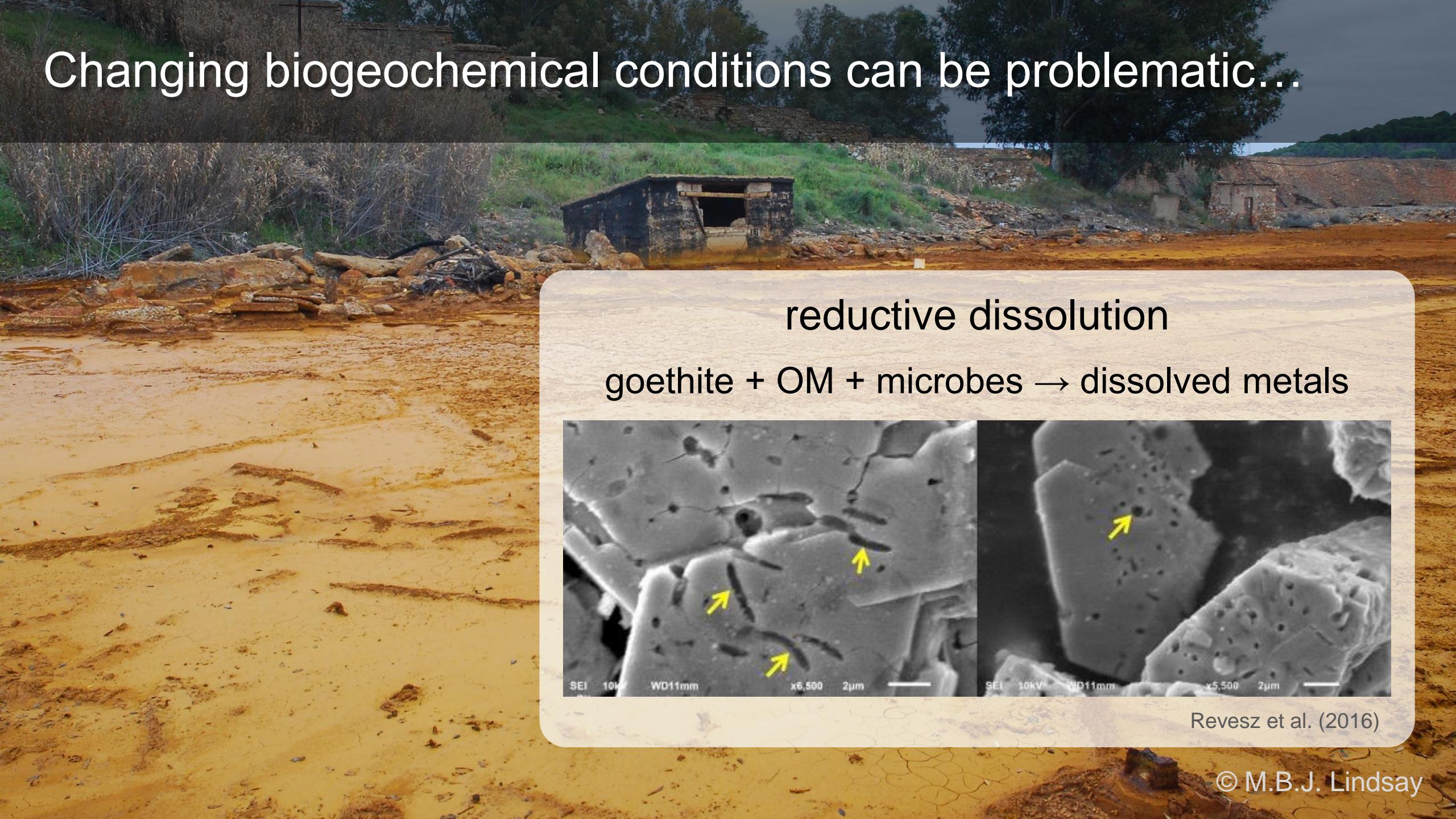


- may be accompanied by trace element release

Cruz-Hernández et al. (2016)

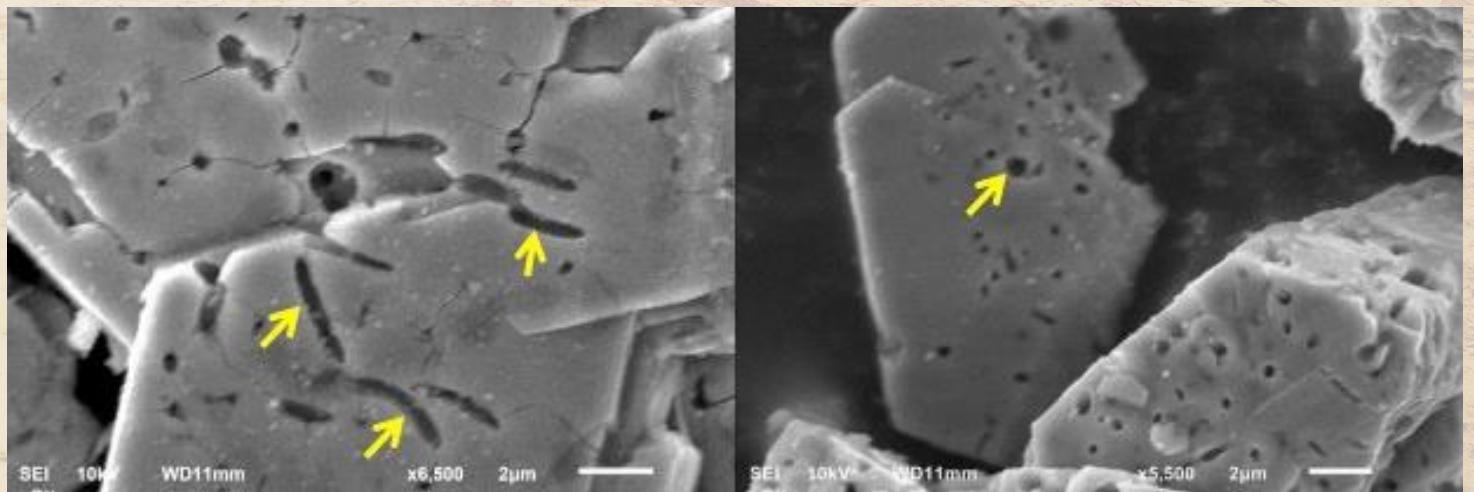
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Changing biogeochemical conditions can be problematic...



reductive dissolution

goethite + OM + microbes → dissolved metals

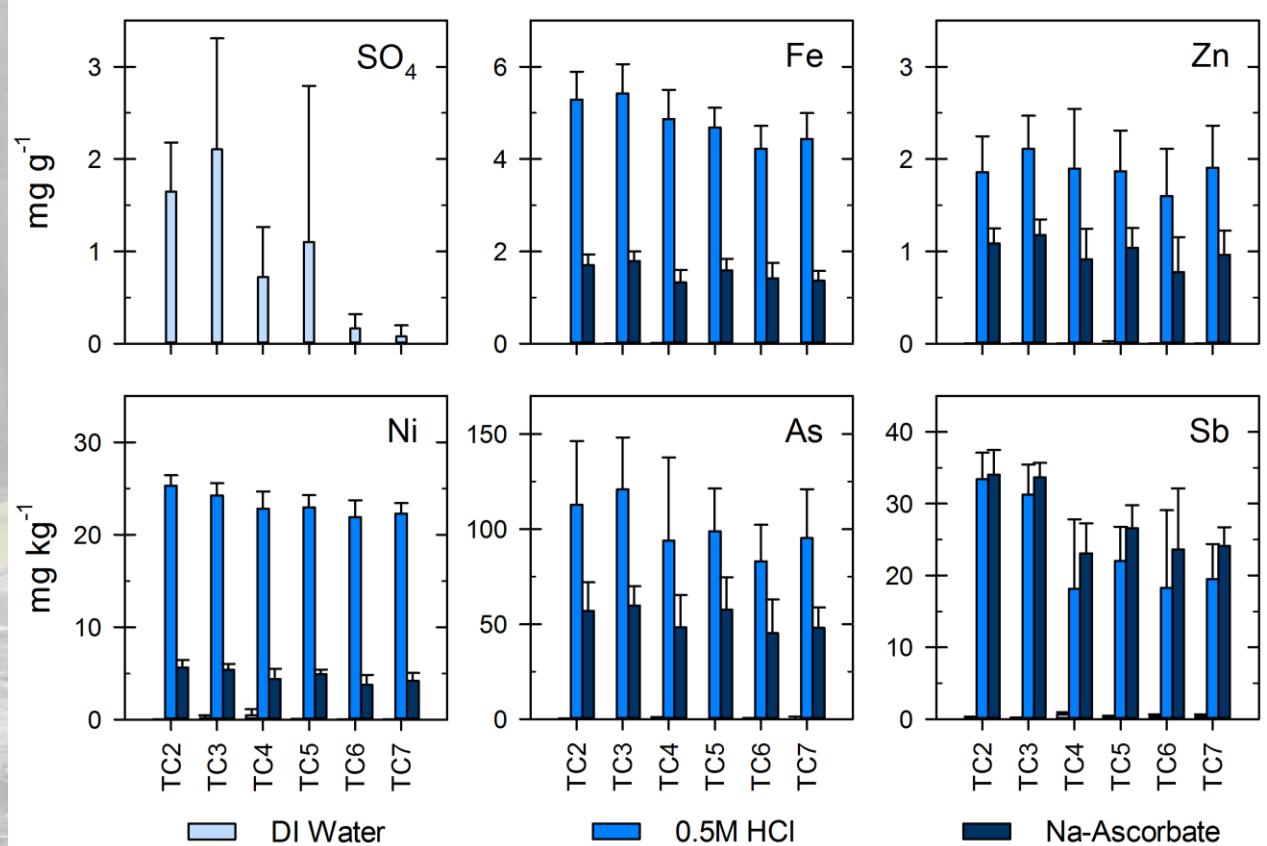


Revesz et al. (2016)

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...even in wastes exposed to limited period of weathering.

Selective chemical extractions



Lindsay et al. (2011a)

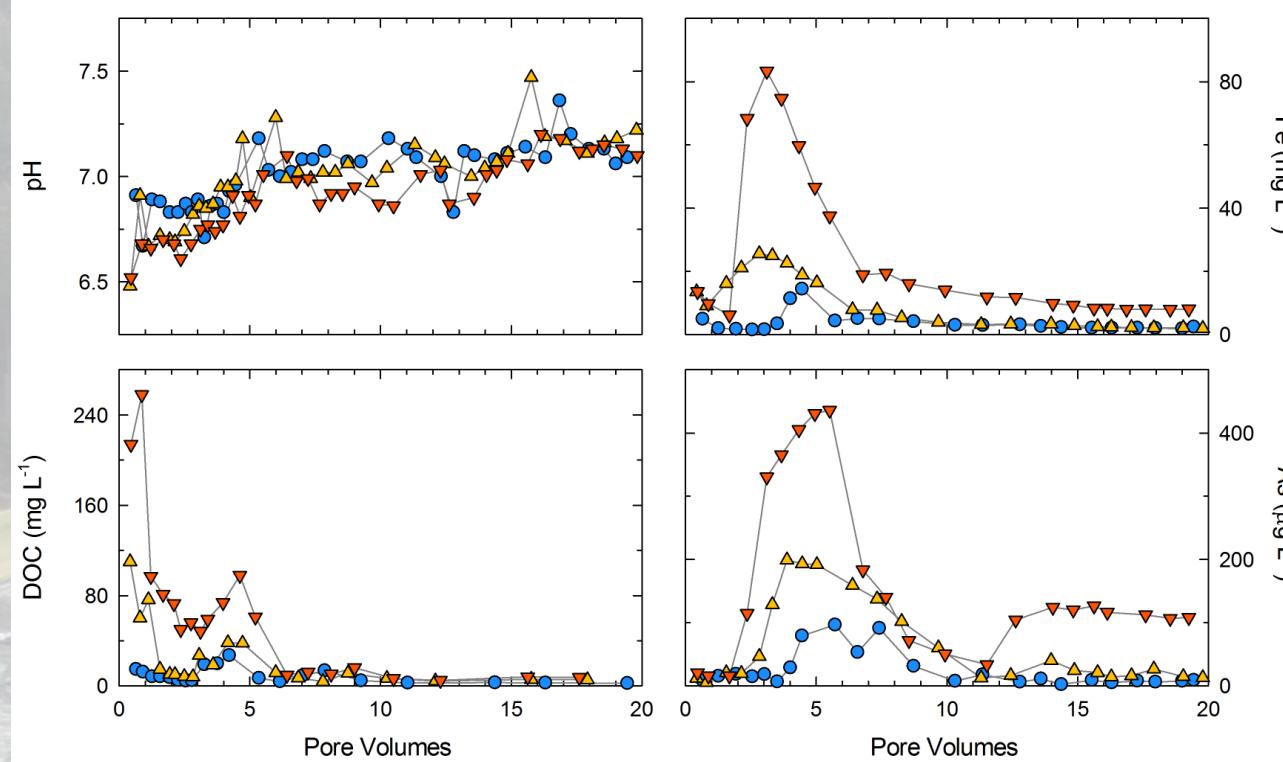
Greens Creek Mine,
Alaska, USA



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...even in wastes exposed to limited period of weathering.

Column experiments: organic carbon addition



- soil covers can promote reductive dissolution

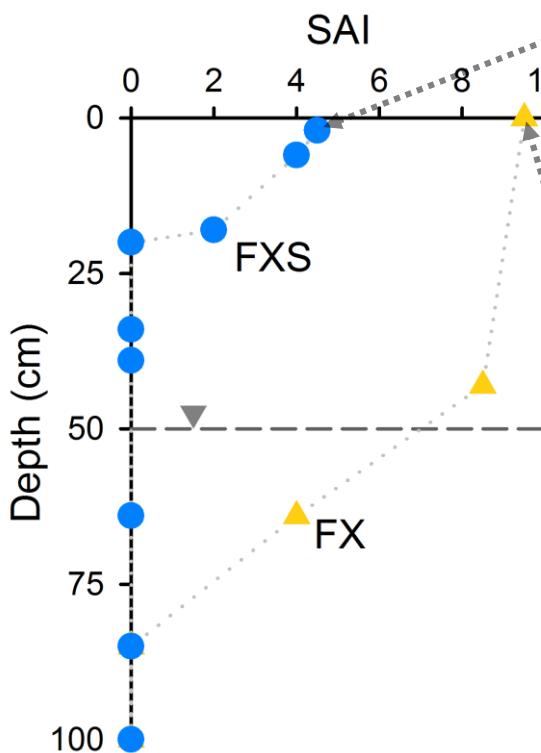
Lindsay et al. (2011b)

Greens Creek Mine,
Alaska, USA

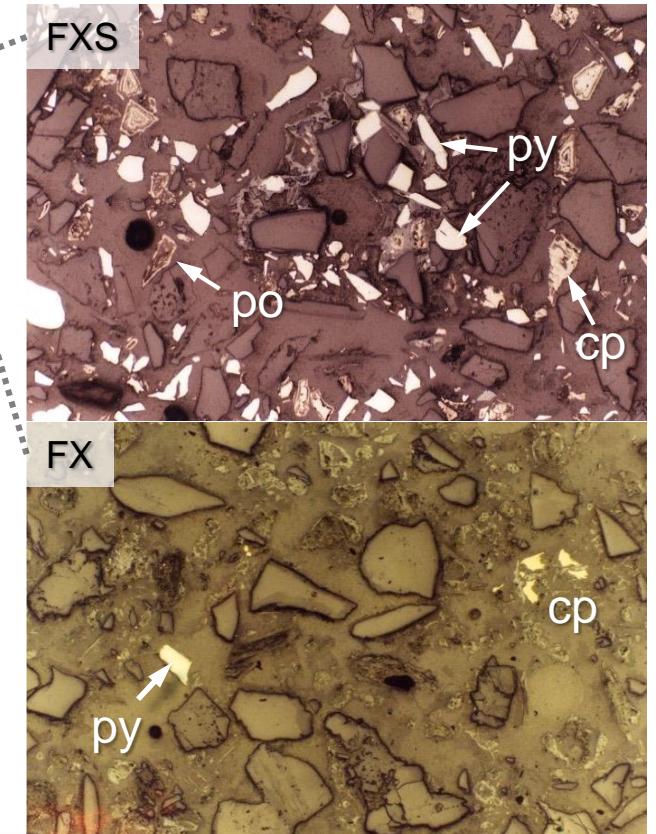
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Preventing sulfide-oxidation is incredibly challenging.

Subaqueous disposal can be effective.



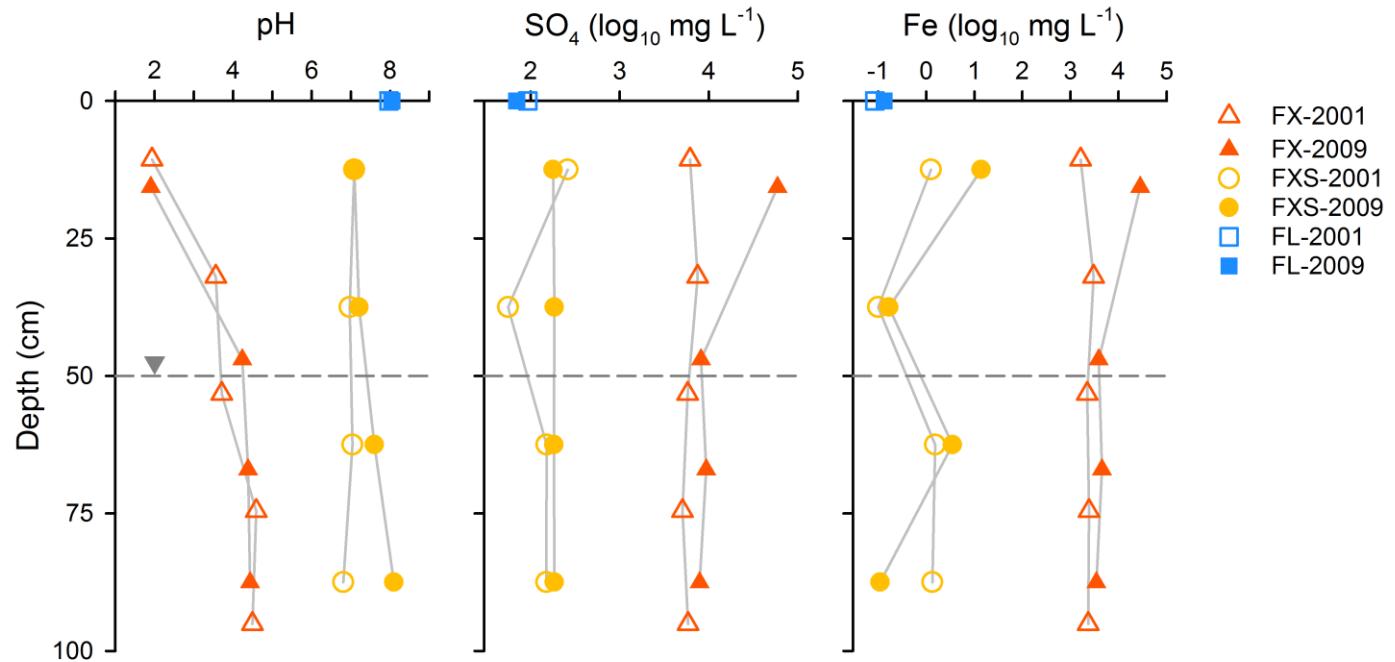
Moncur et al. (2016)



Width of field 2.6 mm

Preventing sulfide-oxidation is incredibly challenging.

Subaqueous disposal can be effective.



Moncur et al. (2016)

“Mine remediation is experimental...” Kirk Nordstrom, USGS

...and also site specific.

- Excluding O₂ and H₂O can limit sulfide-mineral oxidation and acid generation rates, but:
 - difficult to achieve in terrestrial setting
 - metals may remain elevated or even increase
- Geotechnical and geochemical considerations often at odds...this need not be the case



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