

From Soil Resistivity to Interface Mechanisms: Improving Predictions of Buried Metal Corrosion

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UNIVERSITY OF
BIRMINGHAM

Buried Metallic Infrastructure



Soil Reinforcement



Buried Steel Bridge



Retaining Walls



Structural Frames



Pipelines



Foundations



Most infrastructure around us rely on the integrity of buried metals...

Buried Metallic Infrastructure: Corrosion

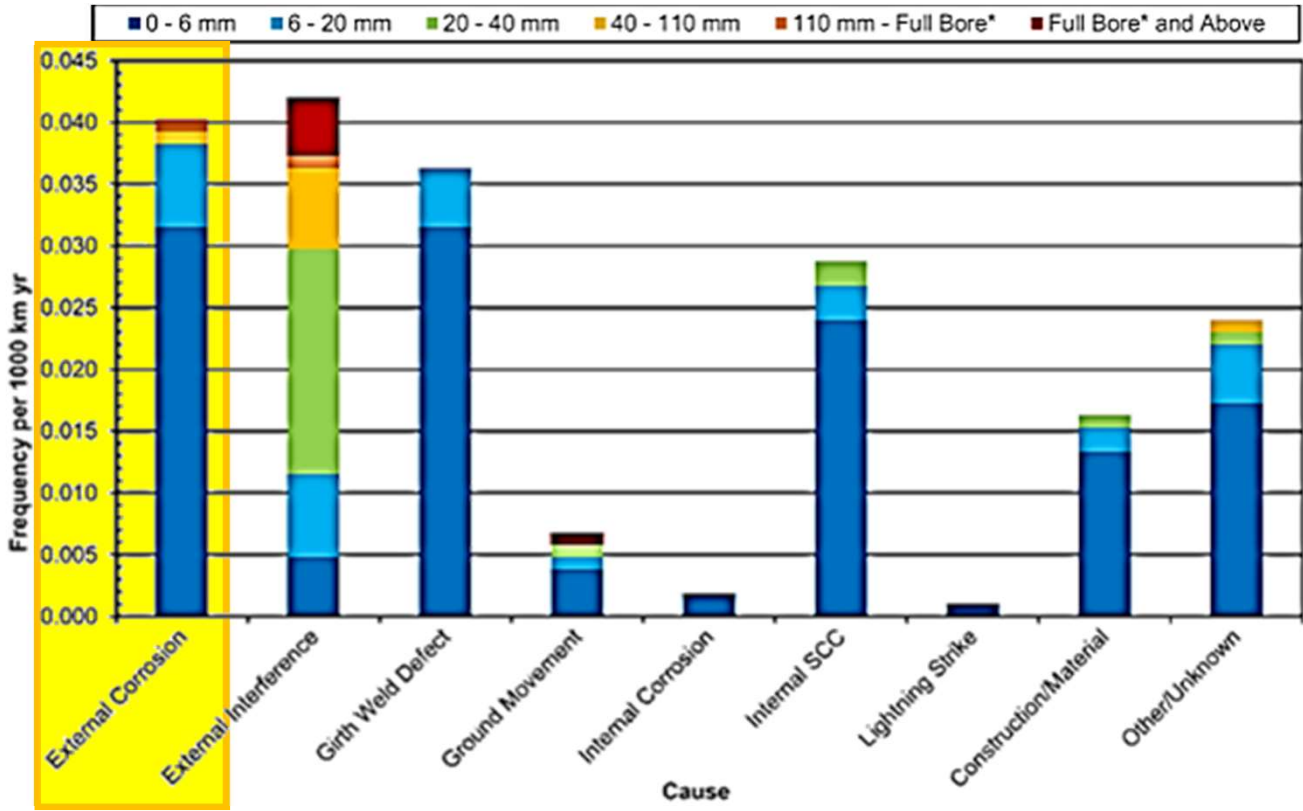
Overall corrosion cost:

- \$1 trillion/yr worldwide
- £55 billion/yr UK

Maintenance/repair



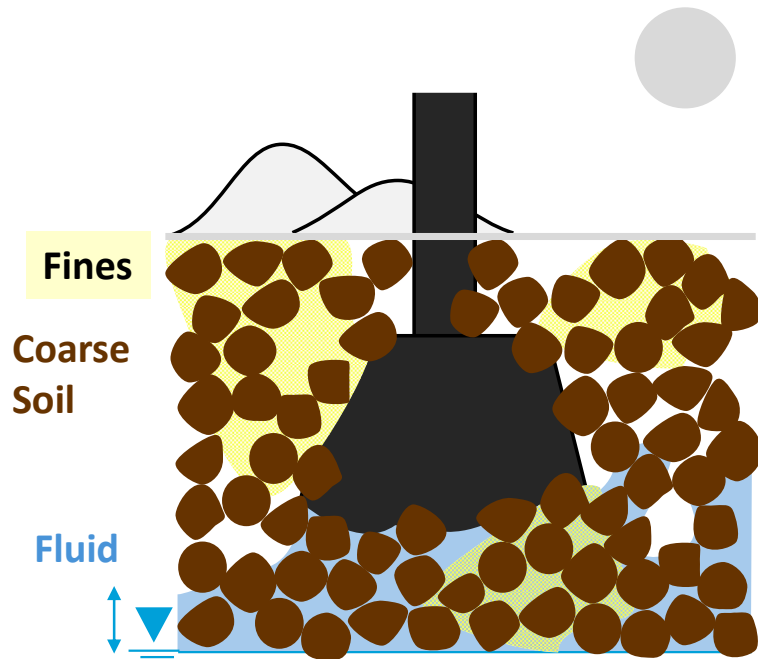
Construction



Product loss incidents reported by the UK Onshore Pipeline Operators' Association UKOPA (2023)

Focus since 1920's yet it remains the cause of extensive monetary losses... to get worst by climate change

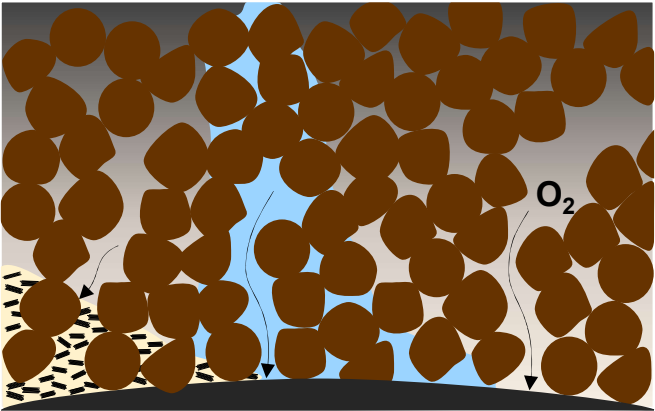
What Should be Done Different?



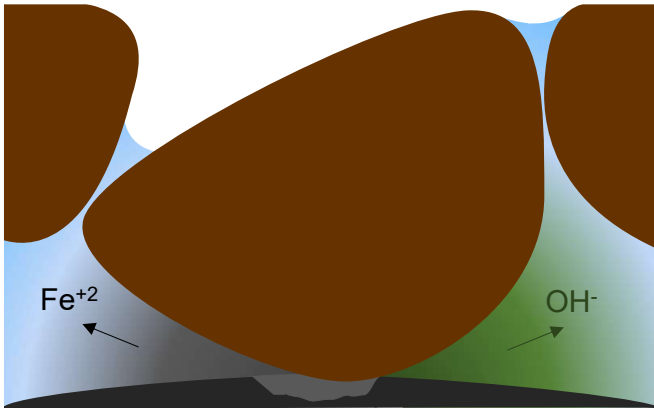
Current efforts → high resistivity, low bioactivity
Artificial ground, grouts, coatings, cathodic protection.

**BASED ON THE ASSUMPTION THAT SOILS ARE THE
ELECTROLYTE IN OUR CIRCUIT**

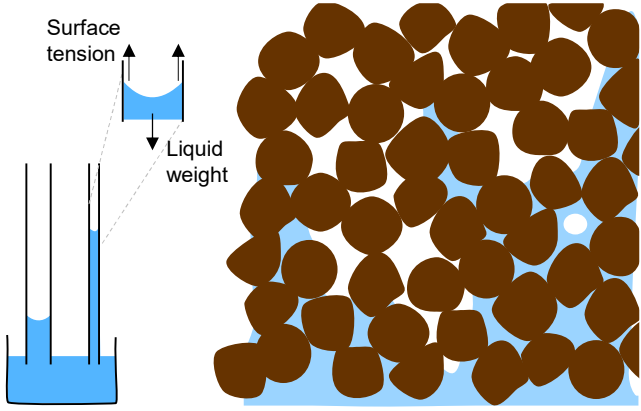
Metal Corrosion in Soils



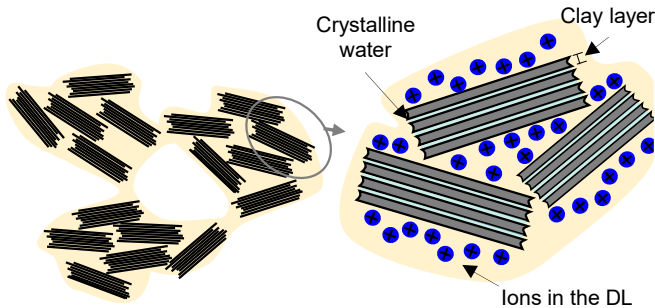
Differential Aeration



Bi-products Diffusion



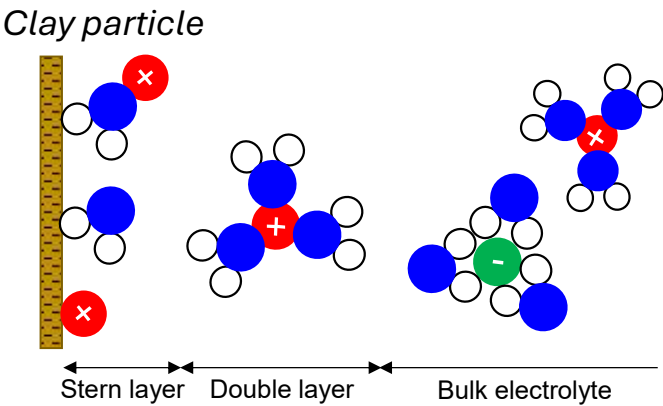
Capillarity



Macro- structure

Clay aggregate

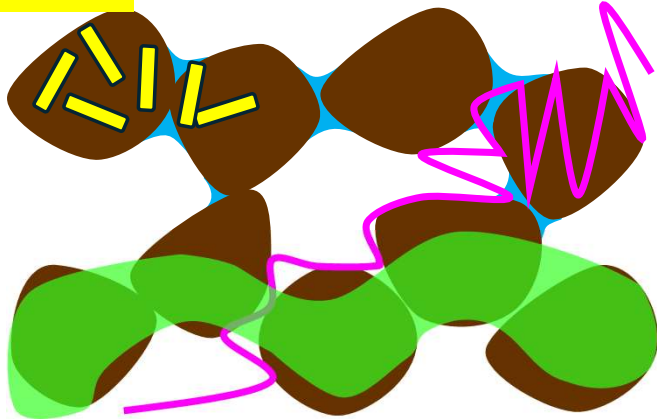
Particle Aggregation



Double Layer

Bacteria

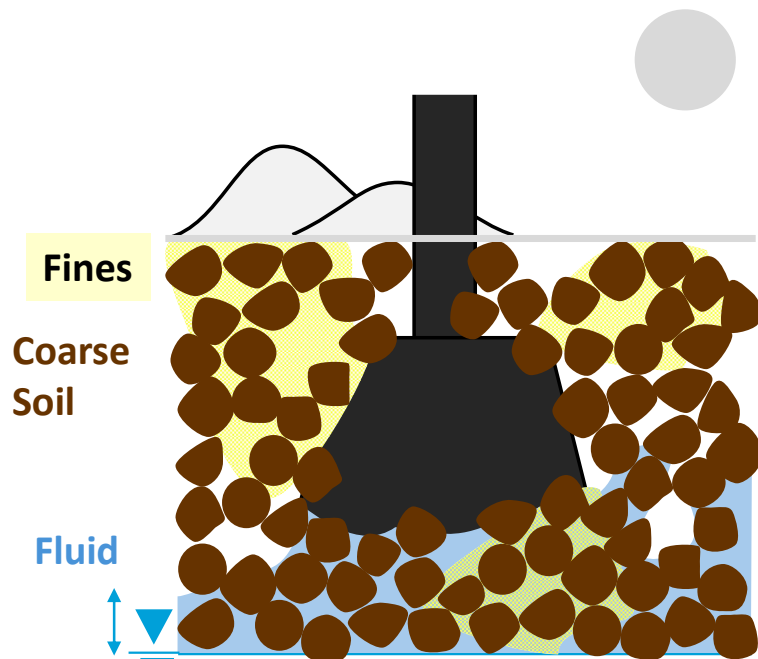
Fungi



Highly Bio-active

Biofilm

What Should Be Done Different?



Current efforts → high resistivity, low bioactivity

Artificial ground, grouts, coatings, cathodic protection.

BASED ON THE ASSUMPTION THAT SOILS ARE THE ELECTROLYTE IN OUR CIRCUIT

Multiple and interconnected phenomena in porous media makes the study of buried metal corrosion a **very complex problem**



Romanoff 1957

Current advanced characterisation techniques allow for a better understanding of the electro-chemo-bio processes that occur at the soil-metal interface → make use of available anti-corrosion resources

Corrosion prevention solutions should consider particular soil and environmental conditions

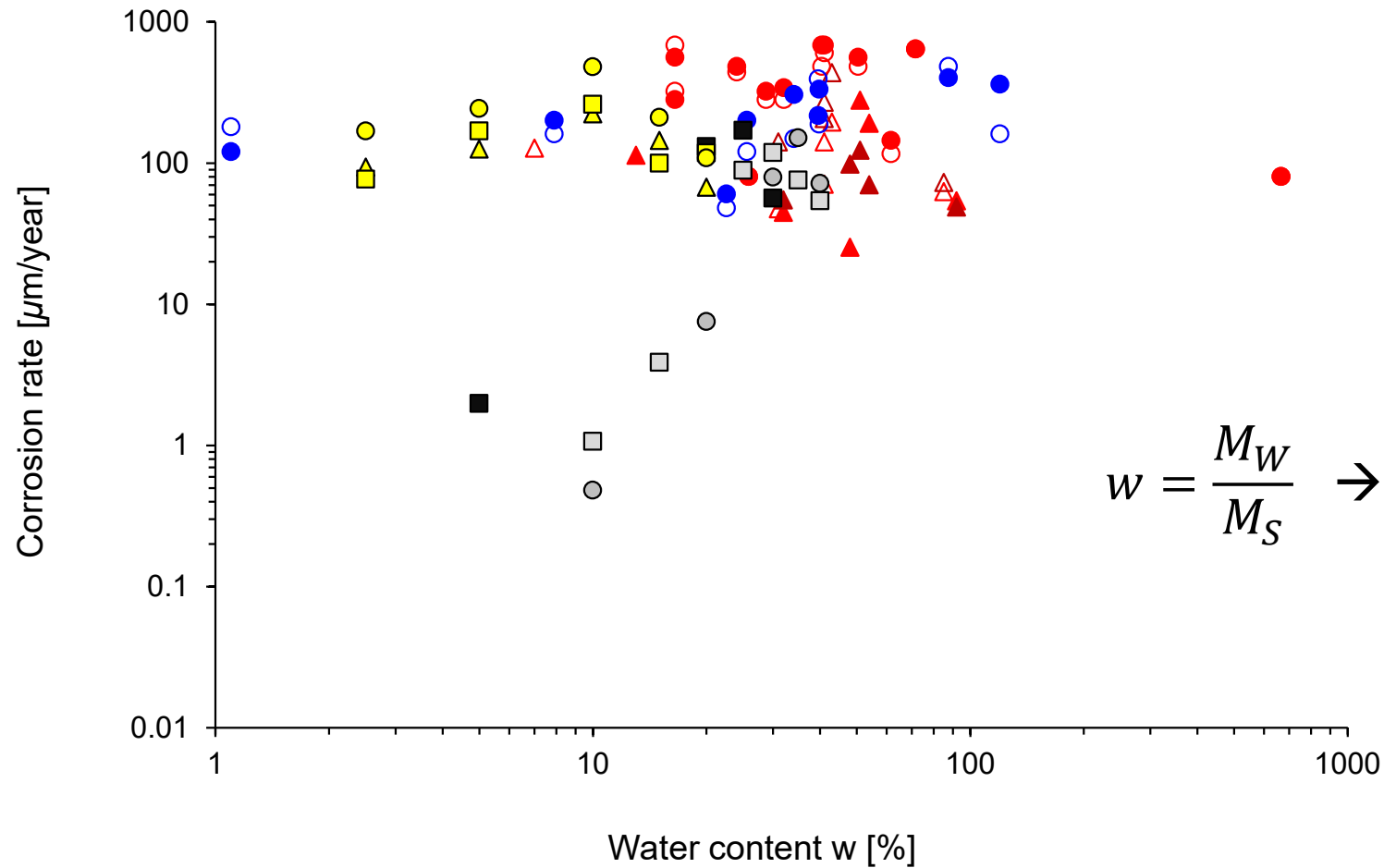
Outline

1. Resistivity→ Moisture, Saturation, Salinity?
2. Dynamics: Moisture Cycles
3. Soil Mixtures
4. Soil Mixtures
5. Laboratory and Field Investigations: Resources
6. Ongoing Research

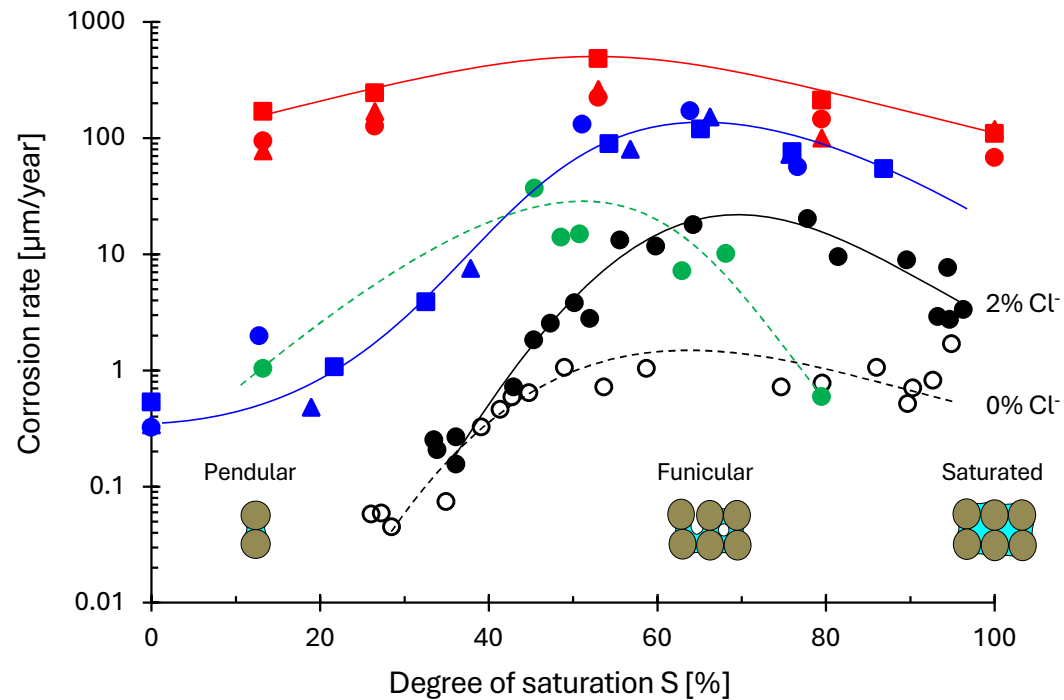
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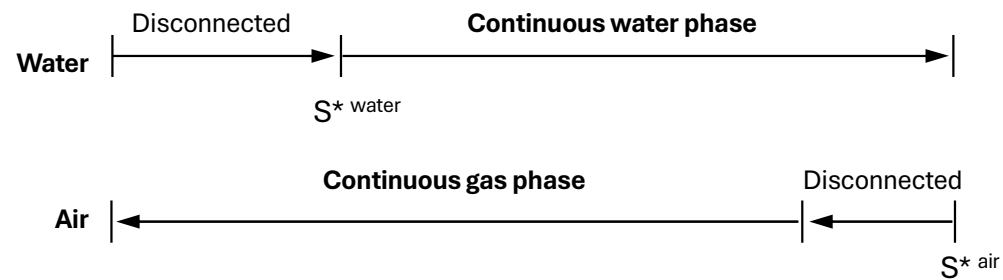
Corrosion in Buried Metals: Moisture?



Corrosion in Buried Metals: Saturation



Salinity?



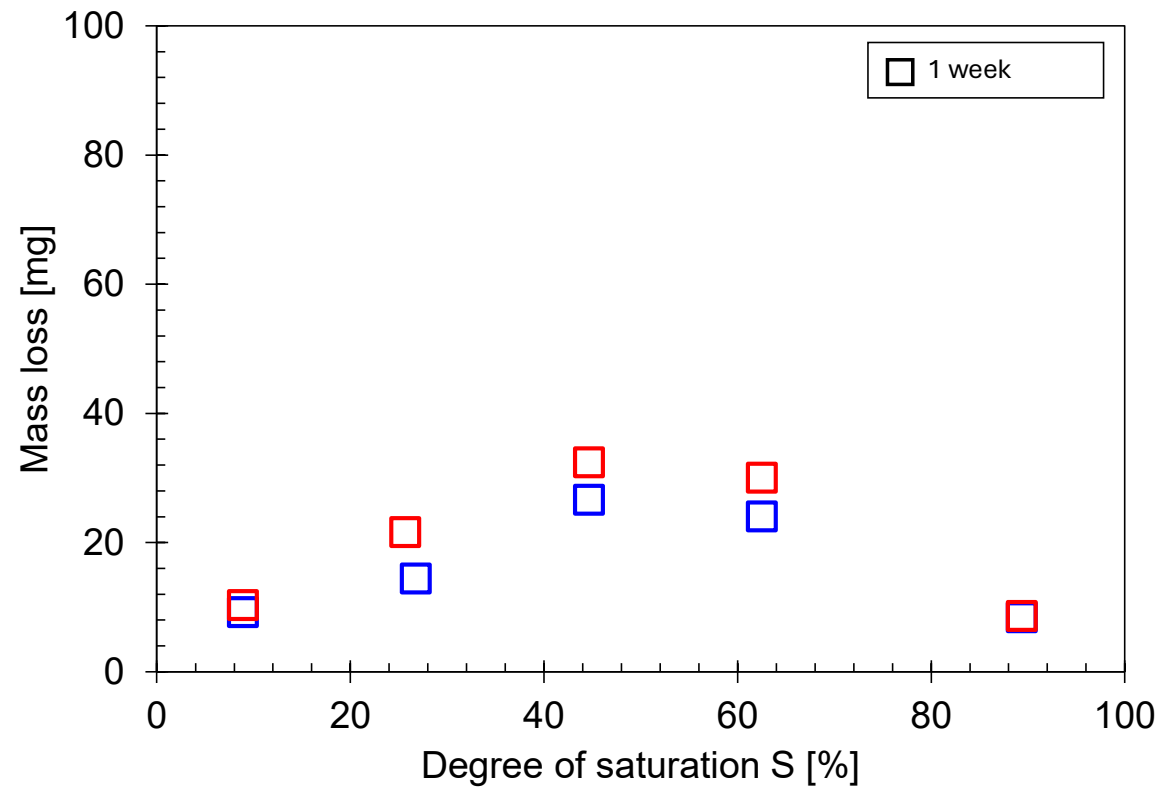
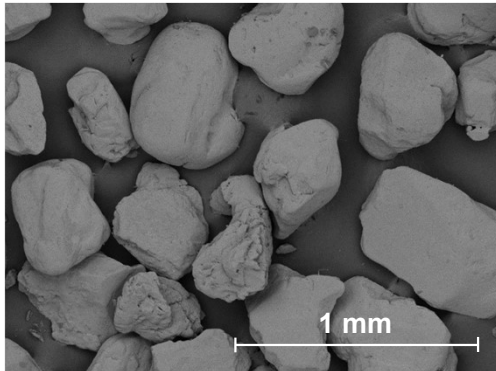
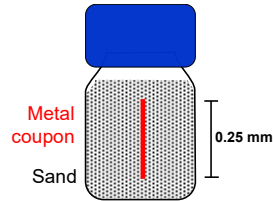
$$S = \frac{V_W}{V_V}$$

Data source: Cohen & Brock, 1995; Noor & Al-Moubaraki, 2014; Gupta & Gupta, 1979; Lopez & Gonzalez, 1993

Figure: GM Castro et al. (2024)

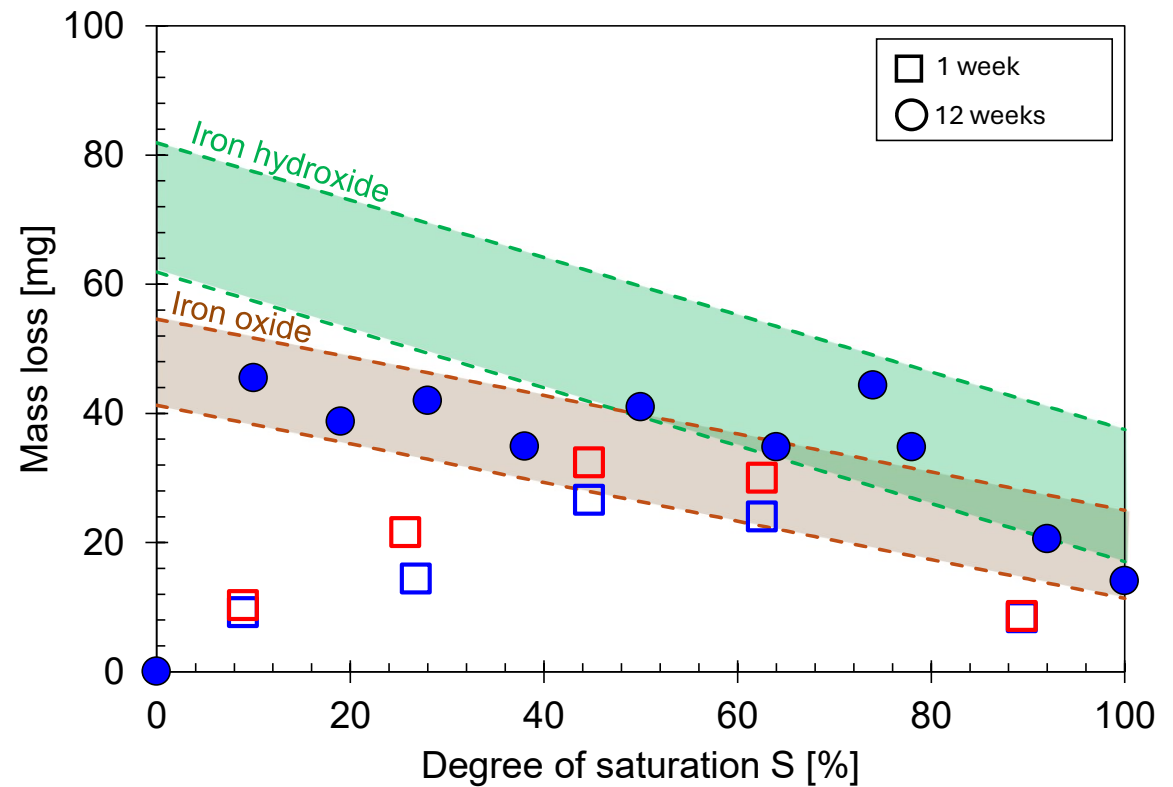
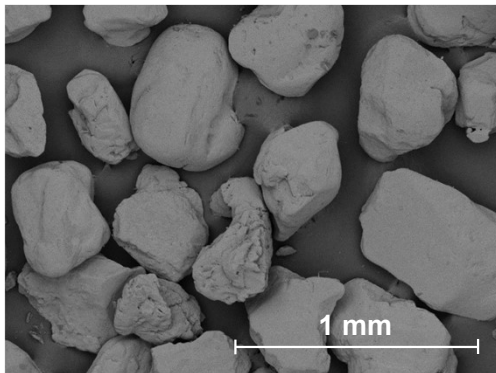
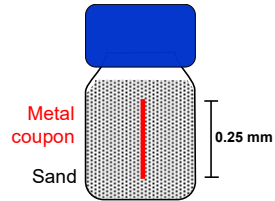
Study #1: Saturation vs. Salinity

- 61 samples using clean sand
- Two pore fluids:
 - **DI water**
 - **0.7 M NaCl brine**
- Spanding from 0- 100% saturation

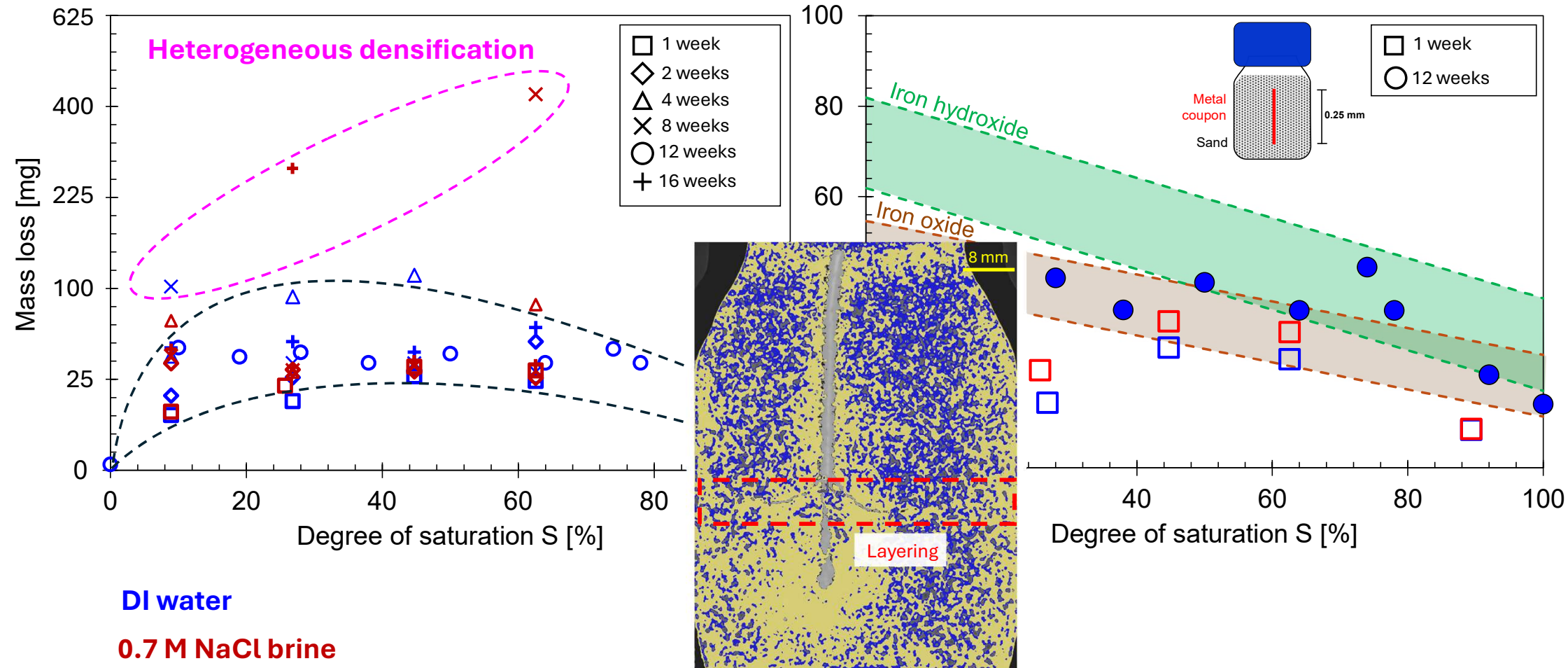


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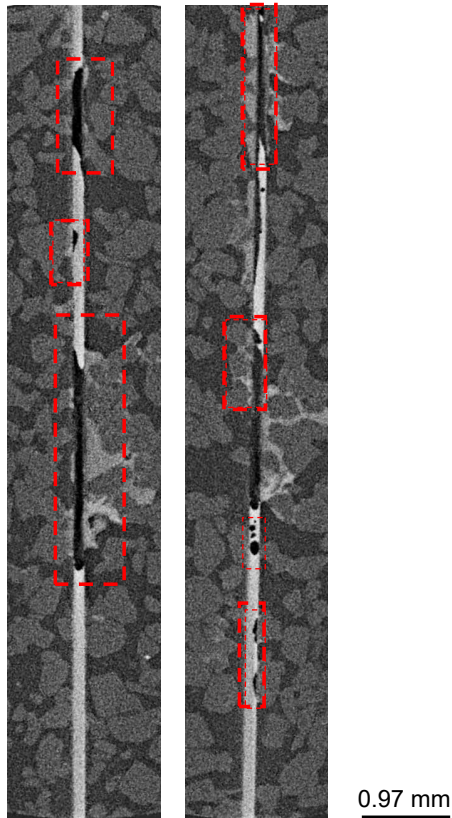
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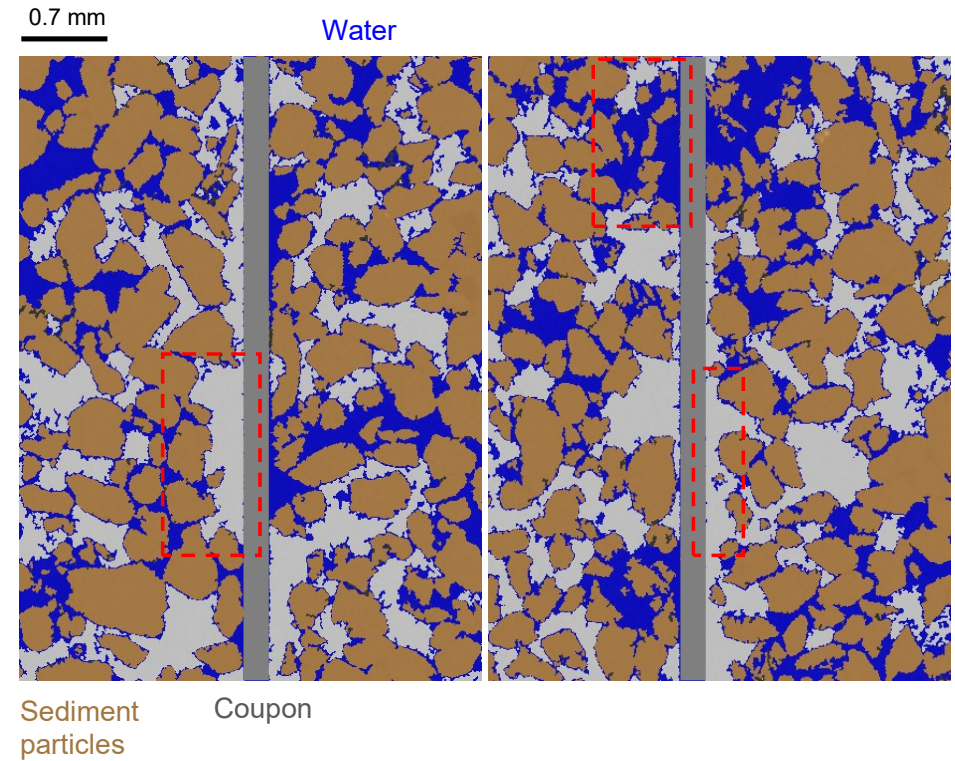
Study #1: Saturation vs. Salinity



Study #1: Active area: X-ray CT

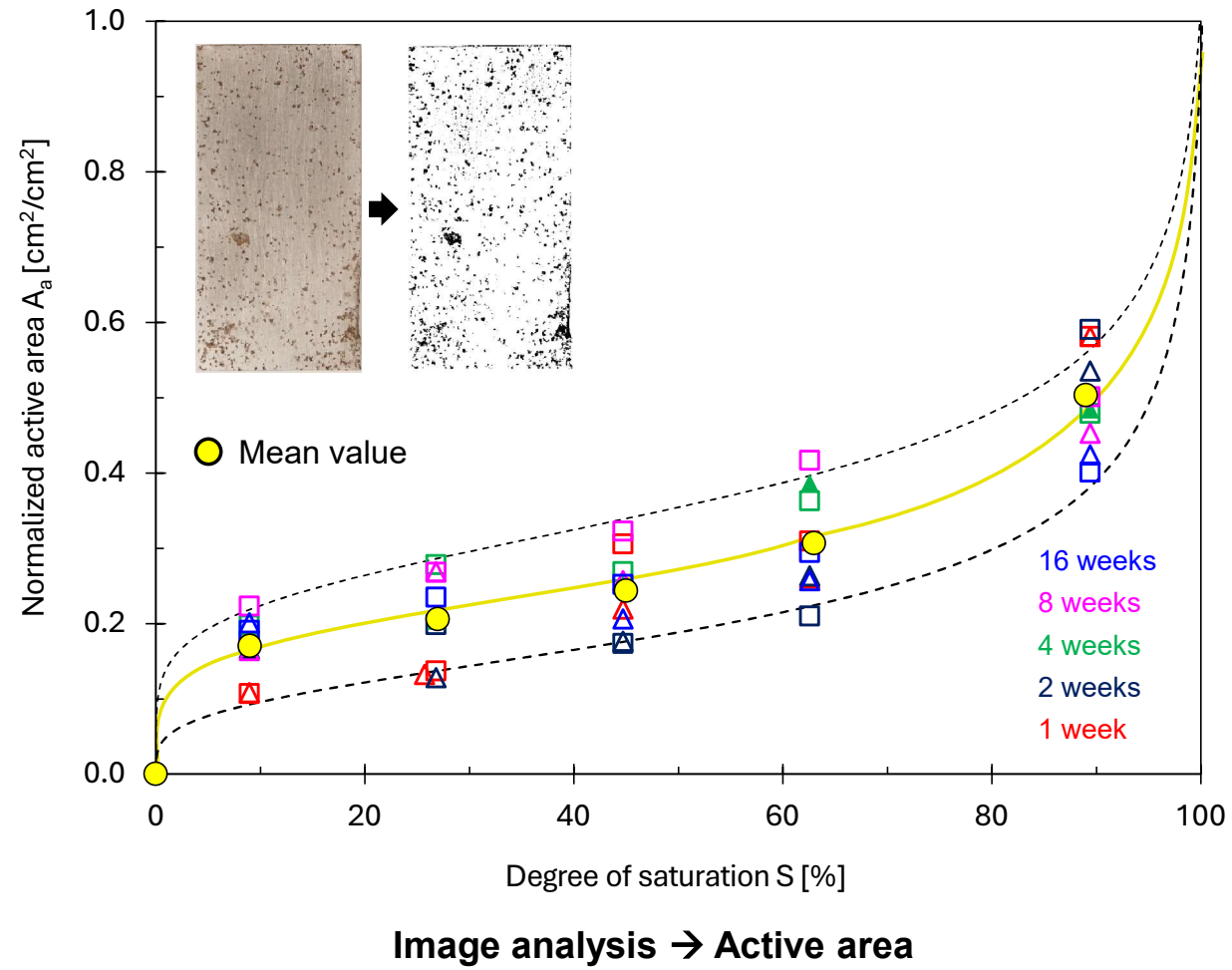


Corroded metal in 30% S specimen

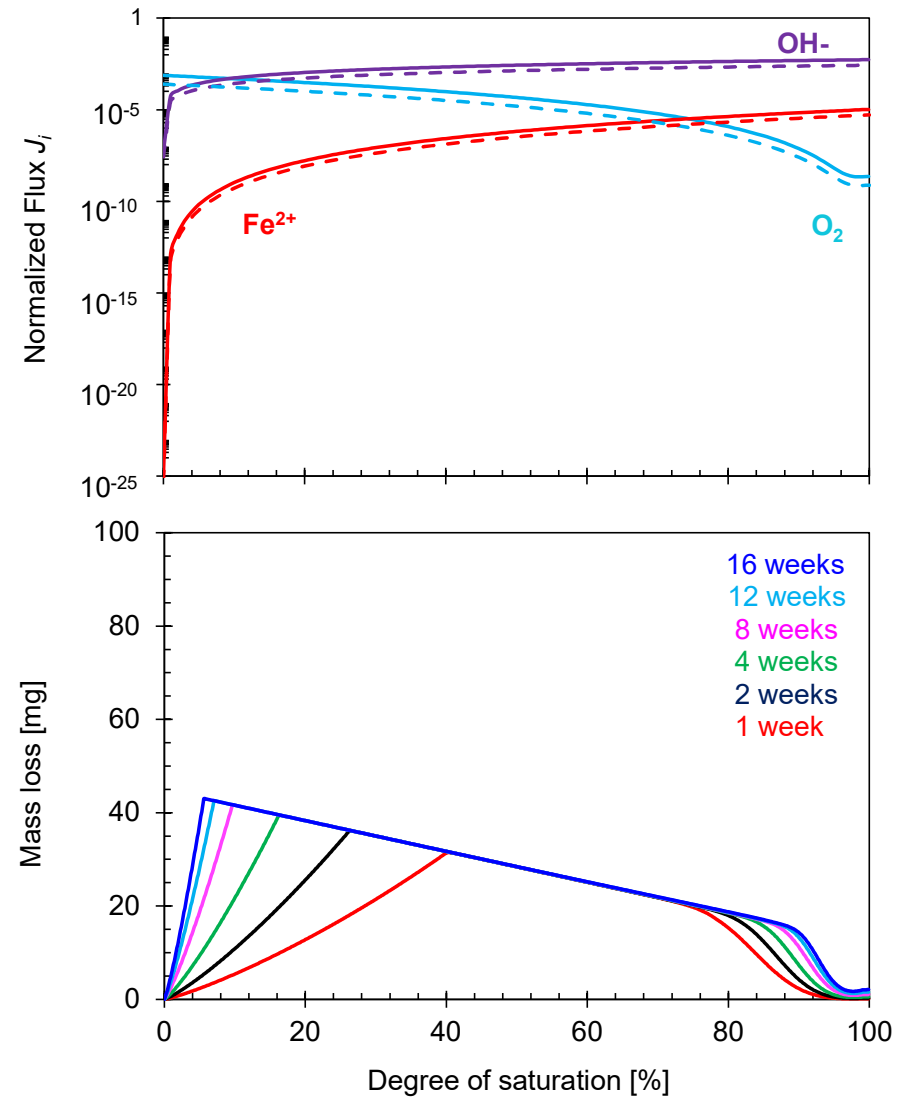
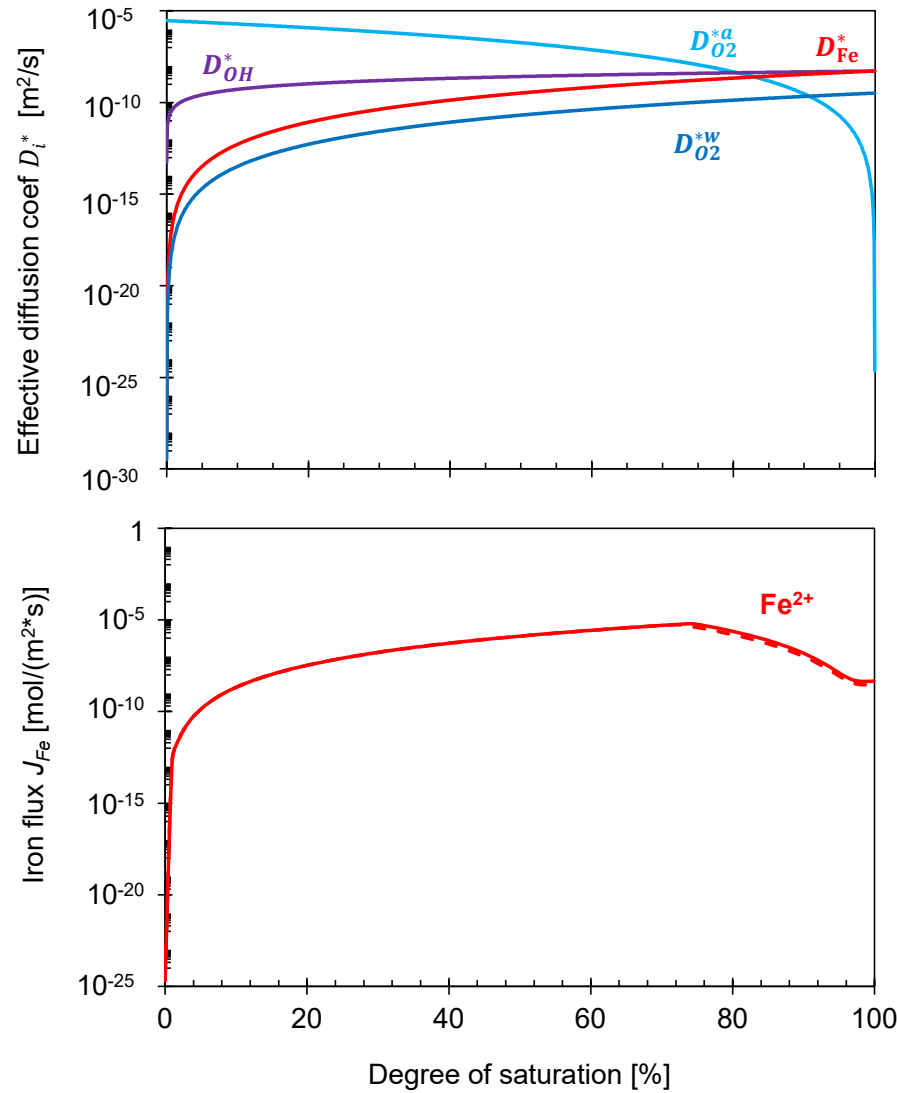


Particles, fluid and air around coupon

Study #1: Active area



Study #1: Transport Controlled

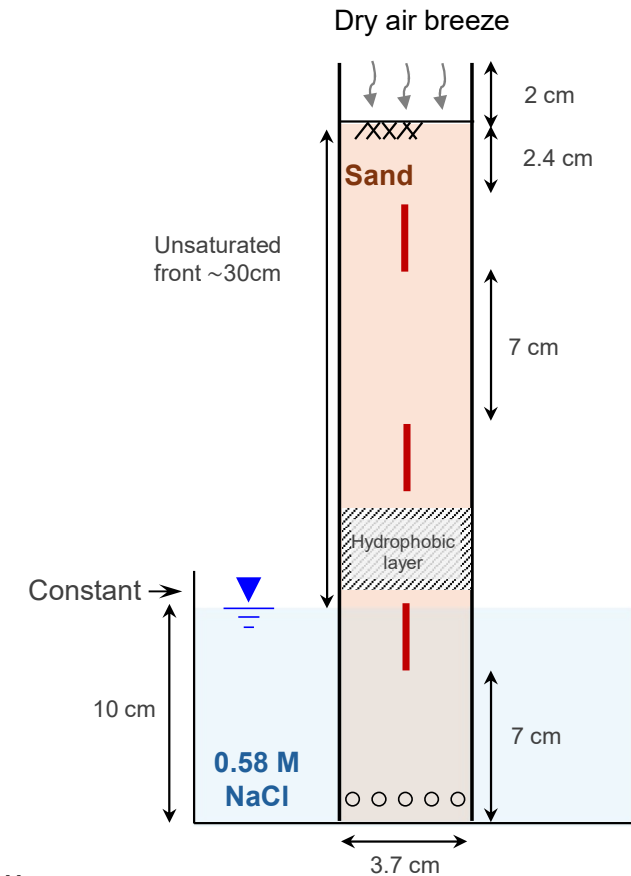


Study #2: Salt Accumulation- Enhanced Evaporation



Salt flat

discoveryuk.com

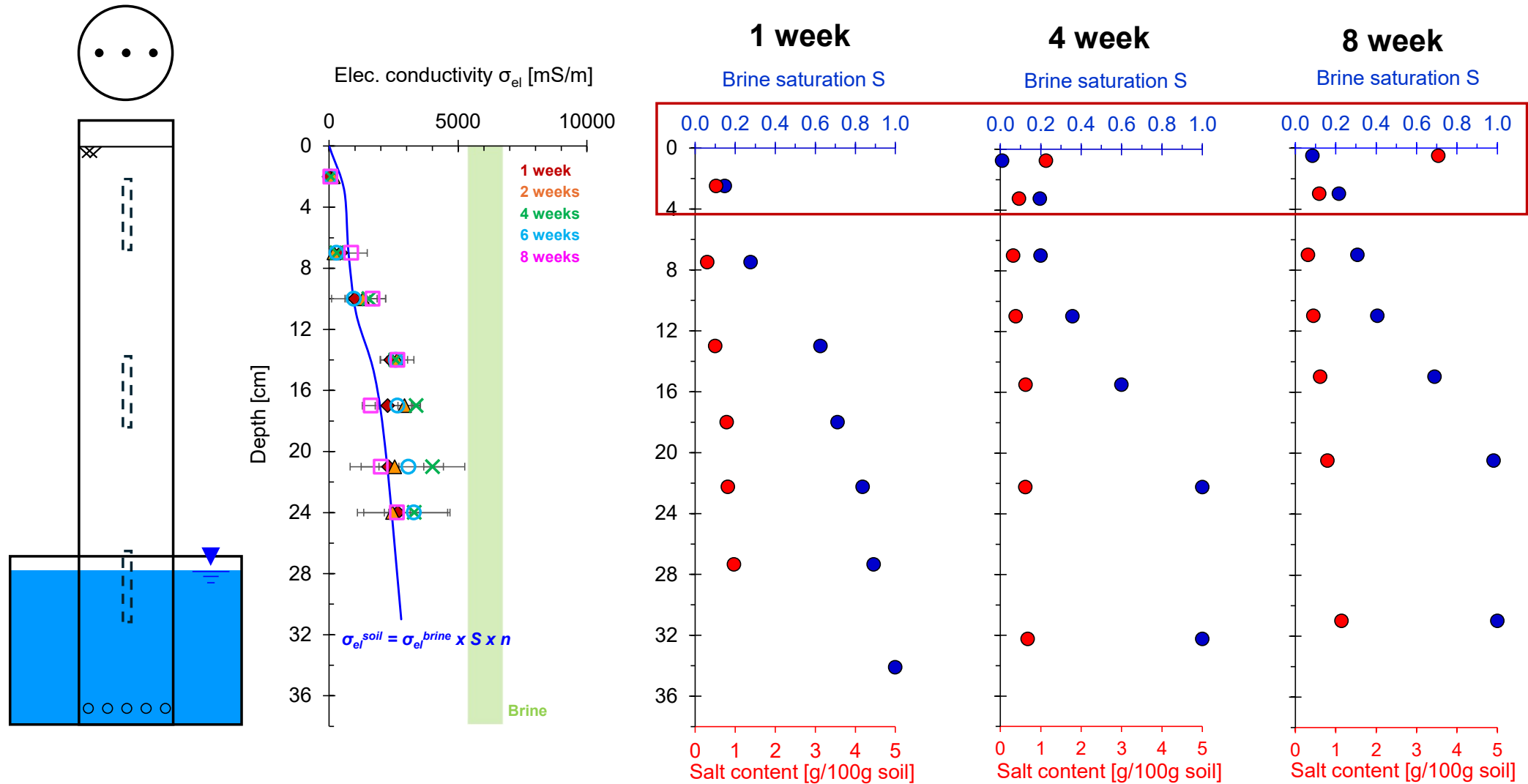


x 8 cells:

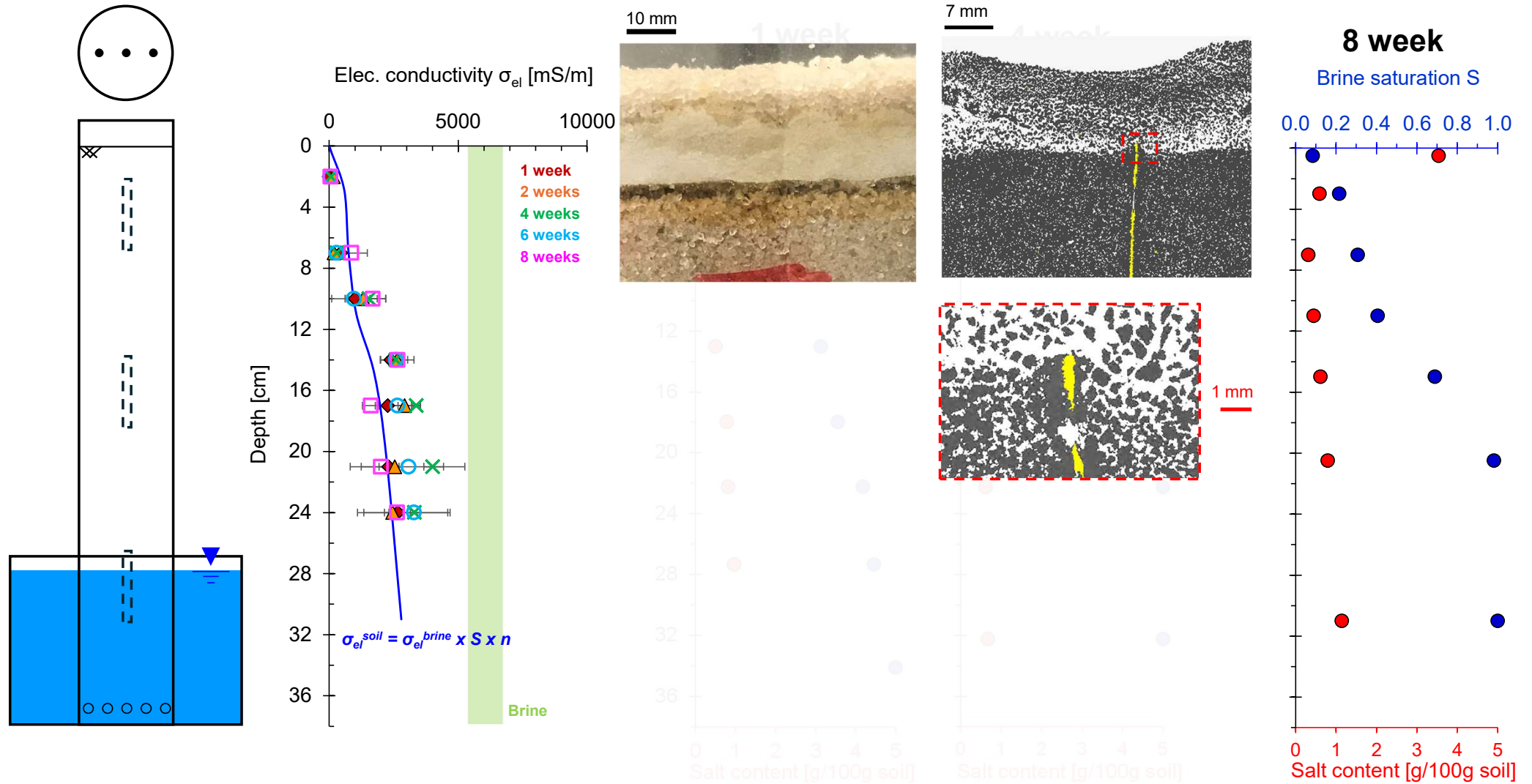
- 5: 1- 8 weeks
- 1: proposed solution
- 2: Monitor electrical conductivity

Castro et al. (2026)

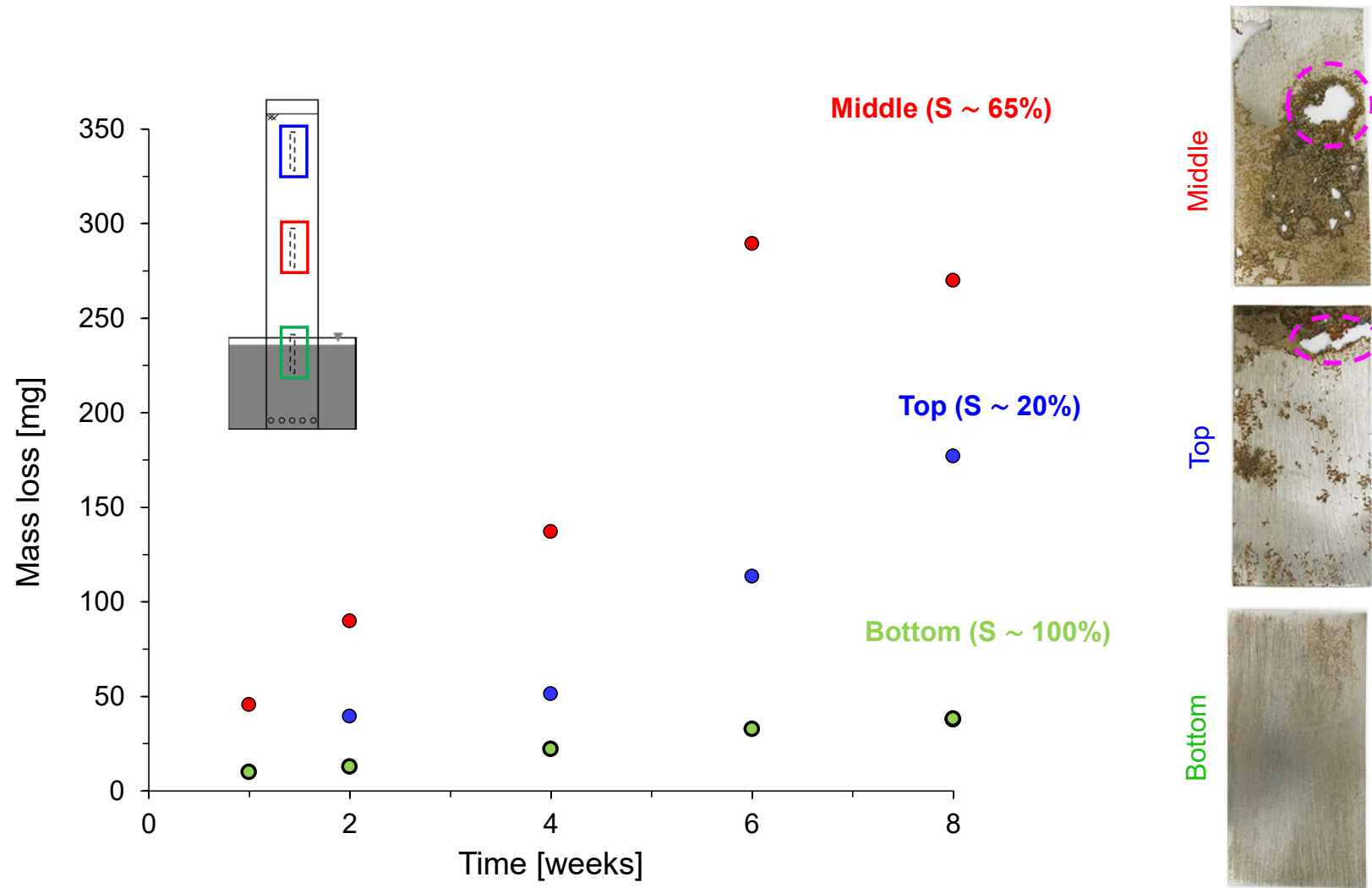
Study #2: Conductivity= Saturation & Salinity



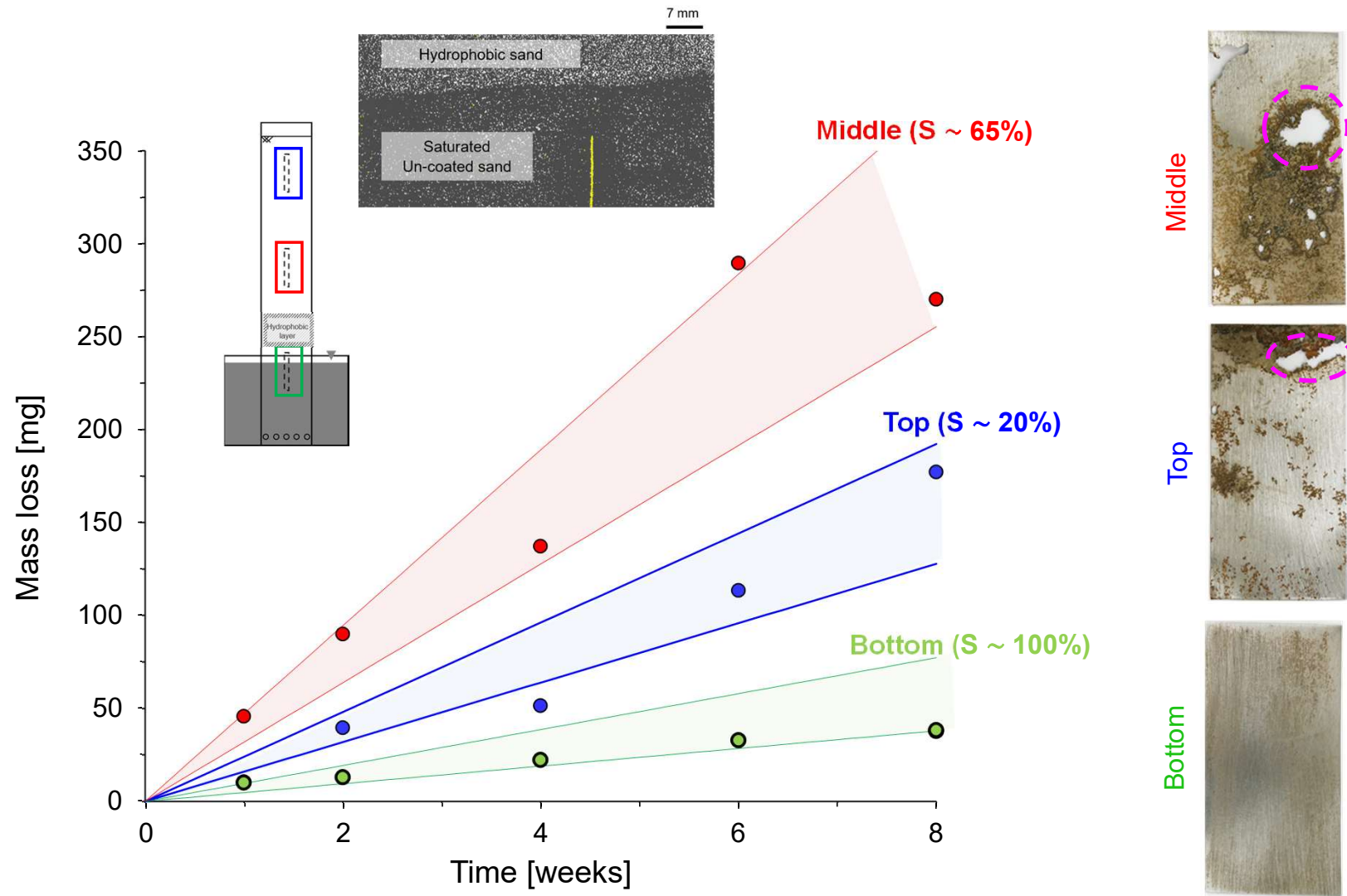
Study #2: Conductivity= Saturation & Salinity



Study #2: Mass Loss Measurements & Predictions

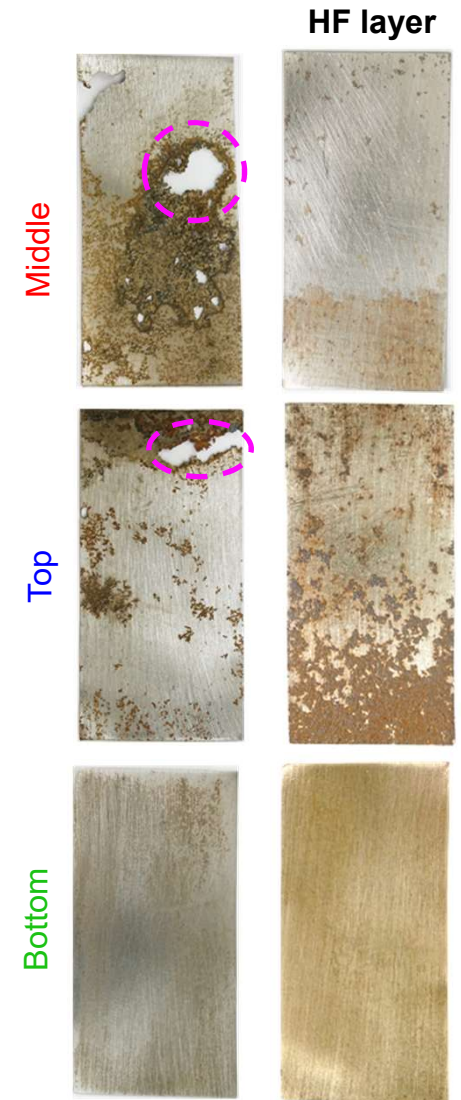
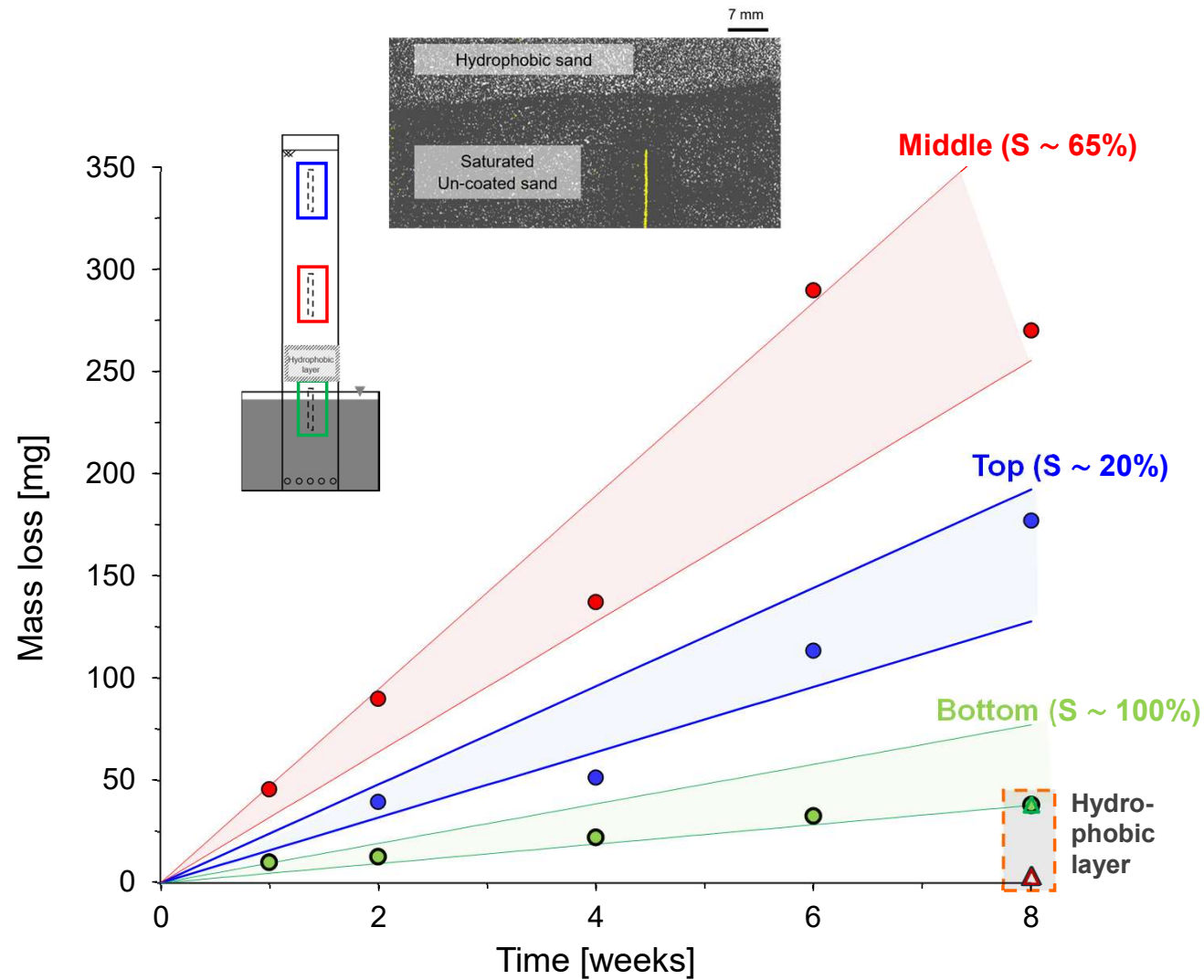


Study #2: Mass Loss Measurements & Predictions



Corrosion as a function of redox reactants transport rate...

Study #2: Mass Loss Measurements & Predictions



Corrosion as a function of redox reactants transport rate...

Outline

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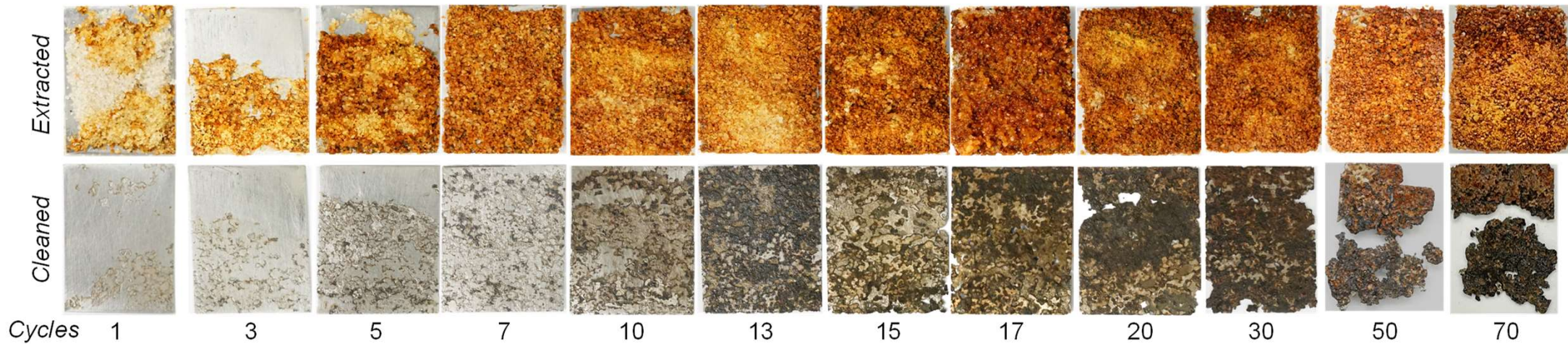
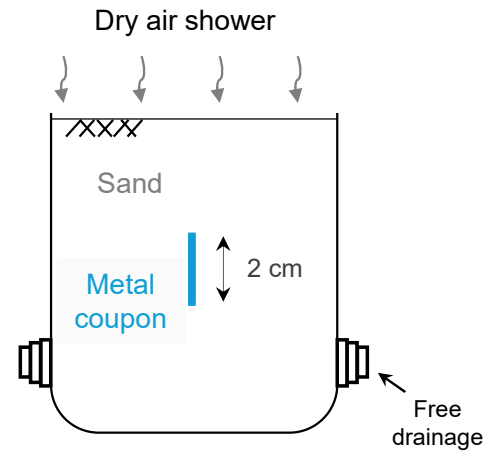
2. Dynamics: Moisture Cycles

4. Soil Mixtures

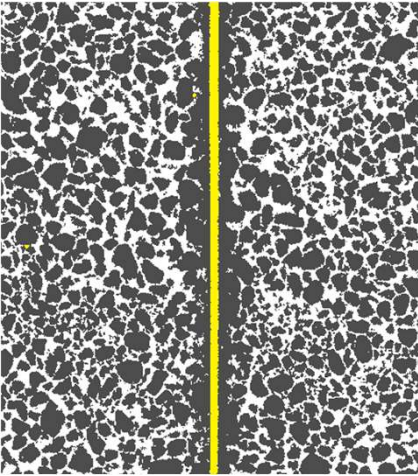
5. Laboratory and Field Investigations: Resources

6. Ongoing Research

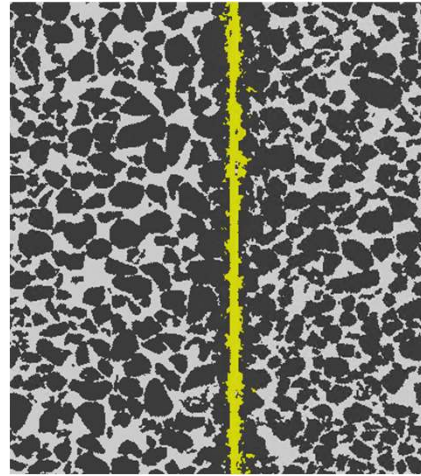
Corrosion in Buried Metals During Moisture Cycles



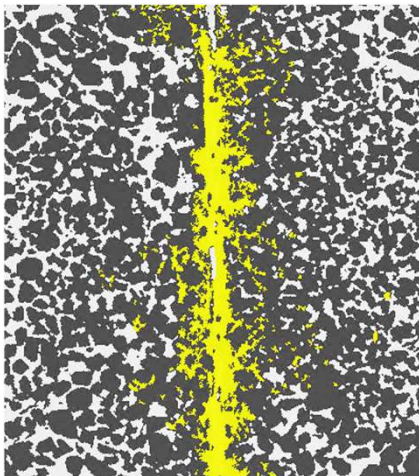
Corrosion in Buried Metals During Moisture Cycles



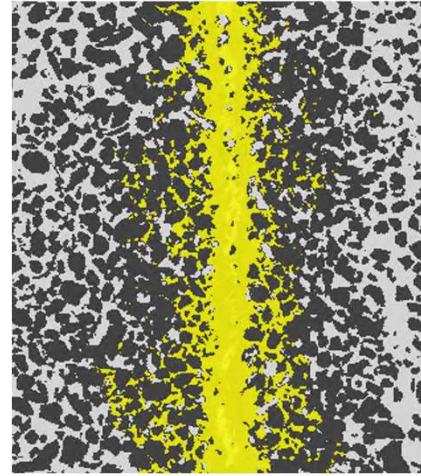
Initial condition



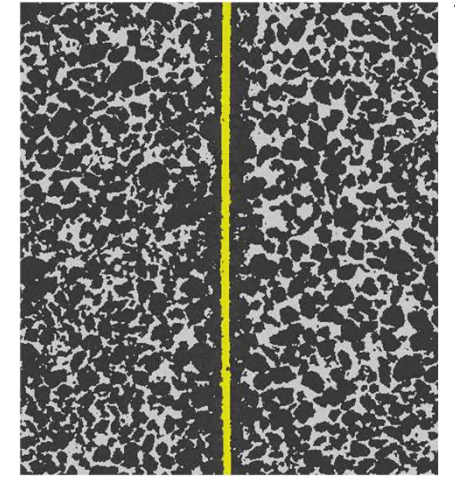
7 cycles



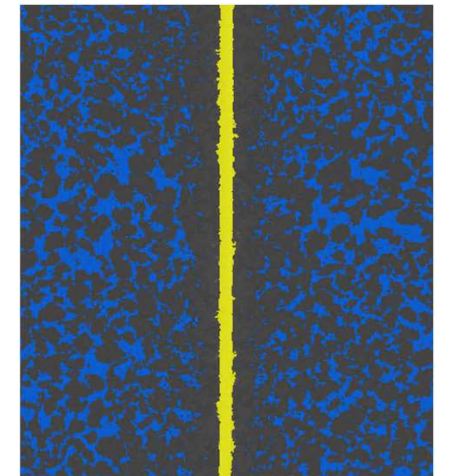
20 cycles



100 cycles (200 days)



"Dry" after 190 days

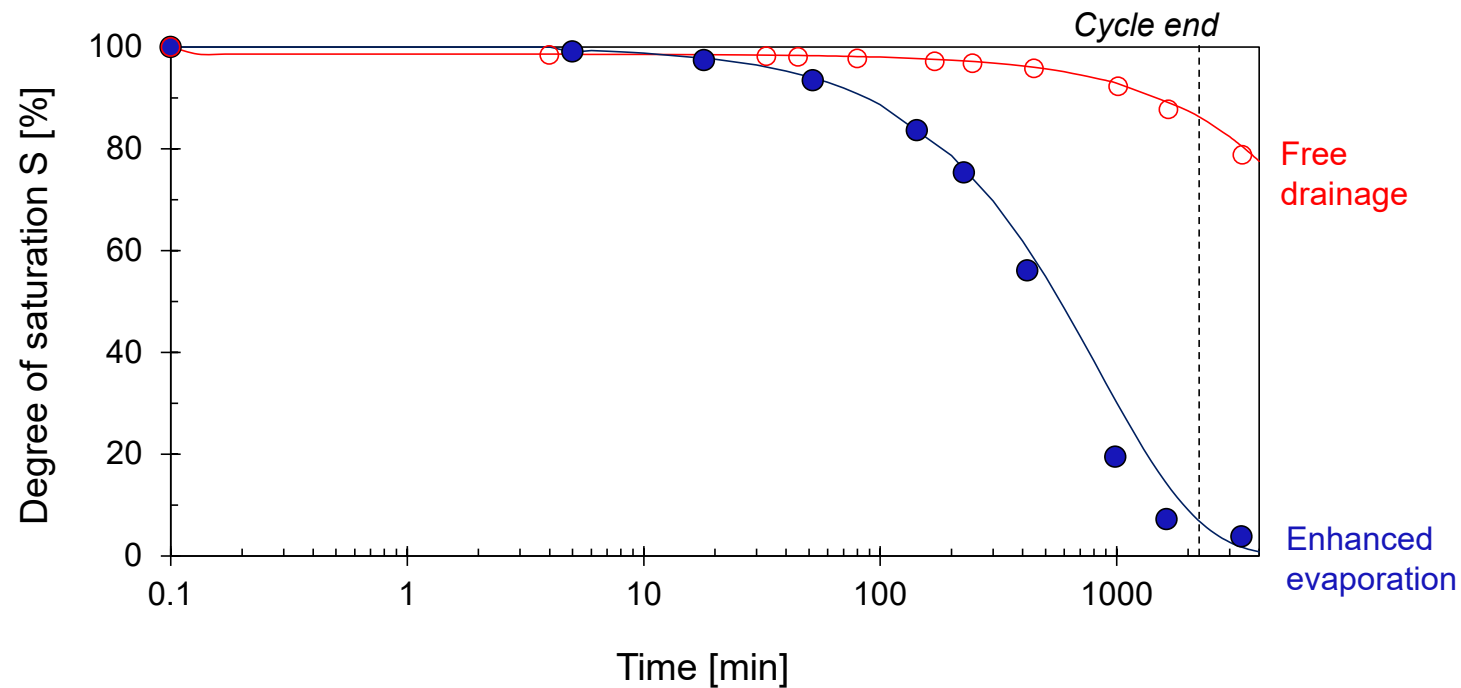


Fully Saturated after 190 days

Corrosion in Buried Metals: Concurrent Processes Time Scales ²⁶

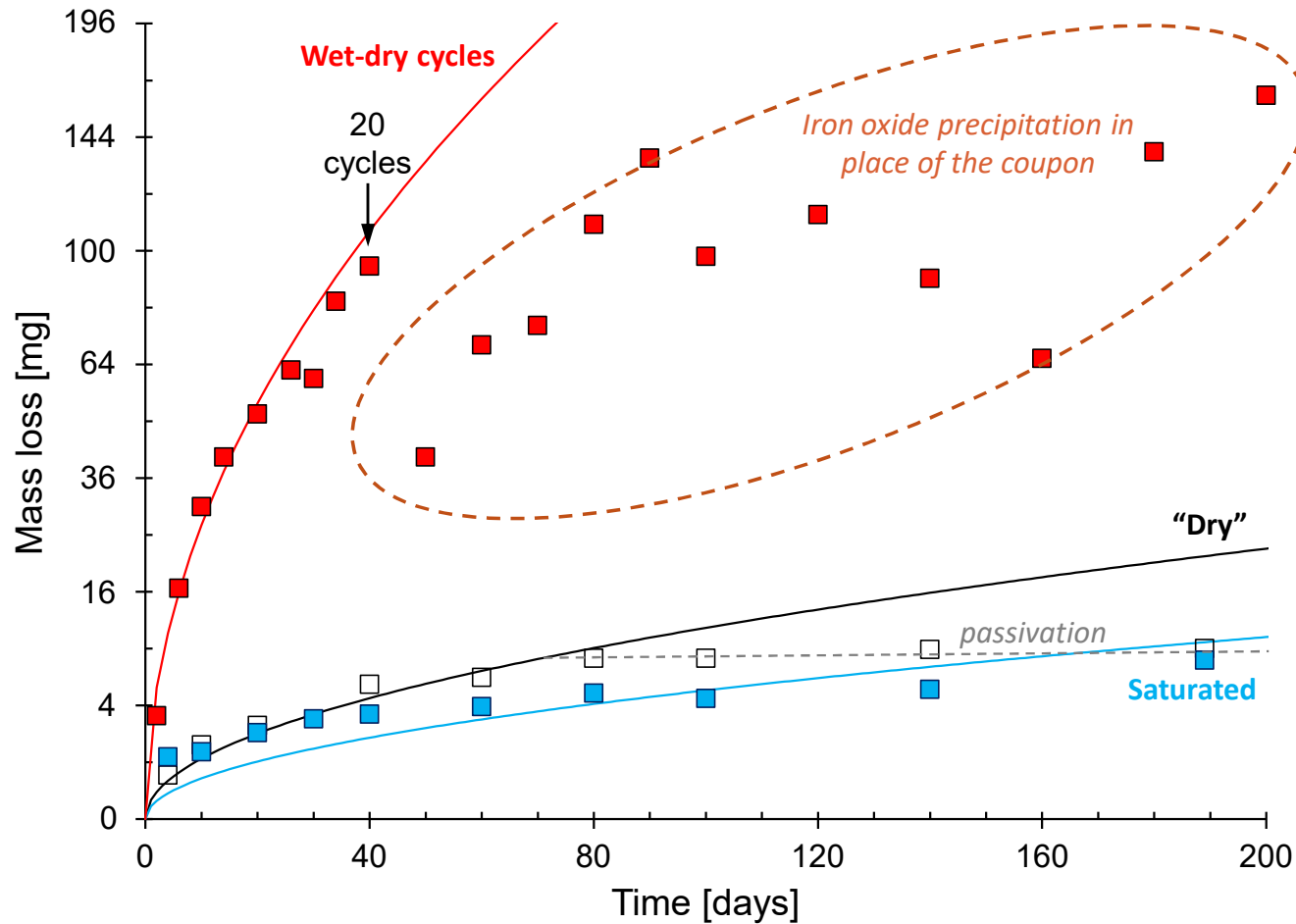
Physical processes with competing timescales:

- (1) the duration of the saturation period: i.e., rain duration and water table oscillations
- (2) time for oxygen diffusion or enhanced transport to the metal surface → **Oxygen always available**
- (3) time for the residuals to transport away from the buried metal: sediment effective diffusivity or related accelerated transport. → **Highly dependent on saturation**



100% active area → water is transported along the coupon surface

Corrosion in Buried Metals: Concurrent Processes Time Scales

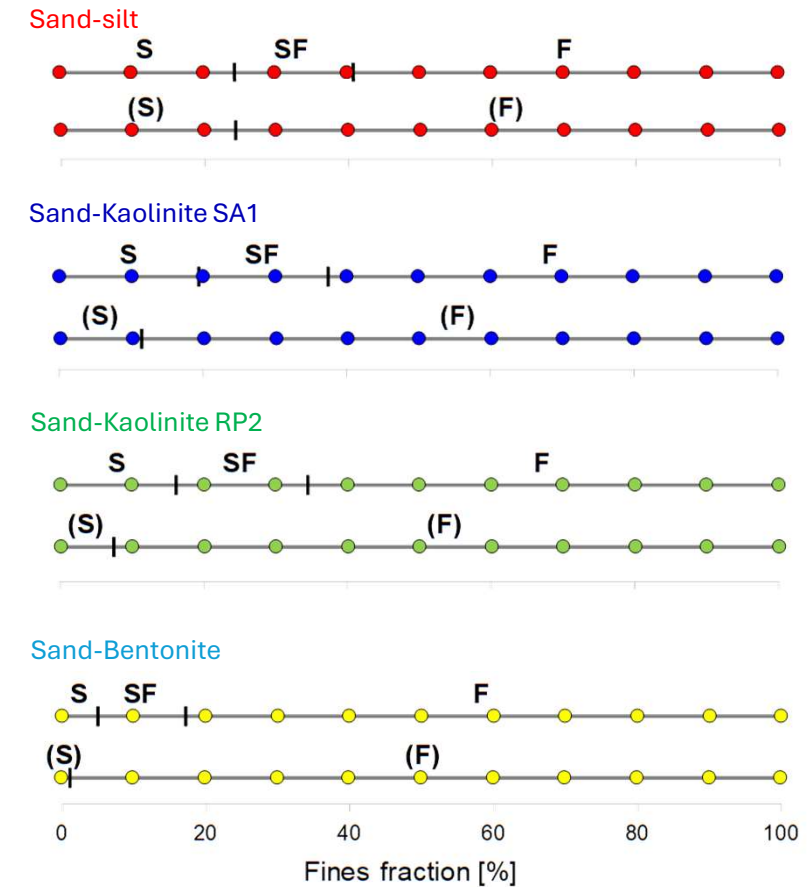
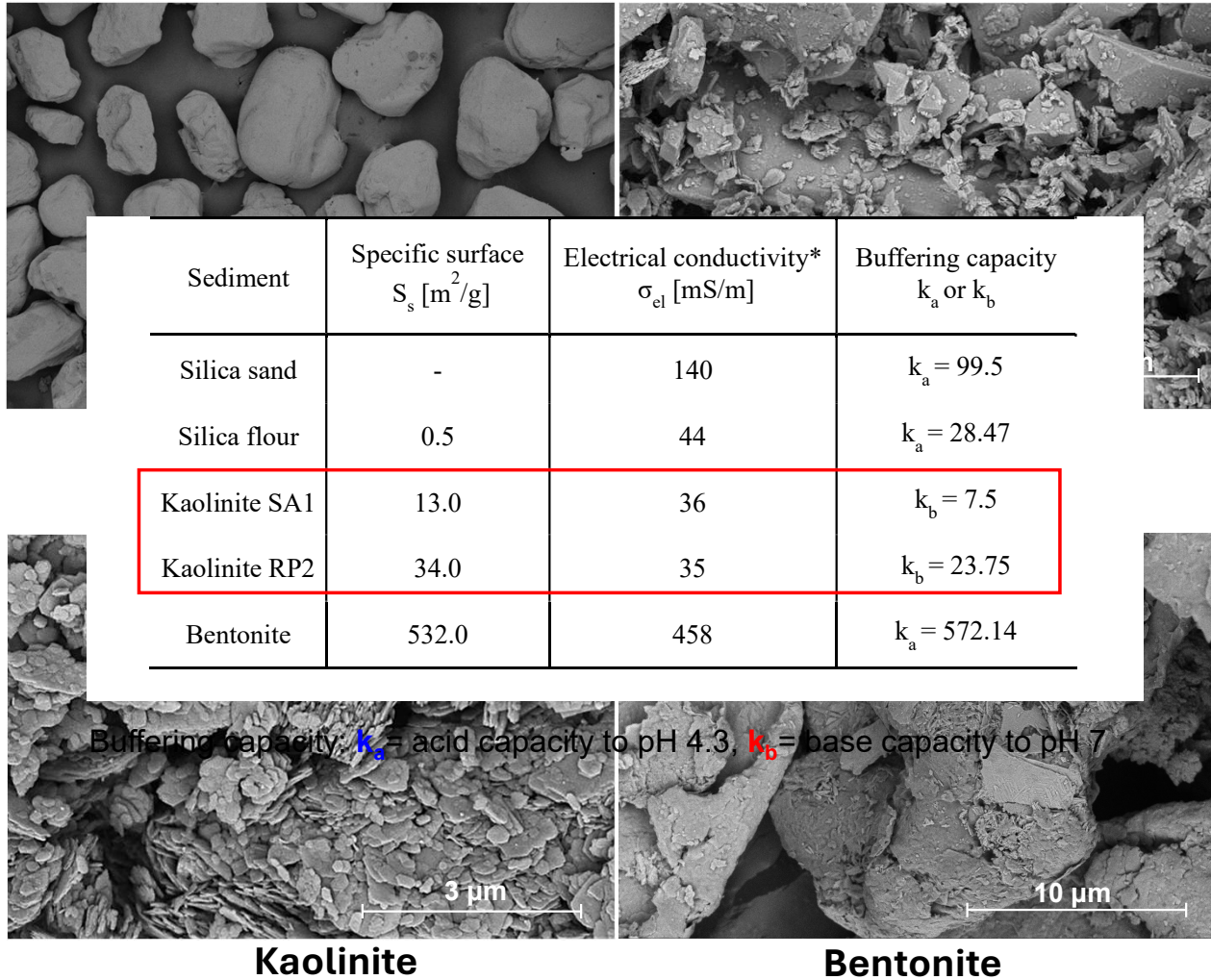


Key: Understand the process that drives your corrosion rate

Outline

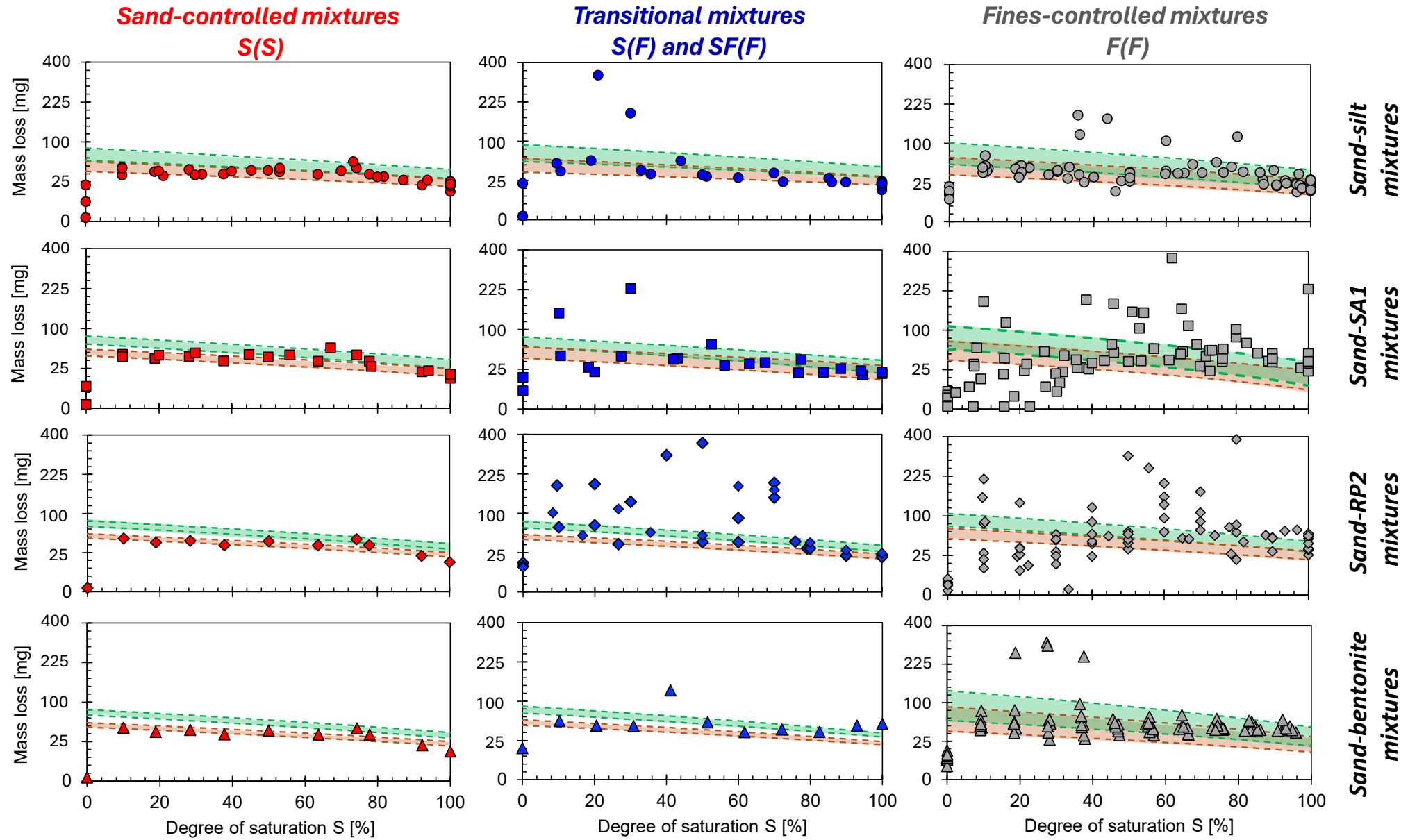
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Corrosion in Buried Metals: Mixtures



RSCS

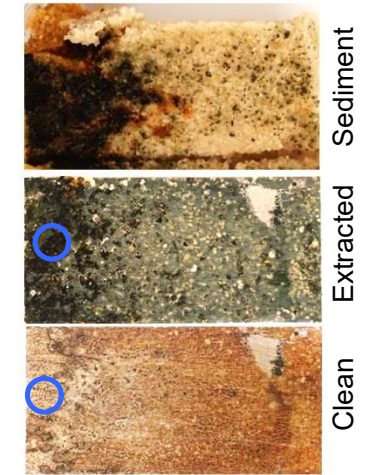
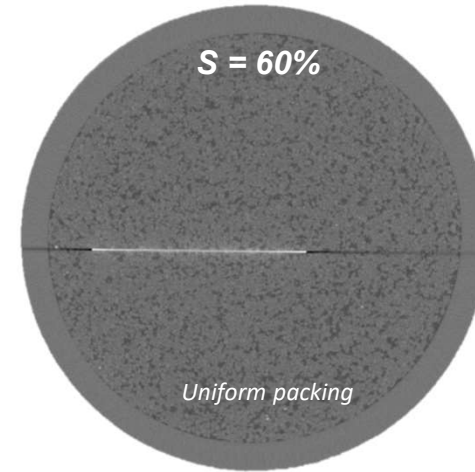
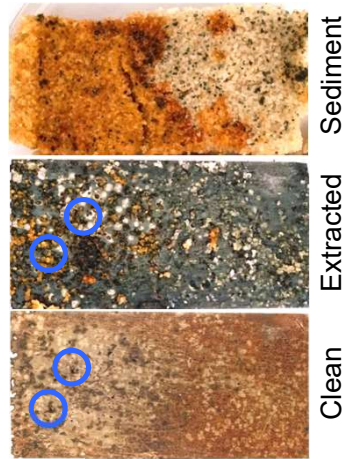
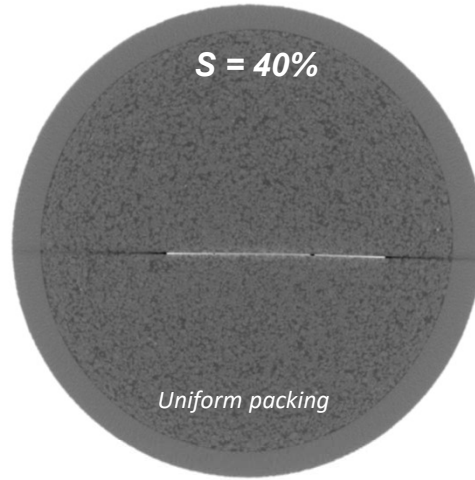
451 samples → 12-week exposure time



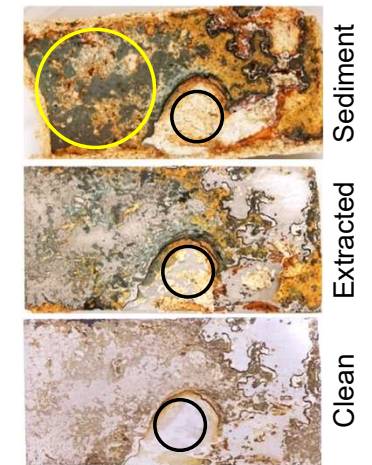
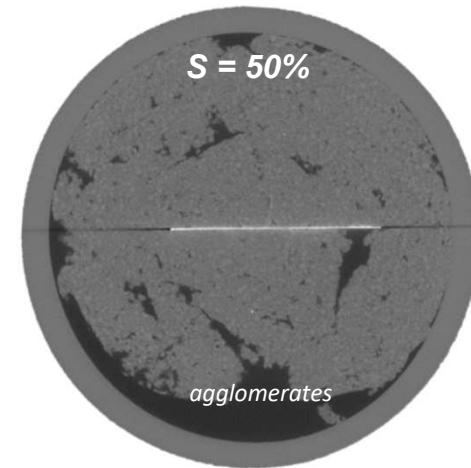
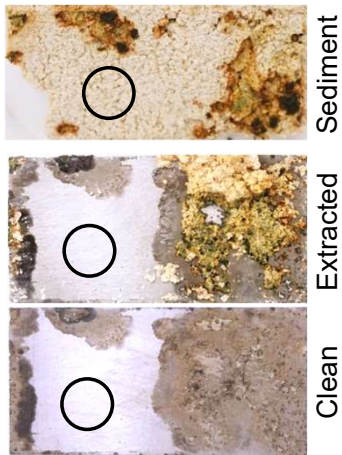
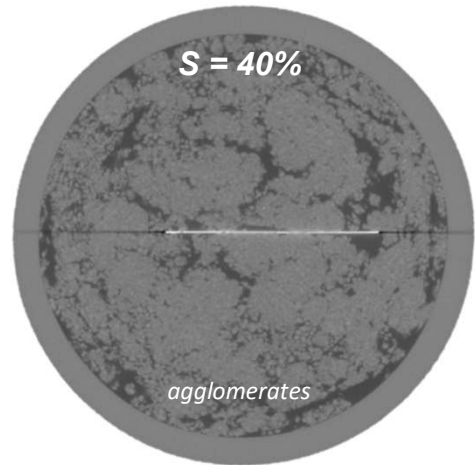
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Corrosion in Soil Mixtures: Fines Agglomerates

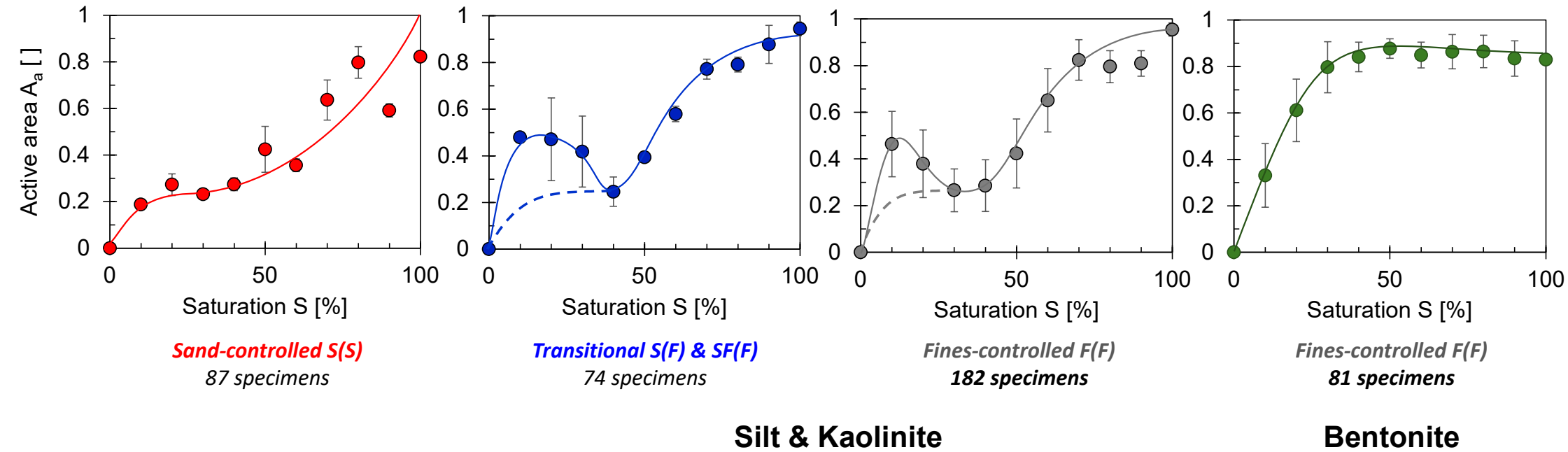
(a) Clean Sand



(b) Pure Kaolinite



Corrosion in Soil Mixtures: Active Area



Corrosion in Soil Mixtures: Who Drives Corrosion?

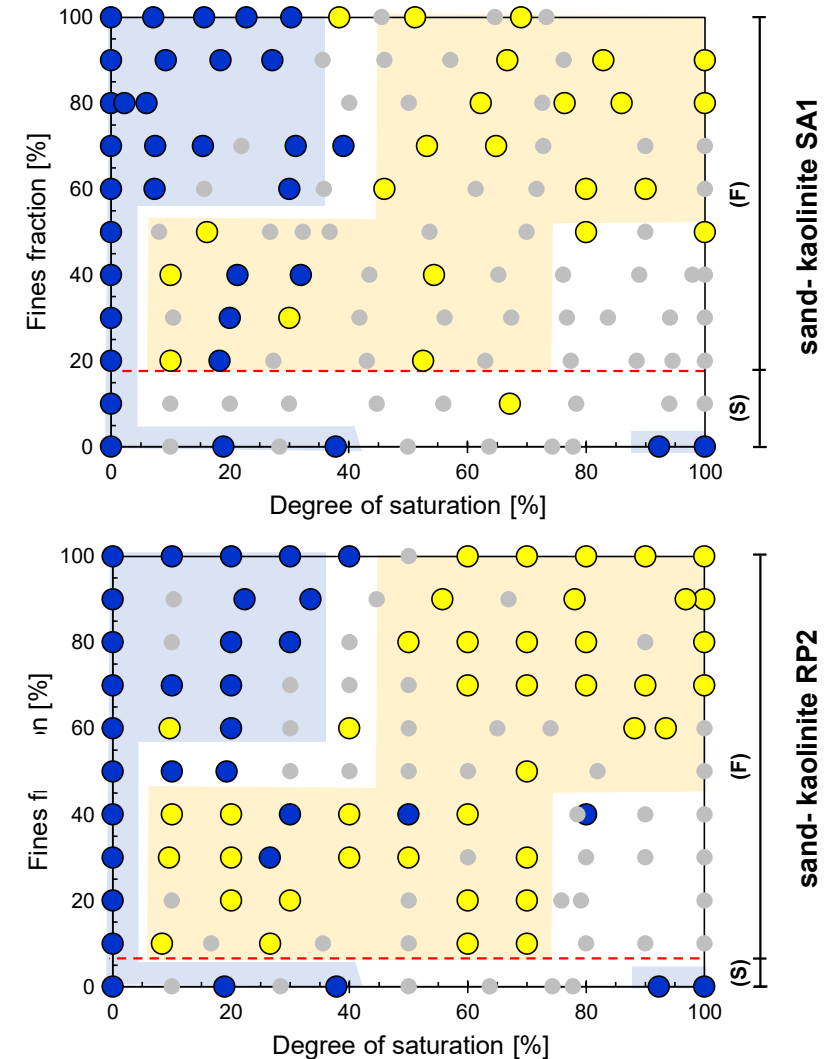
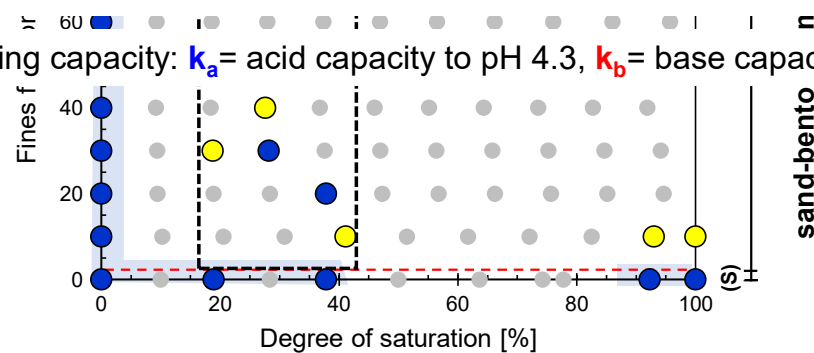
Higher than oxygen bounds

Within oxygen bounds

Lower than oxygen

Sediment	Specific surface S_s [m ² /g]	Electrical conductivity* σ_{el} [mS/m]	Buffering capacity k_a or k_b
Silica sand	-	140	$k_a = 99.5$
Silica flour	0.5	44	$k_a = 28.47$
Kaolinite SA1	13.0	36	$k_b = 7.5$
Kaolinite RP2	34.0	35	$k_b = 23.75$
Bentonite	532.0	458	$k_a = 572.14$

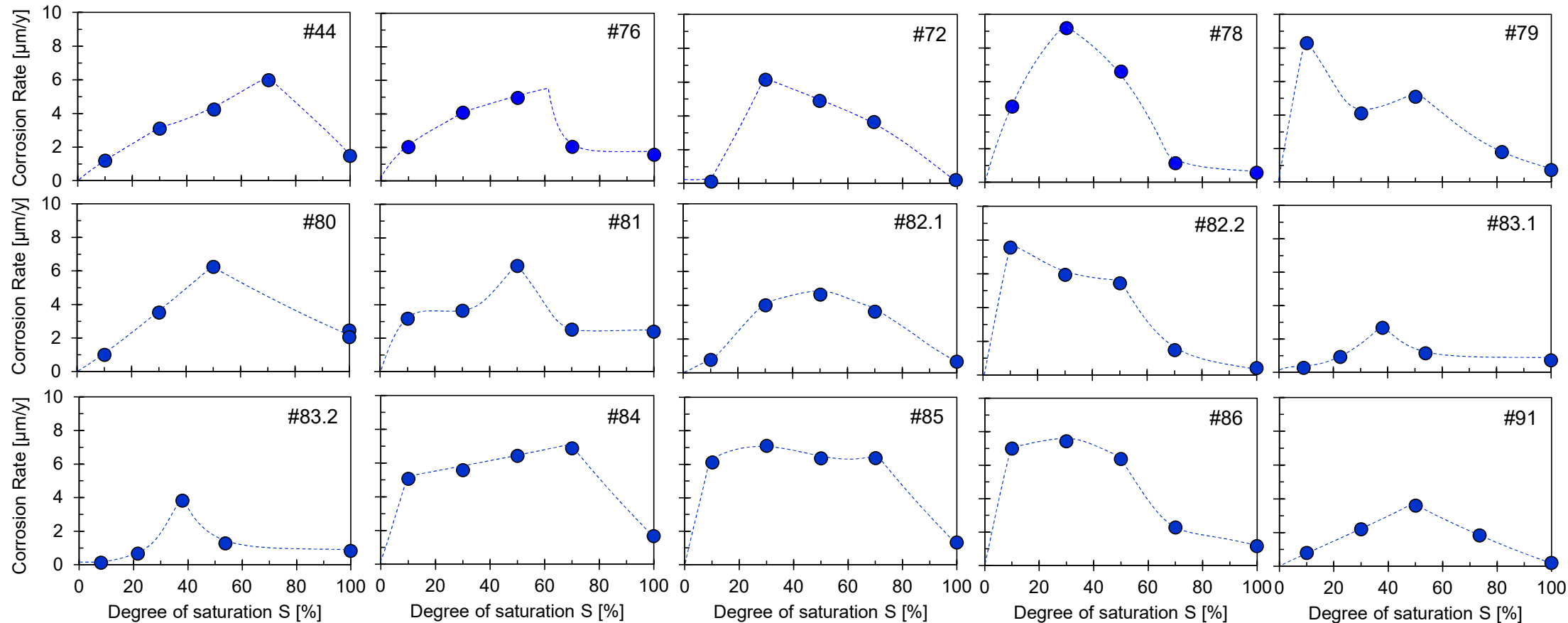
Buffering capacity: k_a = acid capacity to pH 4.3, k_b = base capacity to pH 7



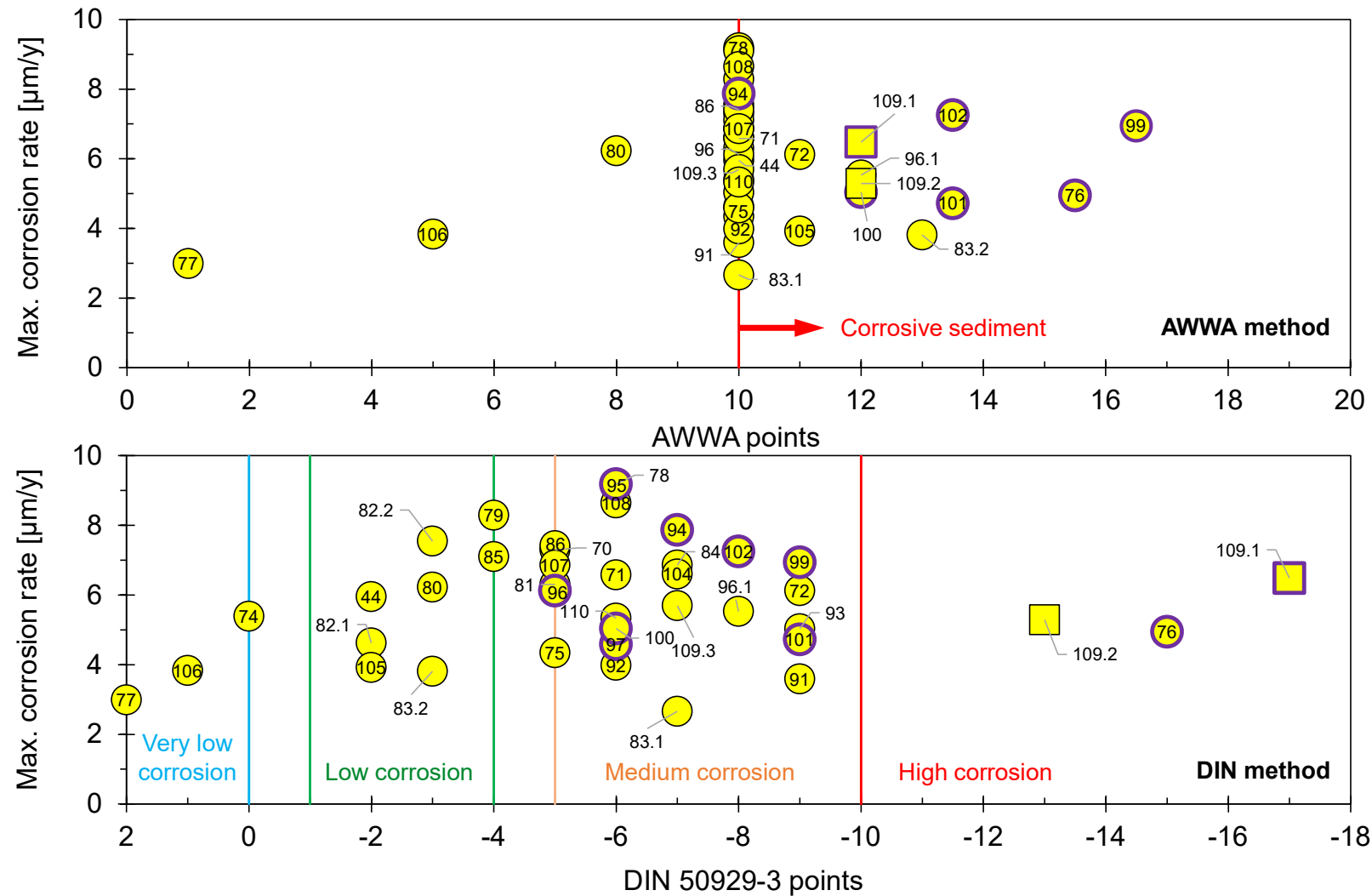
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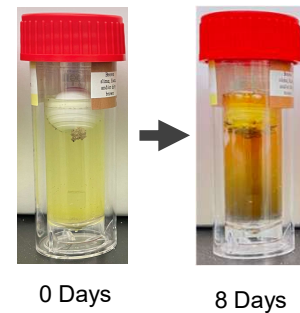
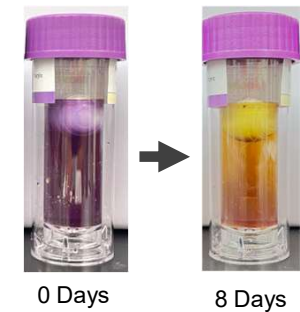
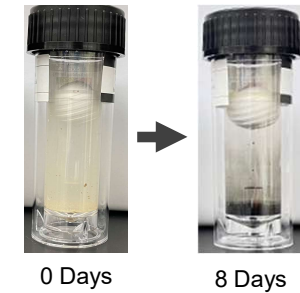
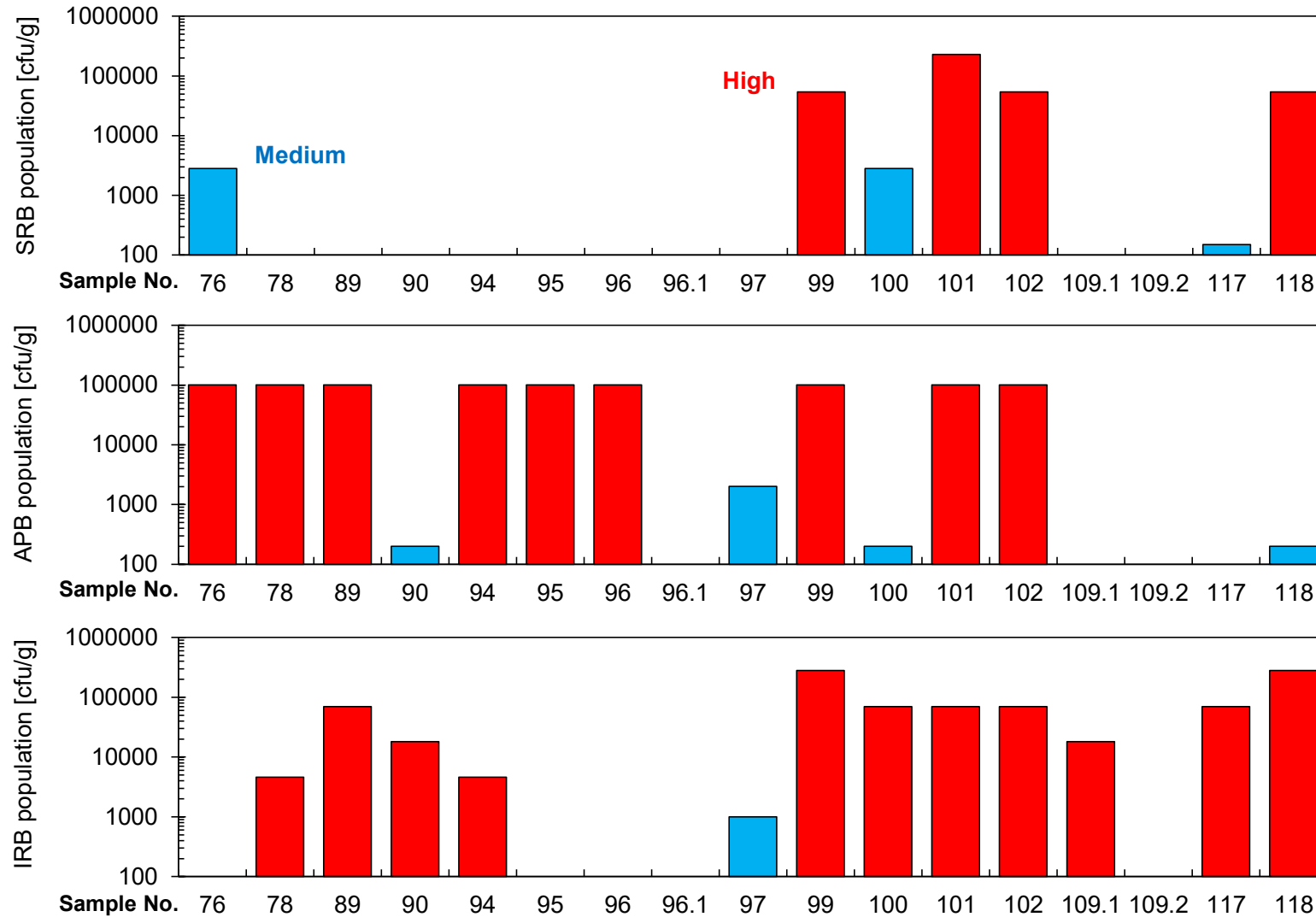
Soil Corrosivity Assessment: Saturation



Soil Corrosivity Assessments vs. Measurements

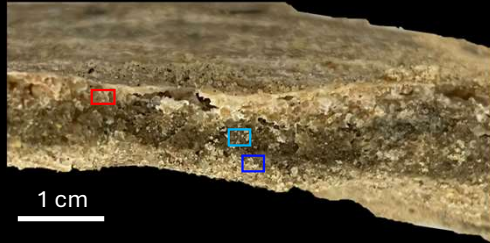


Corrosion in Buried Metals: Bioactivity → Opportunity?

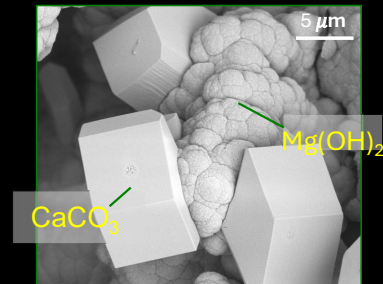
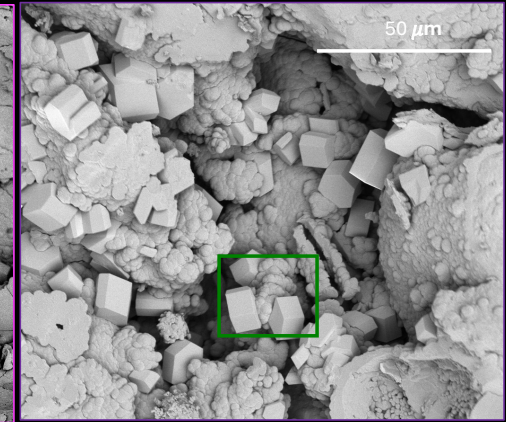
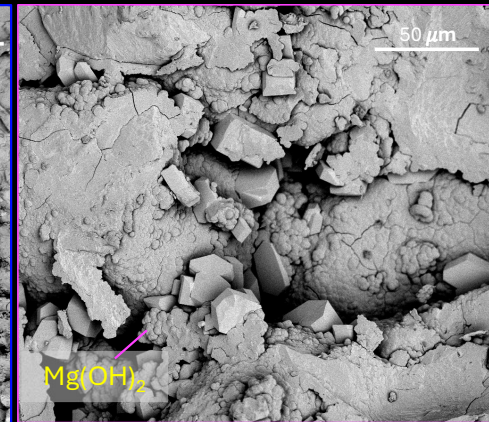
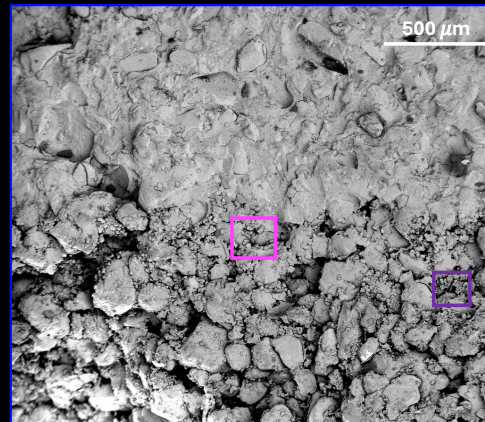
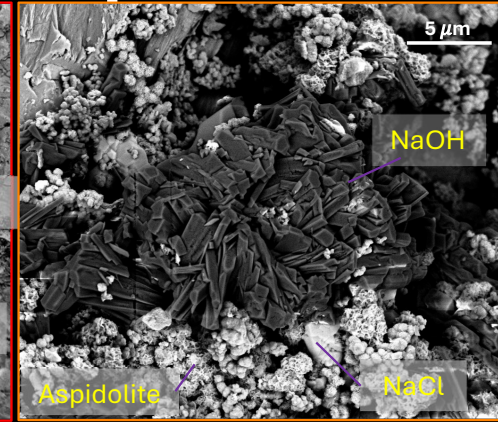
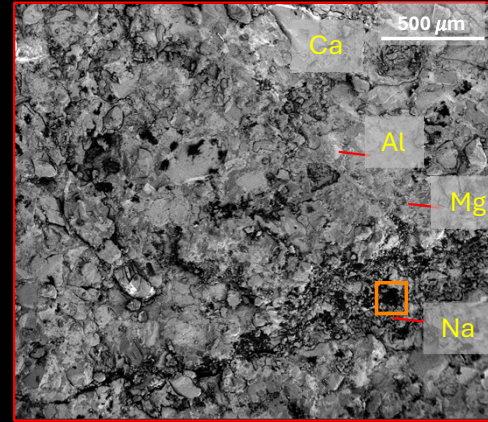
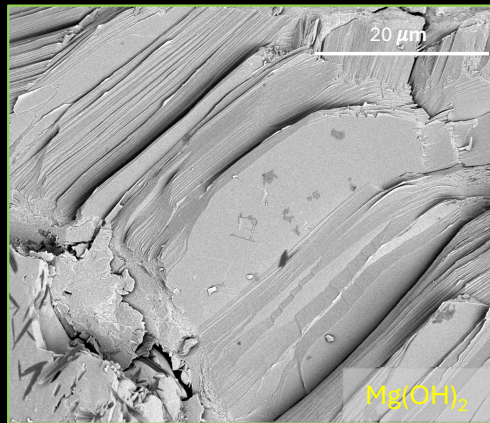
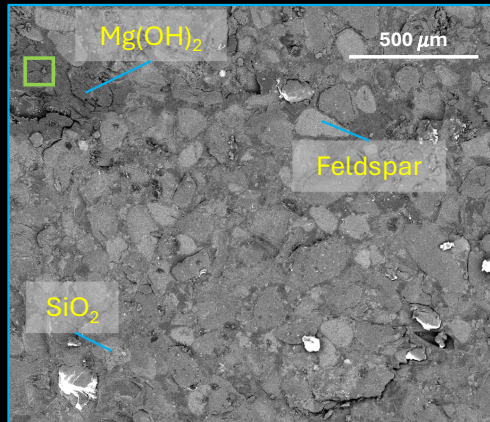


BART tests

Corrosion in Buried Metals: Calcareous Deposits



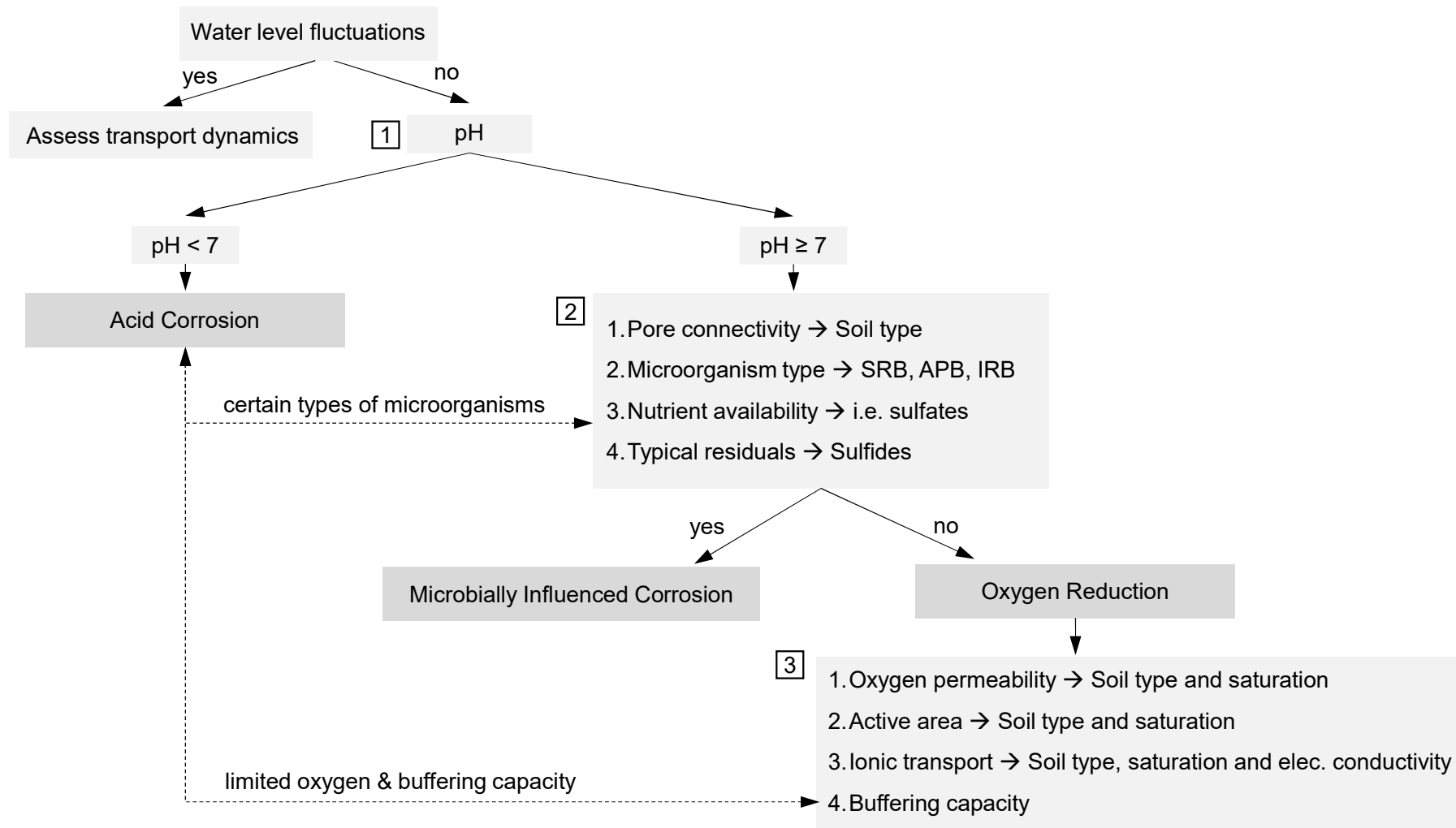
Towards buried metal



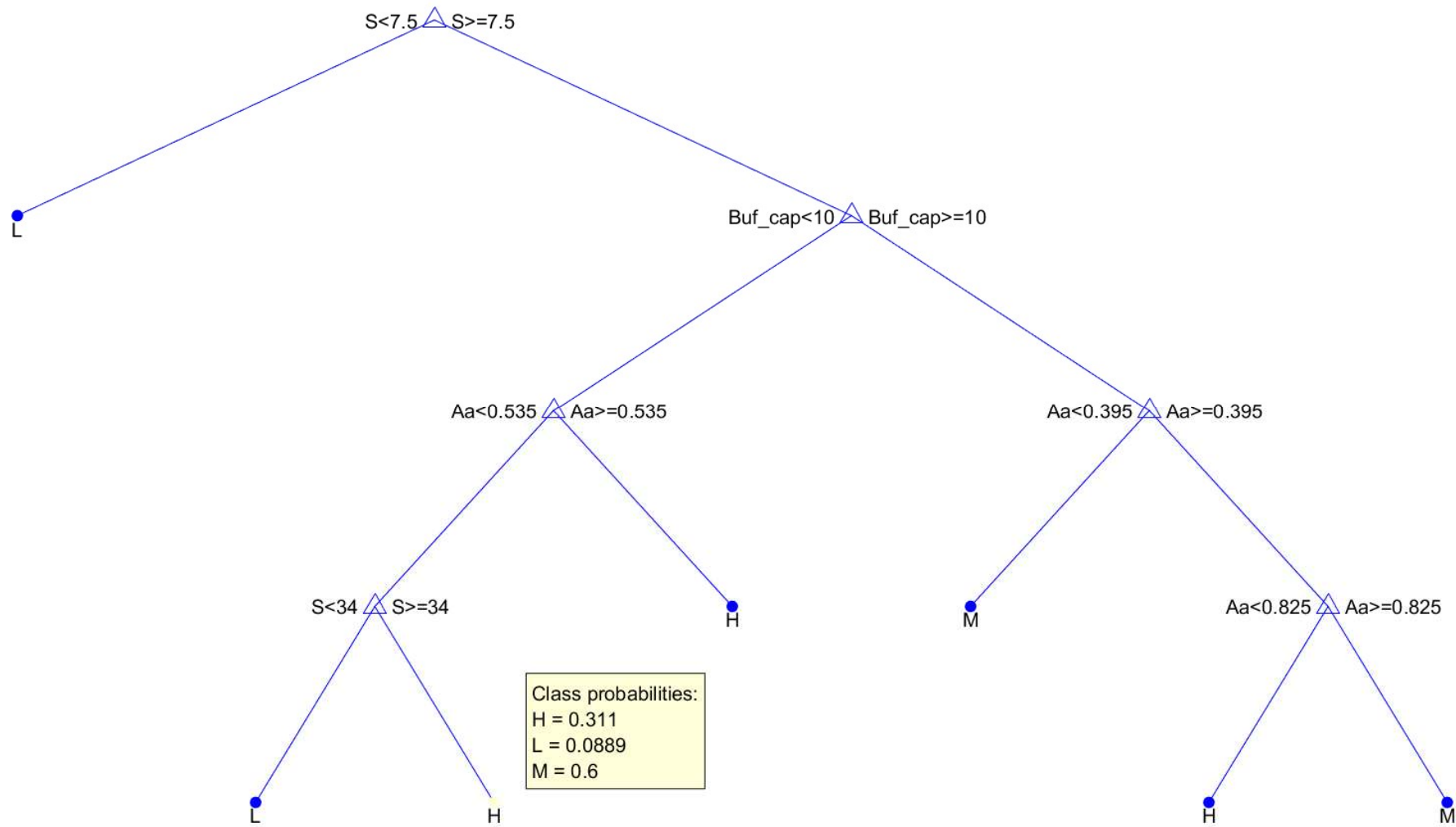
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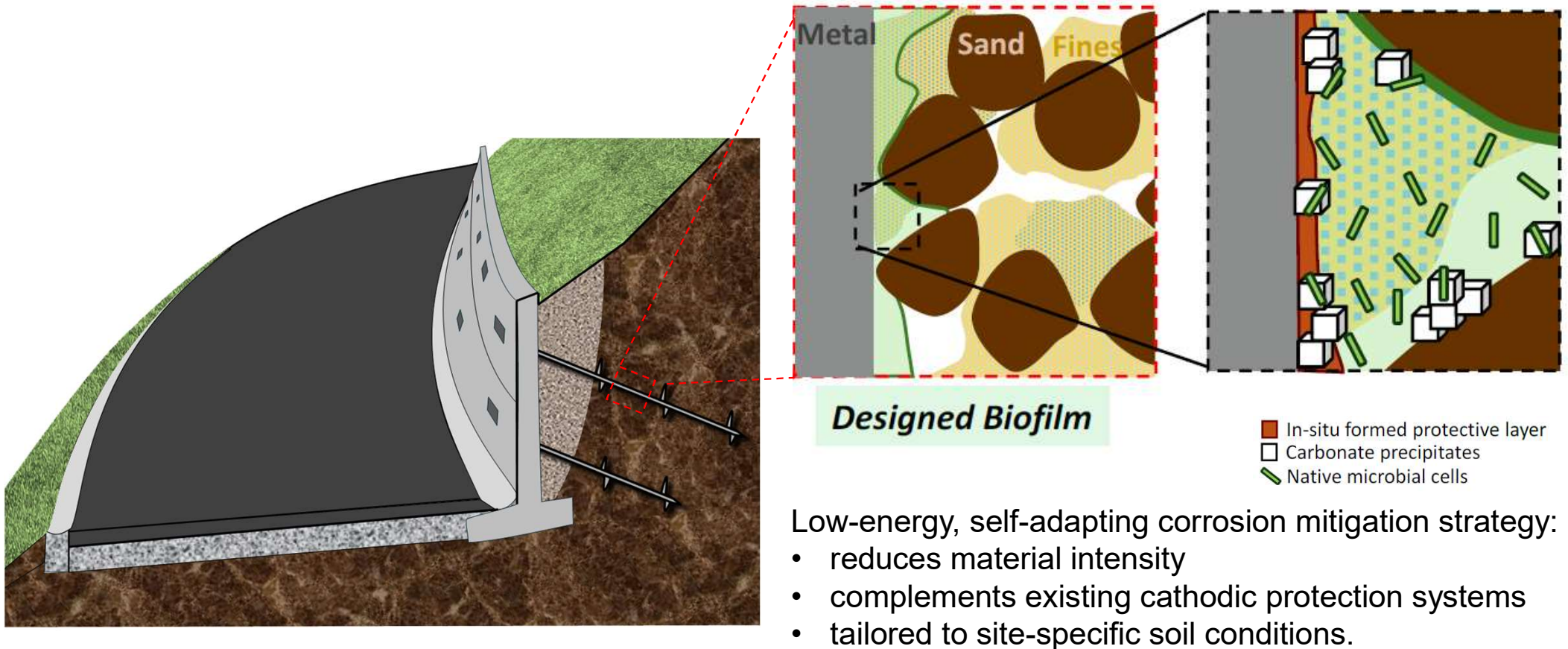
#1 Soil Corrosivity Assessments: Learnings



#1 ML-enabled Probabilistic Approach



#2: Bio-based Corrosion Protection



Transform a corrosive environment into a protective one

#3: Effect of Corrosion in Metallic Piles

UK Government's goal: decarbonise electricity by 2030 → x2 onshore wind by 2030, and x5 solar by 2035

Onshore

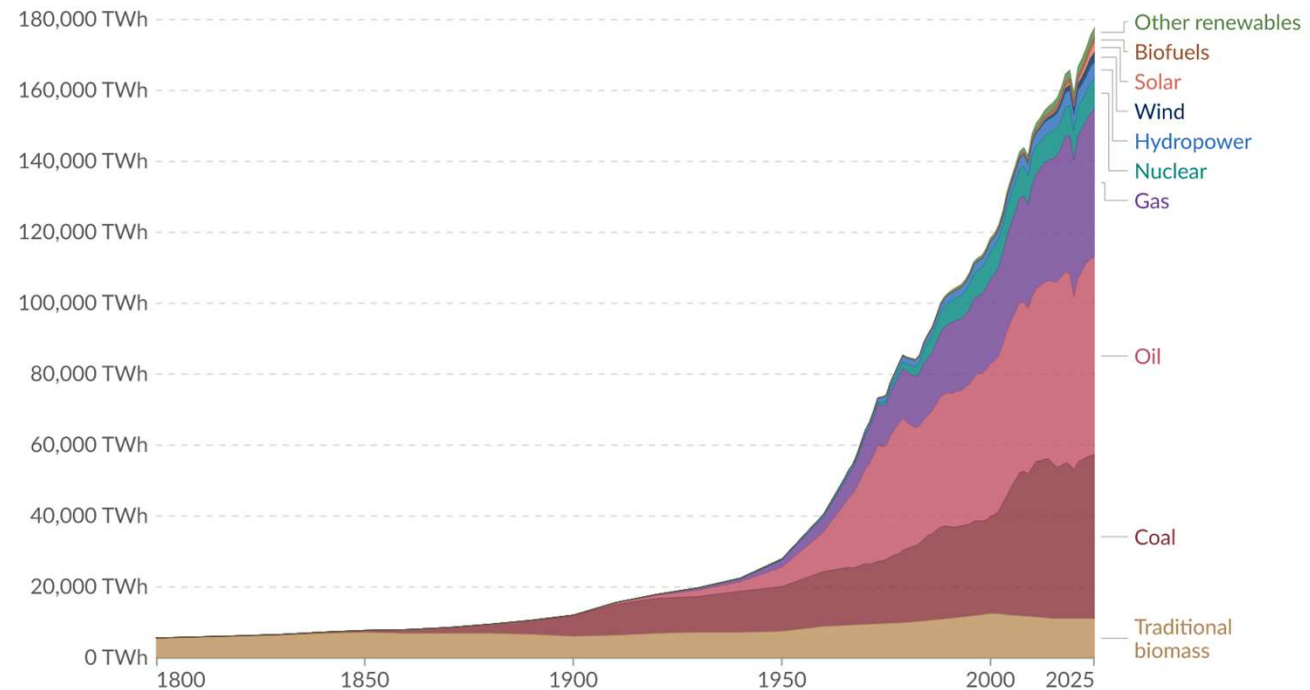
- Un-saturated conditions
- Current assumption: Provide sacrificial thickness → **How dangerous is this in dynamic systems? (i.e., groundwater changes, flooding)**

Offshore

- High microbial action
- Current assumption: Corrosion enhances soil-pile strength → **How brittle corrosion residuals react to fatigue?**

Global primary energy use by source

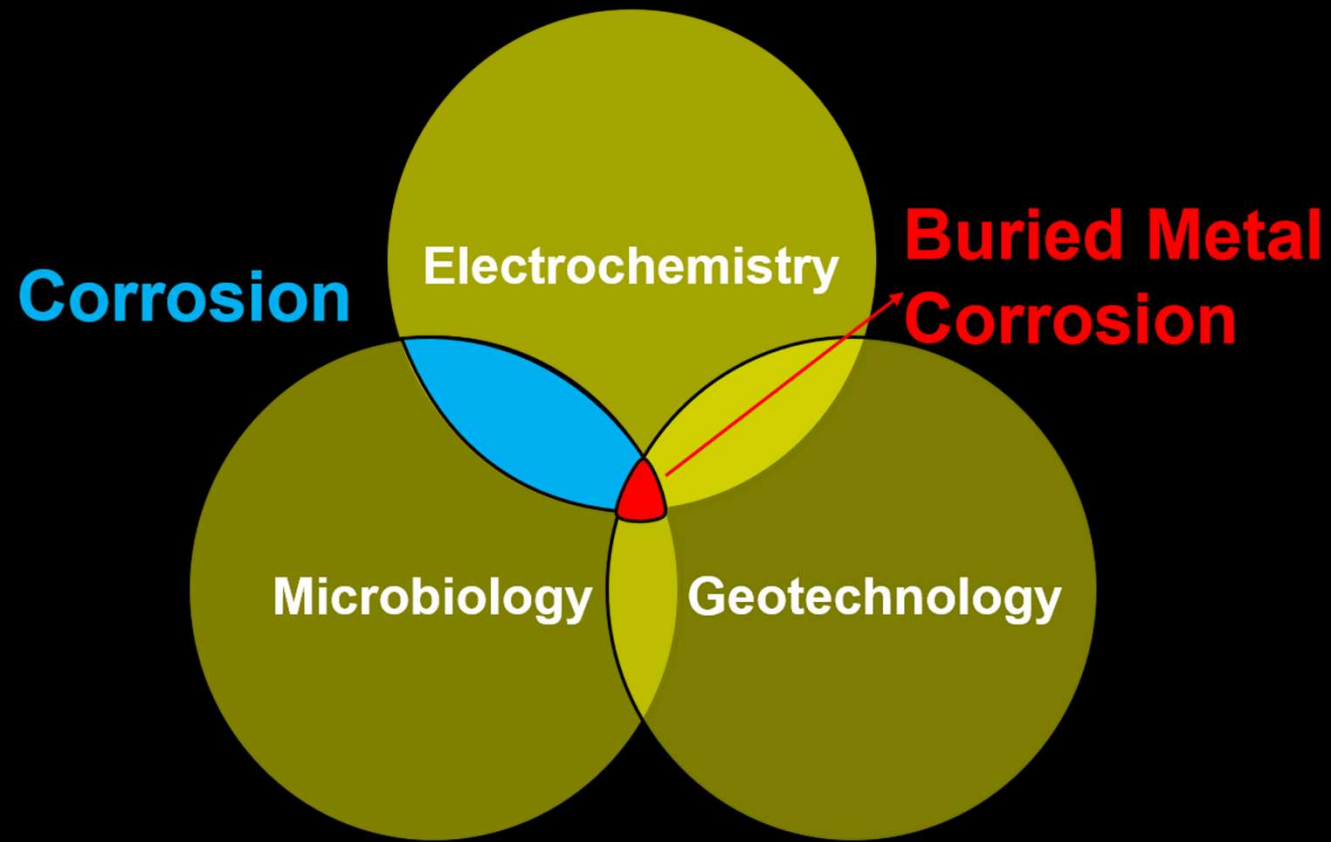
Measured in terawatt-hours of total energy supply.



Data source: Energy Institute – Statistical Review of World Energy (2026); Smil (2017)

OurWorldinData.org/energy | CC BY

Note: Other renewables include geothermal, biomass, and waste. Traditional biomass is included but, in the absence of more recent data, it is assumed constant since 2015.



A very complex problem that should be tackled by joint multidisciplinary efforts...

Thank You!



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