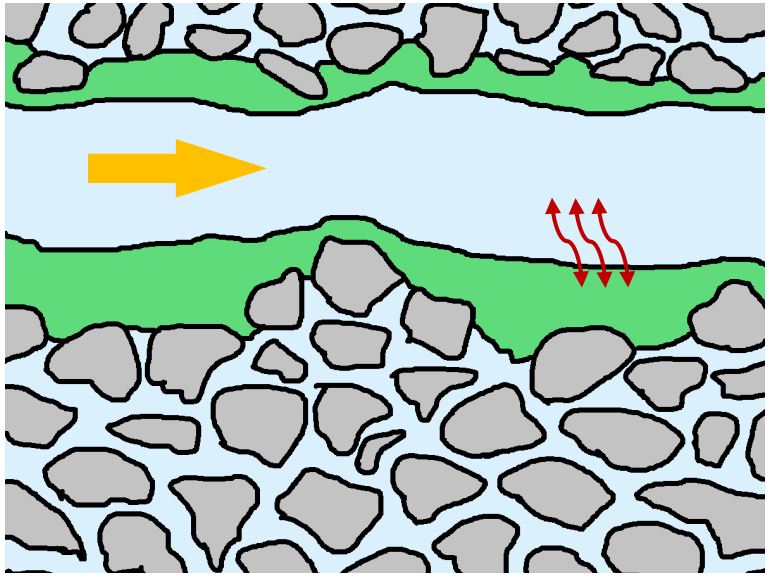
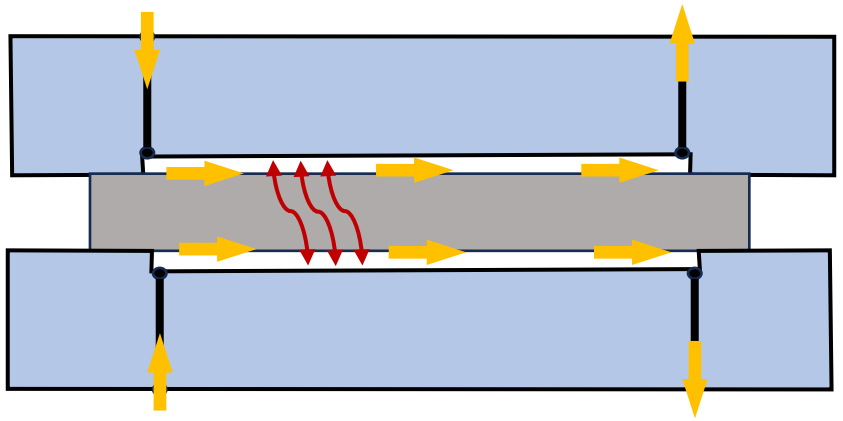
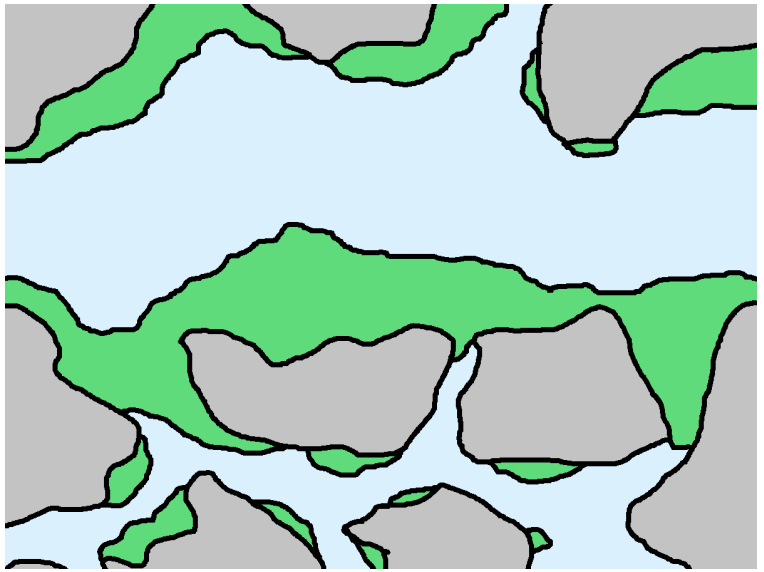


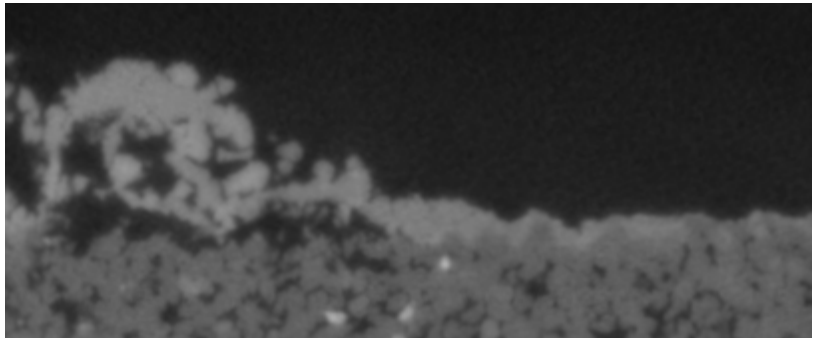




Real Rock Microfluidics Investigation of Solute Diffusion in Biofilm-Rock Systems

Eva M. Albalghiti, Brian R. Ellis

University of Michigan – Civil and Environmental Engineering



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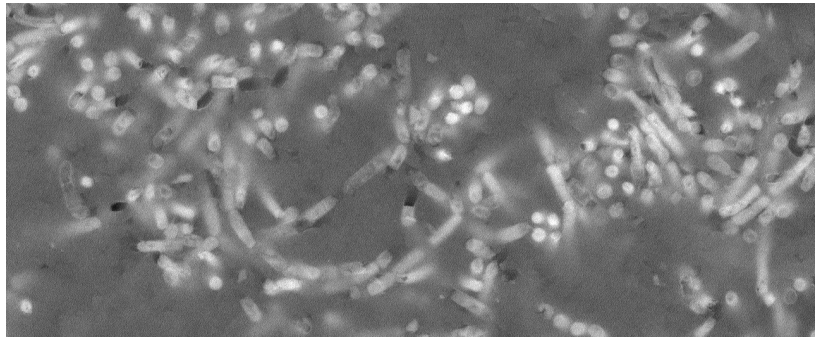
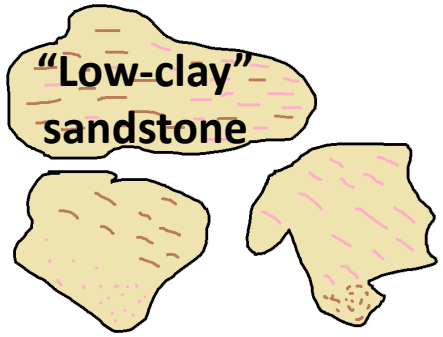


Mineral composition of rock surfaces controls microbial attachment



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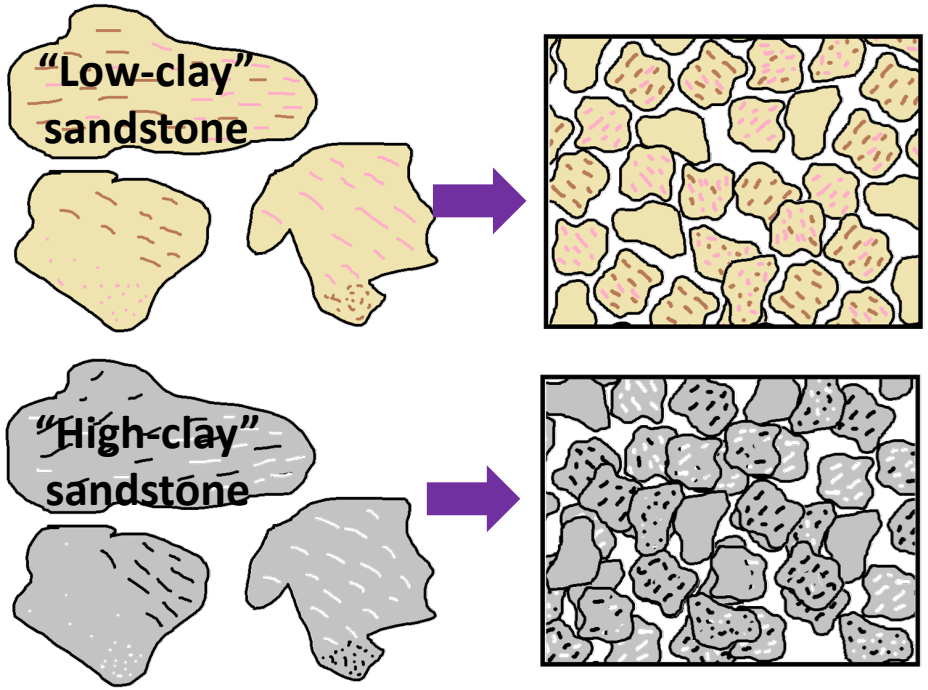
Homogenize to a defined grain size range



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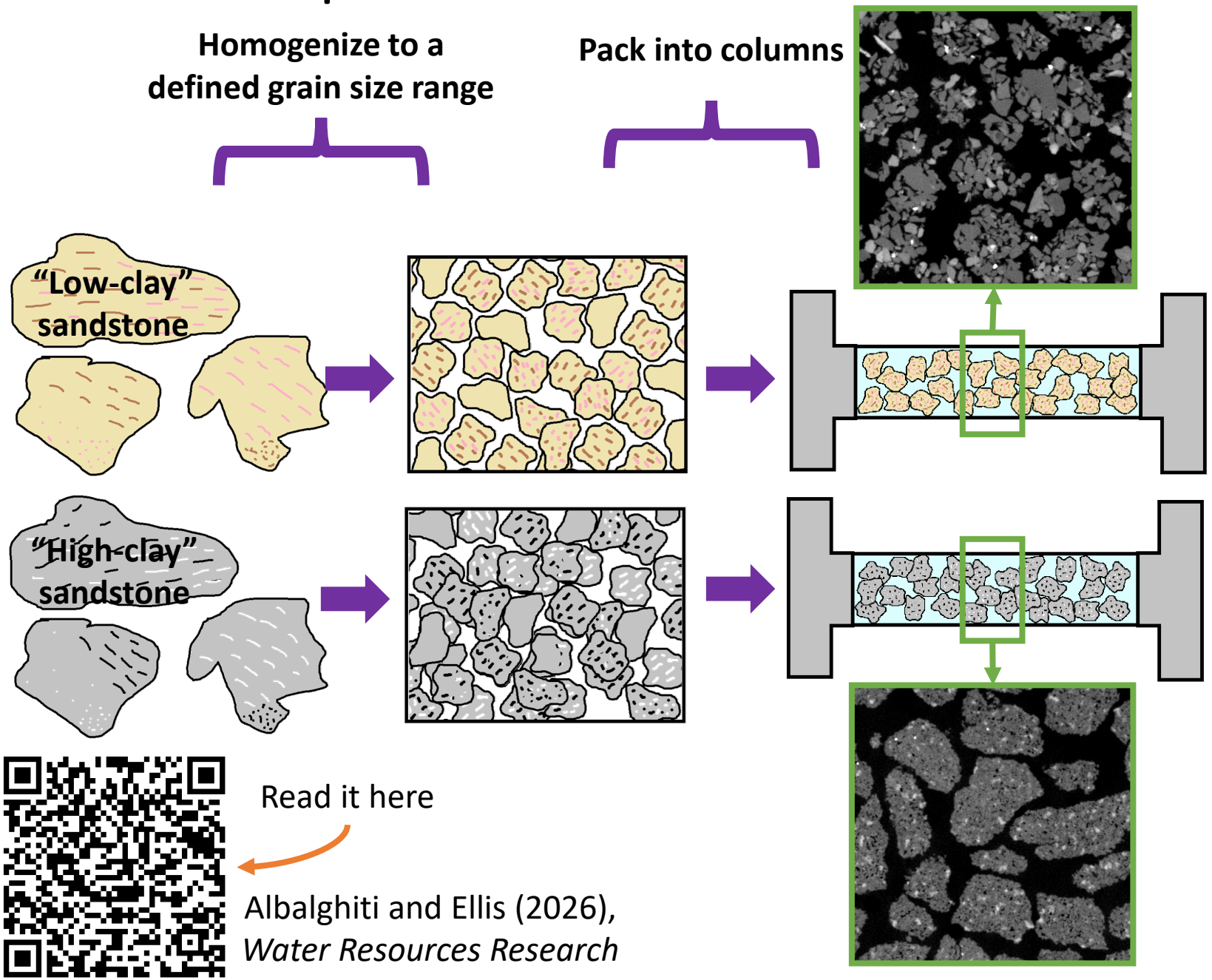

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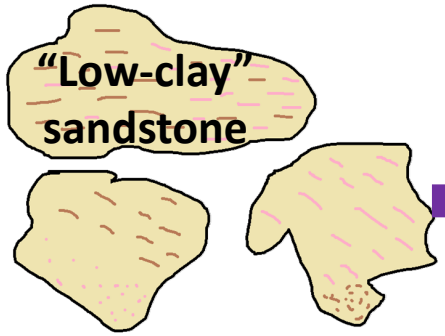

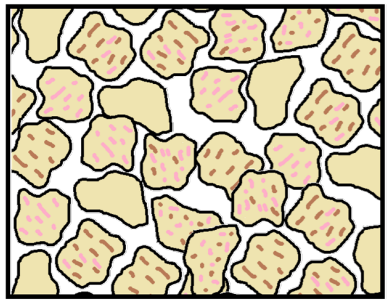

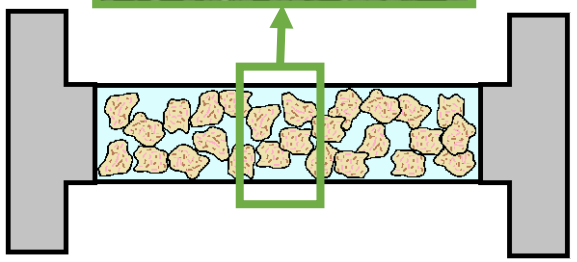

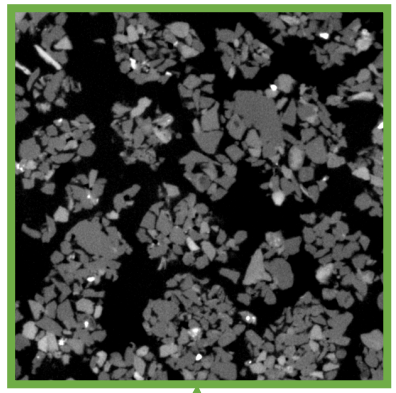

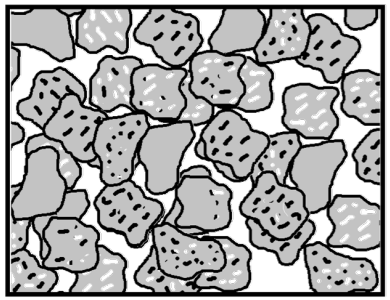

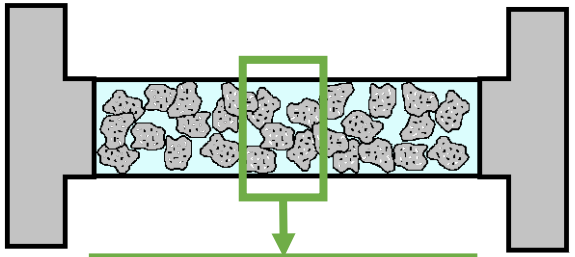

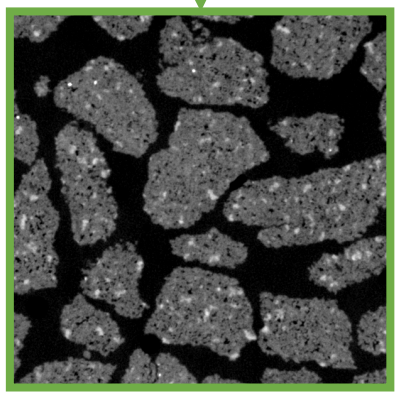

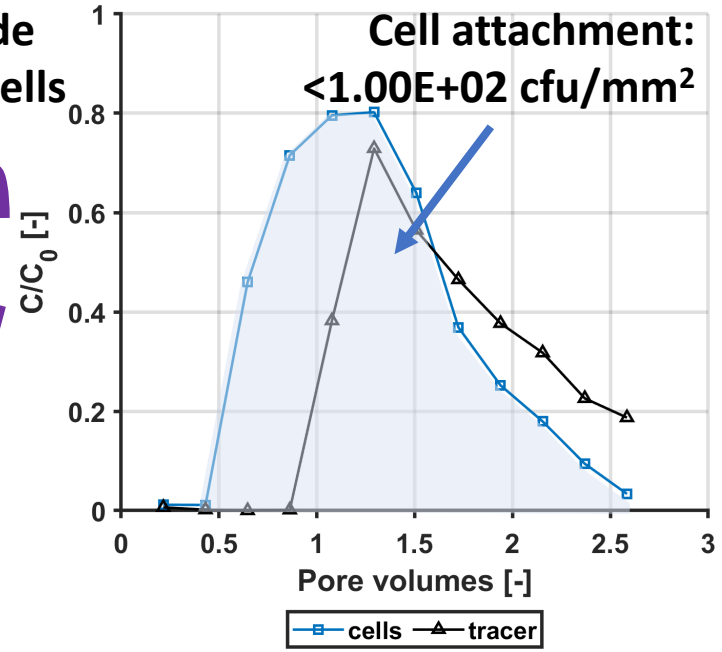

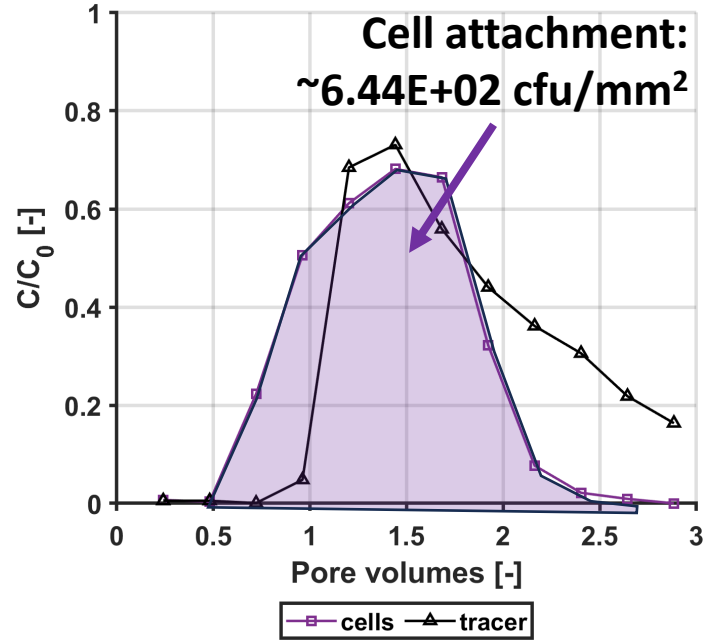

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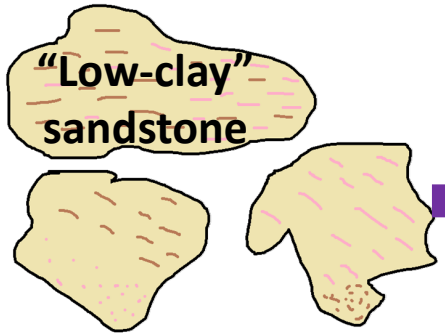

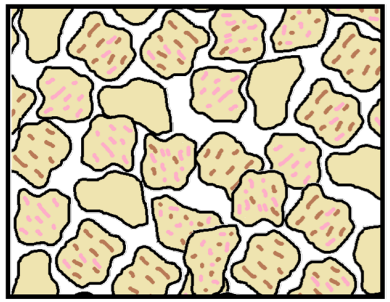

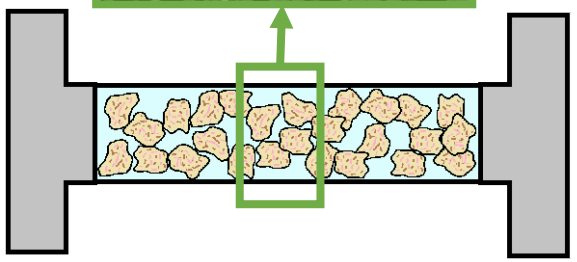

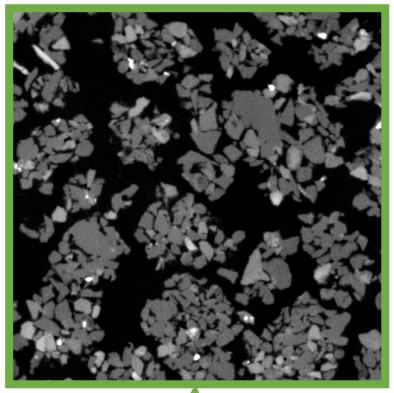

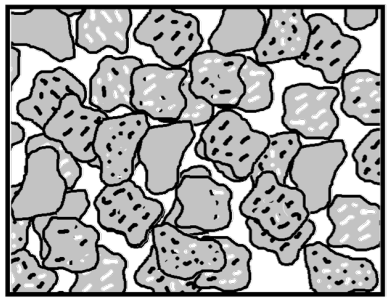

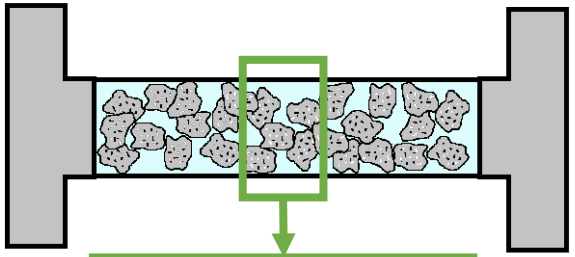

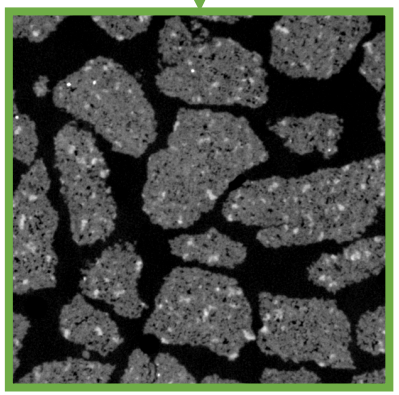

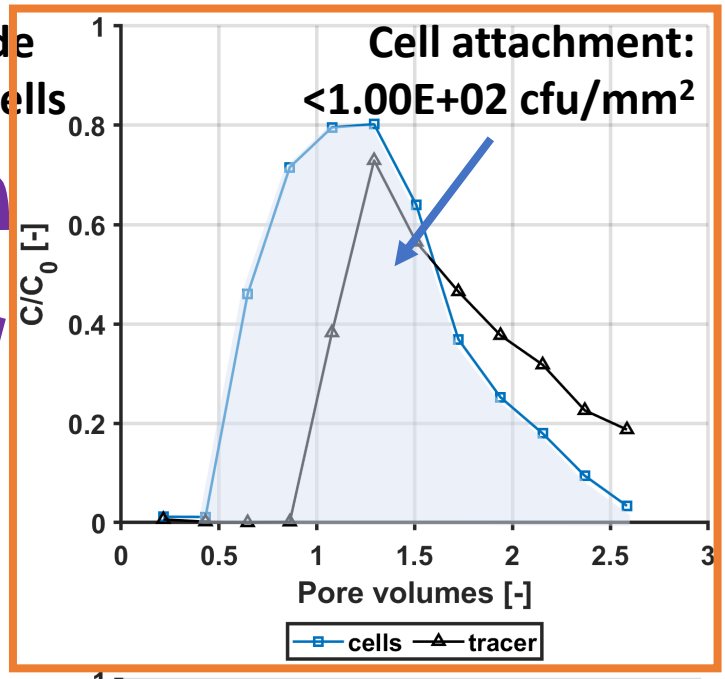

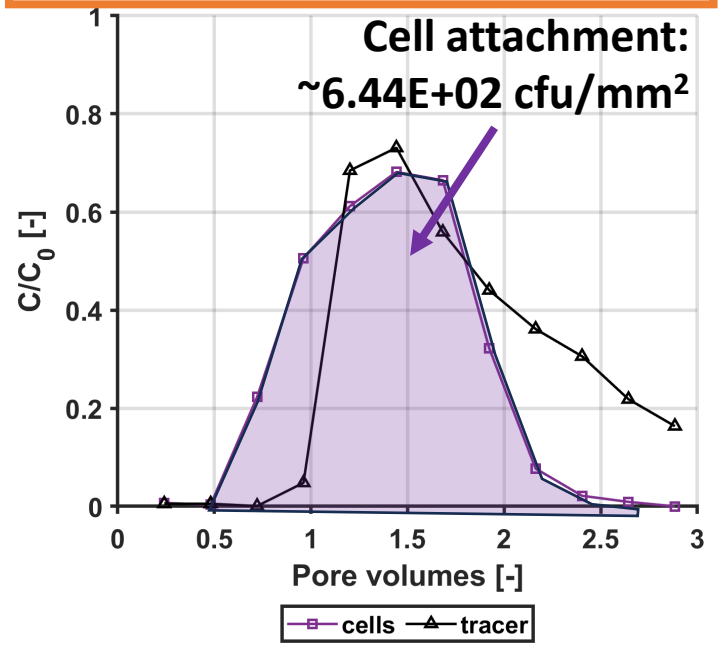

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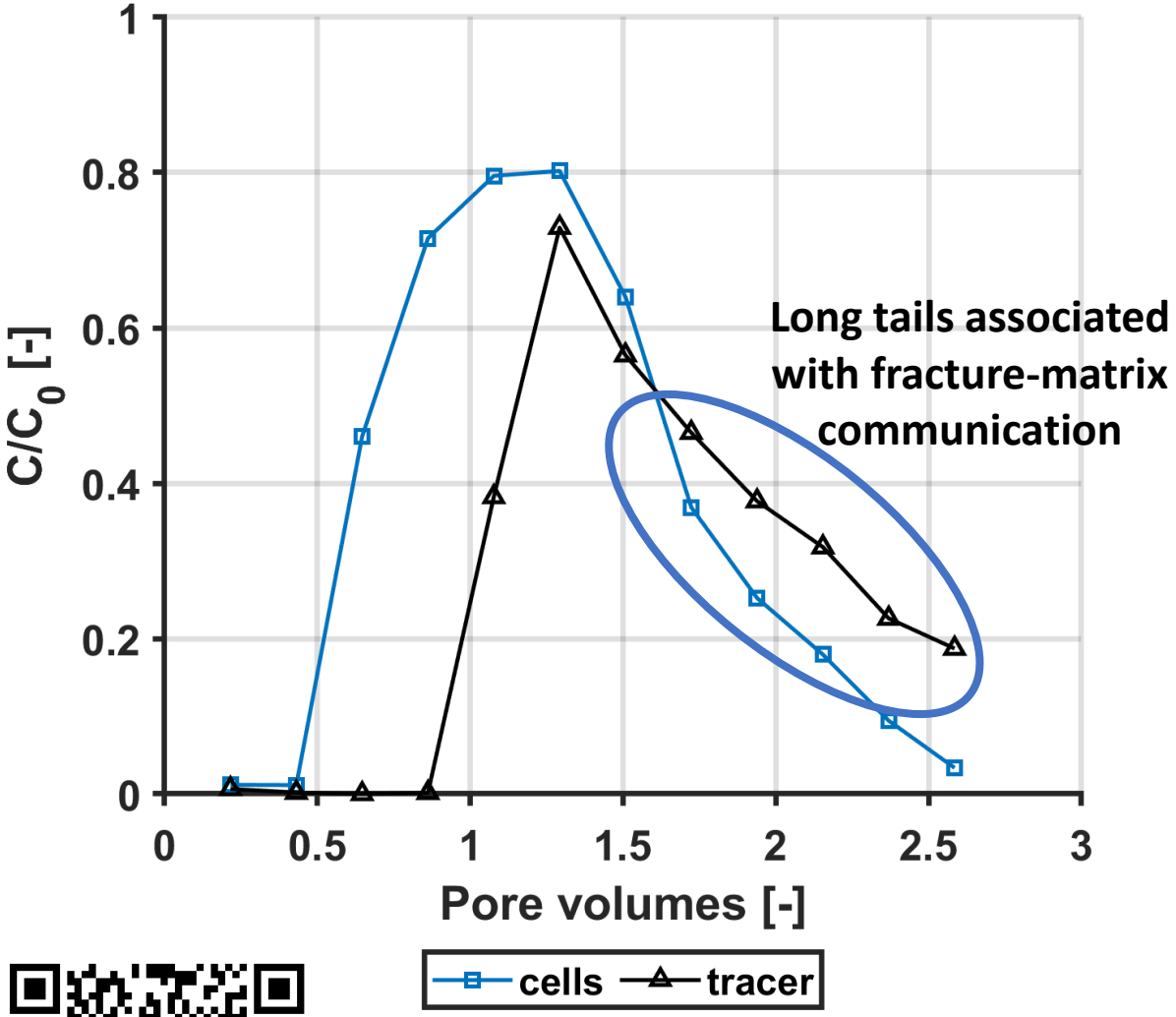
Pore structure controls microbial access to rock interiors



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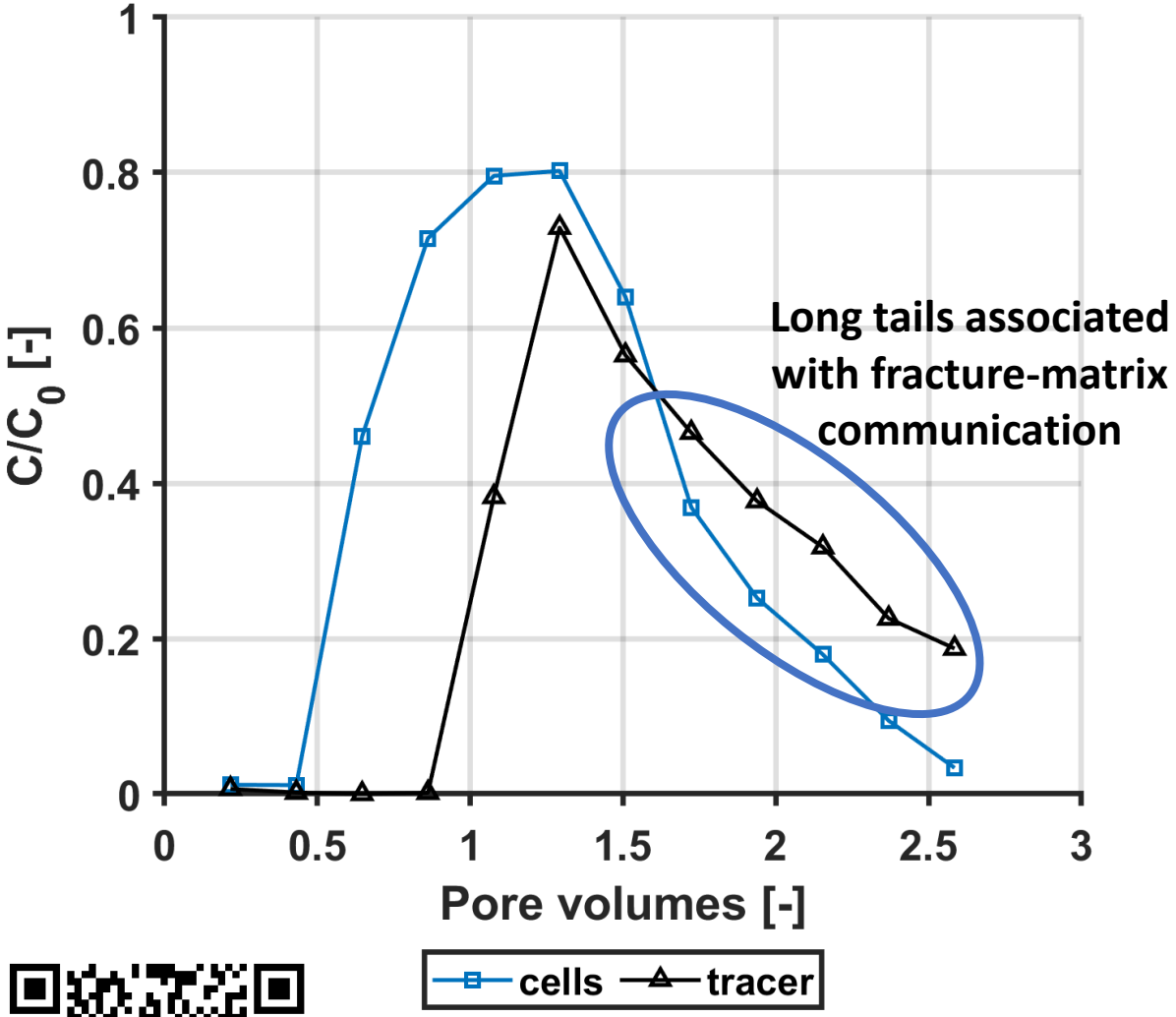

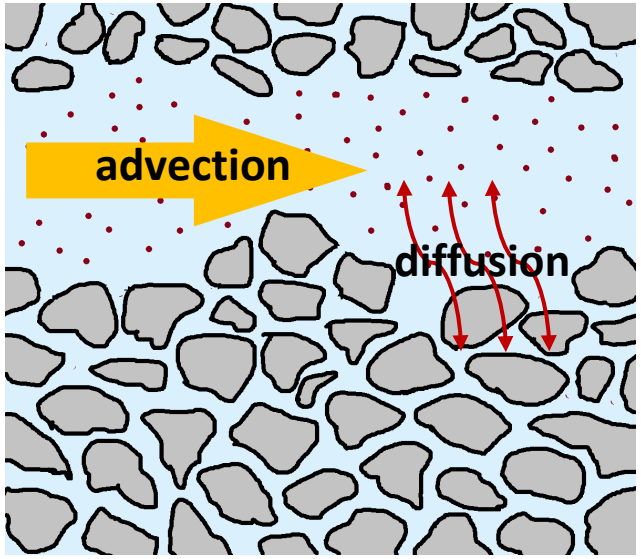

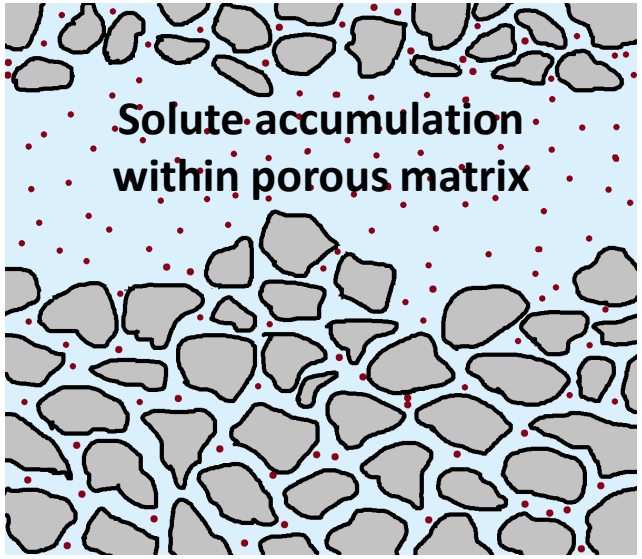

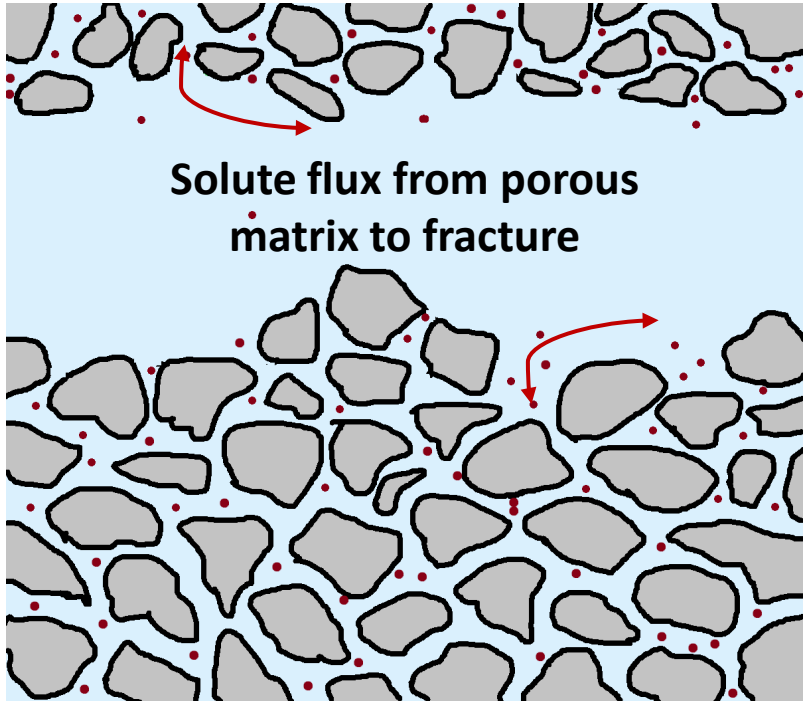

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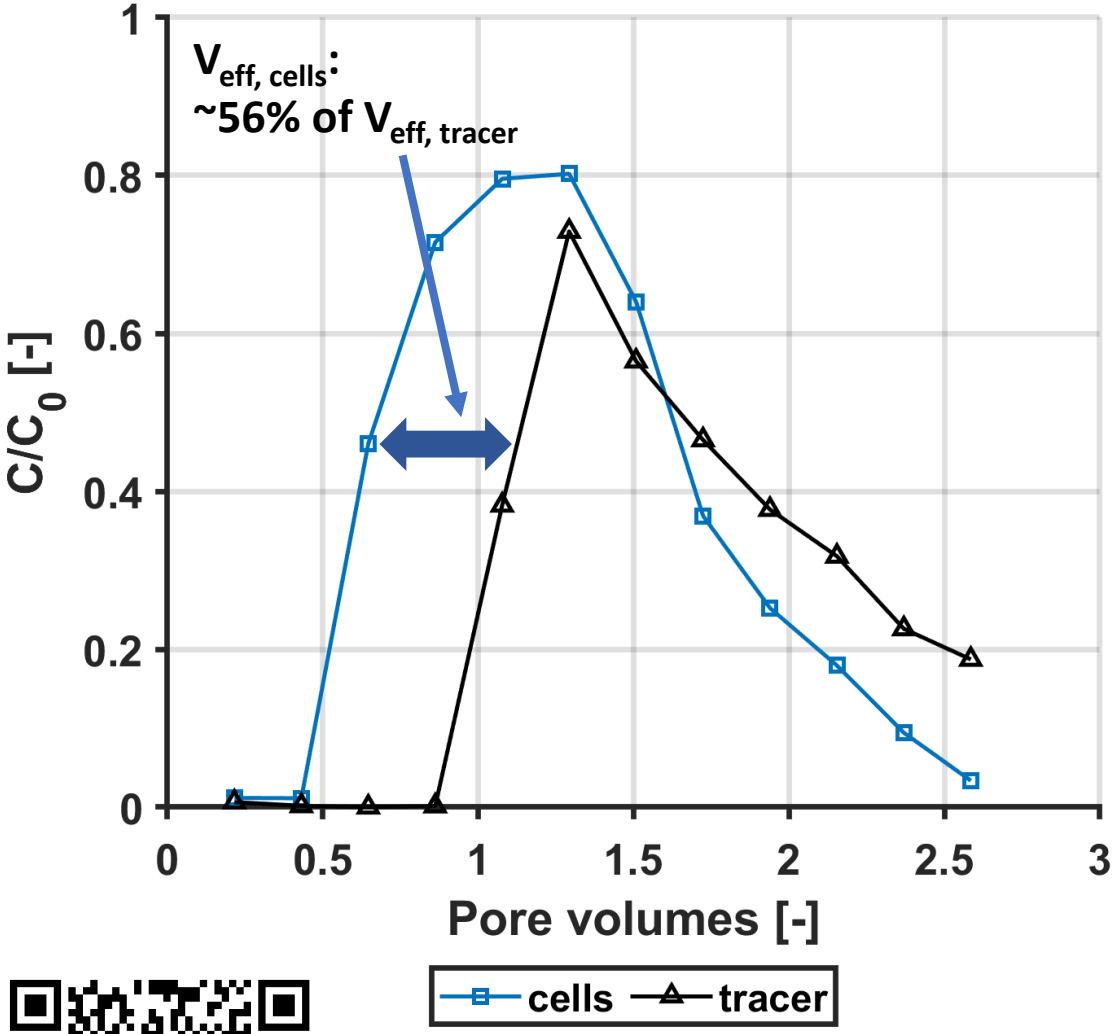

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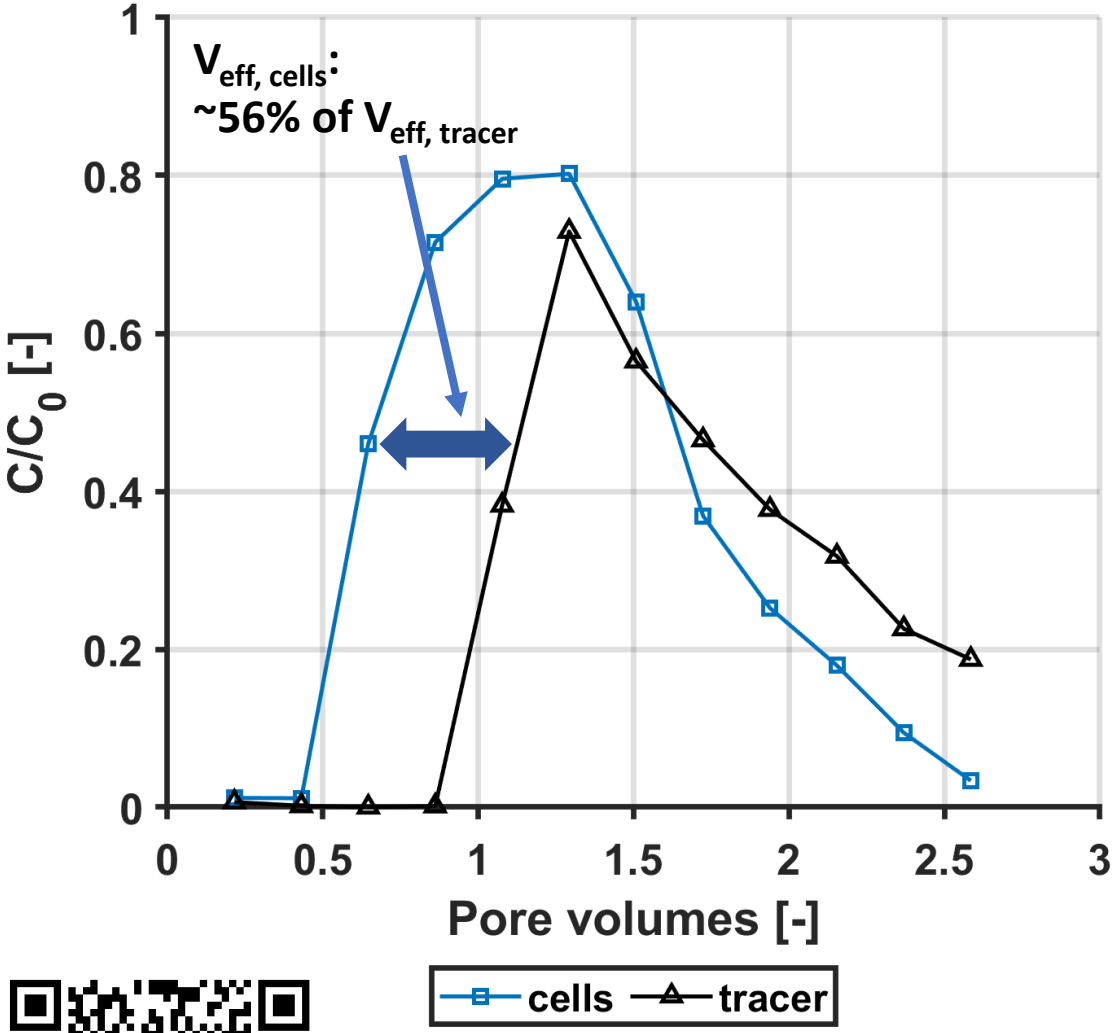

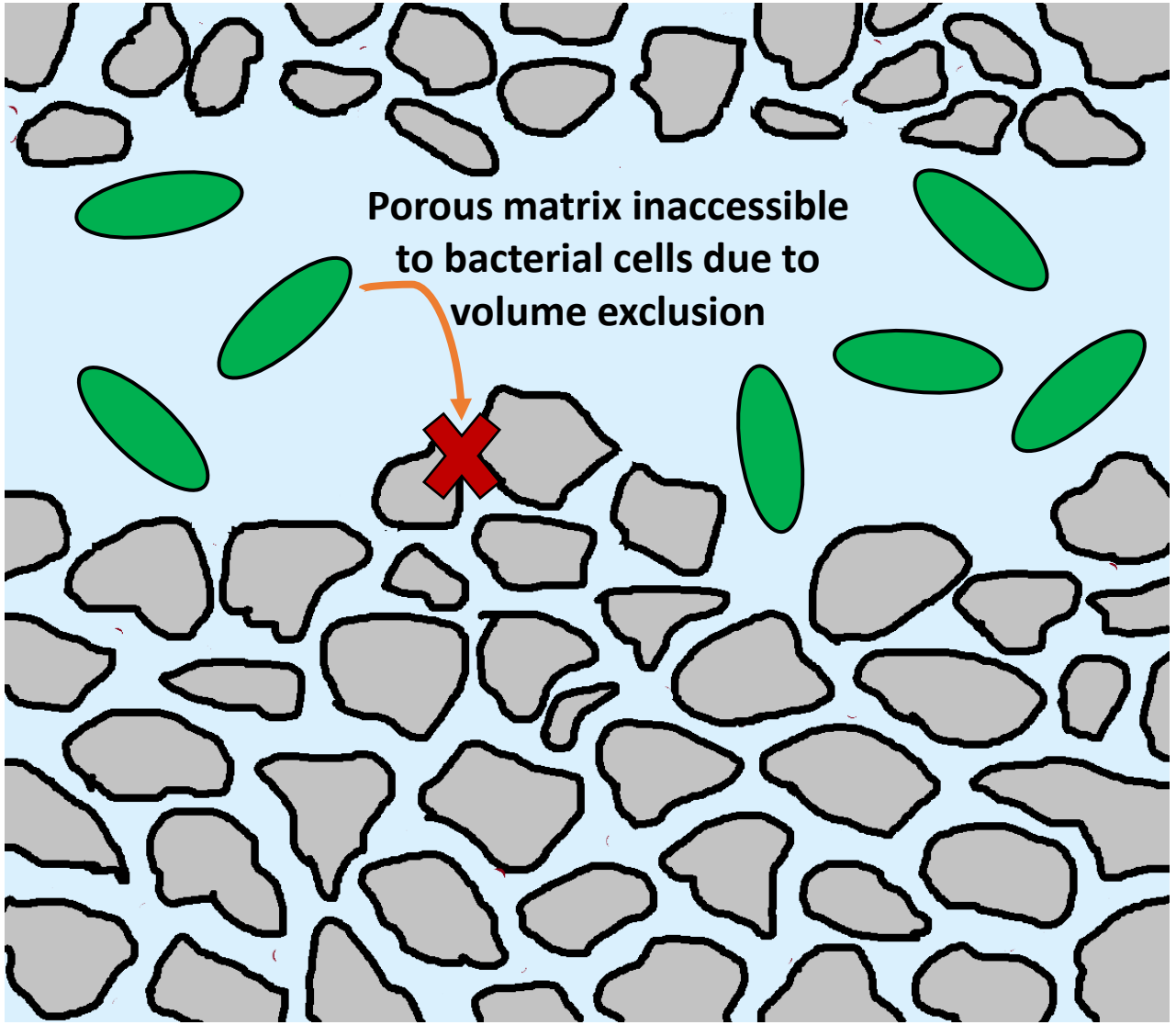

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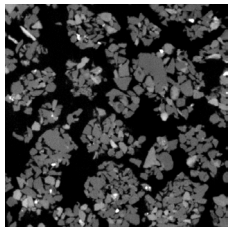

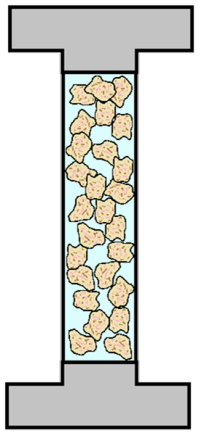

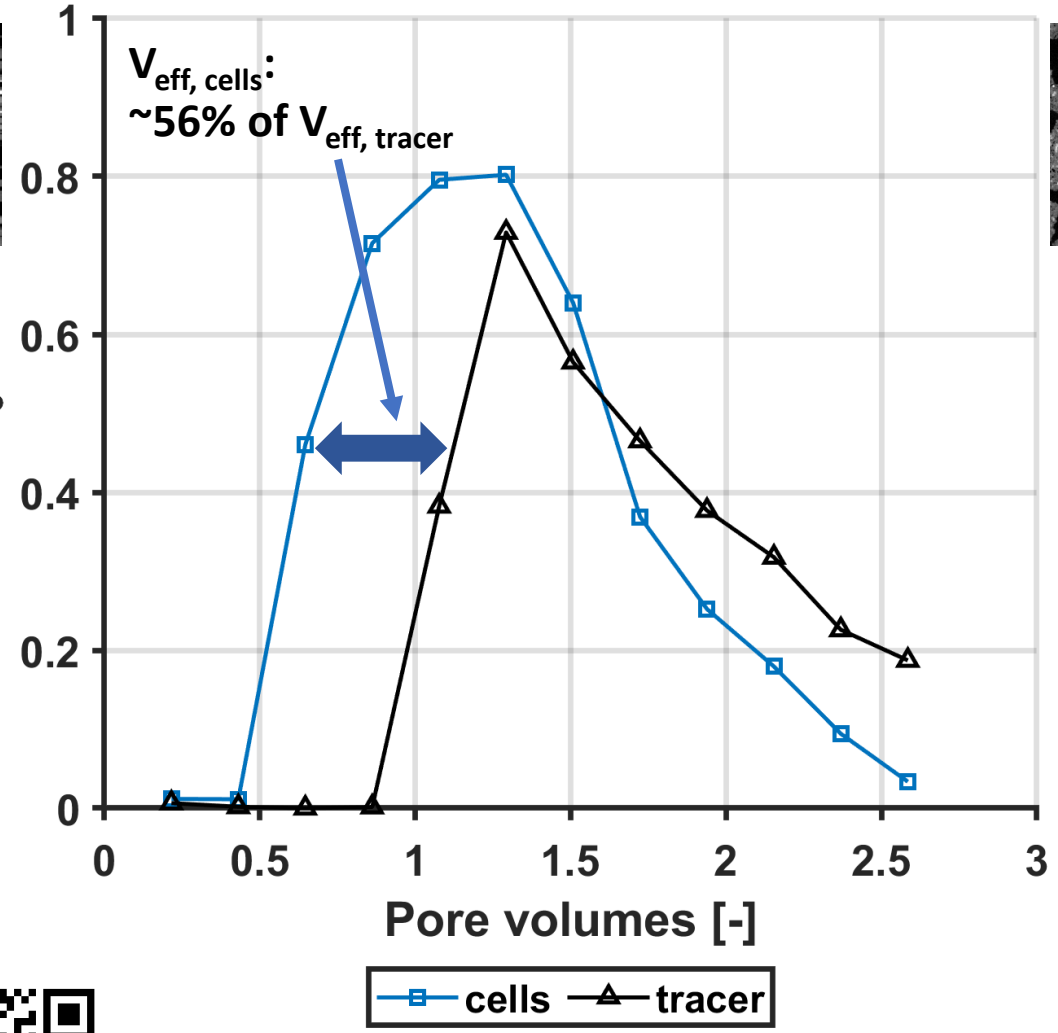

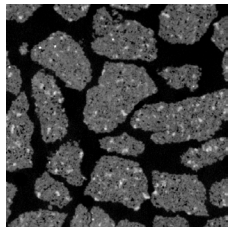

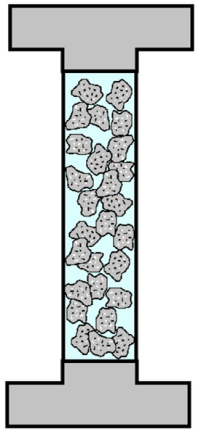

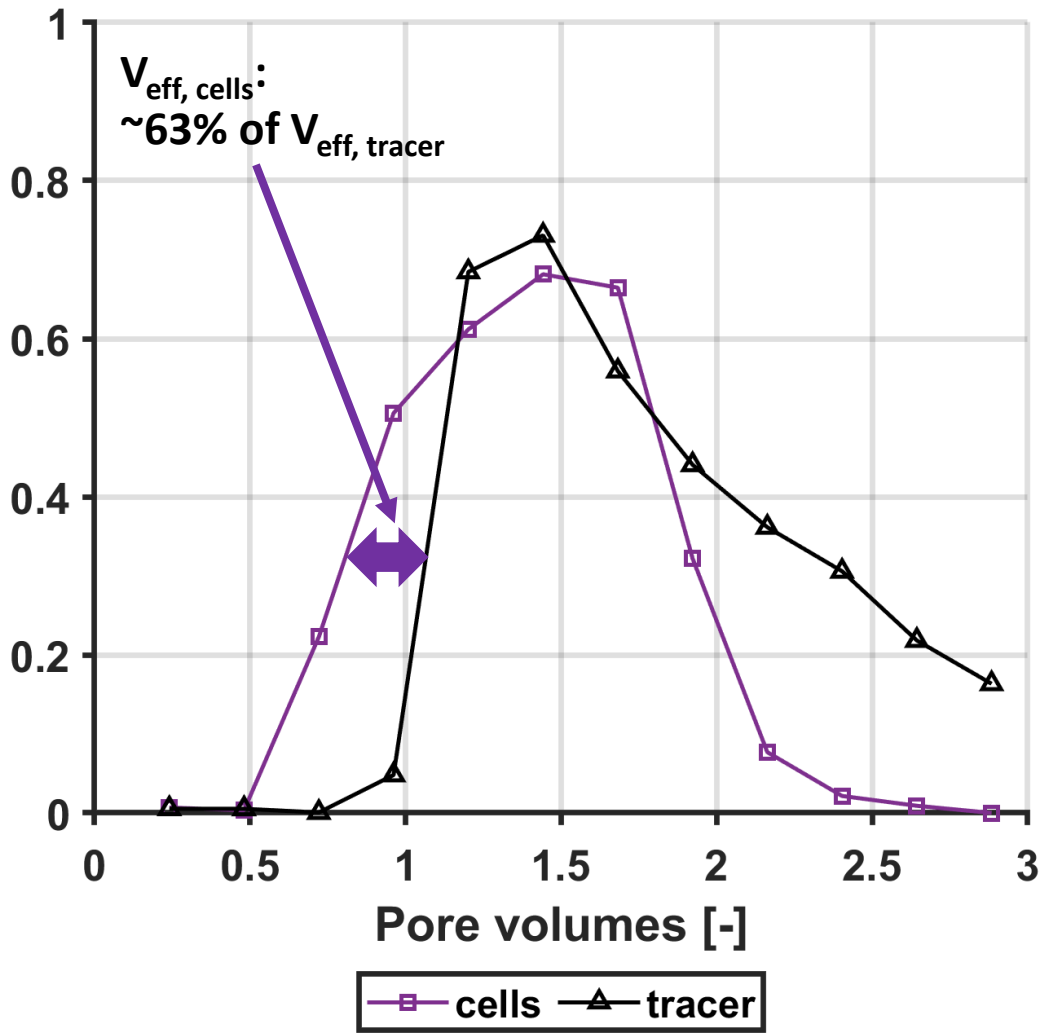

→Rock type influences not only cell affinity for surfaces, but also whether cells can access intra-grain porosity.

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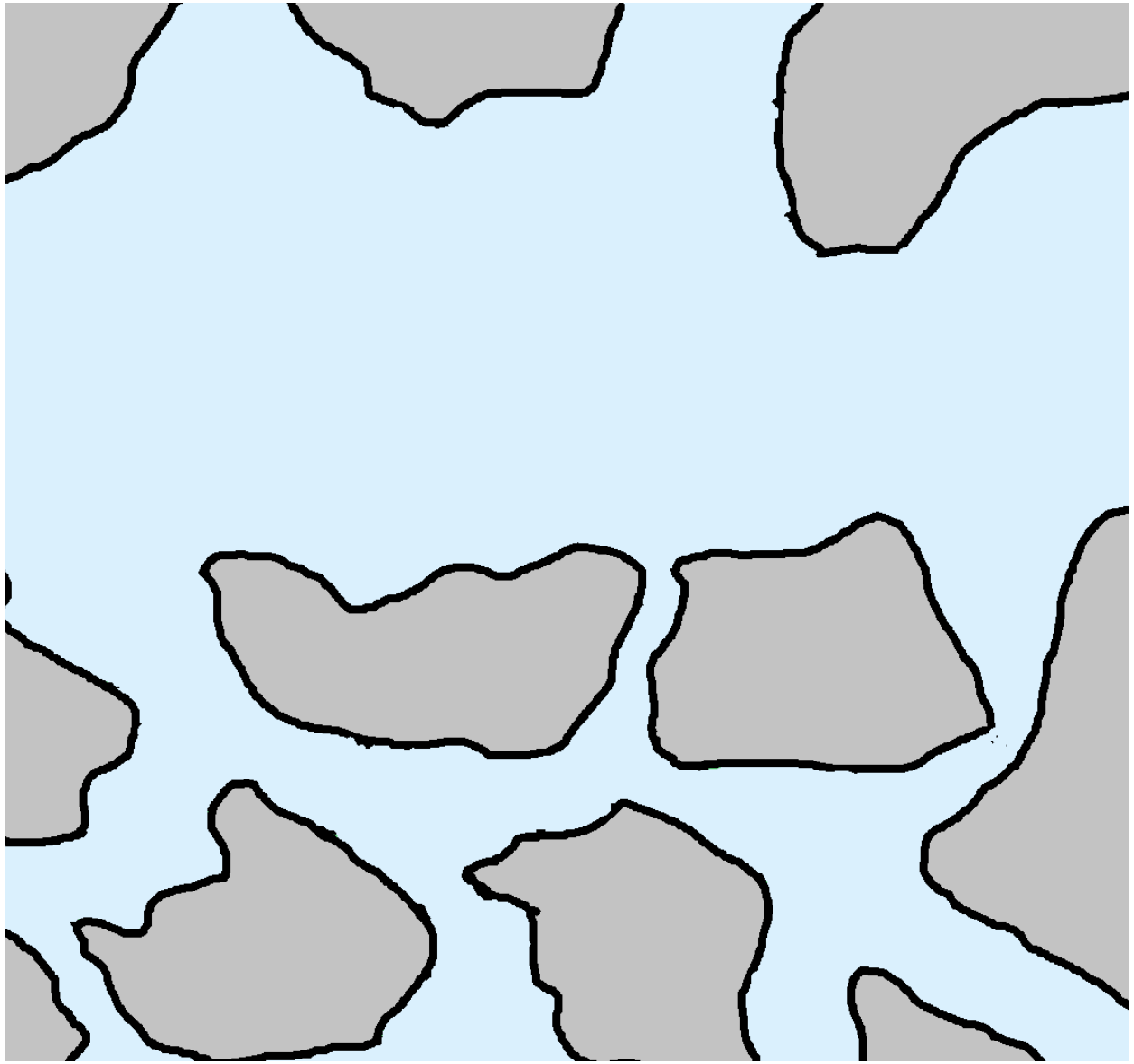
Shear stress and nutrient availability control biofilm density



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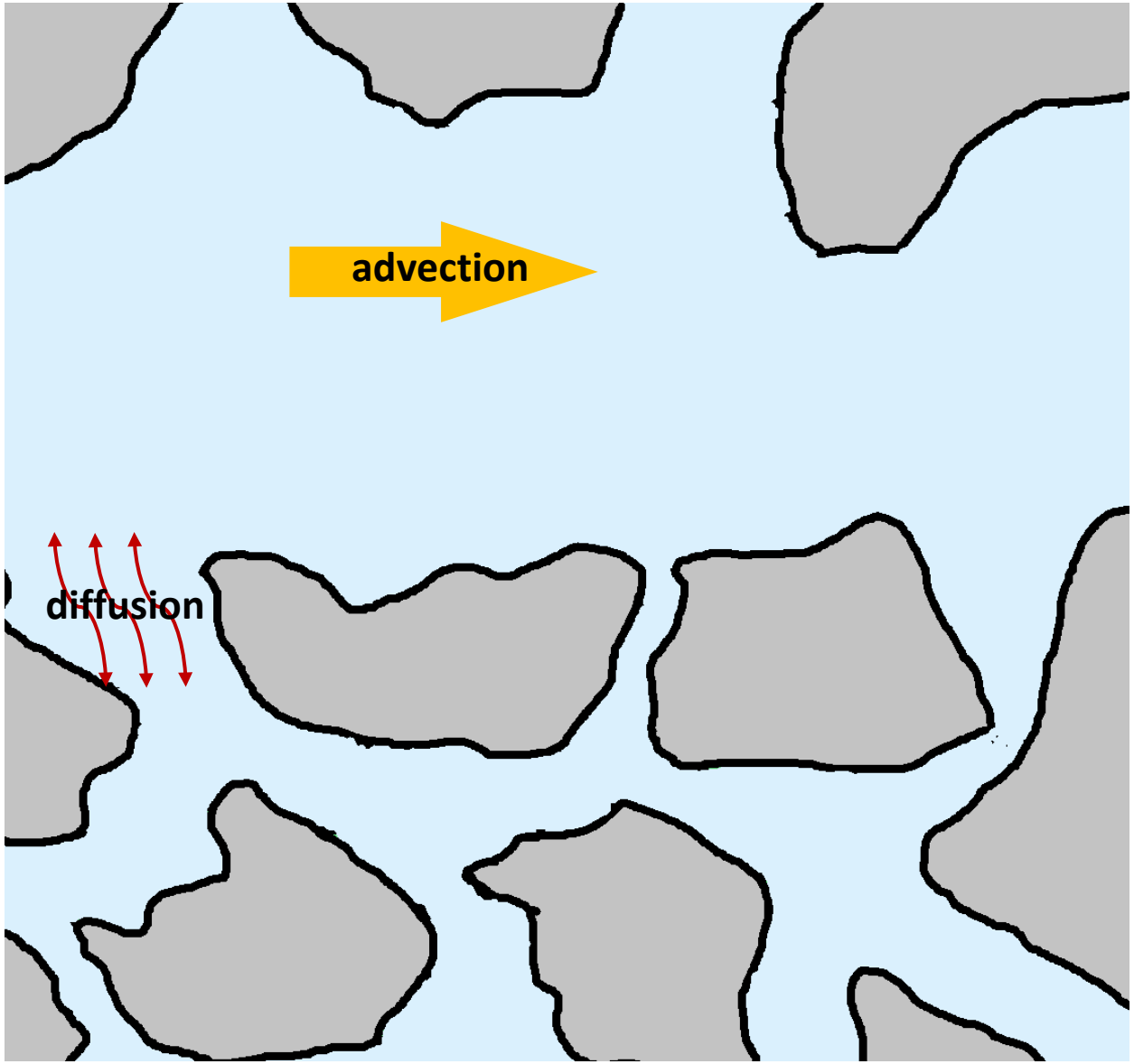

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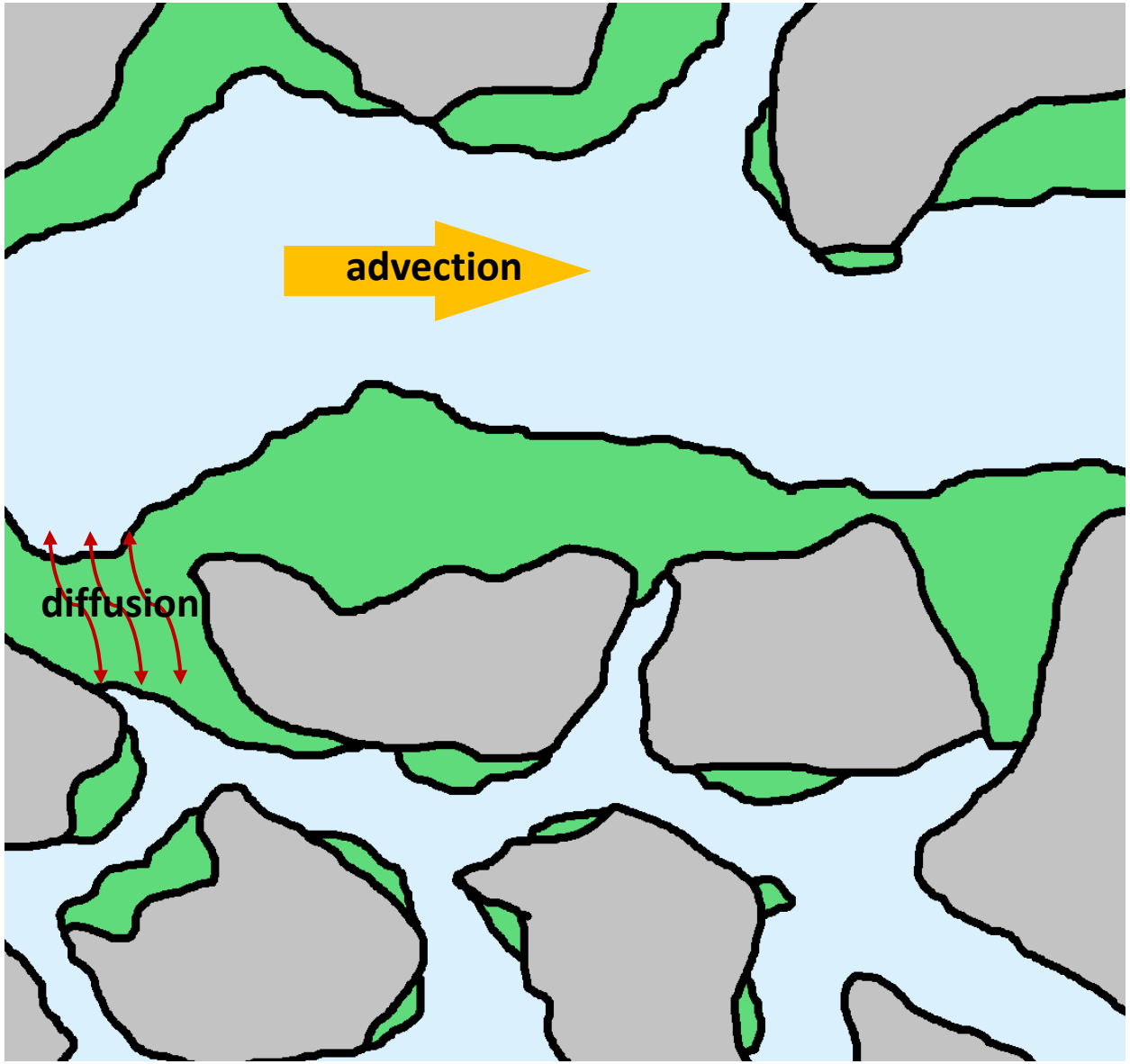

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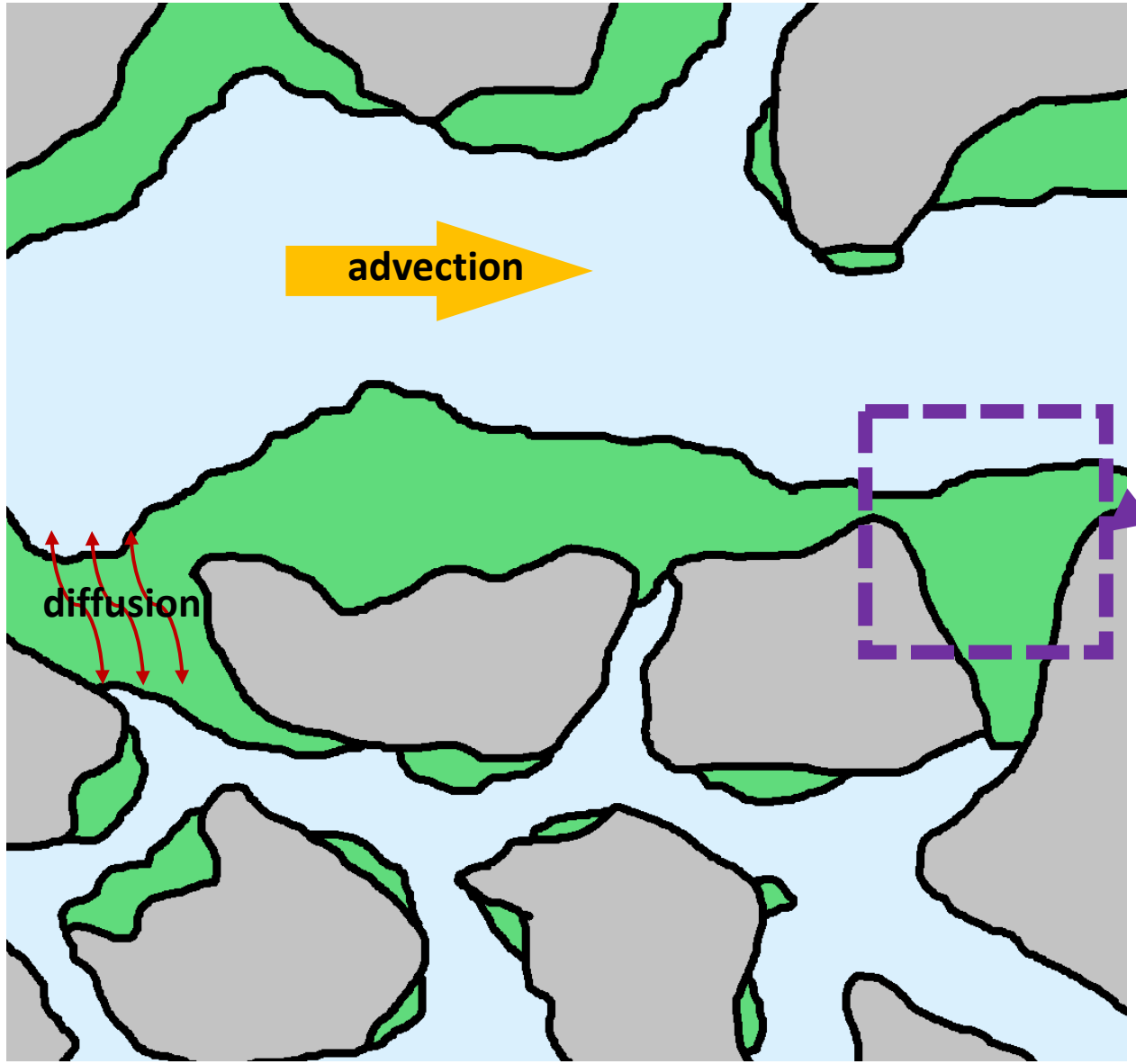
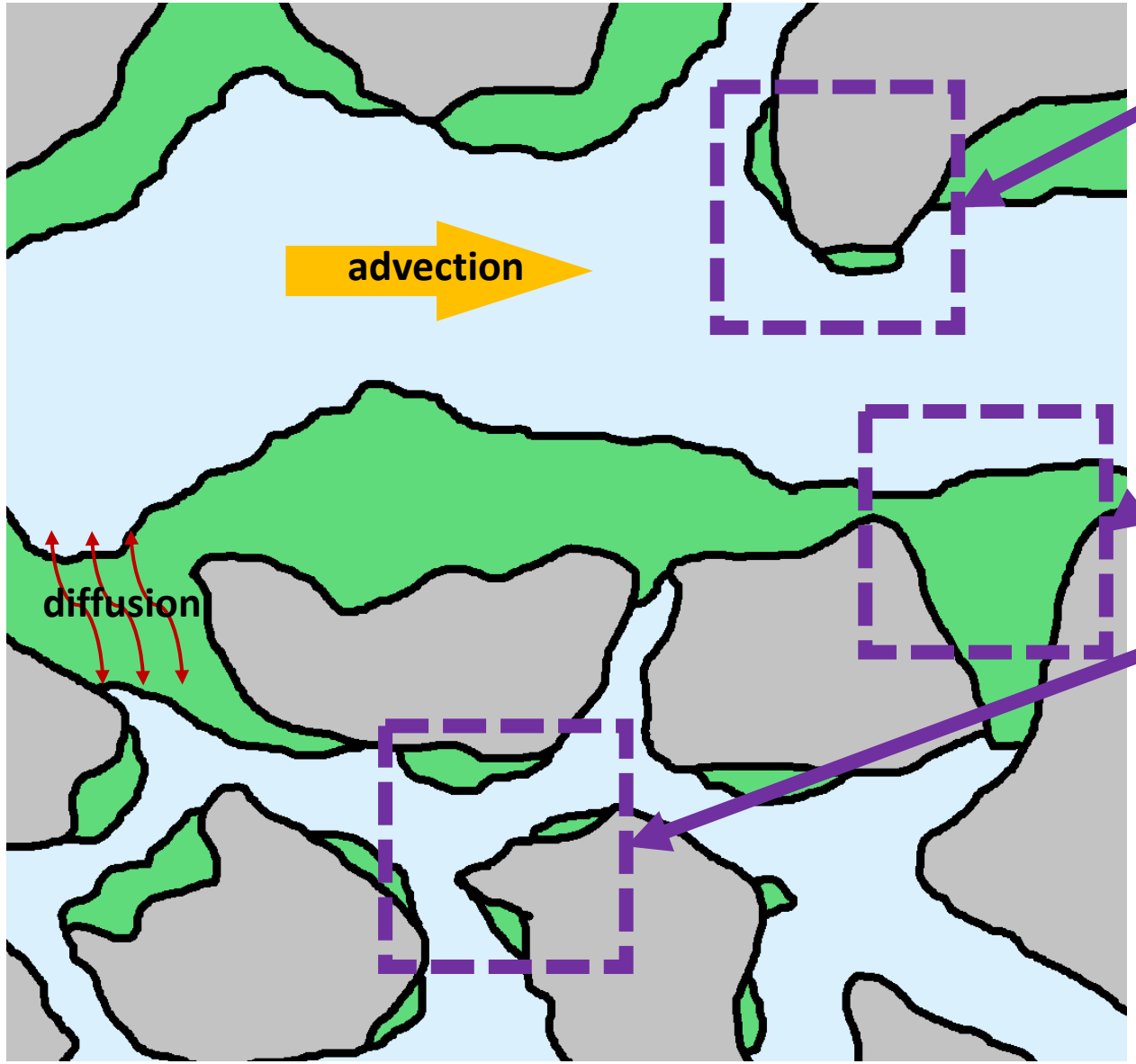


Optimal growth conditions

Shear stress and nutrient availability control biofilm density

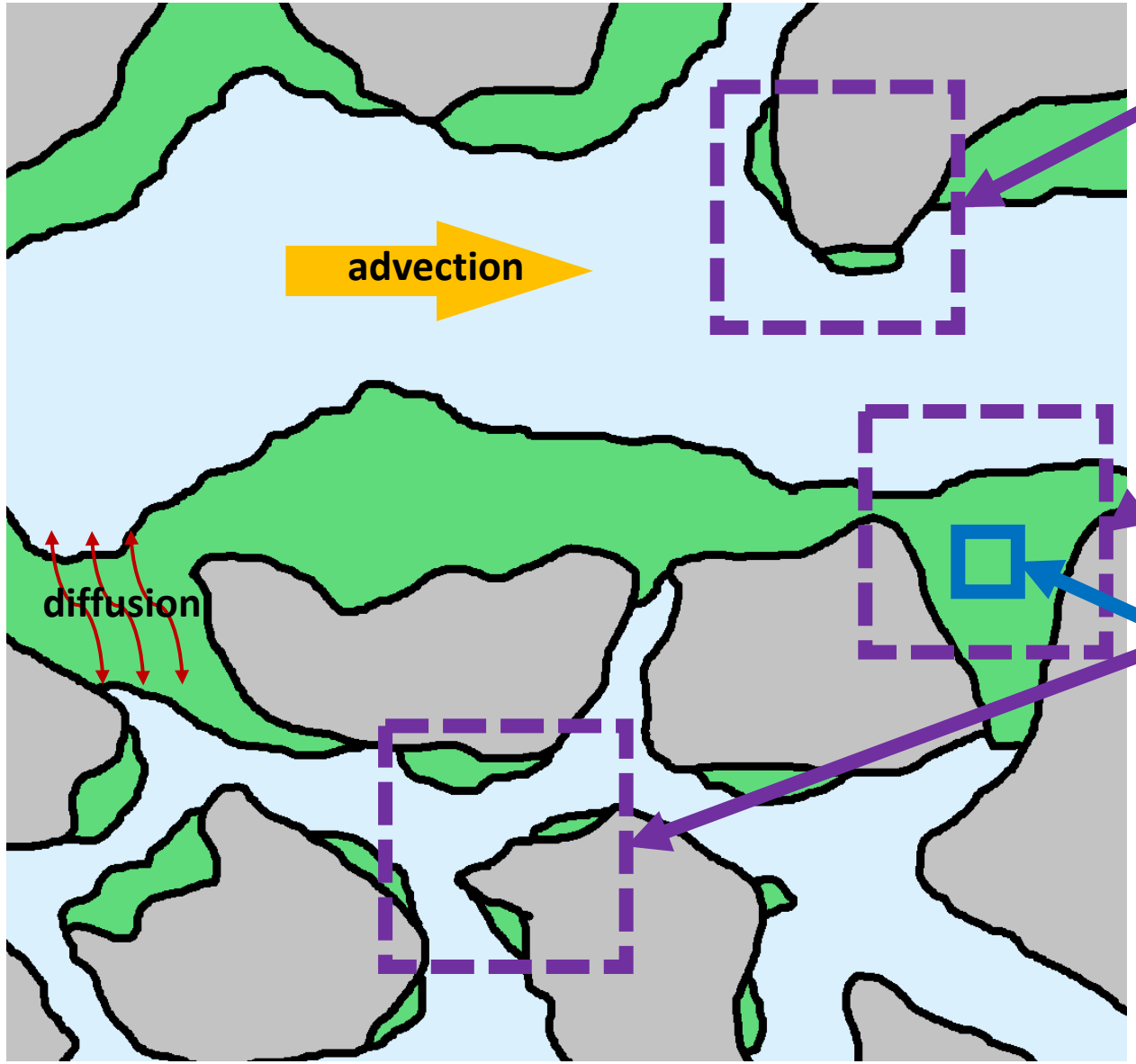


Abundant nutrients, but high shear stress

Optimal growth conditions

Low shear stress, but also low nutrients

Shear stress and nutrient availability control biofilm density

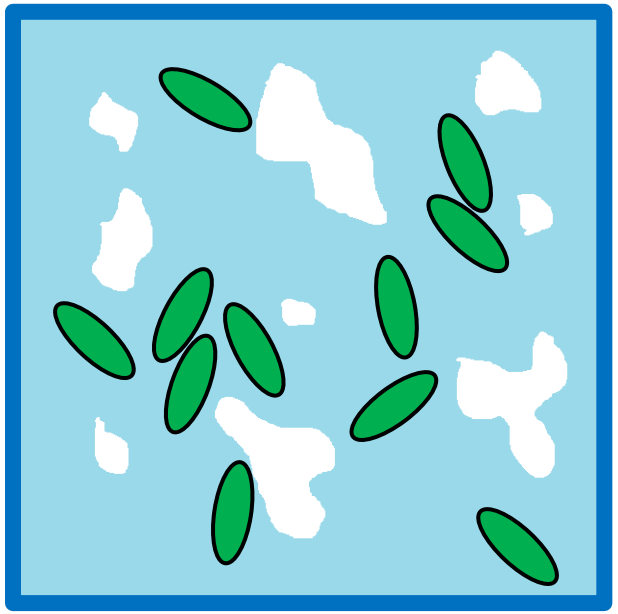


Abundant nutrients, but high shear stress

Optimal growth conditions

Low shear stress, but also low nutrients

Variation in the spatial arrangement of cells, EPS, and void space within the biofilm



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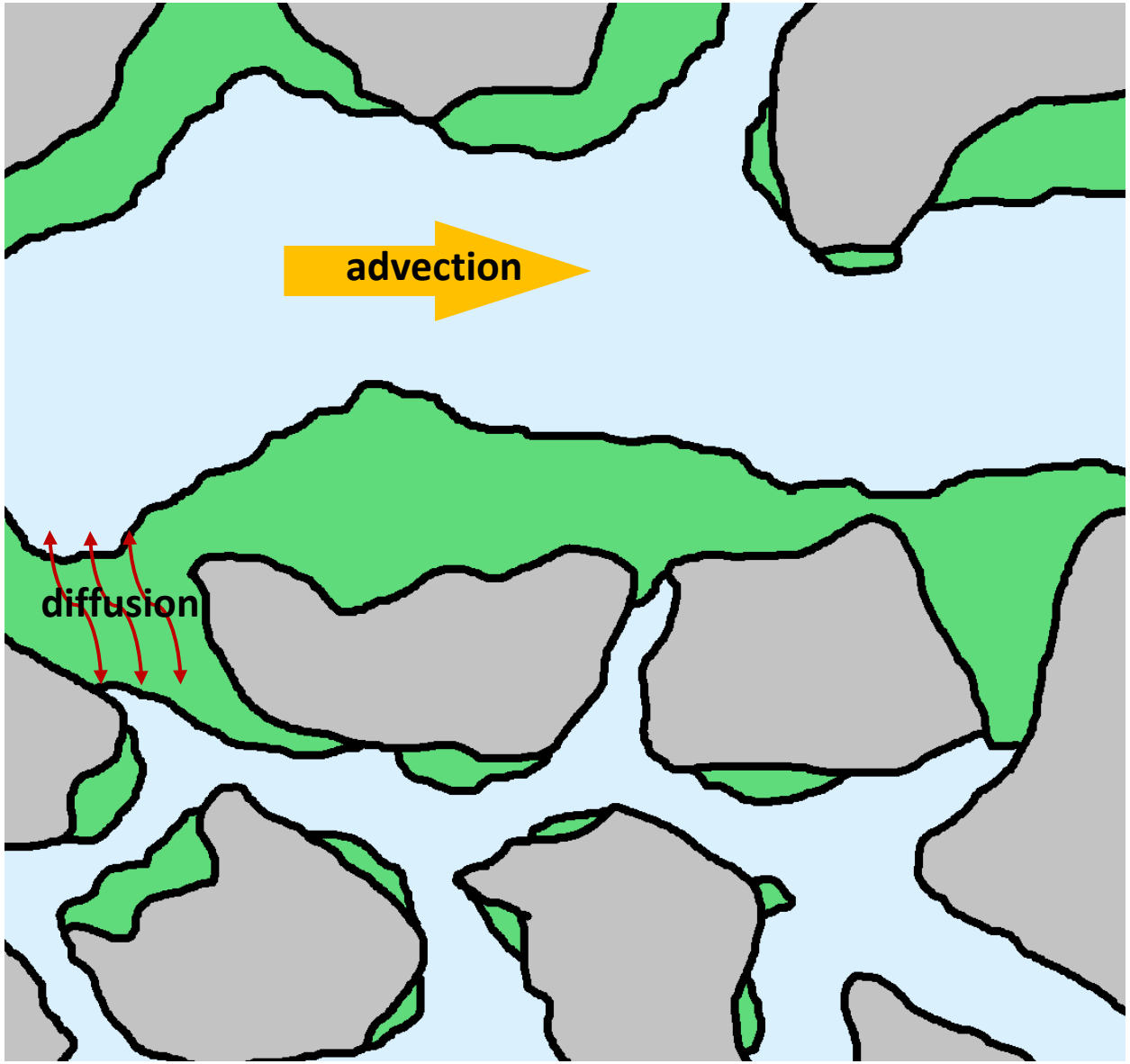
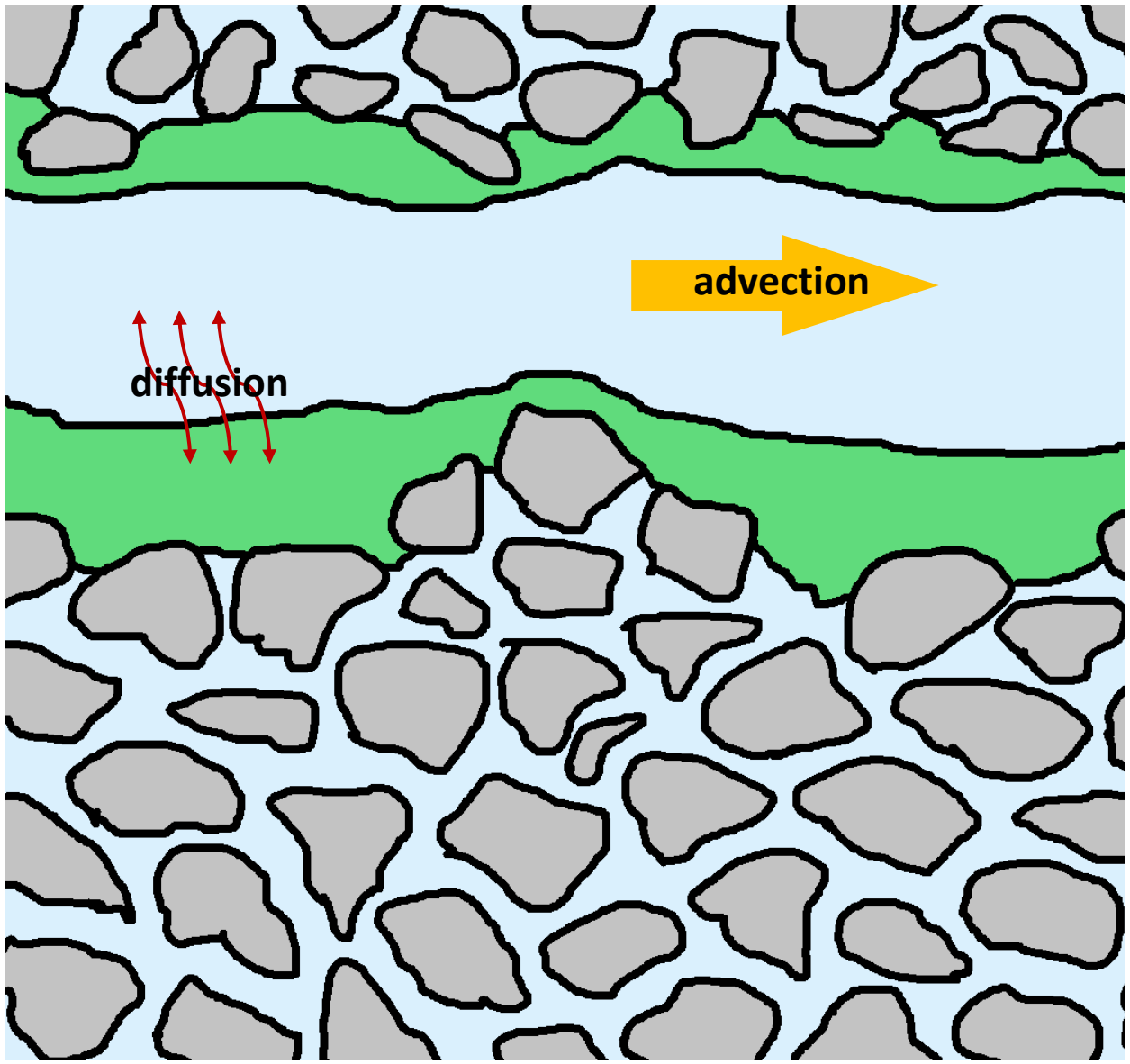
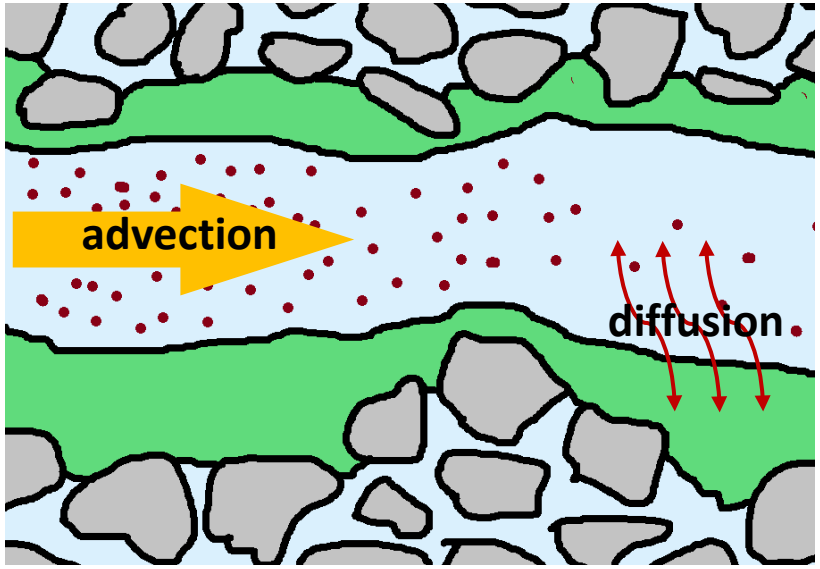


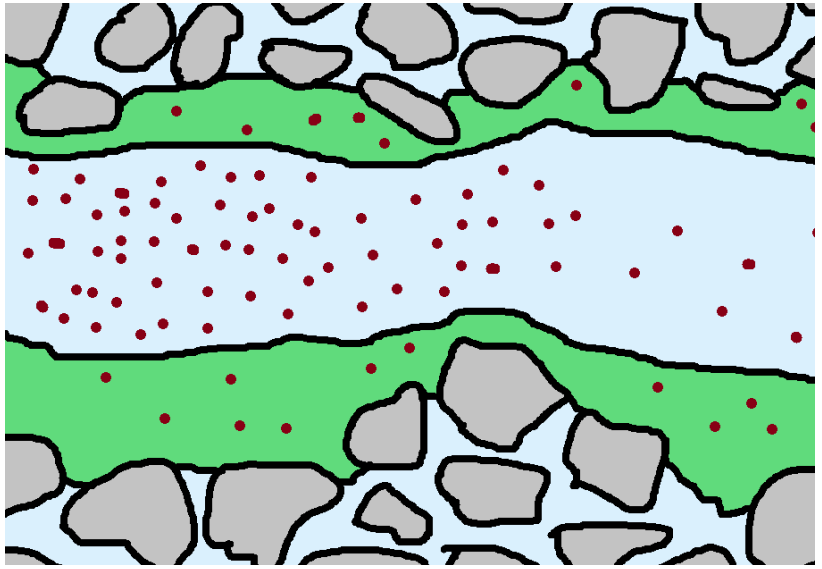


→**The structure of the porous matrix likely influences biofilm development**

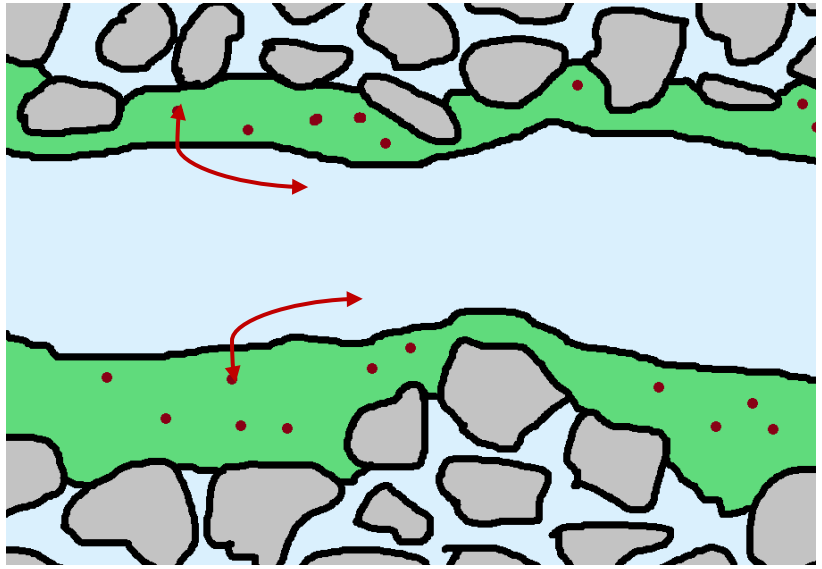
Biofilm density also mediates solute transport



Net flux of solute into biofilm

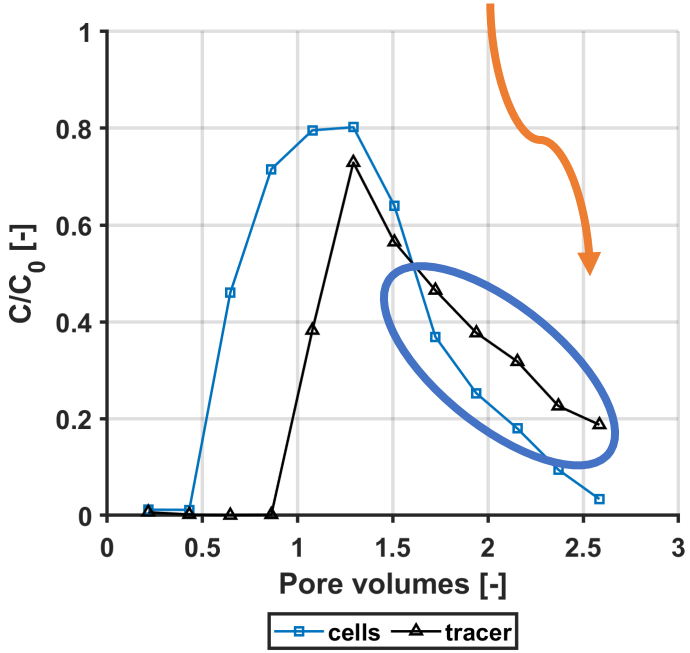


Solute accumulation within biofilm

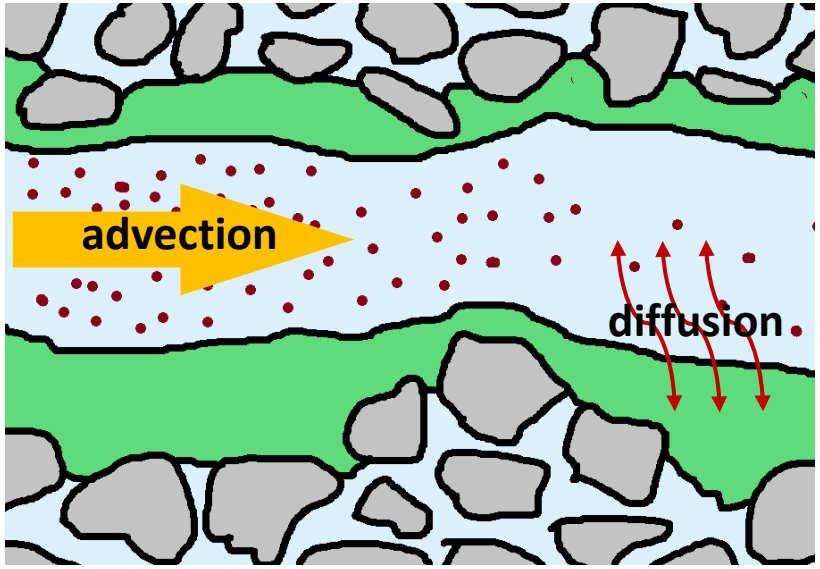


Net flux of solute into fracture

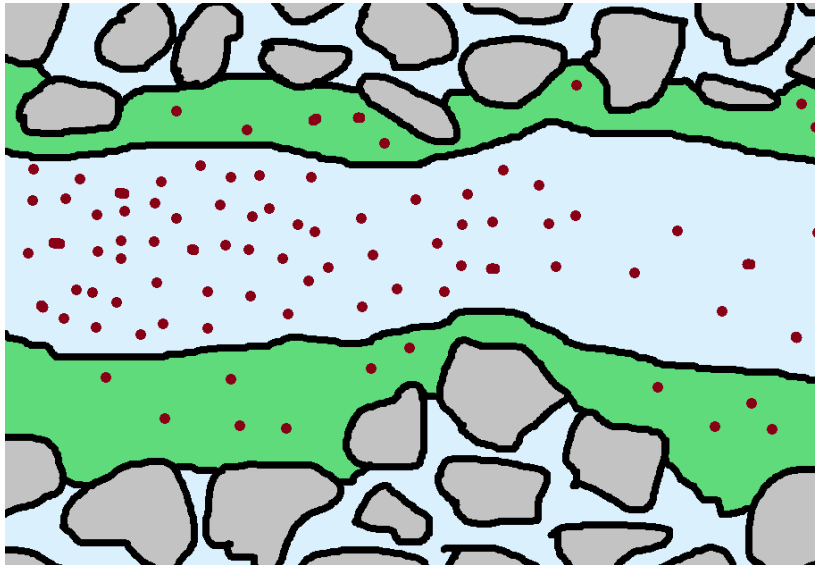
→Biofilms can enhance or dampen anomalous transport behaviors



Biofilm density also mediates solute transport



Net flux of solute into biofilm



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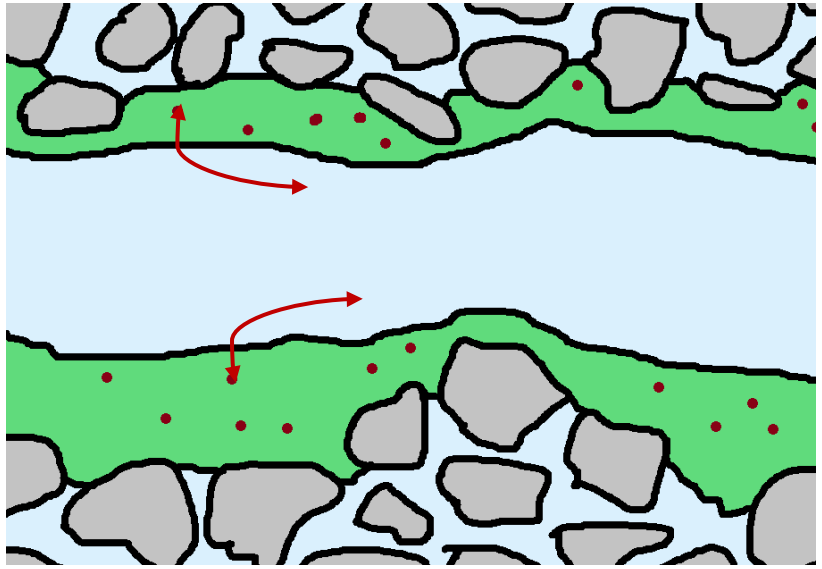
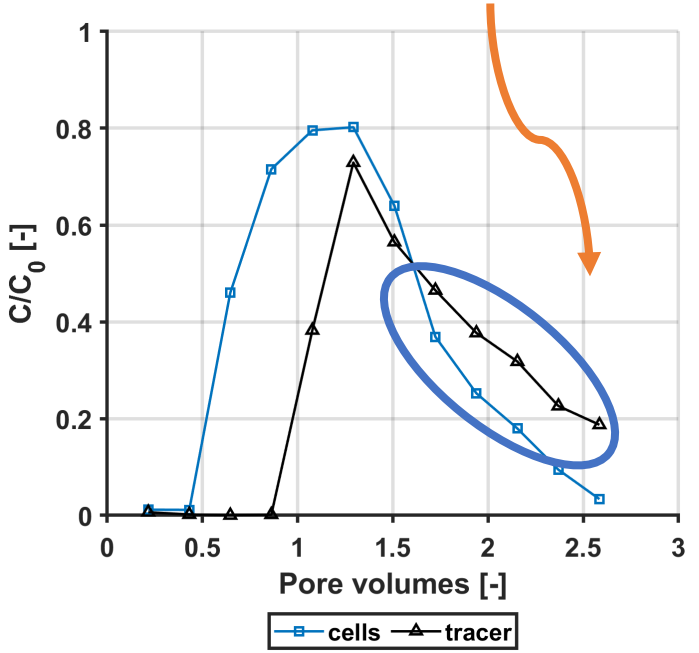


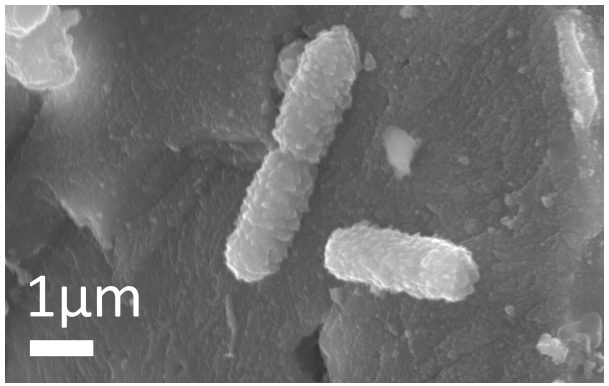
Net flux of solute into fracture

→Biofilms can enhance or dampen anomalous transport behaviors

→Solute transport within biofilms is also important for biofilm-induced chemical reactions

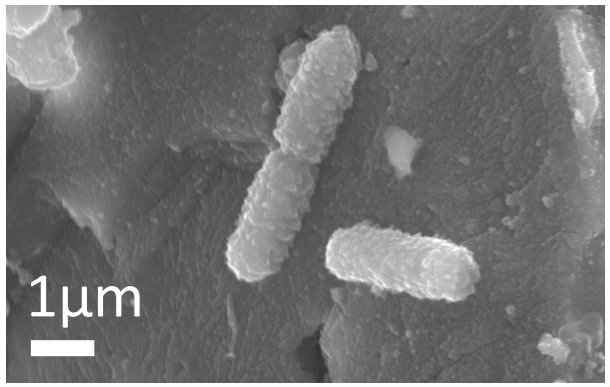


Biofilm density also mediates solute transport

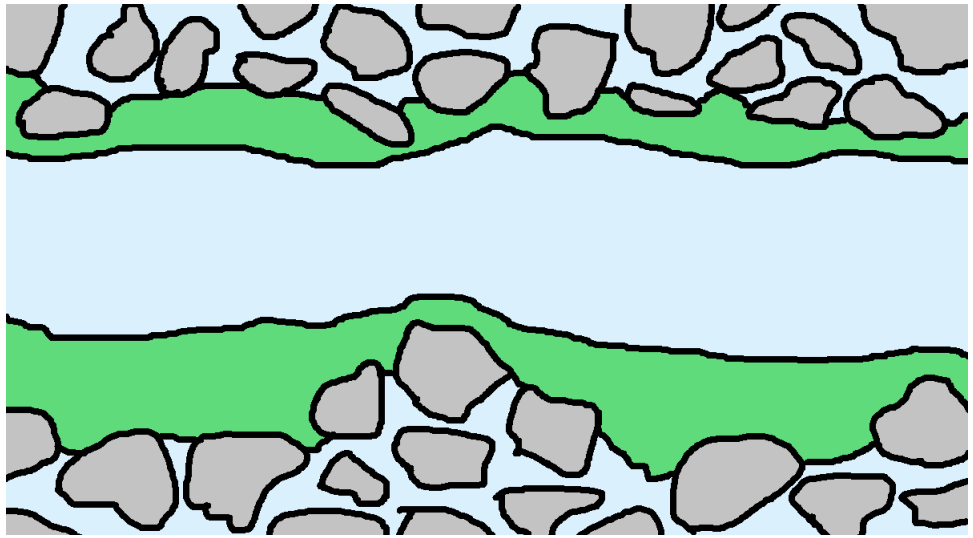


Microbial carbonate precipitation processes self-limit through “encapsulation”

Biofilm density also mediates solute transport

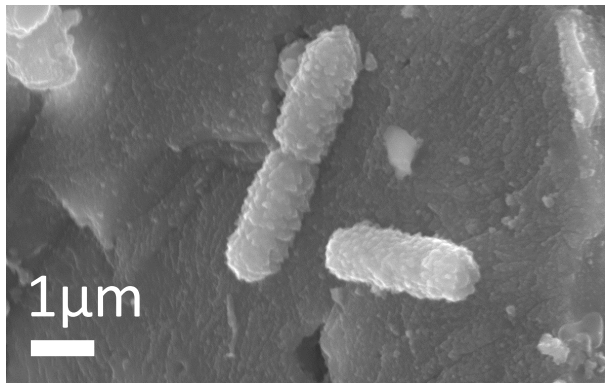


Microbial carbonate precipitation processes self-limit through “encapsulation”

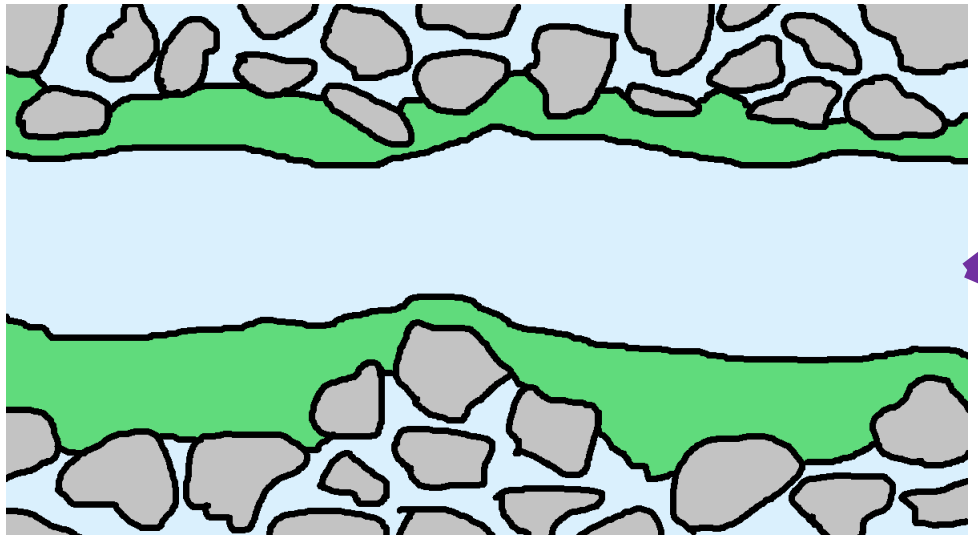


Carbonate-precipitating biofilm

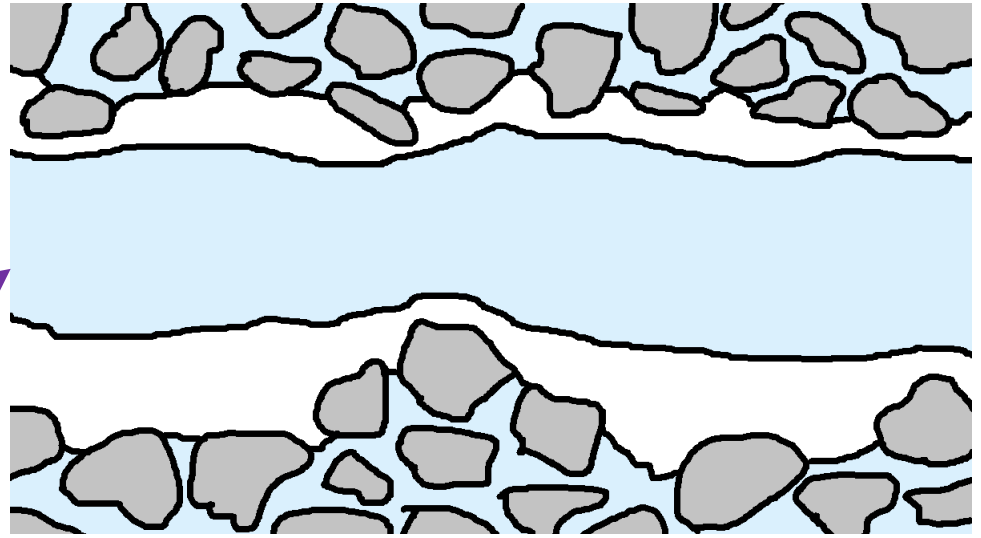
Biofilm density also mediates solute transport



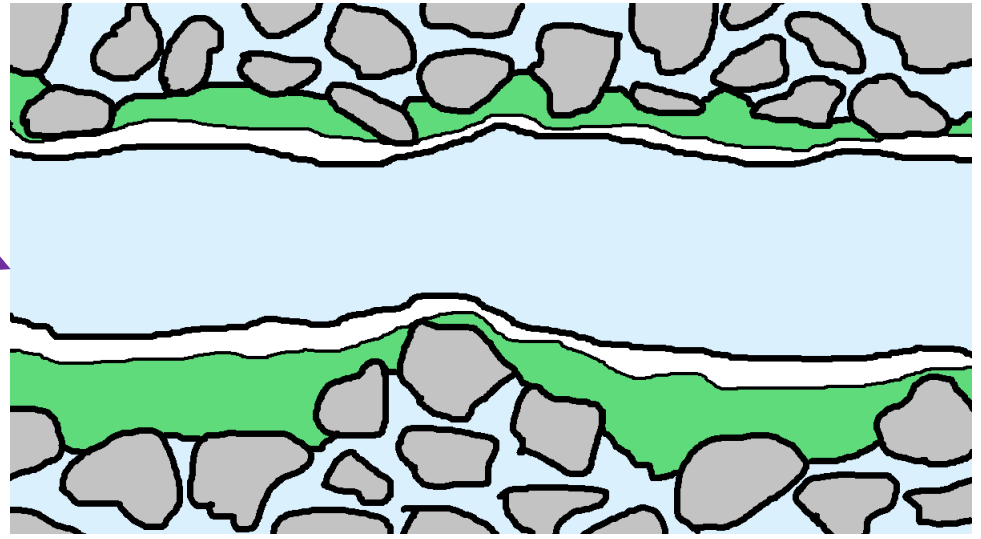
Microbial carbonate precipitation processes self-limit through "encapsulation"



Carbonate-precipitating biofilm



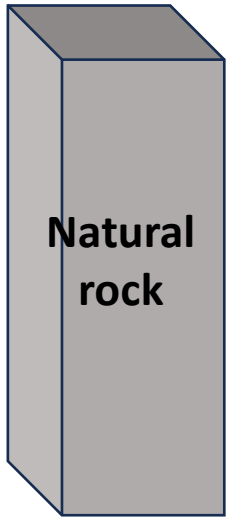
Completely-mineralized biofilm



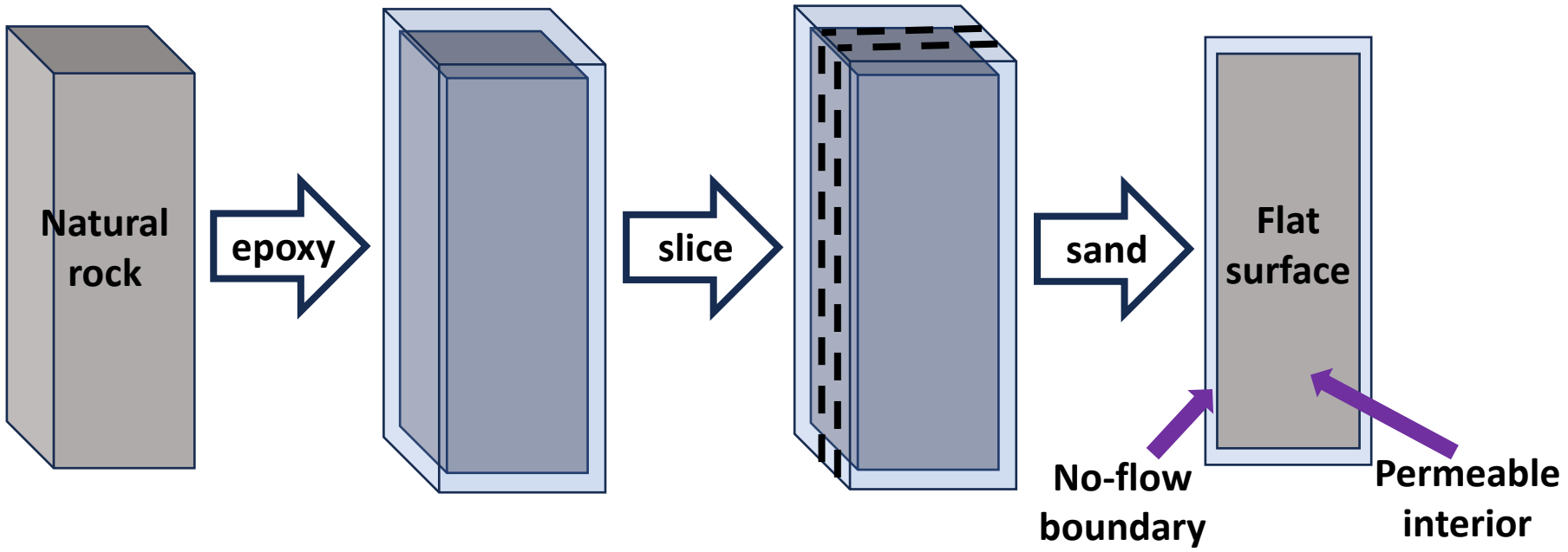
Partially-mineralized biofilm

→Biofilm density may also constrain the spatial extent of precipitate formation

Relating rock properties, biofilm density, and solute transport



Relating rock properties, biofilm density, and solute transport



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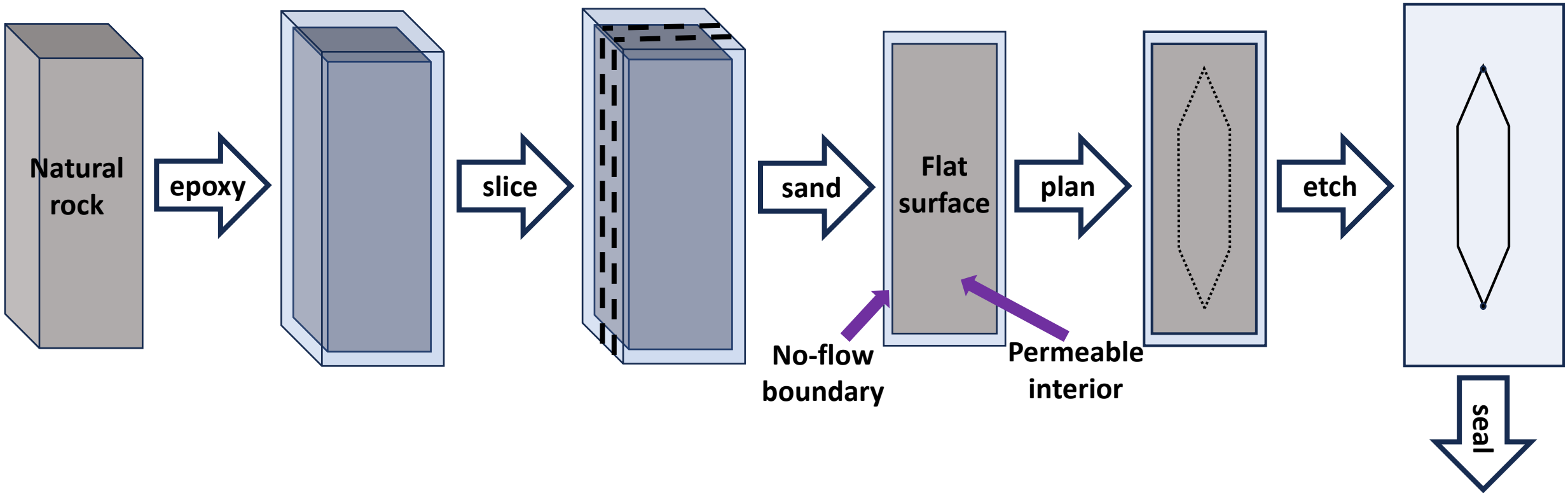
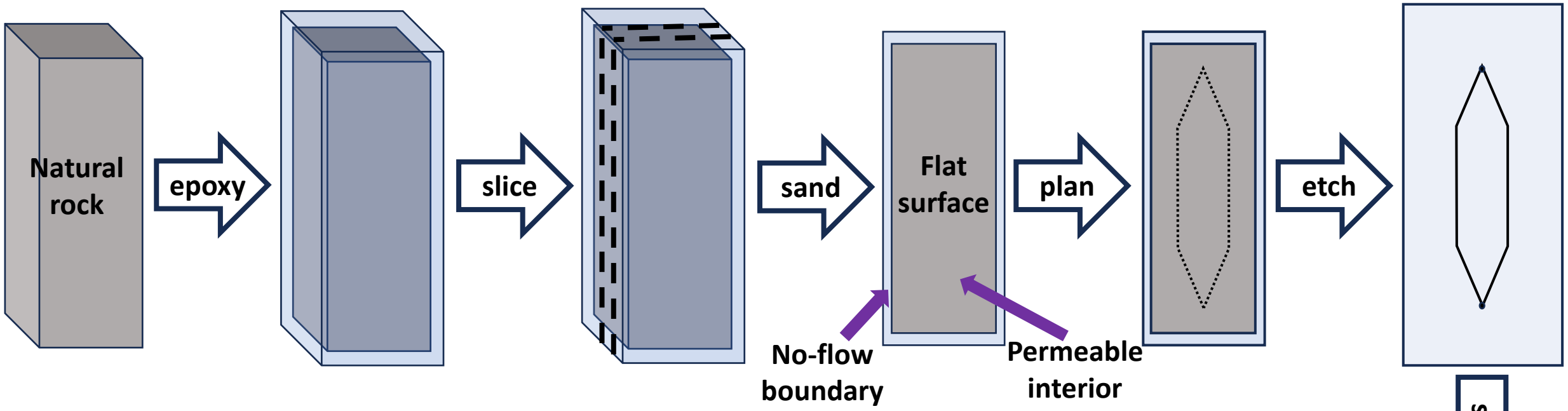
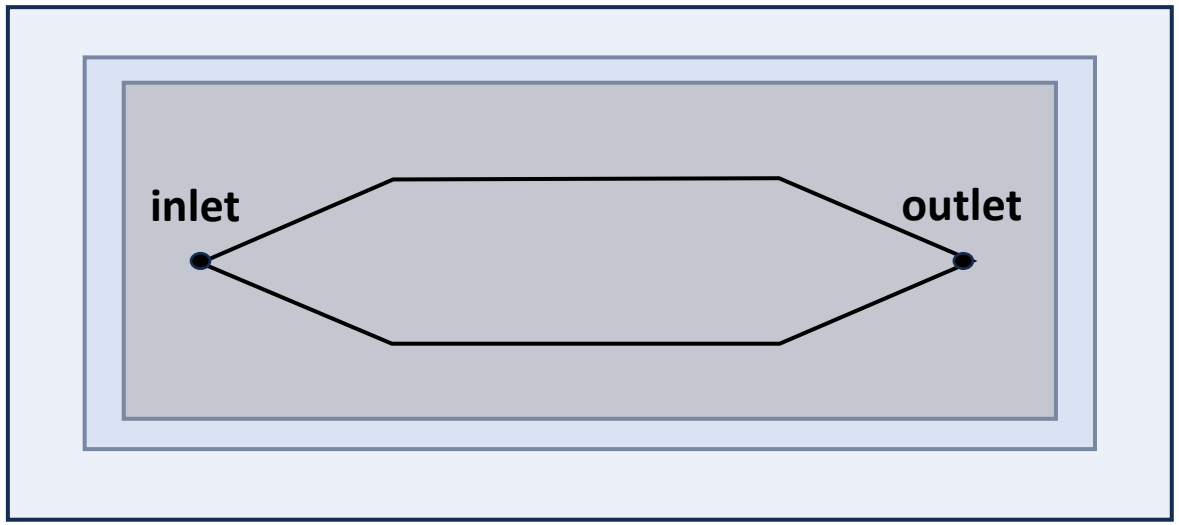
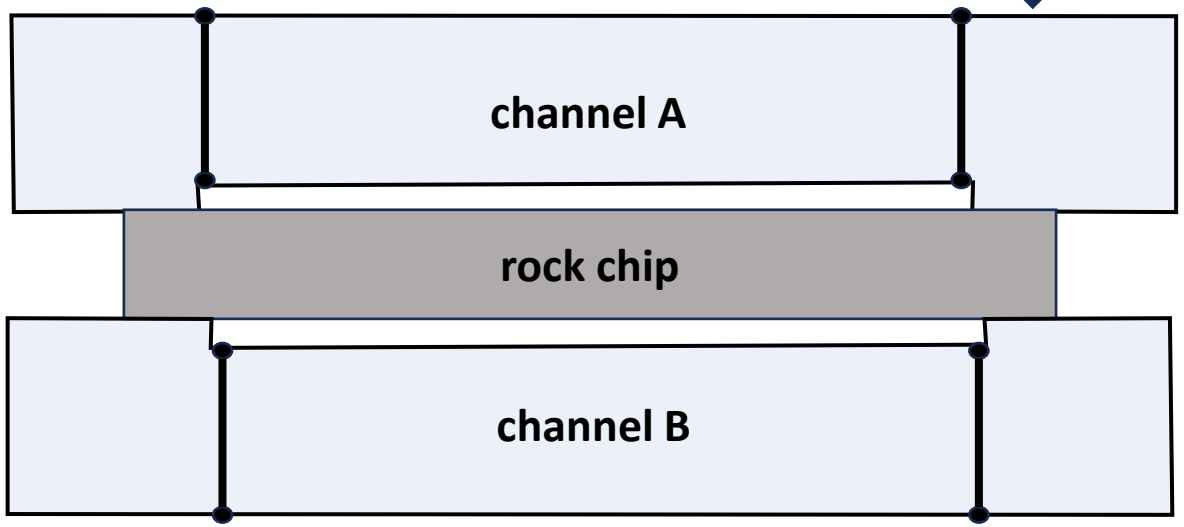


Relating rock properties, biofilm density, and solute transport







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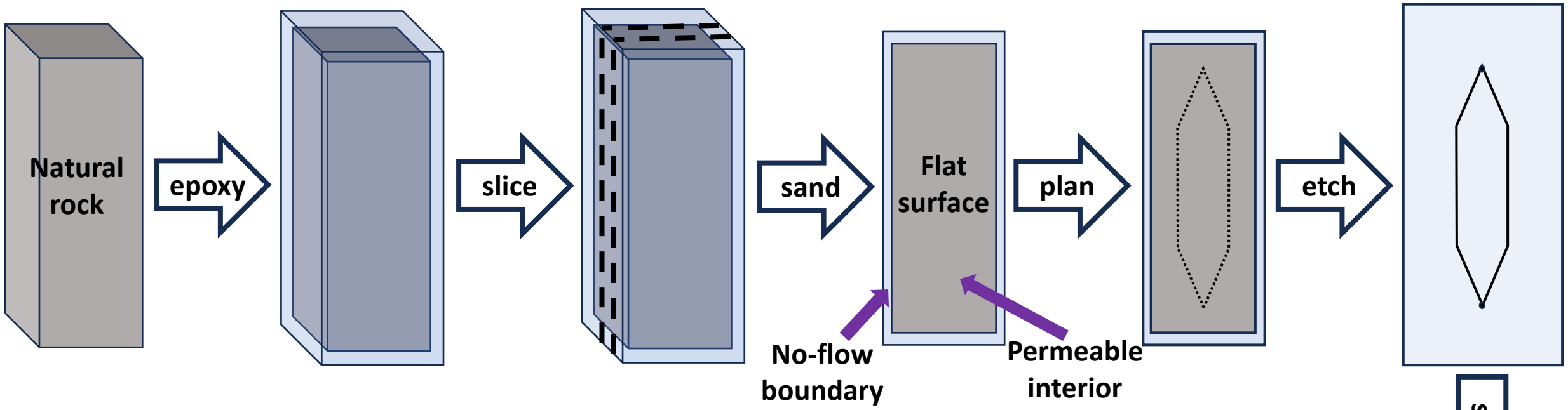

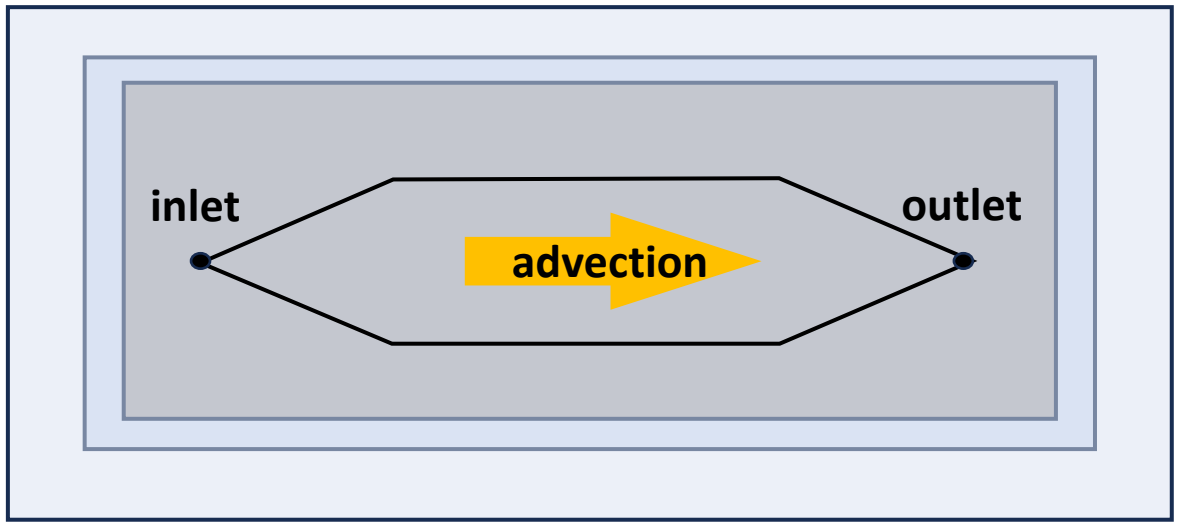

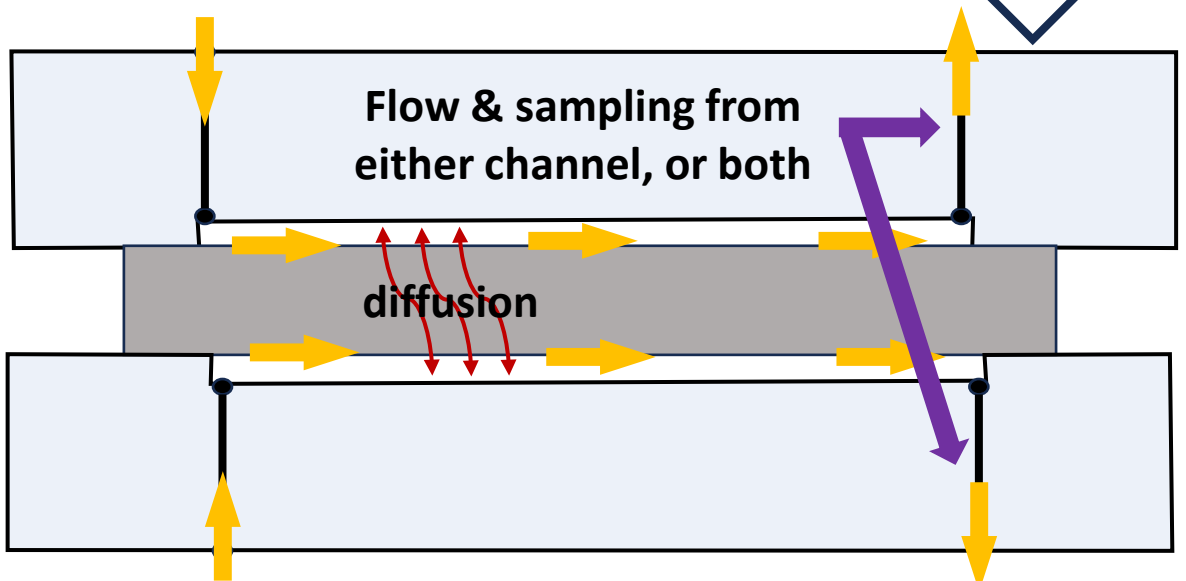

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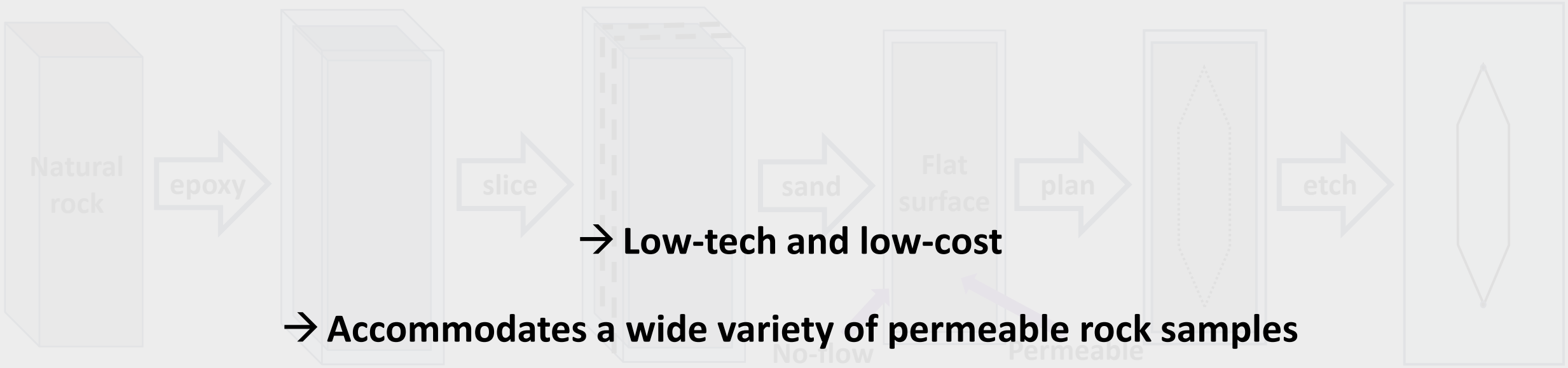
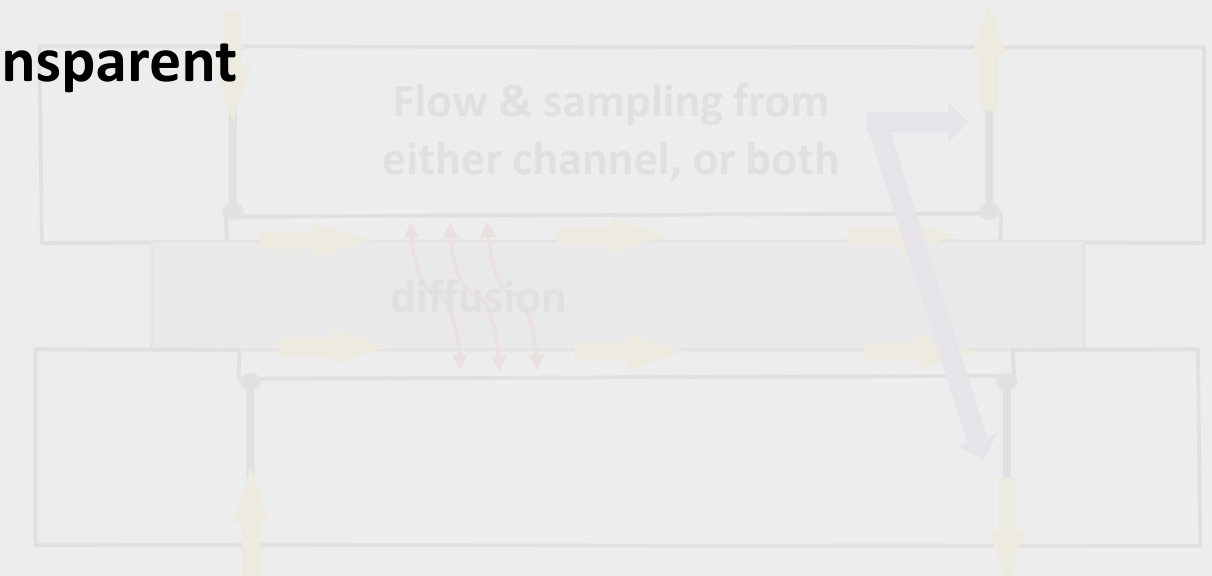


→ **Low-tech and low-cost**

→ **Accommodates a wide variety of permeable rock samples**

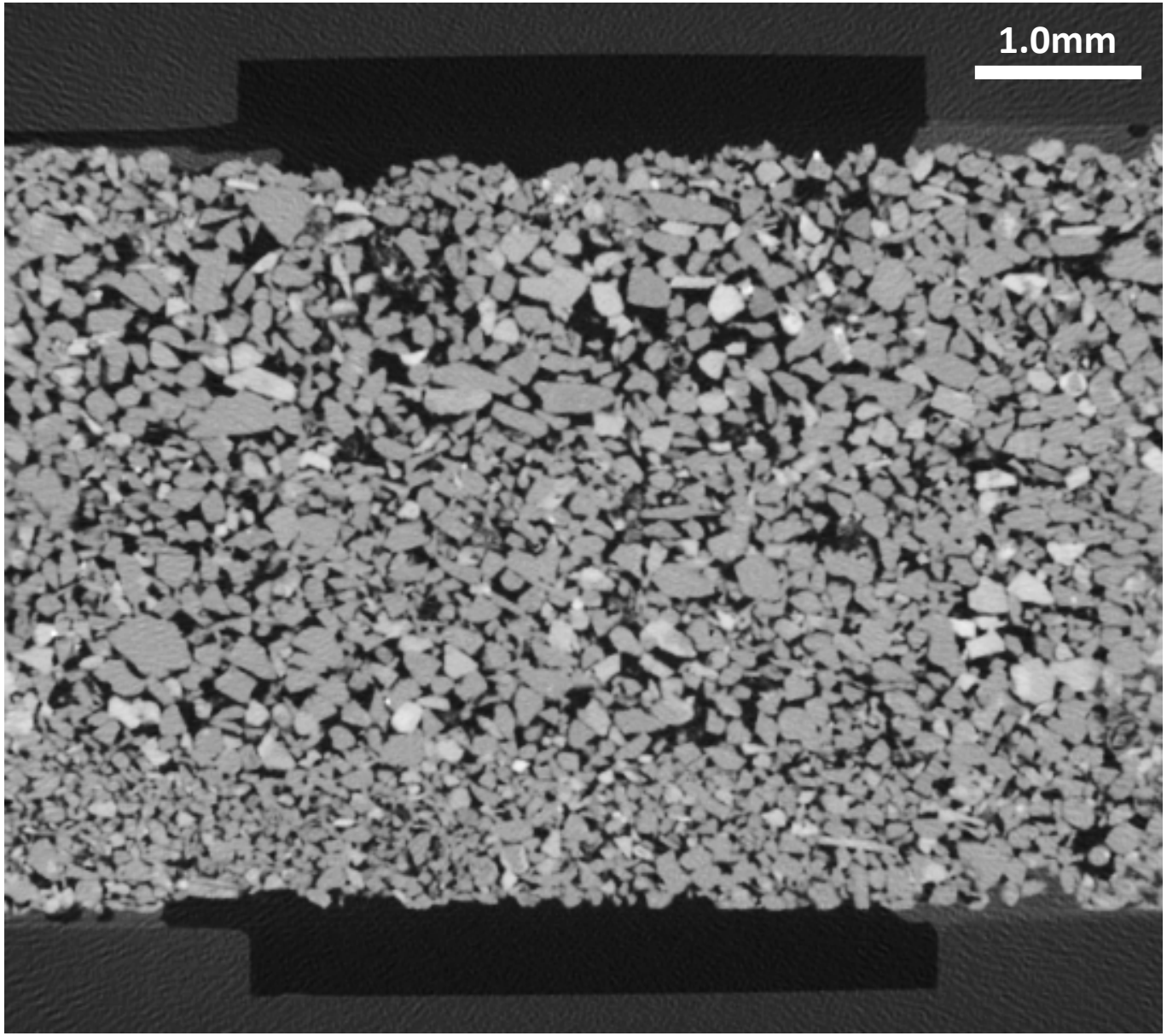
→ **Allows changes in diffusion and advection through porous matrix to be quantified**

→ **X-ray transparent**



Relating rock properties, biofilm density, and solute transport

XCT scans for 3D visualization of rock and channel



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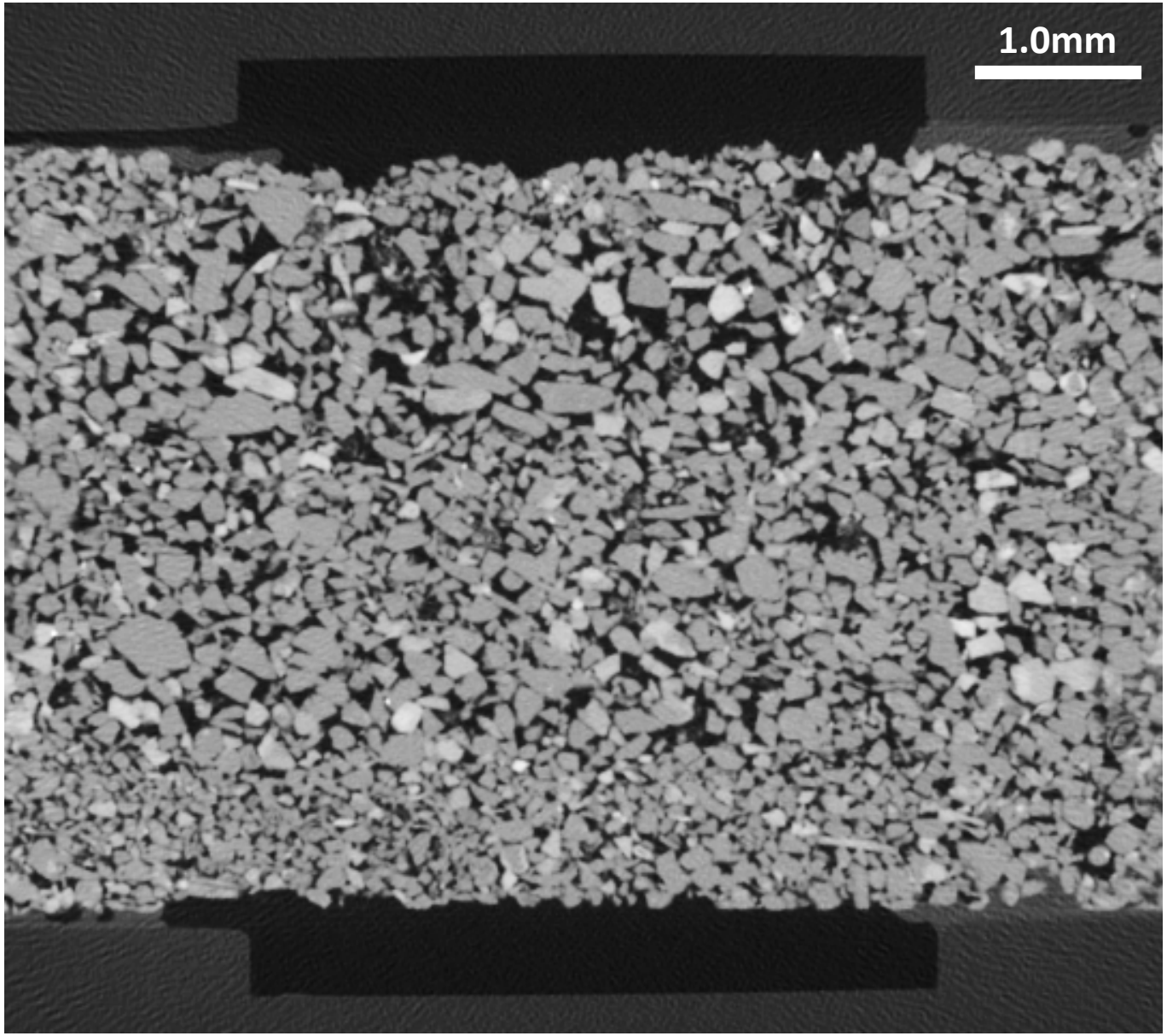
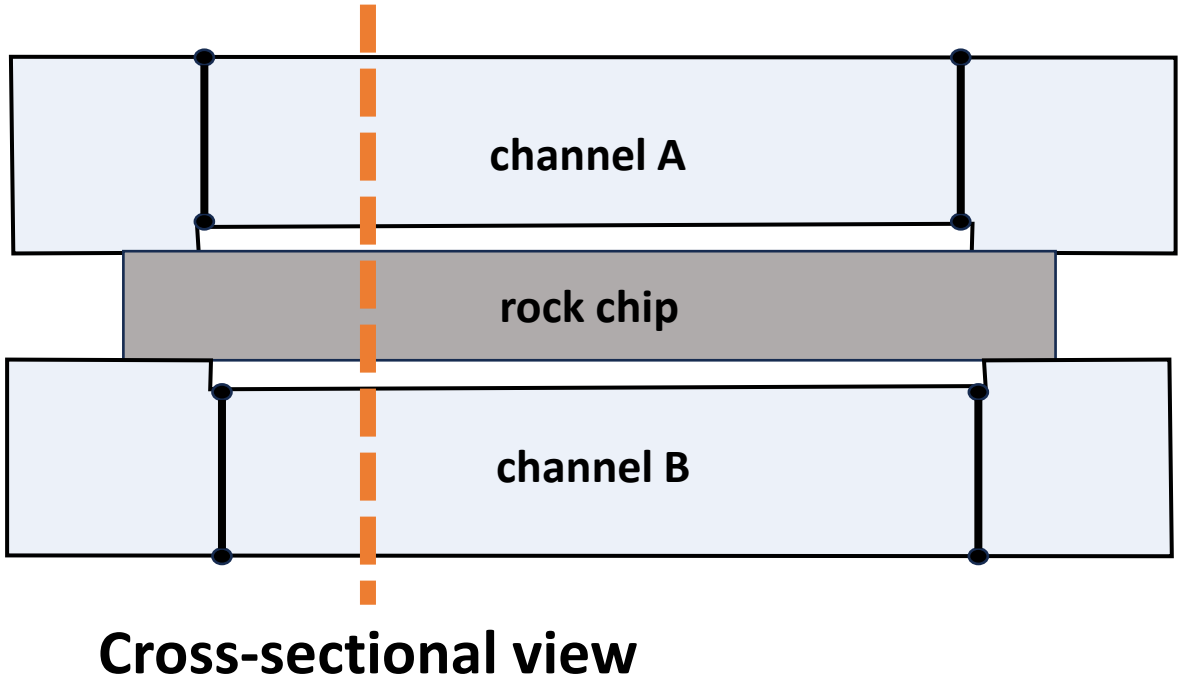
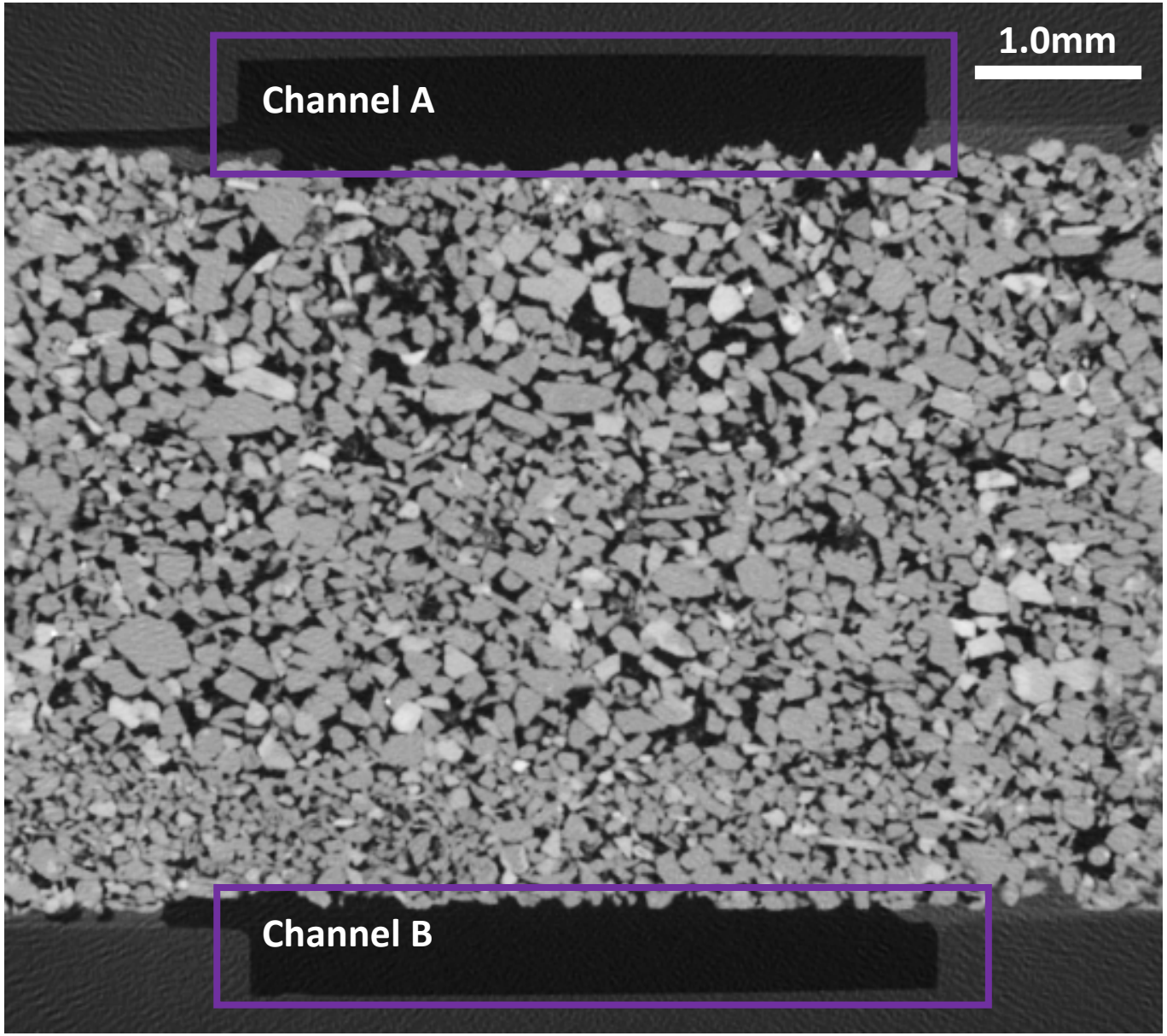


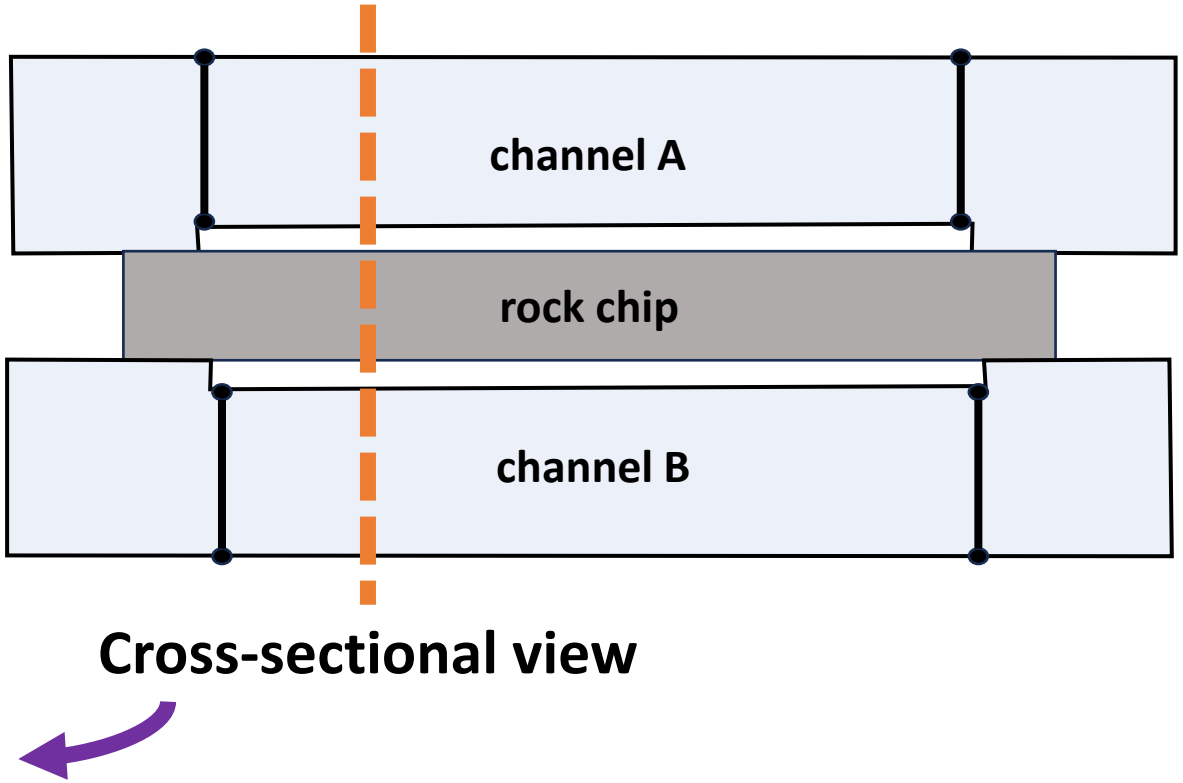


Cross-sectional view

Relating rock properties, biofilm density, and solute transport

XCT scans for 3D visualization of rock and channel

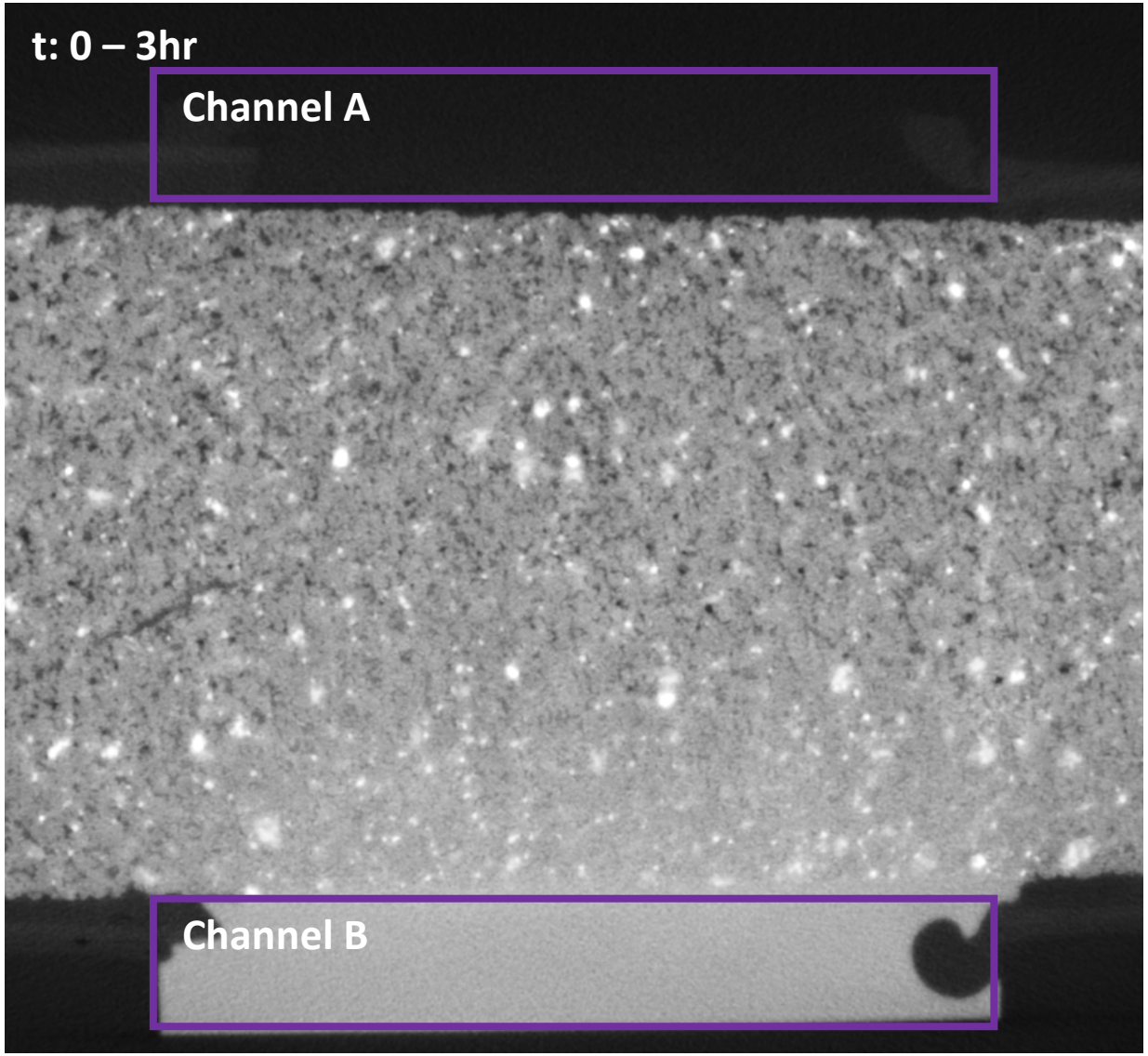




Cross-sectional view

Relating rock properties, biofilm density, and solute transport

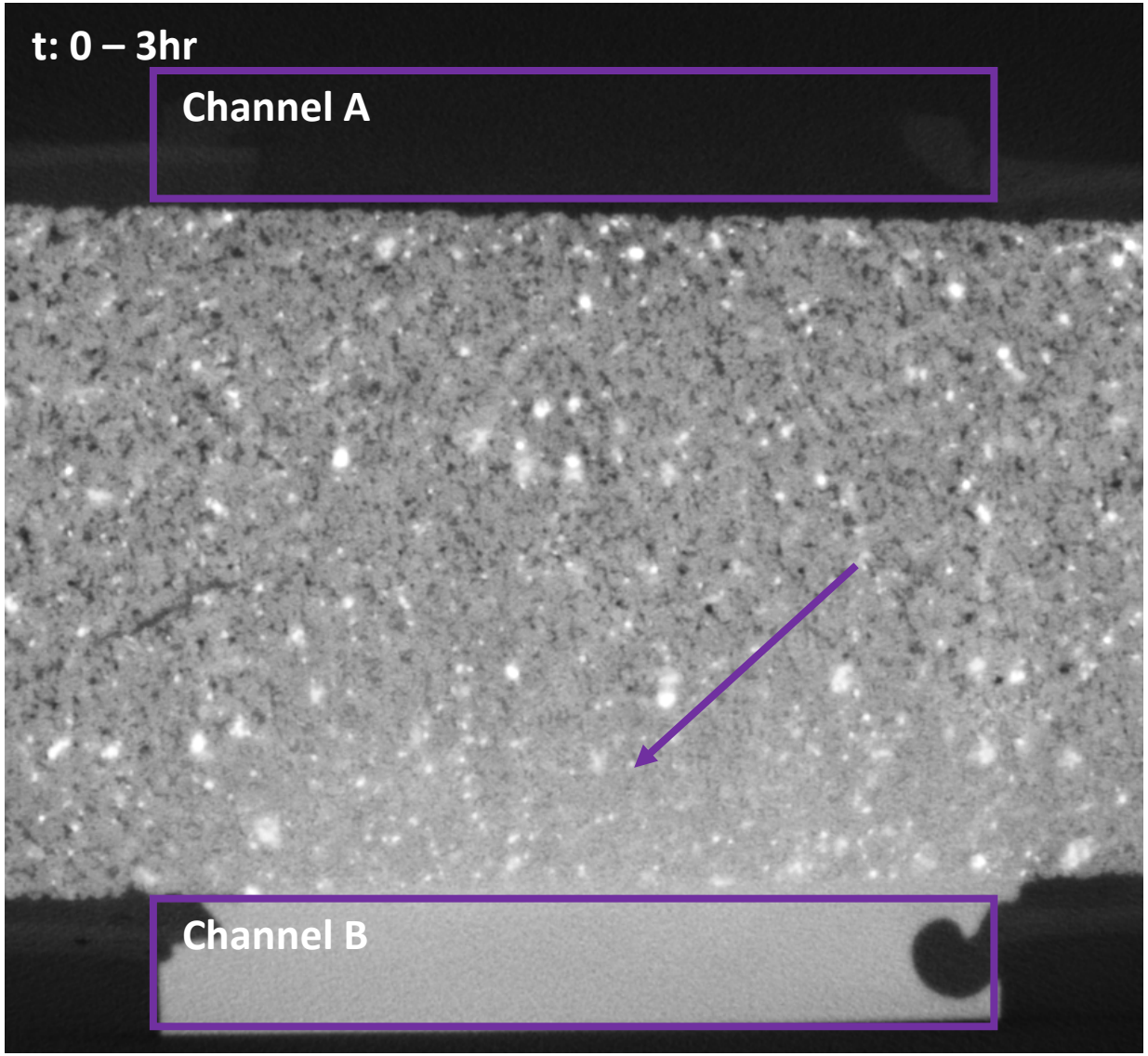
KI (contrast agent) injection into channel B



Relating rock properties, biofilm density, and solute transport

KI (contrast agent) injection into channel B

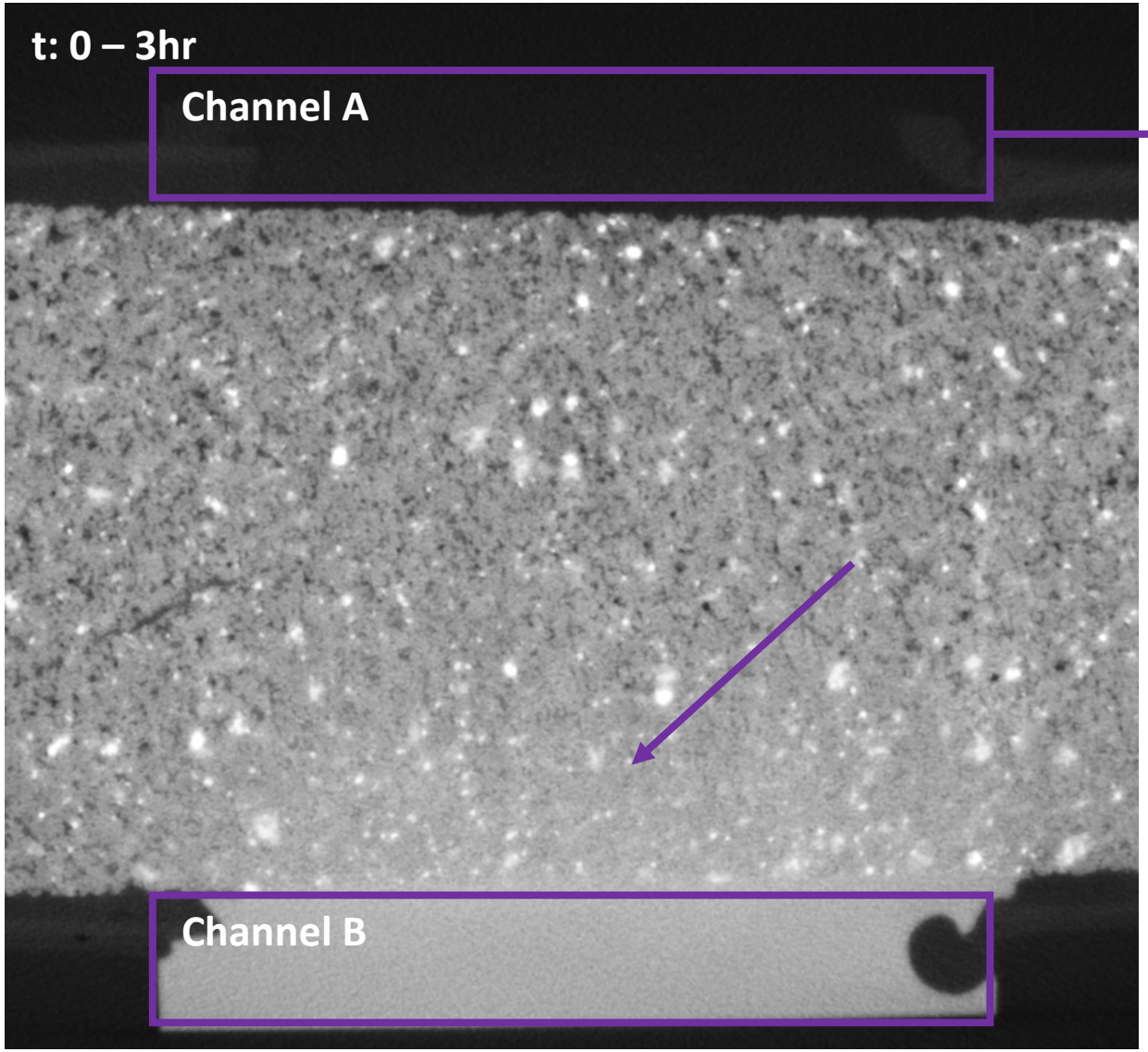
→ Transport front visible from 0 – 3hr

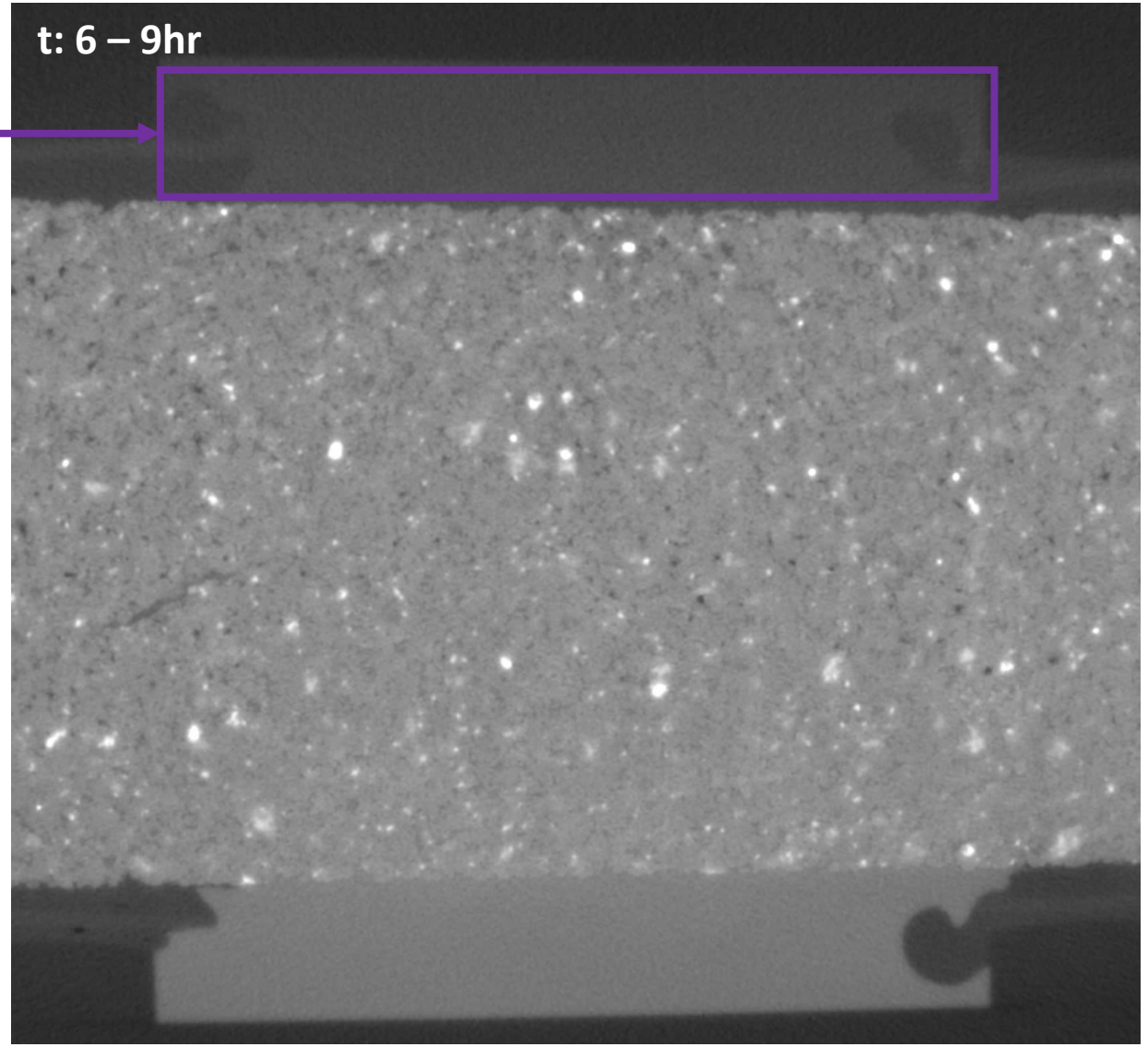


Relating rock properties, biofilm density, and solute transport

KI (contrast agent) injection into channel B
→ Transport front visible from 0 – 3hr

In subsequent hours, front fades and KI becomes visible in channel A

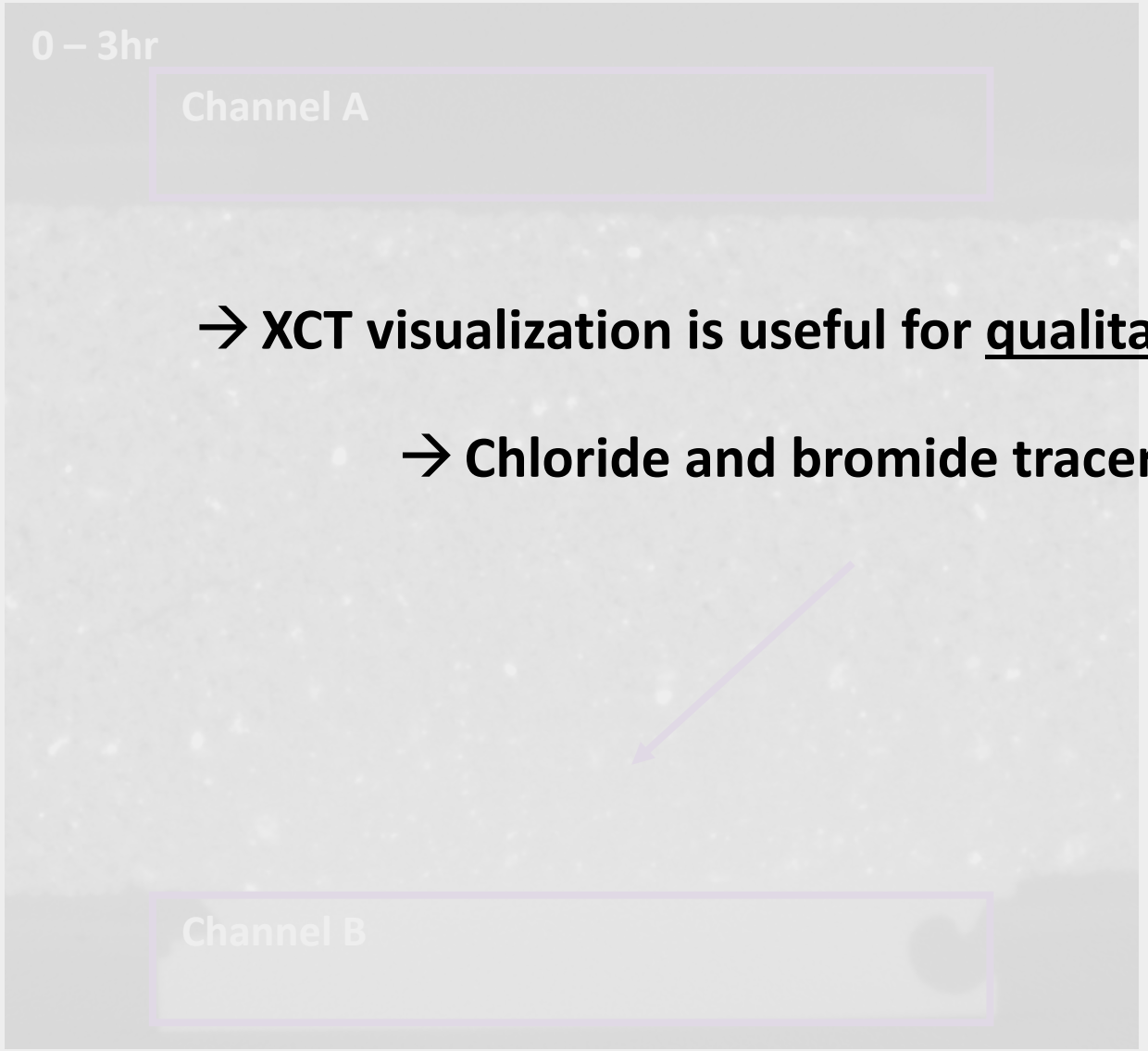


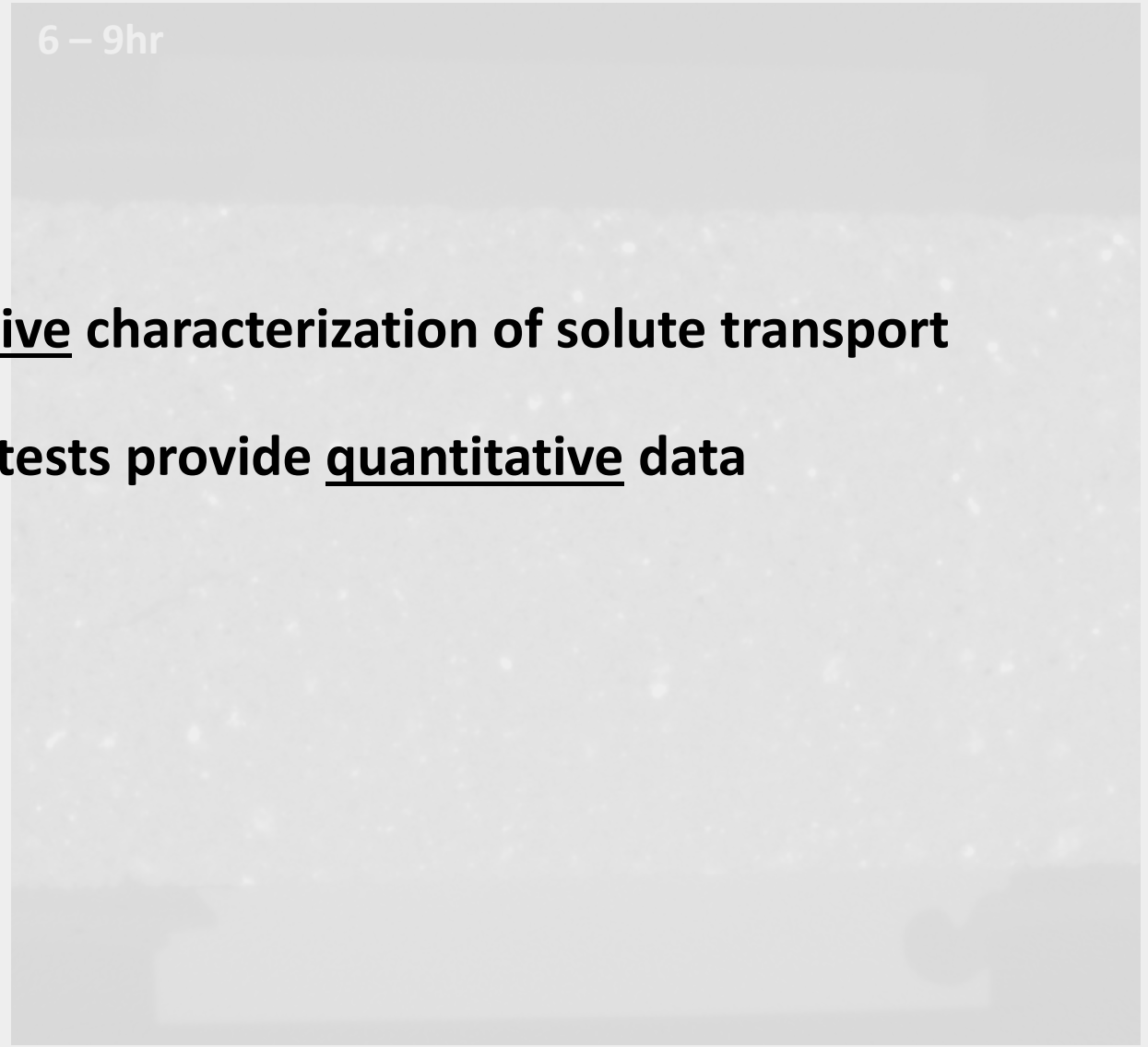


Relating rock properties, biofilm density, and solute transport

KI (contrast agent) injection into one channel
→ Transport front visible from 0 – 3hr

In subsequent hours, front disappears and KI becomes visible in opposite channel

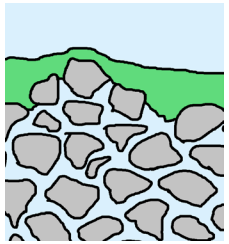




→ XCT visualization is useful for <u>qualitative</u> characterization of solute transport

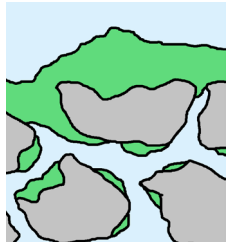
→ Chloride and bromide tracer tests provide <u>quantitative</u> data

Biofilm growth alters diffusive and advective transport



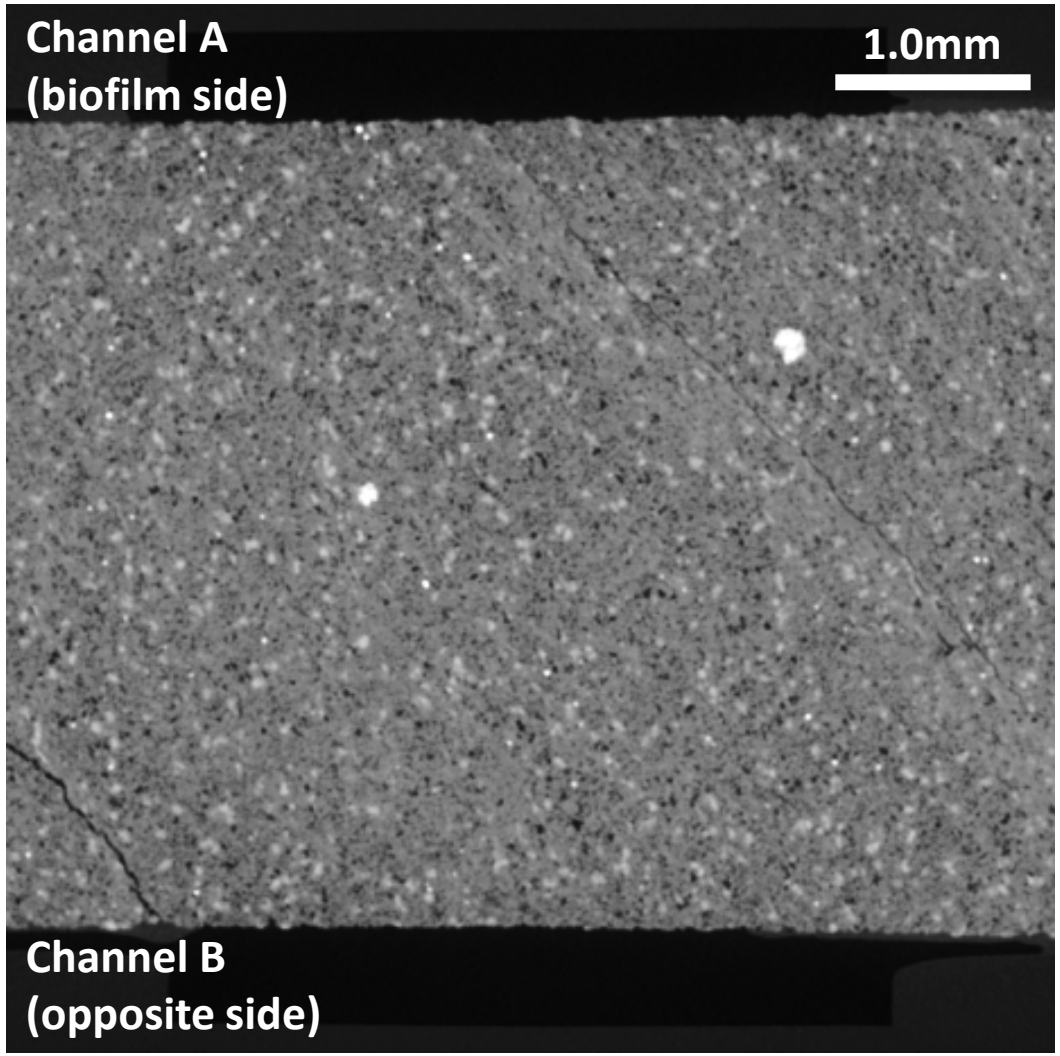
Bandera sandstone ("Small pores")

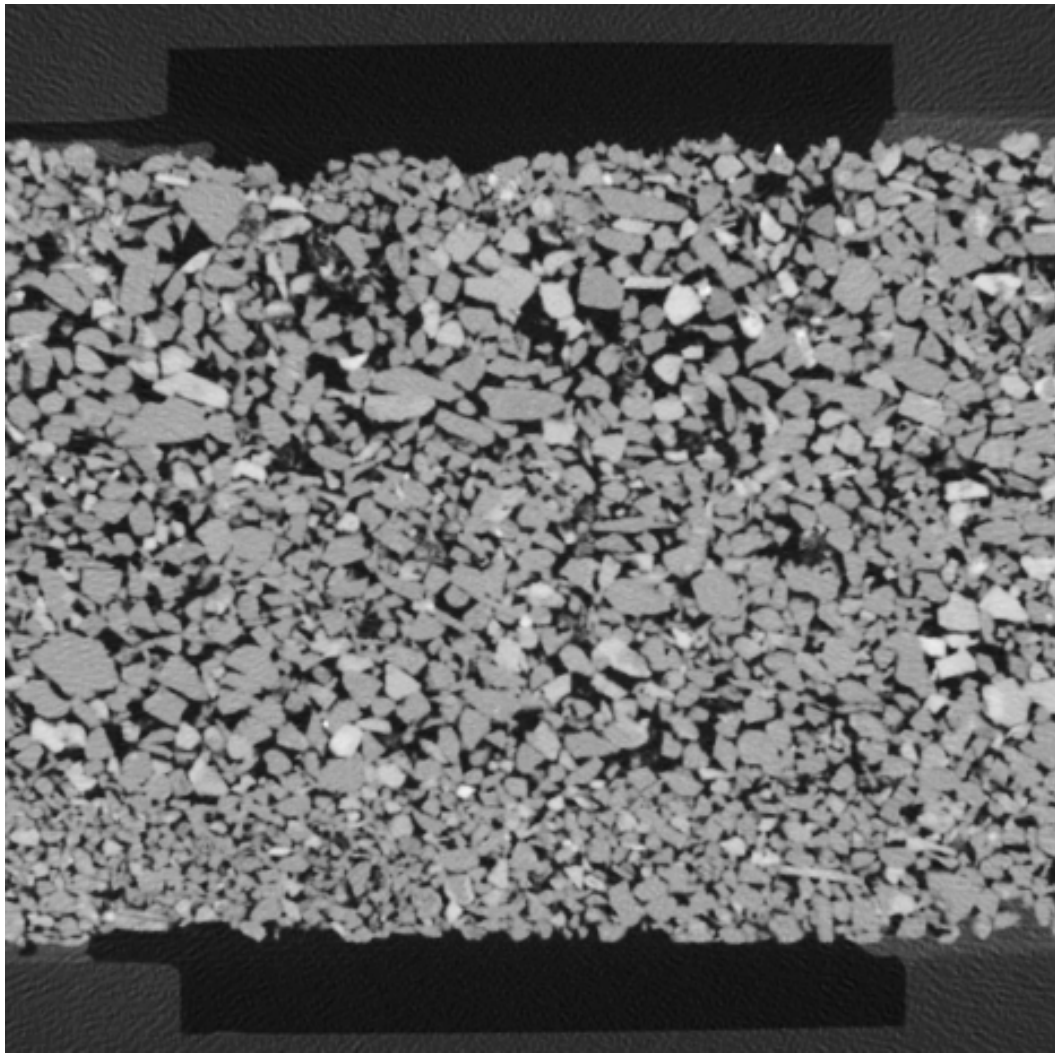
Expect thin, dense biofilm on surface



Boise sandstone ("Large pores")

Expect distributed, lower-density biofilm





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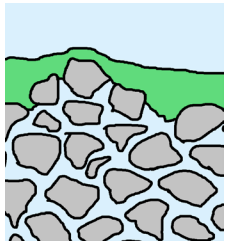

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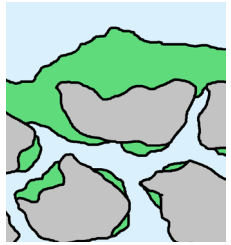

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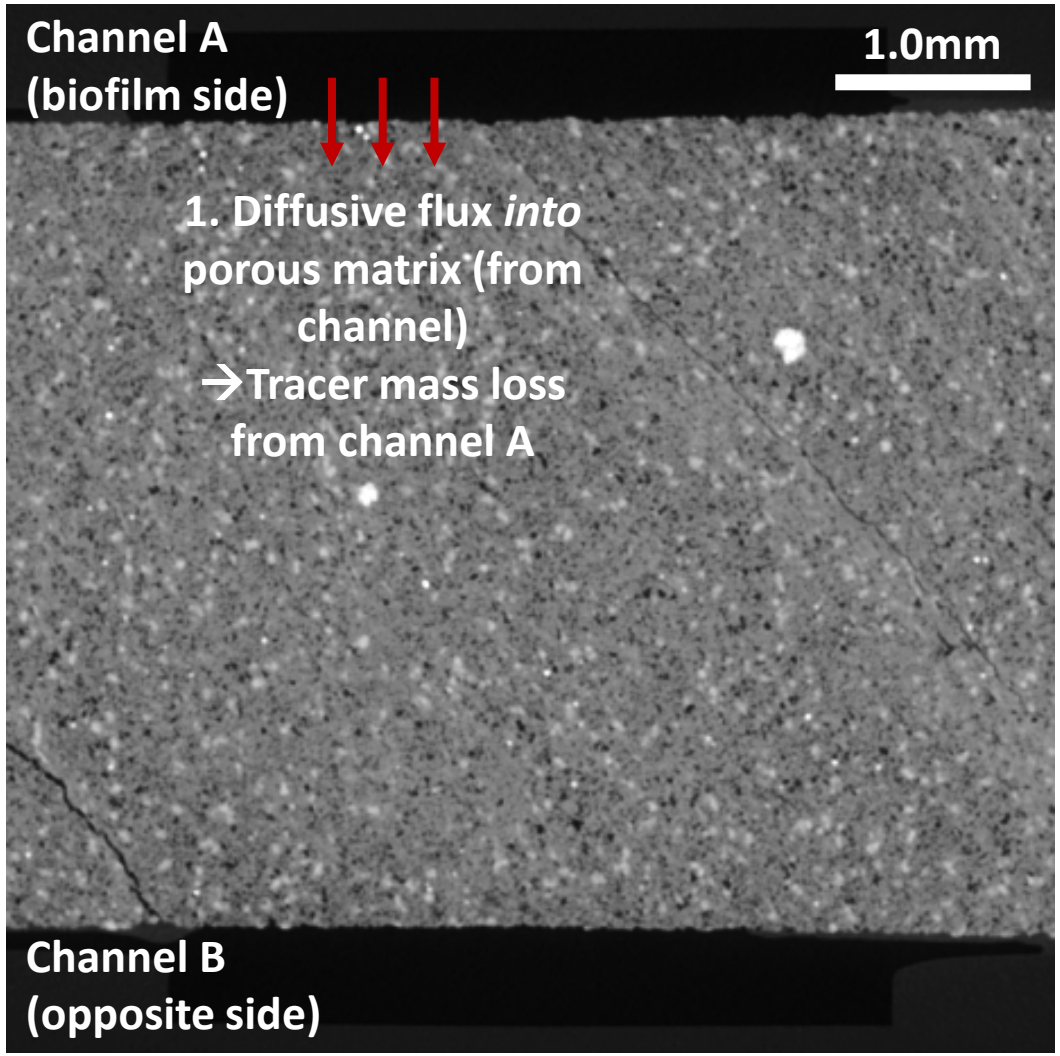
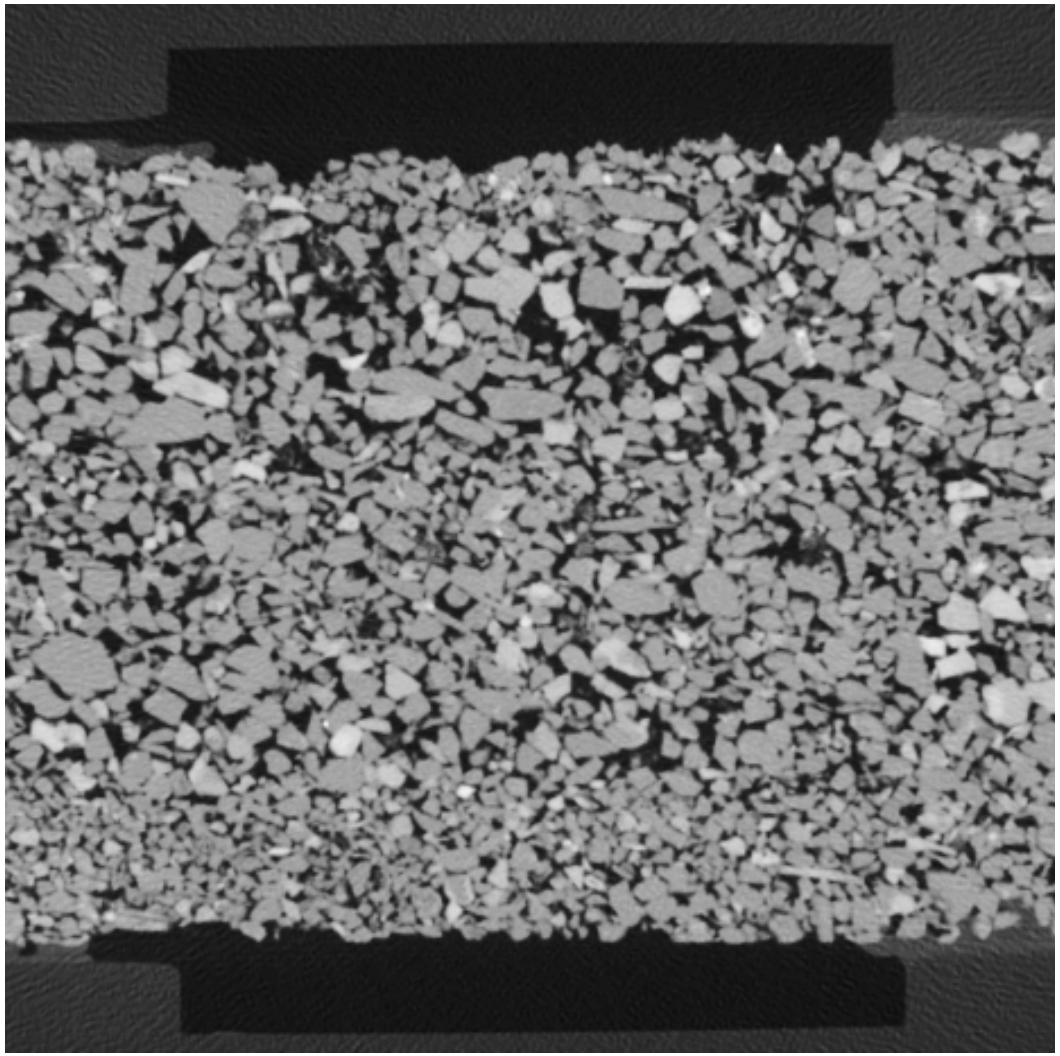
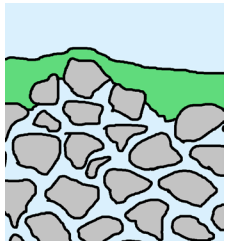




Biofilm growth alters diffusive and advective transport



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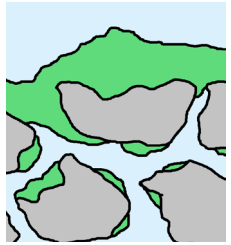

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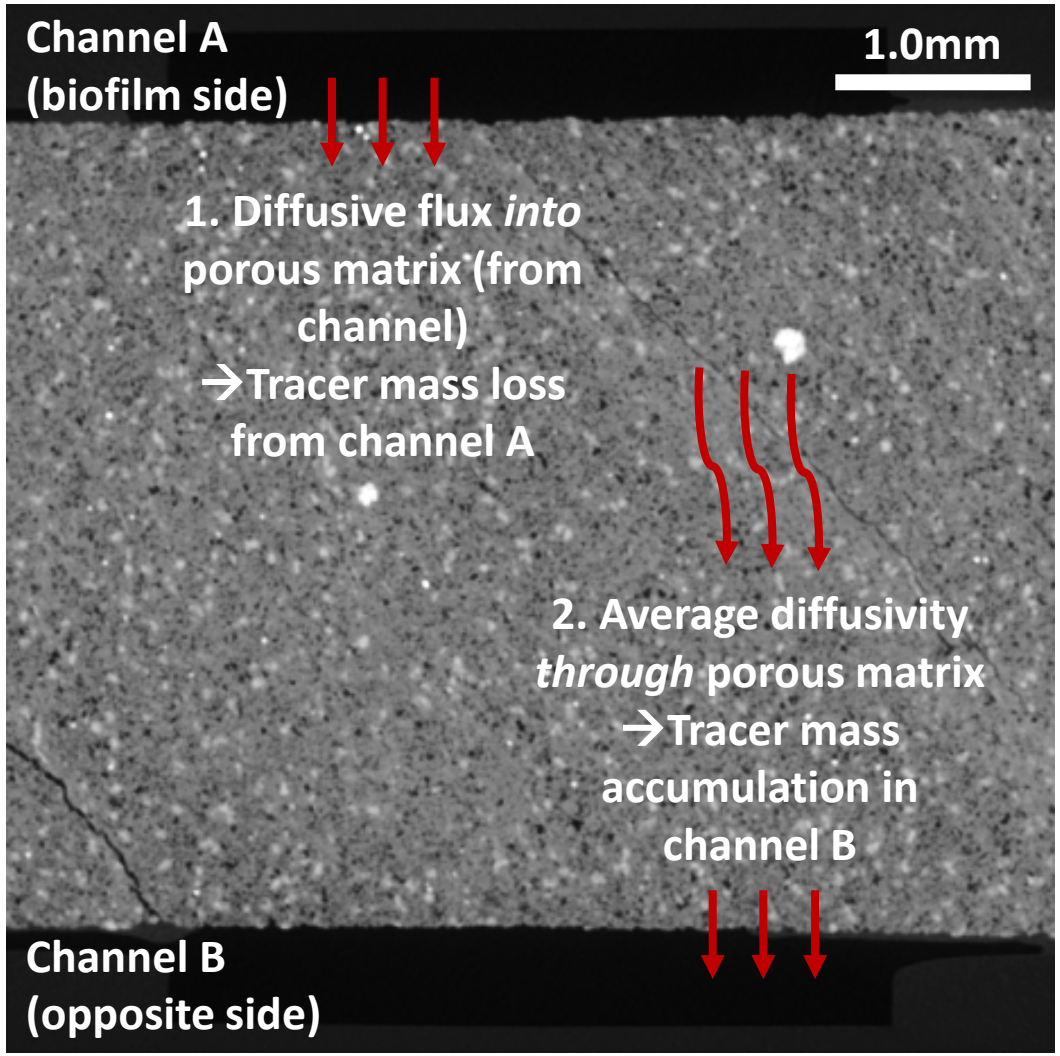

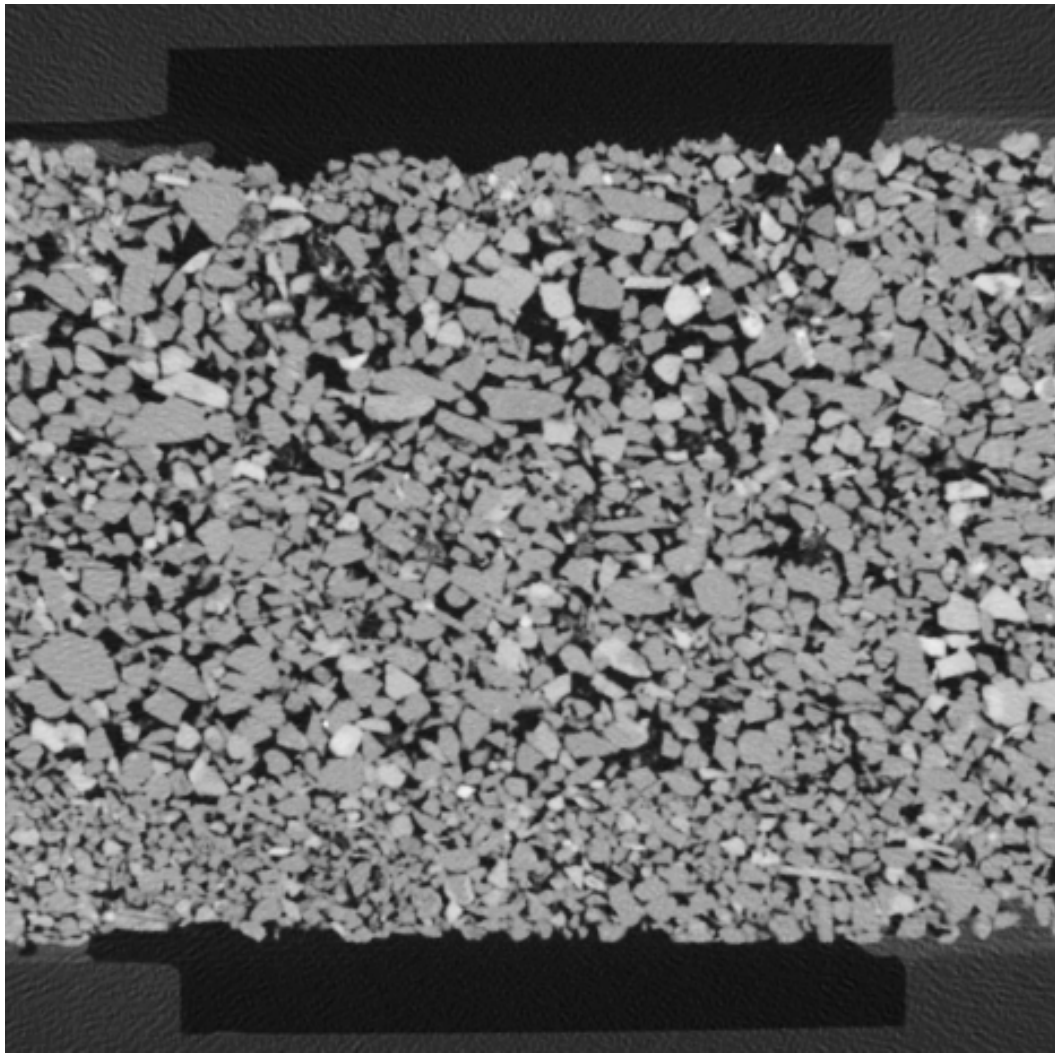

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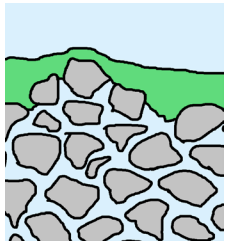

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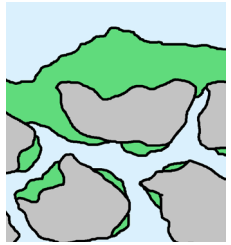

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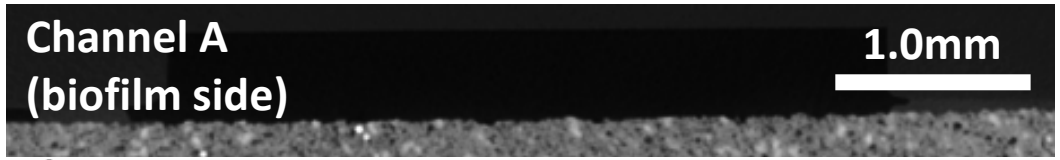
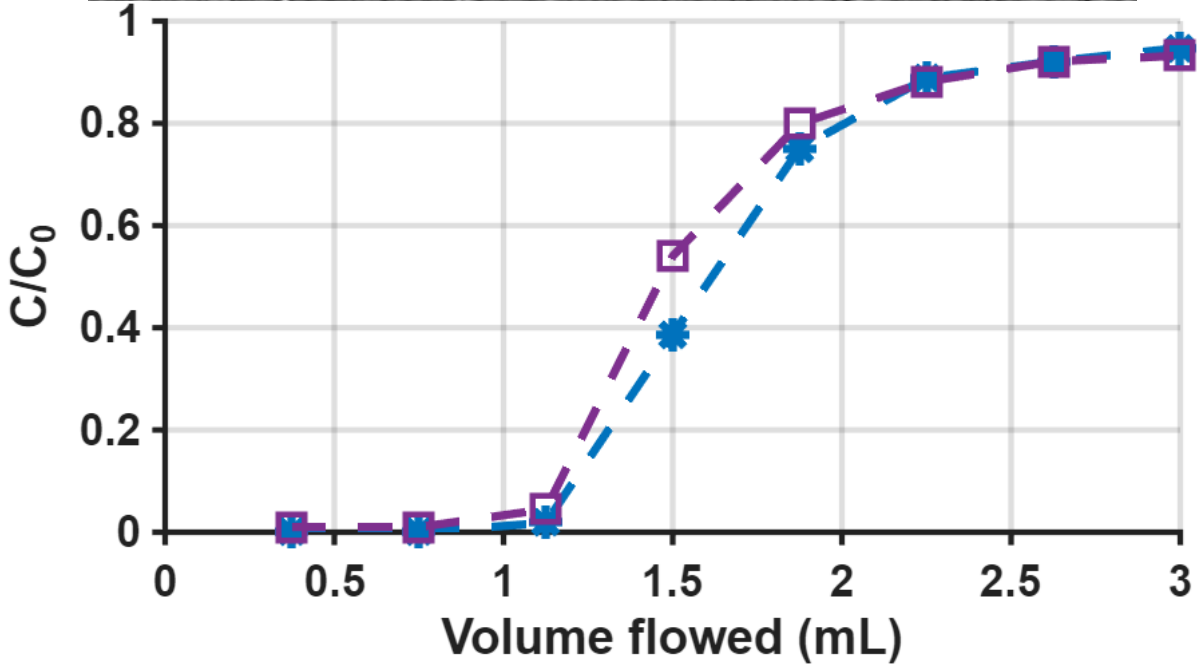
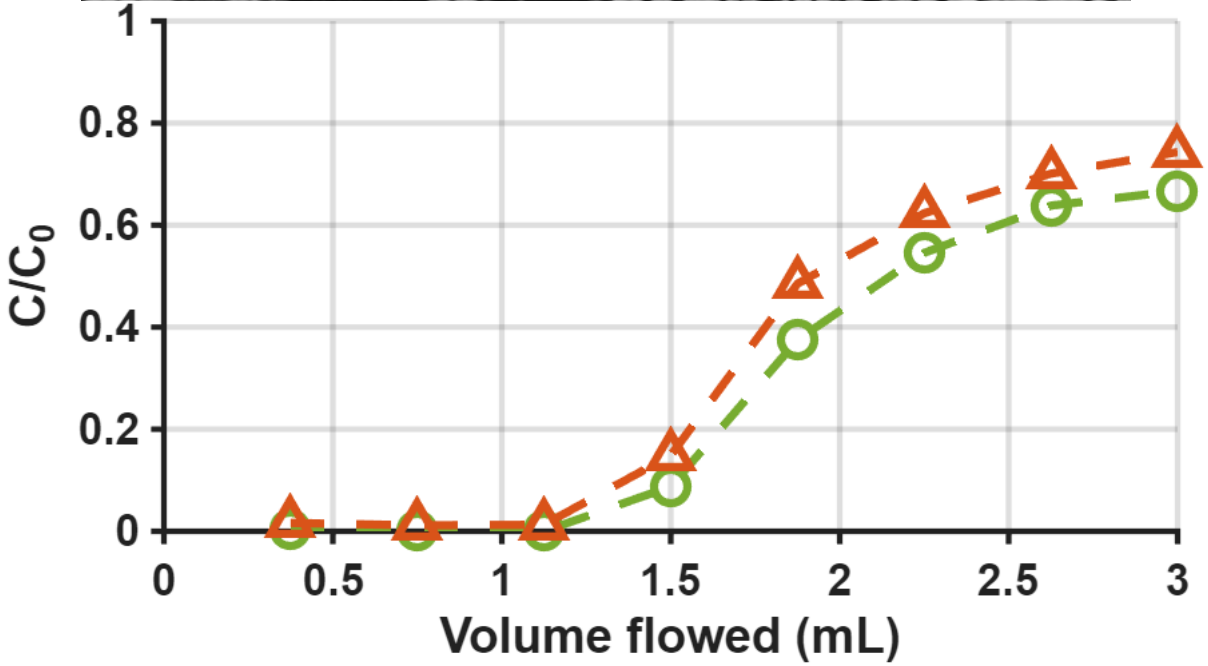
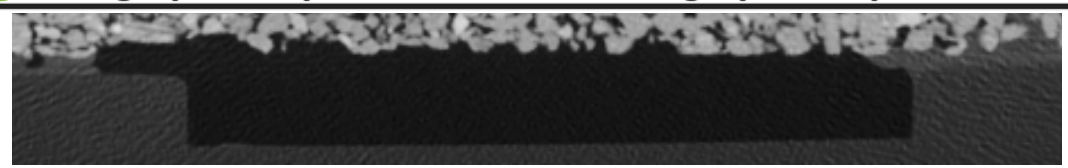
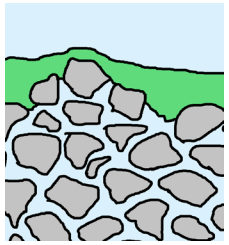








Biofilm growth alters diffusive and advective transport



Bandera sandstone ("Small pores")

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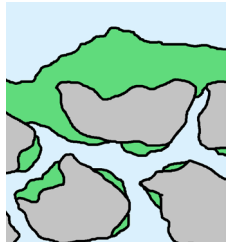

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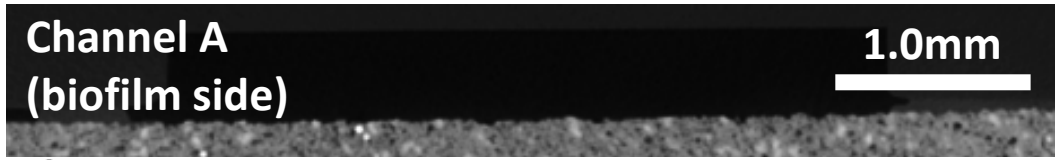

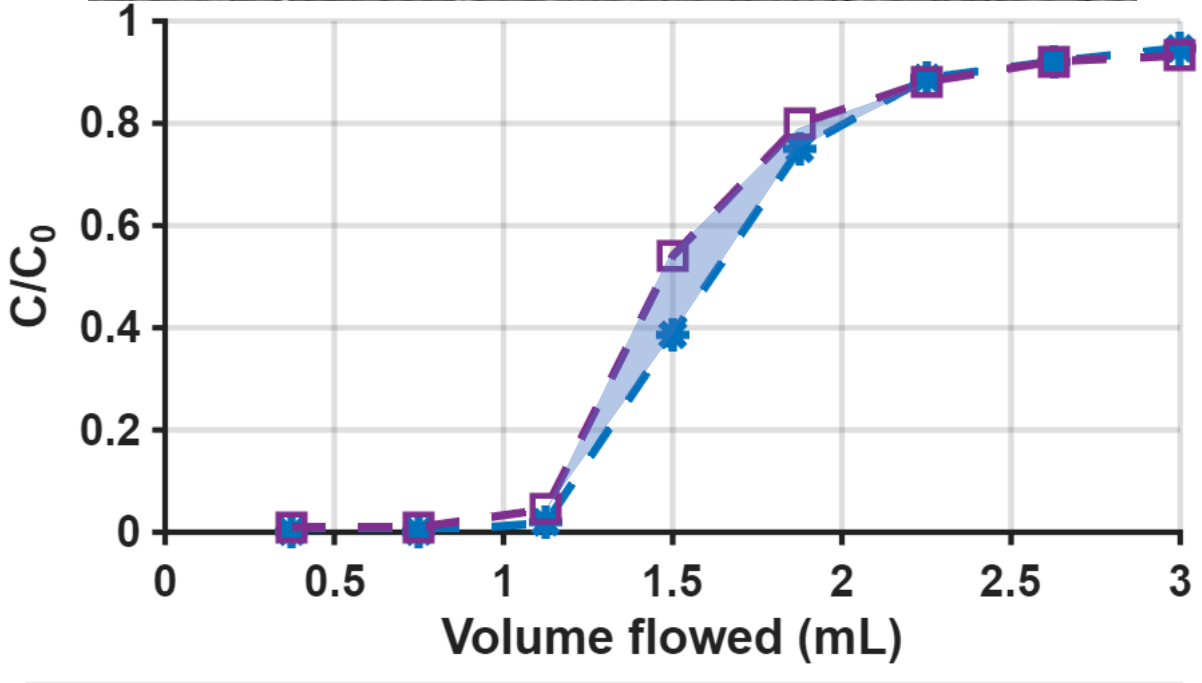

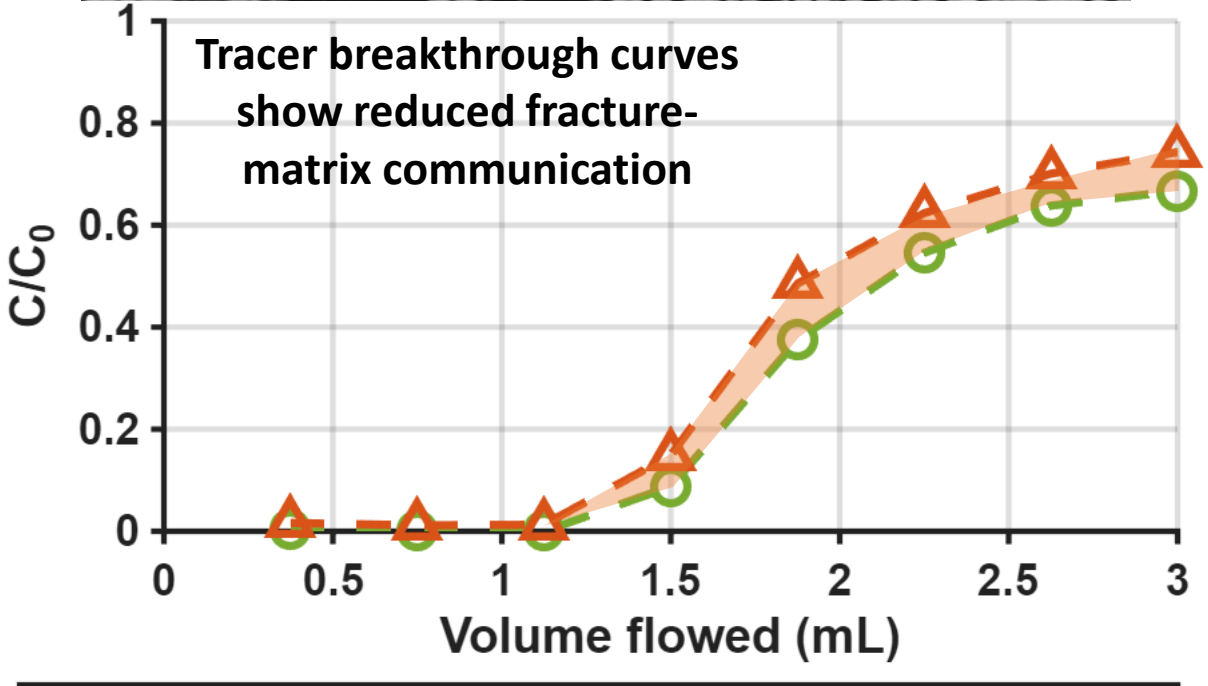

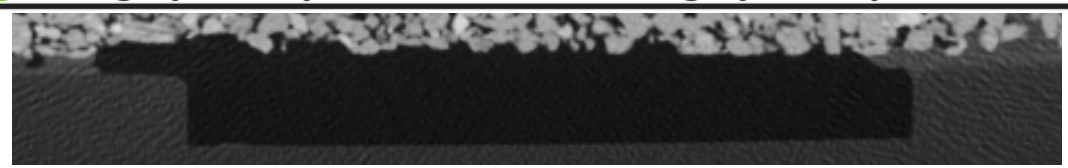

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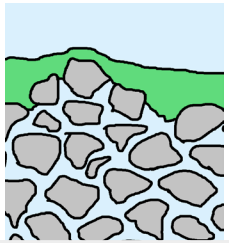
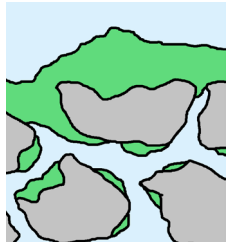


<u>Bandera sandstone ("Small pores")</u>

Expect thin, dense biofilm on surface

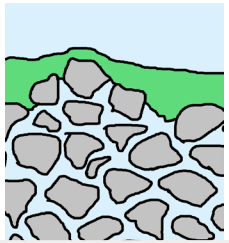


<u>Boise sandstone ("Large pores")</u>

Expect distributed, lower-density biofilm

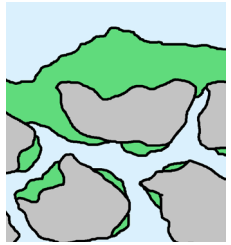
During static period, see *no significant change* in diffusive flux *into* or *through* the rock

Biofilm growth alters diffusive and advective transport



Bandera sandstone ("Small pores")

Expect thin, dense biofilm on surface



Boise sandstone ("Large pores")

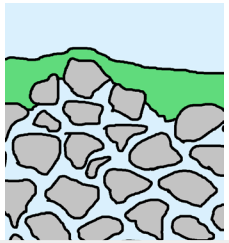
Expect distributed, lower-density biofilm

During static period, see *no significant change* in diffusive flux *into* or *through* the rock

***~15% decrease* in diffusive flux *into* the rock**

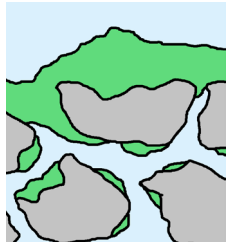
***~40% decrease* in diffusive flux *through* the rock**

Biofilm growth alters diffusive and advective transport



<u>Bandera sandstone ("Small pores")</u>

Expect thin, dense biofilm on surface



<u>Boise sandstone ("Large pores")</u>

Expect distributed, lower-density biofilm

During static period, see *no significant change* in diffusive flux *into* or *through* the rock

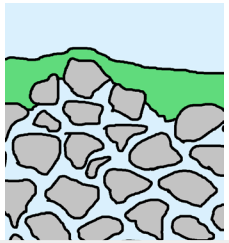
~60% decrease in permeability across the rock

***~15% decrease* in diffusive flux *into* the rock**

***~40% decrease* in diffusive flux *through* the rock**

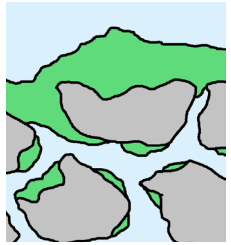
<10% decrease in permeability across the rock

Biofilm growth alters diffusive and advective transport



Bandera sandstone ("Small pores")

Expect thin, dense biofilm on surface



Boise sandstone ("Large pores")

Expect distributed, lower-density biofilm

During static period, see *no significant change* in diffusive flux *into* or *through* the rock

~60% decrease in permeability **across the rock**

→Suggests a thin, dense, surficial biofilm layer

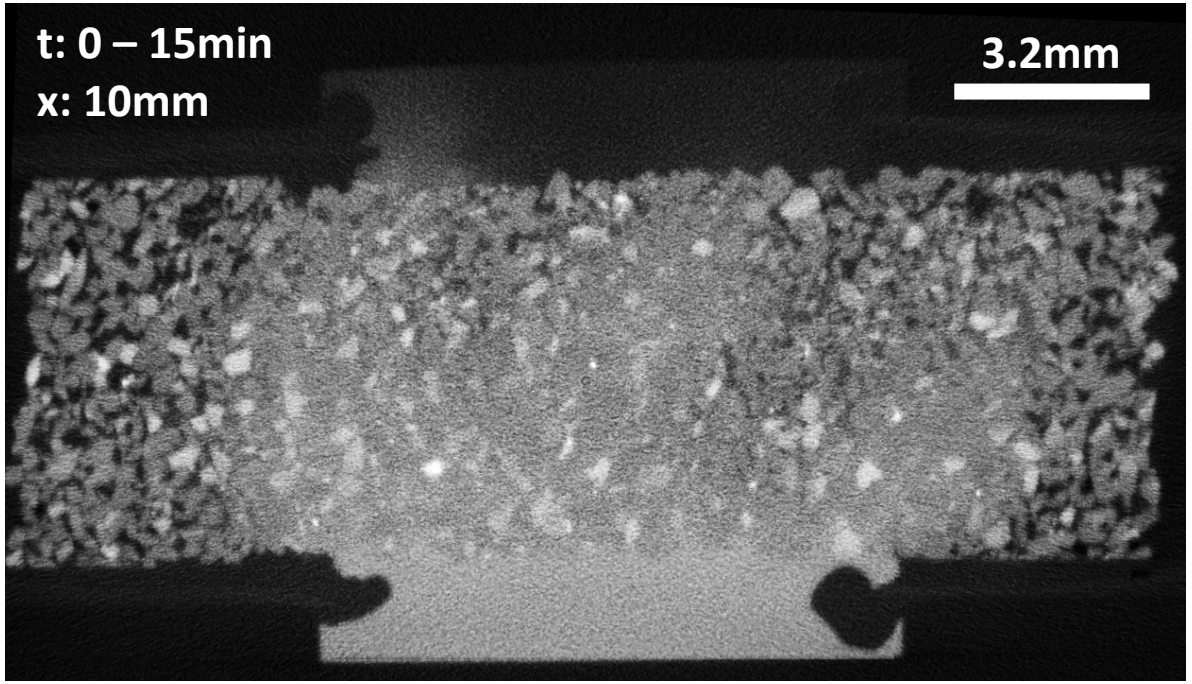
~15% decrease **in diffusive flux *into* the rock**

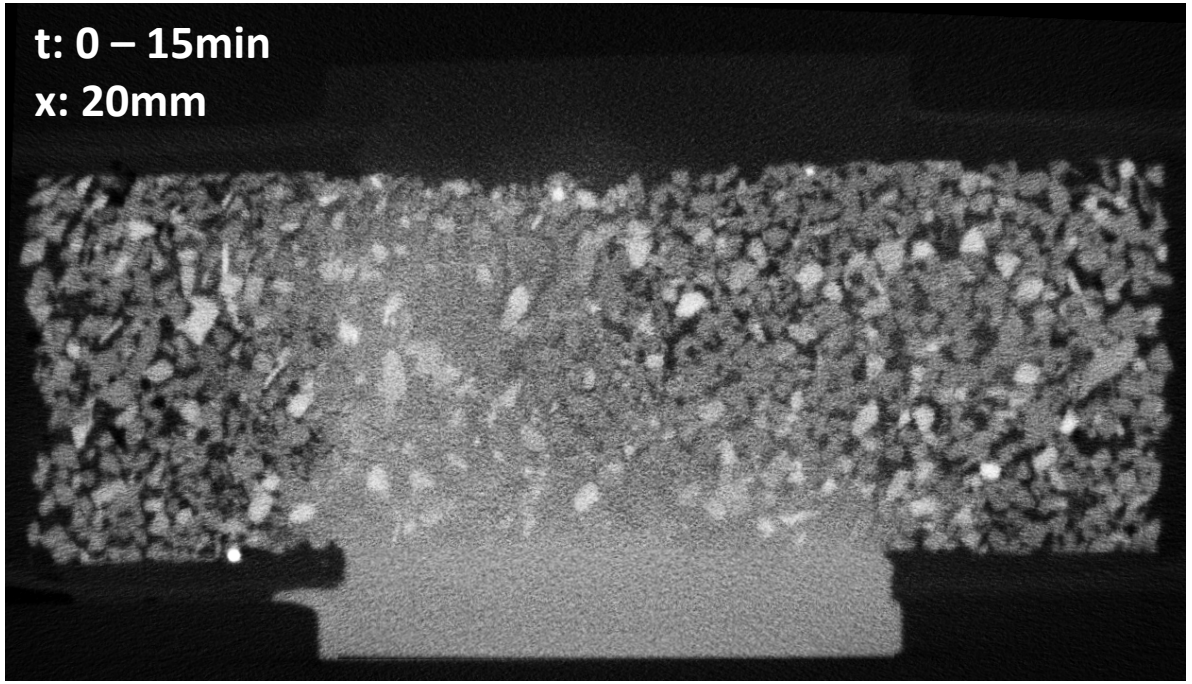
~40% decrease **in diffusive flux *through* the rock**

<10% decrease in permeability **across the rock**

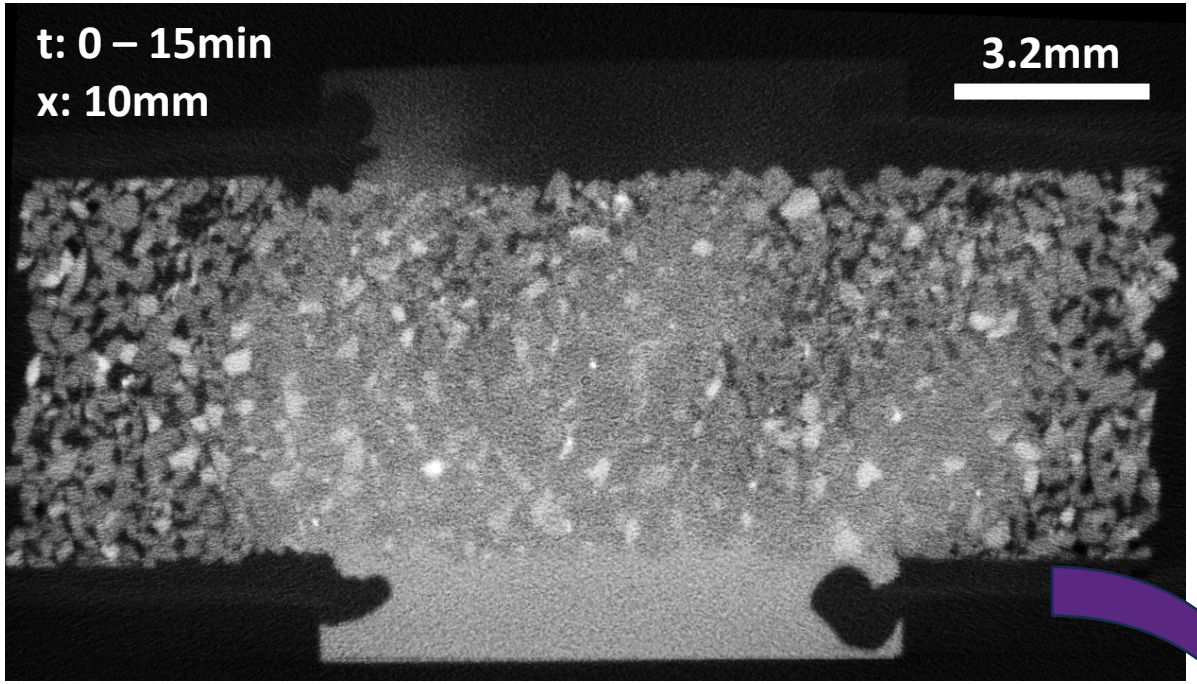
→Suggests a distributed biofilm, with preferential flow paths

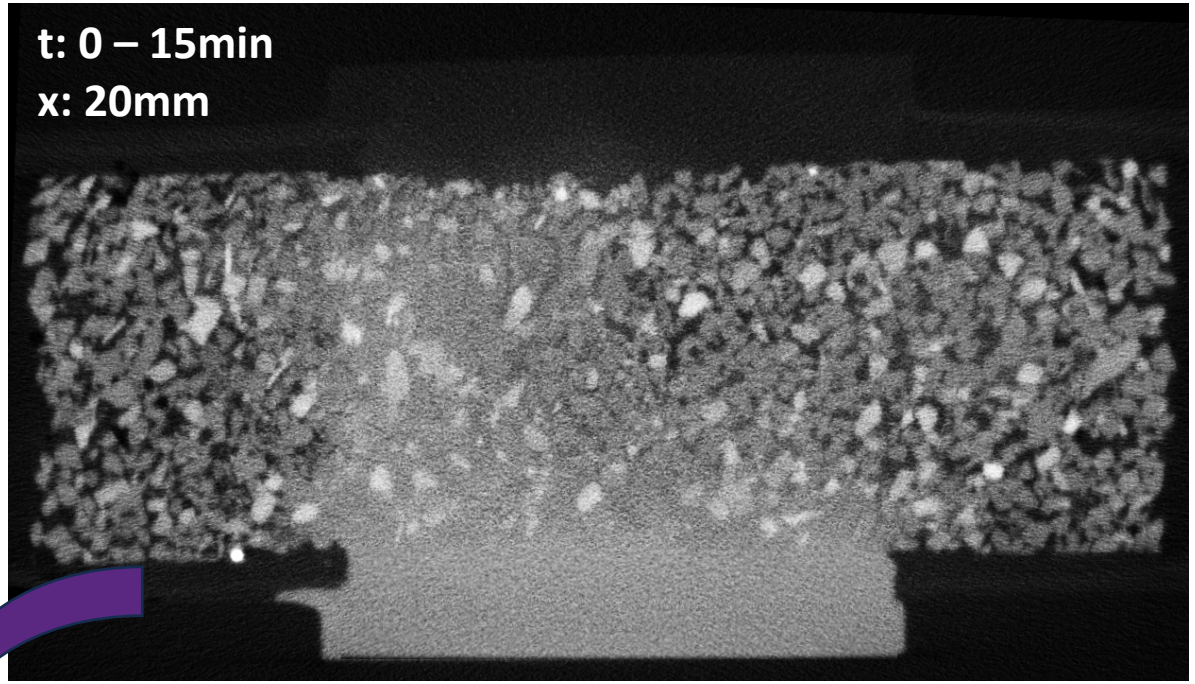
Biofilm growth alters diffusive and advective transport

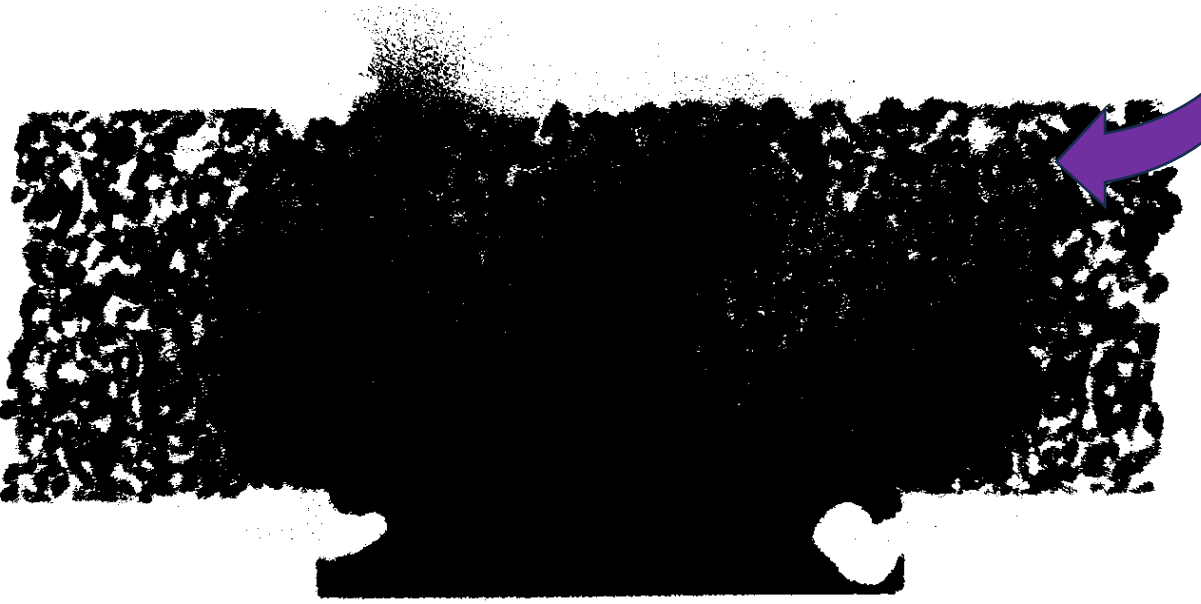




Biofilm growth alters diffusive and advective transport

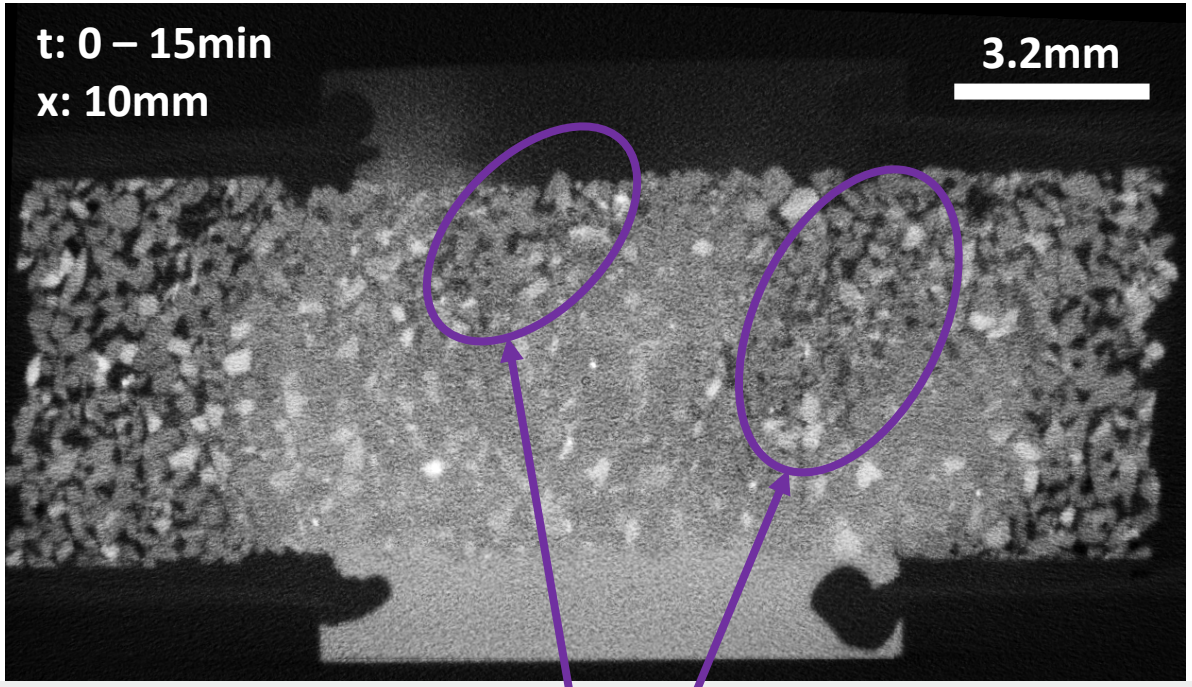


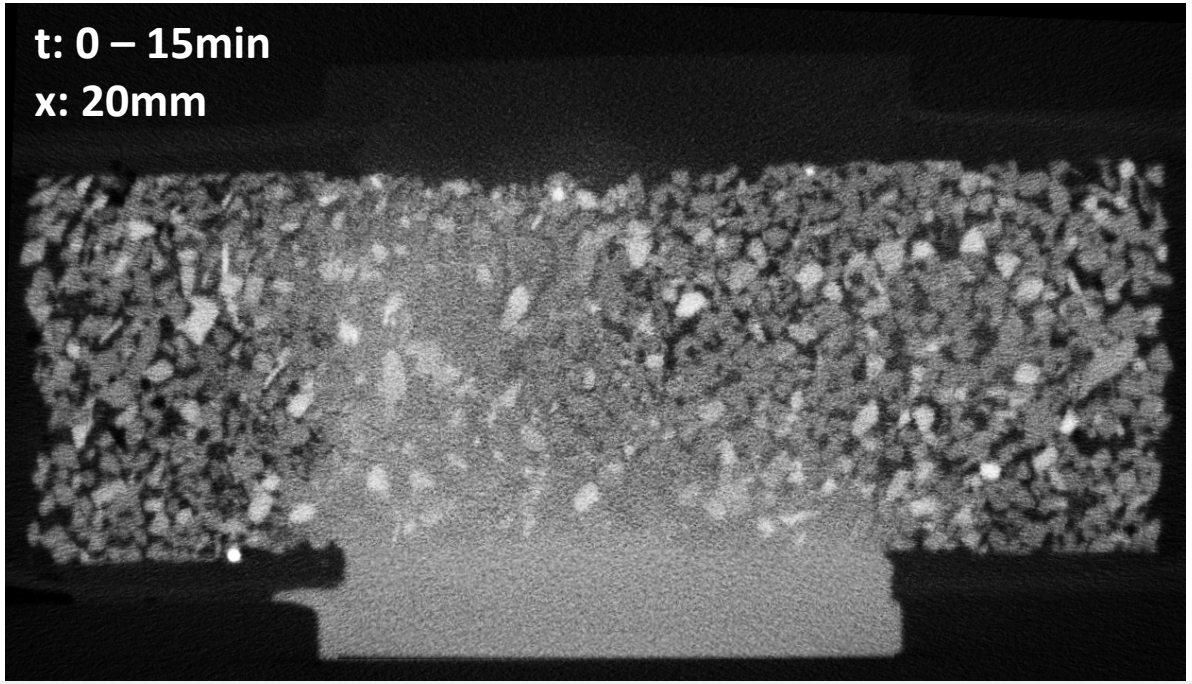




Apply threshold

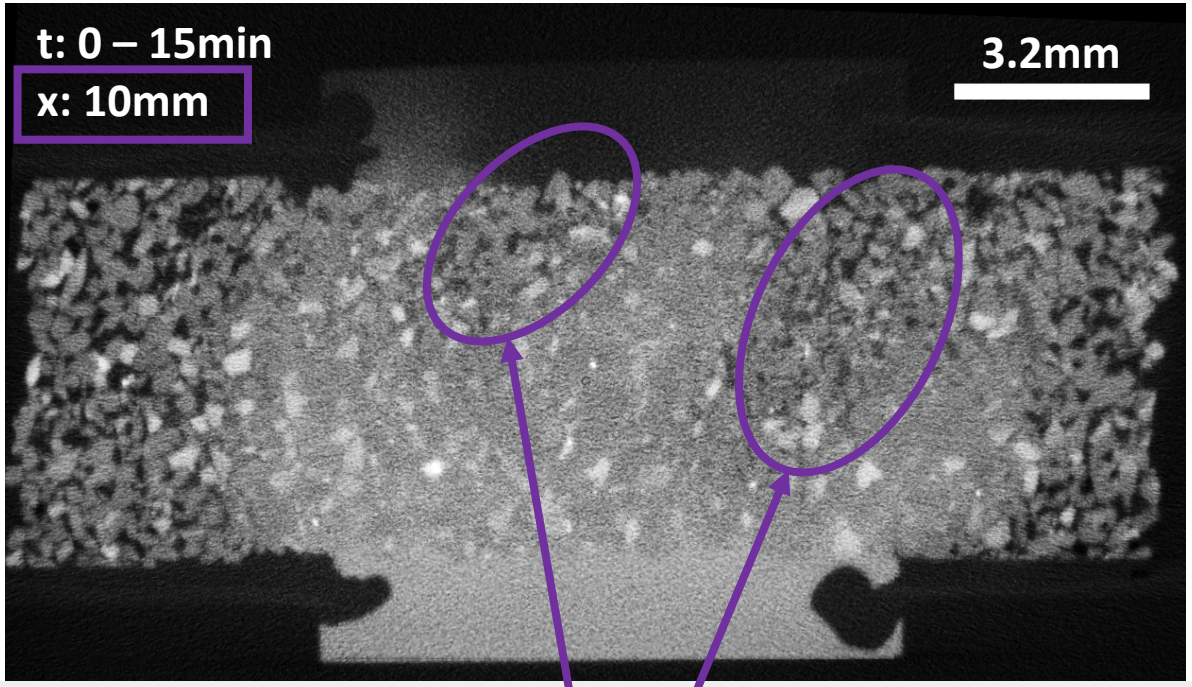
Biofilm growth alters diffusive and advective transport

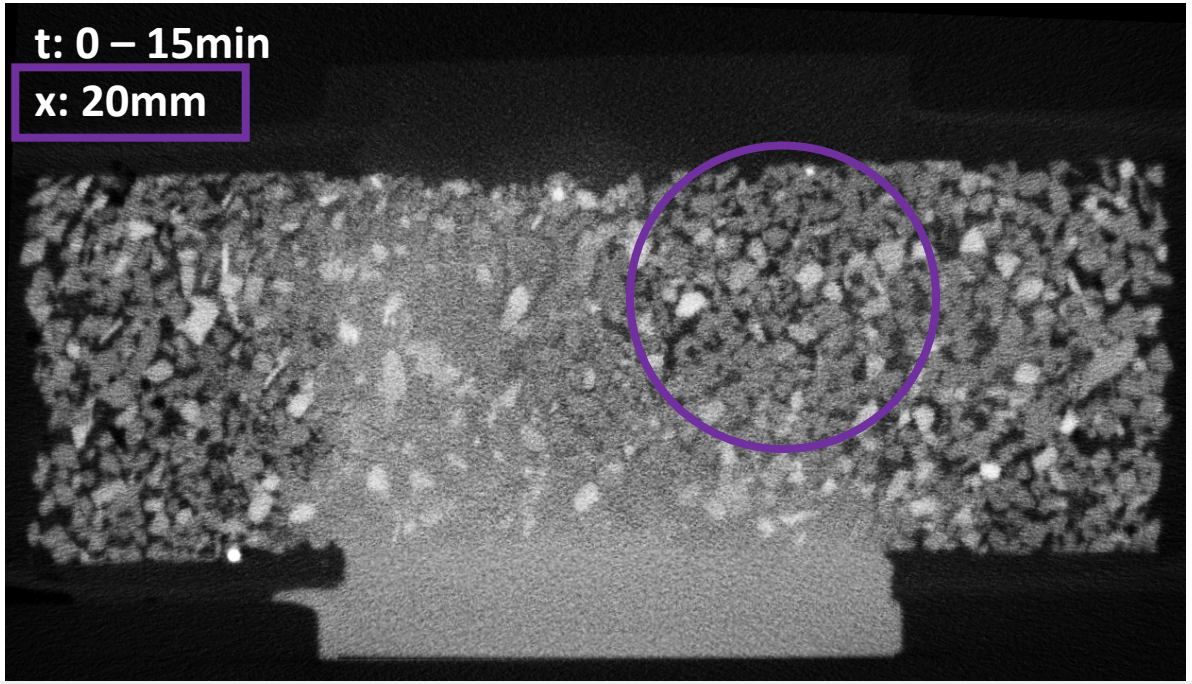




Regions of hypothesized high biofilm density

Biofilm growth alters diffusive and advective transport

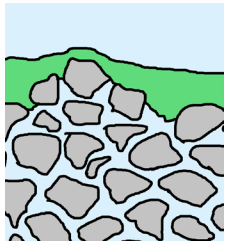




Regions of hypothesized high biofilm density

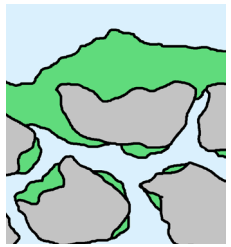
Biofilm growth is not uniform along the length of the channel

Biofilm growth alters diffusive and advective transport



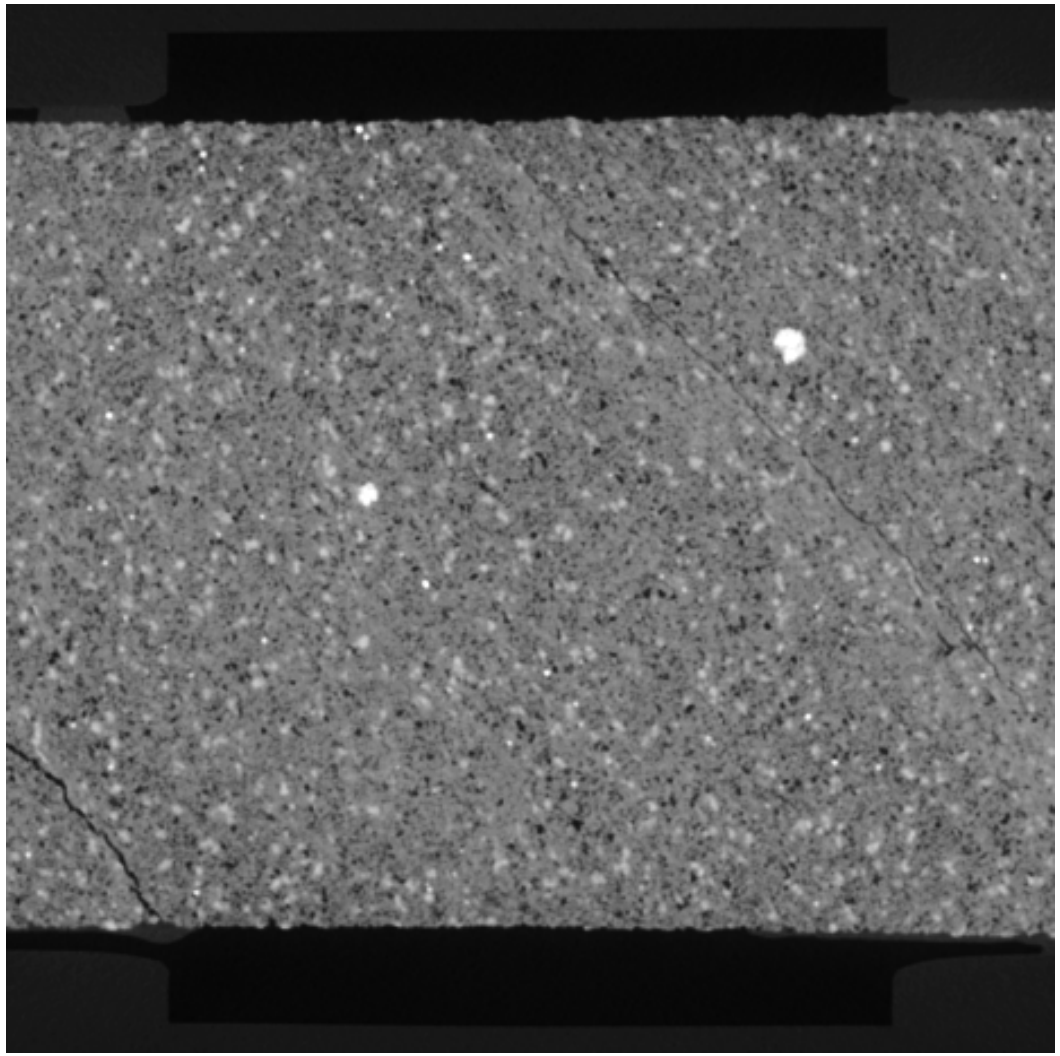
Bandera sandstone ("Small pores")

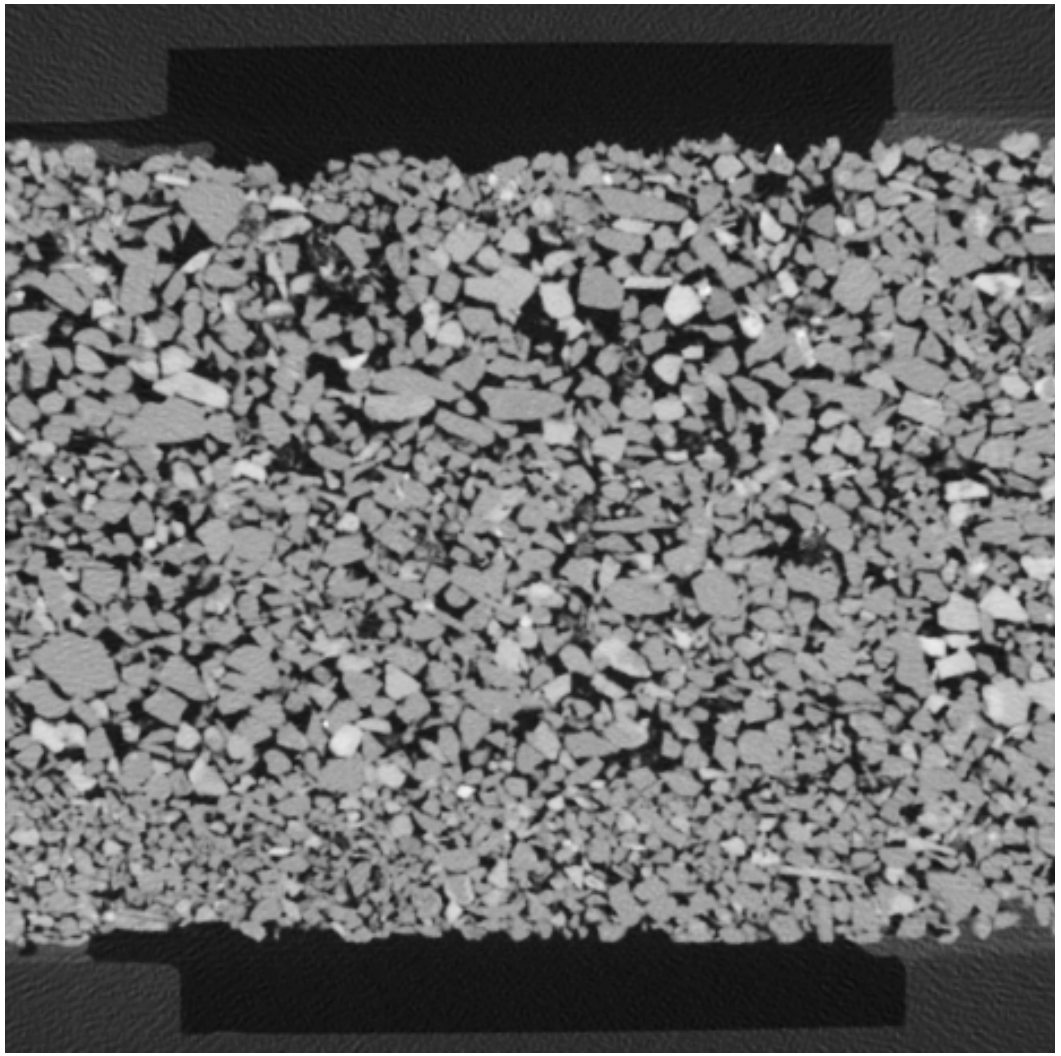
Thin, dense, surficial biofilm



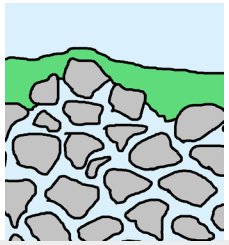
Boise sandstone ("Large pores")

Distributed, lower-density biofilm



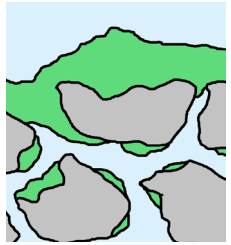


Biofilm growth alters diffusive and advective transport



Bandera sandstone ("Small pores")

Thin, dense, surficial biofilm

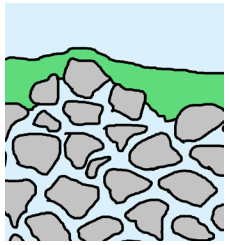


Boise sandstone ("Large pores")

Distributed, lower-density biofilm

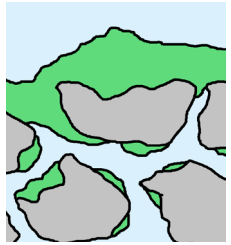
What are the consequences of different biofilm distributions for carbonate precipitation?

Biofilm growth into the porous matrix promotes carbonate precipitation



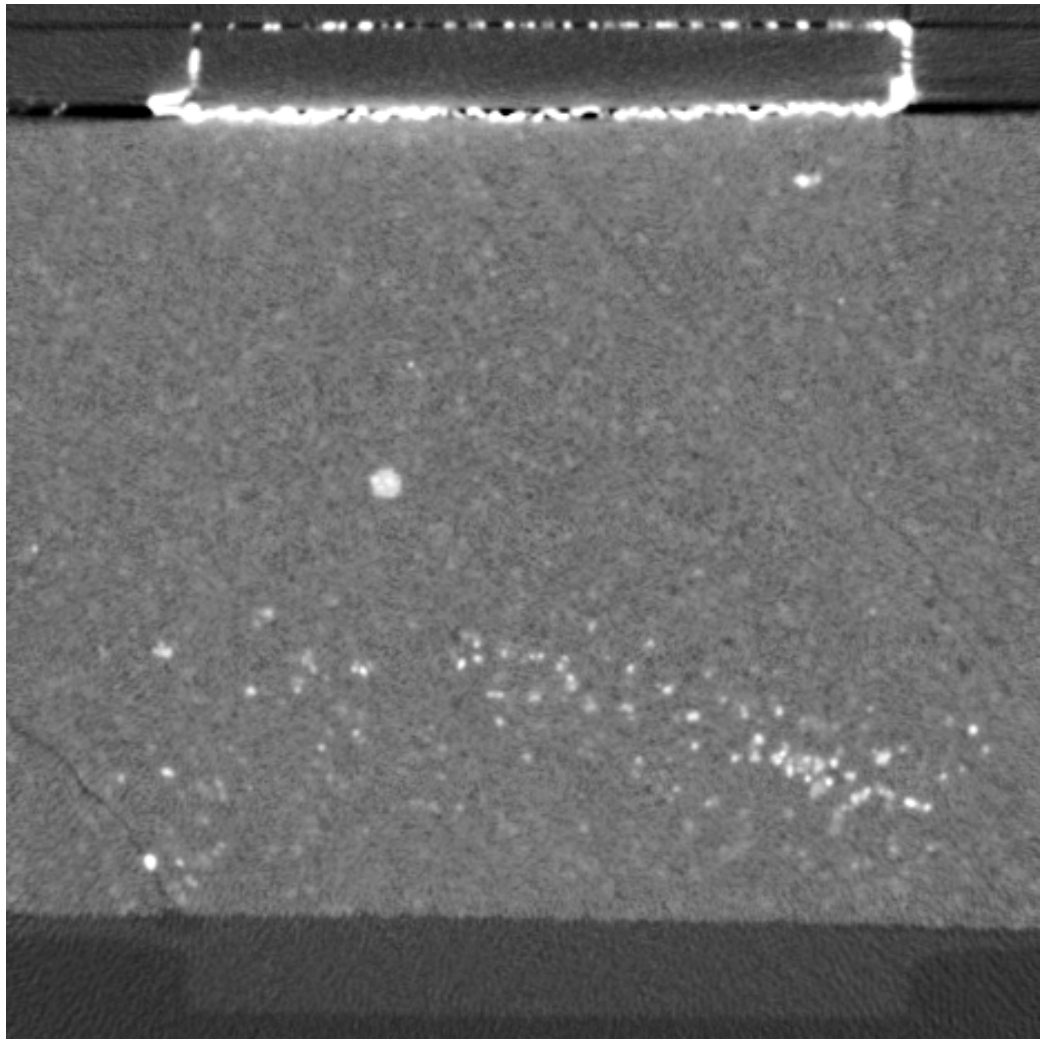
Bandera sandstone ("Small pores")

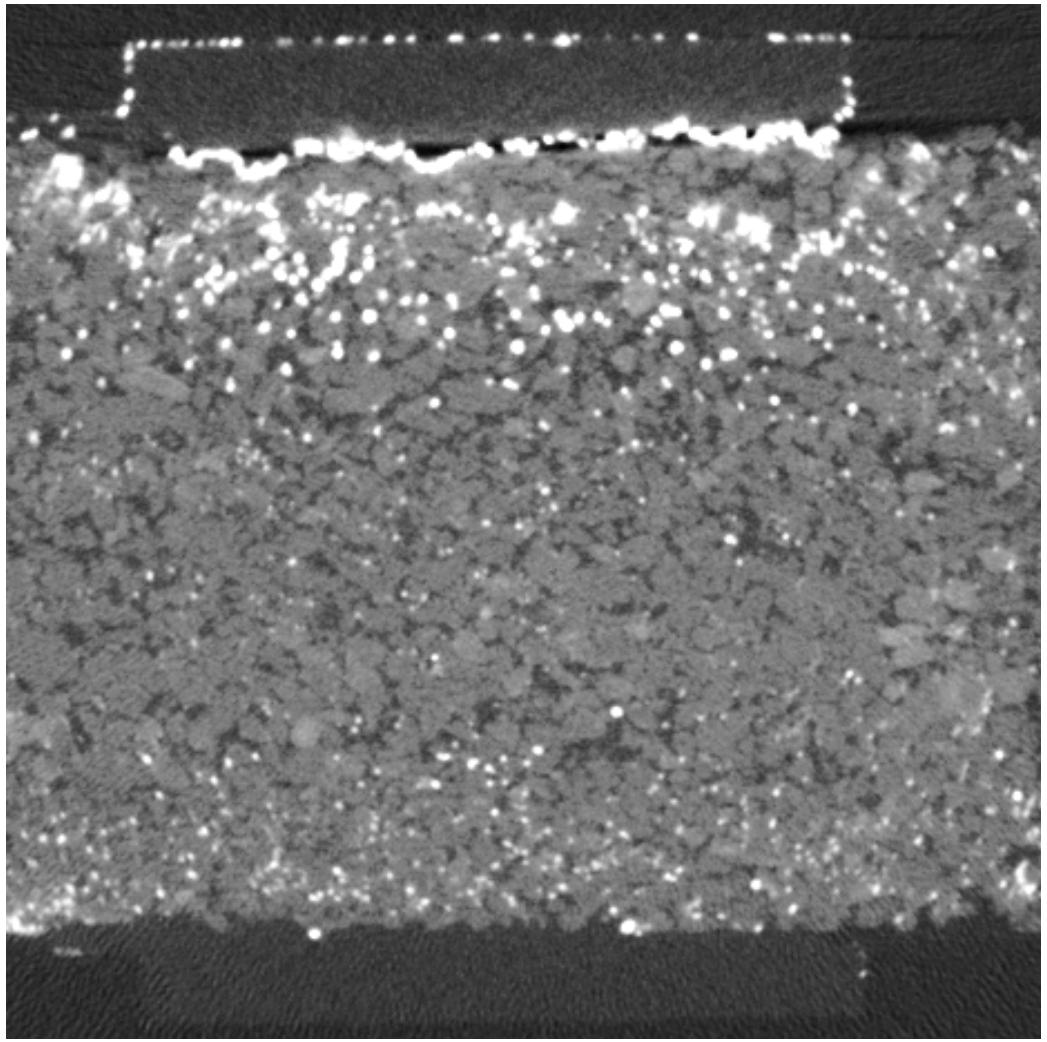
Thin, dense, surficial biofilm



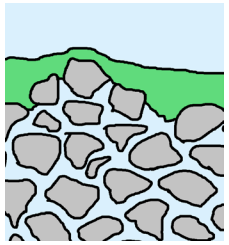
Boise sandstone ("Large pores")

Distributed, lower-density biofilm



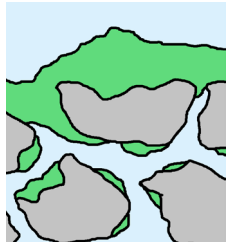


Biofilm growth into the porous matrix promotes carbonate precipitation



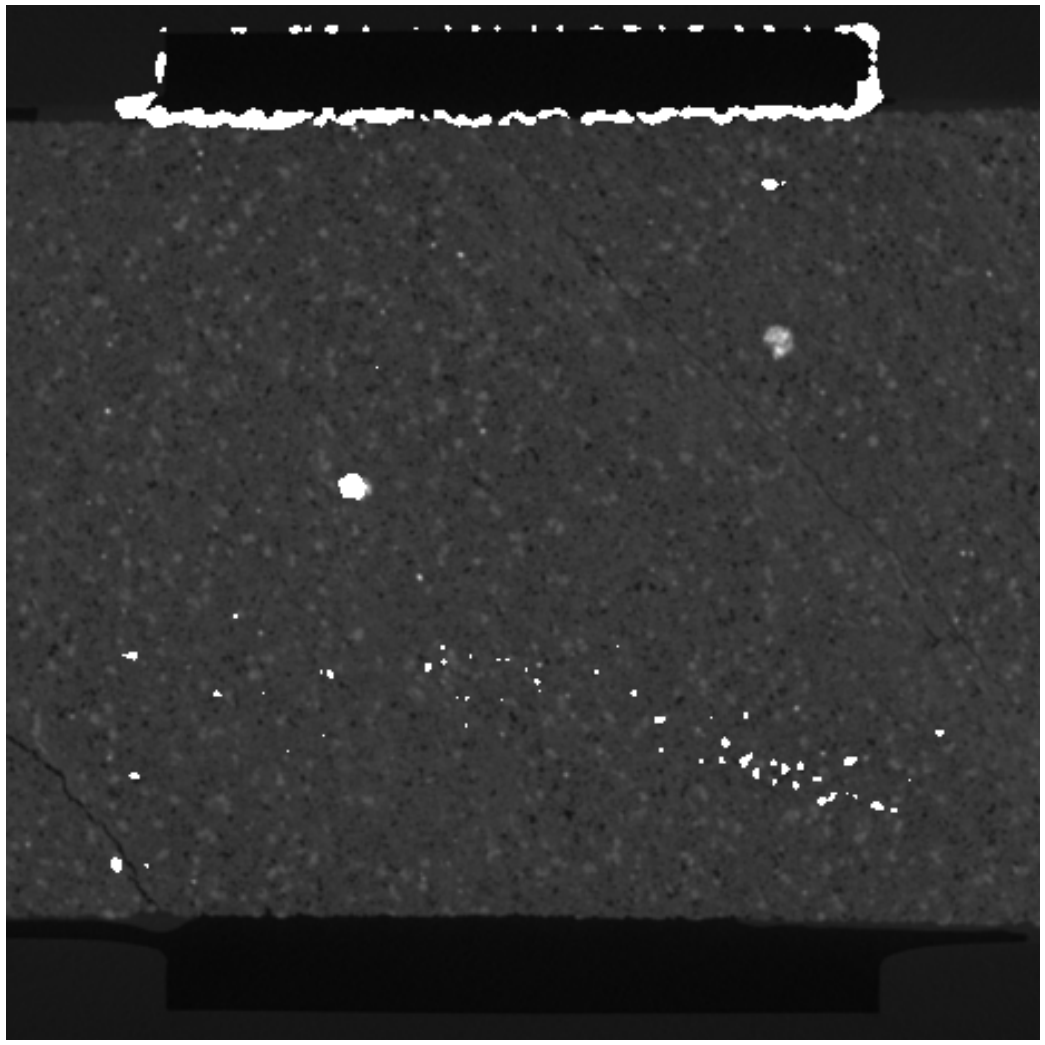
Bandera sandstone ("Small pores")

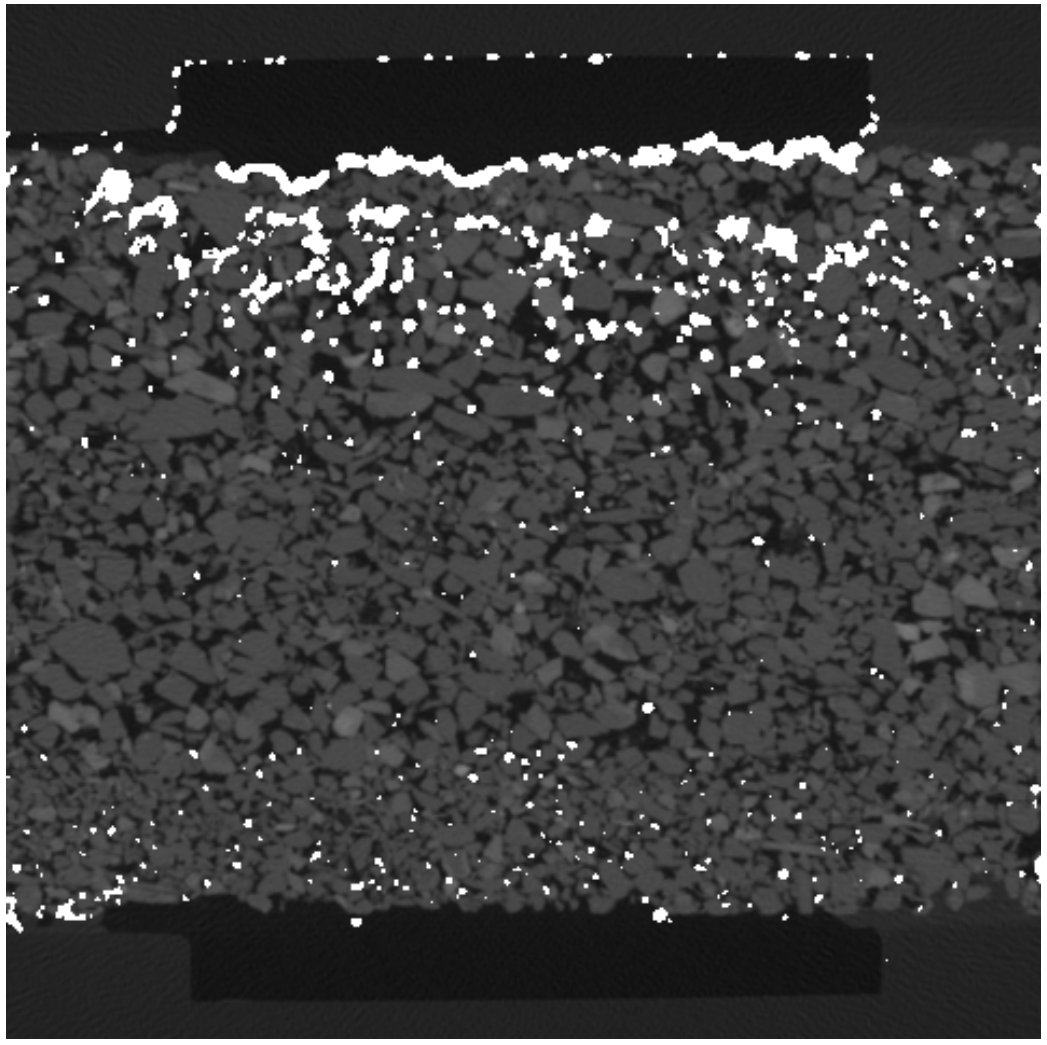
Thin, dense, surficial biofilm



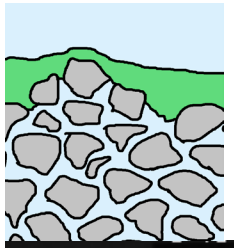
Boise sandstone ("Large pores")

Distributed, lower-density biofilm



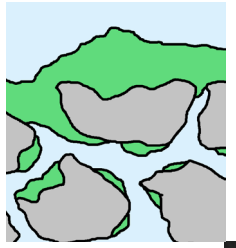


Biofilm growth into the porous matrix promotes carbonate precipitation



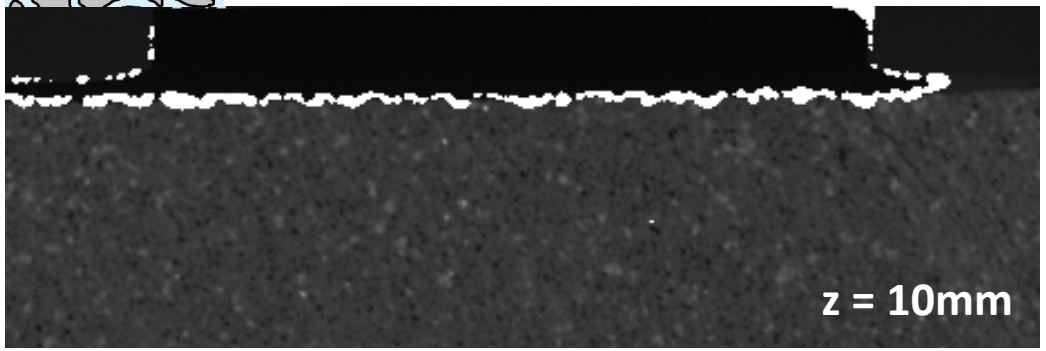
Bandera sandstone ("Small pores")

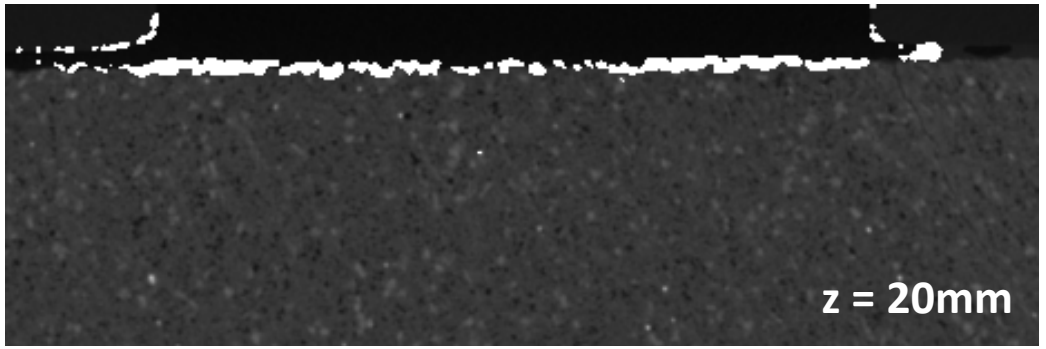
Thin, dense, surficial biofilm

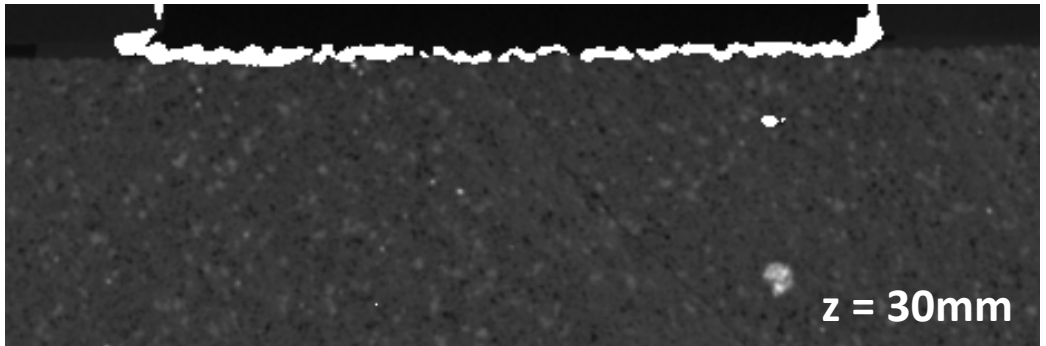


Boise sandstone ("Large pores")

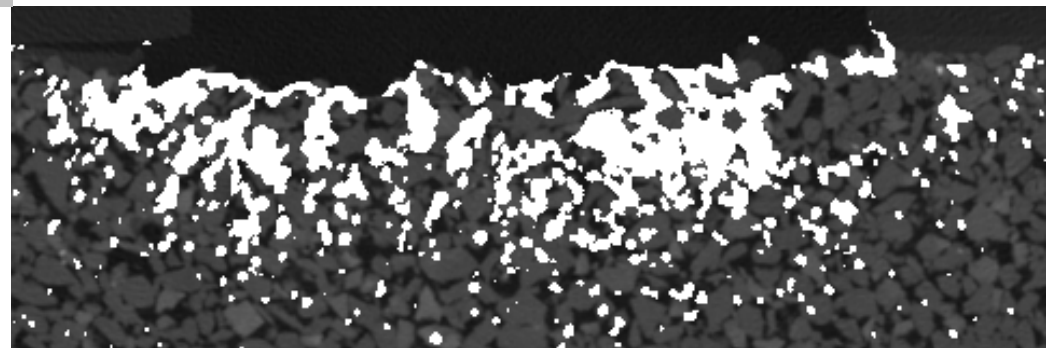
Distributed, lower-density biofilm

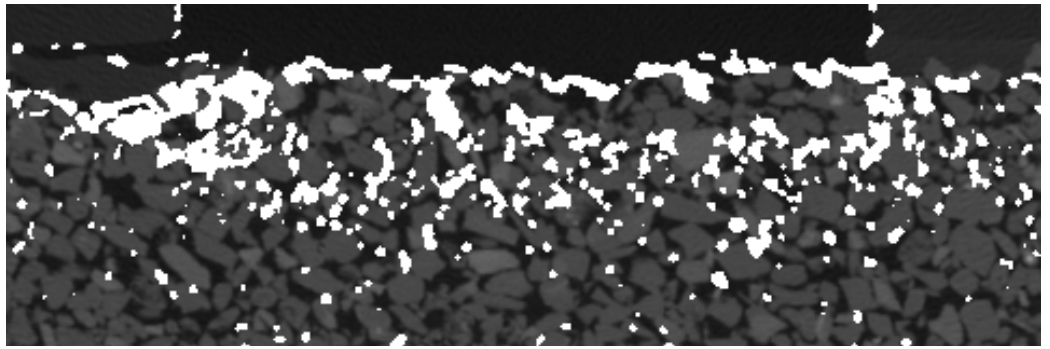


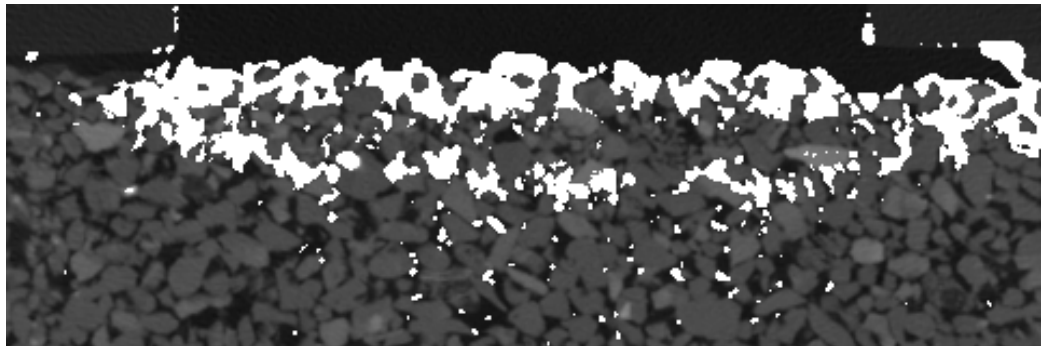




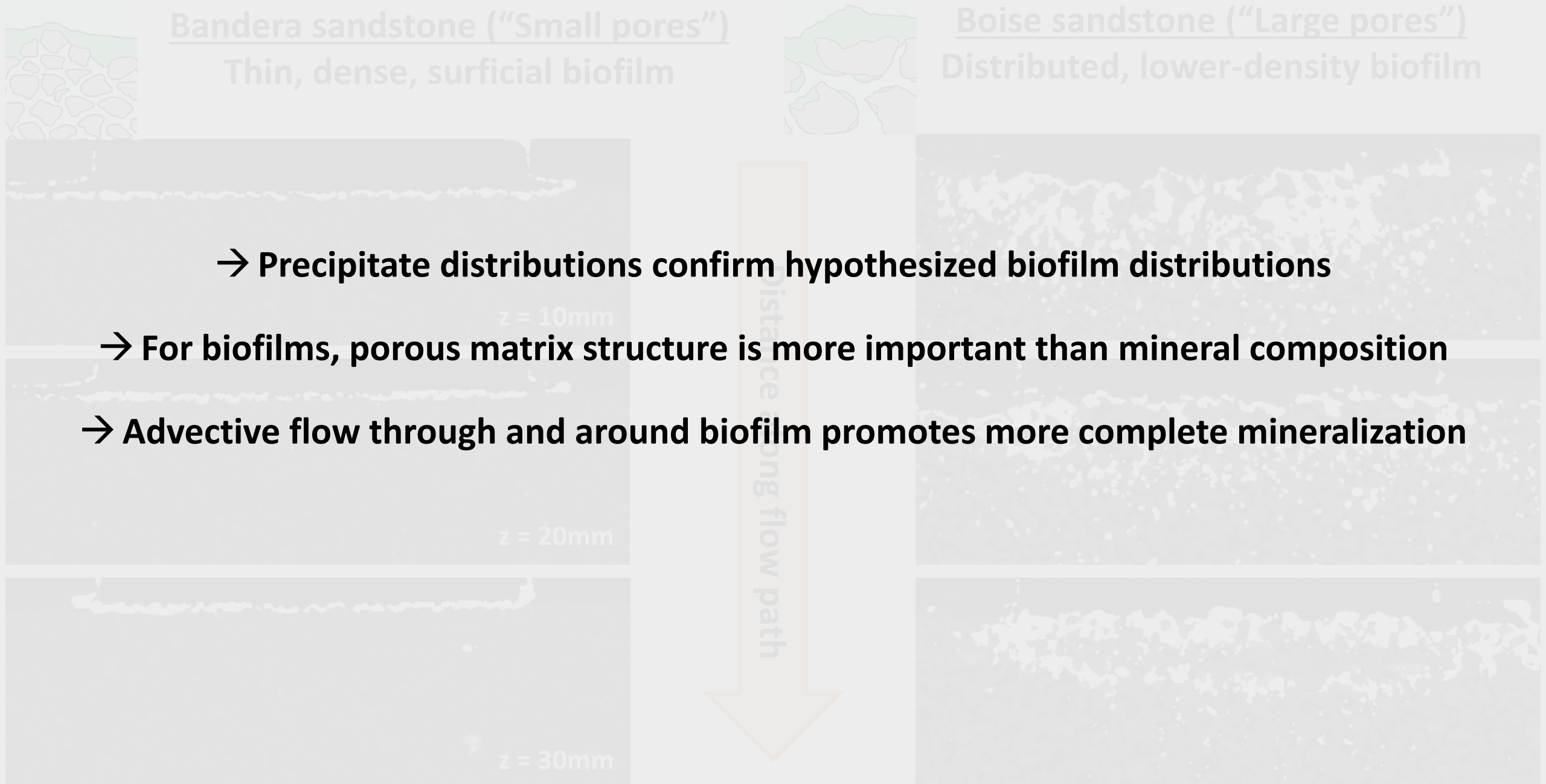
Distance along flow path







Biofilm growth into the porous matrix promotes carbonate precipitation

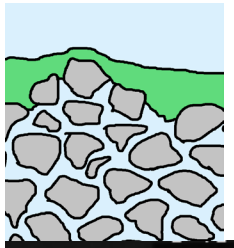


→ **Precipitate distributions confirm hypothesized biofilm distributions**

→ **For biofilms, porous matrix structure is more important than mineral composition**

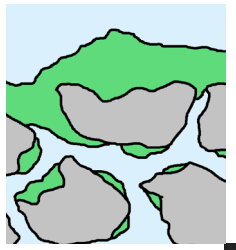
→ **Advective flow through and around biofilm promotes more complete mineralization**

Biofilm growth into the porous matrix promotes carbonate precipitation



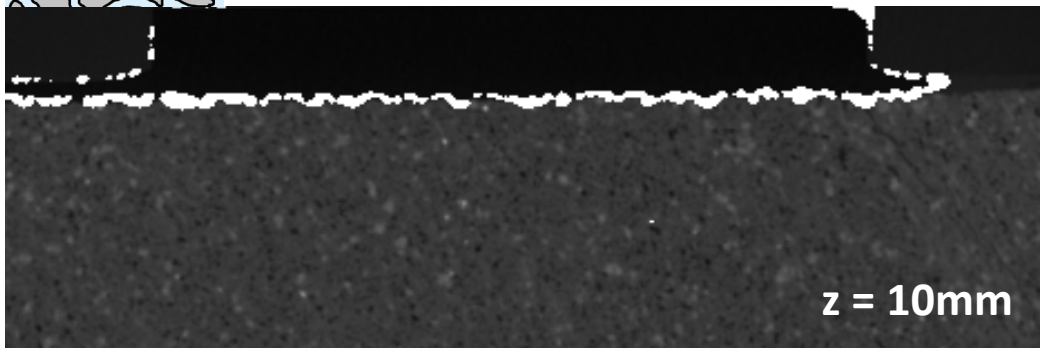
Bandera sandstone ("Small pores")

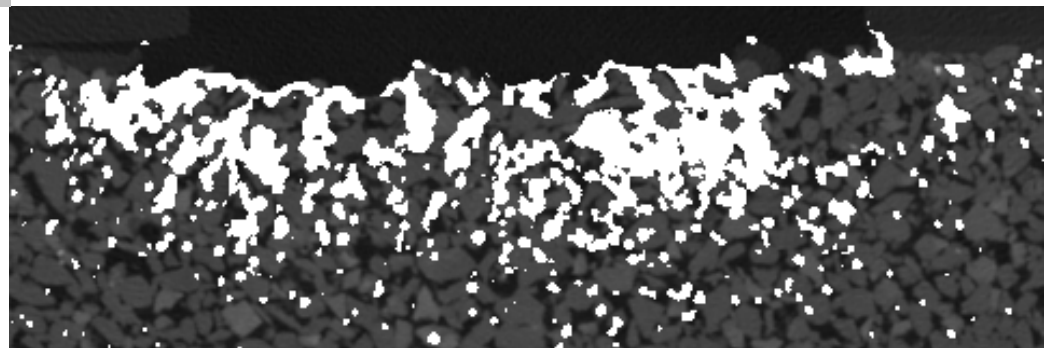
Thin, dense, surficial biofilm

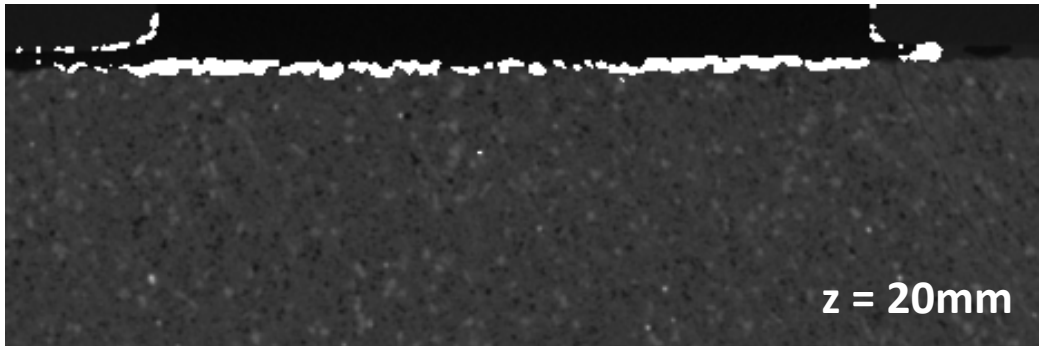


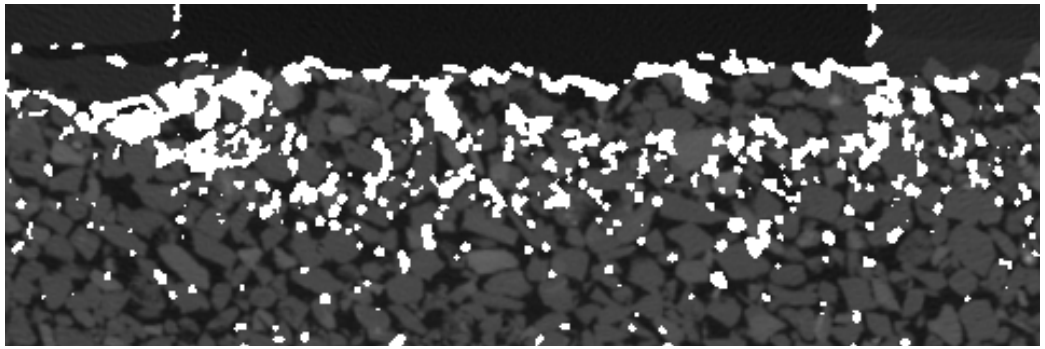
Boise sandstone ("Large pores")

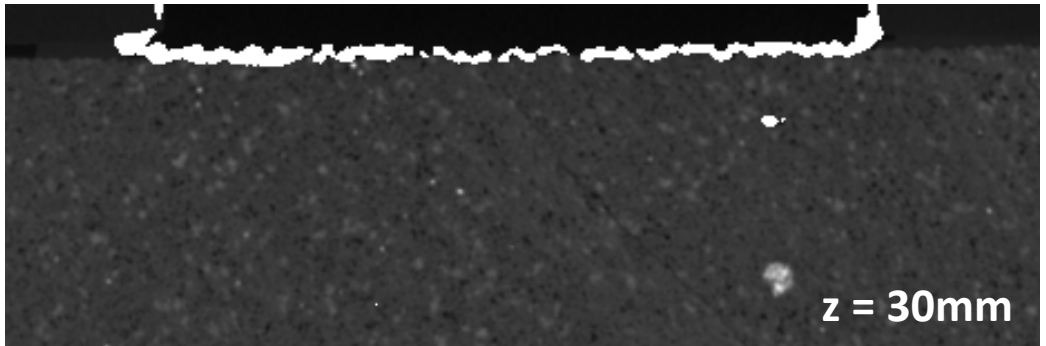
Distributed, lower-density biofilm

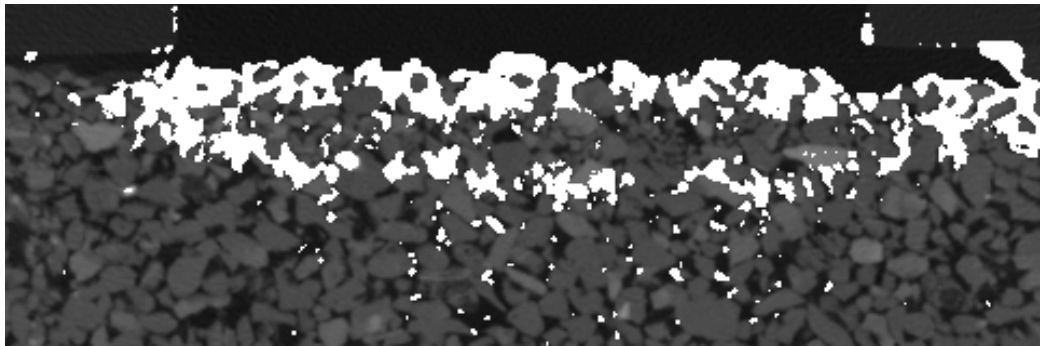




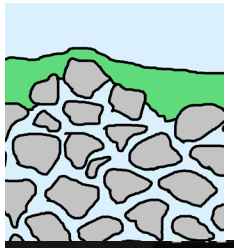






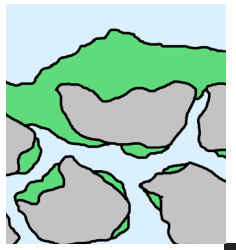


Biofilm growth into the porous matrix promotes carbonate precipitation



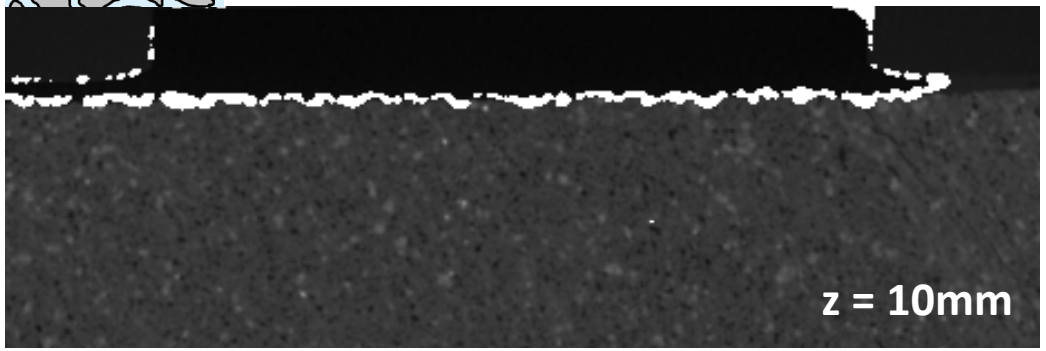
Bandera sandstone ("Small pores")

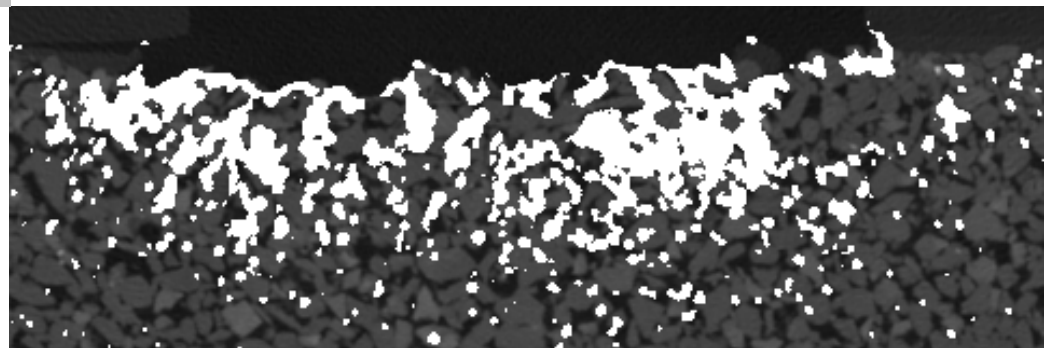
Thin, dense, surficial biofilm

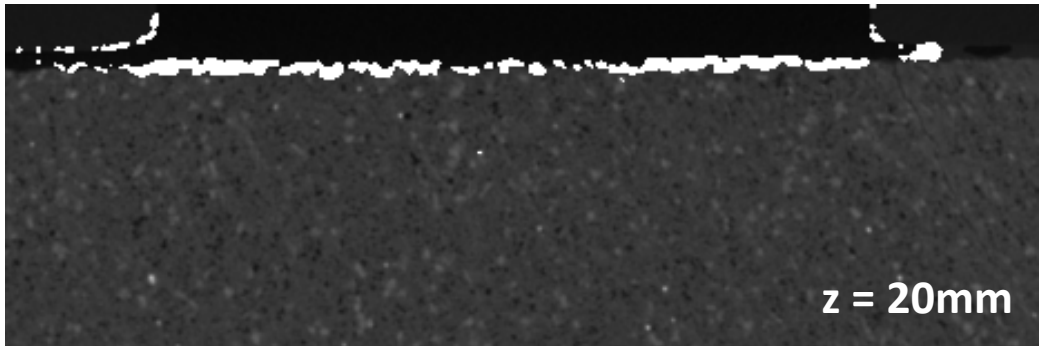


Boise sandstone ("Large pores")

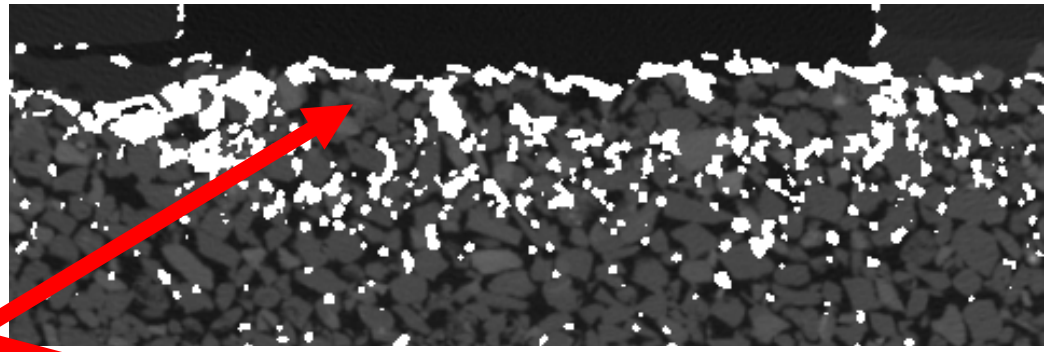
Distributed, lower-density biofilm

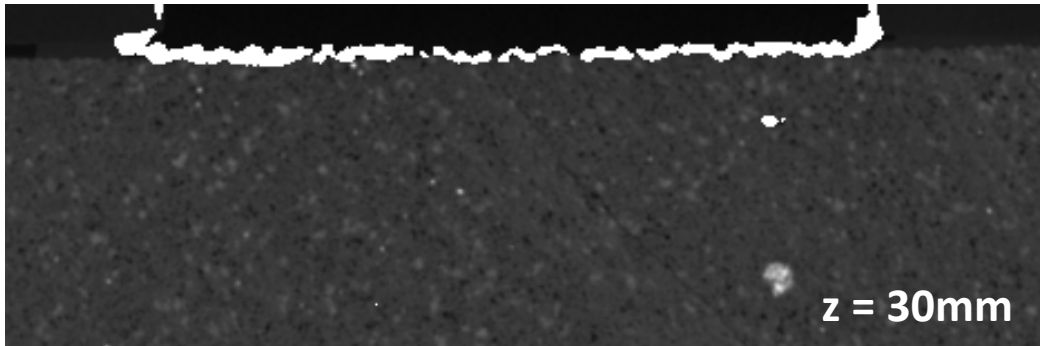


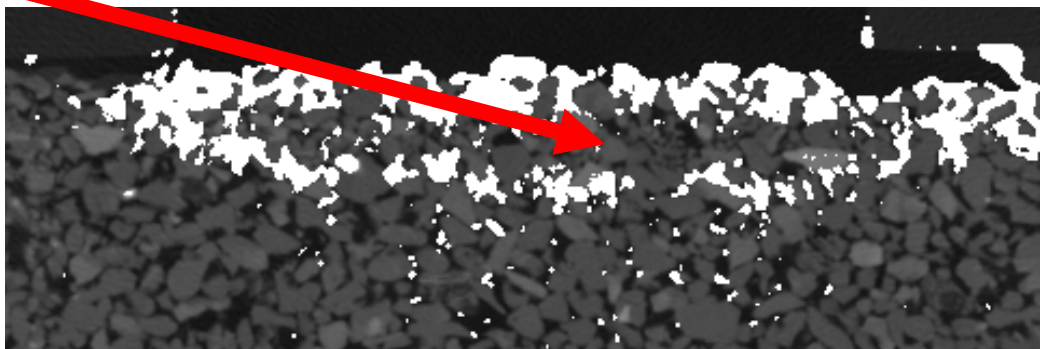




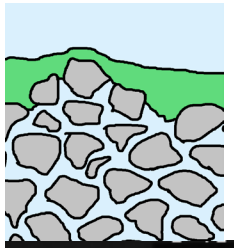
Unmineralized biofilm?





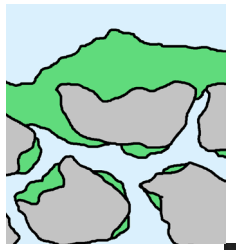


Solute transport limitations may lead to incomplete biofilm mineralization



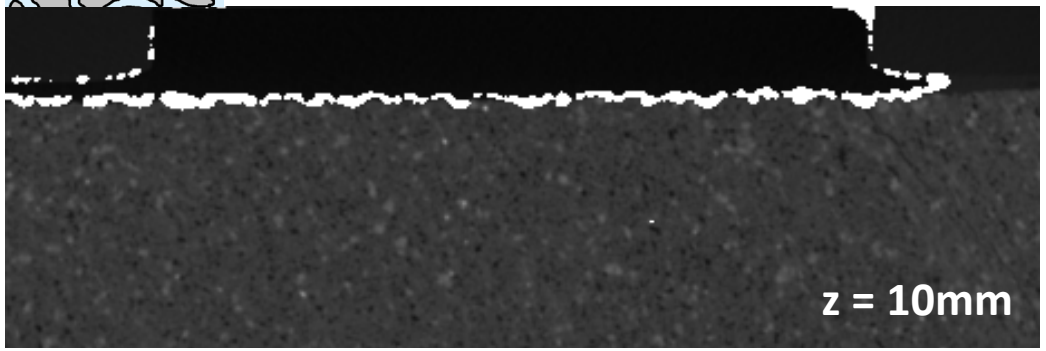
Bandera sandstone ("Small pores")

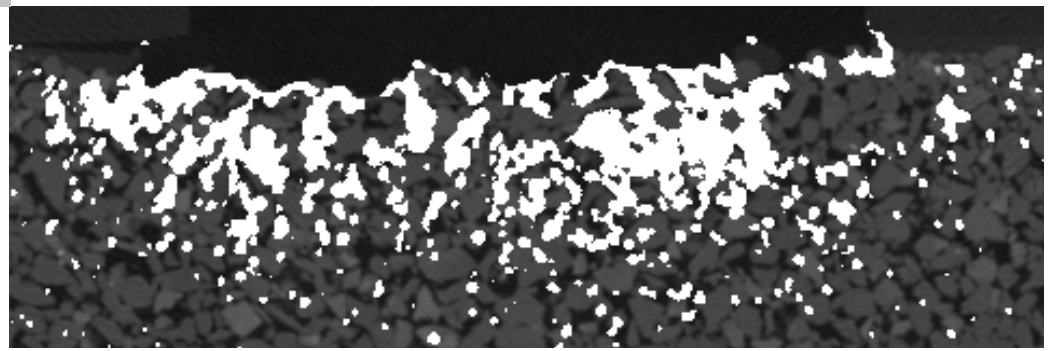
Thin, dense, surficial biofilm

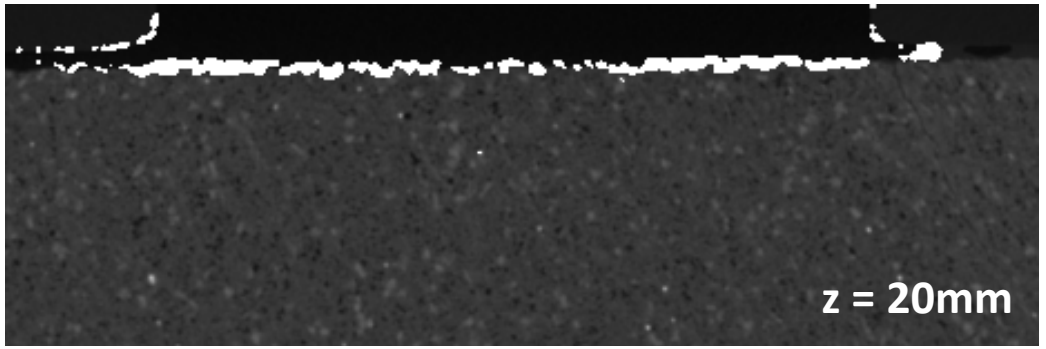


Boise sandstone ("Large pores")

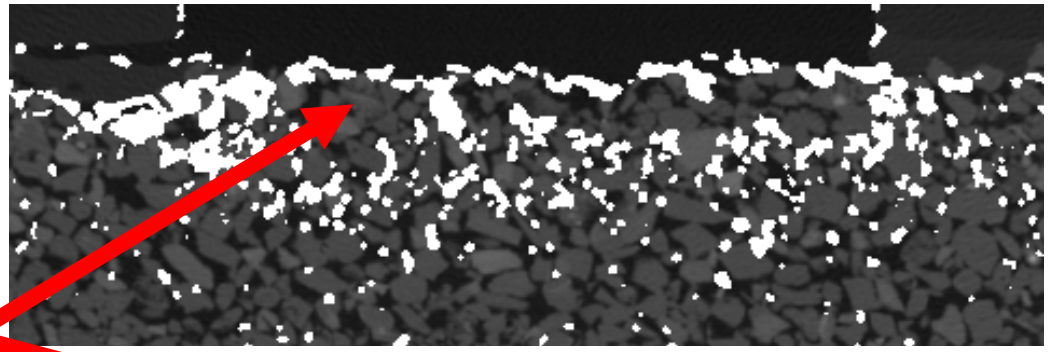
Distributed, lower-density biofilm

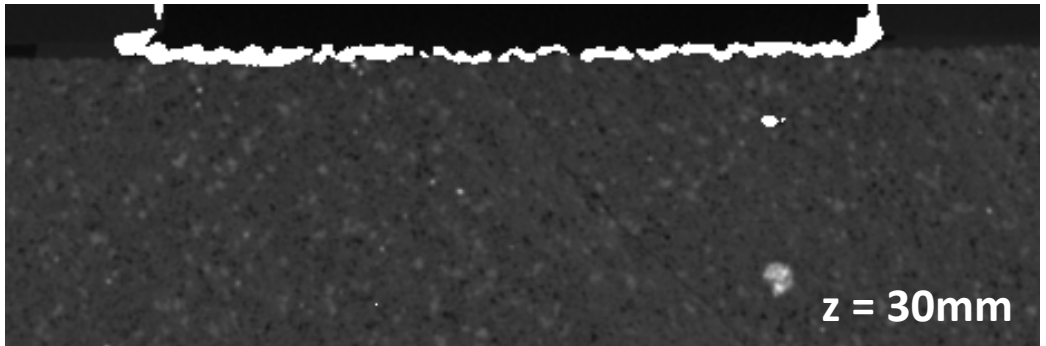


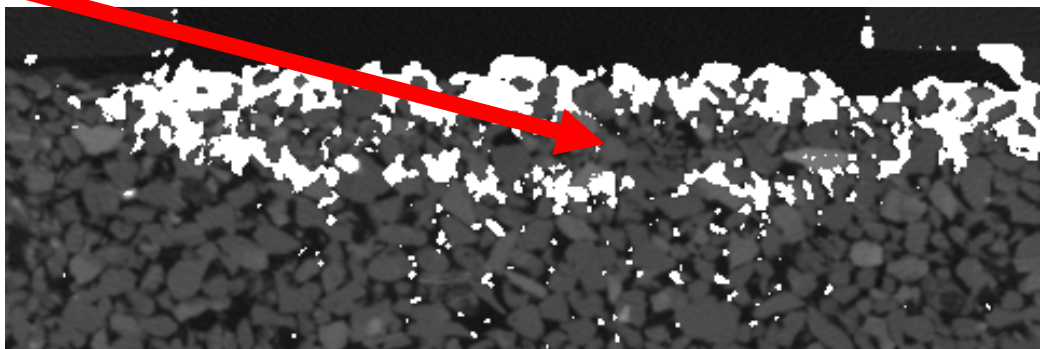




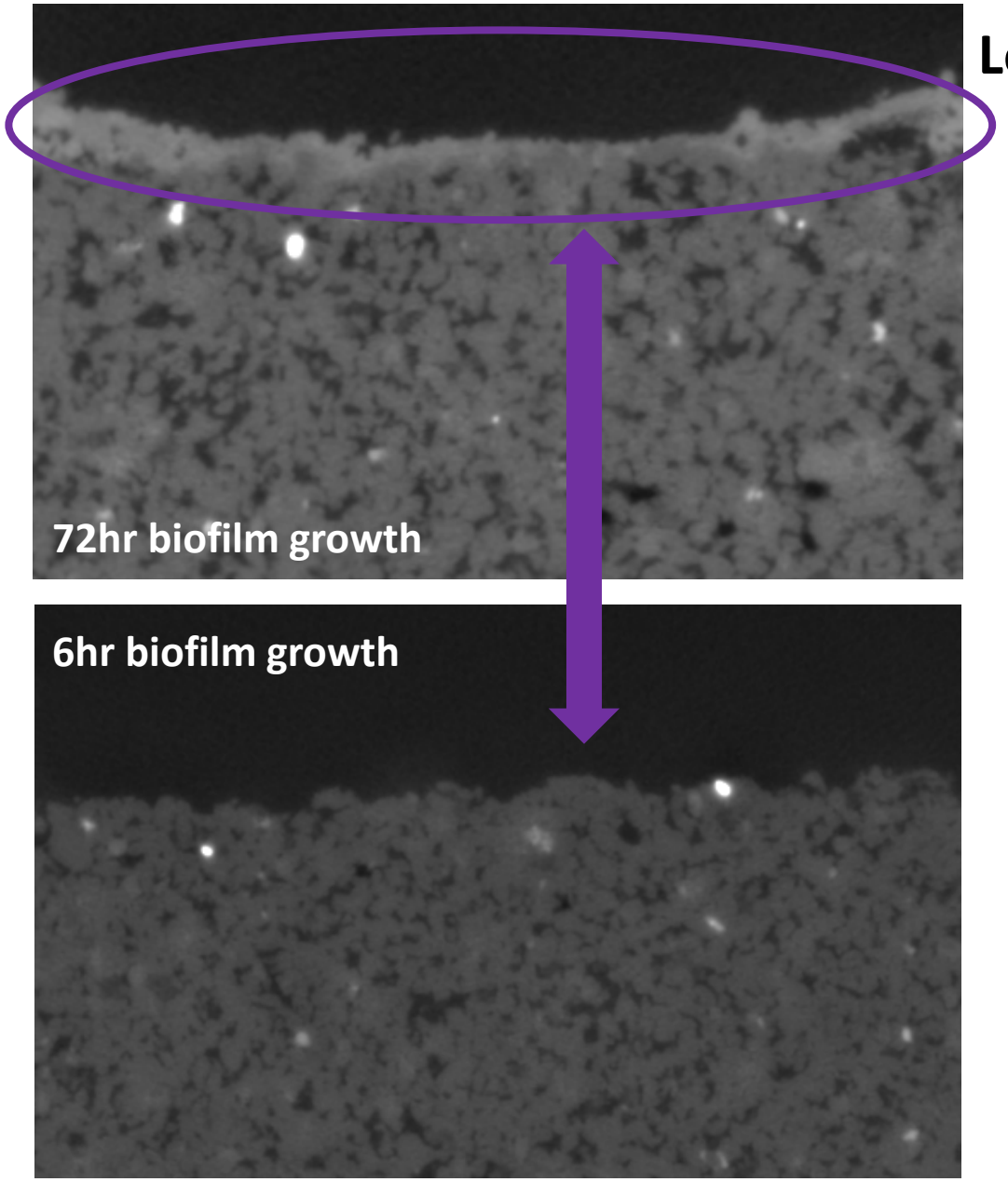
Unmineralized biofilm?





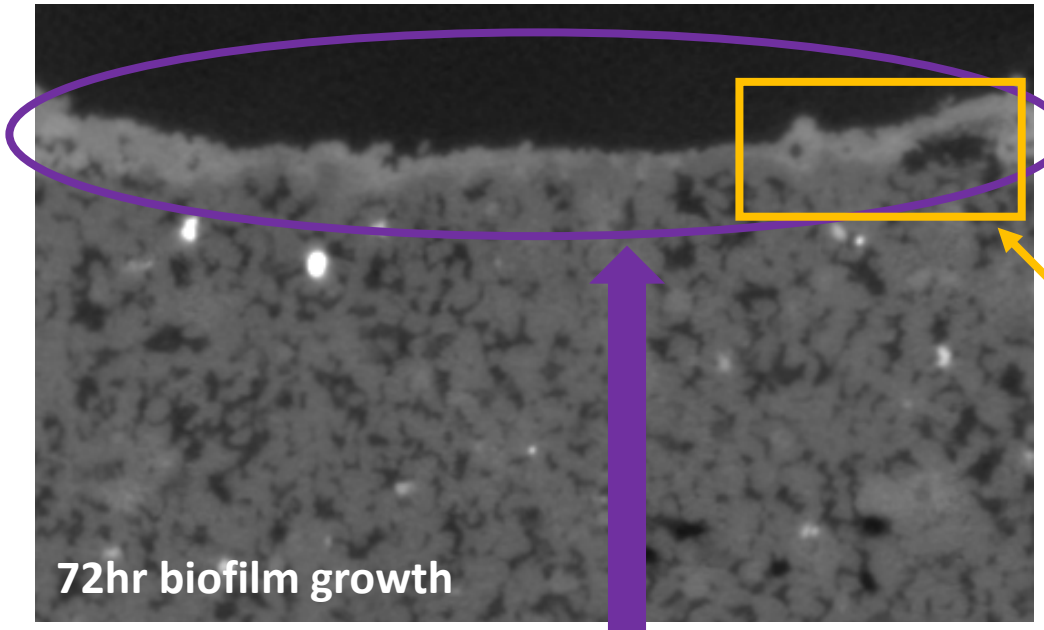


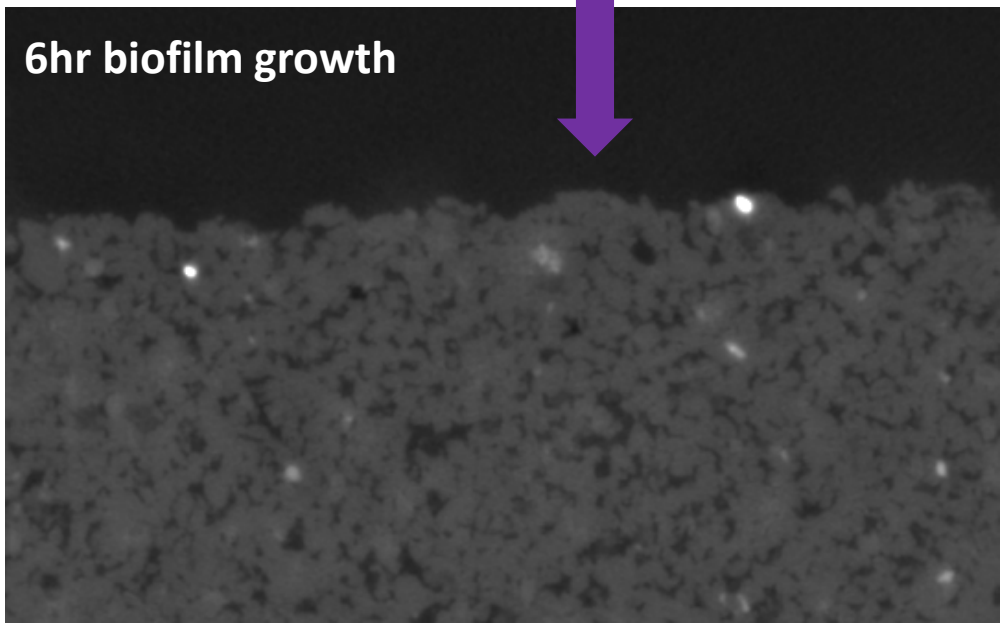
Solute transport limitations may lead to incomplete biofilm mineralization



Longer biofilm growth generally leads to more precipitate…

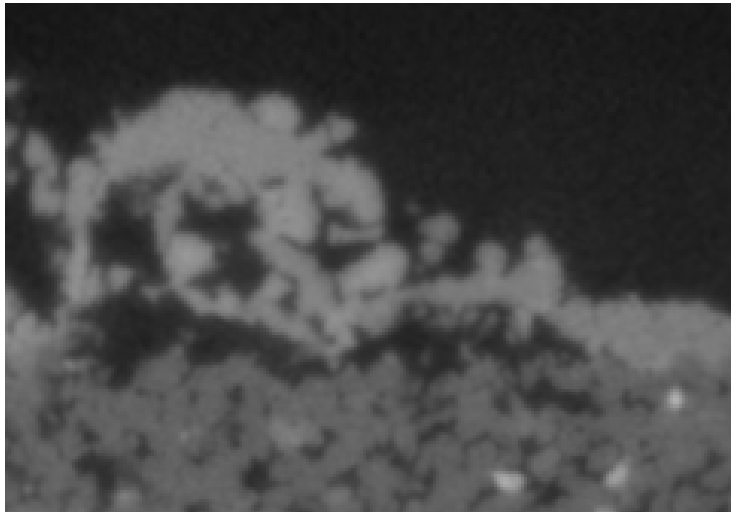
Solute transport limitations may lead to incomplete biofilm mineralization

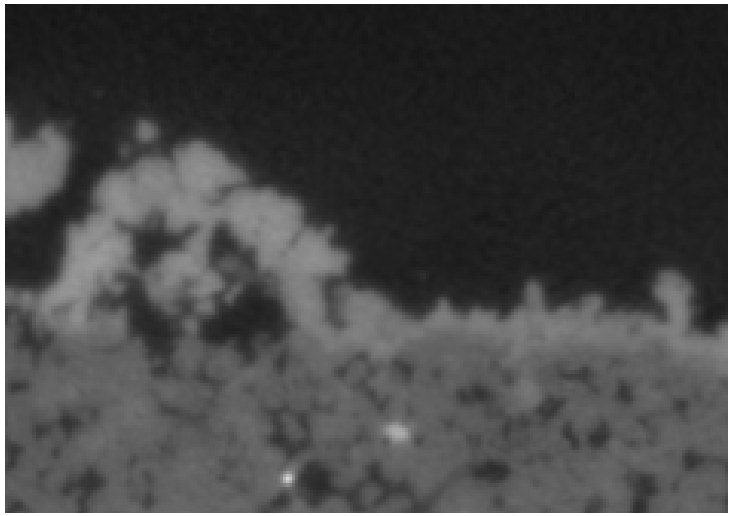


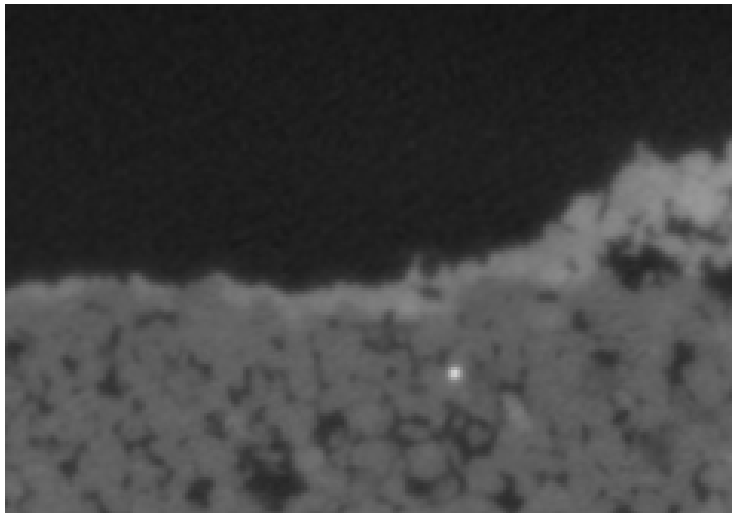


Longer biofilm growth generally leads to more precipitate…

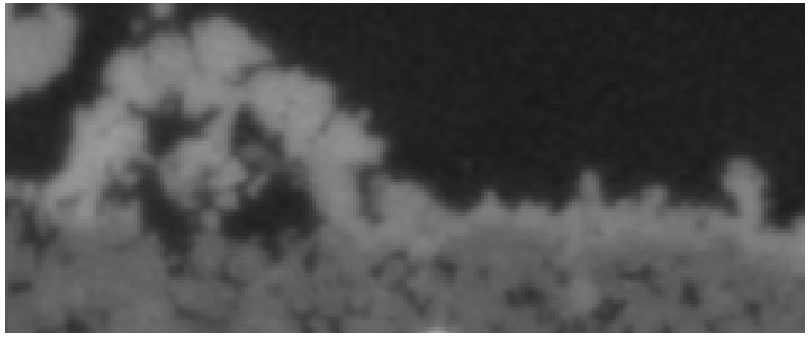
…but many “gaps” are visible between the mineralized layer and the rock surface:



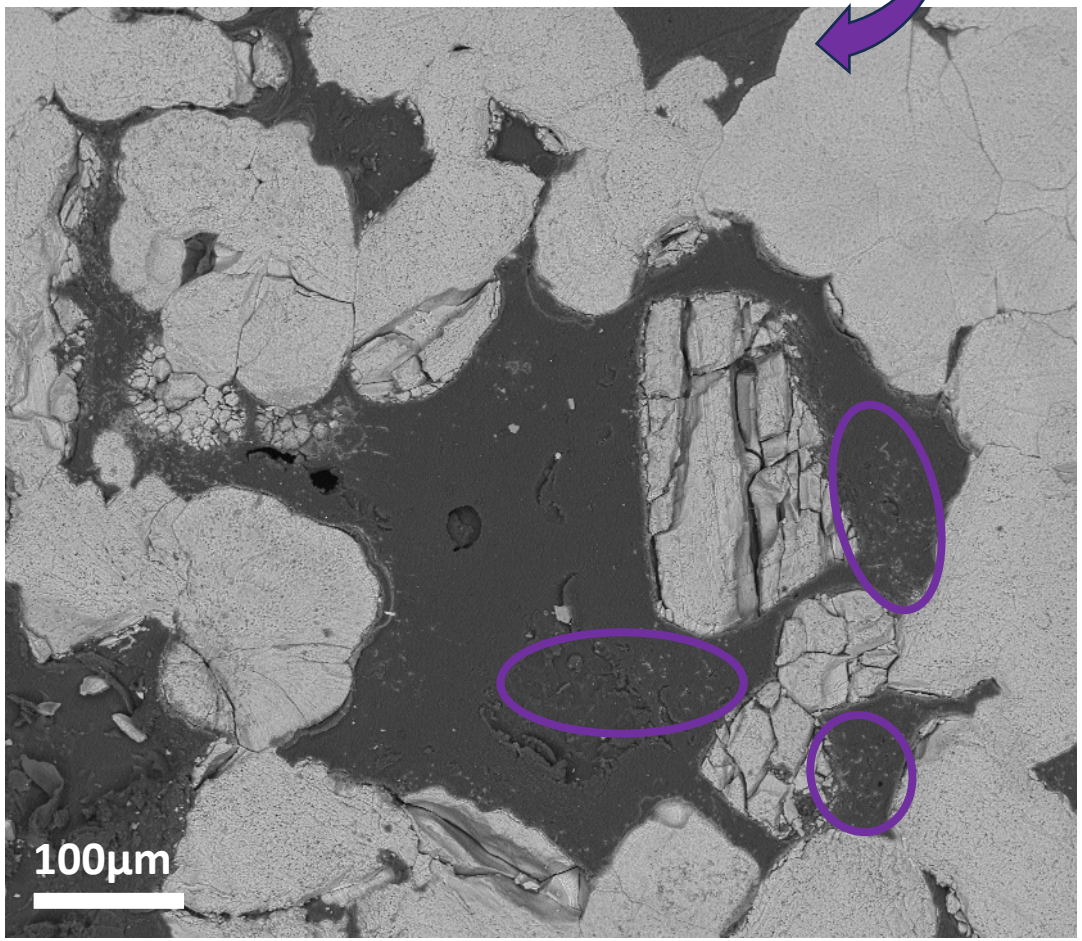




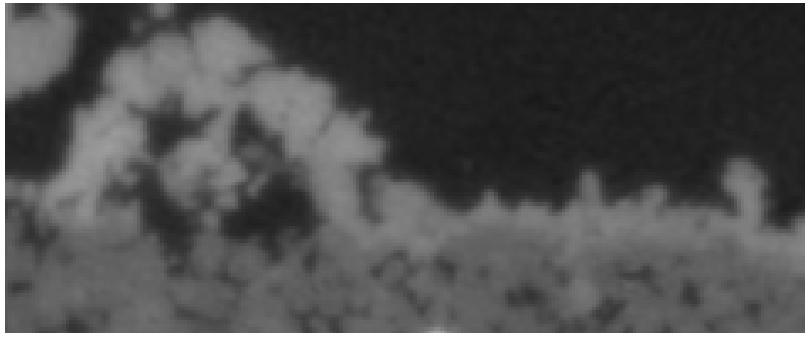
Solute transport limitations may lead to incomplete biofilm mineralization

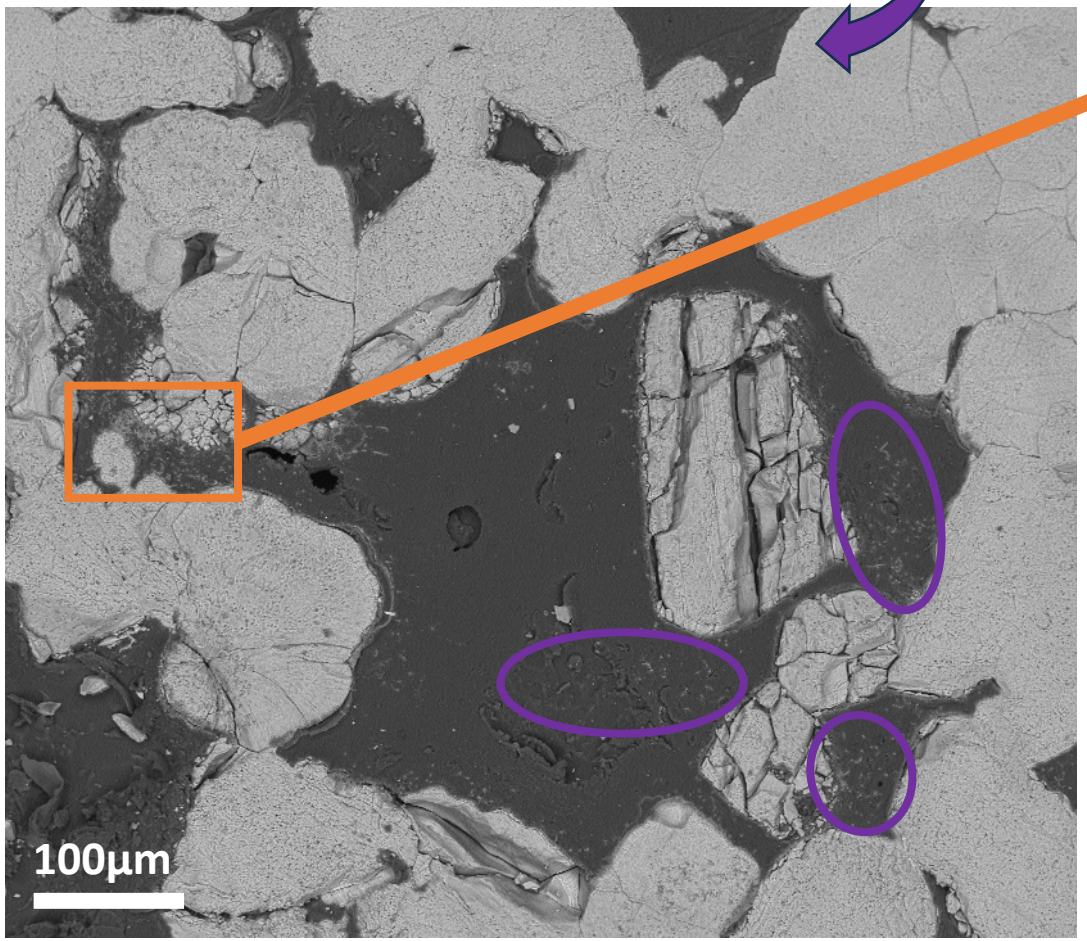


Higher-resolution SEM reveals internal biofilm



Solute transport limitations may lead to incomplete biofilm mineralization





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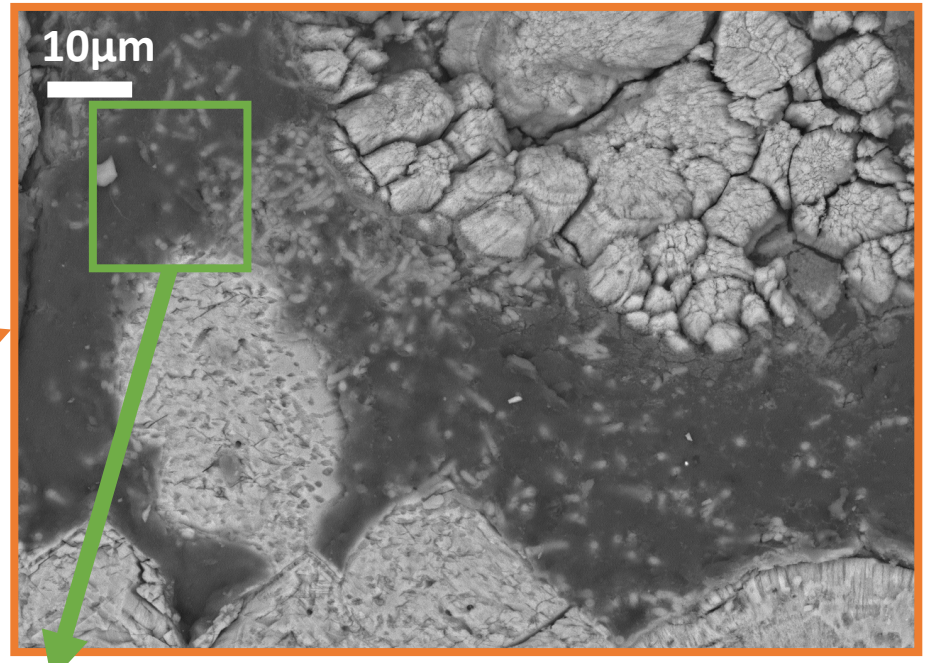
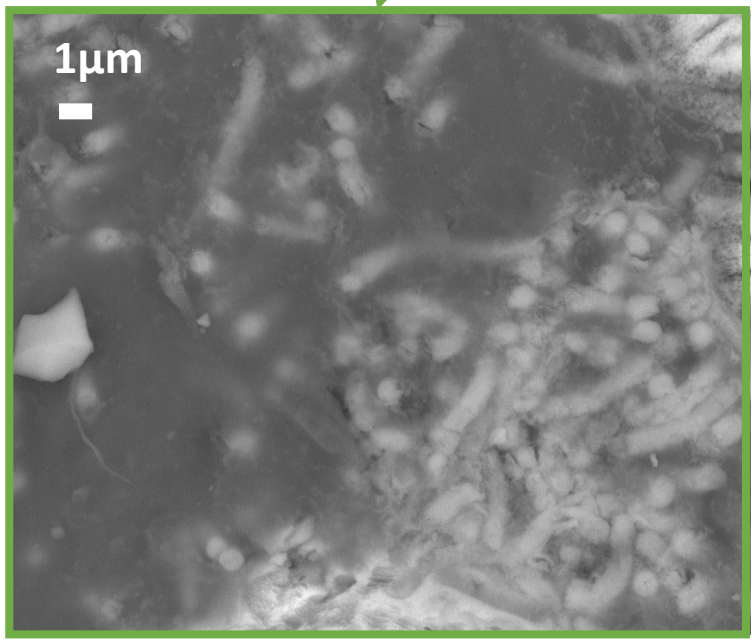
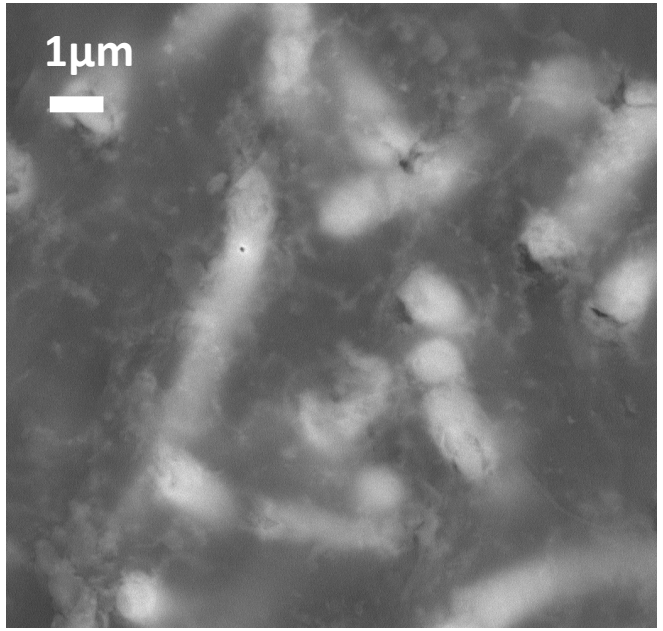
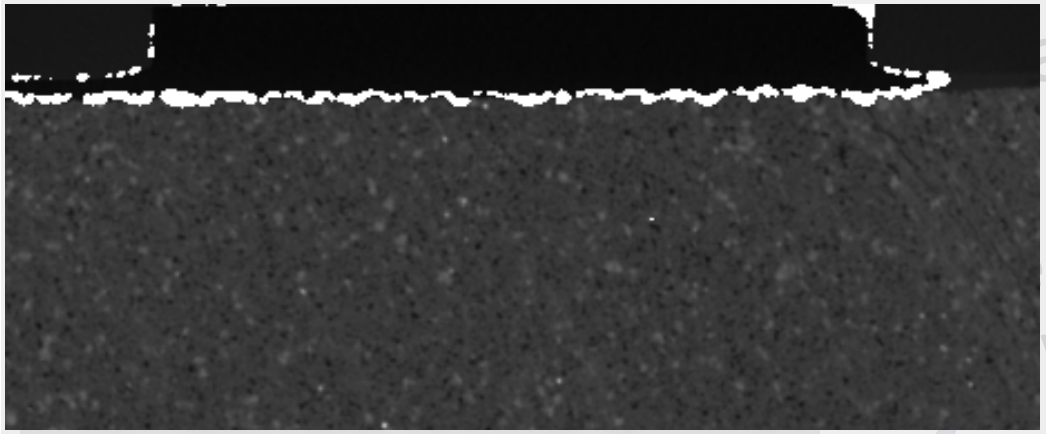
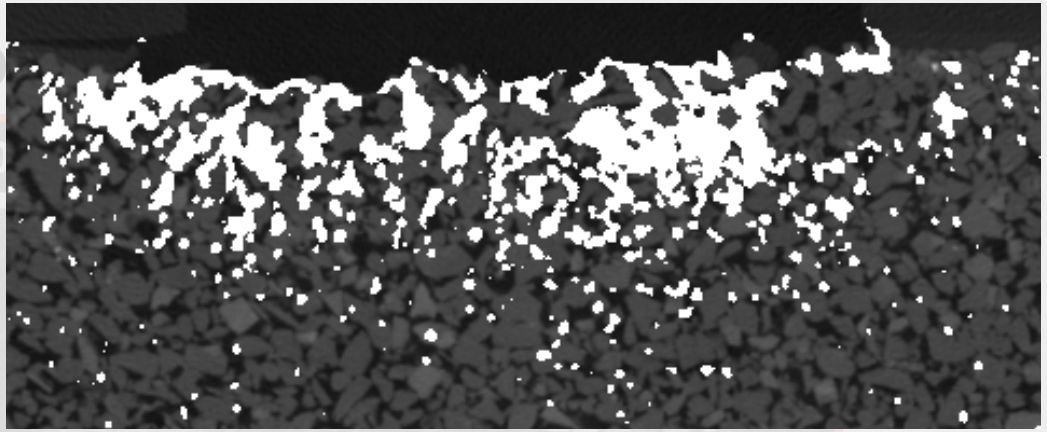






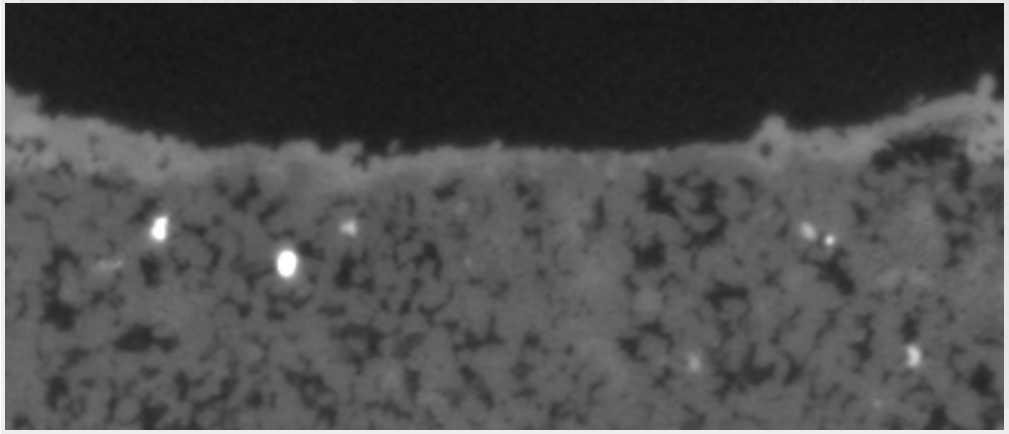


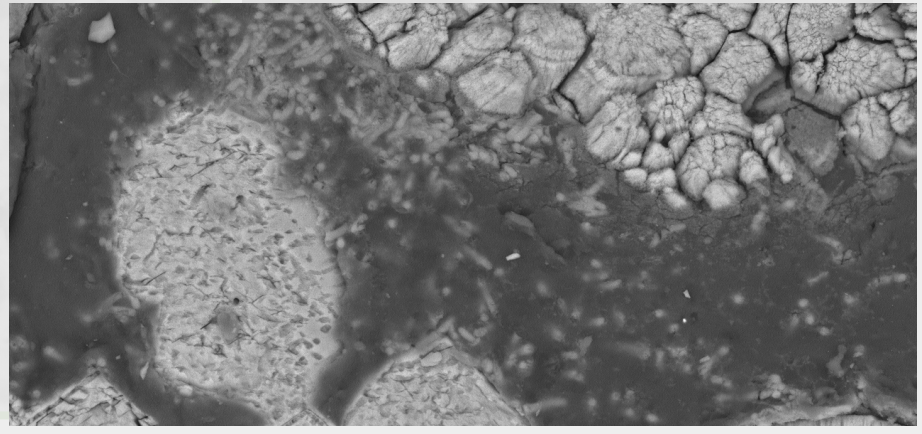


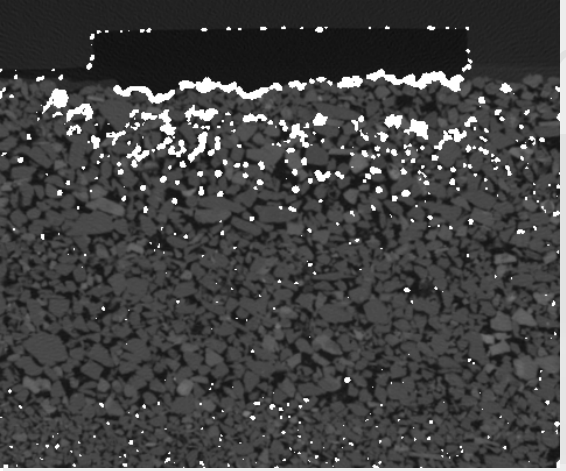
Important questions remain, such as:

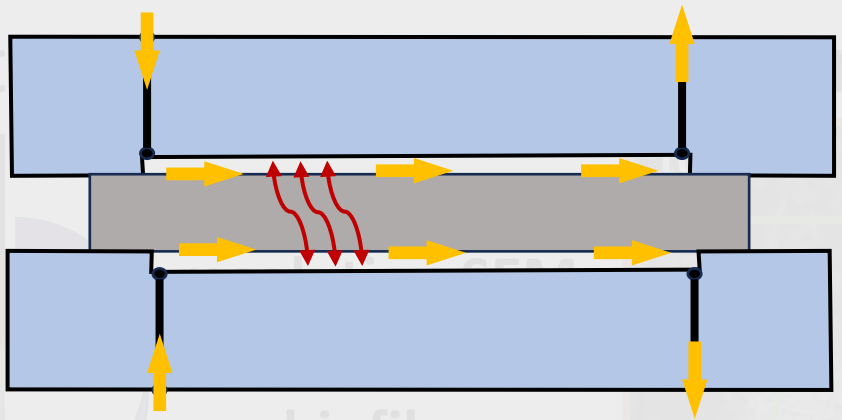
→ How does incomplete mineralization affect permeability reduction, solute transport, and precipitate resilience to shear stress?

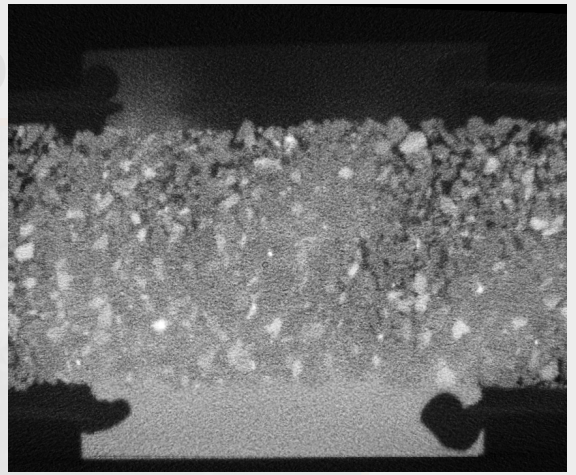
→ Can variables like flow rate and nutrient concentration be tuned to produce biofilms of desired solute transport properties for mineral precipitation?





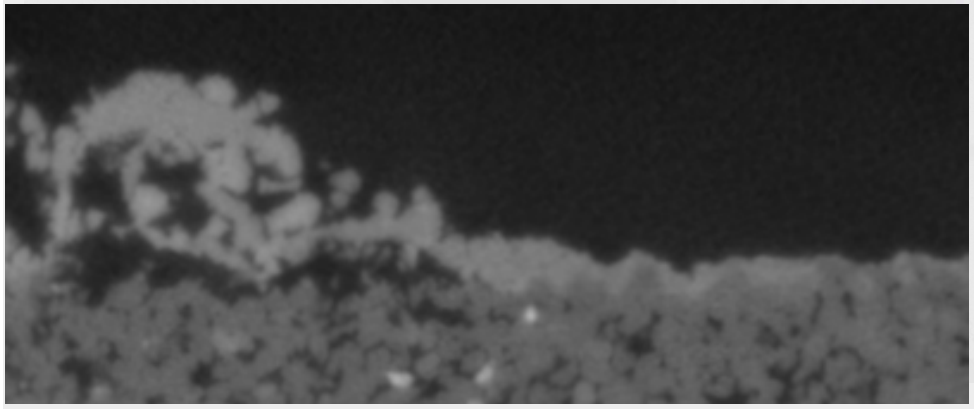






In summary, we can show:

1. **How rock pore size and structure mediates biofilm development**
2. **How biofilms affect solute transport in fractured rock systems**
3. **How solute transport constrains biofilm-induced carbonate precipitation**



THANK YOU ☺