Investigating the Effectiveness of the Dry and Two-Phase Zones Around Heaters for Vapor Extraction

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Thermal Conductive Heating: Best Practices and Lessons Learned
June 4, 2024

Outline

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  - Gas Migration During ISTT
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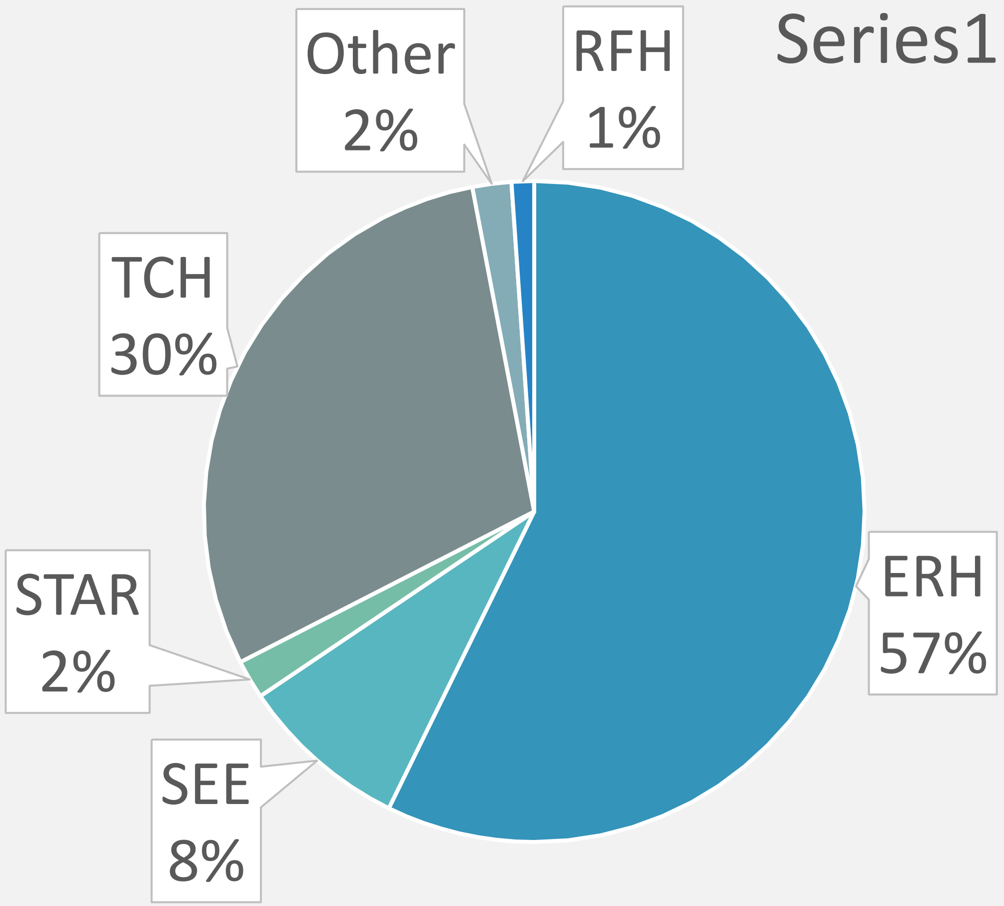
- Experimental Set-Up
  - Light Transmission TCH Experiments
- Results
  - Evolution of Gas Saturation and Temperature During Heating
  - Liquid Migration During and After Heating
- Summary and Conclusions

Motivation

Distribution of ISTT technologies used from 1988–2021 (Horst et al. 2021)



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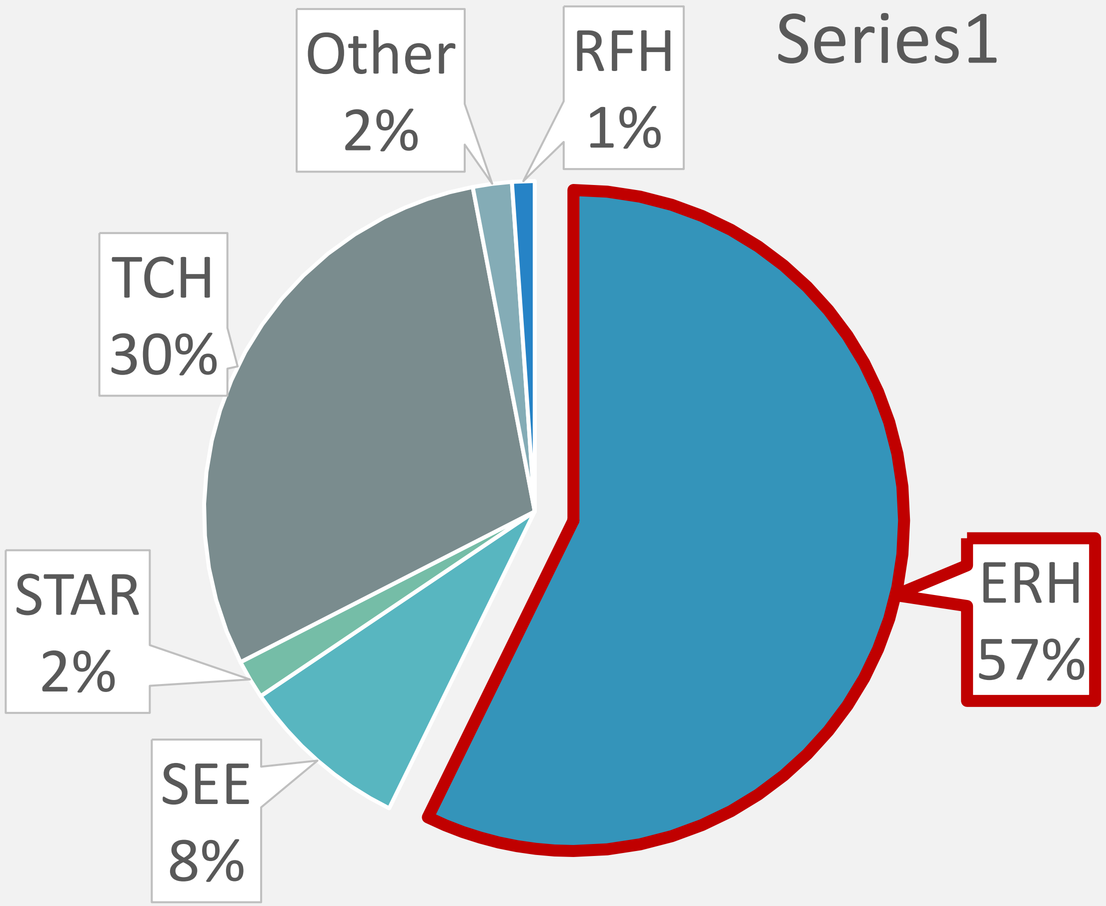

- Most ISTT projects used ERH
- Most investigations of subsurface gas migration during ISTT have also used ERH

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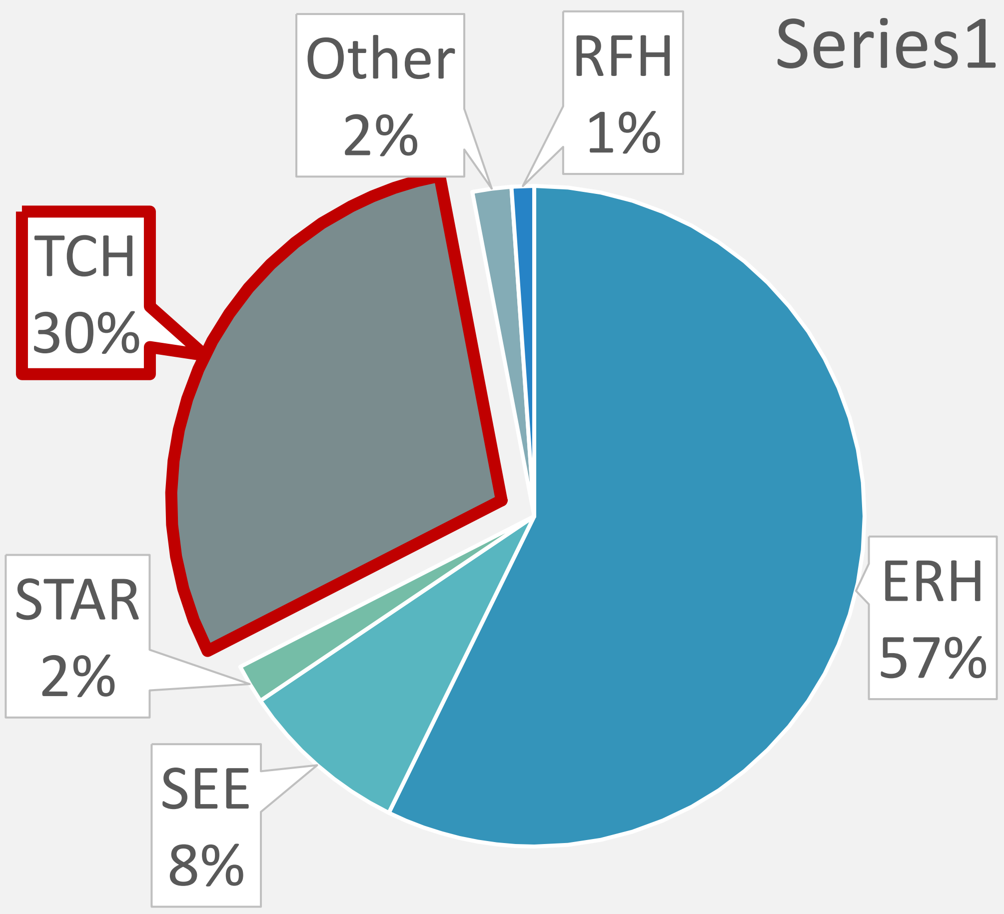

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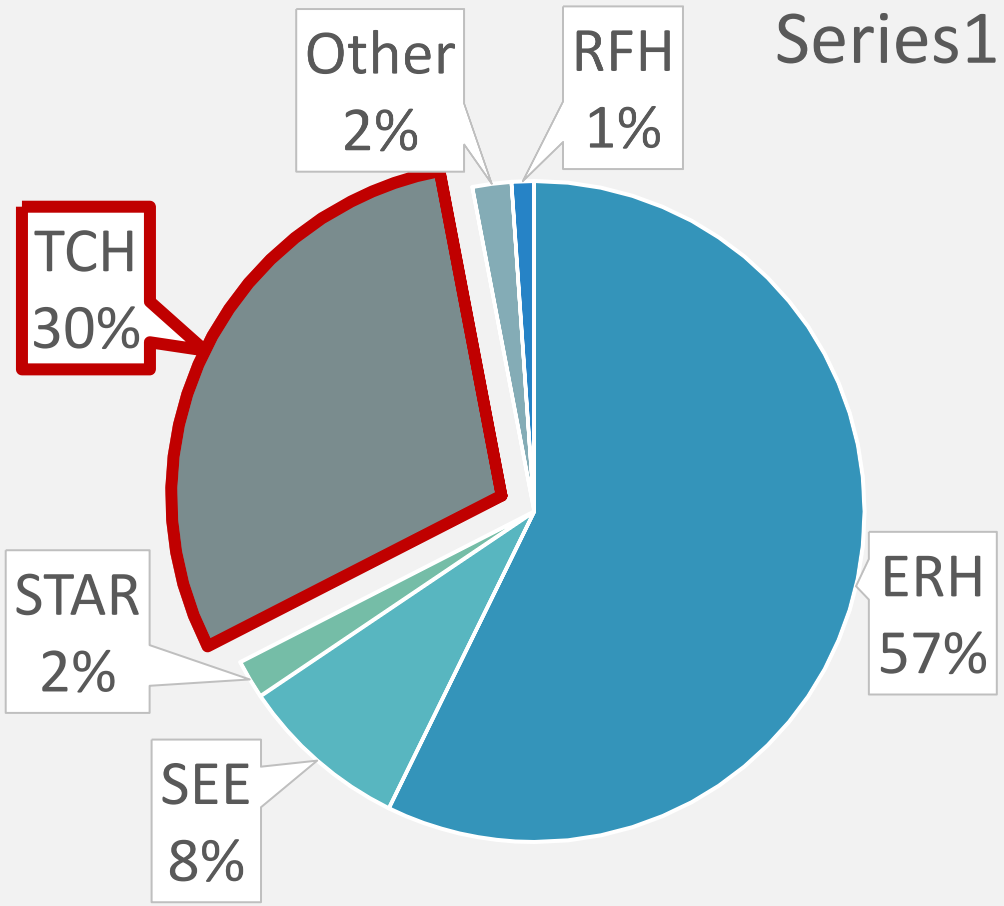
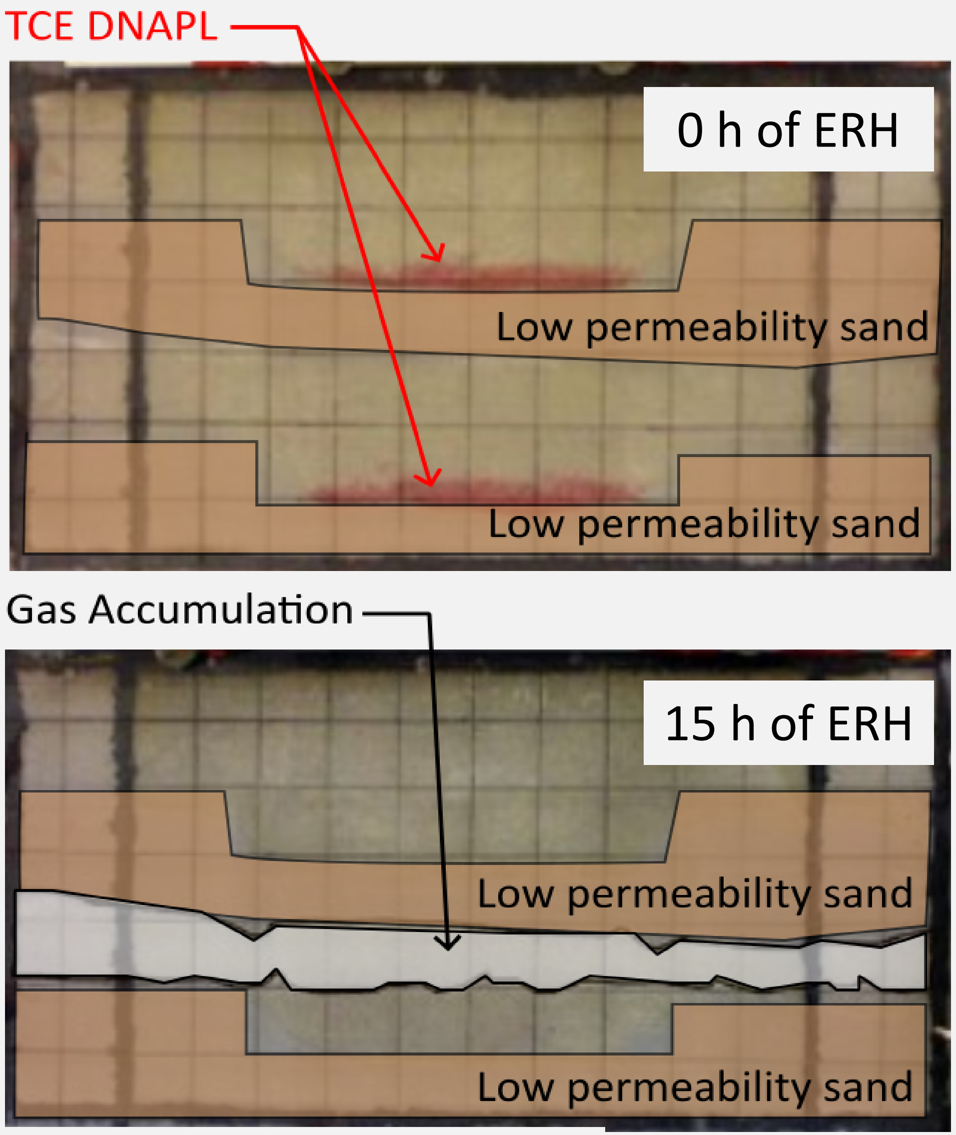


- Most ISTT projects used ERH
- Most investigations of subsurface gas migration during ISTT have also used ERH
- Few experiments have investigated TCH in heterogeneous conditions

Gas Accumulation and Migration

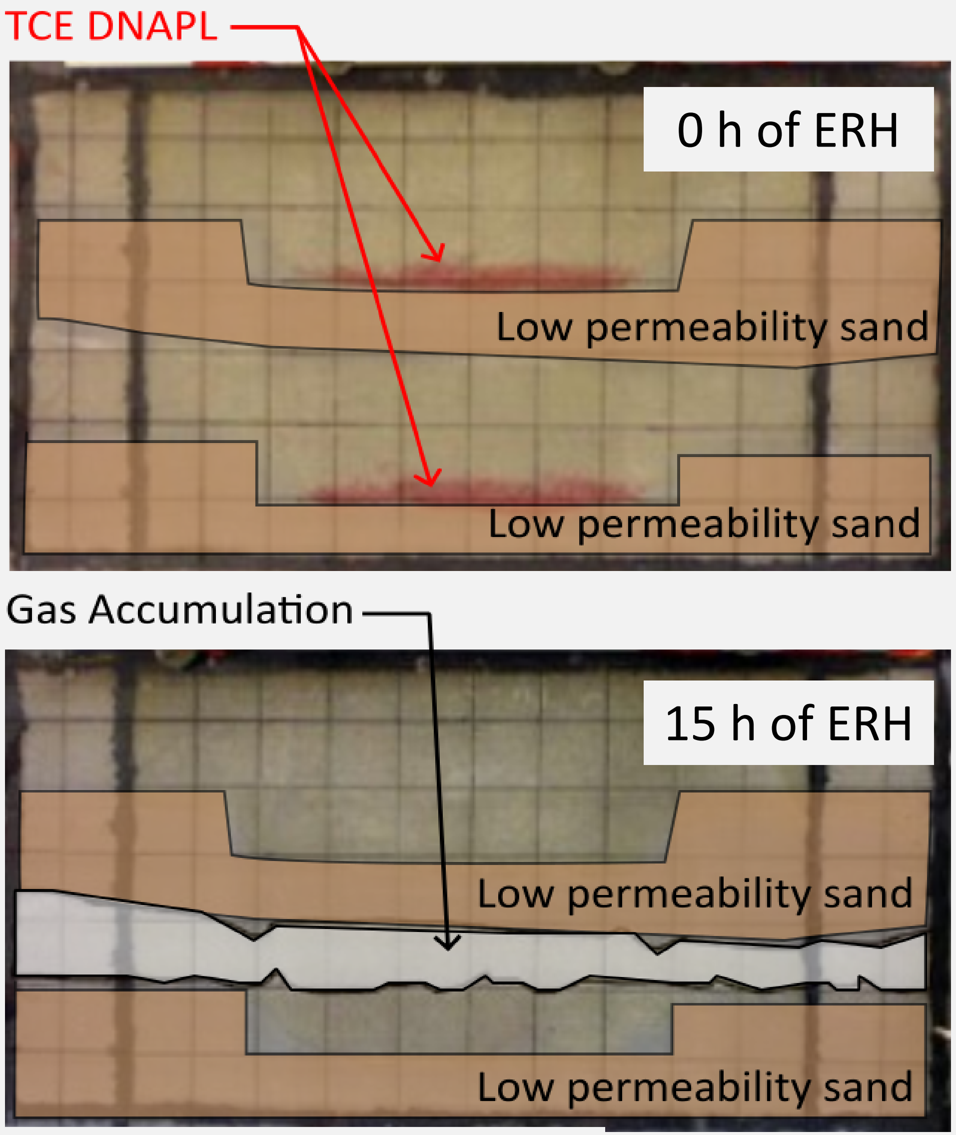
- Gas accumulation underneath capillary barriers has been observed during ERH experiments



Martin and Kueper (2011)

Gas Accumulation and Migration

- Gas accumulation underneath capillary barriers has been observed during ERH experiments
- If contaminant vapor is not intercepted by an extraction well, it can migrate and condense outside of heated region (Munholland et al. 2016)
- Lateral gas accumulation and migration has not been considered in TCH studies



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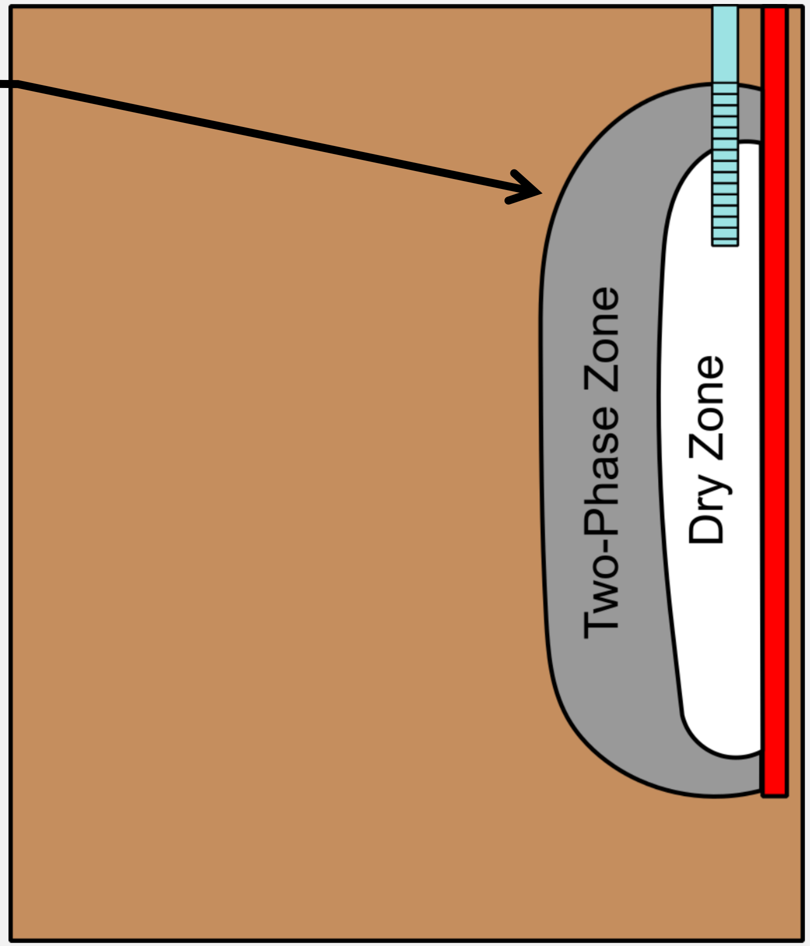
Gas Migration During TCH

- Current conceptual model for gas flow during TCH:

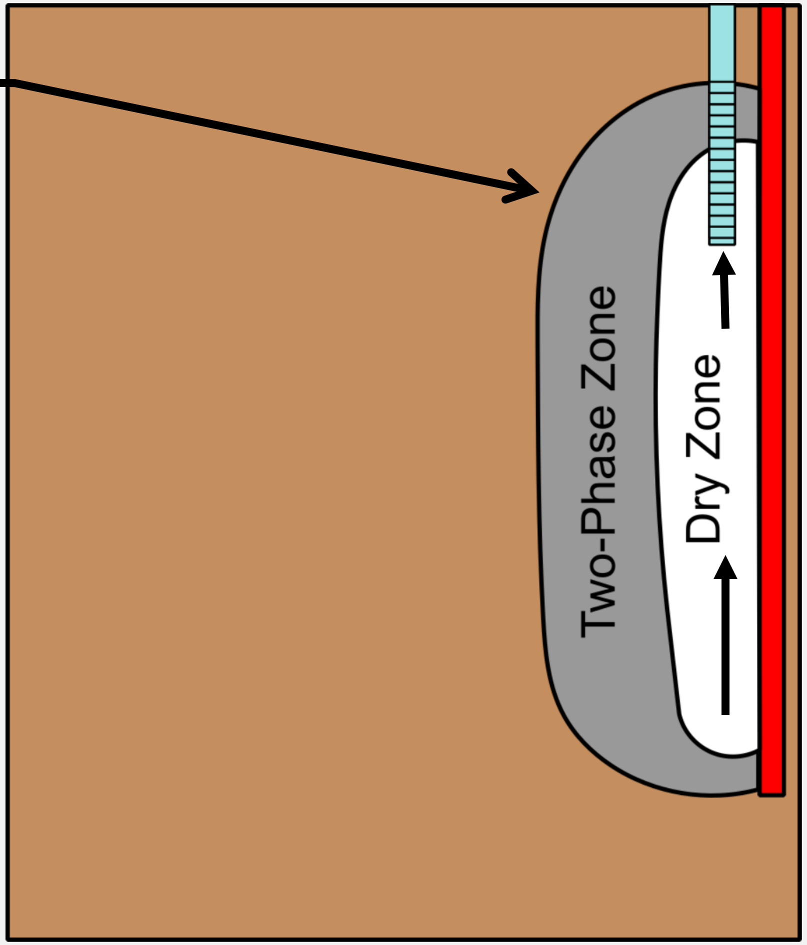


Based on LaChance et al. (2006)

Gas Migration During TCH

- Current conceptual model for gas flow during TCH:

- Dry zone may be an effective pathway for vapor to migrate towards the vadose zone and be extracted (USACE 2014; LaChance et al. 2004; Stegemeir and Vinegar 2001)



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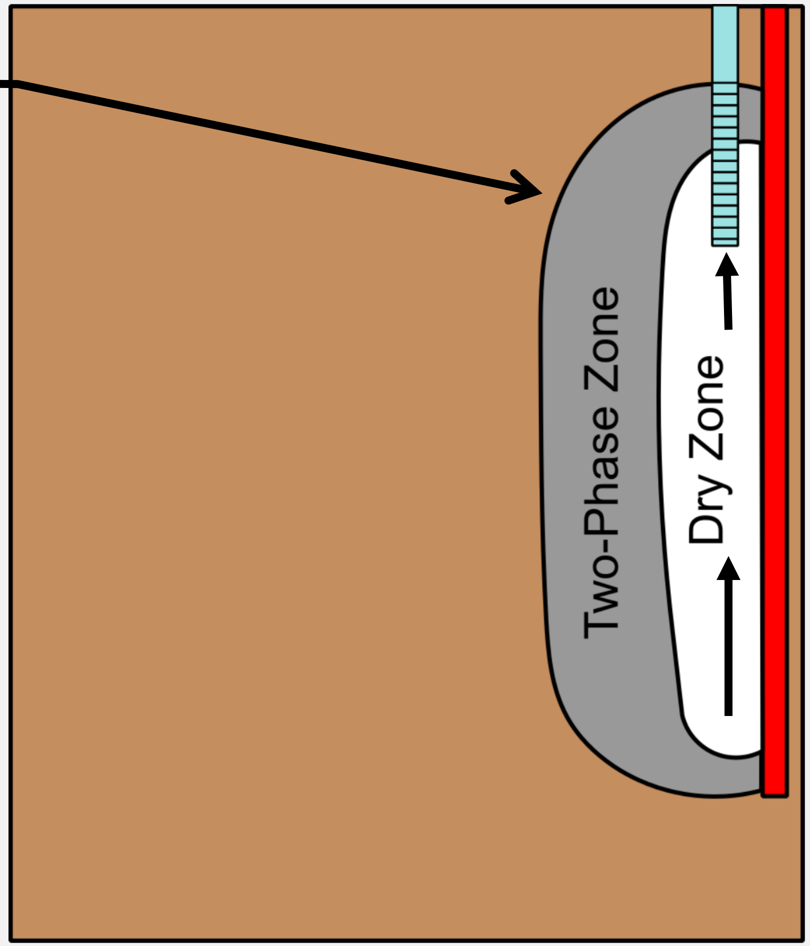
Gas Migration During TCH

- Current conceptual model for gas flow during TCH:

- Dry zone may be an effective pathway for vapor to migrate towards the vadose zone and be extracted (USACE 2014; LaChance et al. 2004; Stegemeir and Vinegar 2001)

How does **geological heterogeneity** affect gas migration and capture during TCH?



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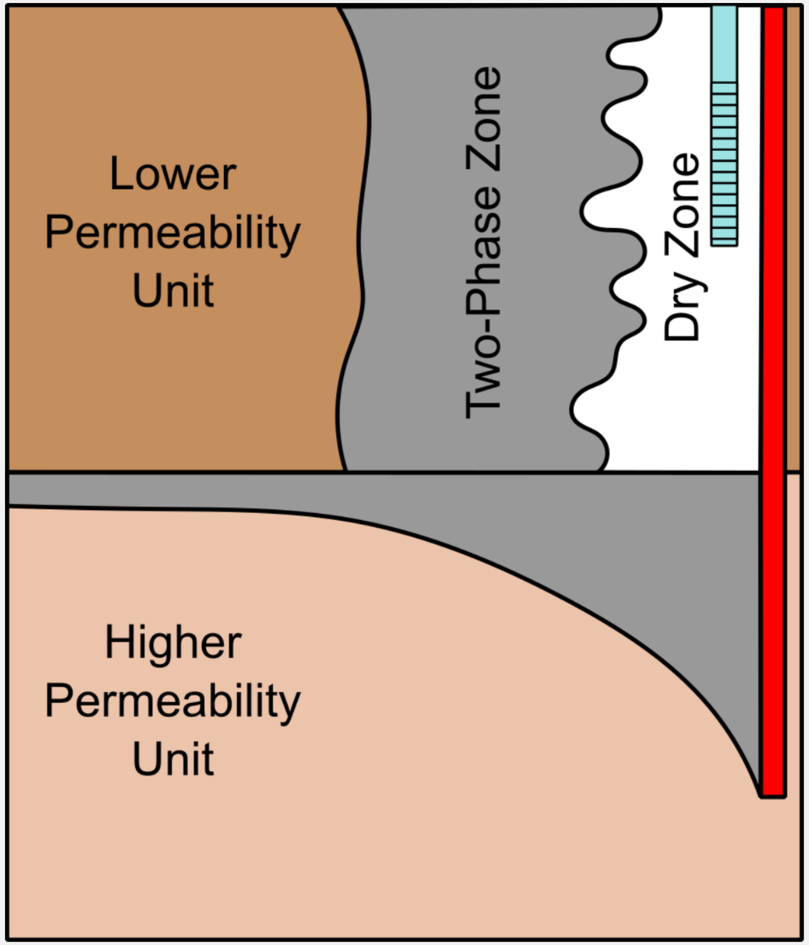
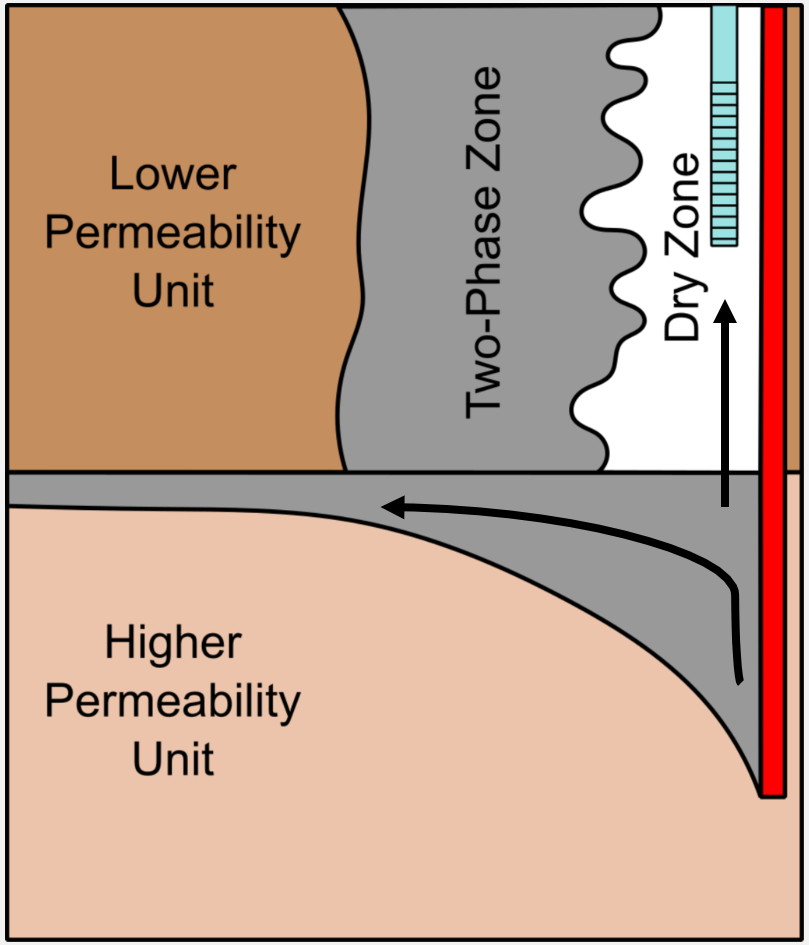
Gas Migration During TCH



Gas Migration During TCH

- If the gas permeability of the dry and two-phase zones is not high enough, gas may migrate laterally away from the heater

- This could influence decisions regarding vapor extraction design



Purpose and Objectives

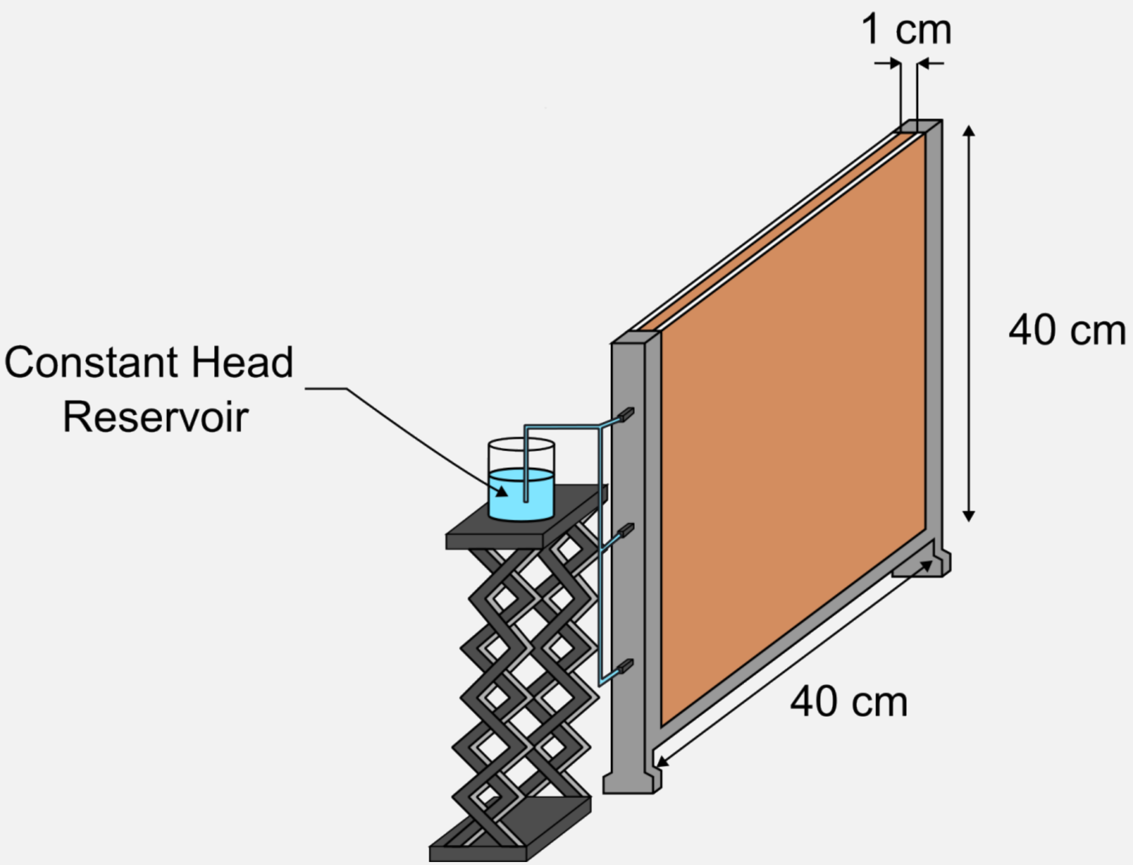
Overall Purpose: Refine the conceptual model of gas migration during TCH for heterogeneous conditions.

Specific Objectives:

1. Quantify the gas saturation at a high resolution
2. Determine the role of heterogeneity on gas movement during boiling
3. Understand the effect of lateral steam migration on the temperature distribution
4. Provide guidance on field-scale implications of geological heterogeneity

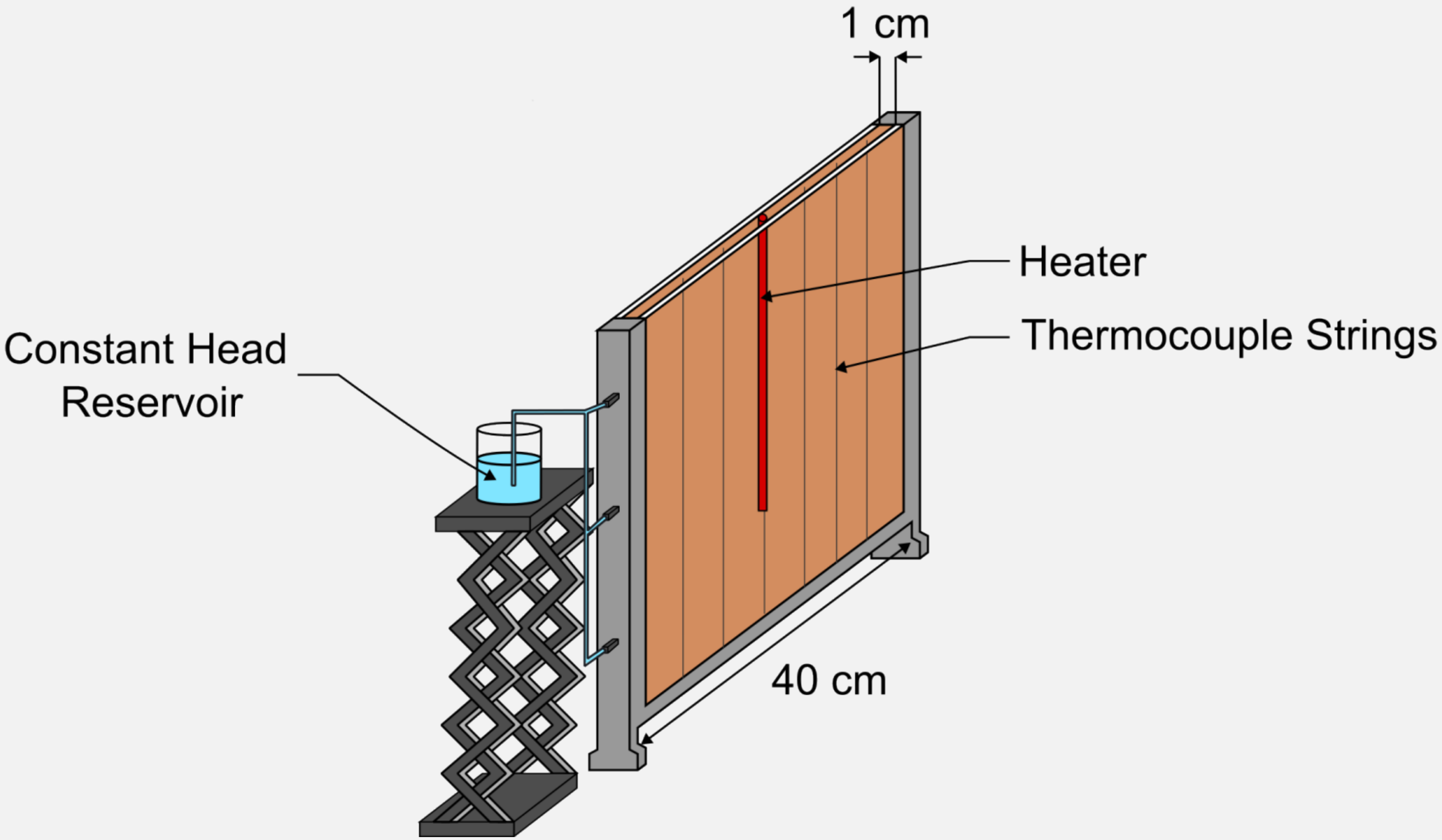
Experimental Set-Up

Experimental Set-Up



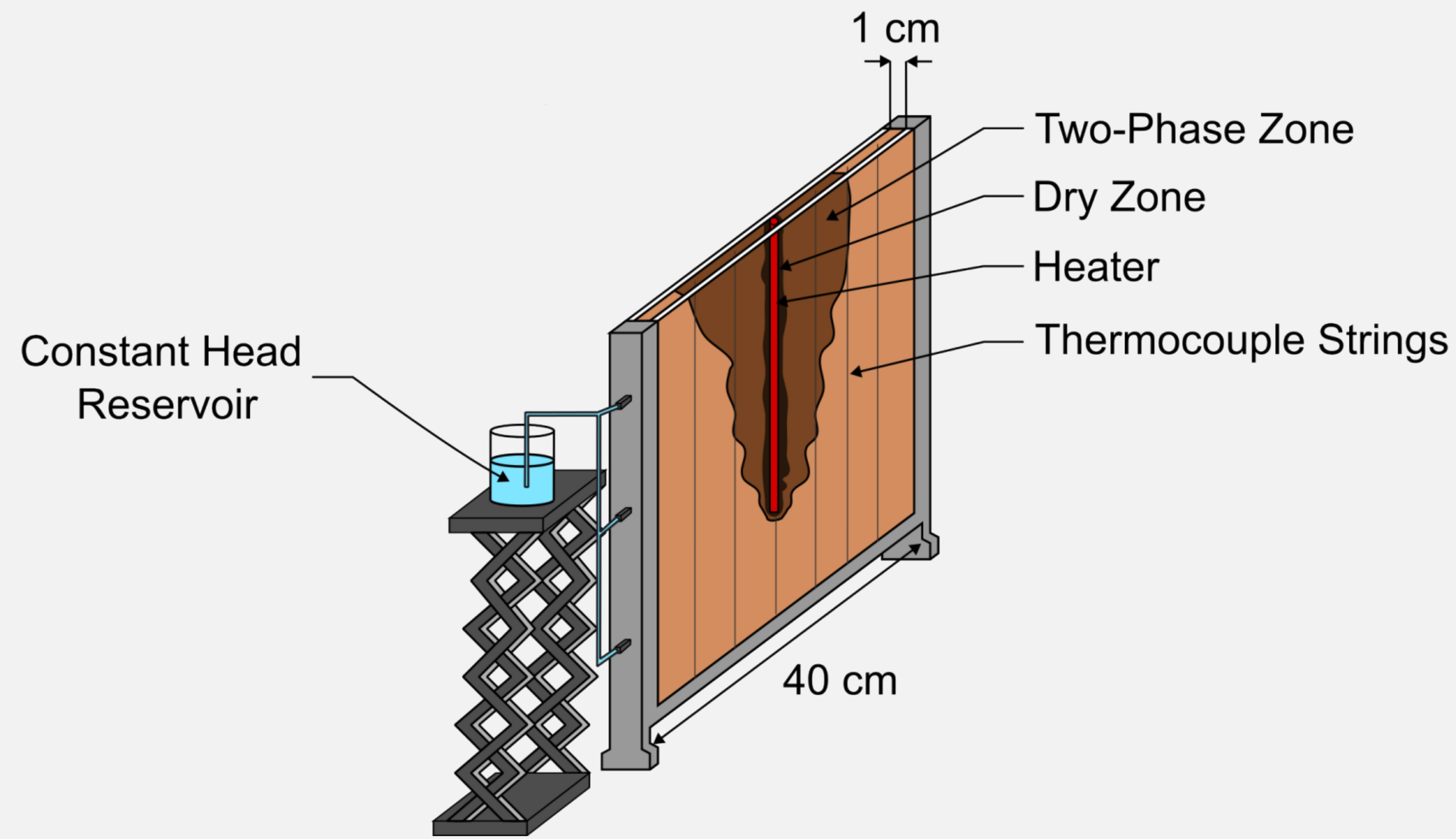
- Two-dimensional cell with glass walls
- Packed with different configurations of coarse, medium and fine silica sands
- Clear well along the left side of the cell to apply a constant head boundary

Experimental Set-Up



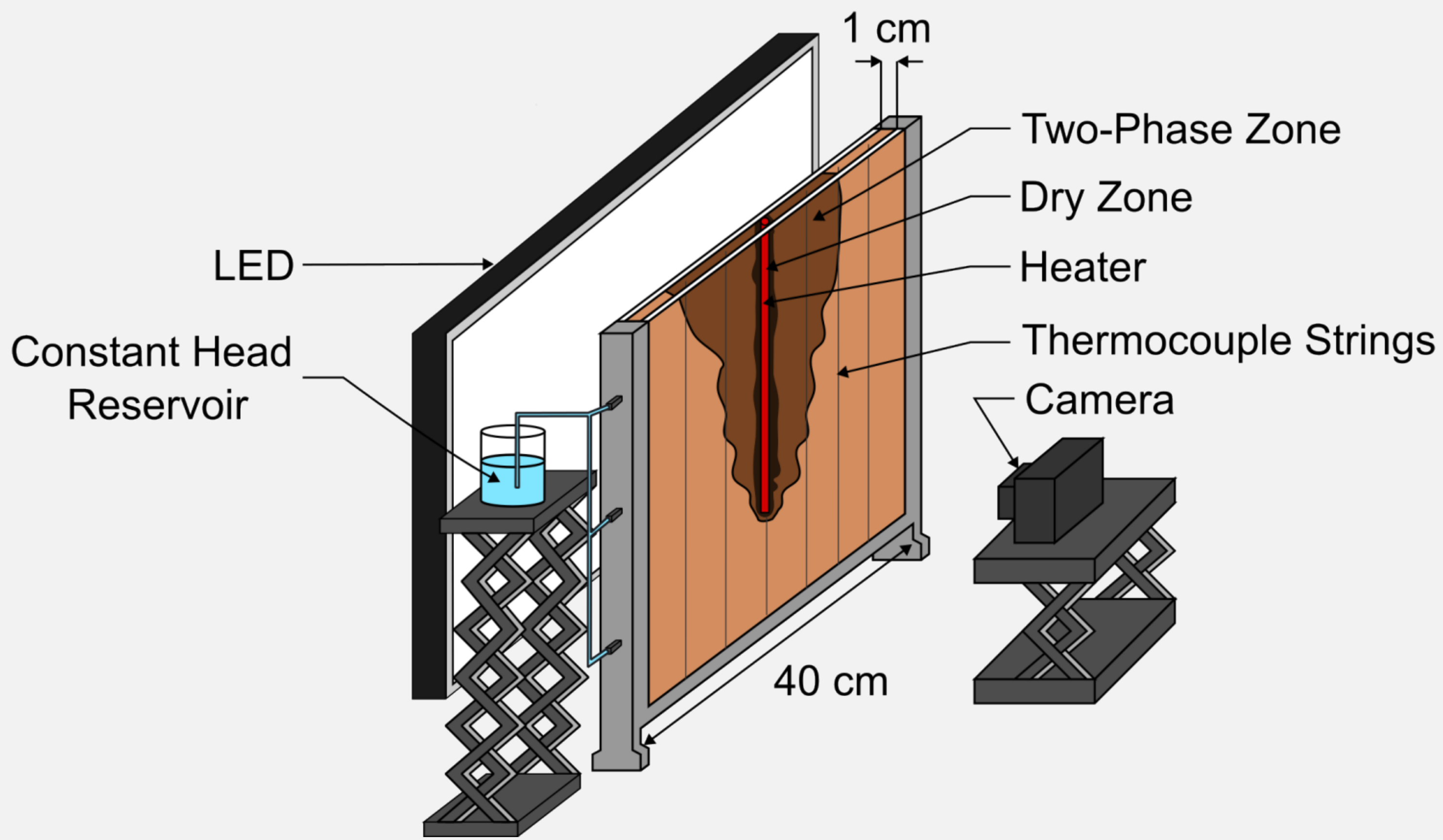
- 240 W heater emplaced in the cell
- Temperature recorded at twenty-four locations

Experimental Set-Up



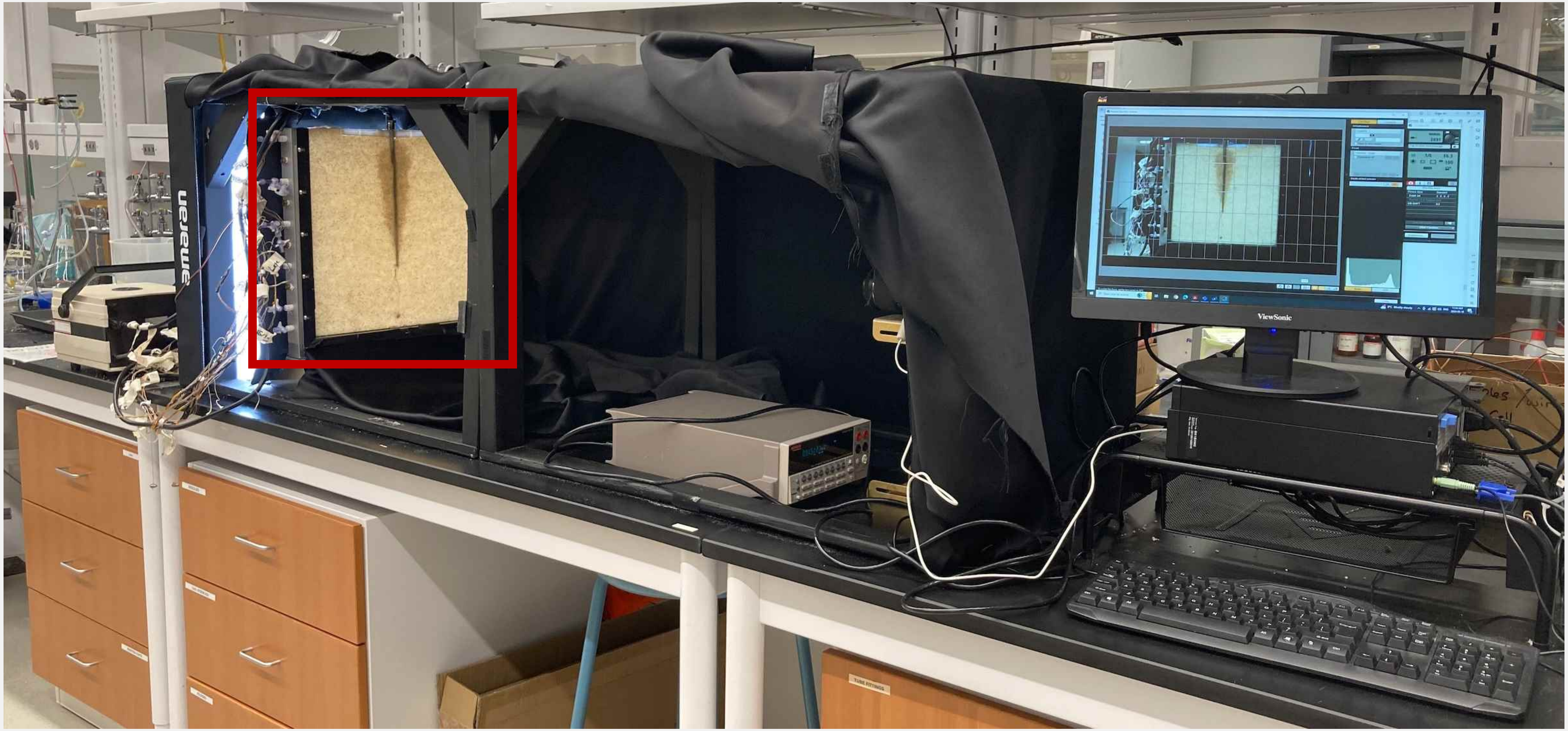
- As heating progressed, the evolution of gas saturation was observed

Experimental Set-Up



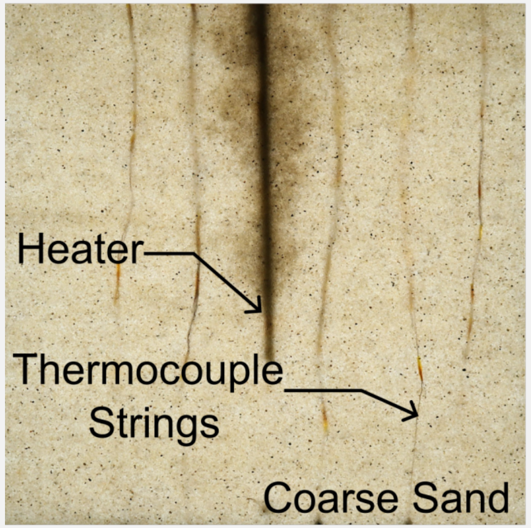
- Light transmission was used to quantify gas saturations
- LED placed behind cell
- High-resolution images captured every 1 minute

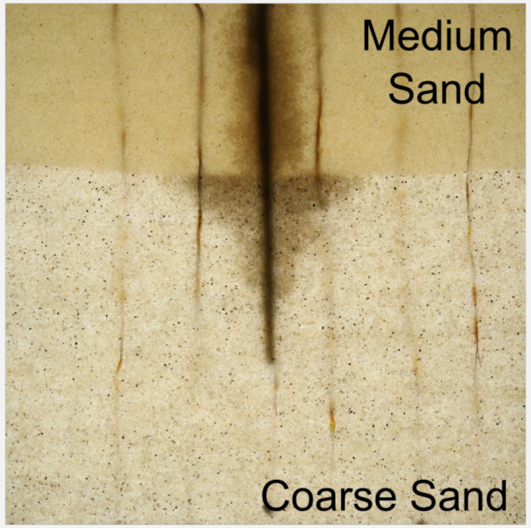
Experimental Set-Up



Results: Evolution of Gas Saturation and Temperature During Heating

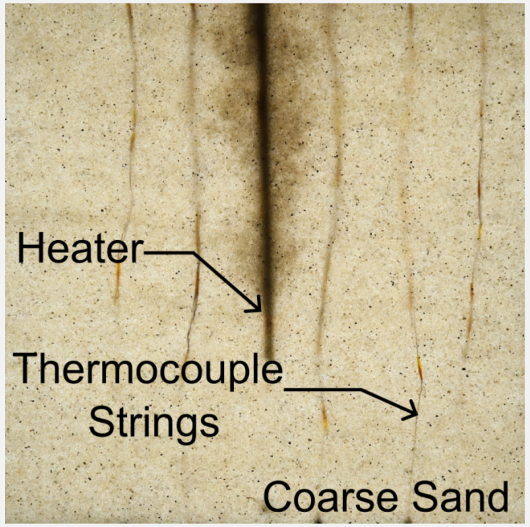
Evolution of Gas Saturation

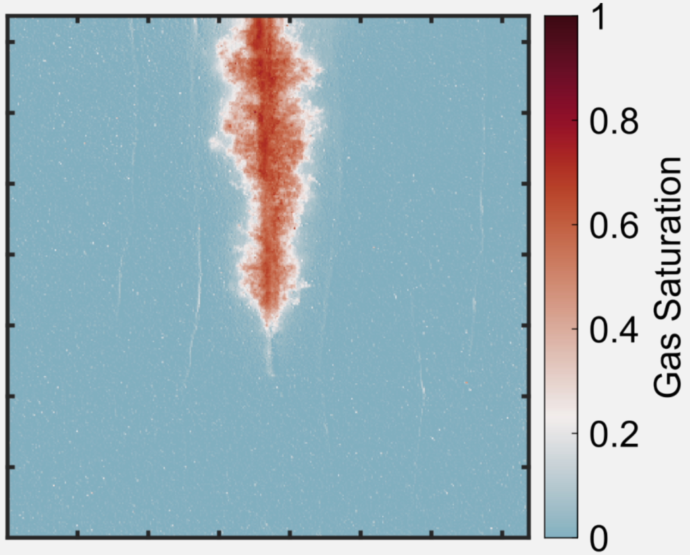


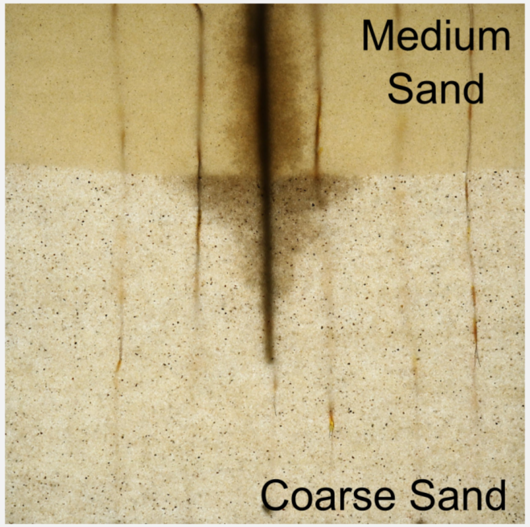


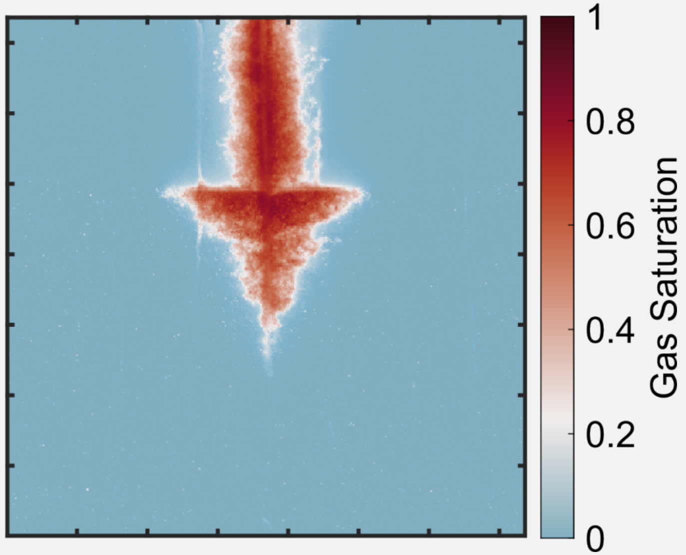
- Steam can be observed in raw images as the darker area adjacent to the heater

Evolution of Gas Saturation





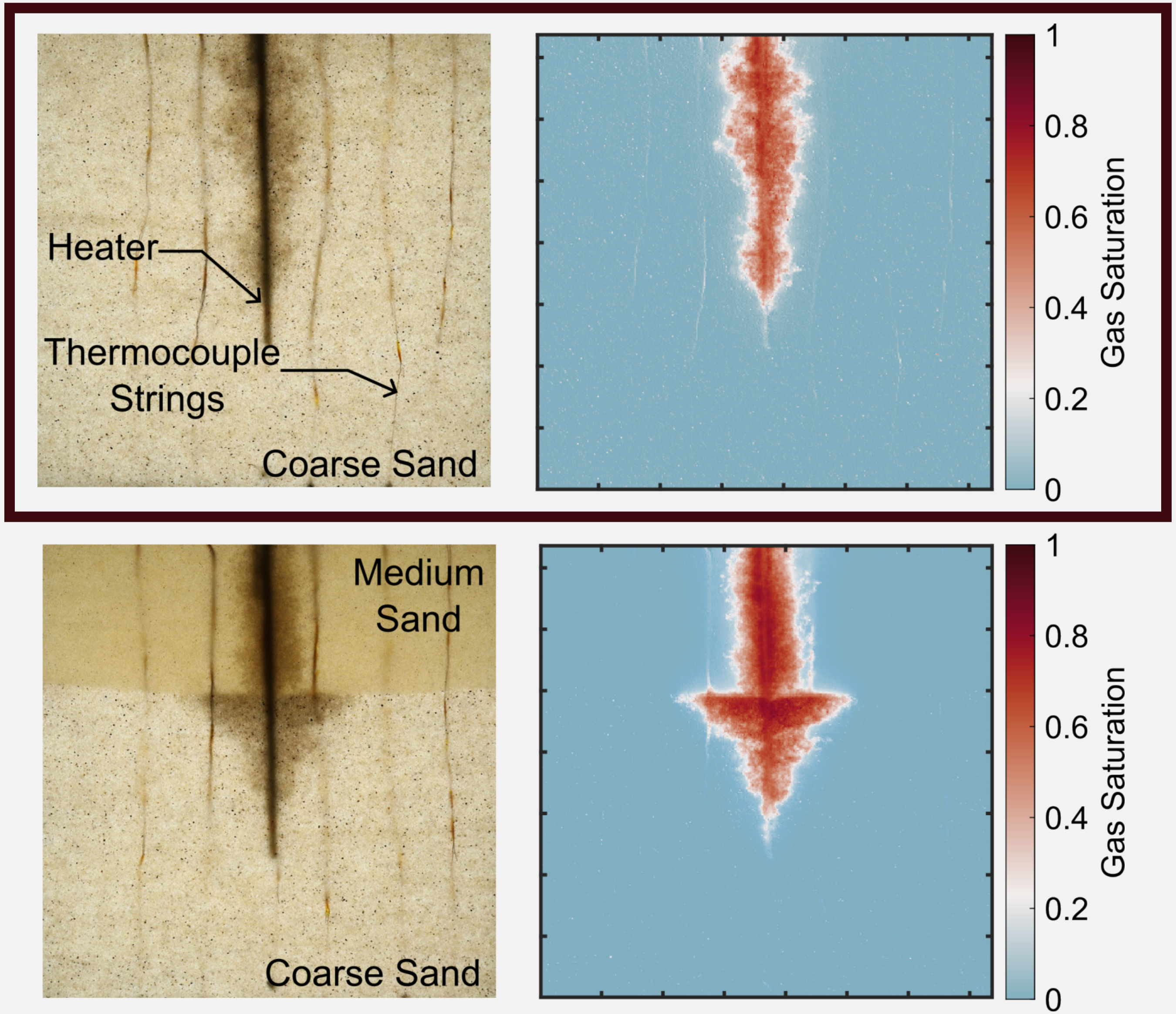




- Steam can be observed in raw images as the darker area adjacent to the heater

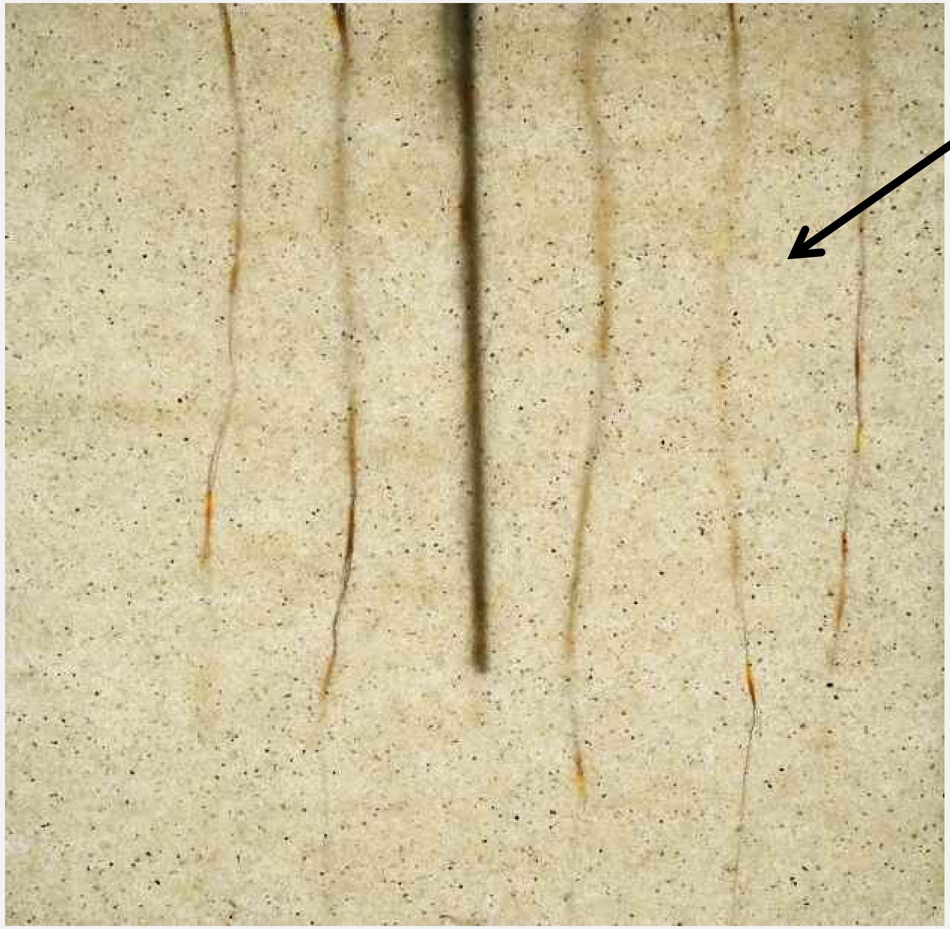
- Gas saturations quantified using light transmission

Evolution of Gas Saturation



- Steam can be observed in raw images as the darker area adjacent to the heater
- Gas saturations quantified using light transmission

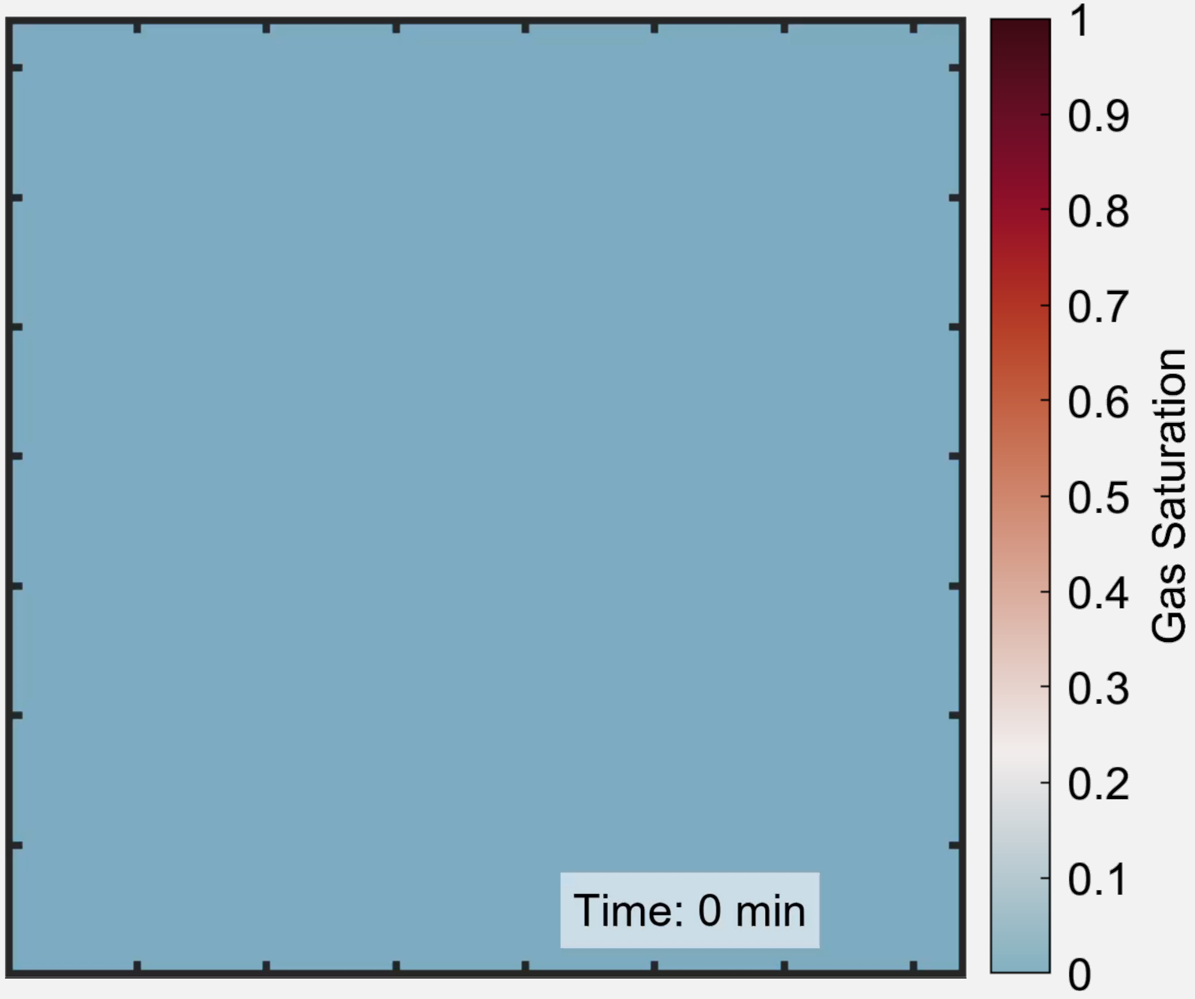
Homogeneous Coarse Sand



High permeability sand ($k = 5.0 \times 10^{-10}\ m^2$)

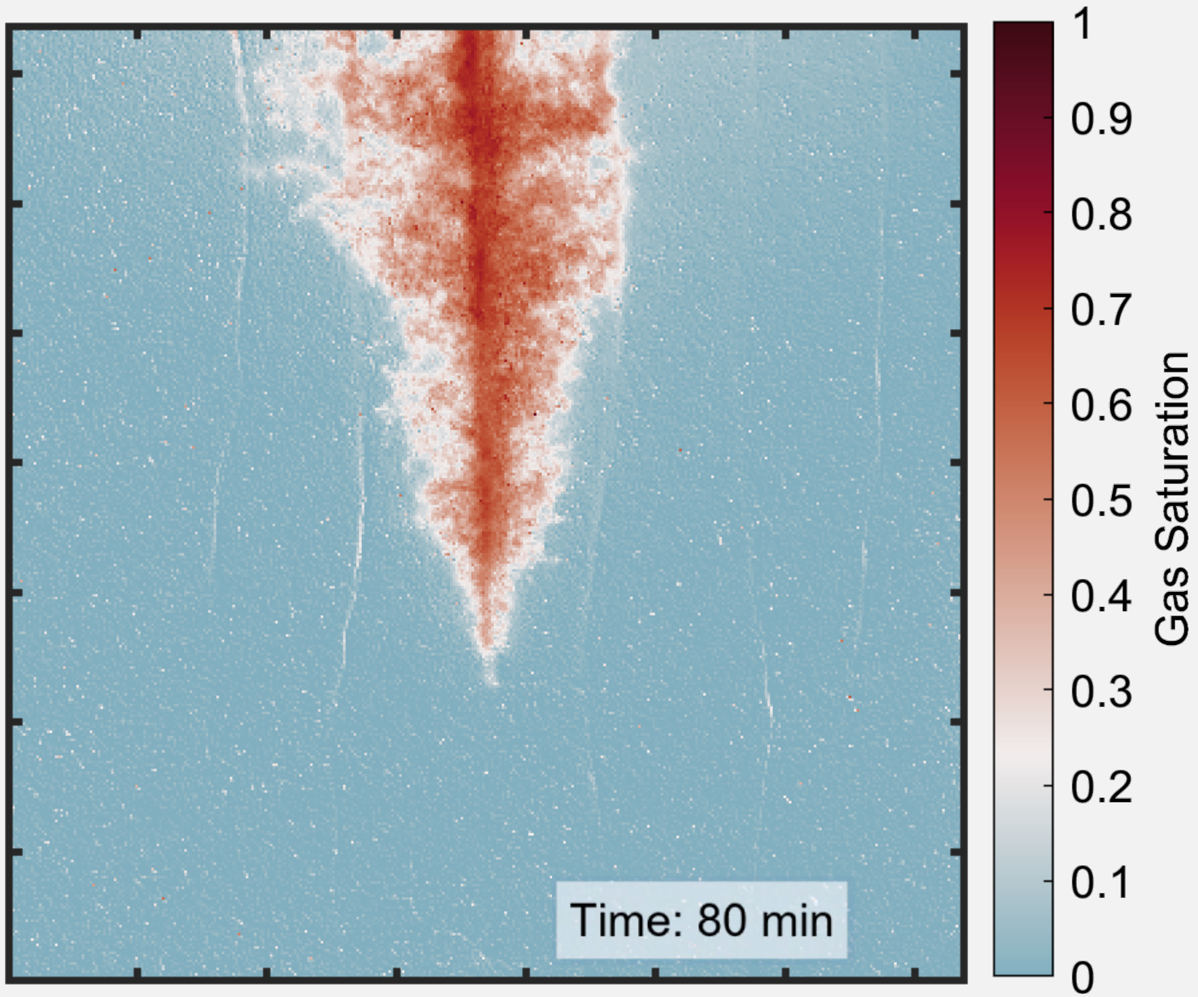
40 cm

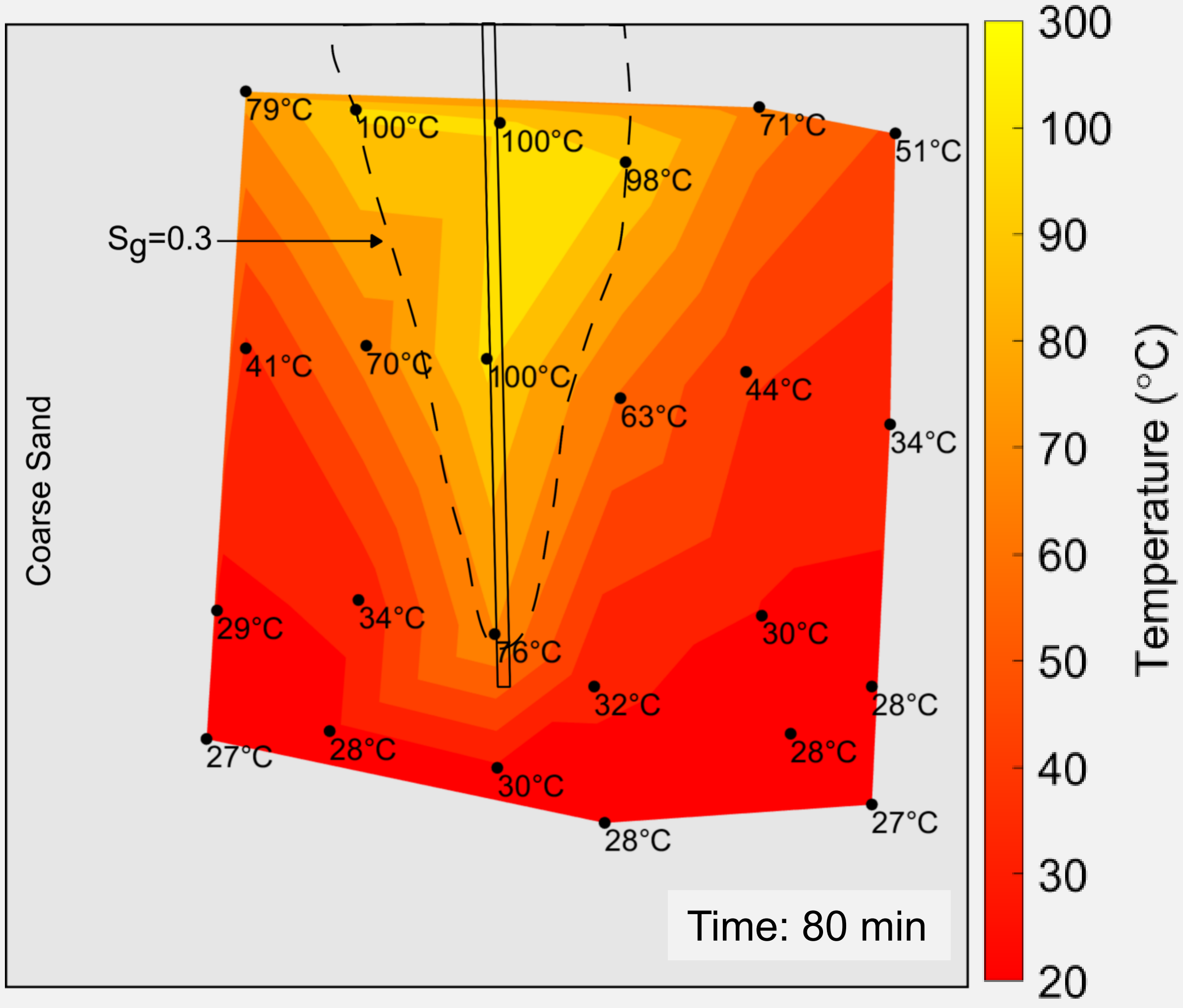
Homogeneous Coarse Sand



- Narrow two-phase zone
- No dry zone
  - Water quickly replenished the two-phase zone during boiling

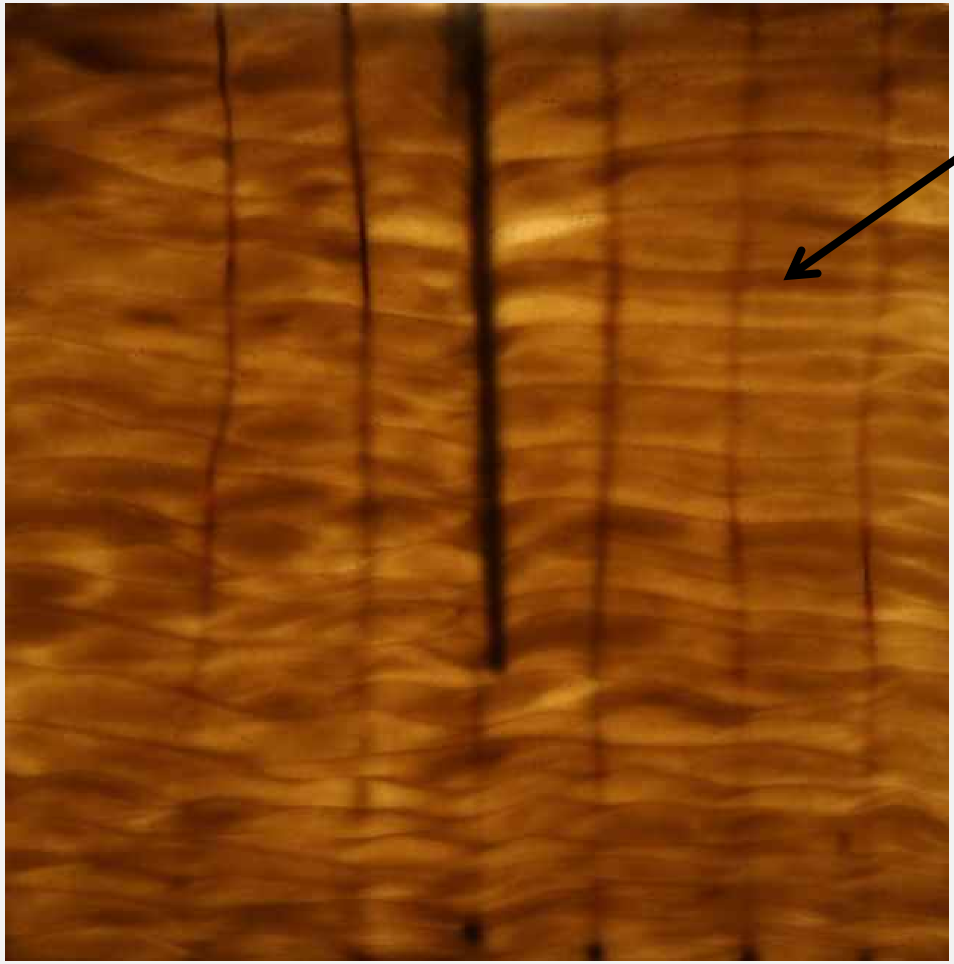
Homogeneous Coarse Sand





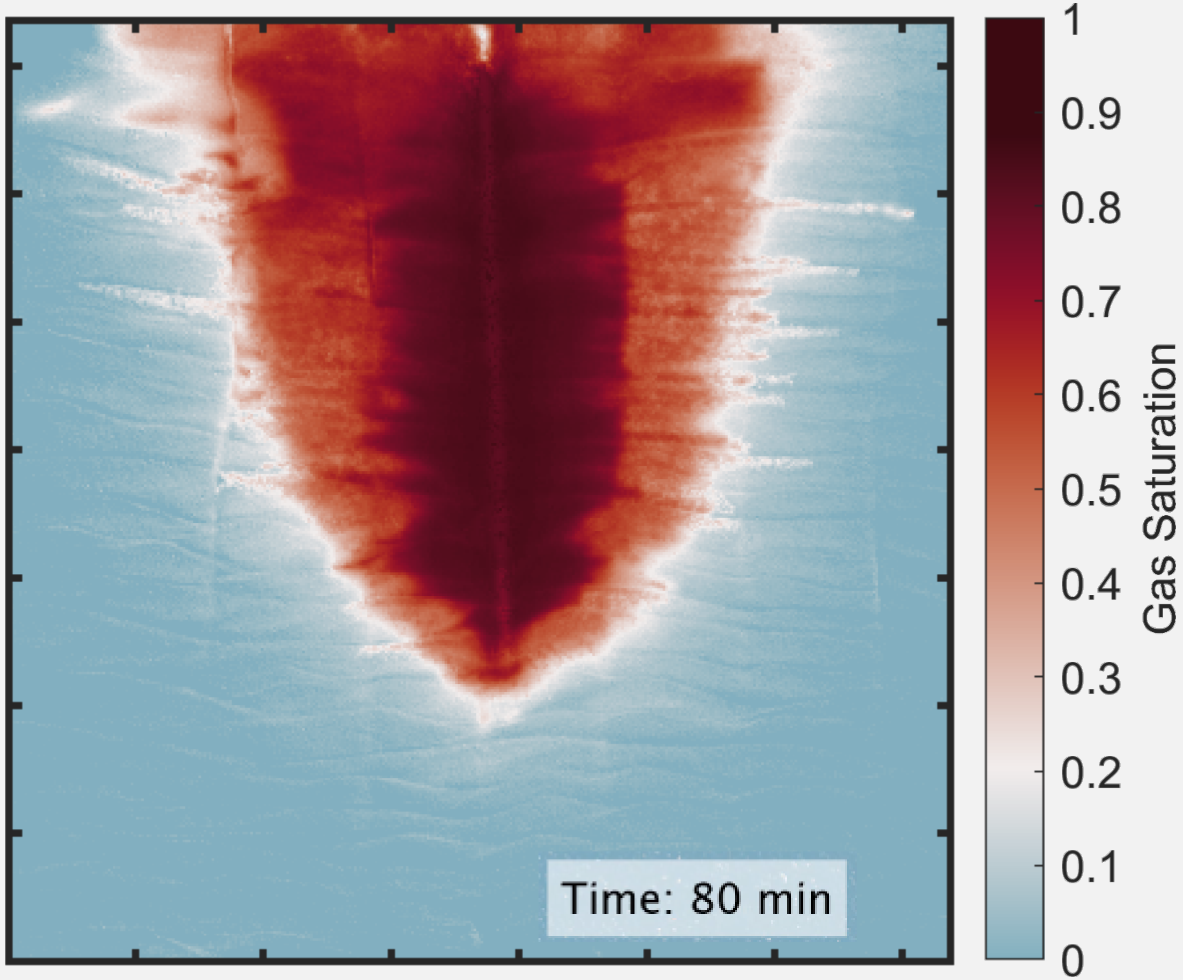
- As expected, the narrow two-phase zone corresponded to a narrow heated area

Homogeneous Fine Sand



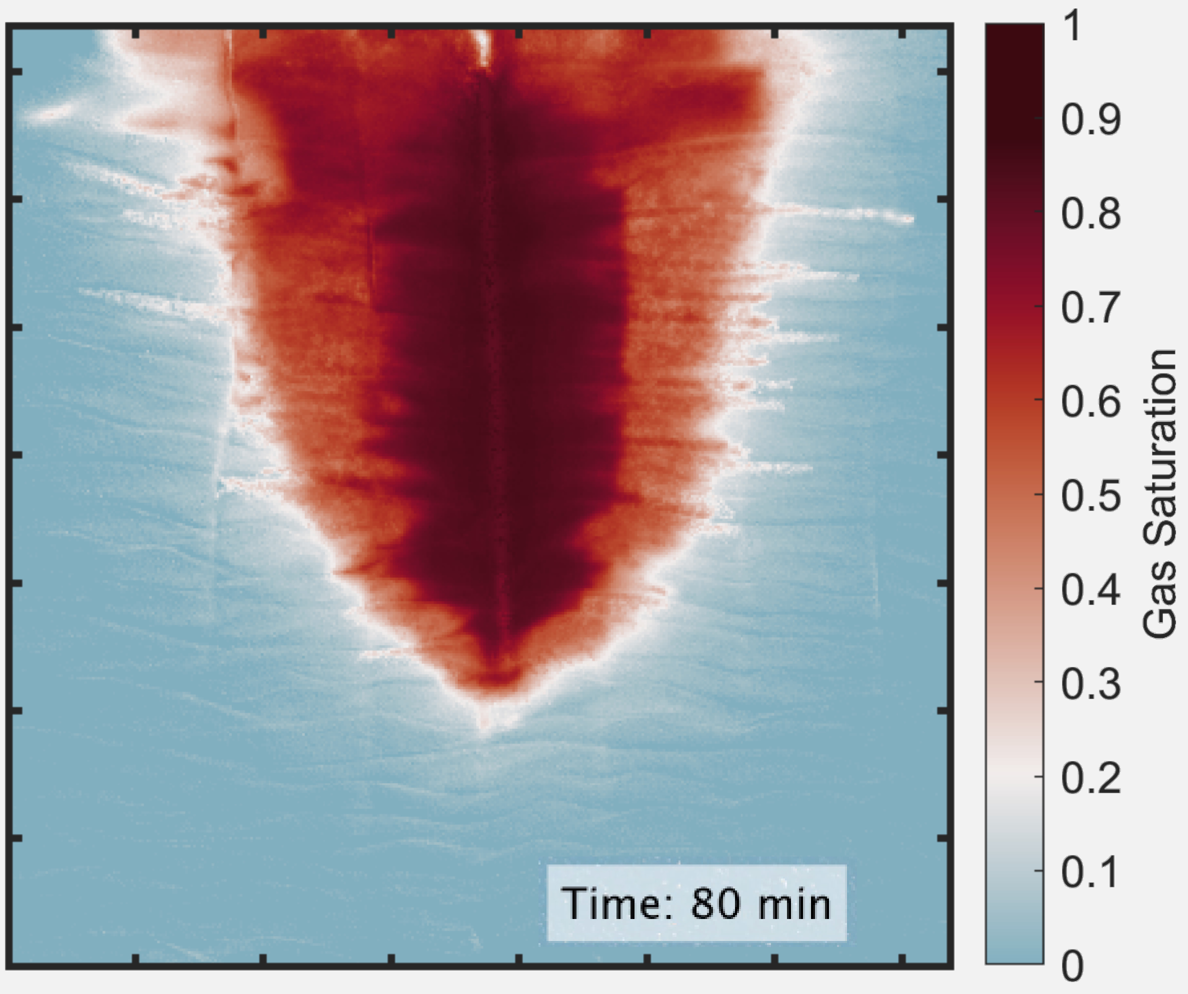
Lower permeability sand ($k_{coarse} = 73\ k_{fine}$)

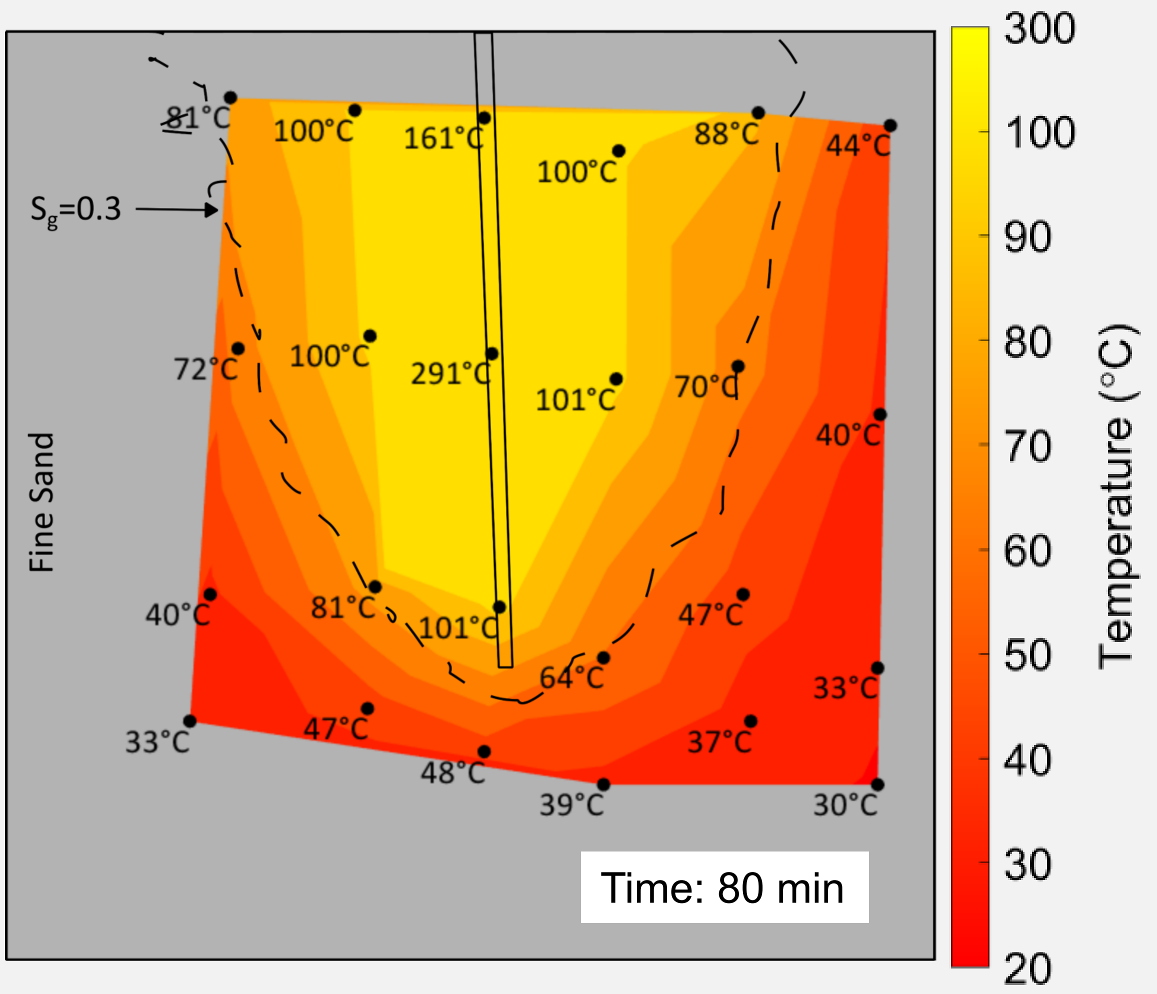
Homogeneous Fine Sand



- Wider two-phase zone and higher gas saturations

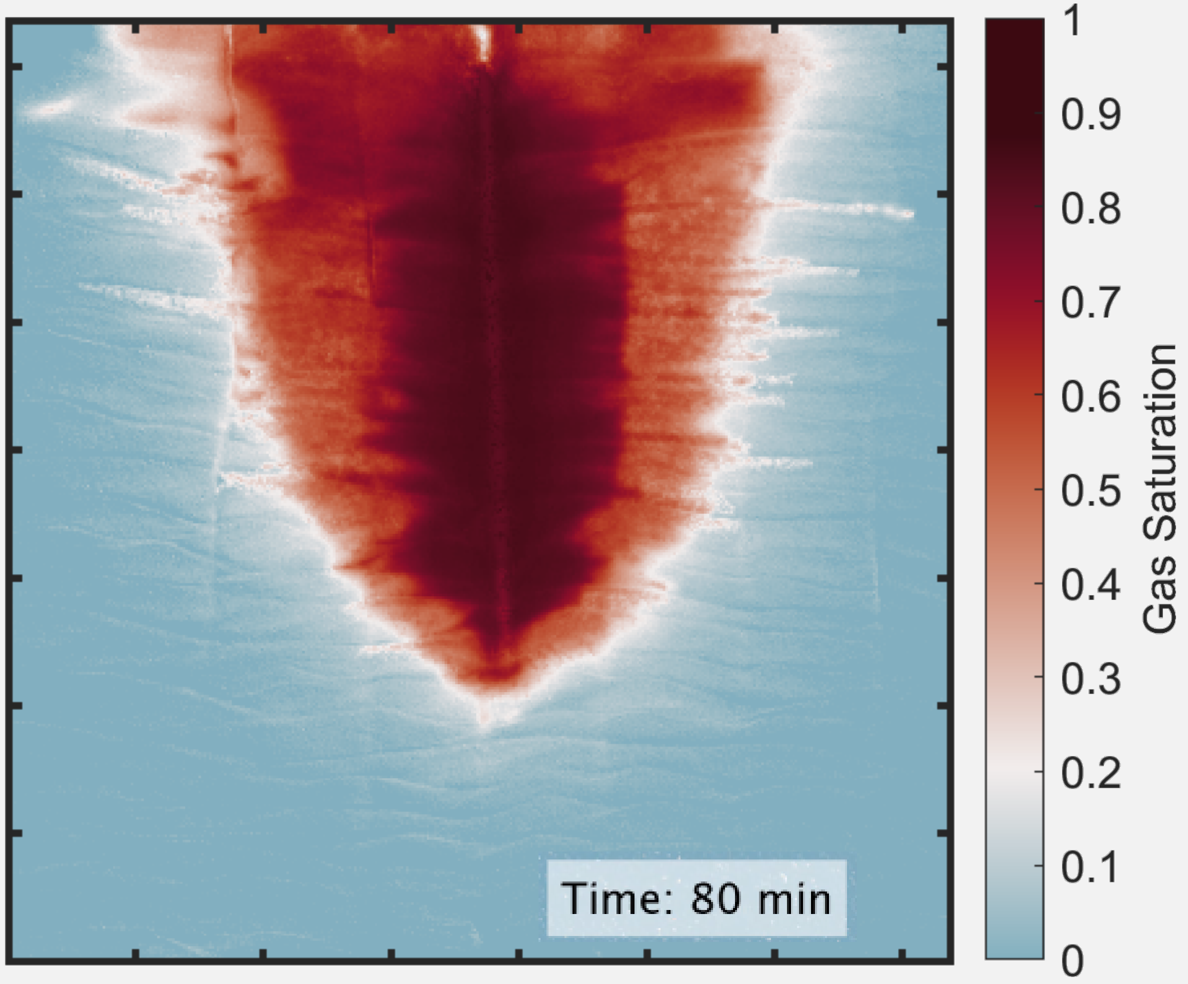
Homogeneous Fine Sand

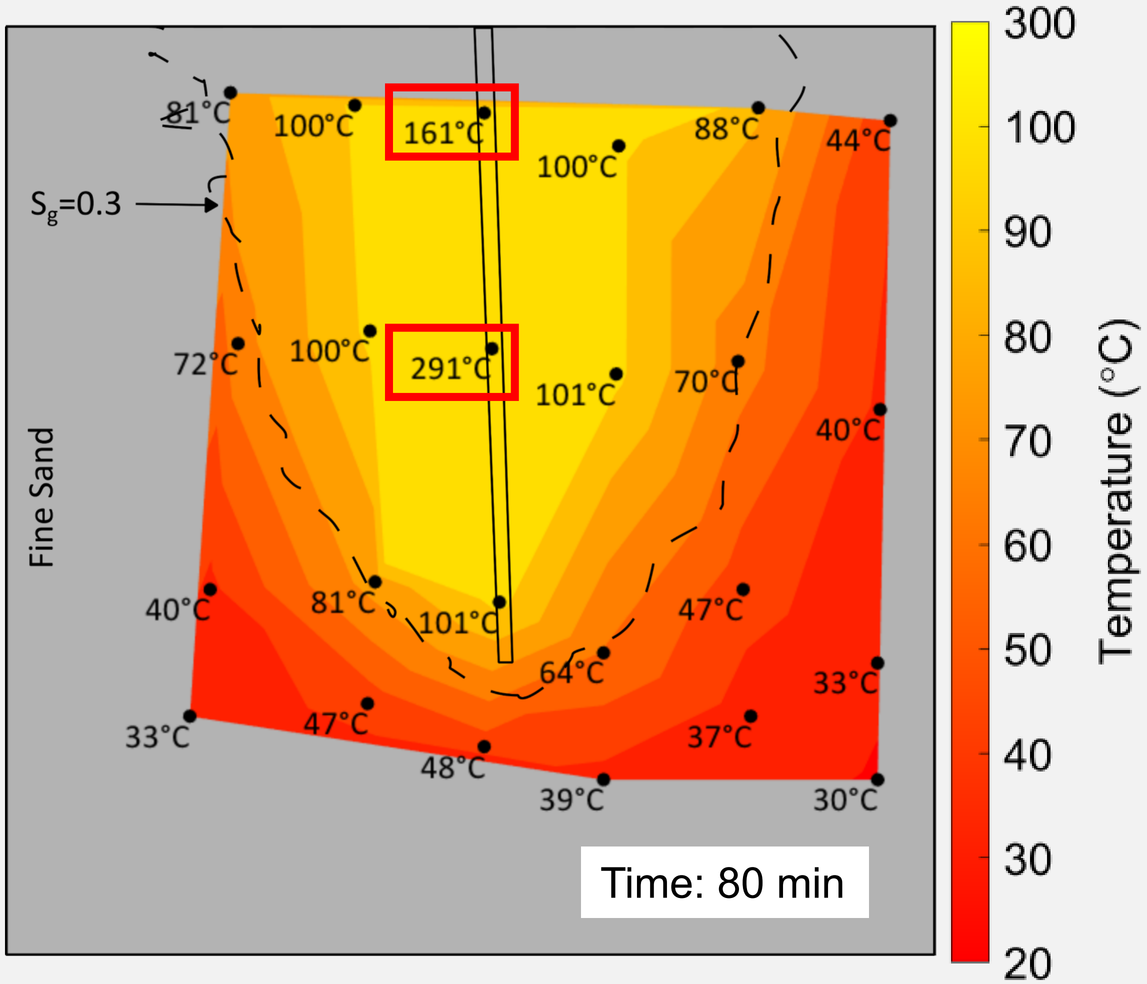




- As expected, the wide two-phase zone corresponded to a wide heated area

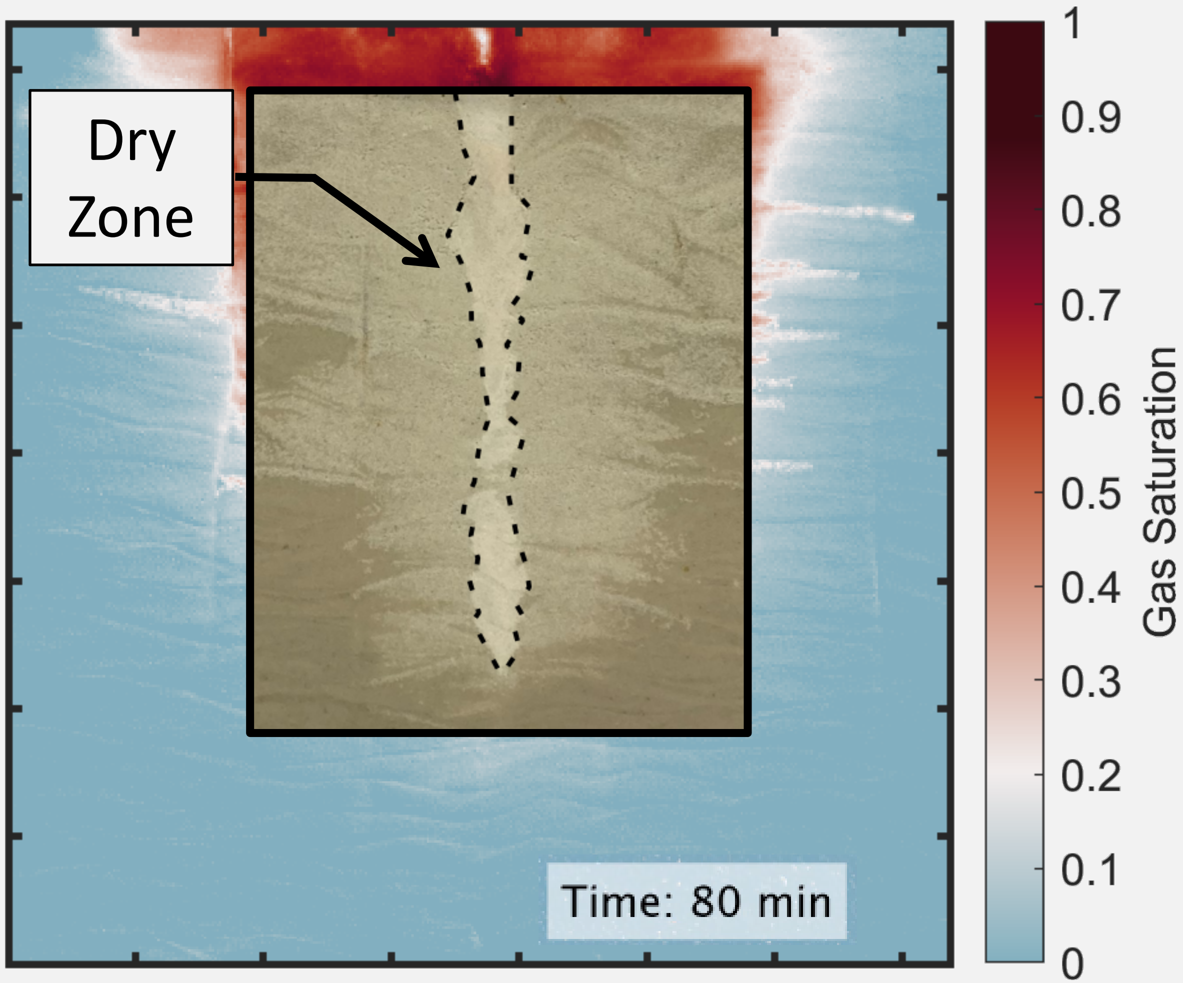
Homogeneous Fine Sand





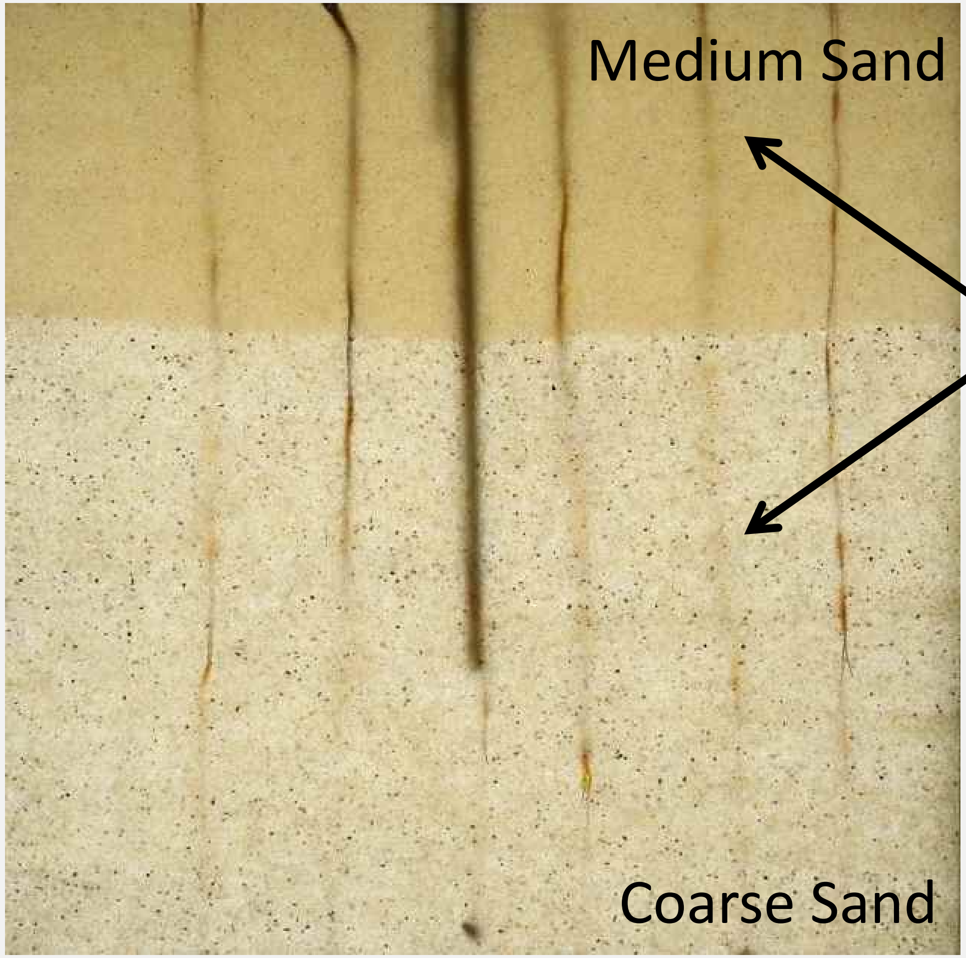
- Near the heater, temperatures were much greater than 100°C

Homogeneous Fine Sand



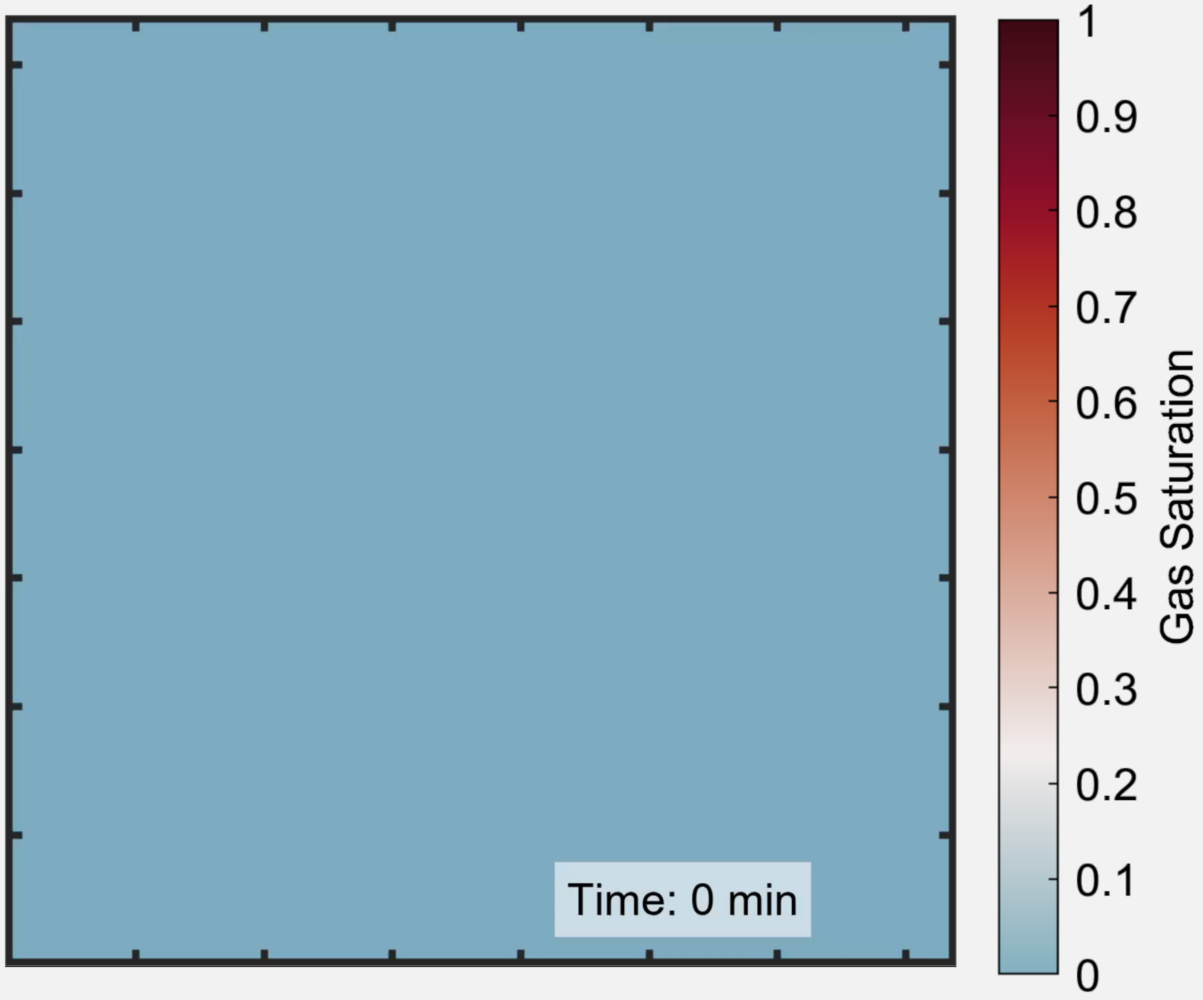
- Dry zone was seen in a light reflection image taken after the experiment
- Low permeability of the fine sand restricted the flow of water to replenish this region

Medium Sand Over Coarse Sand



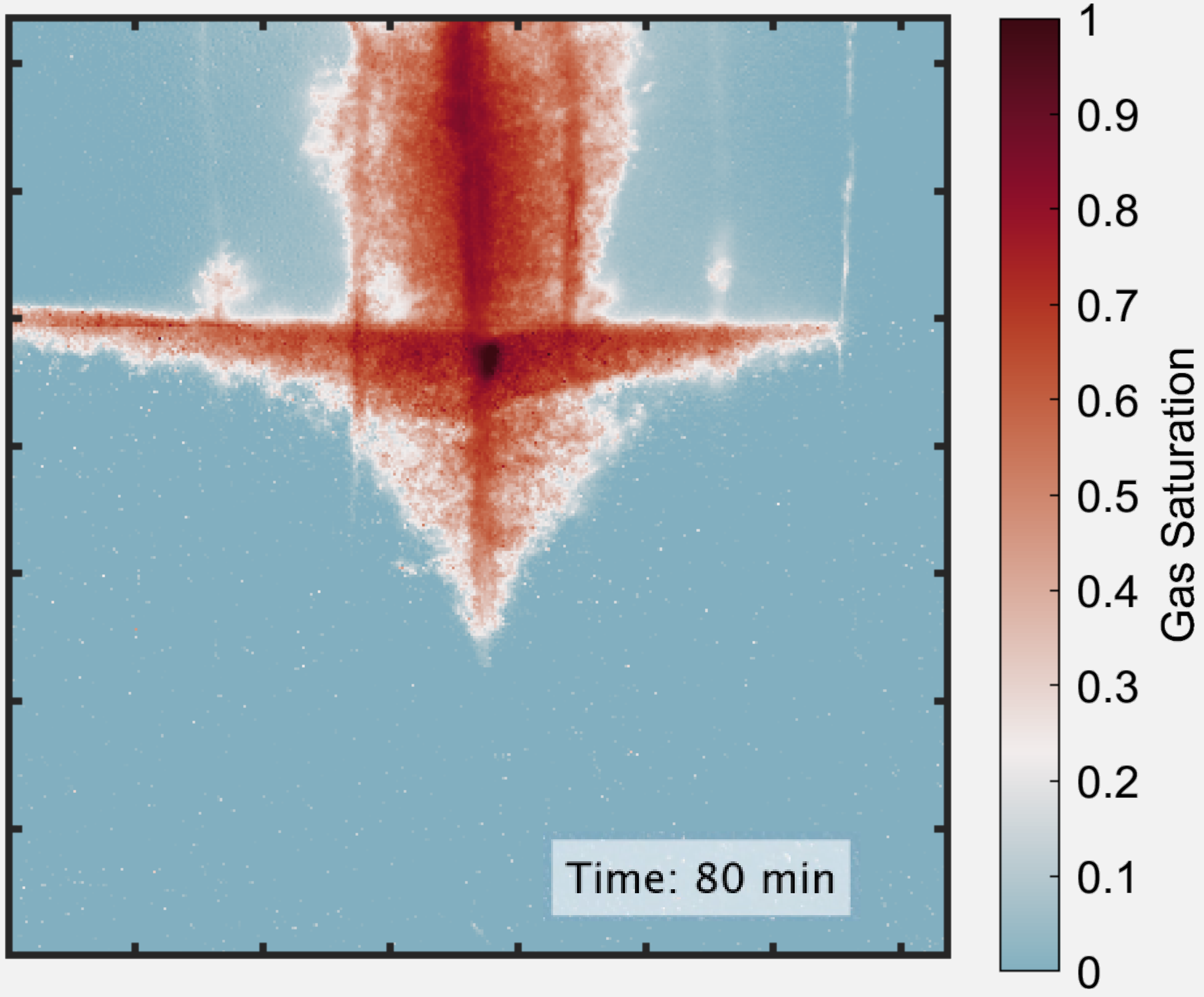
$k_{coarse} = 2.5\ k_{medium}$

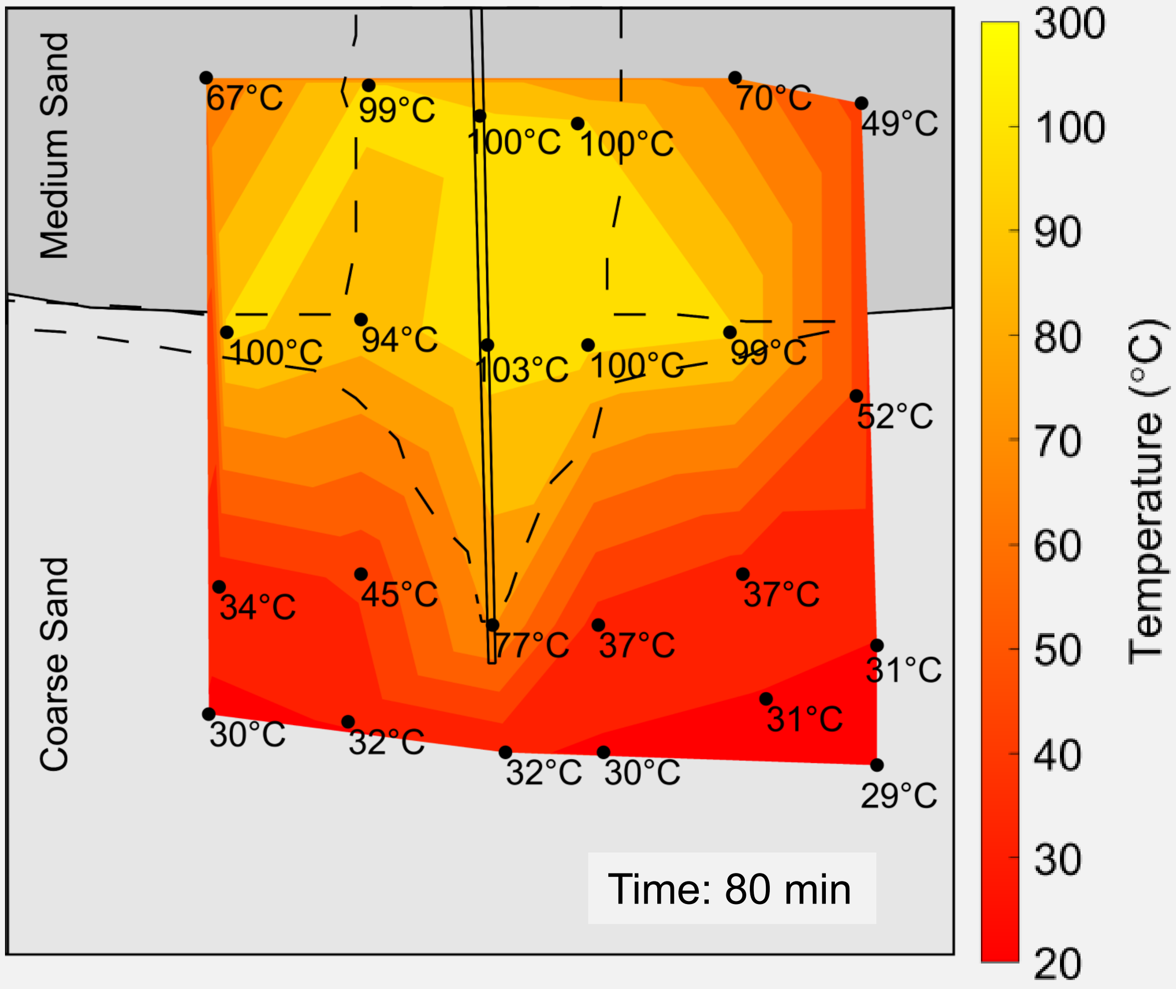
Medium Sand Over Coarse Sand



- Steam accumulated under the capillary barrier and migrated laterally away from the heater

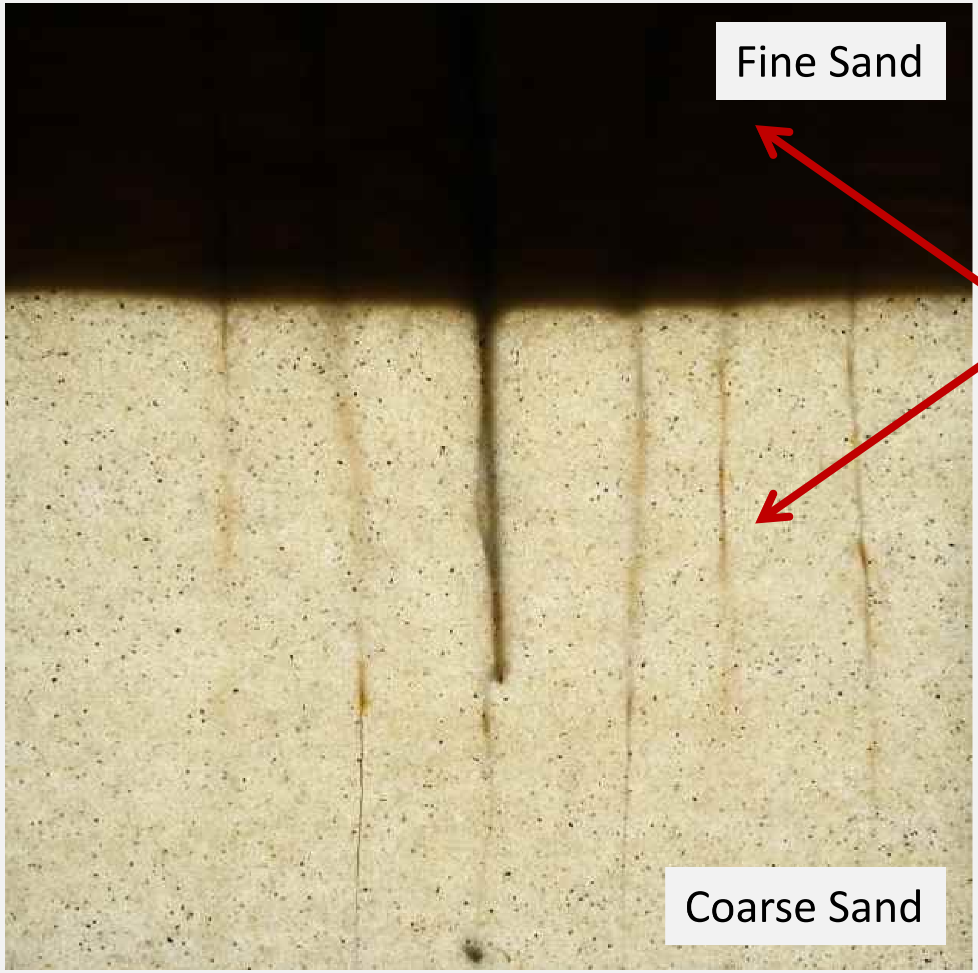
Medium Sand Over Coarse Sand





- As steam migrated, energy transferred to the sand and liquid water (Molnar et al. 2019; Udell 1985)

Fine Sand Over Coarse Sand



$k_{coarse} = 73\ k_{fine}$

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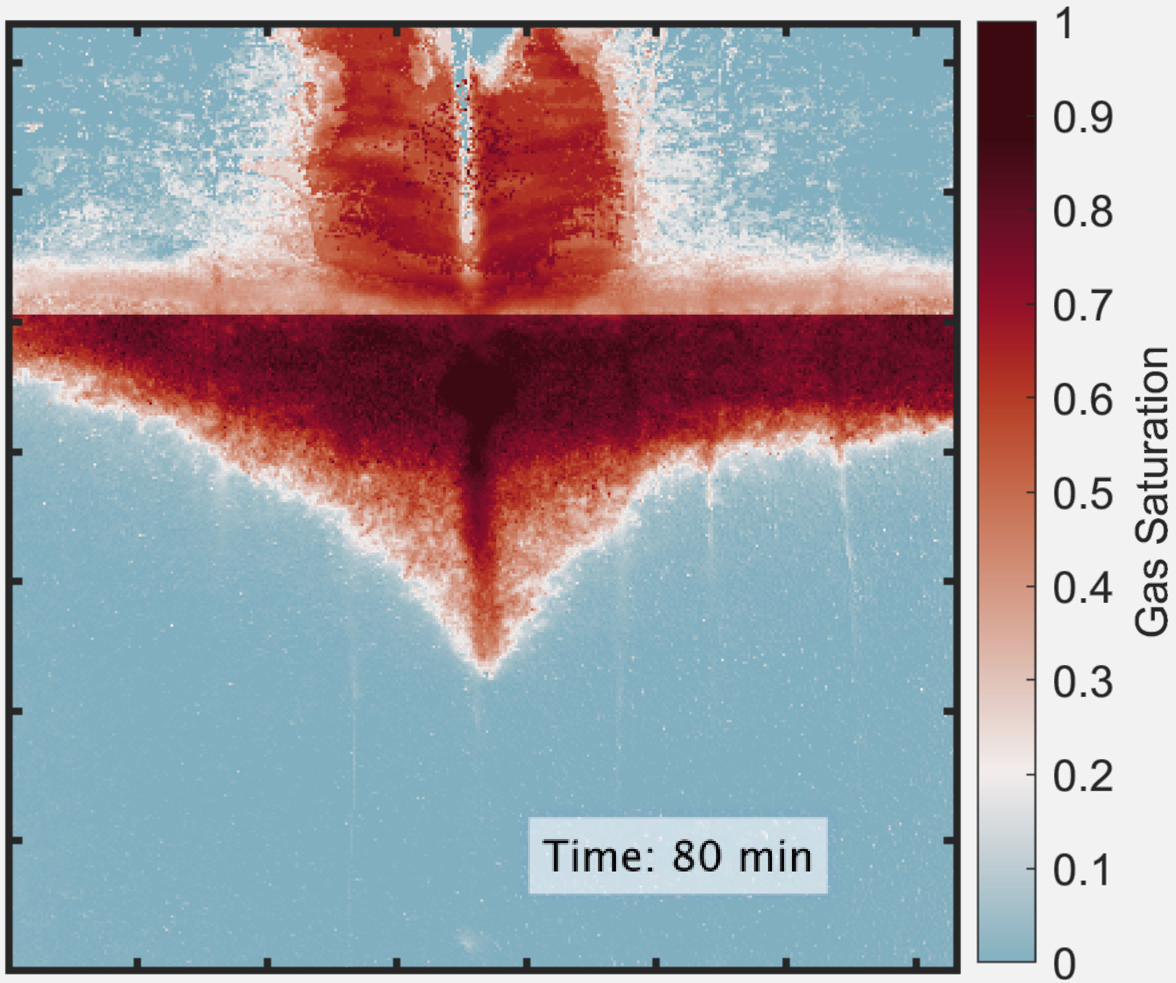
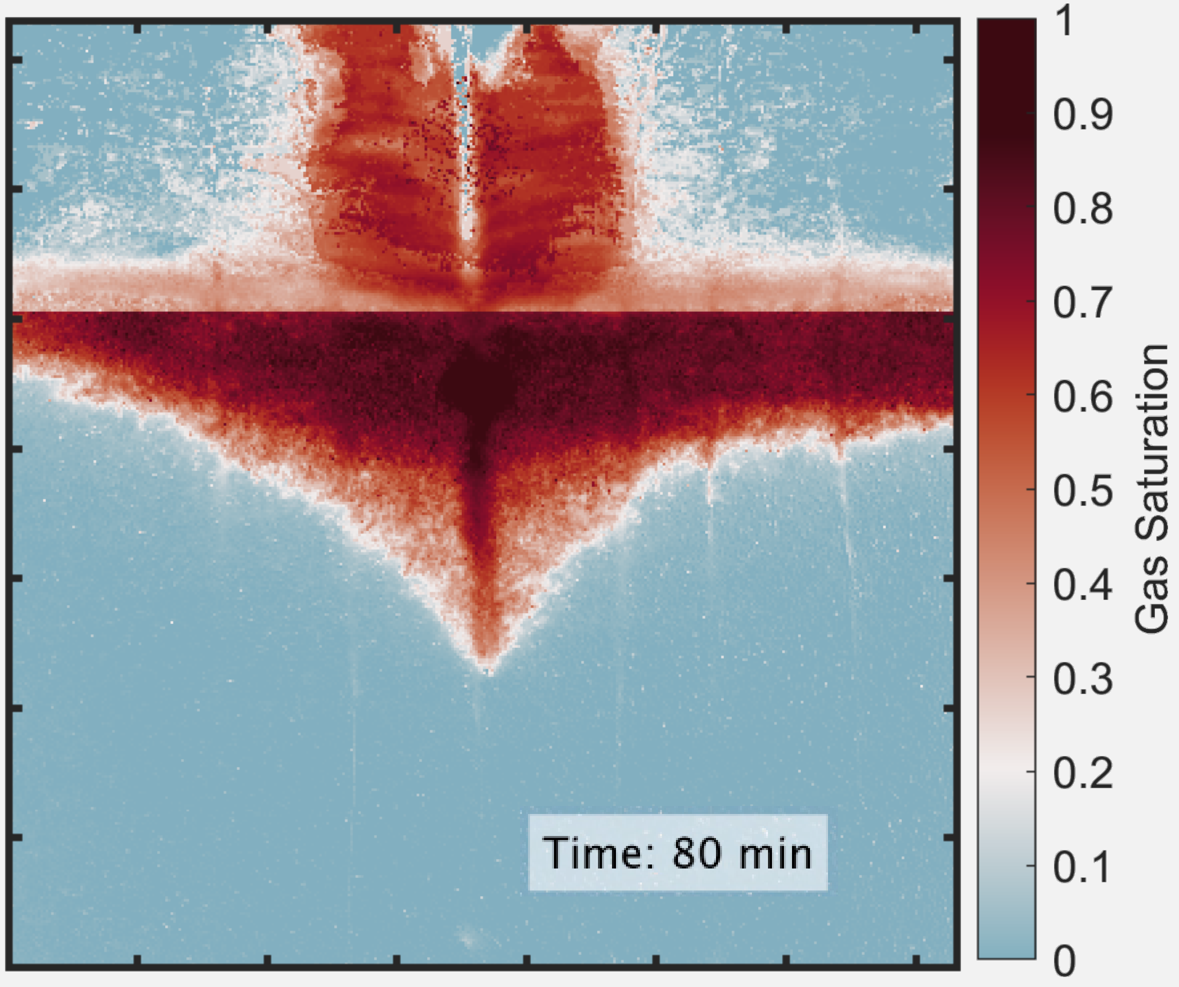
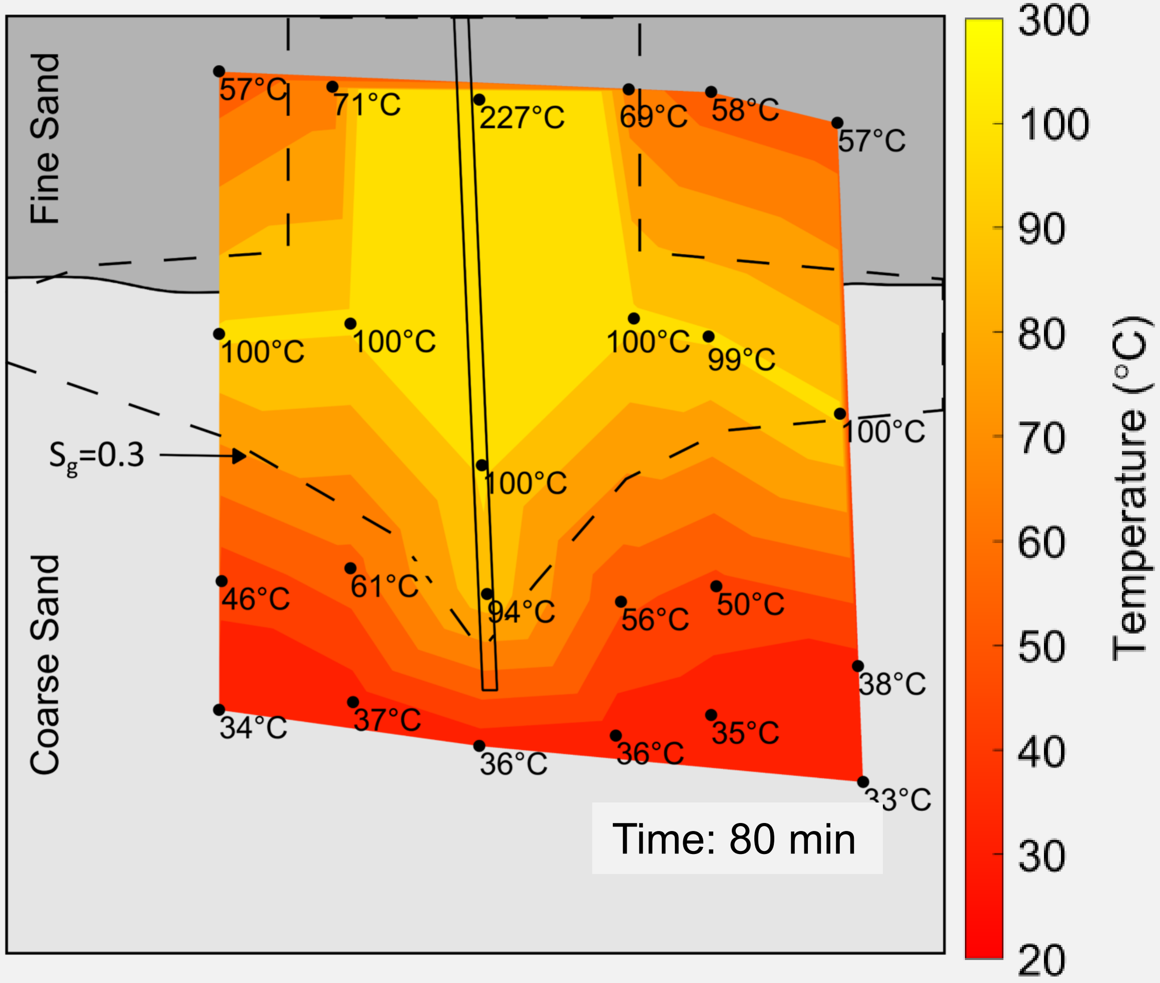


- Much thicker accumulation of steam underneath the capillary barrier

Fine Sand Over Coarse Sand





- Steam accumulation confirmed by temperature measurements

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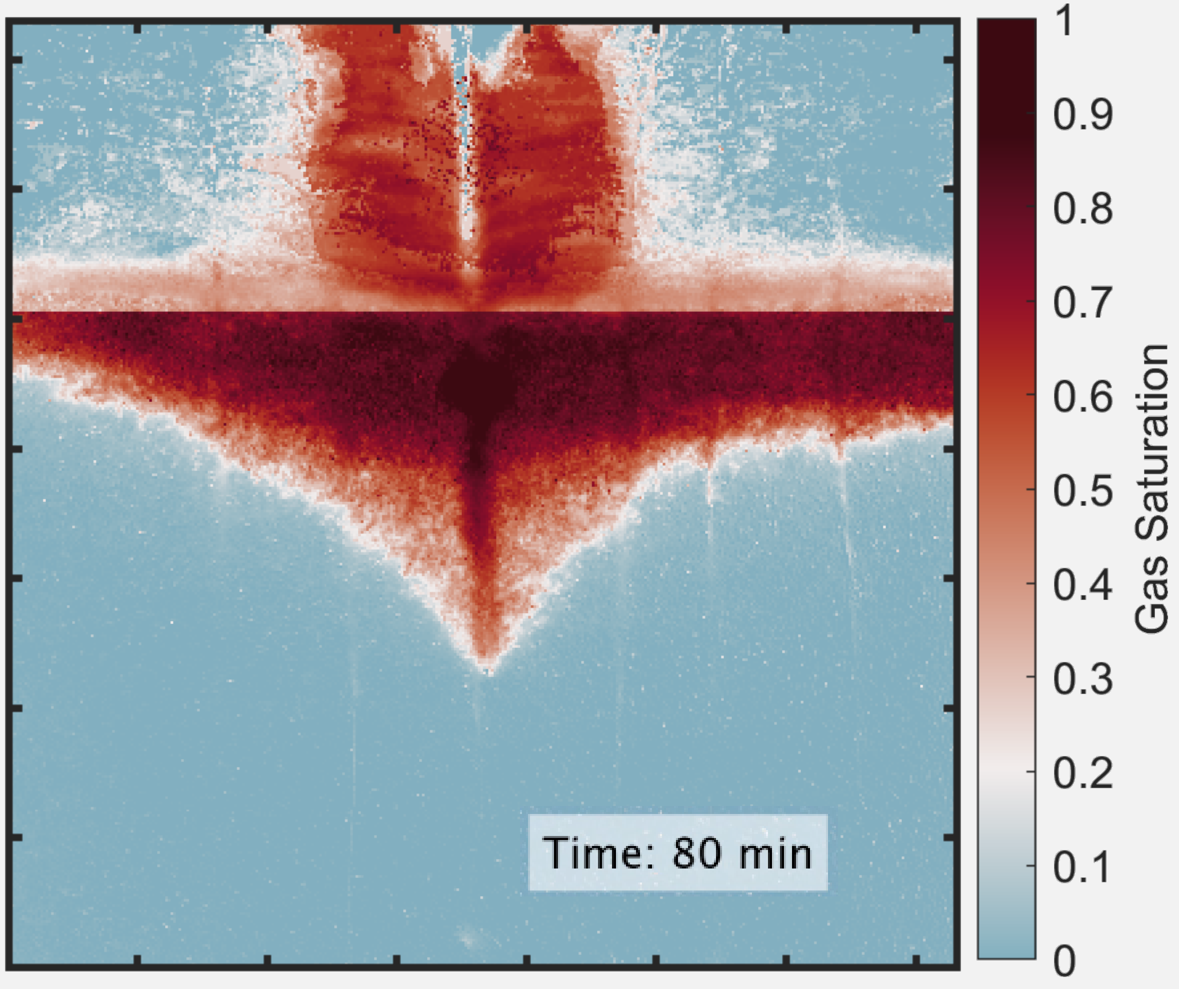
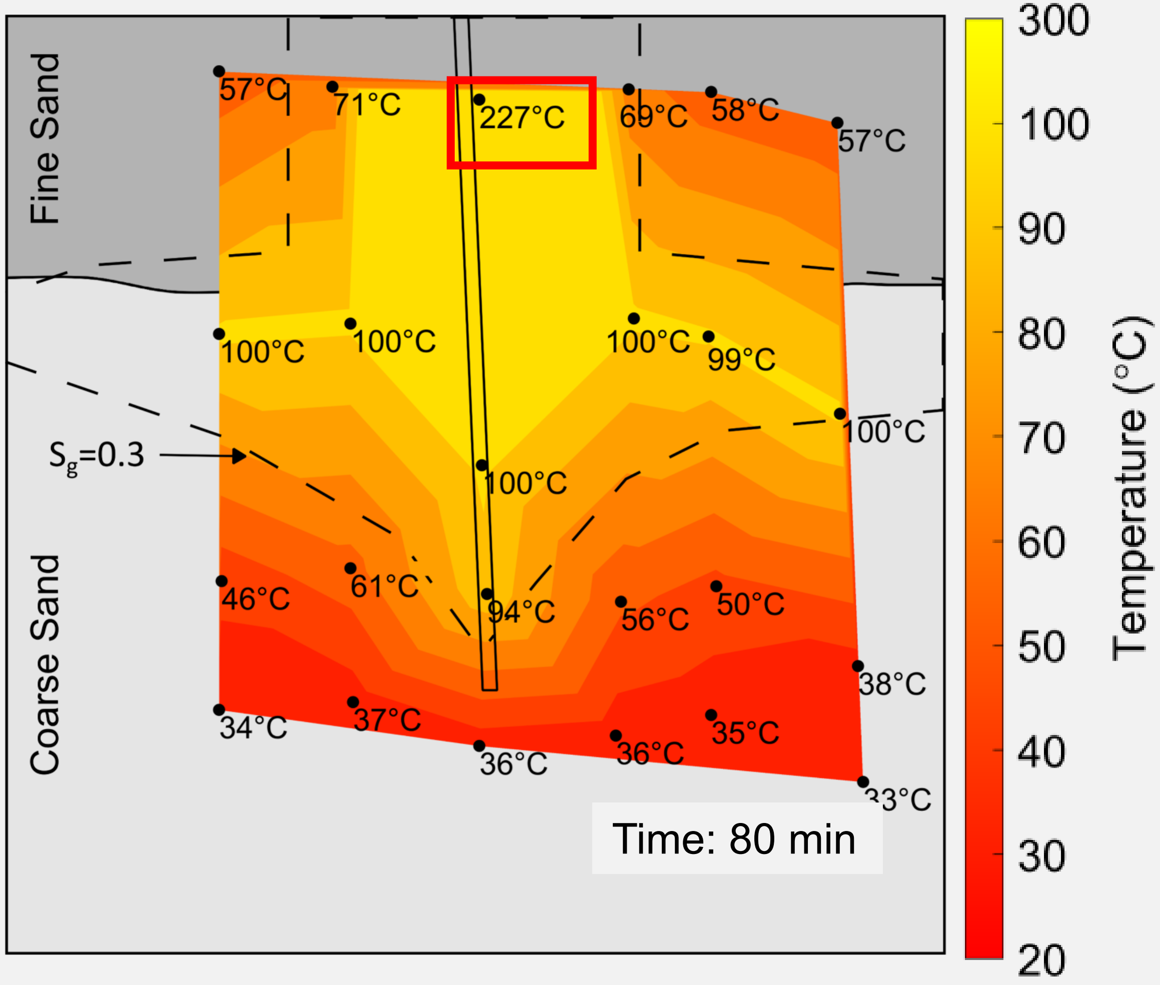
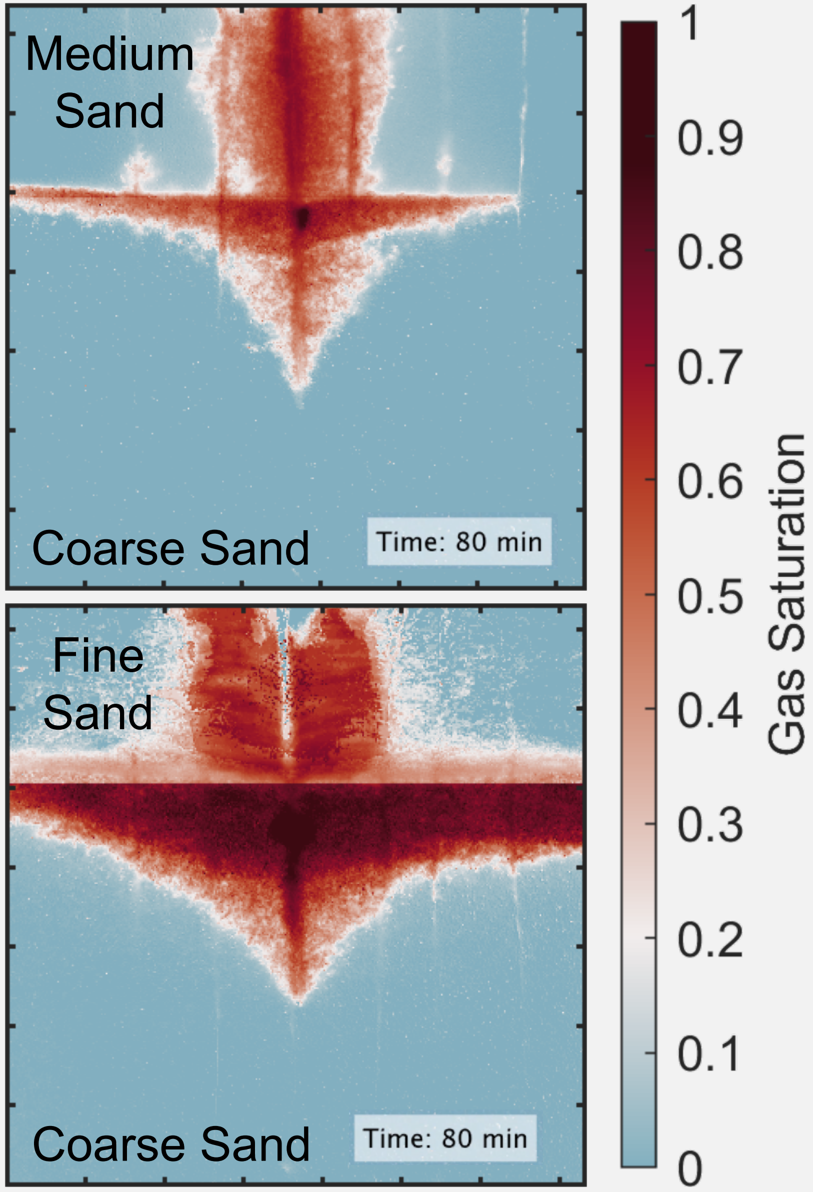




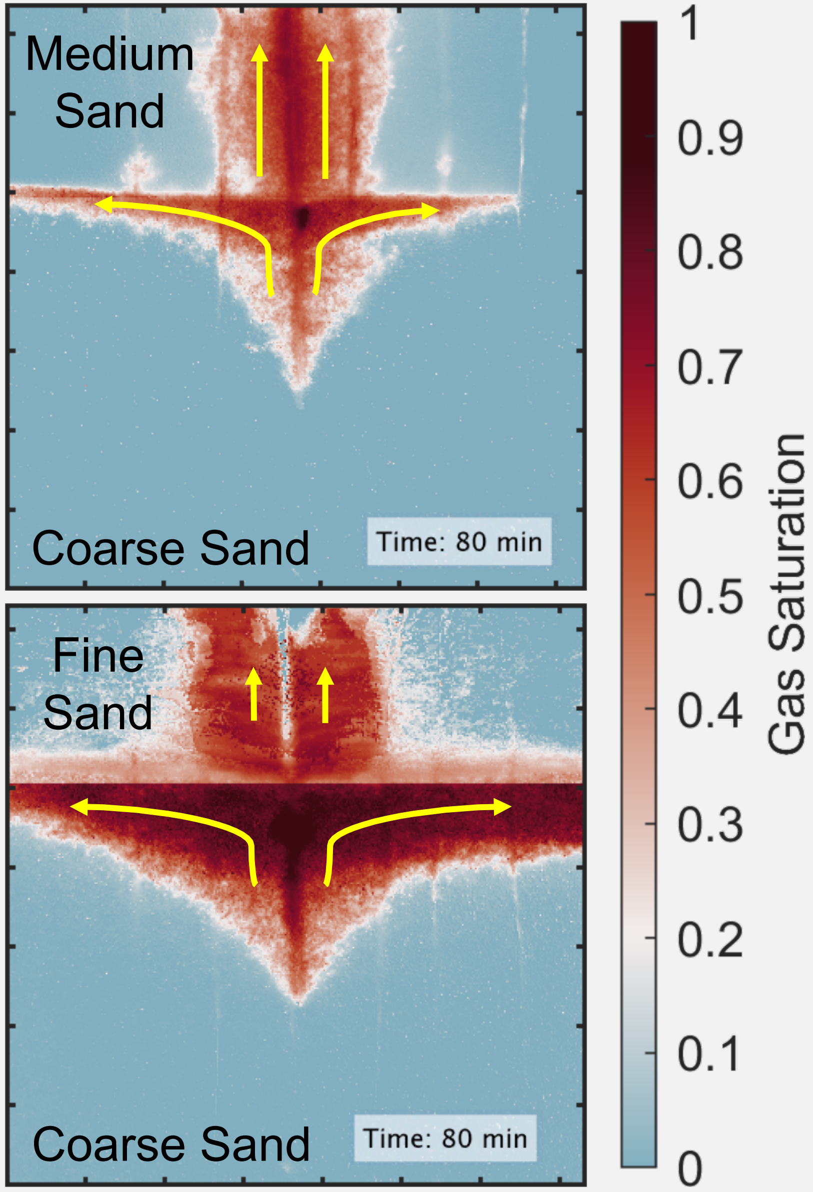
- Steam accumulation confirmed by temperature measurements
- Temperature adjacent to the heater in the fine sand of 227°C indicated a dry zone

Steam Accumulation



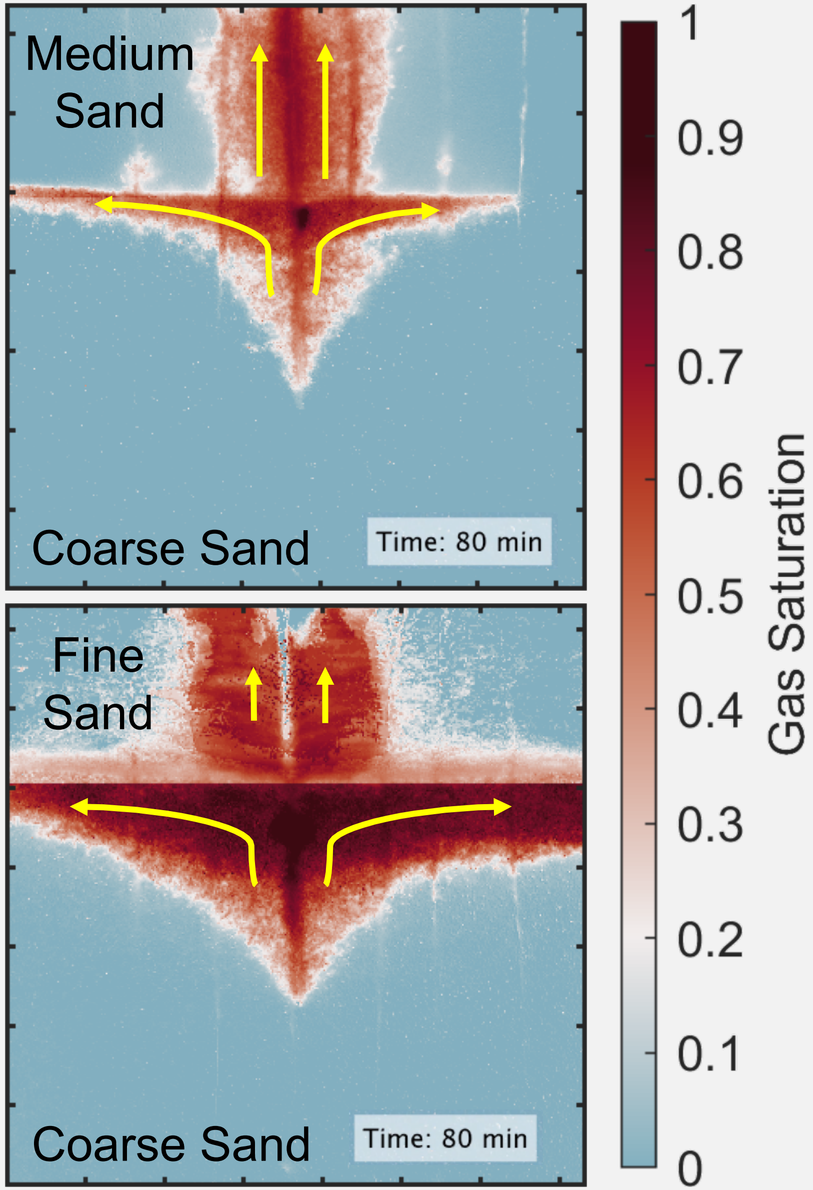
- Why did the steam accumulate?

Steam Accumulation



- Why did the steam accumulate?
- **Because the gas permeability of the two-phase zone was not sufficient to transmit all steam flow.**

Steam Accumulation



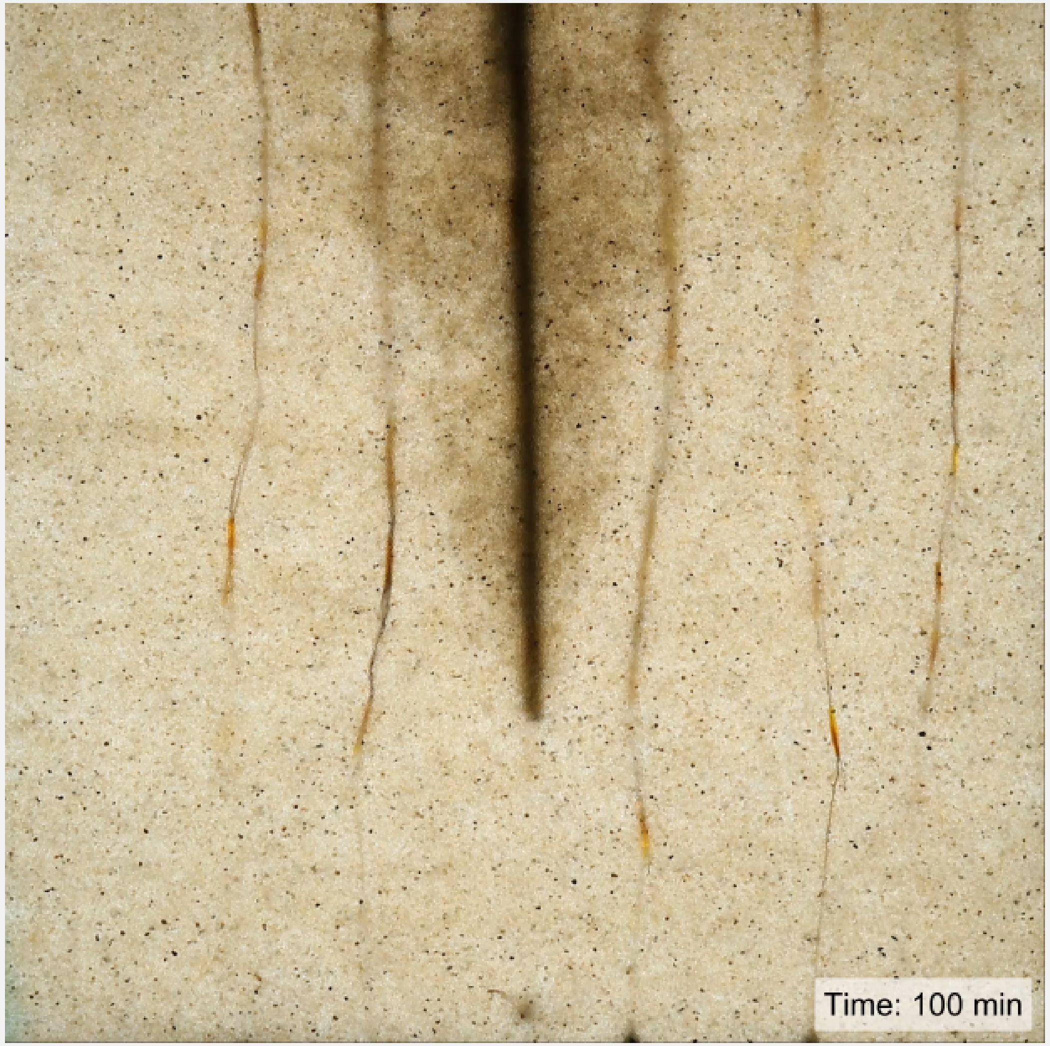
- Why did the steam accumulate?

- **Because the gas permeability of the two-phase zone was not sufficient to transmit all steam flow.**

- As expected, as the permeability of the overlying unit decreased, the pool thickness increased

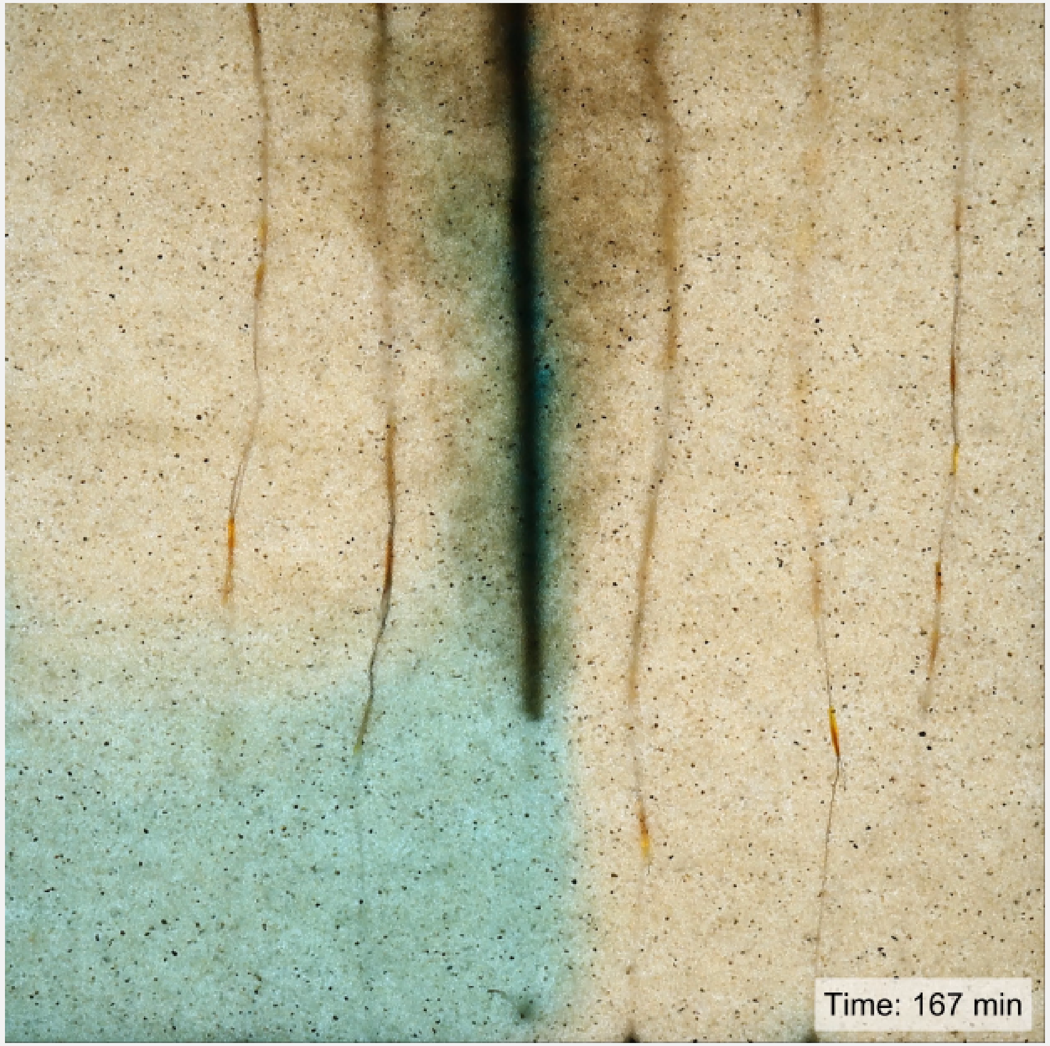
Results: Liquid Water Migration During and After Heating

Homogeneous Coarse Sand With Dye



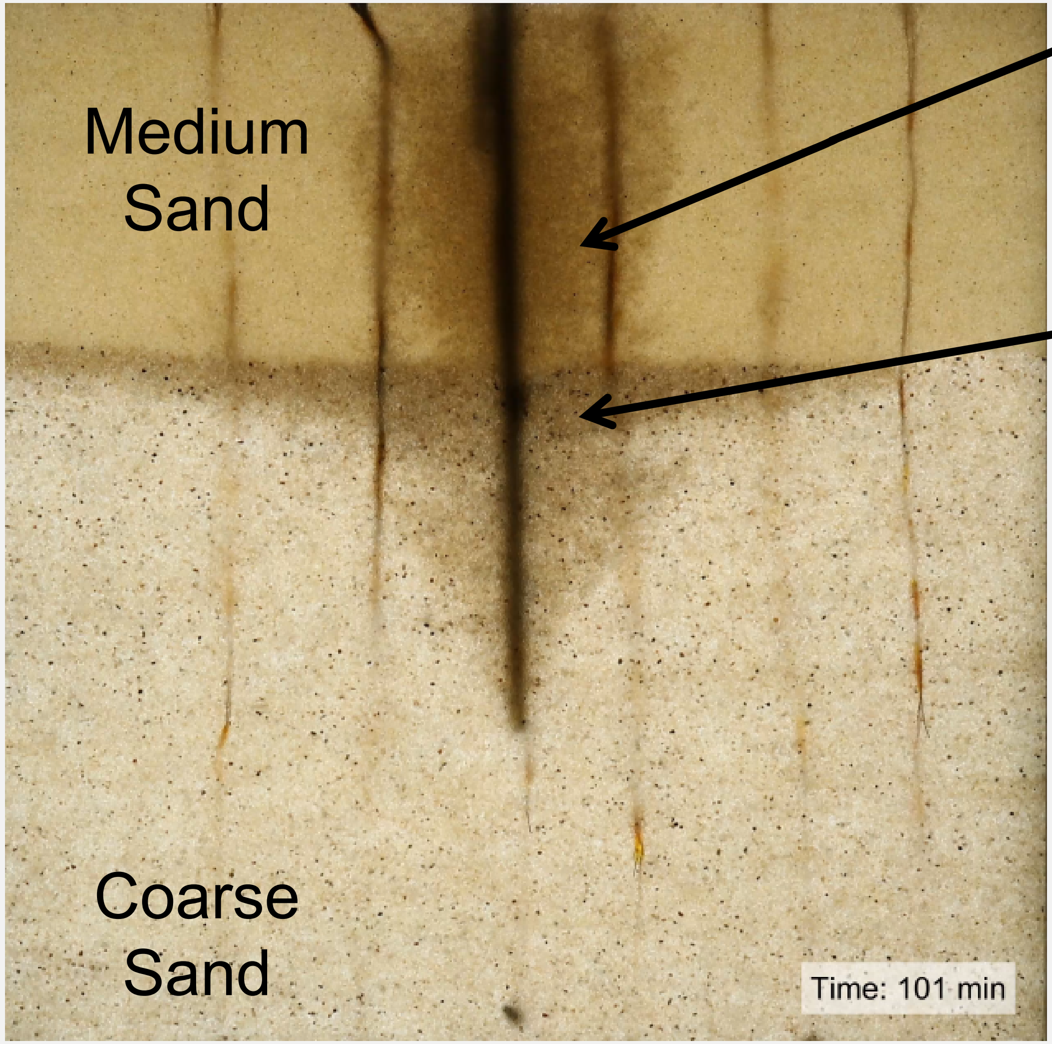
- Dye was added to the reservoir partway through heating
- Dye migrated with convective flow paths

Homogeneous Coarse Sand With Dye



- Dye was added to the reservoir partway through heating
- Dye migrated with convective flow paths
- After shutdown, the steam collapsed, and water imbibed into those pores

Medium Over Coarse Sand With Dye



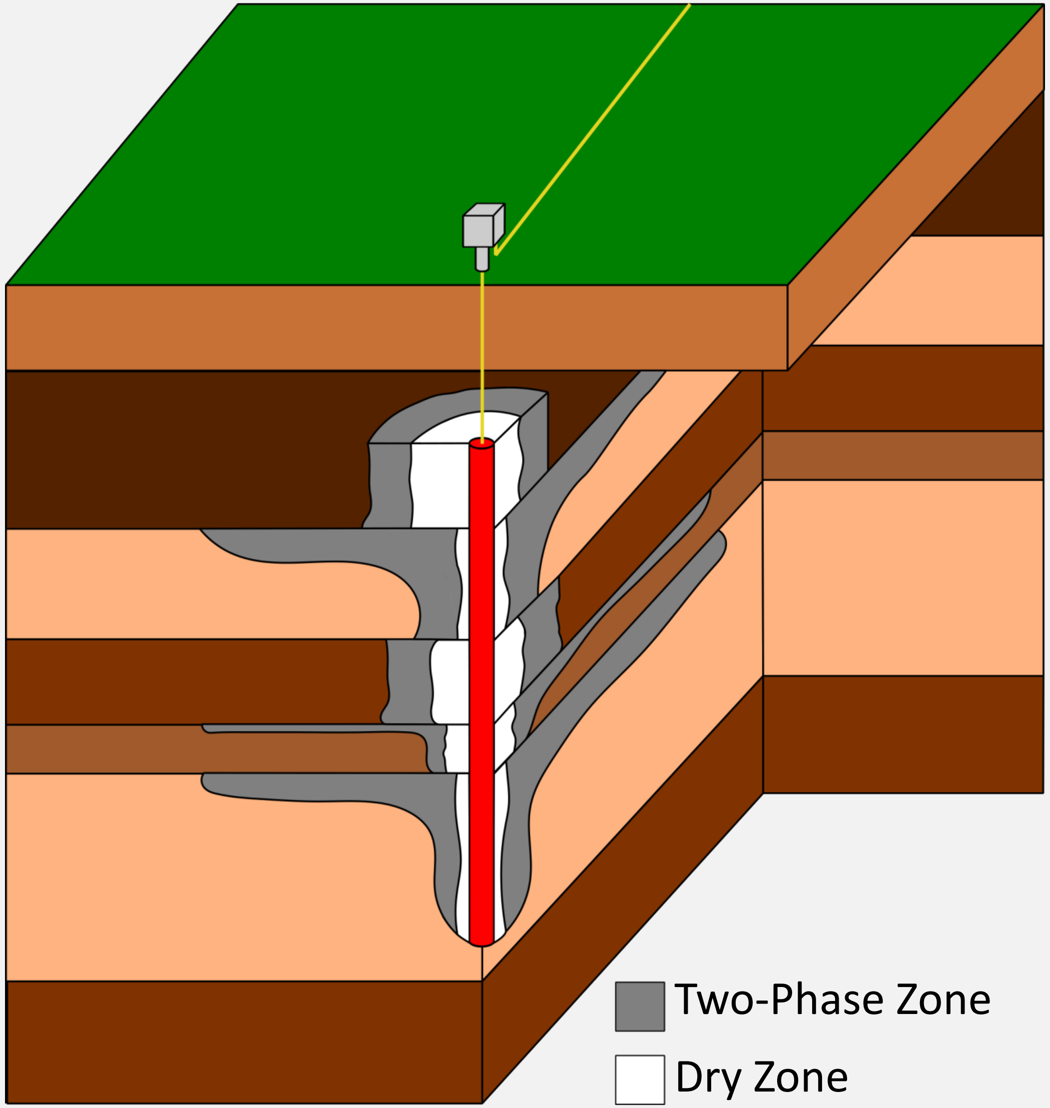
When the heater was turned off, this dye migrated upwards into the capillary barrier

Non-volatile dye was deposited underneath the capillary barrier

- Potential implications regarding condensation of semi-volatile compounds, reagent delivery after shutdown, and timing of cool-down

Refined Conceptual Model

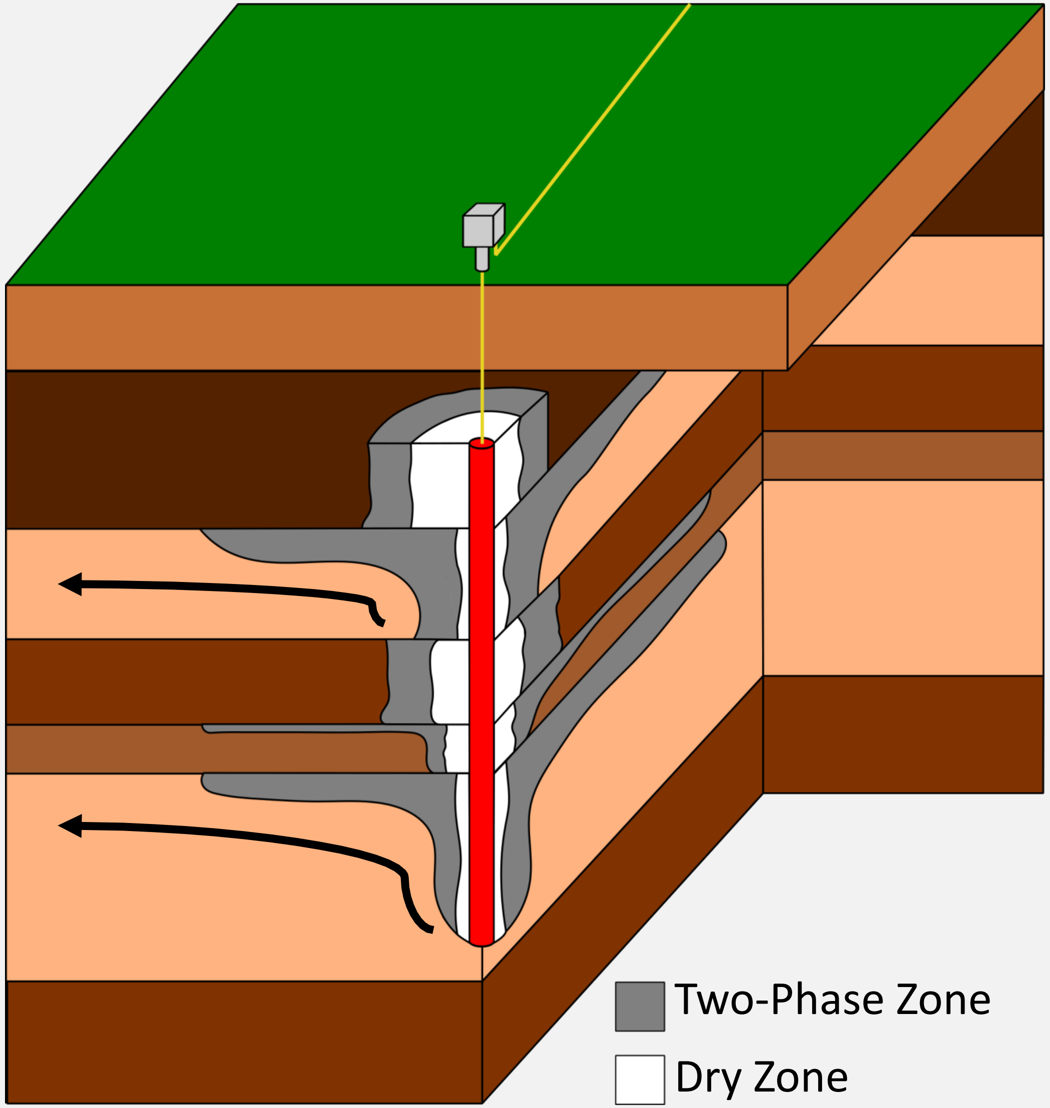
Refined Conceptual Model



- Permeability can be several orders of magnitude different

Based on the conditions depicted in the schematic of Horst et al. (2021)

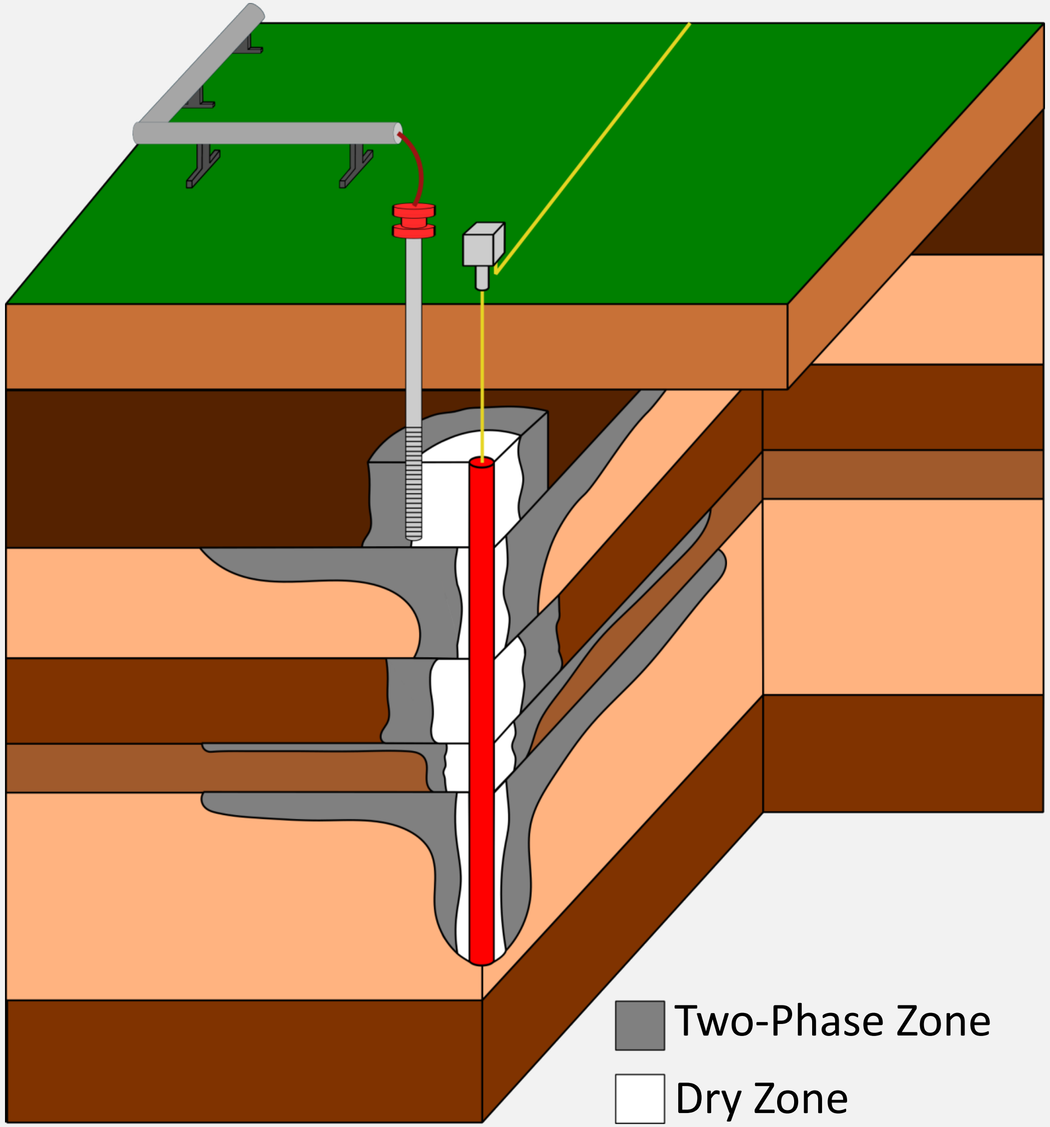
Refined Conceptual Model



- Permeability can be several orders of magnitude different
- Substantial lateral gas migration may occur
- Potential for migration and condensation of contaminants outside of the heated zone

Based on the conditions depicted in the schematic of Horst et al. (2021)

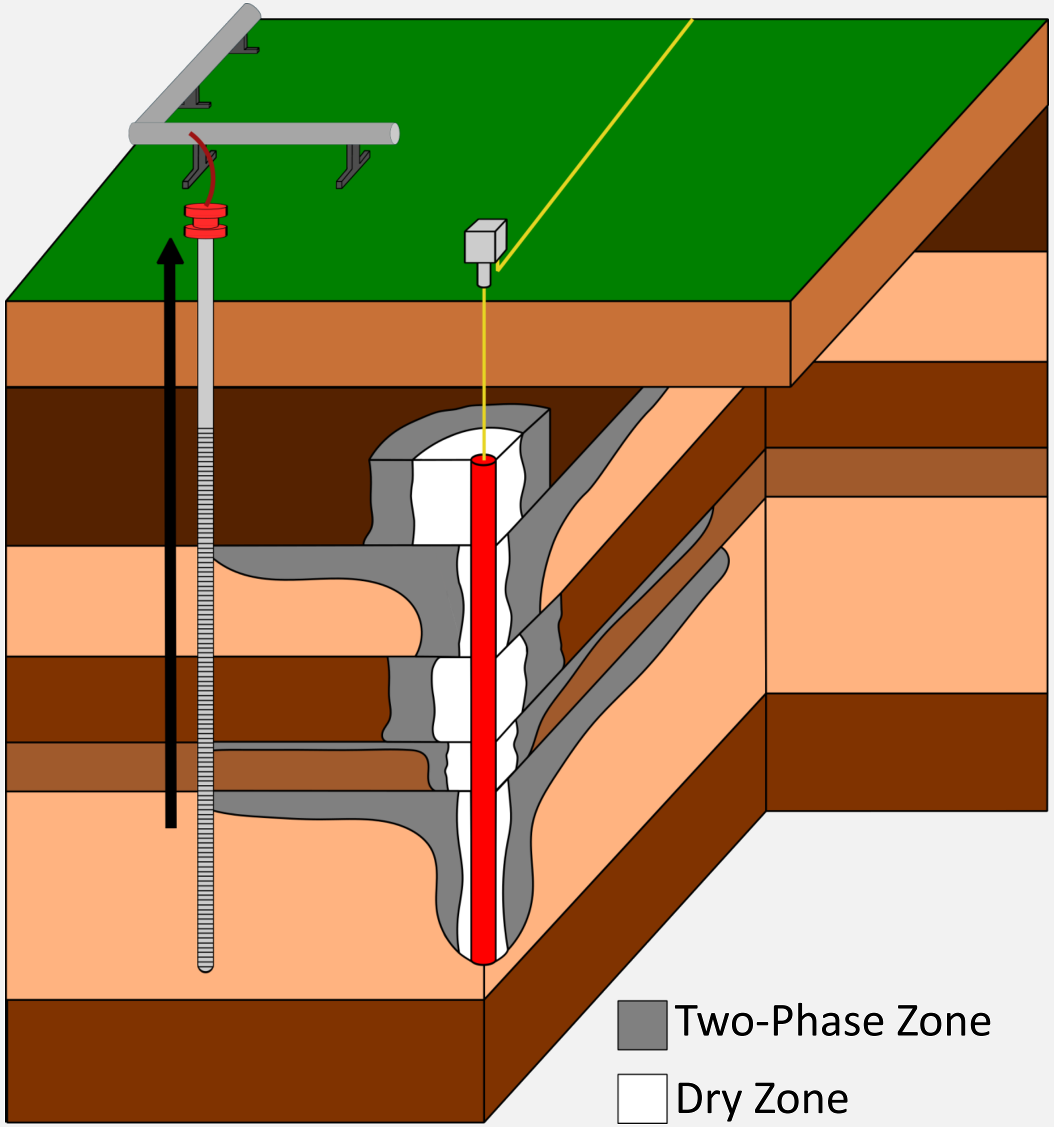
Field Implications



- For vapor capture in the vadose zone, the transmissivity of the dry and two-phase zones adjacent to the heater needs to be considered to mitigate steam migration outside of the treatment zone

Based on the conditions depicted in the schematic of Horst et al. (2021)

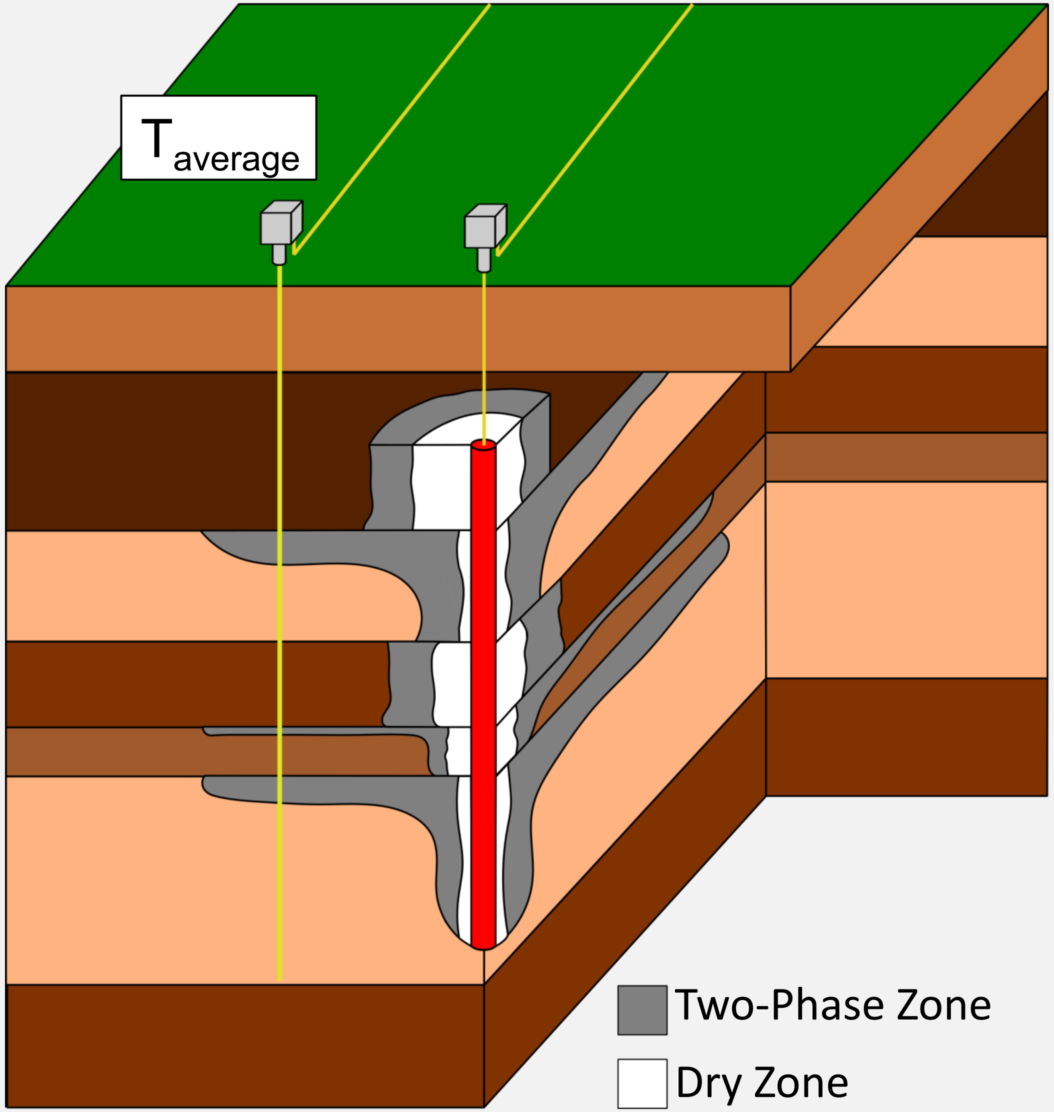
Field Implications



- Extraction wells that fully penetrate the depth of the target treatment zone may be needed

Based on the conditions depicted in the schematic of Horst et al. (2021)

Field Implications



- Also important to consider lateral gas migration when interpreting temperature data
- Thermocouple underneath a capillary barrier could read the temperature of a steam pool rather than the overall conduction heat front

Based on the conditions depicted in the schematic of Horst et al. (2021)

Summary and Conclusions

- **Evolution of Gas Saturation**
  - Light transmission clearly identified the extent of gas saturation
  - Wider two-phase zone observed in finer material
- **Effect of Heterogeneity**
  - Gas permeability of the capillary barriers was not sufficient to transport all gas upwards in heterogeneous experiments
- **Water Migration Pathways**
  - Liquid water imbibed into the two-phase zone following heater shut down
- **These results should be incorporated into future numerical models**

Queen's University

Thank you

Acknowledgements:

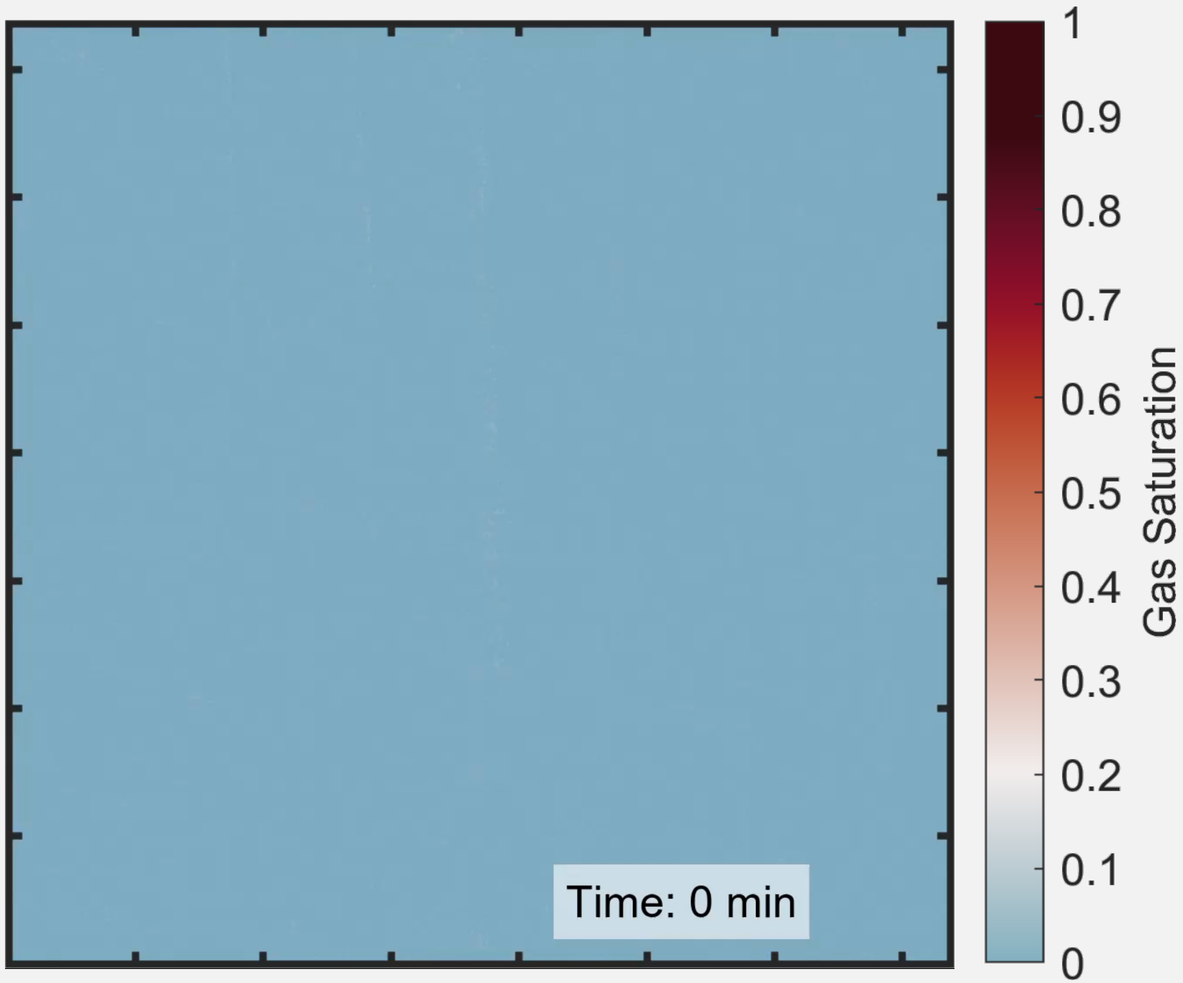
Julia Barnes-James, Brooke Belfall, Madeline Calvert, Zena Lauzon, Ariel Nunez Garcia, Stephen O'Meara, Stan Prunster, and Hal Stephens

McMillan-McGee Corp

Creators of ET-DSP™

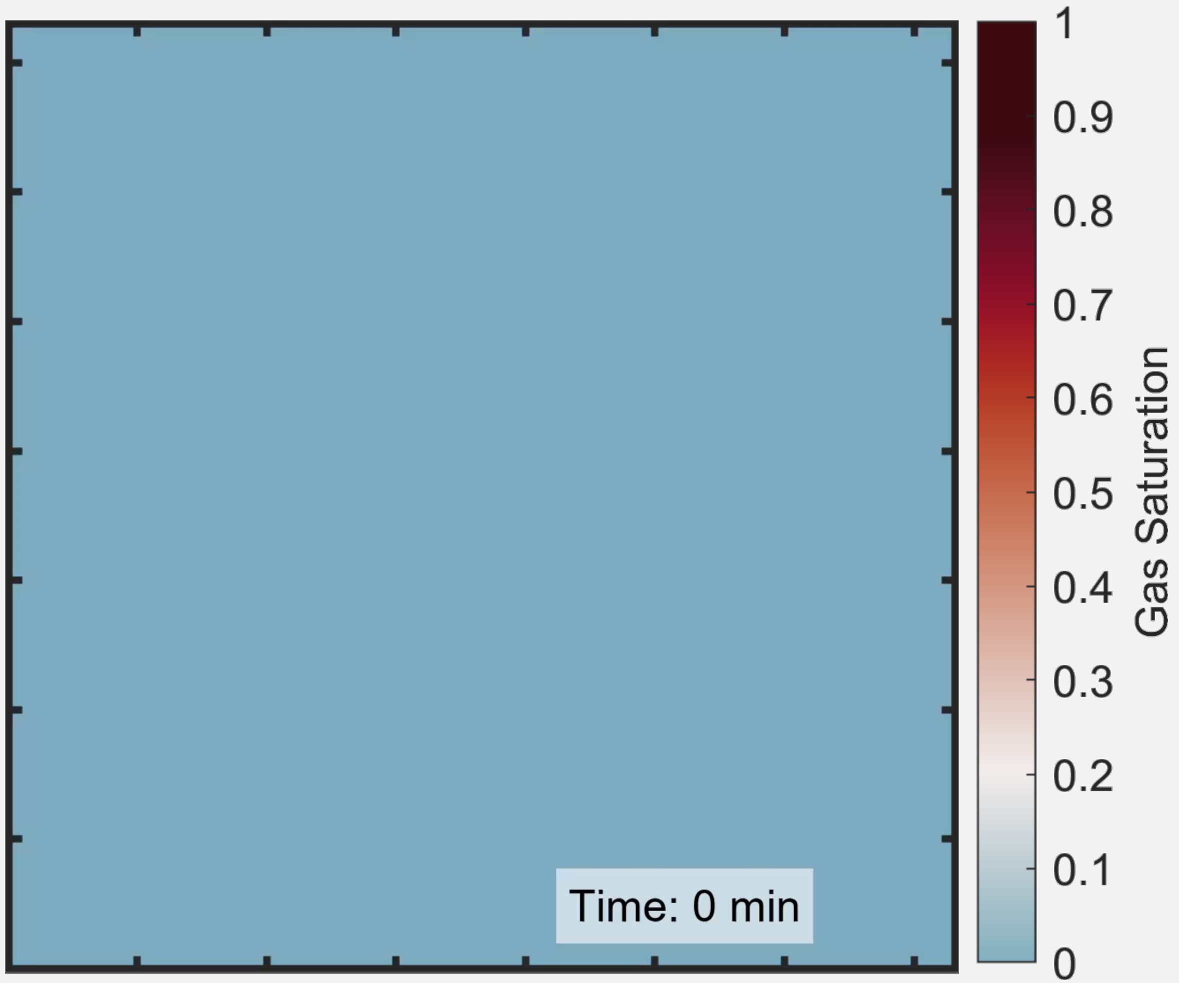
NSERC CRSNG

Homogeneous Fine Sand



- Wider two-phase zone and higher gas saturations

Fine Sand Over Coarse Sand



- Much thicker accumulation of steam underneath the capillary barrier