Simulation of Cement Reactivity with CO_2 in the Wellbore Environment

J. William Carey, Peter Lichtner, and Chuan Lu

Los Alamos National Laboratory

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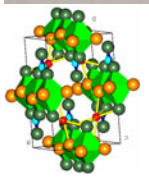

Acknowledgements: DOE's National Energy and Technology Laboratory (04FE04-07)

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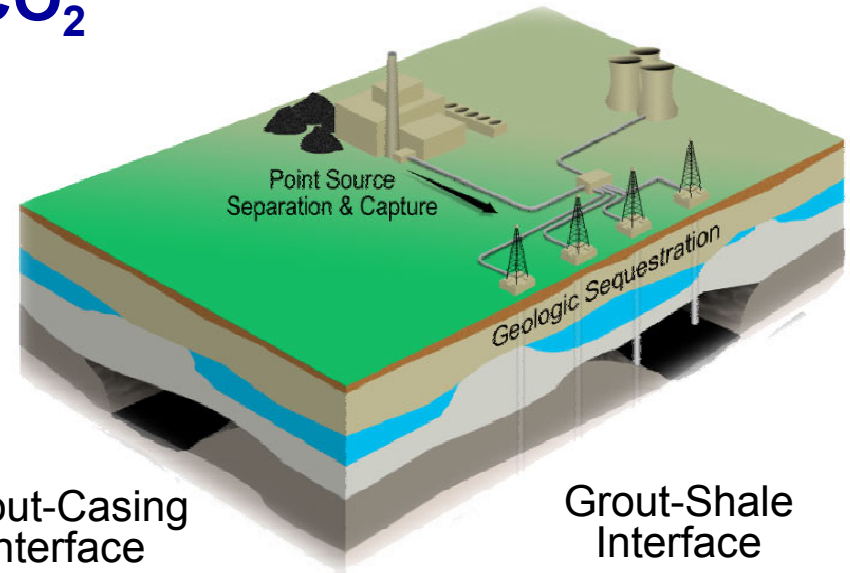
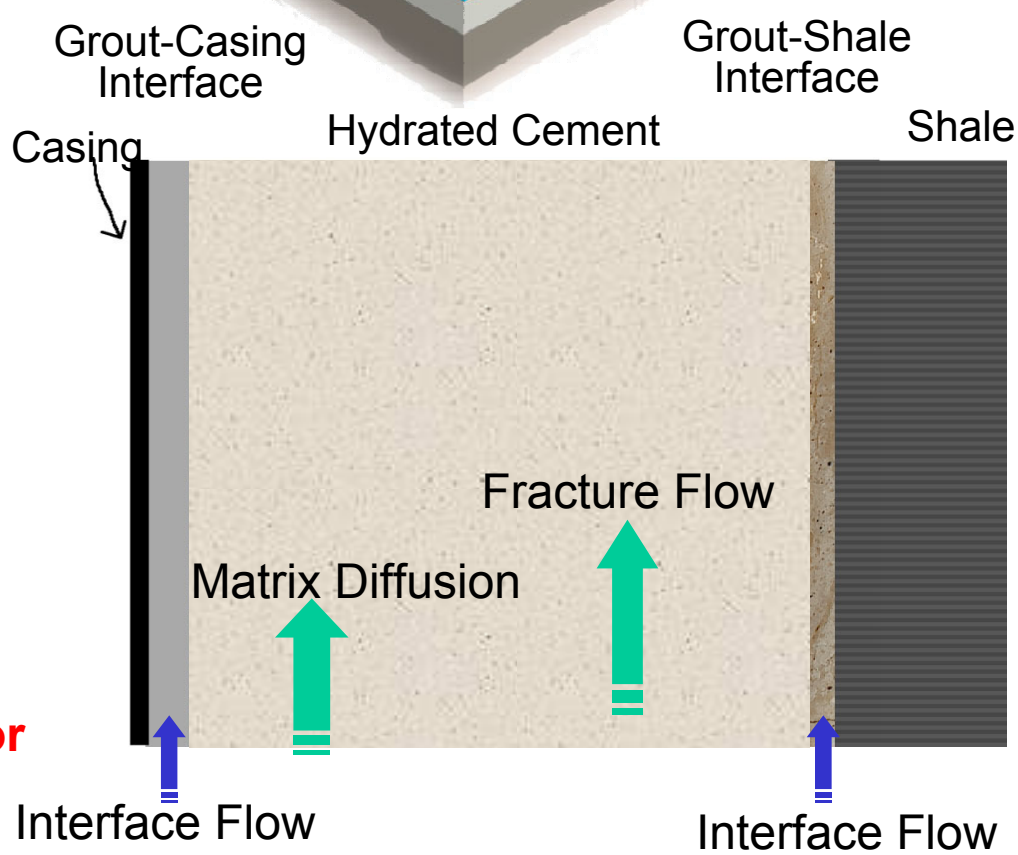
Motivation: Determine the long-term integrity of wellbore cement exposed to CO_2

- Determine mode of CO_2 interaction with cement
- Develop model of changes in effective cement permeability as function of CO_2 reaction
- Need initial conditions of interfaces (width, porosity, effective permeability)
- Need initial drive (diffusion, buoyancy, capillary, gradient)
- Calculate changes in interface permeability
- Ultimately, couple with geomechanics

- How does the two-phase system affect reaction rates? Will CO_2 penetrate cement primarily by diffusion, pressure-driven flow, or capillary pressure?





Effect of Two-Phase Behavior on CO_2 Reactivity with Cement

1-D Calculations

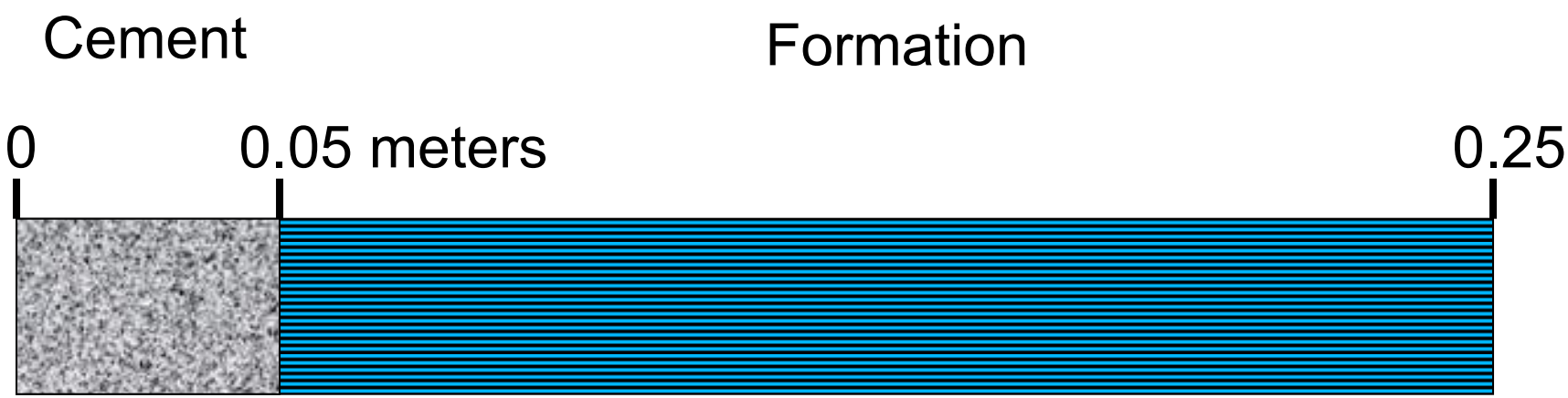
- Role of capillary pressure properties of cement, shale, and reservoir rocks
- Comparison with no-flow (diffusion) results

2-D Calculations

- Problem set-up and boundary conditions
- Preliminary results for flow-only case

Experiments

- Reactivity at the cement-casing interface



38% C-S-H (x_{SiO2}=0.36, Ca/Si = 1.78)

15% portlandite

14% monosulfate

3% hydrogarnet

30% porosity

20% illite

7% quartz

1% kaolinite

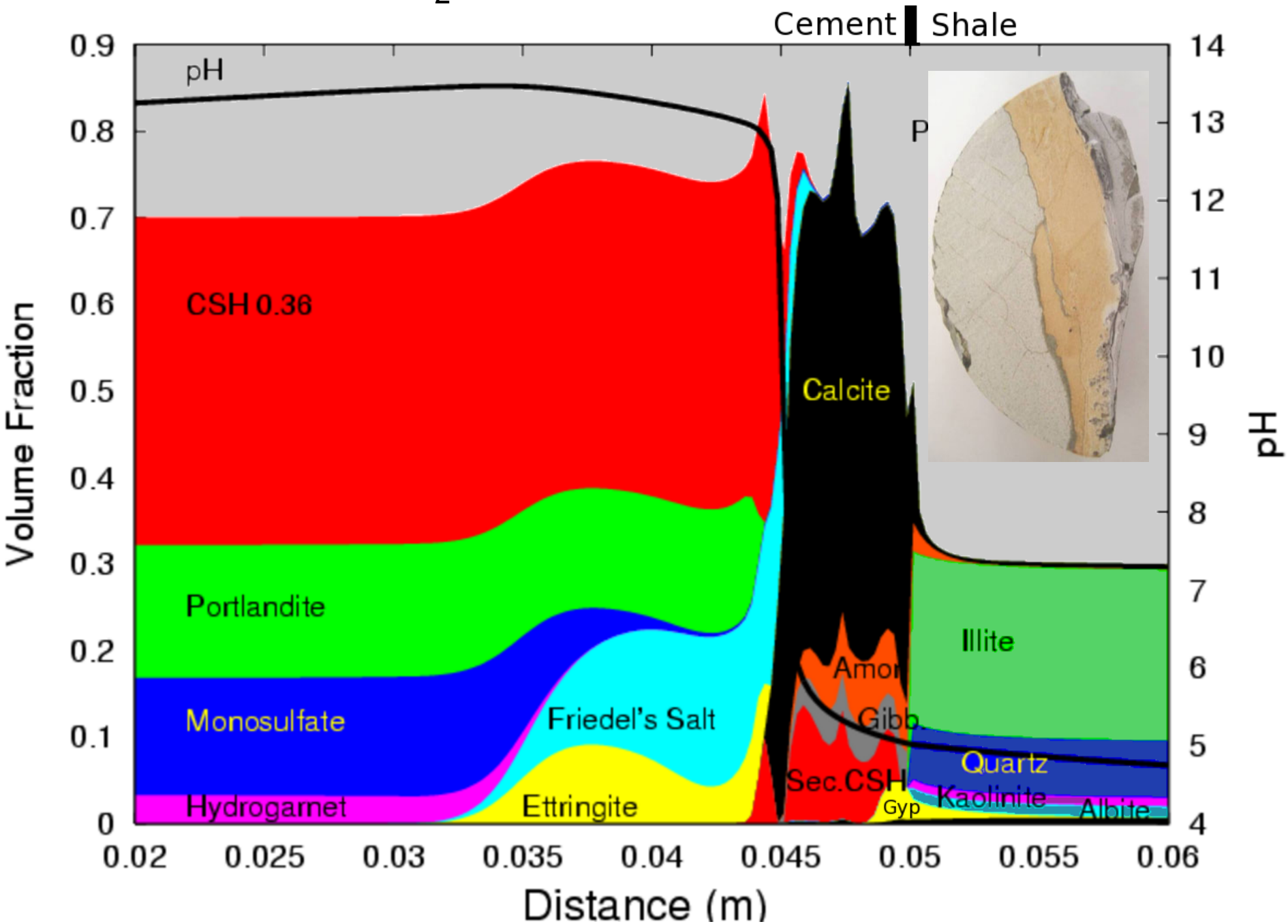
1% calcite

1% dolomite

70% porosity

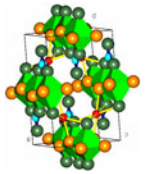
- 1-D diffusion of CO_2-saturated brine into cement
- 25 ^oC and 179 bars $P(CO_2)$
- Variables: Porosity, tortuosity, reaction rates, and solid solution model [Carey & Lichtner (2007) American Ceramic Society]

1-D Diffusion of CO_2-Saturated Brine

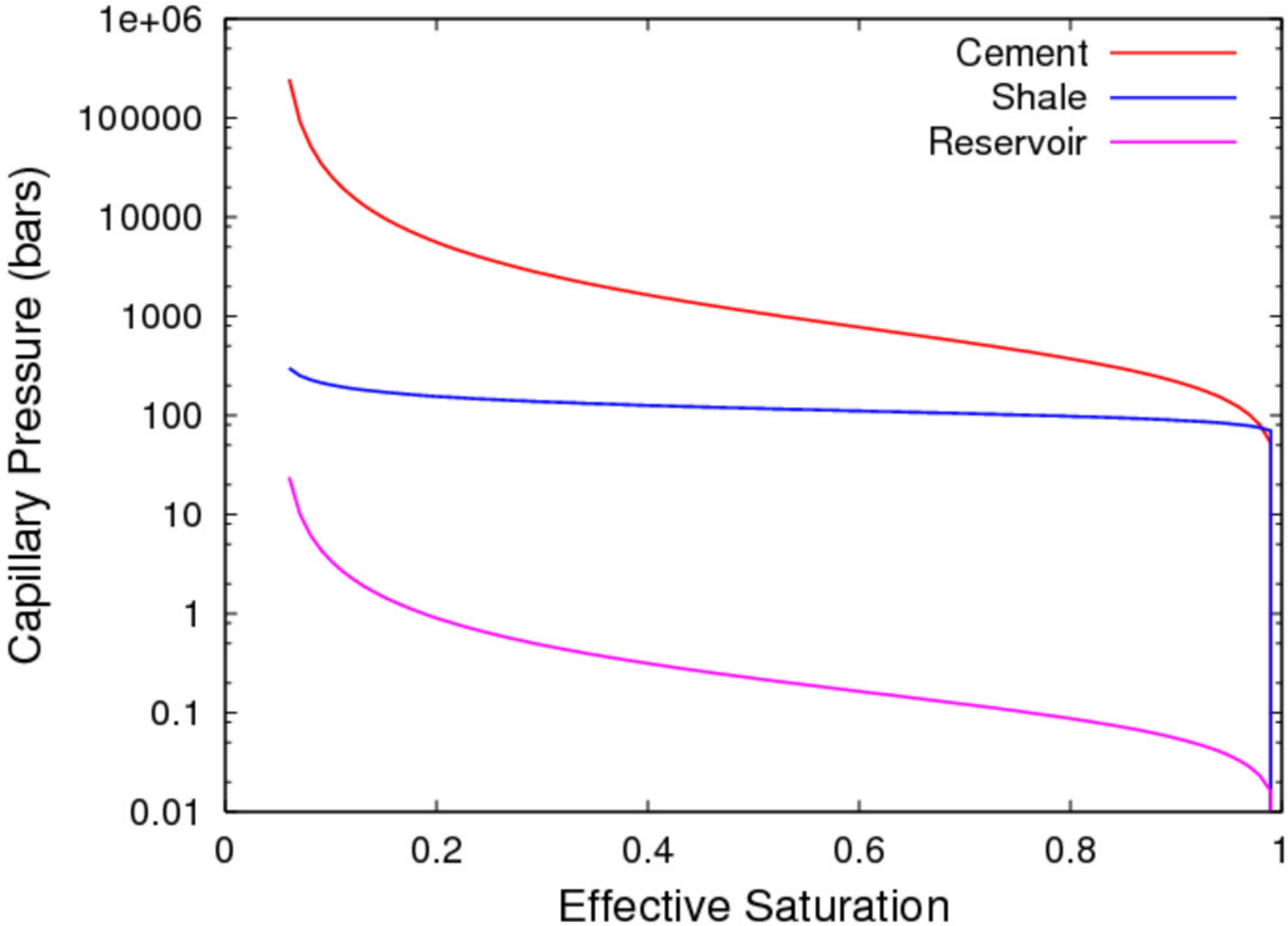


Two-Phase Simulation of Cement-CO_2 Reaction

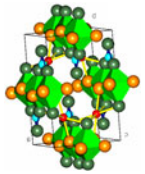
- 1-D (geometry and mineralogy as before)
- Use parallel version of FLOTRAN (PFLOTRAN)
- Parameters:
  - As before (reaction rates, porosity, tortuosity)
  - Without solid solution model
  - Need permeability and relative permeability (capillary pressure relations)
- Horizontal geometry (as at SACROC)
  - CO_2 interaction by diffusion and capillary pressure
- Scoping calculations



Capillary Pressure Relations



(Bennion and Bachu, 2006, SE 99325
Savage and Janssen, 1997, ACI Mat. J.)



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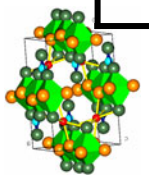
Initial Conditions

- T = 50 C; P = 200 bars
- Cement: saturated with 1.6 M NaCl brine
- Formation: 50% saturated with brine/CO_2

$$\Psi = (S^{-1/m} - 1)^{(m-1)} / \alpha$$

	Perm (mD)	alpha	m	Φ	τ
Cement	0.1	0.0023	0.42	0.4	0.005
Shale	0.1	0.01	0.9	0.2	0.5
Reservoir	100	10	0.5	0.2	0.5



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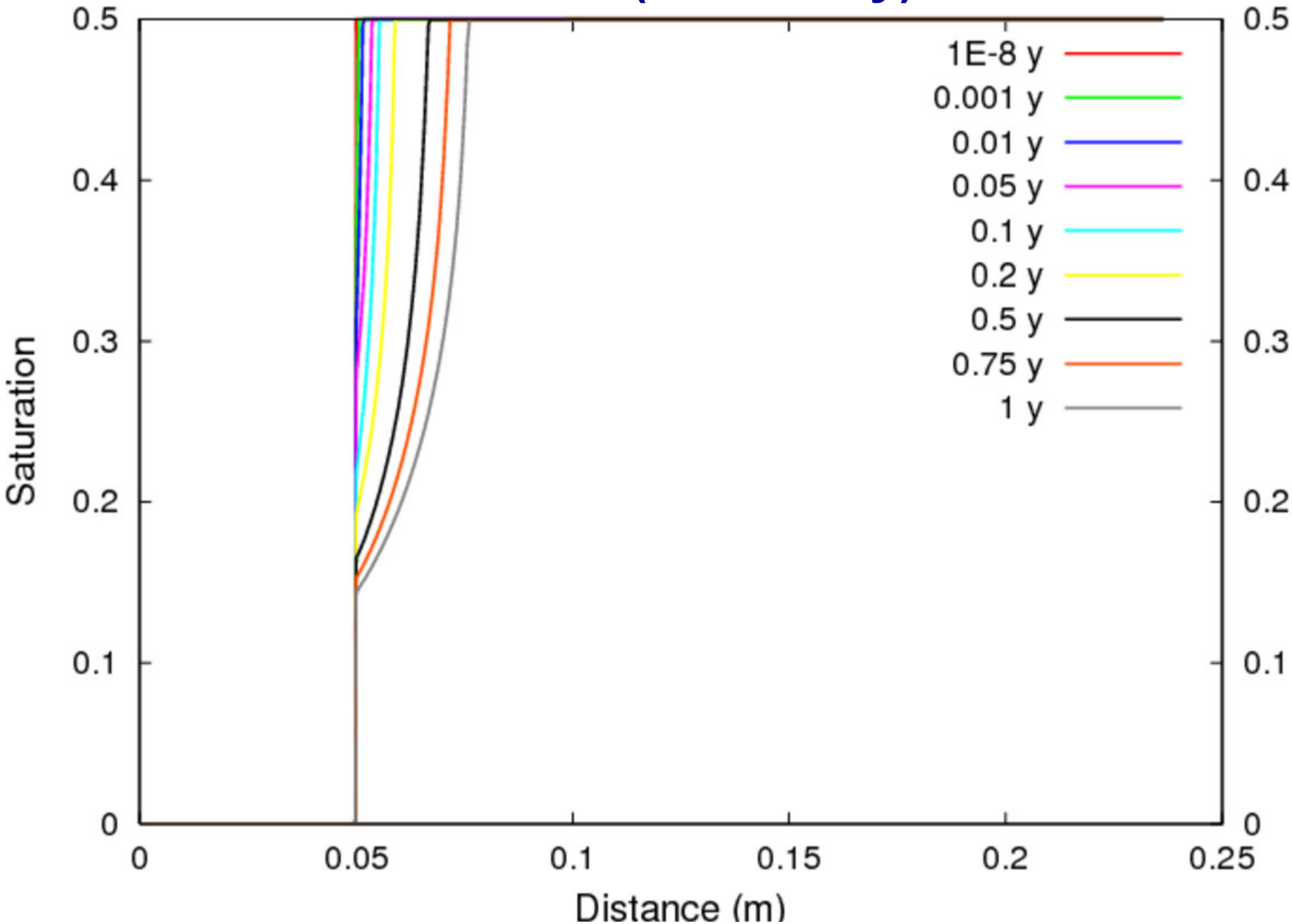
Cement: Reservoir (Flow Only)



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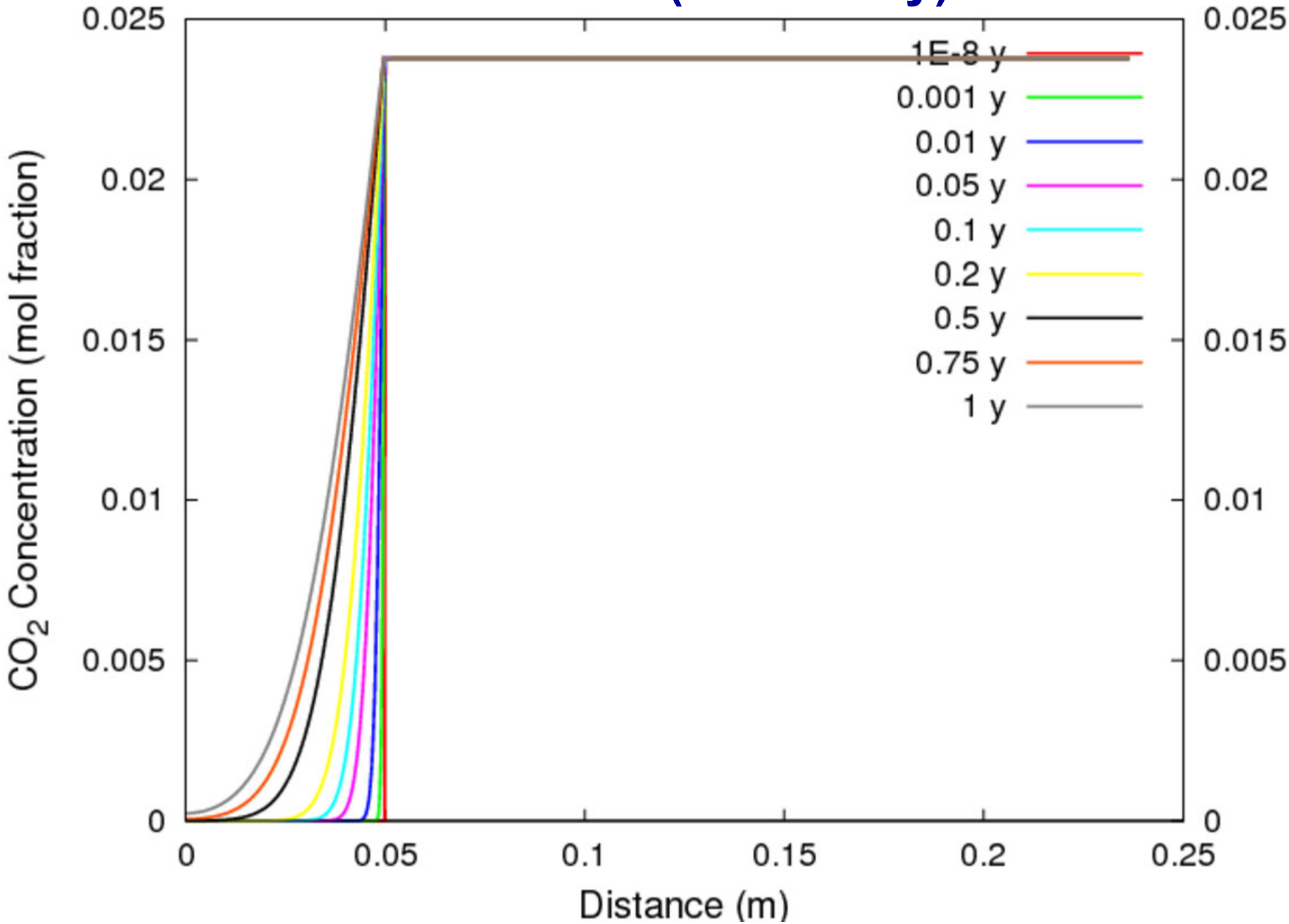
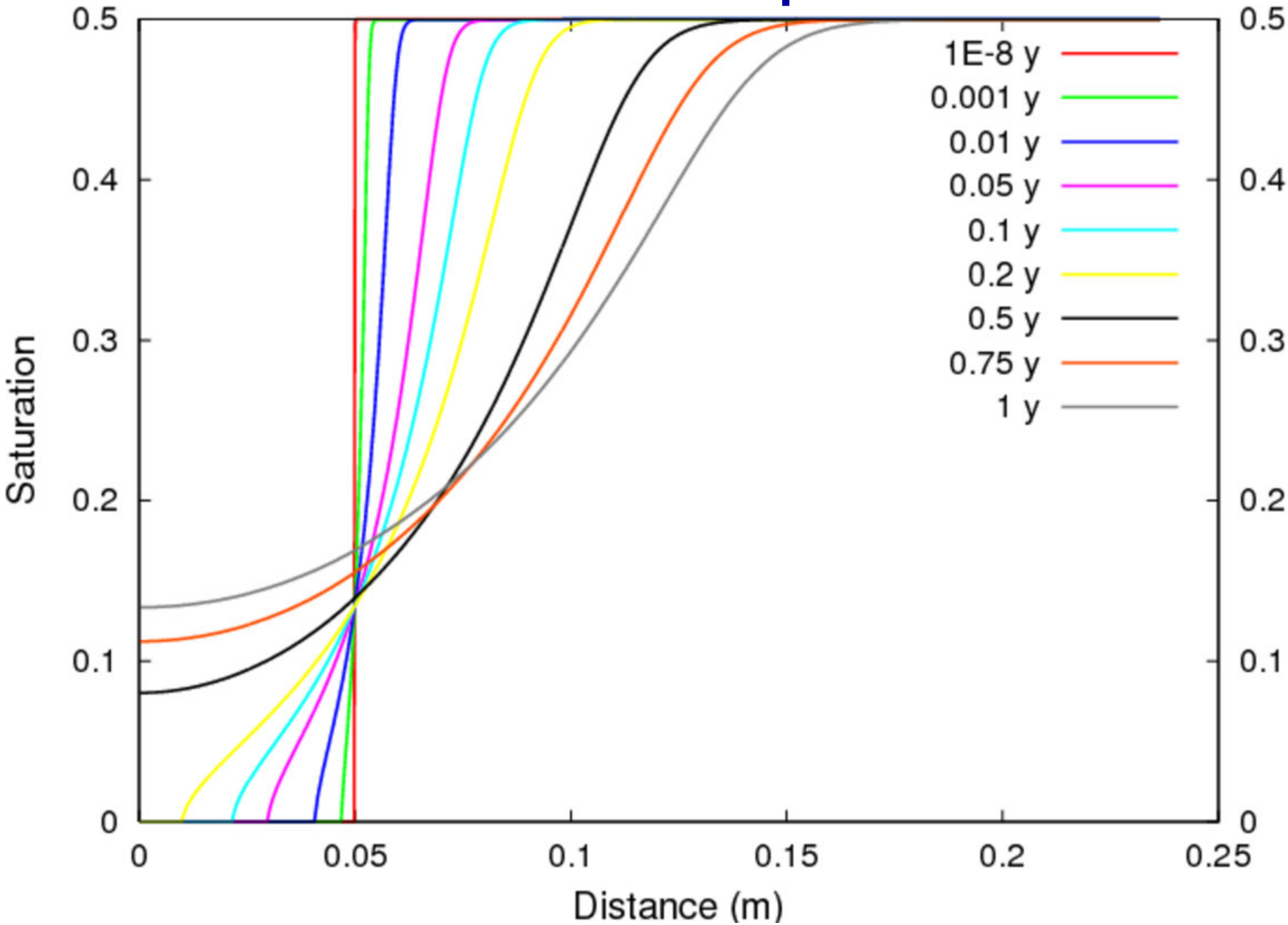


No Contrast: Cement-like Properties



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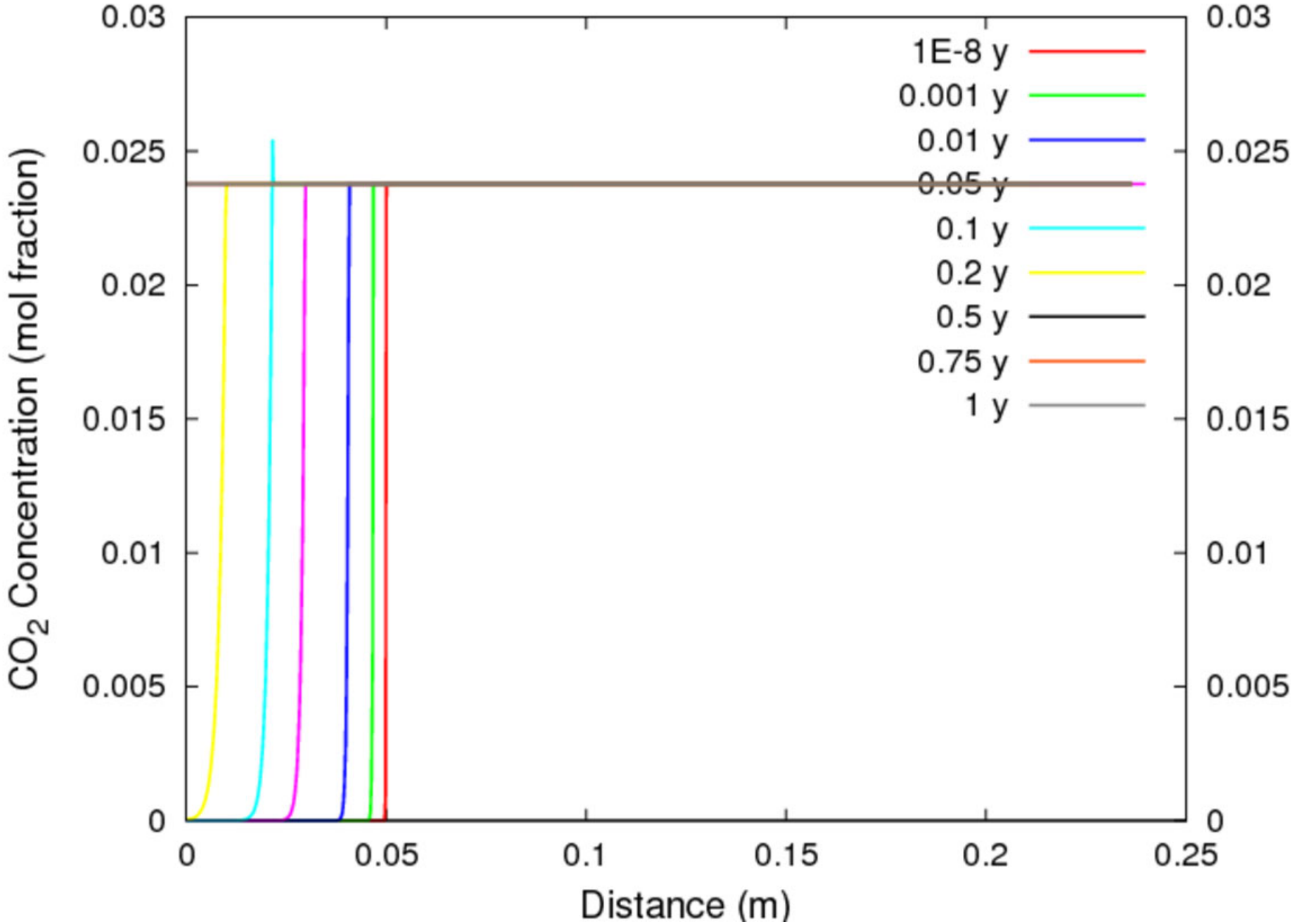
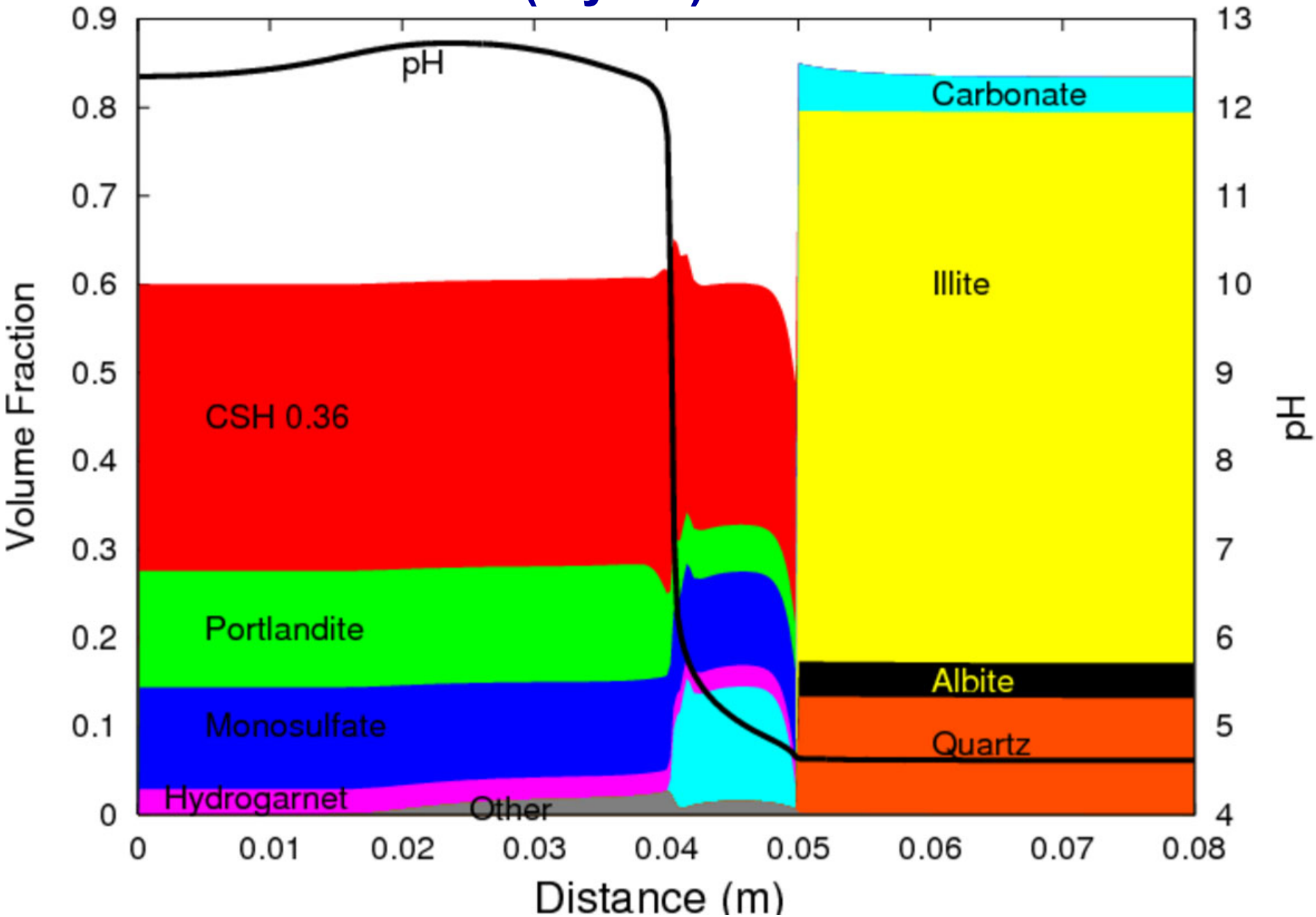
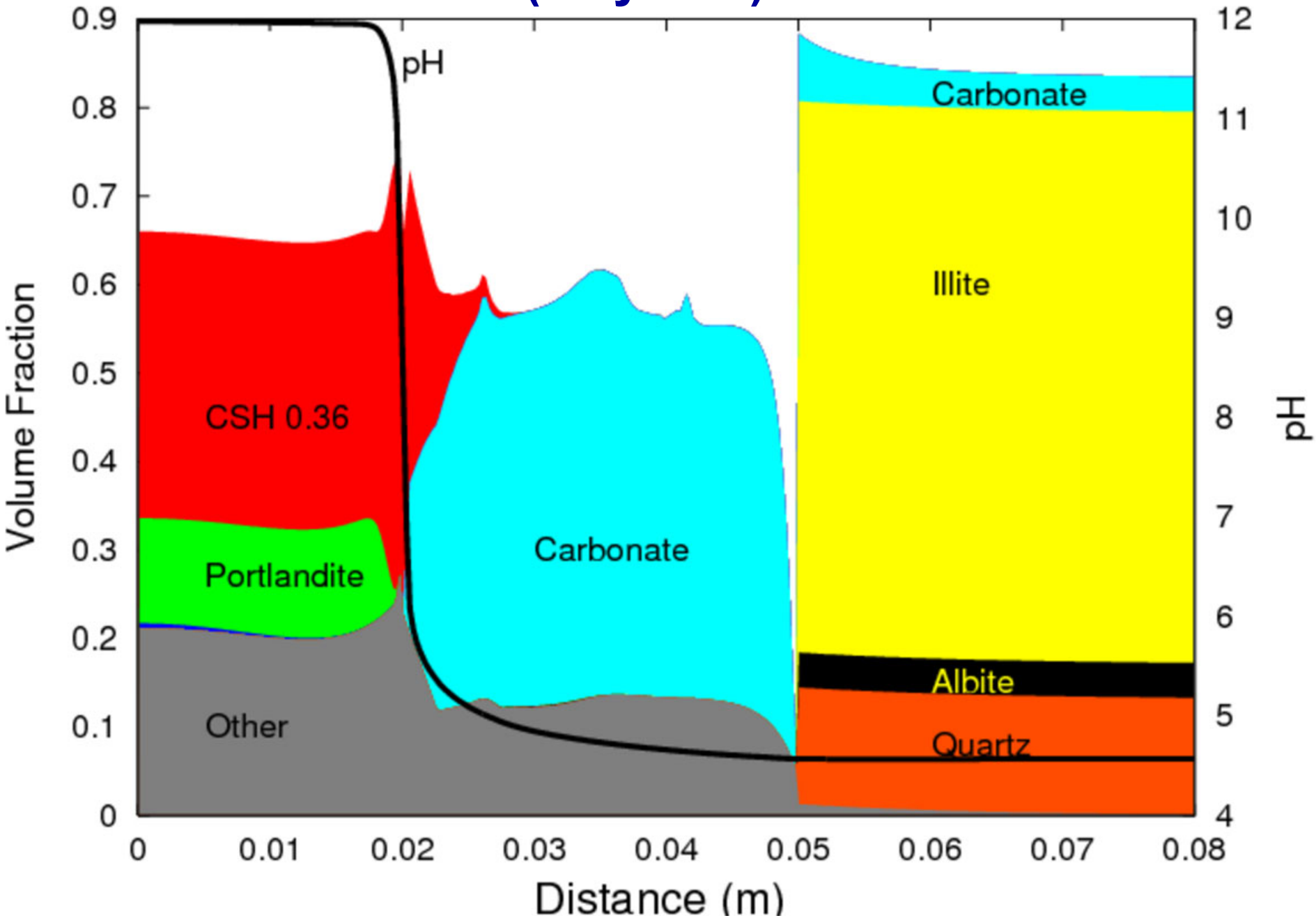


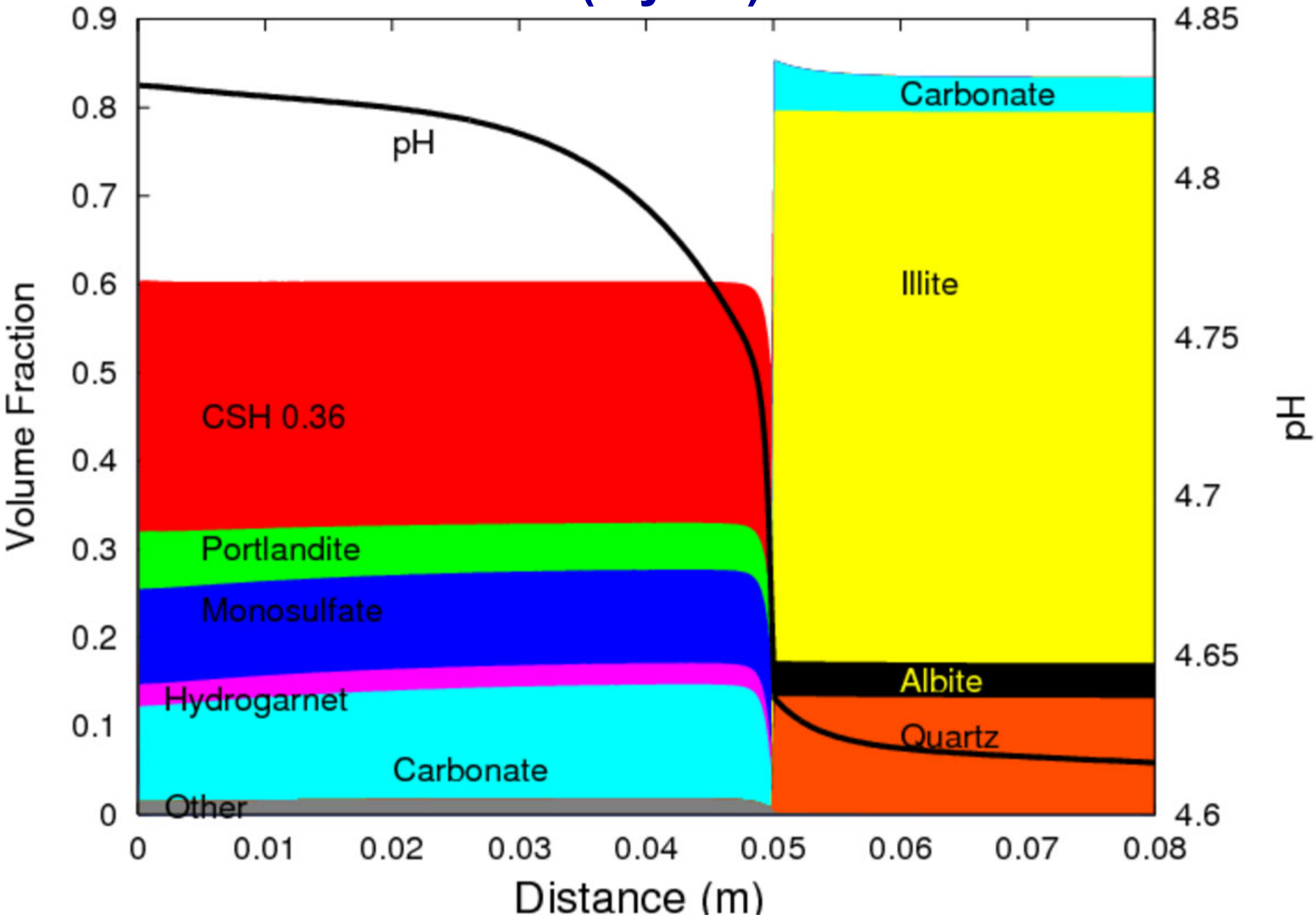
Cement: Reservoir (1 year)



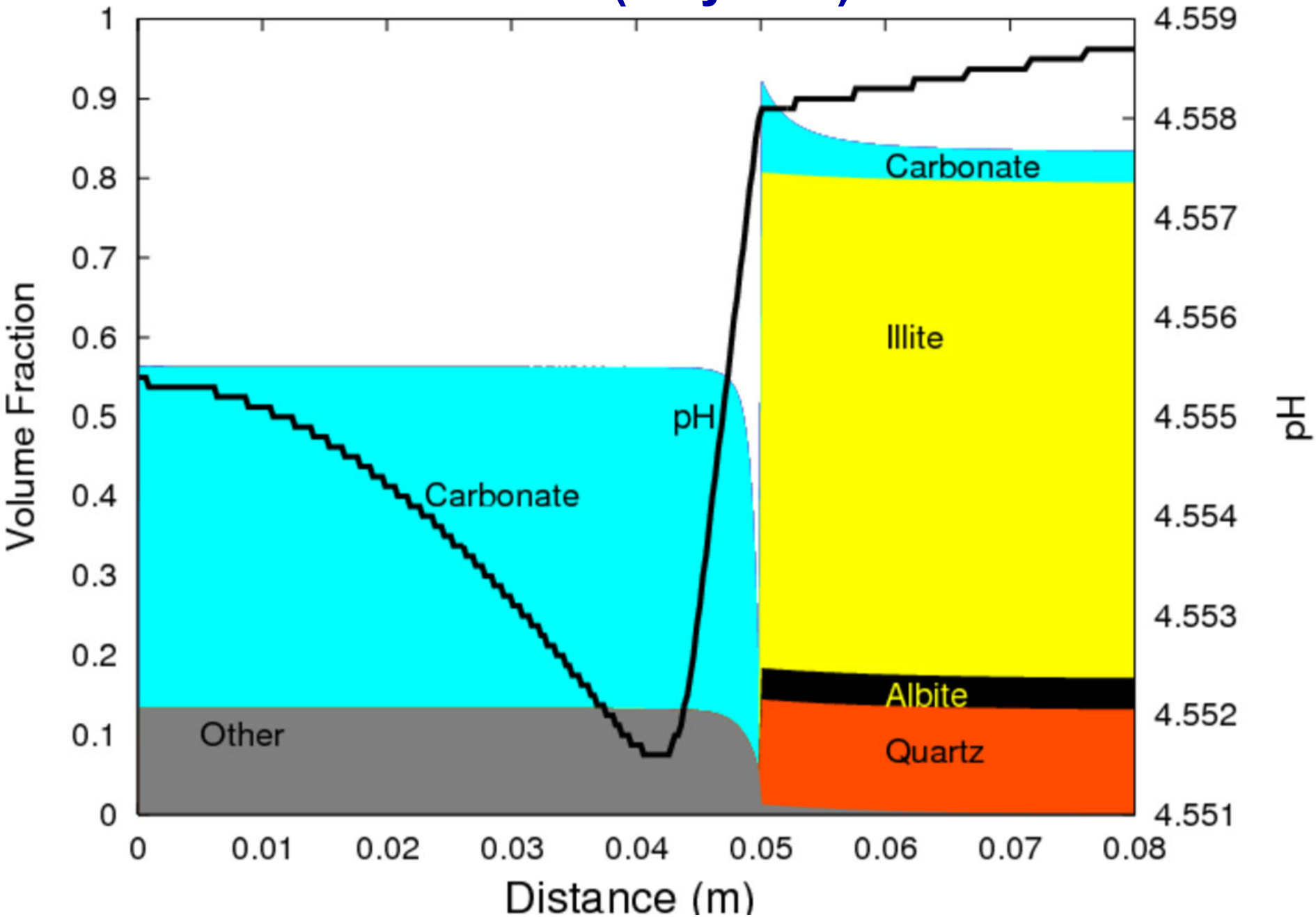
Cement: Reservoir (30 years)



Cement: Cement-like (1 year)



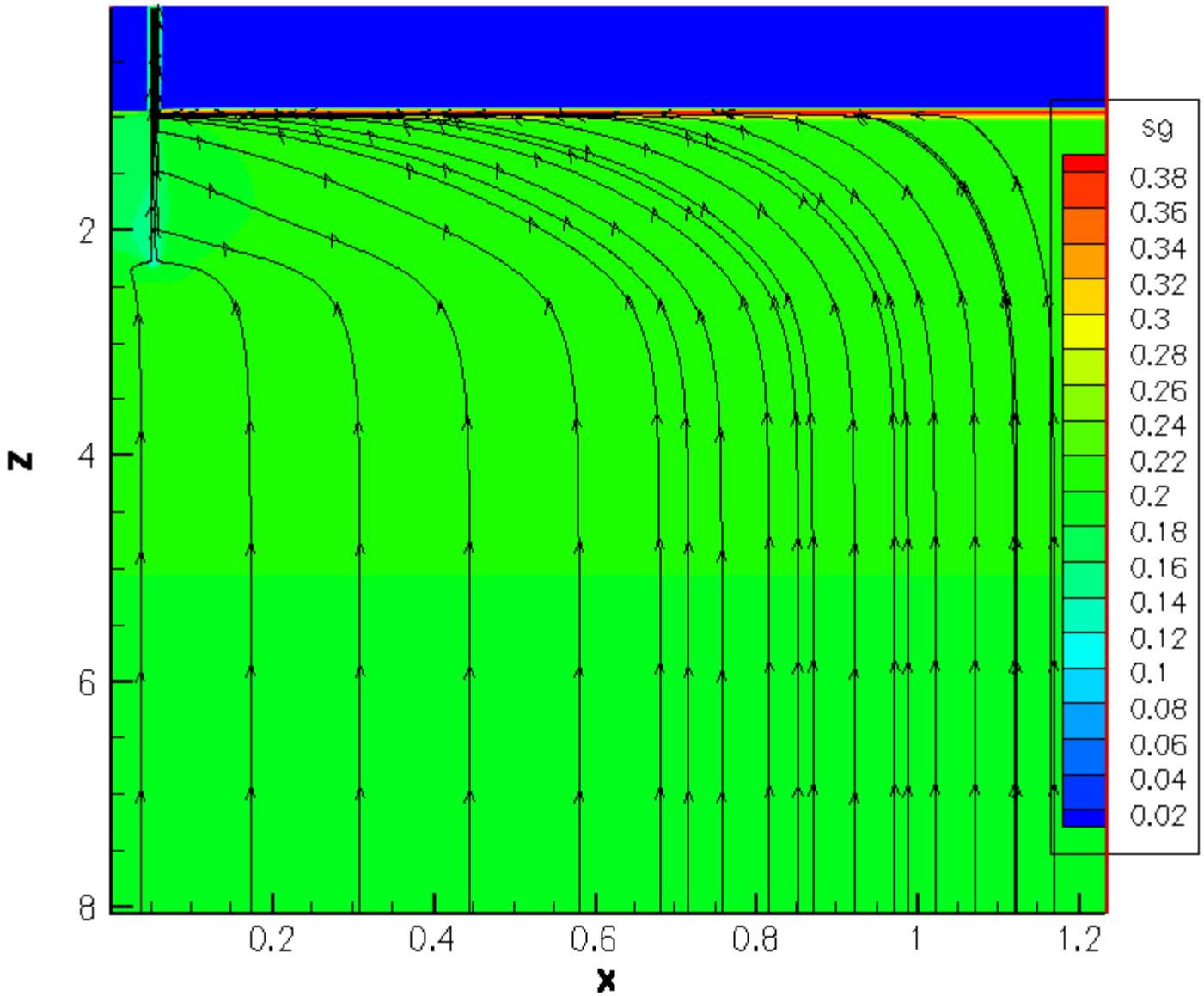
Cement: Cement-like (30 years)

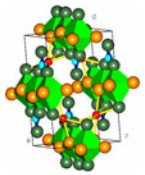


2-D, Two-Phase Wellbore Problem

- Narrow, high permeability zone at cement-caprock interface
- Cement and caprock have similar capillary pressure functions
- Buoyancy driven CO_2 movement (no pressure gradient)
- Minimum CO_2 plume thickness required to overcome capillary barrier
- Constant pressure along top and bottom boundaries (hydrostatic-like pressure gradient)

CO_2 saturation at 0.05 years





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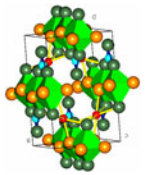
CO_2 saturation at 0.2 year



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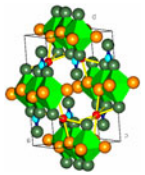
Dissolved CO_2 at 0.2 year



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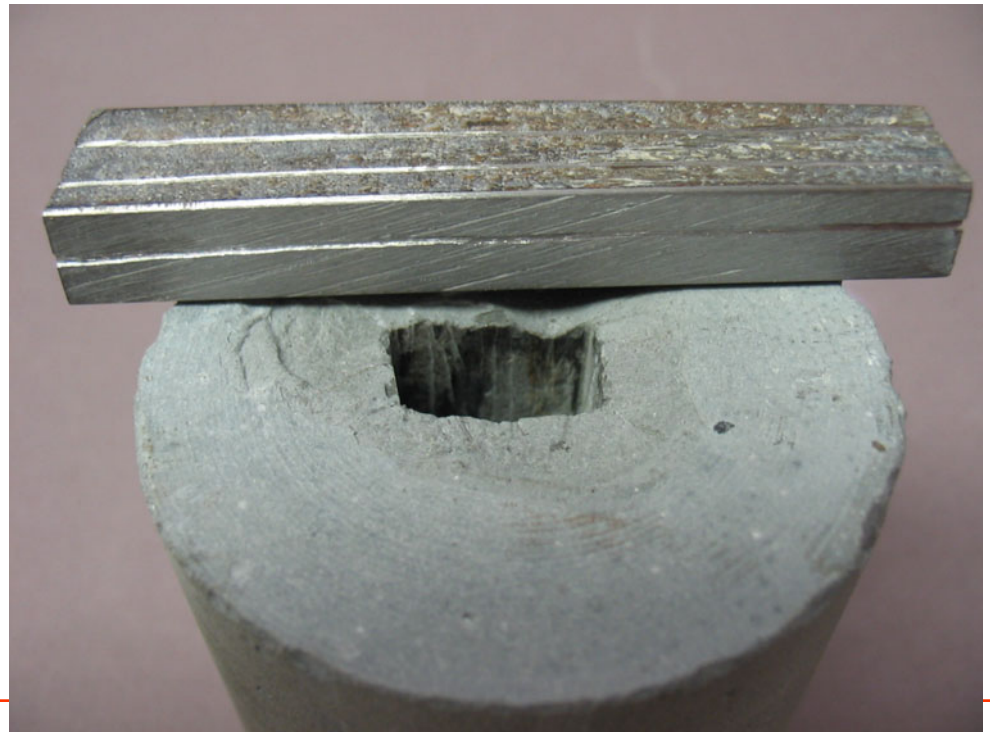
Casing-Cement Interface Stability: Experiments

Conducted by Bob Svec and Reid Grigg at New Mexico Tech

- Flow-through experiments
  - 50:50 CO_2-Brine mixture
  - 20 ml/hour for 274 hours; 10 ml/hour for 120 hours; 6800 ml total
  - 40 ^oC; 140 MPa inlet pressure; 280 MPa confining pressure
- ~ 10 cm Limestone against ~ 6 cm Portland Cement
- Cement with embedded casing (~ 50,000 pore volume equivalent brine)



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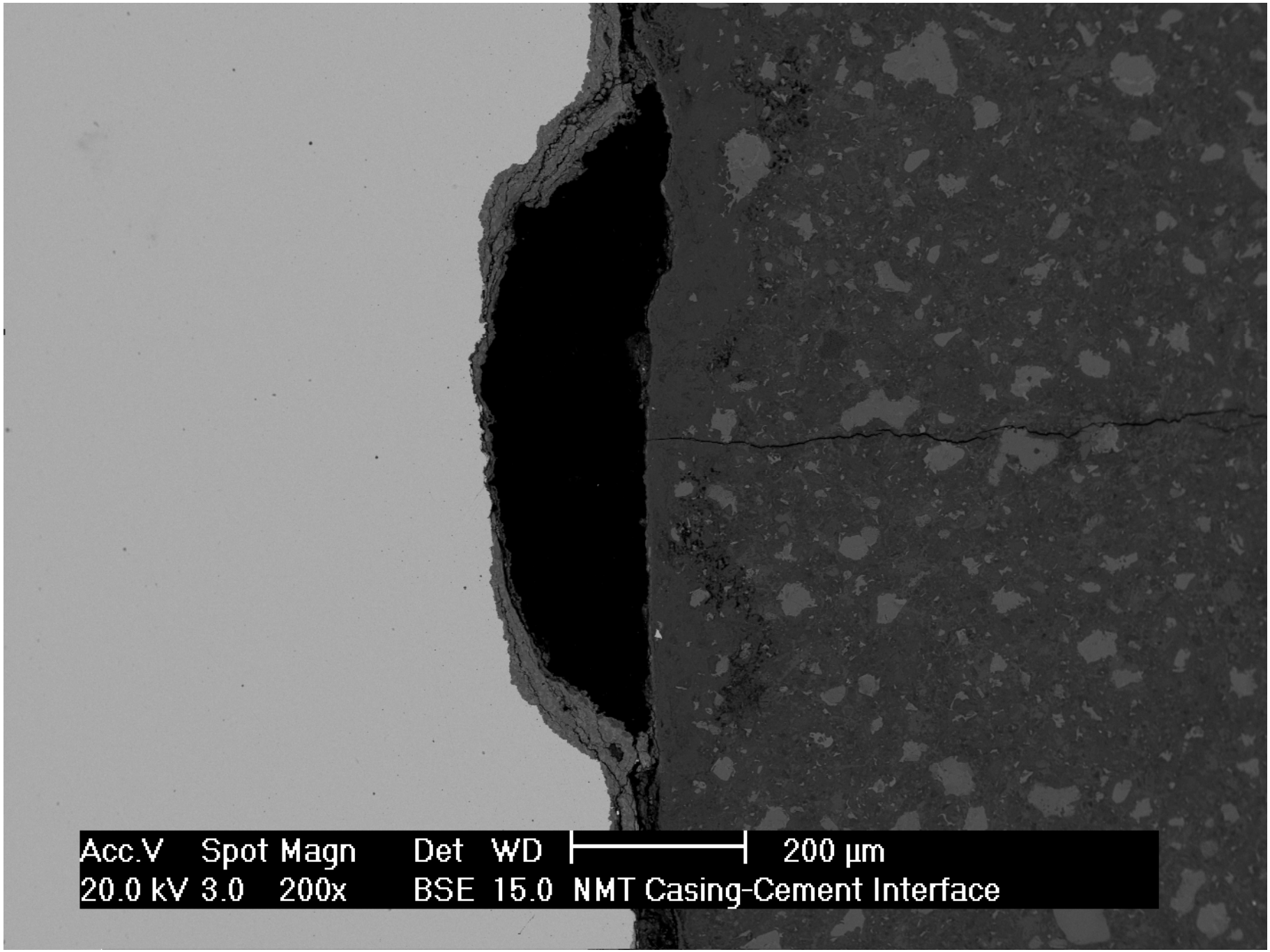
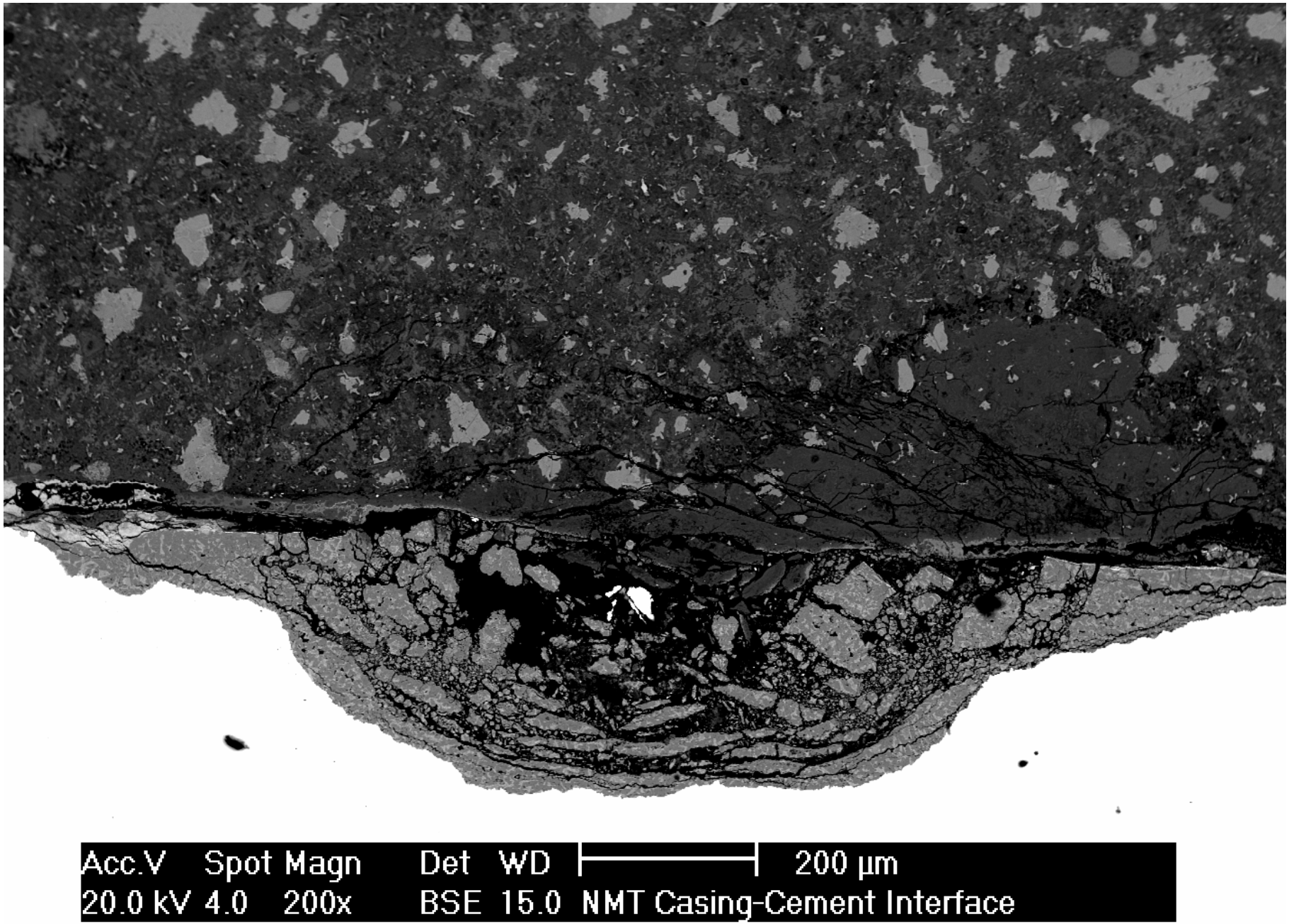
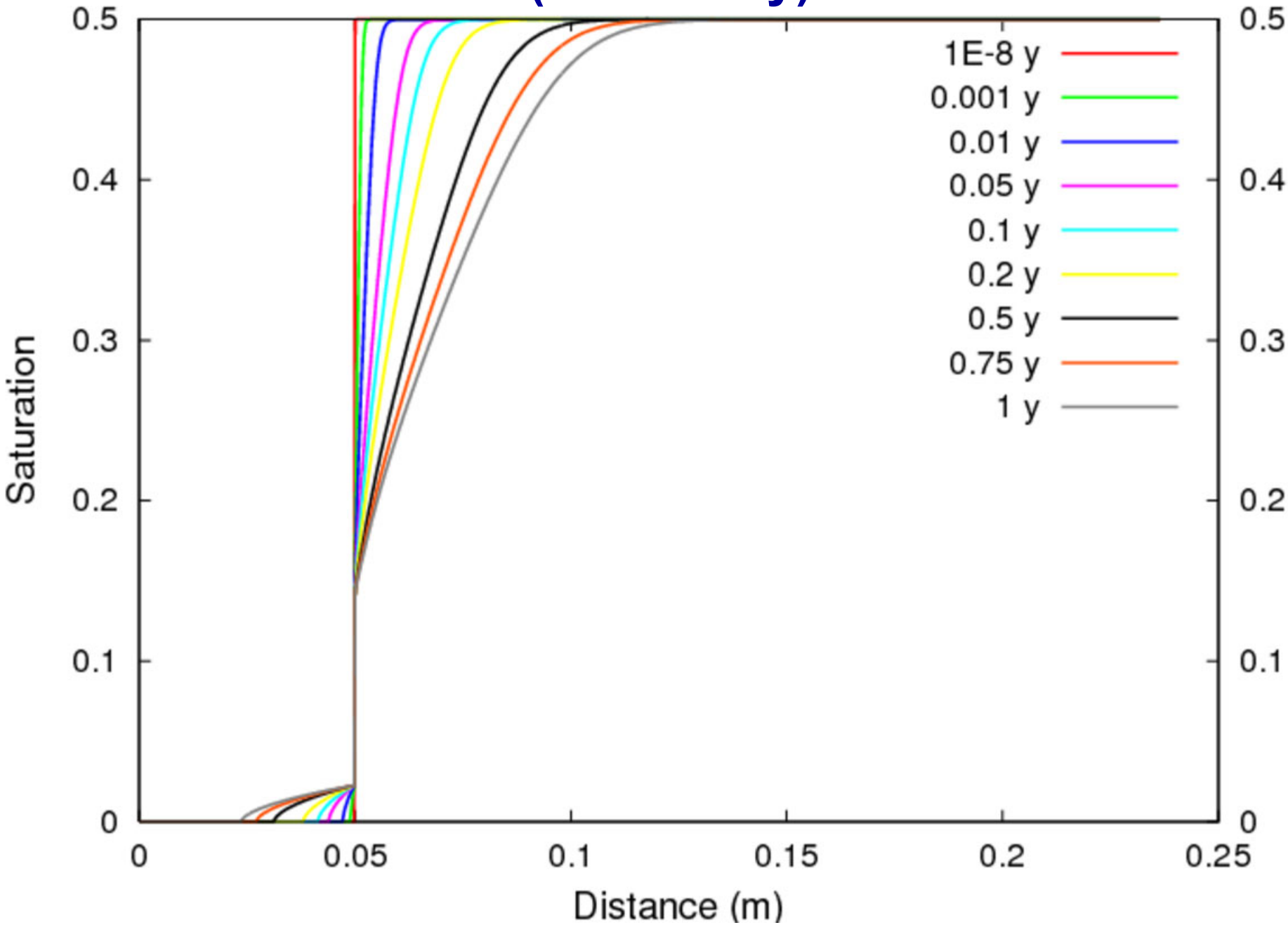
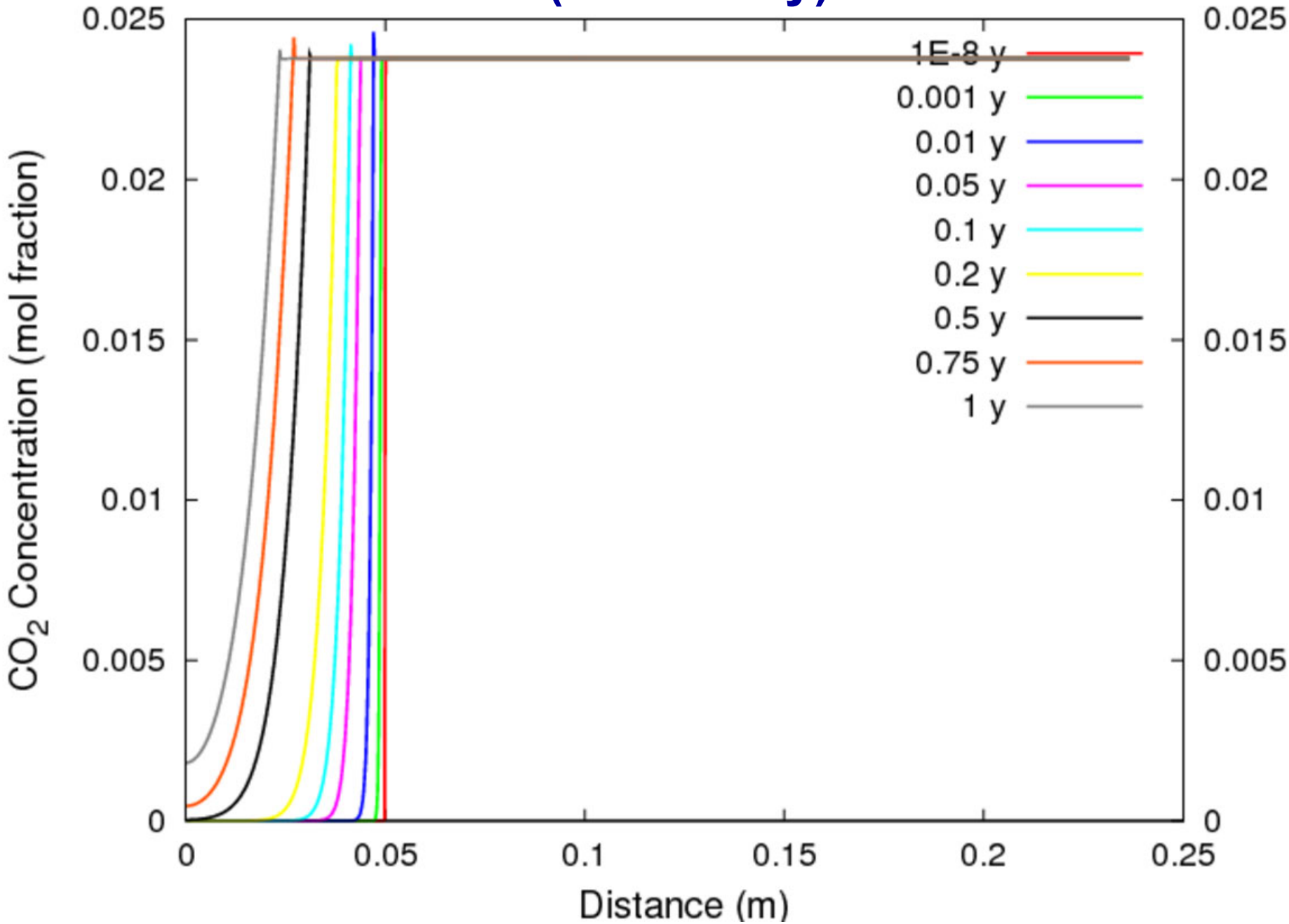

Acc.V Spot Magn Det WD
200 µm
20.0 kV 3.0 200x BSE 15.0 NMT Casing-Cement Interface


Acc.V Spot Magn Det WD 200 µm
20.0 kV 4.0 200x BSE 15.0 NMT Casing-Cement Interface

Conclusions

- Capillary pressure-driven drainage of cement can result in more rapid CO_2 penetration into cement
- Supercritical CO_2 along interfaces or other high porosity (low capillary pressure) contacts has low capillary driving force
- Capillary driven flow of CO_2 into high-quality cement unlikely
- High water/cement ratio promotes low capillary pressure properties and may allow capillary sorption of supercritical CO_2
- 2-D simulations allow investigation of interface flow dynamics; relative importance of drive by pressure gradient versus buoyant flow unclear
- Experiments of two-phase flow along cement-casing interfaces show potential for reduced permeability due to carbonate precipitation

Cement: Shale (Flow Only)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