Effects of Formation Heterogeneity on CO_2 Gas Phase Attenuation in the Shallow Subsurface During Possible Leakage from Geologic Sequestration Sites

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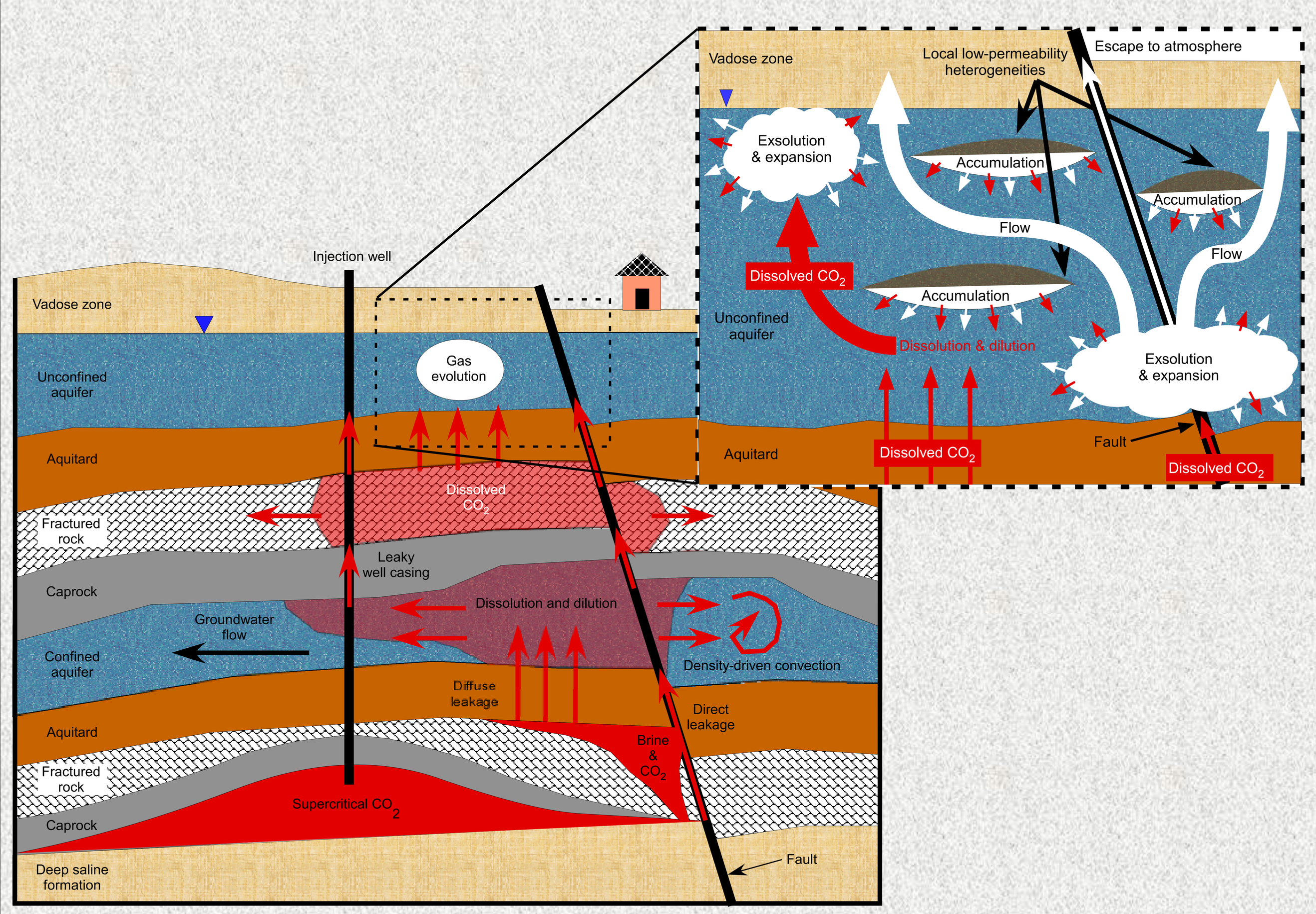
1. BACKGROUND

- As a first step towards developing risk assessment strategies for carbon sequestration projects, we must understand how CO_2 evolves in naturally heterogeneous formations.
- As dissolved CO_2 migrates upward, water pressure decreases and gas may exsolve.
  - Exsolved gas partially blocks the flow of water, thus partially attenuating the plume of dissolved CO_2.
- The spatiotemporal pattern of gas phase growth is governed by the gravity number, B/Ca, which quantifies the relative importance of gravity forces and viscous forces

$$B/Ca = \frac{\Delta \rho g k}{q \mu}$$

- Sakaki et al. (2013, in press) showed the following effects of CO_2 concentration on spatiotemporal gas evolution patterns using a long column with a homogeneous sand pack:
  - In oversaturated cases ($P_{saturation} > P_{injection}$), gas formed from the bottom up as the CO_2-water migrated up
  - In undersaturated cases ($P_{saturation} < P_{injection}$), gas formed from the top down after the CO_2-water had reached the top
- Plampin et al. (2013, in review) showed that gas phase growth can be enhanced by geologic heterogeneity

2. CONCEPTUAL MODEL



3. RESEARCH QUESTIONS

1. How do various soil texture interfaces affect the formation and growth of gas phase CO_2 from aqueous solution in porous media?
   a. Where is gas phase first detected with respect to the interface?
   b. How fast does the gas phase grow in each direction?
   c. For what range of CO_2 concentrations does heterogeneity enhance gas phase formation (and thus CO_2 attenuation)?

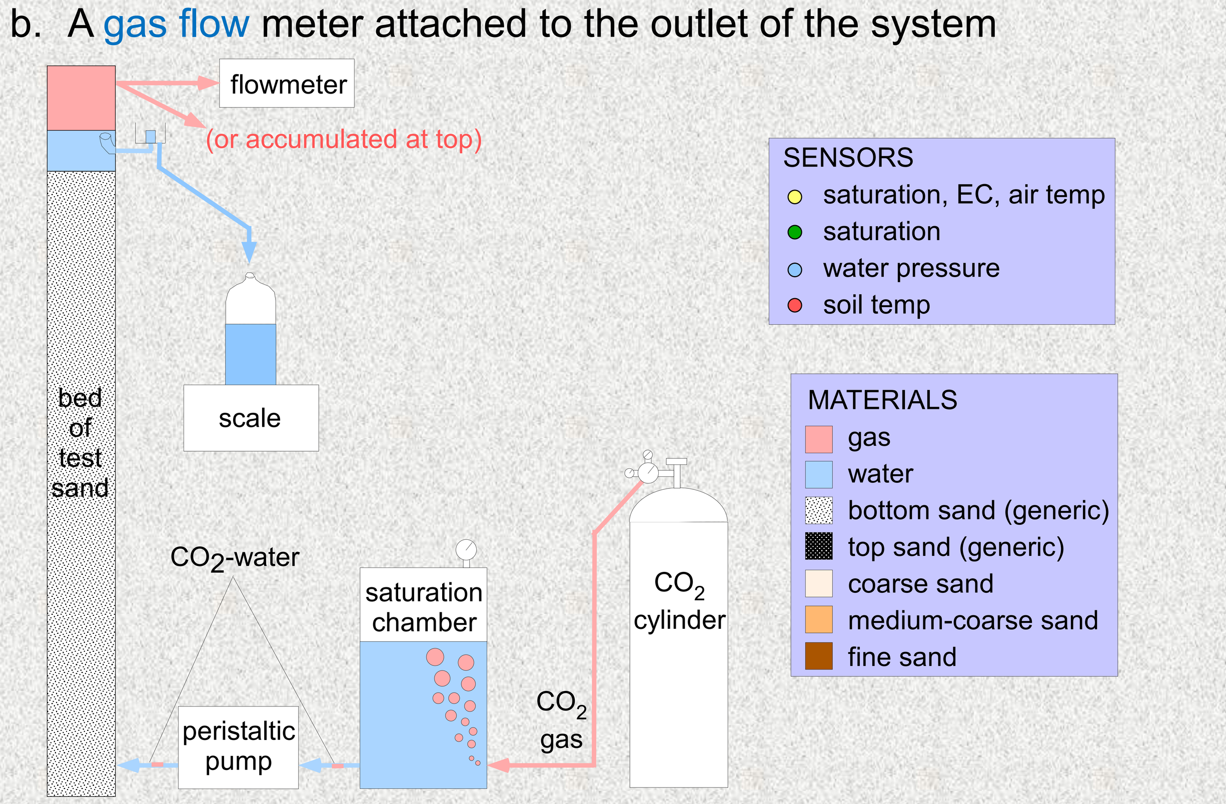
4. EXPERIMENTAL METHODOLOGY

MATERIALS:

Accusand #	Description	Mean particle diameter (mm)	Intrinsic Permeability (cm^2)	Porosity	Air entry pressure (kPa)	Uniformity coefficient
12/20	coarse	1.04	3.8×10^{-6}	0.32	0.8	1.23
20/30	medium-coarse	0.75	2.3×10^{-6}	0.32	1.2	1.19
50/70	fine	0.27	3.0×10^{-7}	0.34	3.4	1.20

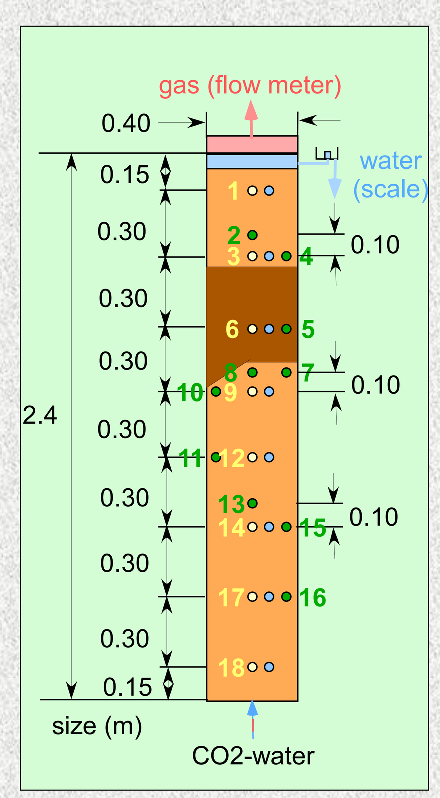
PROCEDURE:

1. Test system wet-packed with test sands to ensure full water saturation
2. CO_2 gas bubbled through DI water overnight at a constant pressure (the "saturation pressure" or $P_{saturation}$)
3. CO_2-saturated water injected through the test system from the bottom at a constant rate (the hydrostatic pressure at the injection port is $P_{injection}$)
4. Gas evolution behavior monitored through time by:
   a. Soil moisture sensors installed at various locations throughout the system
   b. A gas flow meter attached to the outlet of the system

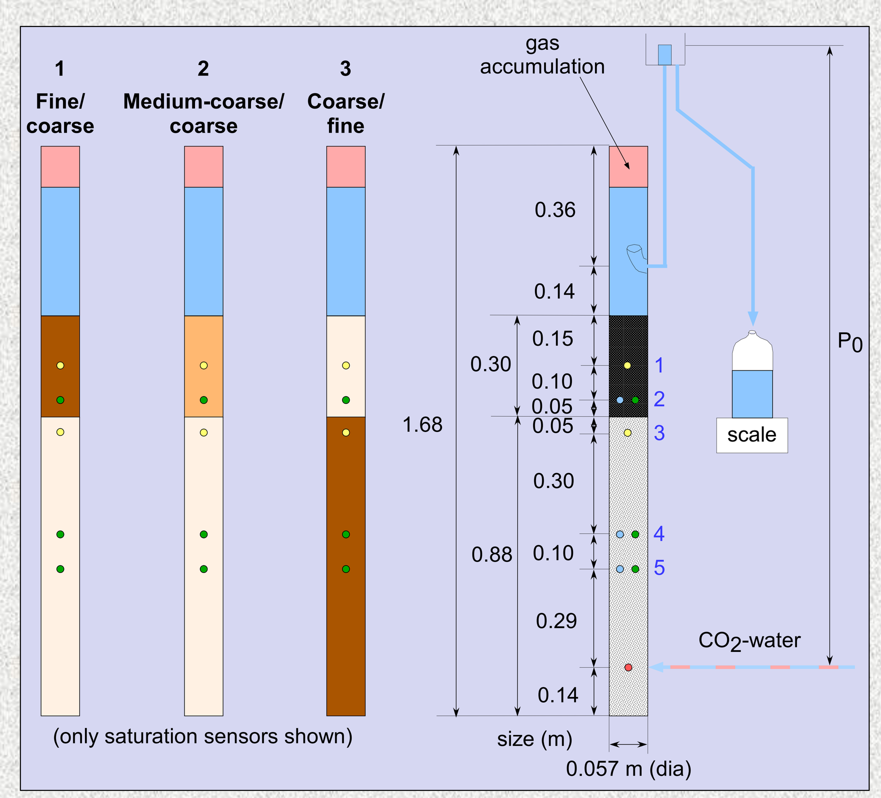


TEST SYSTEMS & PACKING CONFIGURATIONS:

Rectangular Column:



Short Column:



5. EXPERIMENTAL CONDITIONS

TERMINOLOGY:

$$\text{Oversaturation} = P_{saturation} - P_{injection}$$

where: $P_{saturation}$ = the constant pressure at which the injected water was saturated with CO_2 before and during the experiment, and

$P_{injection}$ = the hydrostatic pressure at the injection port

- **Oversaturated cases**: Oversaturation > 0 (i.e., $P_{saturation} > P_{injection}$)
  - Gas grows from the bottom up regardless of packing configuration (Sakaki et al. 2013)
- **Undersaturated cases**: Oversaturation < 0 (i.e., $P_{saturation} < P_{injection}$)
  - Gas grows from the top down in homogeneous cases (Sakaki et al. 2013)
  - Heterogeneous interfaces that exist within the zone of oversaturation enhance the growth of gas phase near those interfaces (Plampin et al. 2013)
    - ➢ **Zone of oversaturation**: region where $P_{saturation} > P_{water}$

RECTANGULAR COLUMN:

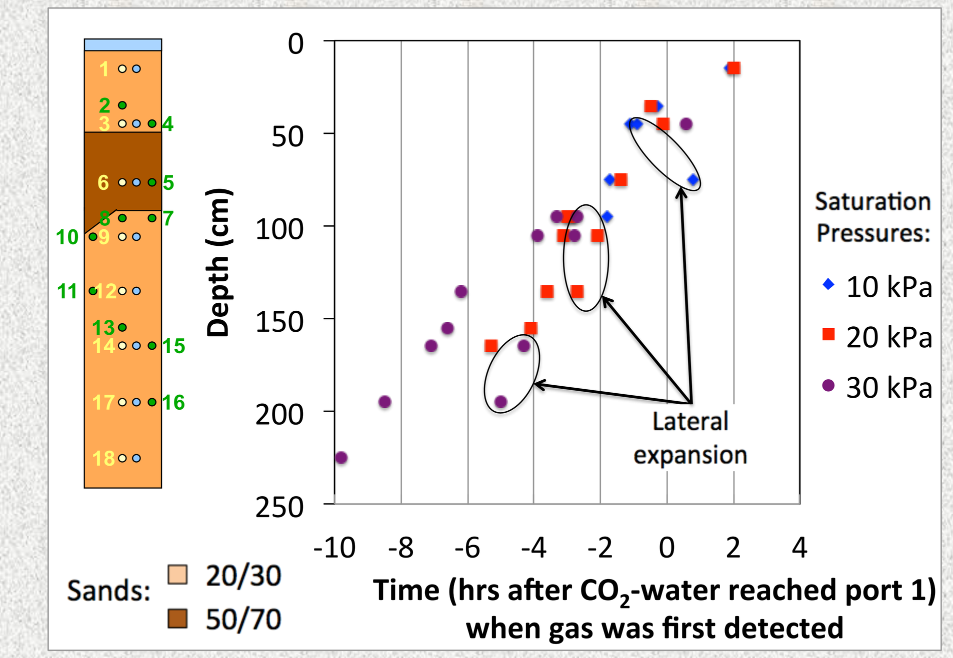
Injection rate (cm^3min^{-1})	Saturation pressure (kPa)	B/Ca	
		Coarse sand	Fine sand
40	10	26.5	3.5
40	20		
40	30		

SHORT COLUMN:

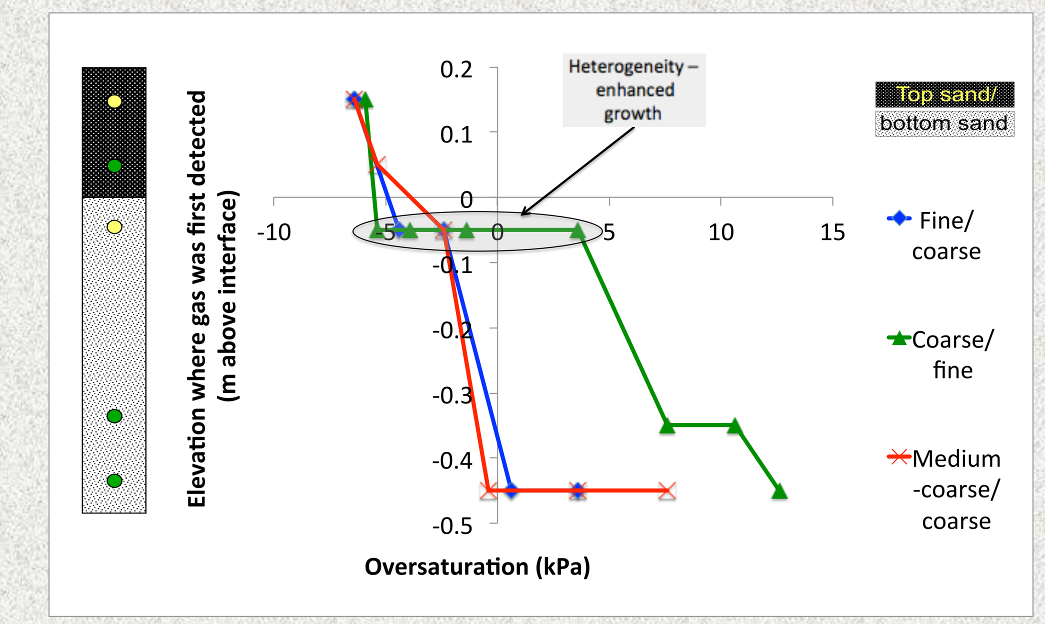
Packing configuration (top sand/ bottom sand)	Injection rate (cm^3min^{-1})	Over-saturation (kPa)	B/Ca	
			Bottom sand	Top sand
Fine/ coarse	4	-6.4	45.7	3.8
	4	-4.4		
	4	-2.4		
	4	0.6		
	4	3.6		
Medium-coarse/ coarse	4	-6.4	45.7	28.1
	4	-5.4		
	4	-2.4		
	4	-0.4		
	4	3.6		
	4	7.6		
Coarse/ fine	4	-5.9	3.8	45.7
	4	-5.4		
	4	-3.9		
	4	-1.4		
	4	3.6		
	4	7.6		
	4	10.6		
	4	12.6		

6. EXPERIMENTAL RESULTS

RECTANGULAR COLUMN:



SHORT COLUMN:



7. CONCLUSIONS

- Higher CO_2 concentrations (i.e., higher saturation pressures) cause faster gas phase growth in both horizontal and vertical directions.
- There is a finite range of oversaturation values for which heterogeneity controls the rate of gas phase growth. This range is:
  - Largest for coarse/fine interfaces
  - Fairly small for fine/coarse interfaces
  - Barely present for medium-coarse/coarse interfaces
  - * (the above descriptions are structured as follows: "top sand/bottom sand")

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