Simulation de l'injection de carbone dans un site géologique de séquestration du CO_2

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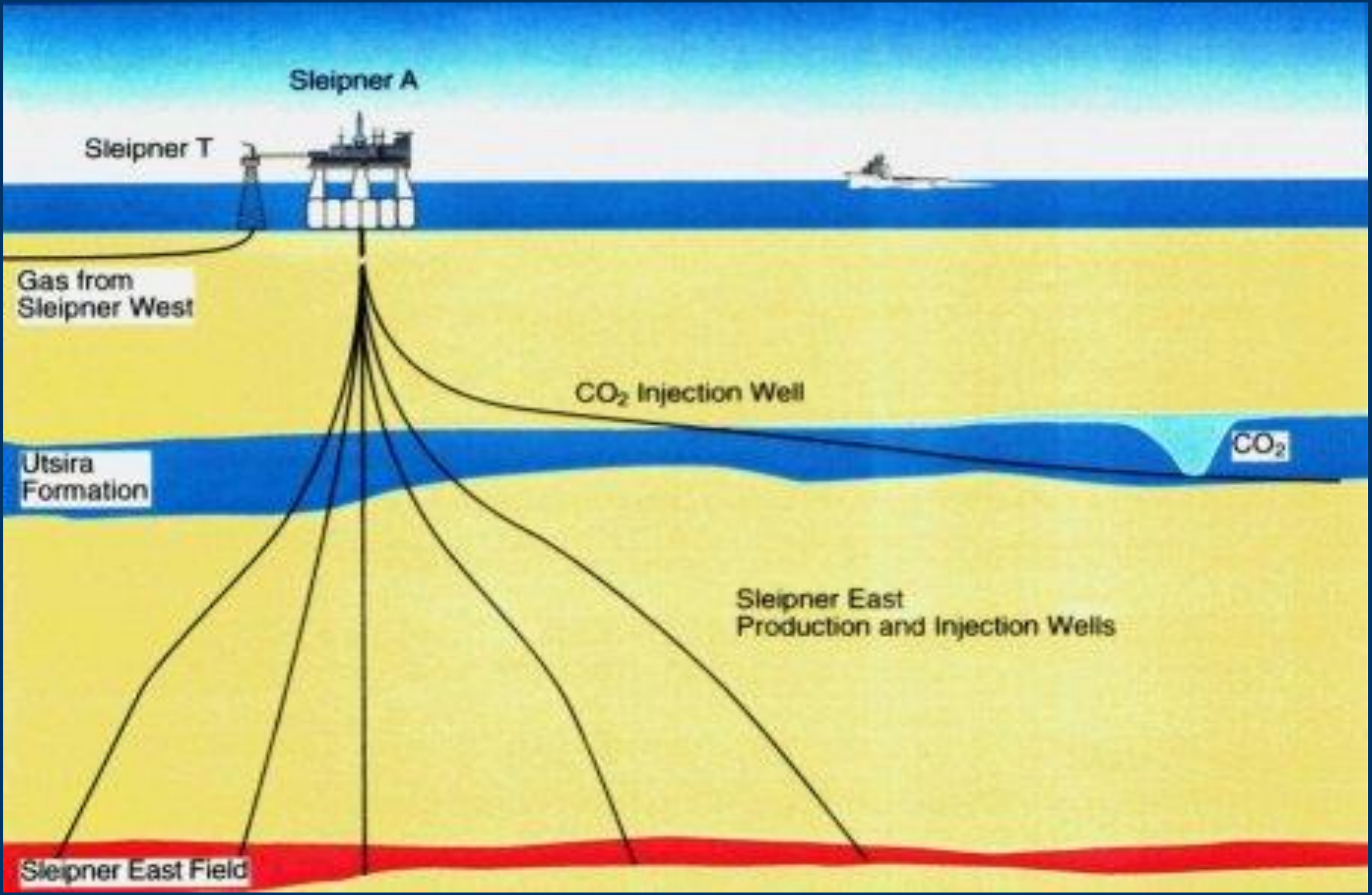
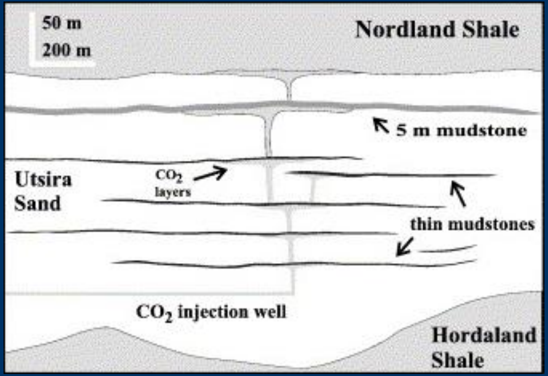
Journée Castem , 25/11/09

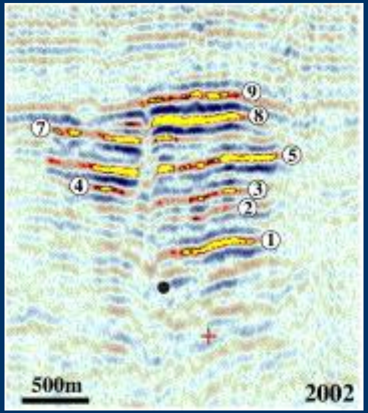
Sleipner, Mer du Nord



CO_2 sequestration in the Sleipner field



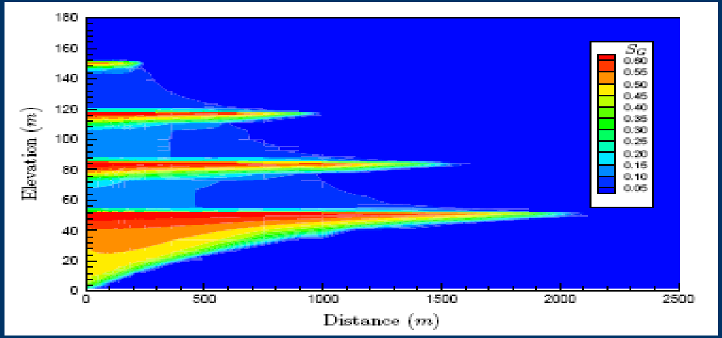
Schematic representation of Utsira aquifer (Sleipner site)



Seismic profiles (Bickle et al. 2007)

CO_2 Stratification:
How and why does it take place ?

Projet ANR (BRGM, IFP, ICMCB, Schlum.)



Simulation results (Pruess et al. 2002)

Outlines

- The model
- The 1D case (injection in vertical column)
  - Solution analysis between two different homogeneities
  - Injection in vertical periodic layered column
- The 2D Vertical case (Sleipner)
  - Numerical simulation (code Cast3M)
  - Theoretical analysis
- Gravity + Capillarity

Buckley-Leverett with gravity including capillarity effects

$$\phi \frac{\partial S}{\partial t} + \frac{\partial}{\partial z} F_{\mathbf{CO}_2}(S) = 0$$

$$S = S_{\mathbf{CO}_2}$$

$$\begin{aligned} F_{\mathbf{CO}_2}(S) &= k(\rho_{\mathbf{CO}_2} - \rho_w) g f_{\mathbf{CO}_2}(S) - k f_{\mathbf{CO}_2}(S) \frac{\partial p_c(S)}{\partial z} \\ &= k(\rho_{\mathbf{CO}_2} - \rho_w) g f_{\mathbf{CO}_2}(S) - f_{\mathbf{CO}_2}(S) \sqrt{\phi k(z)}\, J'(S) \frac{\partial S}{\partial z} \end{aligned}$$

$$f_{\mathbf{CO}_2}(S) = \frac{\dfrac{k_{r\mathbf{CO}_2}(S)}{\mu_{\mathbf{CO}_2}} + \dfrac{k_{rw}(S)}{\mu_w}}{\dfrac{k_{r\mathbf{CO}_2}(S)}{\mu_{\mathbf{CO}_2}} \cdot \dfrac{k_{rw}(S)}{\mu_w}}$$

$$p_c(S) = \sigma \sqrt{\frac{\phi}{k}}\, J(S)$$

$$J(S) = (1 - Se)^{-\frac{1}{\lambda}}$$

Relative Permeability laws

$$Se = \frac{S - S_{rw}}{1 - S_{rw} - S_{rnw}}$$

Linear

$$k_{rw} = Se$$

$$k_{rnw} = 1 - k_{rw}$$

Brooks-Corey

$$k_{rw} = Se^{(2+3\lambda)/\lambda}$$

$$k_{rnw} = (1 - Se)^2 (1 - Se^{(2+\lambda)/\lambda})$$

λ=2

Van Genuchten

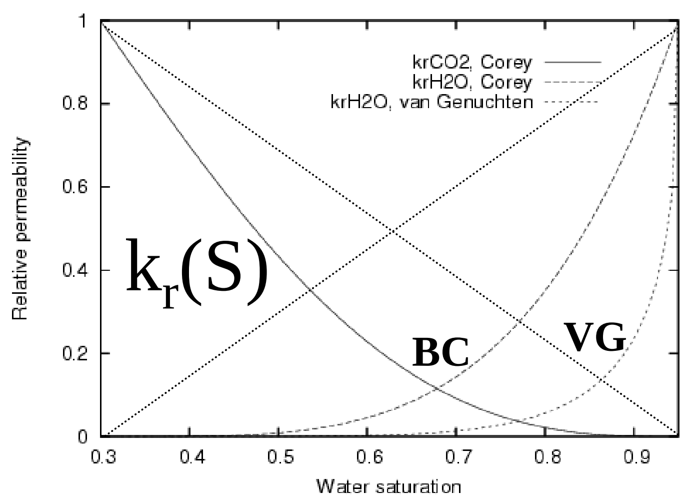
$$k_{rw} = Se^{\varepsilon} (1 - (1 - Se^{1/m})^m)^2$$

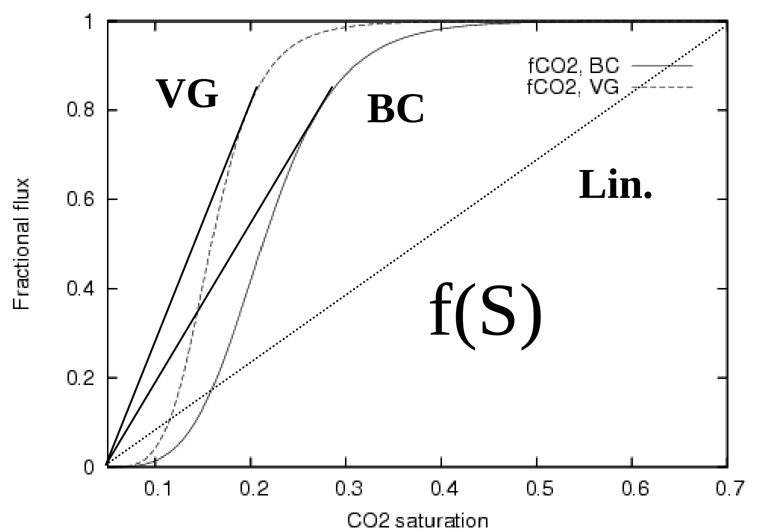
$$k_{rnw} = (1 - Se)^{\gamma} (1 - Se^{1/m})^{2m}$$

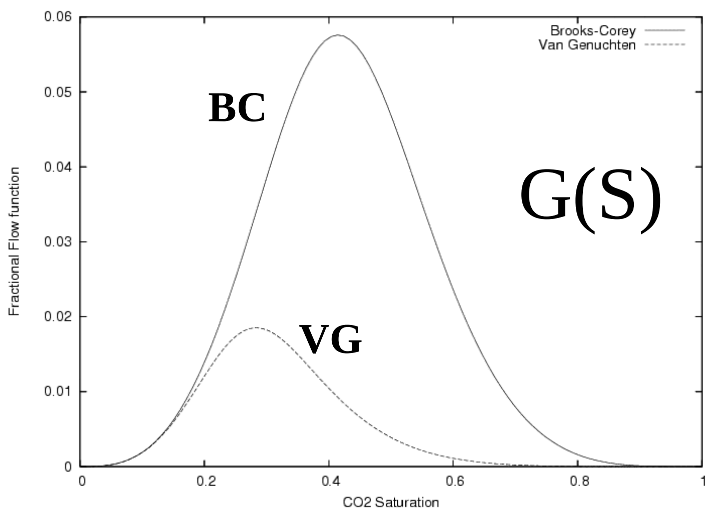
ε=1/2, γ=1/3 et m=0,457

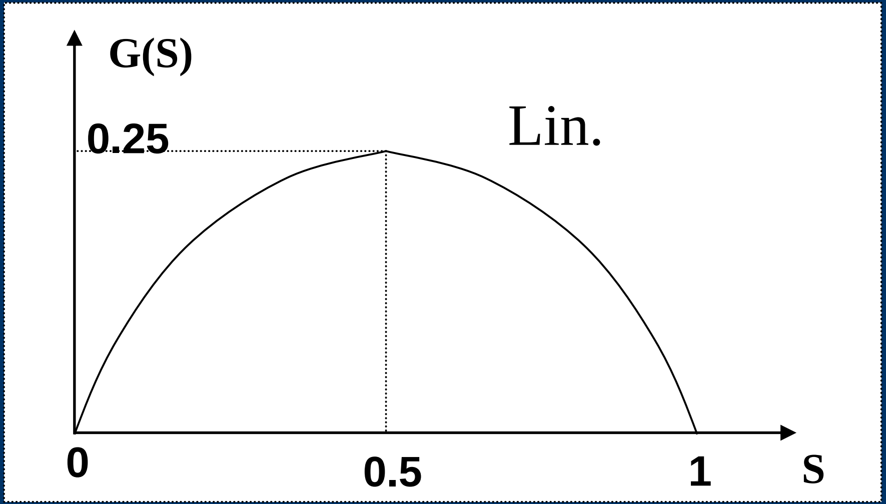
R. Helmig, Multiphase flow and transport processes in the subsurface, Springer-Verlag 1997.

$k_r(S)$, f(S) & G(S)

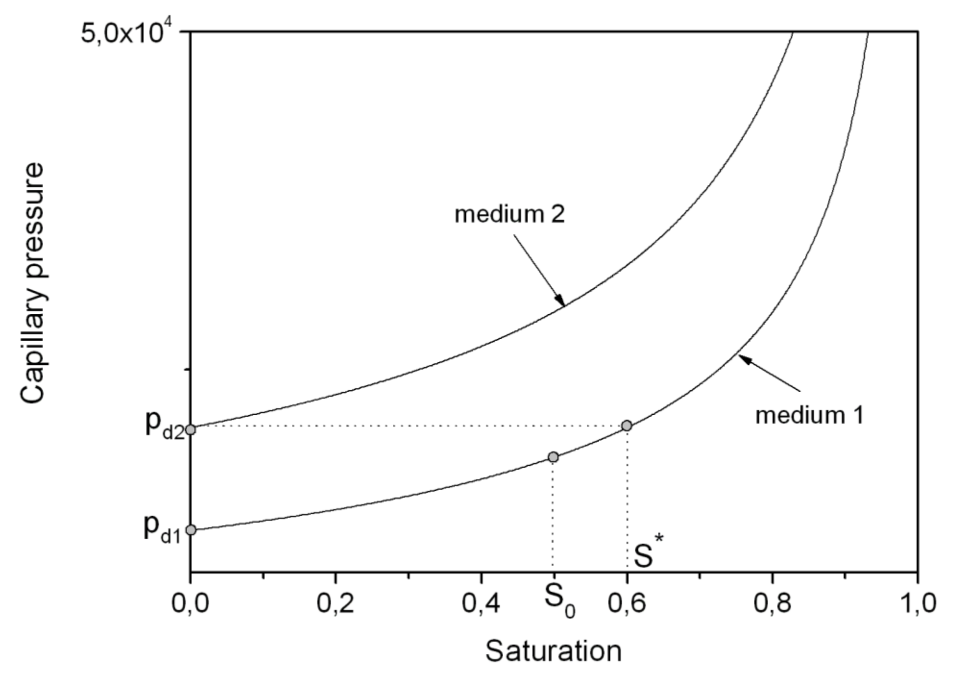

krCO2, Corey
krH2O, Corey
krH2O, van Genuchten
Relative permeability
Water saturation
0
0.2
0.4
0.6
0.8
1
0.3
0.4
0.5
0.6
0.7
0.8
0.9
$k_r(S)$
BC
VG


fCO2, BC
fCO2, VG
Fractional flux
CO2 saturation
0
0.2
0.4
0.6
0.8
1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
VG
BC
Lin.
f(S)

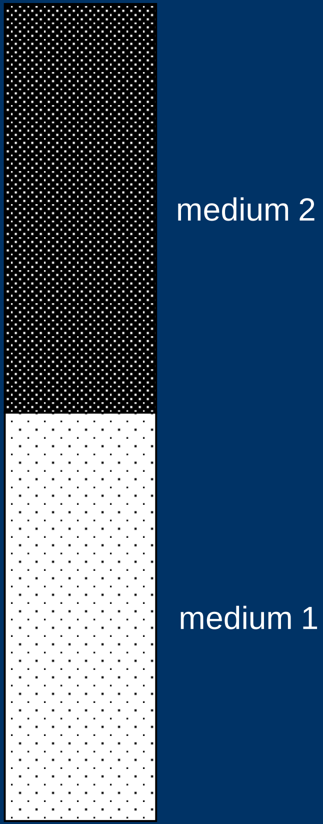

Brooks-Corey
Van Genuchten
Fractional Flow function
CO2 Saturation
0
0.01
0.02
0.03
0.04
0.05
0.06
0
0.2
0.4
0.6
0.8
1
BC
VG
G(S)


G(S)
0.25
Lin.
0
0.5
1
S

Capillarity : Leverett law



$$\begin{array}{rcll} p_{c1}\left(S_1\right) & = & p_{c2}\left(S_2\right), & \text{if } \mathrm{S}_1 \geq \mathrm{S}^* \\ S_2 & = & 0, & \text{if } 0 \leq S_1 < S^* \end{array}$$



Injection in a vertical layered column Buckley Leverett with gravity

$$\phi\frac{\partial S}{\partial t}+\frac{\partial}{\partial z}F(S)=q_{\mathcal{G}}$$

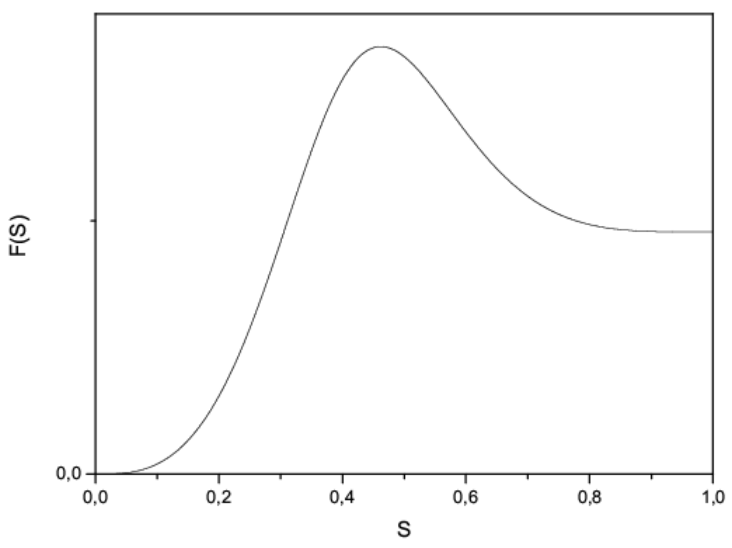
S : CO_2 saturation
$F(S)$: Flux function

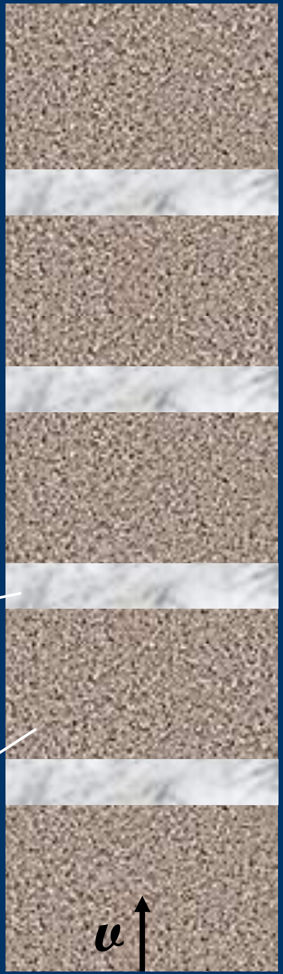
$$F(S)=f(S)\left[v+\frac{k(\rho_{\mathcal{L}}-\rho_{\mathcal{G}})g}{\mu_{\mathcal{L}}}k_{r\mathcal{L}}(S)\right]$$

velocity term

gravity term

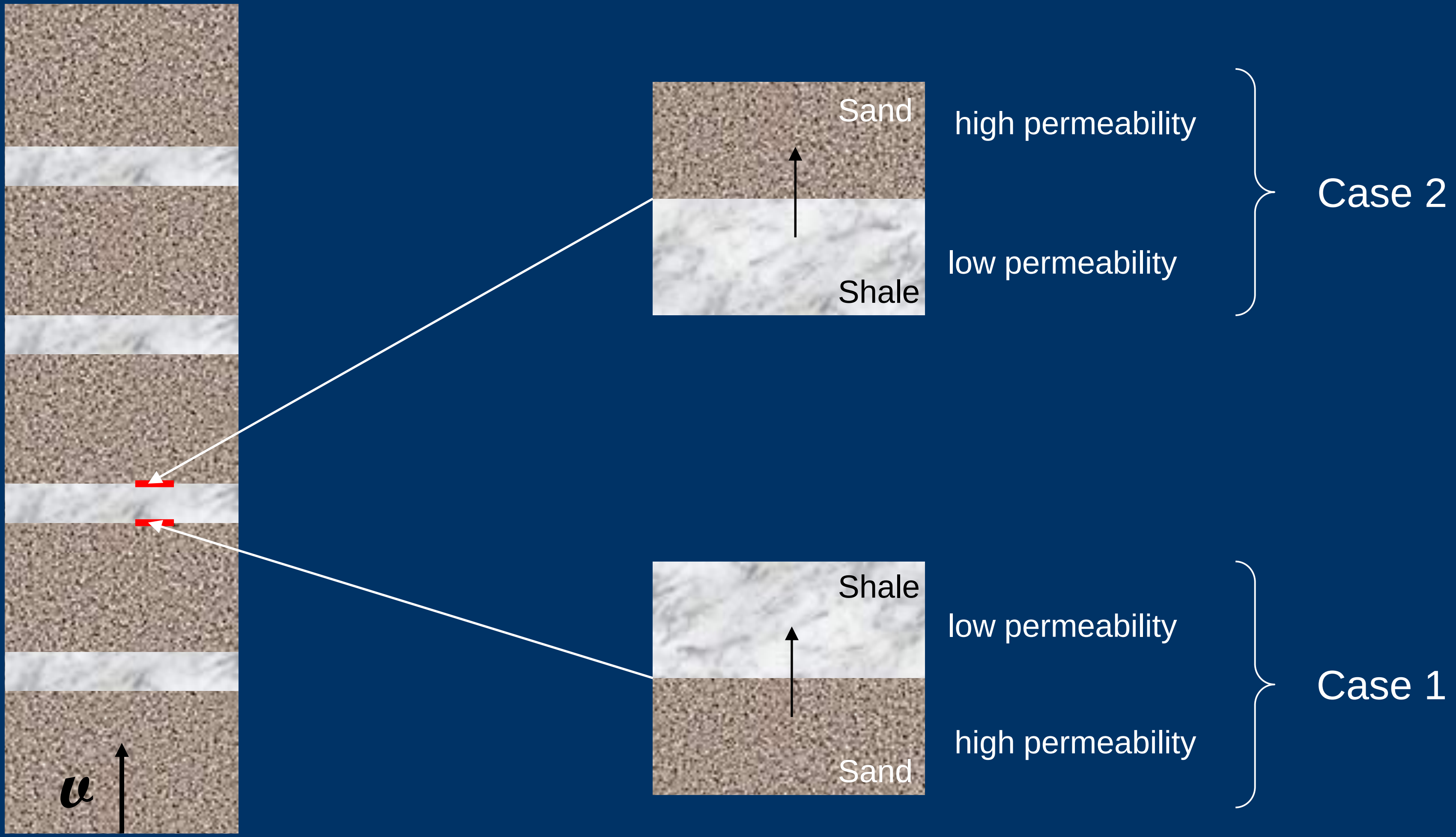
v is constant in 1D



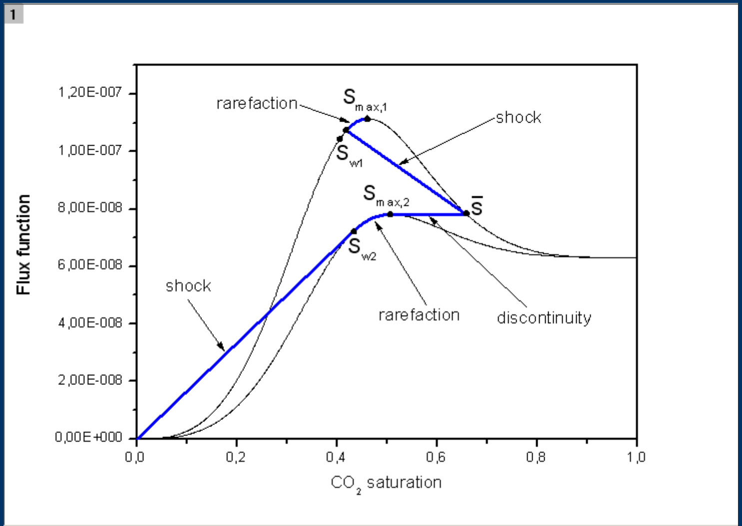


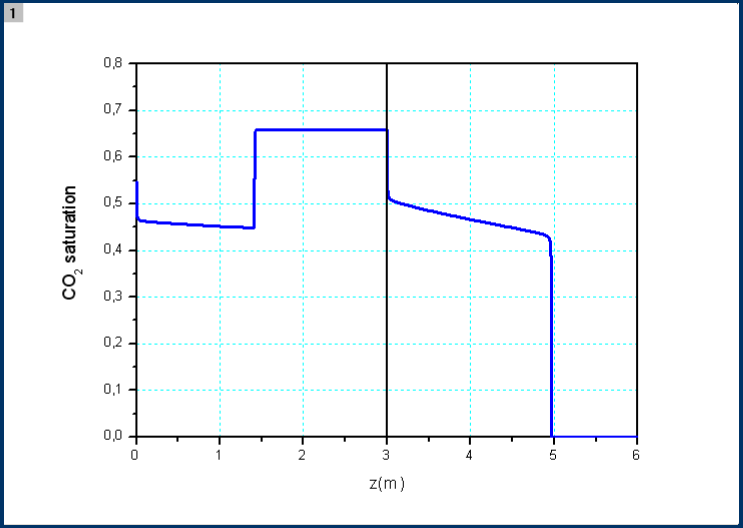
CO_2 injection

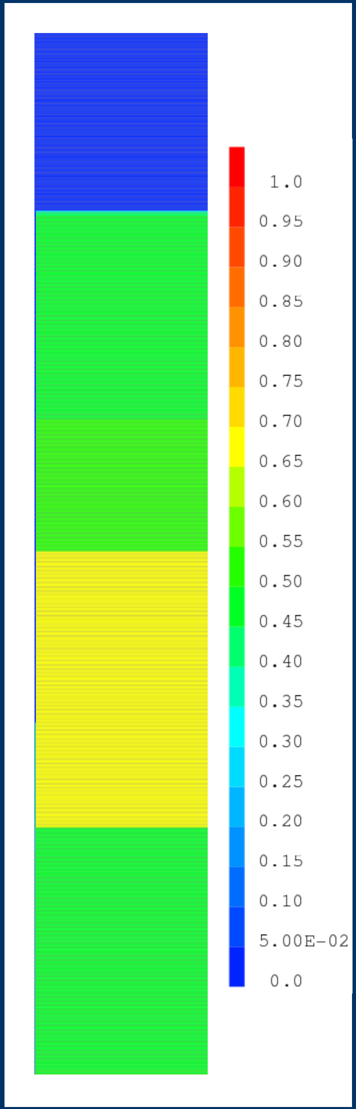
Injection in a periodic layered vertical column



Case 1: ($k_1 > k_2$)



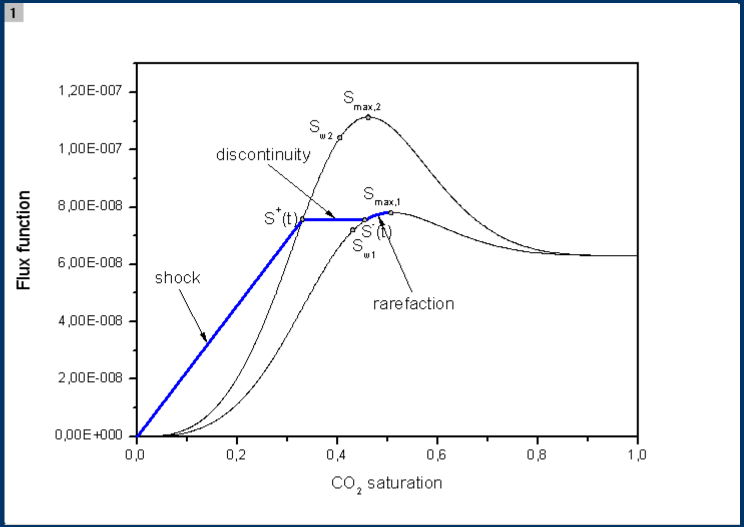


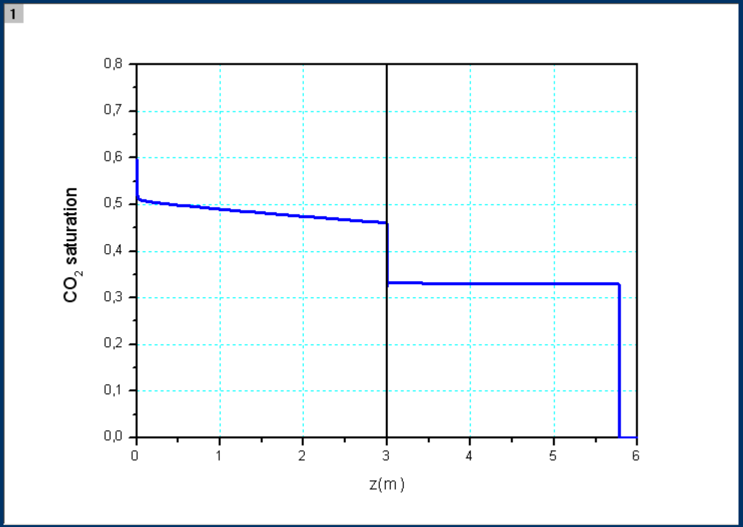


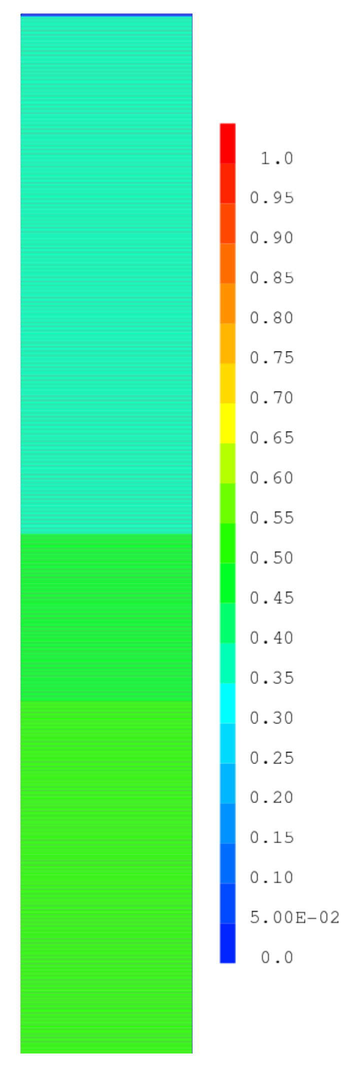
Kaasschieter (1999): Flux continuity at the interface:

$$\Rightarrow F_1(\bar{S}) = F_1(S_{max,2})$$

Case 2: ($k_1 < k_2$)

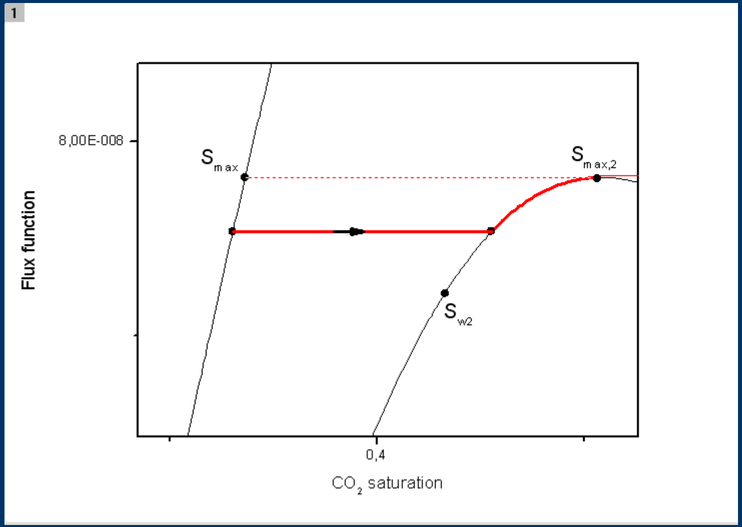


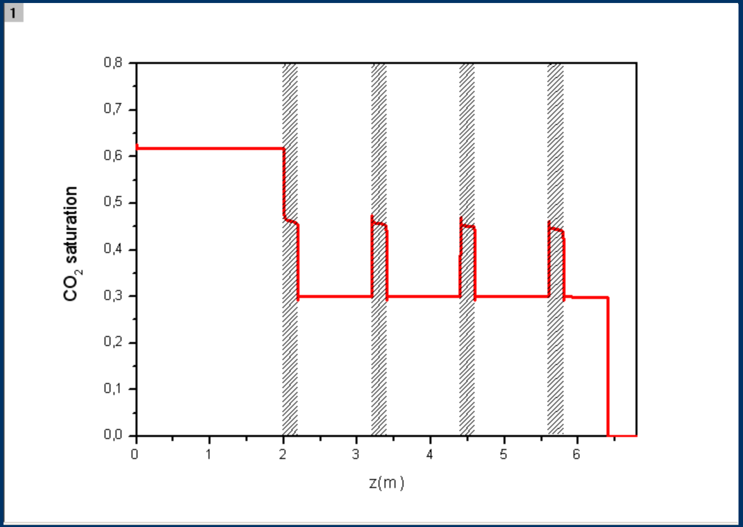


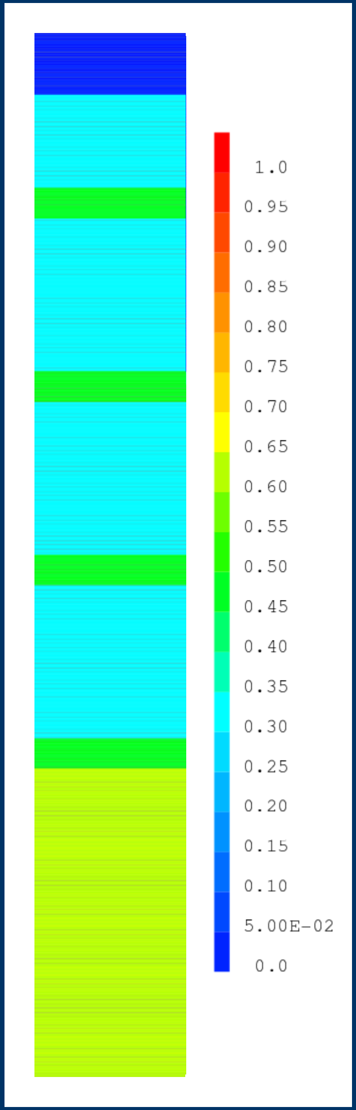


continuity of flux at the interface: $F_1(S^-(t)) = F_2(S^+(t))$

Injection in a vertical periodic layered column

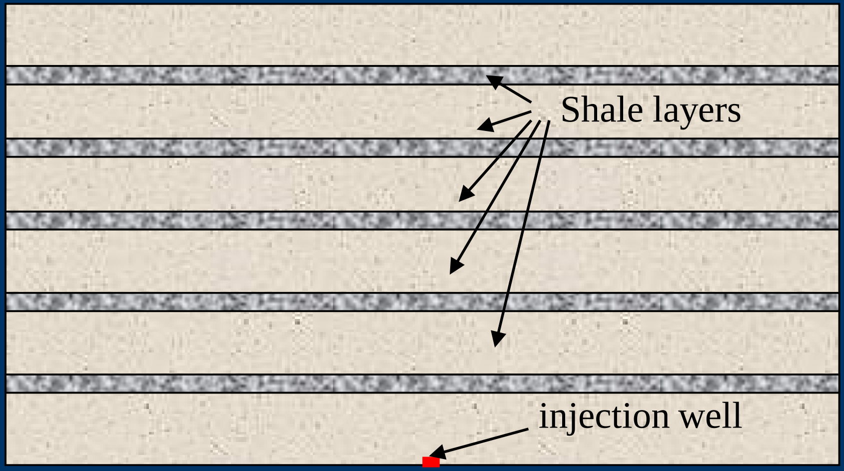




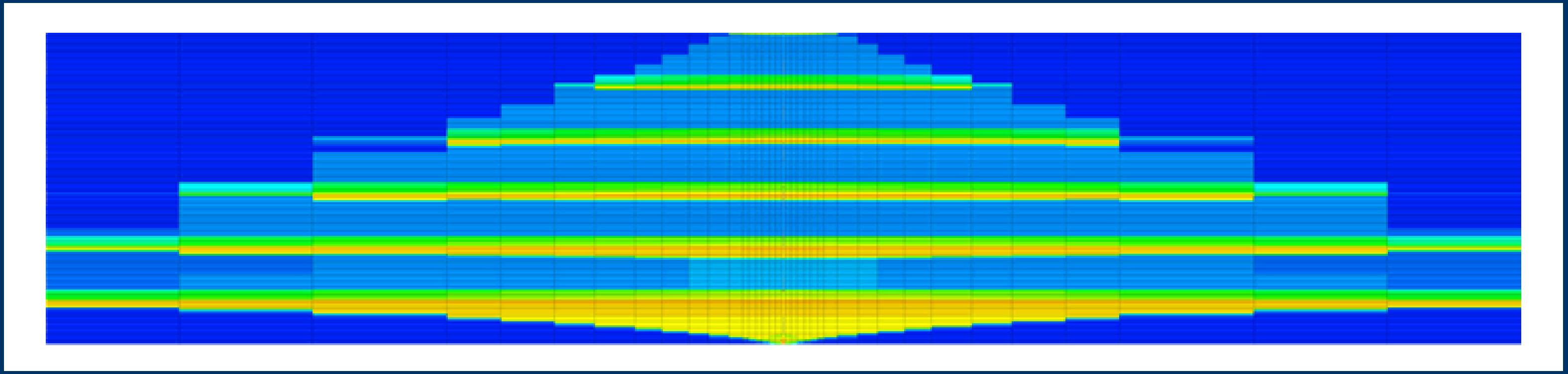


- The CO_2 is filtered by the lower layer ($S = \bar{S}$).
- No CO_2 accumulation under the other layers.
- The maximal saturation between two layers (sand) is S_{max}.

2D vertical formation of Sleipner type



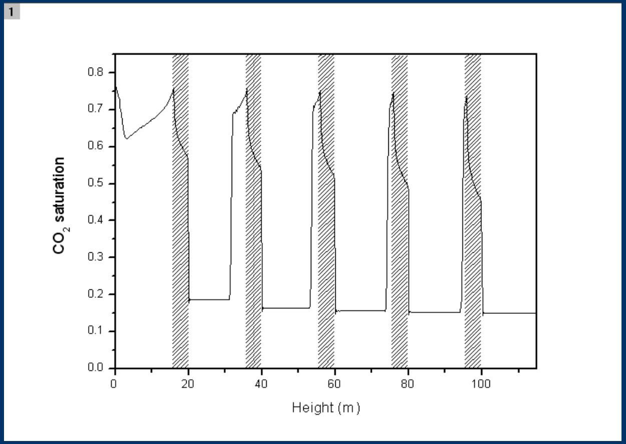
Simulation (Cast3M, CEA)

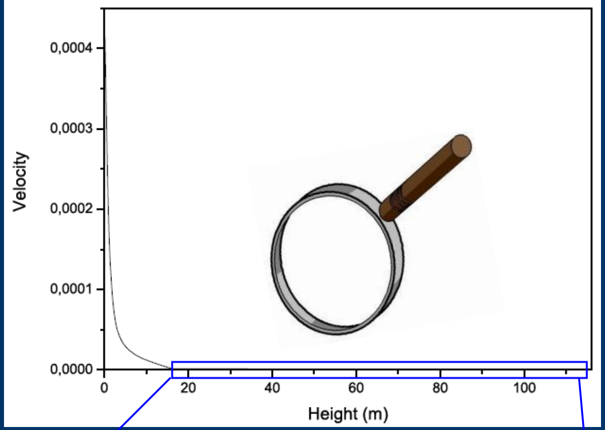


CO_2 accumulation <u>beneath each layer</u> !!!

vertical cut at the injection well

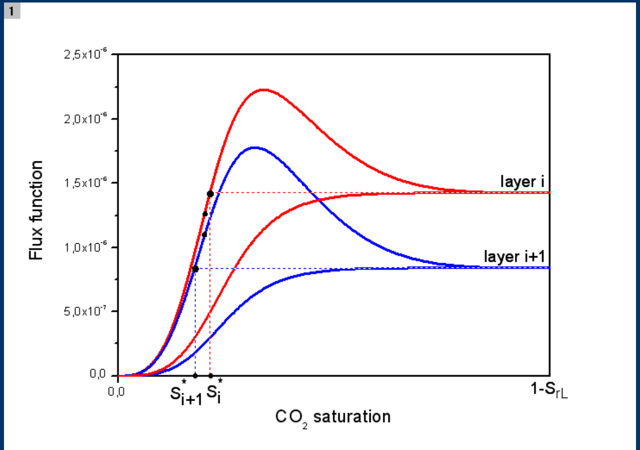
non-constant velocity



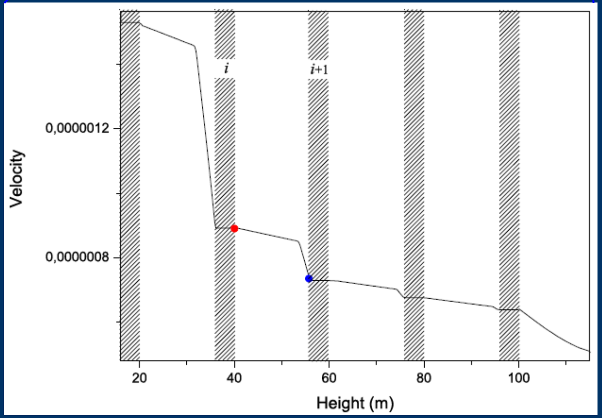


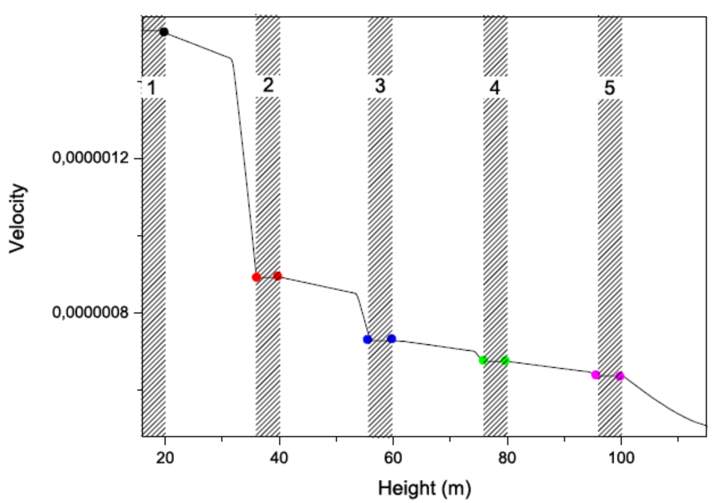
$$F(S,z) = f(S)\left[v(z) + \frac{k(\rho_{\mathcal{L}} - \rho_{\mathcal{G}})g}{\mu_{\mathcal{L}}} k_{r\mathcal{L}}(S)\right]$$

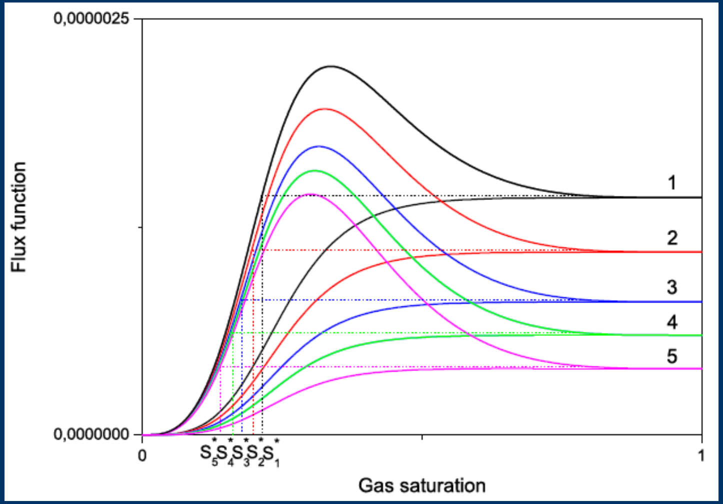
v_i : velocity in layer i



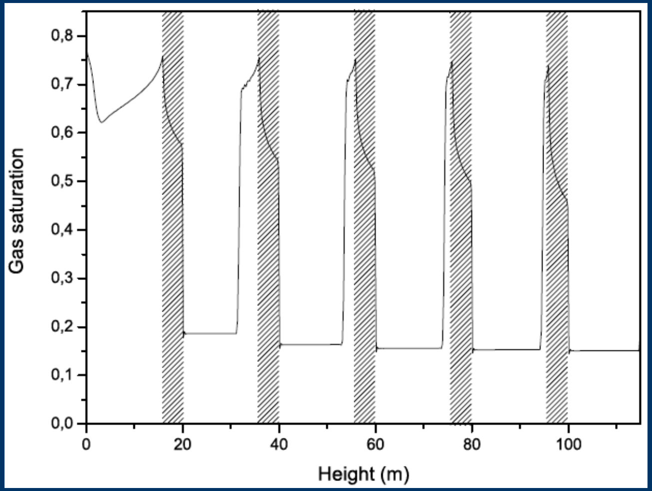
$$v_i > v_{i+1} \Rightarrow S^*_{i+1} < S^*_i$$




1
2
3
4
5
Velocity
0,0000012
0,0000008
20
40
60
80
100
Height (m)

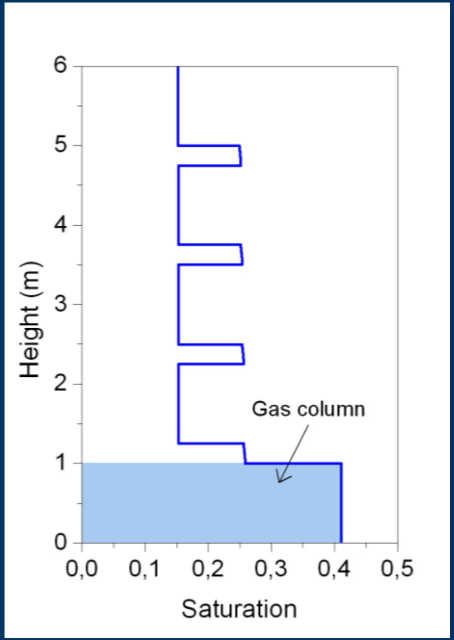

0,0000025
0,0000000
Flux function
1
2
3
4
5
0
S_5^* S_4^* S_3^* S_2^* S_1^*
1
Gas saturation

$$S_1^* > S_2^* > S_3^* > S_4^* > S_5^*$$

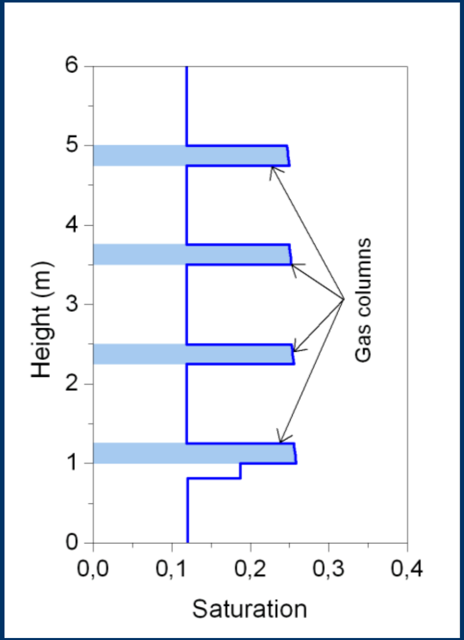

Gas saturation
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
0
20
40
60
80
100
Height (m)

Evolution of a plume in a periodic column with Heterogeneity of relative permeability laws

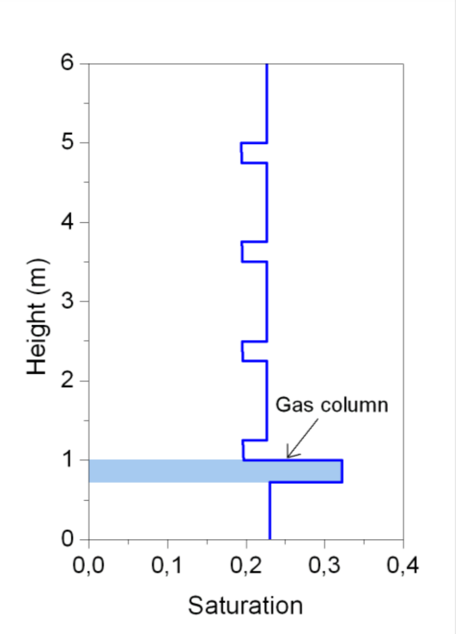
$\lambda_1 = \lambda_2$



$\lambda_1 > \lambda_2$



$\lambda_1 < \lambda_2$



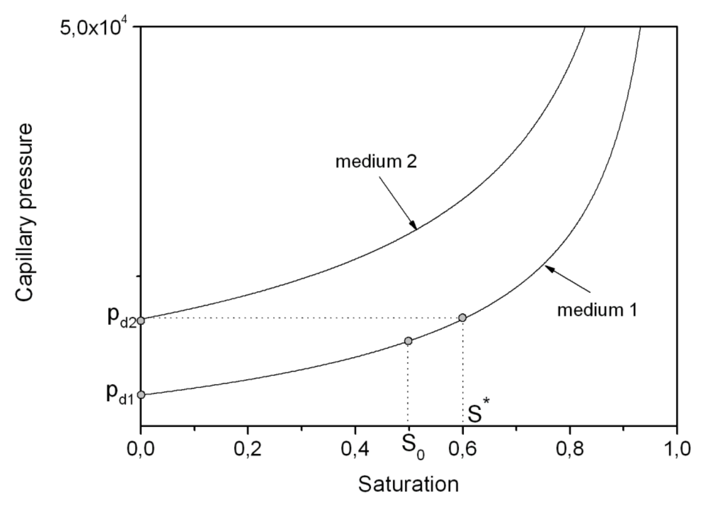
$$k_{rw} = Se^{(2+3\lambda)/\lambda}$$

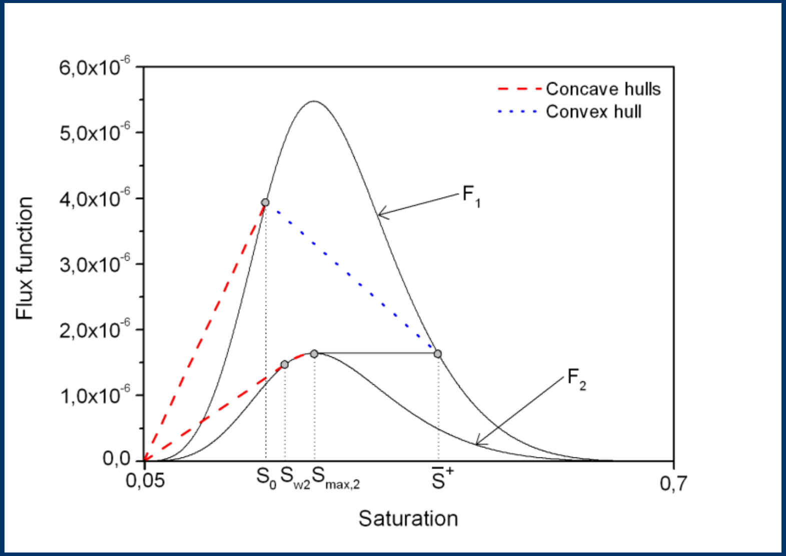
$$k_{rnw} = (1-Se)^2 (1-Se^{(2+\lambda)/\lambda})$$

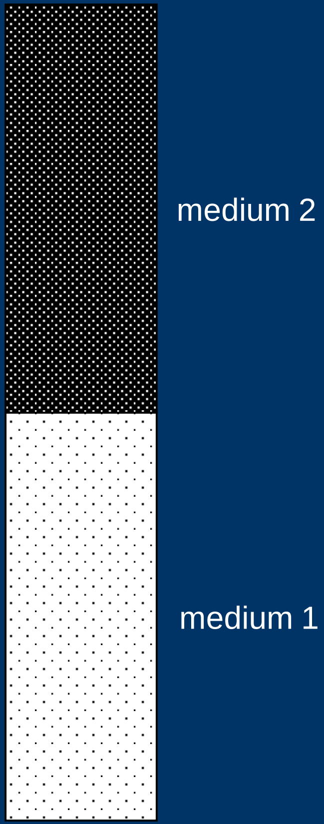
Gravity alone: one condition at the interface (Flux continuity)

Gravity + Capillarity: two conditions at the interface

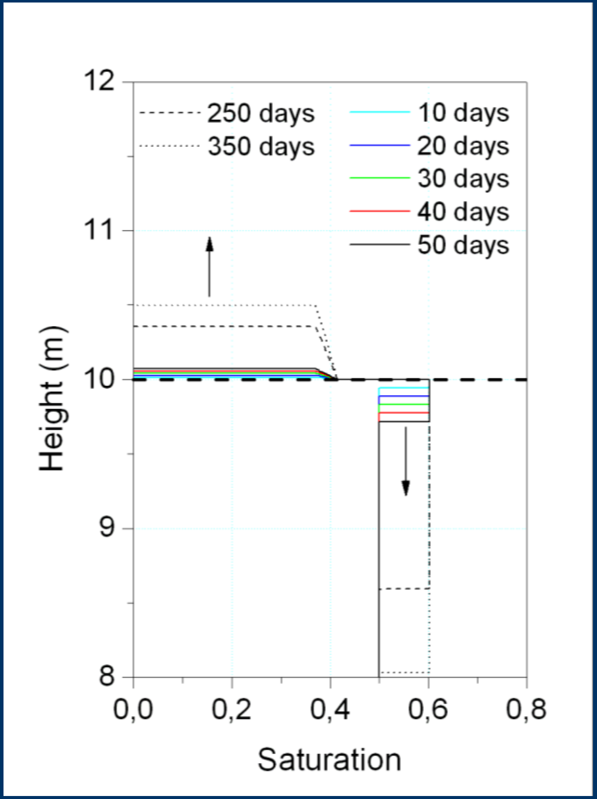
- Flux continuity
- Extended pressure condition (Van Duijn et al., 1995)



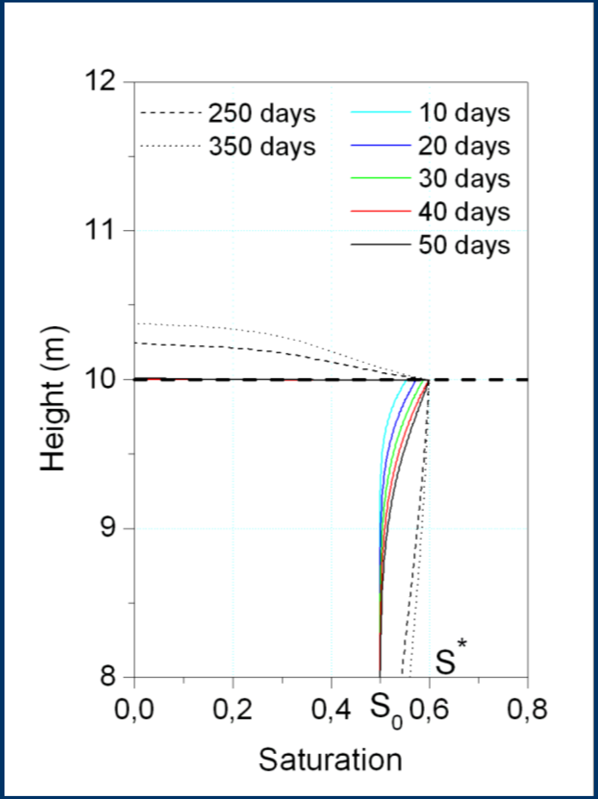




Our simulations (Cast3M)



Gravity alone



Gravity + capillarity

Siddiqui & Lake (SPE, 1997)

SPE International

Society of Petroleum Engineers

Ω

SPE 38682

A Comprehensive Dynamic Theory of Hydrocarbon Migration and Trapping

Fareed I. Siddiqui, SPE, Mobil Technology Company and Larry W. Lake, SPE, The University of Texas, Austin

Abstract

Understanding hydrocarbon migration and trapping is important since it can mean the difference between success and failure in exploration projects. The current understanding is that a capillary pressure change between a seal and a carrier bed (or reservoir) is the main factor responsible for the trapping. The current theory uses capillary pressure gradients under static (no flow) conditions to define the maximum amount of hydrocarbon that can be trapped under a particular seal. It assumes that at the very low flow rates encountered in secondary migration viscous pressure drops are negligible.

Using numerical simulation and theoretical analysis, we show that, even at very low flow rates, viscous pressure drops are not negligible and that pressure gradients within phases can be substantially different from the static gradients. We present a theory that includes the effect of both the capillary and viscous forces. An innovative way of including the effect of capillary pressures in the method of characteristics is used to solve the migration and trapping problem. Migration and trapping are explained as a result of reflection and refraction of non-linear saturation waves from the heterogeneity boundaries. When viscous forces are included the seals can trap substantially more hydrocarbons than those predicted by the current theory. It is possible to classify seals into static and dynamic seals based on their capillary pressure curves and on the petrophysical properties of the carrier bed. In both cases, we are able to associate a time scale to the accumulation and indicate explanations for several other features commonly observed in secondary migration. The results from the proposed theory are confirmed using numerical simulations.

Introduction

Hydrocarbons (oil and gas) are formed by the decomposition of organic solids deposited in fine grained sediments, mostly shales. With subsequent burial, the pressure and temperature in these rocks increase and some of the bonds in the kerogen are broken to produce oil or gas. After their production, these hydrocarbons must be transported and concentrated into more porous and permeable regions to form hydrocarbon reservoirs.

The movement of hydrocarbons just after their formation in the source rocks until they reach the more permeable rocks is called *primary migration* (Fig. 1). Primary migration finishes when hydrocarbons are expelled from the fine grained rocks into the large permeability rocks called *carrier beds*. The subsequent movement of hydrocarbons after they emerge from the source rock is called *secondary migration* (Fig. 1). There are different ways in which secondary migration can occur: in solution, as micelles or as a separate hydrocarbon phase. Most of the evidence points to separate phase migration.[1,2] Even in the case when the migration occurs in other forms, the hydrocarbons must come out of solution to form traps. Thus, the final stage of secondary migration will always be a separate hydrocarbon phase migration. This paper assumes that all the migration occurs in a separate hydrocarbon phase, either an oil or a gas phase, depending on the temperature and pressure conditions and the composition of the fluids.

As hydrocarbons enter the large pores of a carrier bed they may coalesce to form larger globules. These large globules will move up by buoyancy. Hydrocarbons move in these carrier beds until they reach locations where further movement is partially or totally stopped. The obstacles to the further movement of hydrocarbons are called *seals*. The region beneath the seal that contains the trapped hydrocarbons at high concentrations is called a hydrocarbon *trap* or a hydrocarbon *reservoir* (Fig. 1).

No seal is perfect. They all fail under certain conditions, allowing the hydrocarbons to leak from the trap. Leakage is in effect a continuation of secondary migration although it is sometimes also referred as tertiary migration. After leaking from a trap, the hydrocarbons may trap under another seal or may ultimately seep to the surface.

A thorough understanding of secondary migration is

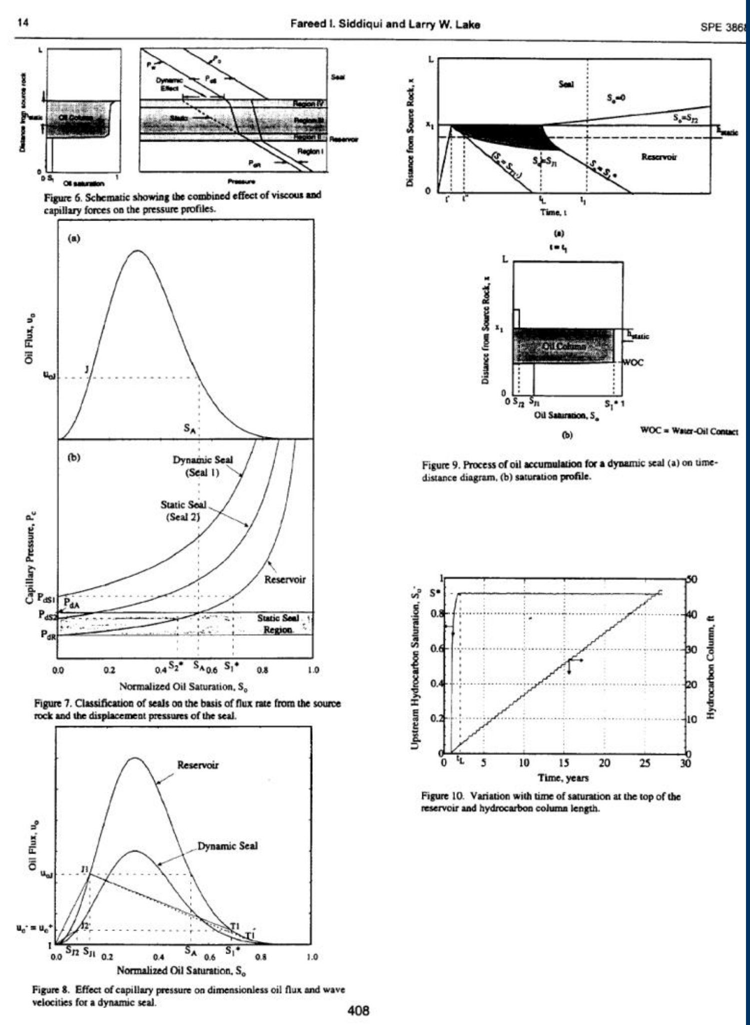


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Figure 6. Schematic showing the combined effect of viscous and capillary forces on the pressure profiles.

Figure 7. Classification of seals on the basis of flux rate from the source rock and the displacement pressures of the seal.

Figure 8. Effect of capillary pressure on dimensionless oil flux and wave velocities for a dynamic seal.

WOC = Water-Oil Contact

Figure 9. Process of oil accumulation for a dynamic seal (a) on time-distance diagram, (b) saturation profile.

Figure 10. Variation with time of saturation at the top of the reservoir and hydrocarbon column length.

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Conclusion

- Upscaling in periodic layered porous media & Influence of relative permeability heterogeneity , submitted AWR.
- Collab. Avec IFP code COORES , pbme grav + capill..

M. Hayek, E. Mouche and C. Mugler, Modeling vertical stratification of CO2 injected into a deep heterogeneous saline aquifer with a Buckley-Leverett equation in presence of gravity. (Advances in Water resources, 2009)