

Dynamics of CO₂ Plumes Encountering a Fault in a Reservoir

Kyung Won Chang, Steven L. Bryant

Abstract

After CO₂ has been injected in the lower part of a dipping aquifer, it will continue to migrate, driven by buoyancy. This movement drives a countercurrent flow of brine leading to increased residual phase trapping. The purpose of this simulation study is to understand the effects of geomechanical structures, especially faults, on the dynamic behavior of the buoyancy-driven CO₂ plume and the amount of residual trapping.

Using GEM (Generalized Equation-of-State Model Compositional Reservoir Simulator) we studied the behavior of CO₂ plumes (speed, direction, saturation at displacement front, residual phase trapping) in 2D formations with a range of fault properties (conductive vs. sealing, angle relative to dip, distance from initial plume location). We developed an analytical approach for estimating plume movement based on Buckley-Leverett theory, which compares favorably with the simulation results; thus, it can explain the basic behavior of CO₂ plume in this simplified reservoir model, which is homogeneous, anisotropic and tilted. Smaller amounts of initially stored CO₂ migrates shorter distances, and in these cases the simple theory predicts the plume movement prior to encountering a fault. If the plume encounters a fault within the reservoir, the fault can create new virtual source (CO₂ build-up at the plume/fault intersection) for migration. It also leads to more complicated fluid movement, including counter current flow. A sealing fault, which acts as another boundary for CO₂ plume, divides the aquifer into two parts: fault-independent zone and fault-dependent zone. The analytical solution can predict the properties of CO₂ plume in the first zone, but not in the latter one due to the counter current flow. In both cases of a declined and an inclined fault, CO₂ accumulates along the fault due to anisotropy causing dominantly parallel migration. The build-up continues until saturation approaches the endpoint dictated by the relative permeability curves (forming a virtual source),

and then CO₂ moves upward along the fault. On the other hand, a conductive fault, which acts as a new pathway for migration, may cause considerable leak of CO₂ toward the top boundary of the reservoir (inclined fault) or increase the width of CO₂ plume (declined fault). In the latter case of the conductive fault, the CO₂ plume passes through larger area, which improves the efficiency of residual saturation trapping. To understand the dynamics of CO₂ behavior, especially countercurrent flow, in the faulted reservoir we analyze flow vectors of both CO₂ and brine phases, which explain the process of gas build-up and/or leakage due to structural heterogeneity.

Introduction

Storage of carbon dioxide (CO₂) in a deep saline aquifer has been suggested as one method to reduce greenhouse gases in the atmosphere. Trapping and sealing CO₂ in deep brine formations underground requires a sufficiently impermeable caprock layer to prevent upward migration from the target reservoir. Accordingly, the risk of CO₂ leakage has been one of the main issues for CO₂ sequestration to be a reliable carbon dioxide management solution. However, caprock layers may contain imperfections, especially faults, which can act as a high-permeability conduit for leakage of CO₂ from depth to the near surface. Faults also pass through the target formations for storage. A fault can separate a formation into non-communicating compartments, or it can establish a conductive path to a juxtaposed but different formation.

The main purpose of this simulation study is to evaluate geometric (slope and angle) and/or petrophysical factors mainly associated with a fault, which should be taken into account in estimating the behavior of CO₂ plumes during carbon dioxide sequestration process. In addition, our works apply the following petrophysical concerns to the simulation model

containing each specific type of a fault: 1) anisotropy and isotropy of permeability; 2) residual gas saturation (residual saturation trapping); and 3) high-permeable portion in the sealing fault (leakage). Many CO₂ sequestration studies have done to explain the impact of the above three factors, but little attention has been paid to how the interaction between those factors and a fault affects the dynamics of CO₂ plumes. Therefore, in this simulation study we explore 1) how a fault within the storage formation affects the buoyancy-driven CO₂ migration, and 2) how the permanent capture of CO₂ can be increased from residual trapping mechanism in a fault-containing reservoir.

Description of the Simulation Model

The base case simulation presents results for the following domain: a relatively short, wide domain, of dimensions 400 ft (length) × 100 ft (height) × 2 ft (width), to establish a wide volume of CO₂ migration along which instabilities could develop. The simulation used 10,000 grid blocks; and, each grid block size is 2 ft × 2 ft × 2 ft. The aquifer was tilted at a dip angle of five degrees. In addition, there are no injection and production wells; the boundaries of the domain are closed. Accordingly, CO₂ migration is driven only by buoyancy. The intention is to study only the interaction with faults after injection has ended. Thus, this initial condition mimics the result of an “inject low and let rise” strategy. CO₂ is placed at high saturation in the lower part of the downdip half of the domain (range of the area is 1st to 100th grid block in j-direction (horizontal) and 40th to 50th grid block in k-direction (vertical)). The scheme of the base model is shown as the following Figure 1, and Table 1 summarizes input parameters including aquifer properties, component properties and well conditions. We use the GEM-CMG simulator

(Nghiem et al., 2004), tuned to the CO₂/brine/rock system in previous work (Kumar et al., 2004; Ozah et al., 2005; Bryant et al., 2006).

The gas saturation profiles during 10,000 years are the principal simulation outputs to represent the dynamics of CO₂ plumes. The increase and/or decrease of the gas saturation in each grid block result from the phase behavior based on the relative permeability curve, which is introduced in Figure 2. The curve can be calculated from following relationships:

$$k_{rg} = k'_{rg} \left(\frac{S_g - S_{gcr}}{1 - S_{wcon} - S_{wir}} \right)^{N_g} \quad \text{for } S_g \geq S_{gcr}$$

$$k_{rw} = k'_{rw} \left(1 - \frac{S_g - S_{gr}}{1 - S_{wcon} - S_{gr}} \right)^{N_w} \quad \text{for } S_g \leq 1 - S_{wcon}$$

$$k_{rg} = 0 \quad \text{for } S_g < S_{gcr}$$

$$k_{rw} = 0 \quad \text{for } S_g > 1 - S_{wcon}$$

To analyze the effect of the residual gas saturation we use two comparative relative permeability curves including: 1) no residual gas saturation and 2) hysteresis with residual gas saturation.

Fault Properties

The CO₂ migration in a faulted reservoir was simulated by adding the petrophysical properties associated with fault characteristics. Such a geological discontinuity can induce the flow (leakage) of "potentially mobile CO₂" in the structural trap at large saturation. In the process of the structural trap, the stored CO₂ will remain in the trap permanently as long as the geological seal remains intact.

We represent faults by assigning appropriate transmissibility multipliers on every contact face of each grid block that would correspond to the prescribed location of a fault. The specific

range of grid blocks should be combined with fault parameters to represent fault properties; therefore, smaller grid blocks are required to simulate more realistically the angled geologic discontinuity. We categorize two types of a fault by geometry: declined (negative dip to horizontal plane) and inclined (positive dip to horizontal plane) fault. Also, the petrophysical characteristics of a fault: high-permeability (conduits) or low-permeability (barriers), can be controlled by setting transmissibility multipliers high (value over 1) or low (zero value). We can also model the presence of a local leak within a sealing fault by adjusting the transmissibility multiplier value of a specific grid block along the fault zone.

Analytical Solution for Buoyant Flow in Anisotropic Domain

Consider the flow of two immiscible fluids (one wetting and another non-wetting phase) in a homogeneous, isothermal and isotropic porous medium. The governing equation for the flow of phase i is from Darcy's law as follows:

$$u_i = -\frac{kk_{ri}}{\mu_i} \left(\frac{dp}{dx} + \rho_i g \sin \alpha \right)$$

This simulation study focuses on the immiscible displacement only between two phases: gas (CO₂) and water (brine). Also, the reservoir model is based on two-dimensional domain; thus, it requires analyzing flow parallel to the bedding plane and vertical (Chang, 2007):

$$u_{g,parallel} = \frac{k(\rho_w - \rho_g)g \sin \alpha}{\frac{\mu_w}{k_{rw}} + \frac{\mu_g}{k_{rg}}}$$

$$u_{g,vertical} = \frac{k(\rho_w - \rho_g)g \sin 90^\circ}{\frac{\mu_w}{k_{rw}} + \frac{\mu_g}{k_{rg}}} = \frac{k(\rho_w - \rho_g)g}{\frac{\mu_w}{k_{rw}} + \frac{\mu_g}{k_{rg}}}$$

The flux can be referred to the Darcy velocity of fluid, which represents its rates of flow per unit of surface at right angles to the direction of flow. The Darcy velocity differs from the interstitial velocity (v_g) of fluid because of the action of porosity and saturation:

$$u_g = v_g S_g \phi$$

Then, the distance and direction of CO₂ migration can be estimated as follows:

1) Distance

$$d_g = v_{\text{total}} \cdot t$$

$$v_{\text{total}} = \sqrt{v_{g,\text{parallel}}^2 + v_{g,\text{vertical}}^2 - 2v_{g,\text{parallel}}v_{g,\text{vertical}} \cos(90^\circ + \alpha)}$$

2) Angle

$$\theta = \cos^{-1} \left(\frac{v_{\text{total}}^2 + v_{\text{parallel}}^2 - v_{\text{vertical}}^2}{2v_{\text{total}}v_{\text{parallel}}} \right)$$

Simulation Results

Base Case

We first consider behavior in an aquifer containing no fault. The base model is assumed to be homogeneous and tilted. The only variable is vertical to horizontal permeability ratio (k_v/k_h) and the values are varied with 1 and 0.01. The first case represents the isotropic condition ($k_v/k_h=1$), which shows dominantly vertical movement of CO₂ plumes in spite of dipping condition. CO₂ plumes reach the top seal and spread out along the top boundary of the aquifer before approaching the side boundary. On the other hand, as the value of k_v/k_h becomes smaller, CO₂ migrates more parallel to the bedding plane in the up-dip direction. Accordingly, the lower k_v/k_h values are more efficient for storage of CO₂ gas. (Figure 3 and Figure 4)

The analytical estimation (angle and distance of movement) is quite reasonable to adapt Buckley-Leverett theory in analyzing the CO₂ plume behavior (Table 2). The agreement is remarkable, because the countercurrent flow exists at the edge of plumes except the frontal part. This violates the premises of Buckley-Leverett theory.

Effects of Fault Properties

The existence of a fault plays a significant role in controlling the CO₂ behavior corresponding to its geometric and petrophysical properties.

Geometric variables for a fault are location, angle and slope. In this simulation, every fault type bisects the domain by locating in the middle of the aquifer from 1st (top) to 50th (bottom) layers. Plus, all faults are placed at 45 degrees from the bottom of the aquifer. The declined fault contains a negative slope to the plane; while, the inclined fault has a positive slope. To represent petrophysical properties of a fault, transmissibility multiplier are used: zero (GEM code, *TRANSF*=0 and *IDIR*+/-, *JDIR*+/- and *KDIR*+/-) for the sealing (low-permeable) fault and 100 for the conductive (high-permeable) fault (*TRANSF*=100 and *IDIR*-, *JDIR*- and *KDIR*+/-). The simulation results for four distinct cases are categorized as follows:

1) Declined and Sealing Fault

First, the simulation work focuses on how the declined fault, which has negative slope corresponding to the dip of bedding plane, affects CO₂ migration under the anisotropic reservoir condition. The ration of vertical permeability to horizontal permeability is 0.01; thus, the flow parallel to the bedding plane will be greater than the vertical movement.

The declined fault plays a significant role as one of typical geological traps (Figure 5). In this case, the sealing fault forms a CO₂-trap-zone combined with the pre-existing boundaries of

an aquifer such as the top seal and side boundaries. Furthermore, from the above series of gas saturation profiles, the most remarkable phenomenon is the accumulation of CO₂ at the fault before the vertical CO₂ migration along the sealing fault. In detail, the flow vector analysis indicates there would be countercurrent flow between phases inside the CO₂ plume. Countercurrent flow means that applying the Buckley-Leverett theory (Buckley and Leverett, 1942) can not be valid to interpret the flow model during the process of CO₂ build-up.

2) Inclined and Sealing Fault

In the case of an inclined fault, the sealing fault cannot act as a geological trap; instead, it alters the path of the CO₂ migration (or leakage). In this simulation, the fault divides the CO₂-rich area into two parts, which induce separated behaviors of CO₂ plume. As Figure 6 shows, the left part (behind portion) of stored CO₂ moves upward along the sealing fault and then accumulates at the upper part of given reservoir. On the other hand, CO₂ plume in the right part (frontal portion) has a normal trend of fluid migration, which is observed from outputs of the base case as Figure 3. If the reservoir has smaller anisotropy or isotropy of permeability, we can expect that CO₂ of the left side will show a preferential movement toward the upper boundary as shown in Figure 4; while, CO₂ in the right side will migrate along the sealing fault.

3) Declined and Conductive Fault

Faults can provide channels for basement fluids to move across laterally continuous barriers to vertical fluid migration. The structural deformation of rocks during faulting and folding can enhance permeability with open joints, which exhibit only opening displacement. Higher transmissibility multiplier values ($TRANSF=100$) allow a specific series of grid blocks with inclination to represent high-permeable fault characteristics. This assumed fault can affect CO₂ migration as a conduit (so-called "channeling effect").

As shown in Figure 7, CO₂ does not accumulate in the fault zone, which means that the gas phase flows quickly across the fault due to relatively larger transfer capacity of the fault. CO₂ migration did not occur along the fault zone because the reservoir properties (anisotropy and dipping) have a great effect on the flow of the gas phase. As a result, despite the conductive fault property, CO₂ propagation tends to be parallel to the bedding plane not aligned to the fault zone. However, we can discover CO₂ buildup on the other side of a fault, which can be a virtual source for another CO₂ migration. It enlarges the contact area of CO₂ invasion so that the efficiency of residual saturation trapping will be increased.

4) Inclined and Conductive Fault

Through the outputs (Figure 8) from the inclined fault simulation we can discover that CO₂ flows dominantly through the conductive fault, and accumulates at the top seal of the aquifer. This phenomenon is exactly what we expected in the case of the conductive fault property, which can be regarded as “CO₂ leakage.” (Figure 8) In addition, the conductive fault zone creates additional virtual sources of CO₂ along the fault. The combination of the dipping of the reservoir and the conductive fault geometry allows more residual CO₂ trapping by enlarging the contact area of the migration. In contrast to the previous case (declined fault model), the geometry of the fault (inclined condition) interplays with the petrophysical properties of the fault zone; and, positively affects CO₂ migration through the large-transfer-capacity geologic channel.

Residual Saturation Trapping

As CO₂ migrates through the formation, some of it is captured and permanently remained in the pore space, which is referred to “residual CO₂ trapping” (Obdam *et al.*, 2003). When the rate of

this trapping is relatively high and CO₂ is injected at the bottom of a sufficiently thick formation, almost all of the injected CO₂ can be trapped by the mechanism before it reaches the surface boundary of the formation. Likewise, the residual trapping mechanism plays a significant role in capturing CO₂ to be immobile.

From the simulation results (shown in Figure 9), we can easily figure out that all of grid blocks which CO₂ passes through show residual gas saturation: the blue color indicates 0.2 of gas saturation, which is the value of residual gas saturation, S_{gr} . Consequently, this case represents quite similar trend of CO₂ primarily-upward migration compared with the base case due to isotropic condition; however, the explicit difference is that CO₂ cannot reach the upper surface of the reservoir.

Flow Vector Analysis

For analyzing the dynamics of each phase we add flow vectors on the gas saturation profile. These show when and where the imbibition and/or drainage take place.

From Figure 10 through 11, we can discover counter current flow boundaries of the CO₂ plume except the propagating portion. Before CO₂ meets a fault, its lateral migration is controlled by counter current flows of the water phase. Once a fault begins to affect CO₂ migration, the behavior of CO₂ plume is controlled mainly by fault properties. In addition, counter current flows are detected inside the CO₂ plume, which means that CO₂ trapping can be enhanced by the counter current flow due to fault geometry.

The simulation results reveal that before CO₂ encounters a fault, counter current flow of brine exists inside CO₂ plume, but after hitting the fault, it disappears gradually in the region corresponding to the build-up saturation. On the contrary, counter current flow persists outside

CO₂ plume except the head of the plume at any migration step. This fact implies that counter current flow due to anisotropy (small value of k_v/k_h) results in parallel-dominant migration; but, the presence of a fault controls the dynamics of CO₂ behavior more than any other factors.

Conclusions

This study concludes that the properties of a fault and the interactions between the fault and the reservoir matrix can play a critical role in quantifying the behavior of CO₂ after injection ends. A fault within the target formation can have a positive or negative effect on the capture of the buoyancy-driven CO₂ with residual trapping mechanism depending on its geometry and/or petrophysical property. In addition, the counter current flow of water phase inside CO₂ plumes provides benefits to CO₂ trapping. Accordingly, when it comes to the injection and storage of CO₂, an accurate prediction of the fault conductivity and petrophysical properties of the reservoir would be required to optimize the rate of injection and the storage capacity of the reservoir for the permanent capture of CO₂.

Acknowledgements

This simulation works are performed at CPGE (Center for Petroleum and Geosystems Engineering) of the University of Texas at Austin. Plus, this project is supported by CCP2 (CO₂ Capture Project 2) and the Geologic CO₂ Storage Joint Industry Project. The members of the JIP include Chevron, ENI, ExxonMobil, Shell, TXU and Computer Modeling Group, Ltd.

Nomenclature

k_v vertical permeability

k_h	horizontal permeability
k_{rg}	relative permeability for gas phase
k'_{rg}	gas end point relative permeability
k_{rw}	relative permeability for water phase
k'_{rw}	water end relative permeability
S_g	gas saturation
S_{gcr}	critical gas saturation
S_{gr}	residual gas saturation
S_w	water saturation
S_{wcon}	connate water saturation
S_{wir}	irreducible water saturation
N_g	gas relative permeability exponent
N_w	water relative permeability exponent
α	dip angle (positive for upward flow)
u	flux
μ	viscosity
ρ	density
g	gravitational acceleration
v	interstitial velocity
ϕ	porosity
t	total

References

1. Bryant, S.L. *et al.*: "Buoyancy-Dominated Multiphase Flow and Its Impact on Geological Sequestration," paper SPE 99938 presented at SPE/DOE Symp. Improved Oil Recovery, Tulsa, 22-26 Apr. 2006
2. Buckley, S.E. and Leverett, M.C., "Mechanism of Fluid Displacement in Sands," Trans. A.I.M.E.; Vol. 146; pp107-116, 1942
3. Chang, K., "A Simulation Study of Injected CO₂ Migration in the Faulted Zone," thesis; the University of Texas at Austin, 2007
4. Collins, R.E., "Flow of Fluids through Porous Materials," published by Penn-Well Pub. Co., Tulsa, OK; pp142-149, 1961
5. Kumar A. *et al.*: "Reservoir Simulation of CO₂ Storage in Deep Saline Aquifers," paper SPE 89343 presented at SPE/DOE 14th Symp. Improved Oil Recovery, Tulsa, 17-21 Apr. 2004
6. Main, I.G. *et al.*: "Fault Sealing during deformation-band growth in porous sandstone," Geology, Vol. 28; No. 12; pp1131-1134, Dec. 2000.
7. Manzocchi, T. *et al.*: "Fault transmissibility multipliers for flow simulation models," Petroleum Geoscience, Vol. 5; pp53-63, 1999
8. Nghiem, L., Sammon, P., Grabenstetter, J. and Ohkuma, H., "Modeling CO₂ Storage in Aquifers with a Fully-Coupled Geochemical EOS Compositional Simulator," paper SPE 89474 presented at the 2004 SPE/DOE 14th Symp. on Improved Oil Recovery, Tulsa, OK, April 17-21, 2004
9. Pasala, S.M. *et al.*: "Simulating the Impact of Faults on CO₂ Sequestration and Enhanced Oil Recovery in Sandstone Aquifers," paper SPE 84186 presented at SPE ATCE, Denver, 5-8 October. 2003

10. Obdam, A., L.G.H. Van der Meer, May, F., Bech, N., Kervevan, C., and Wildenberg, A.,
“Effective CO₂ Storage Capacity in Aquifers and in Hydrocarbon Fields,” 6th International
Conference on Greenhouse Gas Control Technologies; Vol.I; pp.489-494, Kyoto, Japan, 2002
11. Ozah, R.C. *et al.*: “Numerical Simulation of the Storage of Pure CO₂ and CO₂-H₂S Gas
Mixture in Deep Saline Aquifers,” paper SPE 97255 presented at SPE ATCE, Dallas, 9-12
October. 2005
12. Pruess, K., “Numerical Studies of Fluid Leakage from a Geologic Disposal Reservoir for
CO₂ Show Self-Limiting Feedback between Fluid Flow and Heat Transfer,” Geophysical
Research Letter; Vol.32; No. L14404; doi:10.1029, June 2005
13. Walsh, N.P. *et al.*: “An Analysis of Gravity-Dominated, Immiscible Flows in Dipping
Reservoirs,” paper SPE 21651 presented at Symp. Production Operations, Oklahoma City, 7-9
Apr. 1991

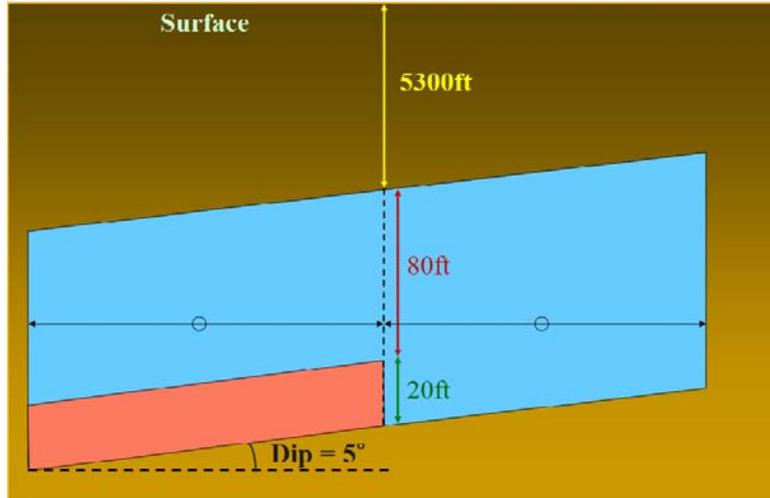


Figure 1: The scheme of base model for this simulation; the red color indicates the initial CO₂ location and the blue color represents the H₂O saturated zone.

General Property of Whole Aquifer	
Width, ft	400
Thickness, ft	100
Depth at top of the center of the reservoir, ft	5300
Temperature, degF	140
Salinity, ppm	100,000
Initial pressure at 5300 ft depth, psi	2295
Constant boundary pressure, psi	2295
Specific Property	
Permeability, md	1
Horizontal to vertical permeability ratio	1
Transmissibility	1
Horizontal to vertical transmissibility ratio	1
Porosity, fraction	0.15

Table 1: General Properties of the Reservoir Model

k_v/k_h	Analytical Solution		Simulation Output	
	Distance, ft	Angle, deg	Distance, ft	Angle, deg
0.01	122.55	6.46	123.27	4.63
0.1	57.38	46.09	57.52	41.15
1	34.9756	80.08	27.88	77

Table 2: Quantities Comparison of Analytical Solution and Simulation Output

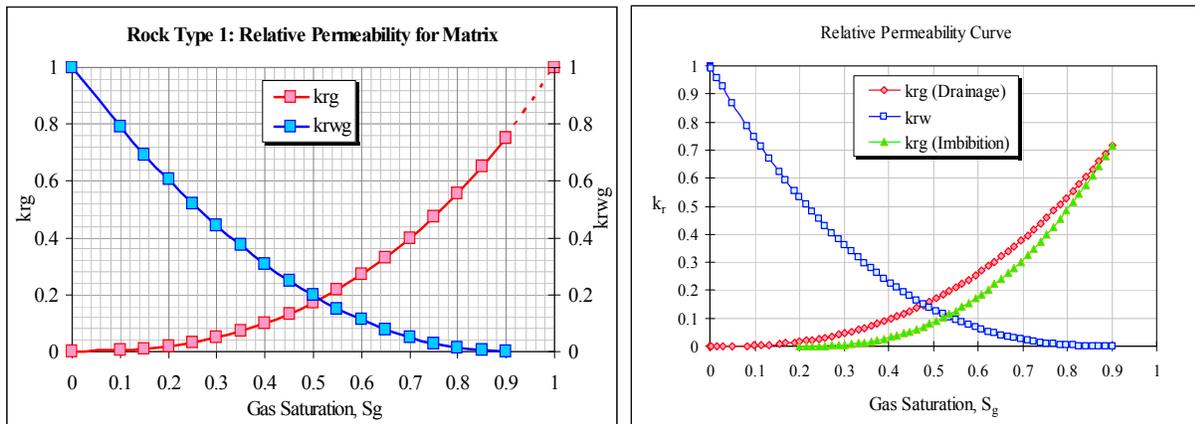


Figure 2: Relative permeability curves: the first one does not contain residual gas saturation, while the second one involves residual gas saturation ($S_{gr}=0.2$) by using hysteresis

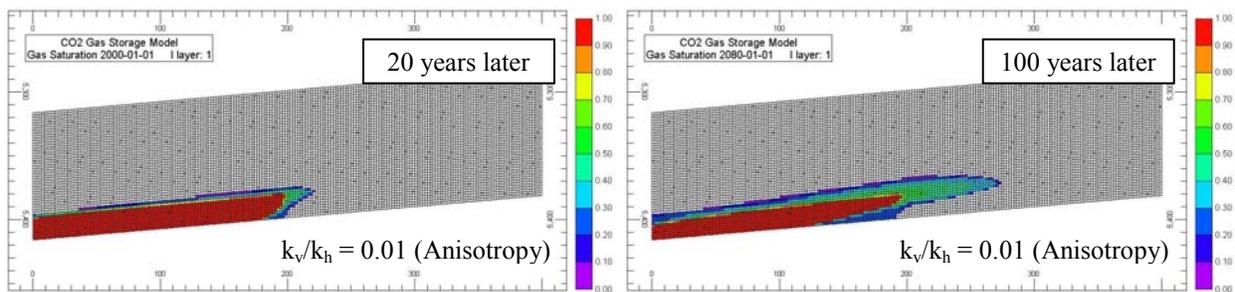


Figure 3: The gas saturation profiles after 20 years and 100 years; the aquifer involves 0.2 of residual gas saturation and anisotropic permeability ($k_v/k_h=0.01$)

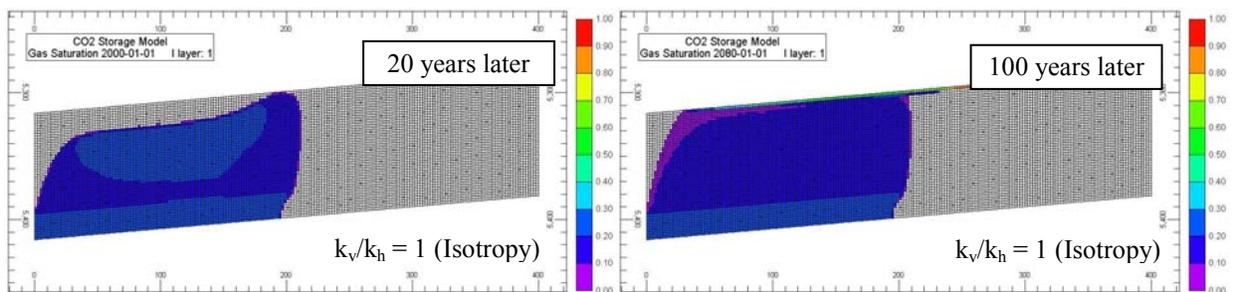


Figure 4: The gas saturation profiles after 20 years and 100 years; the aquifer involves 0.2 of the residual gas saturation and isotropic permeability ($k_v/k_h=1$)

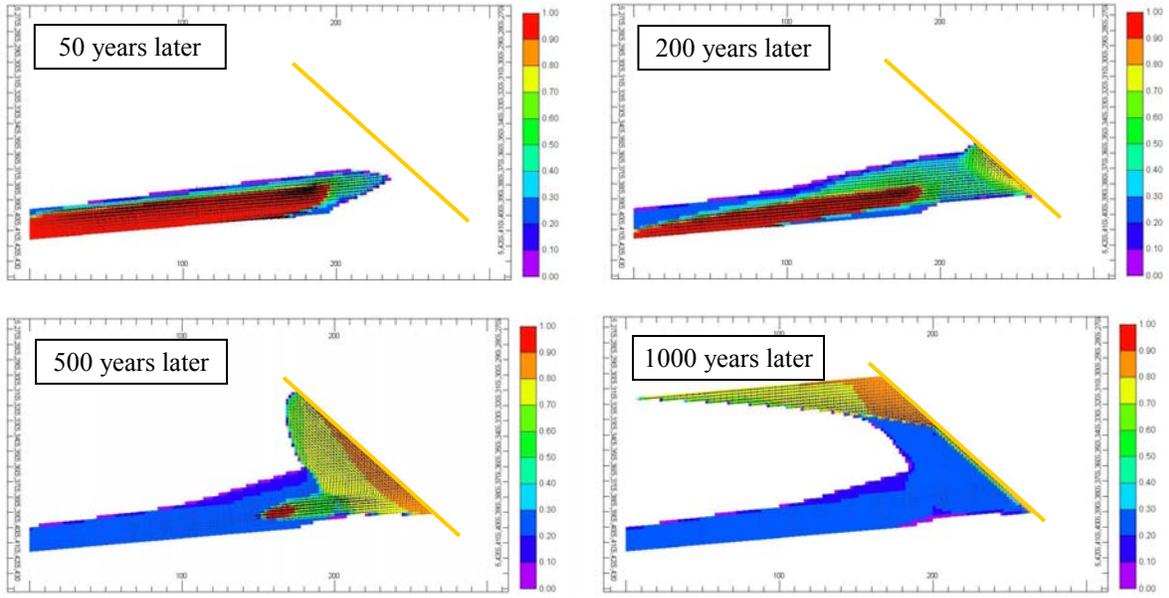


Figure 5: Gas saturation profiles for declined and sealing (low-permeable) fault; the model contains anisotropy ($k_v/k_h=0.01$) and residual gas saturation ($S_{gr}=0.2$); the yellow line represents the fault.

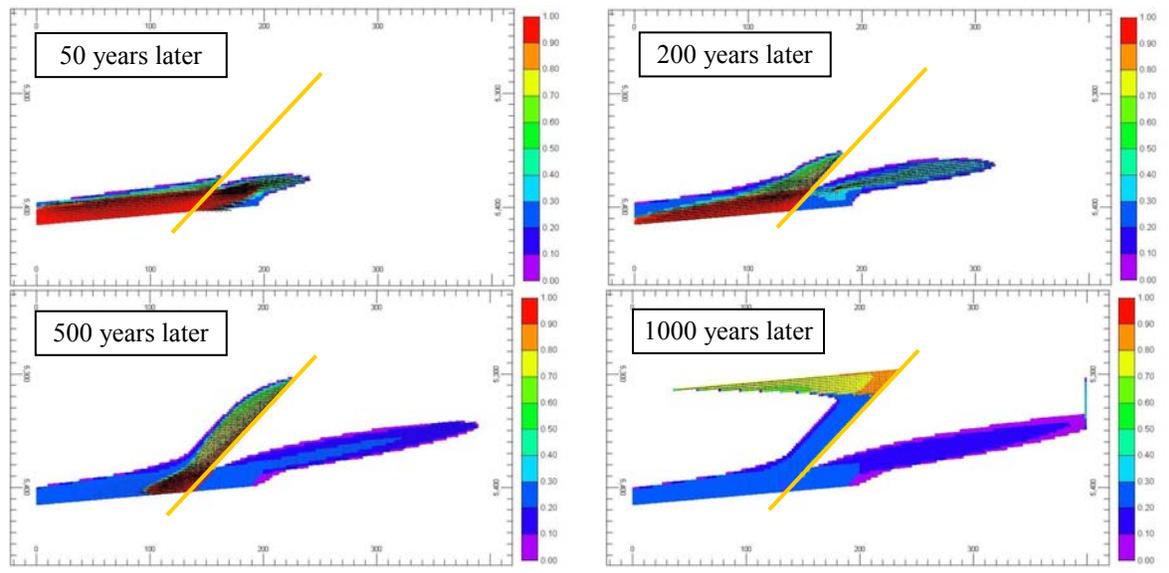


Figure 6: Gas saturation profiles for inclined and sealing (low-permeable) fault; the model contains anisotropy ($k_v/k_h=0.01$) and residual gas saturation ($S_{gr}=0.2$); the yellow line represents the fault.

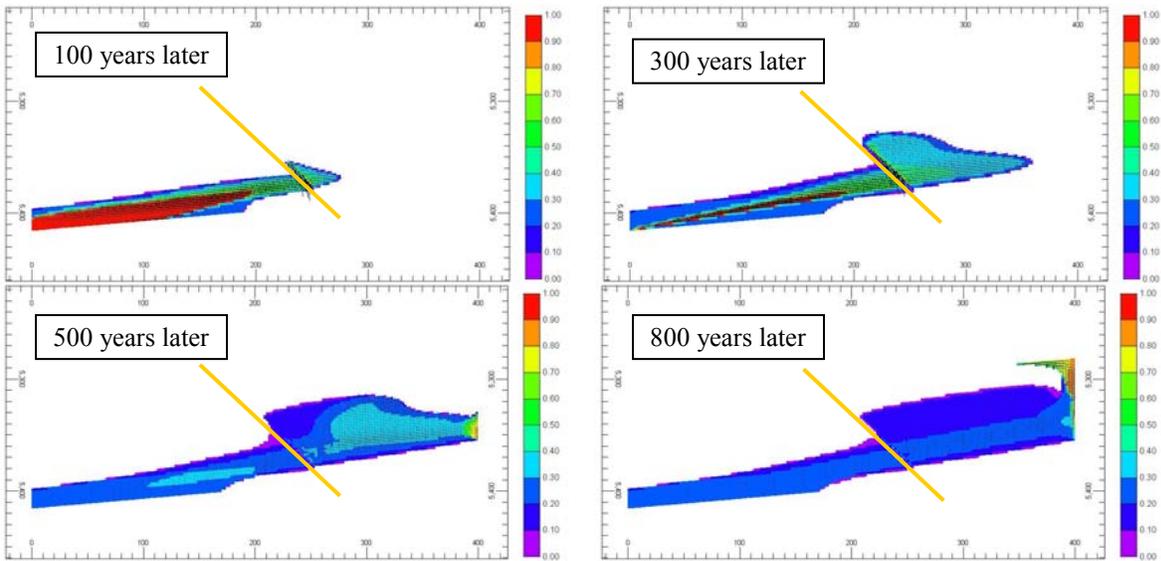


Figure 7: Gas saturation profiles for declined and conductive (high-permeable) fault; the model contains anisotropy ($k_v/k_h=0.01$) and residual gas saturation ($S_{gr}=0.2$); the yellow line represents the fault

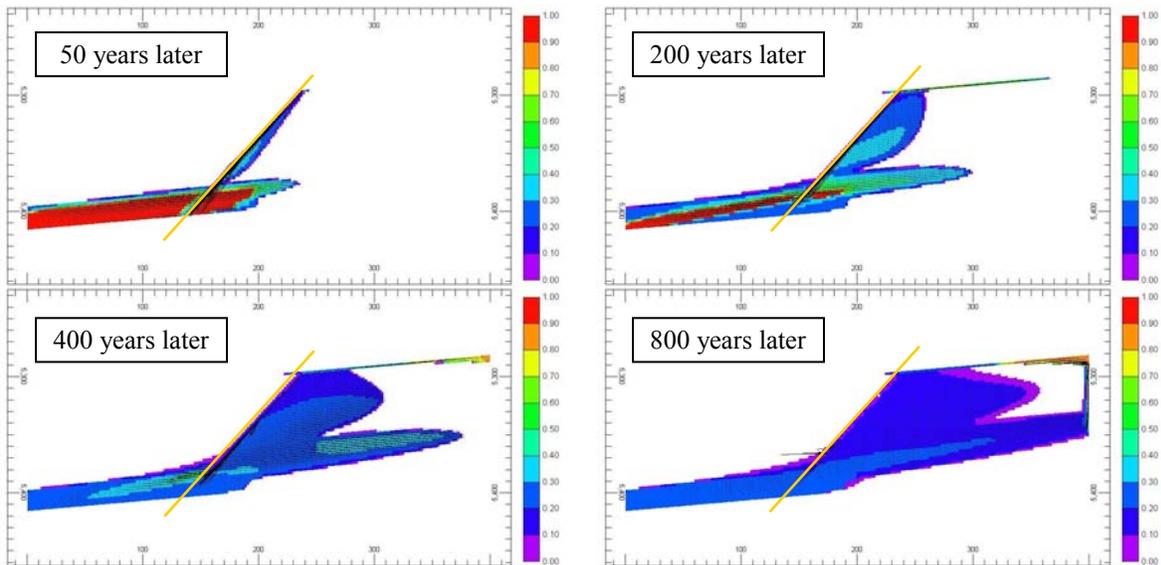


Figure 8: Gas saturation profiles for inclined and conductive (high-permeable) fault; the model contains anisotropy ($k_v/k_h=0.01$) and residual gas saturation ($S_{gr}=0.2$); the yellow line represents the fault

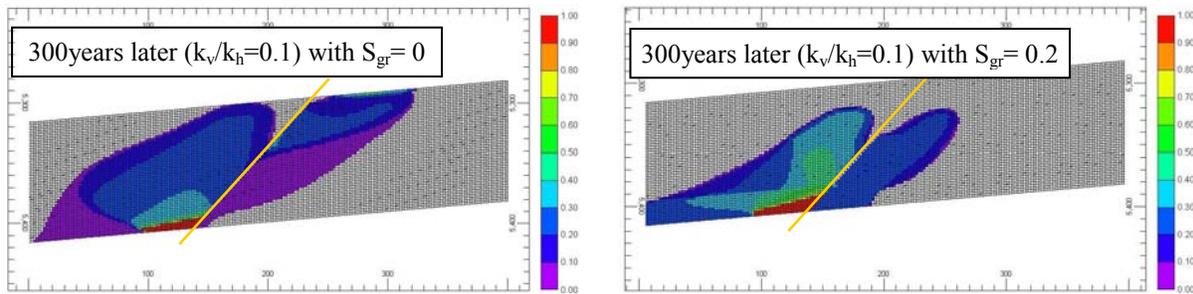


Figure 9: Gas saturation profiles for revealing the effect of residual gas saturation; the fault is inclined and sealing; the yellow line represents the fault

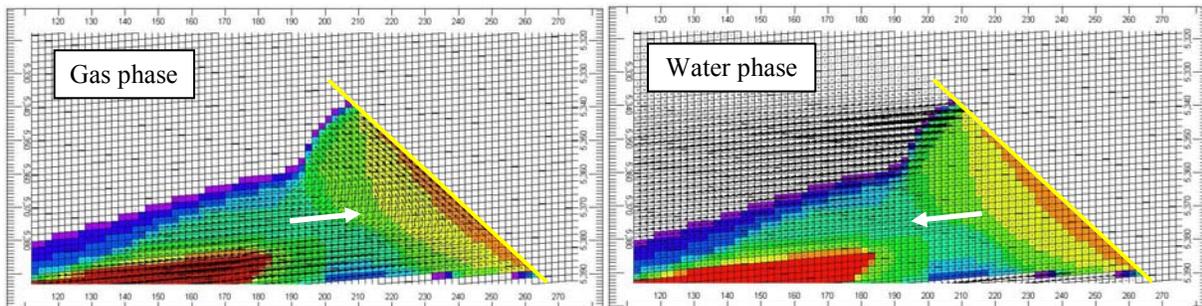


Figure 10: Gas saturation profiles with flow vectors to analyze the dynamics of CO₂ plumes of the model involving declined and sealing fault; the white arrows represent the major direction of phase vectors; the yellow line represents the fault

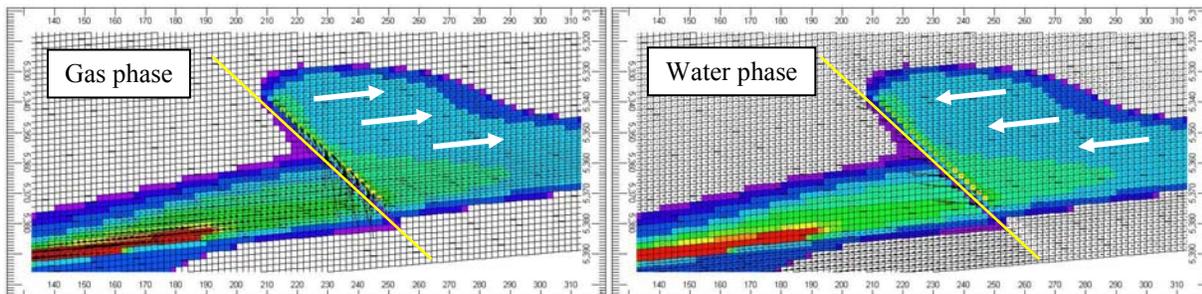


Figure 11: Gas saturation profiles with flow vectors to analyze the dynamics of CO₂ plumes of the model involving inclined and conductive fault; the white arrows represent the major direction of phase vectors; the yellow line represents the fault