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The effect of faults on dynamics of CO₂ plumes

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Abstract

The injected CO₂ in a target formation can continue to migrate through permeable pathways due to geological heterogeneity as well as 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 geological structures, especially faults, on the dynamic behavior of the buoyancy-driven CO₂ plume and the amount of residual trapping. We studied the behavior of CO₂ plumes (speed, direction, saturation at displacement front, residual phase trapping) in 2D and 3D formations with a range of fault properties (conductive vs. sealing, angle relative to dip, distance from initial plume location).

Before CO₂ plumes enter the fault-influenced region of the aquifer, the reservoir properties determine the plume behavior. The analytical approach for estimating plume movement based on Buckley-Leverett theory 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. 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 and/or dissolution.

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 countercurrent 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. According to Land's model the larger the gas saturation reached as gas invades, the larger the residual gas saturation when water invades. Therefore, the saturation of CO₂ plumes moving in the reservoir will determine the efficiency of residual saturation trapping. On the other hand, a conductive fault, which acts as a new pathway for migration, may cause considerable leakage of CO₂ toward the top boundary of the reservoir (inclined fault) or increase the width of CO₂ plume (declined fault). In the latter case, 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 CO₂ phase build-up and/or leakage due to structural heterogeneity.

Keywords: CO₂ sequestration; Fault; CO₂ trapping mechanism; CO₂ plume dynamics; Reservoir simulation.

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1. Introduction

Carbon dioxide (CO₂) sequestration technology has been regarded as one of the most efficient strategies to reduce anthropogenic emission of CO₂. For the permanent capture of CO₂, a sufficiently impermeable caprock layer is the essential geological structure which prevents upward migration of buoyancy-driven CO₂ plumes from the target formation. However, geological imperfections in the caprock can result in CO₂ leaks and attenuation into permeable strata (Chang et al. [1]). Therefore, the risk assessment for leakage has emerged as one of the main issues for CO₂ sequestration (Figure 1). Faults are the main naturally occurring disruptions and are prevalent in many regions suitable for CO₂ storage. Abandoned wells are the main man-made disruption to sealing layers, which may present permeable pathways for CO₂ leaks (Huerta et al. [2]).

If injected CO₂ encounters a fault, the fault zone properties, especially permeability, plays a significant role in determining the preferential flow of CO₂ plumes. CO₂ plume behaviors include bypassing (high-permeable conduits) or compartmentalization (low-permeable barriers) (Pasala et al. [3]). Large injection rate and pressure will increase overall reservoir pressure, which can induce irreversible mechanical stresses and formation deformation including fracturing or reactivating existing faults. Such a change of stress field could open new pathways for flow units through the impermeable caprock (Rutqvist et al. [4]). A conductive fault can be a main pathway for CO₂ leaks due to its large transfer capacity.

The simulation models presented here were developed to analyze the effect of faults on CO₂ by evaluating geometric (slope and angle) and/or petrophysical properties mainly associated with a fault. In addition, our works evaluate the effect of anisotropy of reservoir permeability and residual saturation (trapping). Many CO₂ sequestration studies have studied the impact of these two factors, but little attention has been paid to how their interaction with a fault affects the dynamics of CO₂ plumes. Therefore, in this simulation study we explore 1) how a fault affects the buoyancy-driven CO₂ migration, and 2) how the permanent capture of CO₂ takes an advantage from residual trapping mechanism in the faulted reservoir.

2. Modeling Approach

2.1. Assumptions.

Throughout our simulation works, we assume the situation of interest is an idealized end-of-injection state. In this state, the storage volume is completely saturated with CO₂, with brine occupying space above and beside the stored CO₂. From this state, buoyancy drives the CO₂ to migrate through preferential pathways (Bryant et al. [5]). All reservoir boundaries are assumed as perfectly closed so that the top and side boundaries can be presumed seals for CO₂ capture.

The whole structure in our model is based on 2D or 3D Cartesian grid system. We treat the fault as a multi-dimensional conduit or barrier using spatially varying transmissibility multipliers on each contact side of grids (Manzocchi et al. [6]). Thus the complexities of the fault core and the damage zone surrounding it are averaged into a single array of transmissibility multiplier values. This simplification is extreme but it is consistent with concepts such as the shale gouge ratio (Yielding et al. [7]). The series of transmissibility multiplier in the fault model can represent petrophysical properties of a fault, such as conductive (high-permeable), sealing (low-permeable) or other heterogeneous figures such as leakage spot or reactivated zone.

The model is based on multi-phase flows of two fluids (carbon dioxide phase and aqueous phase). The interaction between two fluids will result in cocurrent or countercurrent flow during CO₂ migration. Phase transitions can have a significant impact on CO₂ plume behaviors (Pruess et al. [8]). For our model, however, the top-seal of reservoir is located 5300ft (1600m) below the surface where CO₂ can remain as a single phase so that we can assume simplified phase behavior as well as constant physical properties (especially, density and viscosity) throughout our model.

2.2. Overview & Descriptions.

As summarized in Table 1, the base case 2D model contains no fault and consists of a relatively short, wide domain, of dimensions 400ft(W)×100ft(H)×2ft(L), 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 2ft×2ft×2ft. The aquifer was tilted at a dip angle of five degrees. 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 (Ozah et al. [9]). As shown in Figure 2, initially CO₂ is placed at high saturation ($S_g = 1.0$) 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)). We use the GEM-CMG simulator (Nghiem et al. [10]), tuned to the CO₂/brine/rock system in previous work (Kumar et al. [11]; Ozah et al. [9]).

The CO₂ migration in a faulted reservoir was simulated by imposing the petrophysical and geometric properties associated with fault characteristics. The set of grid blocks corresponding to the desired spatial location of the fault were assigned these properties. Smaller grid blocks (local refinement of the coarse grid) were used to simulate more realistically the angled geologic discontinuity.

2.3. Applications.

The main purpose of our simulation study is to analyze (1) how the presence of a fault will affect CO₂ plume behaviors and (2) how trapping efficiency can be improved or lessened by fault properties interacting with reservoir properties such as permeability anisotropy and rock-fluid relation. We categorize fault properties by two types of geometry (declined or negative slope to the bedding plane and inclined, or positive slope to the bedding plane) and two types of conductivity (high permeability or conductive fault and low permeability or sealing fault). The type of conductivity is controlled by setting transmissibility multipliers (value $\gg 1$ for conductive, value=0 for sealing).

To investigate residual saturation trapping, we create a synthetic relative permeability curve with residual gas saturation $S_{gr} = 0.2$ as shown in Figure 3. In addition, we vary the ratio of vertical and horizontal permeabilities of the reservoir in order to analyze how permeability anisotropy will determine the efficiency of residual saturation trapping.

3. Results and Analysis

3.1. Effect of Reservoir Property.

Here we take the whole domain to be homogeneous and tilted. The only variable is vertical to horizontal permeability ratio (k_v/k_h) and three values are considered, 0.01, 0.1 and 1. The last case represents isotropic condition ($k_v/k_h=1$). As seen in Fig. 4, this case shows predominantly vertical movement of CO₂ in spite of the dip. The CO₂ plume reaches the top seal and spreads out along the top boundary of the aquifer before approaching the side boundary. As the value of k_v/k_h becomes smaller, the direction of CO₂ migration becomes more aligned with the dip angle. Accordingly, the lower k_v/k_h values are more efficient for storage of CO₂ gas.

The presumed residual gas saturation ($S_{gr} = 0.2$) results in trapping CO₂ permanently before the plume reaches the impermeable top seal, which is referred to “residual CO₂ trapping” (Obdam et al. [12]). 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.

3.2. Effect of Fault.

The presence of a fault has a remarkable impact on the behavior of buoyancy-driven CO₂ plumes. The existence of a fault plays a significant role in controlling the CO₂ behavior depending on its geometric and petrophysical properties. The simulation results for distinct cases are categorized as follows:

3.2.1. Sealing & Declined or Inclined Fault

The sealing fault combined with the pre-existing boundaries of an aquifer such as the top seal and side boundaries forms a CO₂-trap-zone, Figure 5. Furthermore, the most remarkable phenomenon is the accumulation of CO₂ before the upward CO₂ migration along the sealing fault. The CO₂ build-up along the fault induces CO₂ phase to reach end-point gas saturation, which implies that residual saturation trapping can be maximized according to Land’s model (Kumar [11]). The phase flux vectors indicate countercurrent flow of the phases inside the CO₂ plume. This results in sufficient CO₂ accumulation to maximize residual saturation. We note that in principle the

countercurrent flow should disqualify application of the Buckley-Leverett theory, yet it provides a very good estimate of the saturation at the leading edge of the plume.

3.2.2. Conductive & Declined Fault

In this case, one might expect CO₂ simply to rise along the fault once the plume reaches the fault. This expectation was only partially fulfilled because the reservoir properties (anisotropy and dipping) dominated the influence of the fault's geometry (Figure 6). The CO₂ does rise along the conductive fault but it does so within the permeable rock on the updip side of the fault. The rise reaches a limiting height and from this virtual source the CO₂ plume propagates along the bedding plane updip of the fault. By increasing the thickness of the CO₂ this phenomenon enhances residual gas trapping efficiency. As a result, a conductive fault can be a critical factor for better CO₂ trapping if it is suitably oriented with respect to the dip angle, as discussed next.

3.2.3. Conductive & Inclined Fault

In this case, CO₂ flows dominantly through the conductive fault, and accumulates at the top seal of the aquifer, Figure 7. This behavior, which can be regarded as "CO₂ leakage," is exactly what we expected in the case of a conductive fault. However, the conductive fault zone creates a virtual source of CO₂ along the fault allowing attenuation of the leaking CO₂ into the updip permeable beds. Significant residual saturation get trapped in these beds. Thus, more CO₂ trapping occurred as the effective contact area for migration was expanded. This reduces the flux on the leakage path along the fault and then along the top seal.

3.3. 3D Fault Model

The above 2D fault models presumed that whole CO₂ plumes would be controlled by the fault. However, faults need not extend uniformly in the plane of the fault, which means that CO₂ plumes could experience faulted and unfaulted conditions simultaneously. As shown in Fig. 8, after encountering the fault, a CO₂ plume breaks into two portions: fault-influenced and normal plumes. The fault-influenced CO₂ plume builds up CO₂ saturation along the sealing fault to end-point gas saturation. The rest of the plume continues its updip migration. The CO₂ accumulation along the sealing fault creates another virtual source for CO₂ propagation parallel to the bedding plane through the upper region, which increases CO₂ contact with brine phase and rock. Therefore, we can increase CO₂ trapping by enhancing structural and residual saturation trapping efficiency due to the presence of a fault.

4. Conclusion

This simulation study reveals that buoyancy-driven CO₂ flows are affected by fault types (sealing and conductive, inclined and declined). A sealing fault (low-permeability) blocks further CO₂ migration and acts as another impermeable boundary for structural CO₂ trapping. CO₂ accumulates along the fault first, and then moves toward the top surface of the aquifer. The remarkable phenomenon is that the CO₂ build-up maximizes the efficiency of residual saturation trapping in accordance with Land's model of hysteresis. On the other hand, a conductive (high-permeable) fault acts as another permeable pathway for CO₂ migration. The behavior of CO₂ plume depends on the fault's geometry. In the case of a declined fault, CO₂ crosses the fault zone and accumulates along the other side of the fault until the CO₂ source depletes. Simultaneously, some CO₂ moves upward along the fault, thereby enlarging the area of updip permeable formation into which CO₂ migrates. In the case of an inclined fault, CO₂ rapidly reaches the top seal by migrating up the fault, then travel along the top seal. The upward migration along the fault creates another virtual source along the fault for migration updip into the adjacent permeable formation. This increases the CO₂ contact area and thus the extent of residual phase and dissolution trapping. Thus in some cases the risk associated with a conductive fault may be reduced, if the formations into which CO₂ migrates do not contain vulnerable assets (fresh water, hydrocarbons, minerals, etc.)

5. Acknowledgement

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Table 1. Description for simulation model properties, geometry and petrophysical properties of the reservoir

<i>General Property of Whole Reservoir</i>		<i>Petrophysical Property</i>	
Width (ft) x Height (ft)	400 x100	Permeability (md)	1
Depth (ft)	5300	Permeability ratio (k_h/k_v)	1 to 100
Temperature (°F)	140	Porosity	0.15
Salinity (ppm)	100,000	Transmissibility for Fault (Using Transmissibility Multiplier)	0 to 1000
Initial pressure (psi)	2295		
Dip (degree)	5	Transmissibility ratio (Anisotropy within Fault)	1

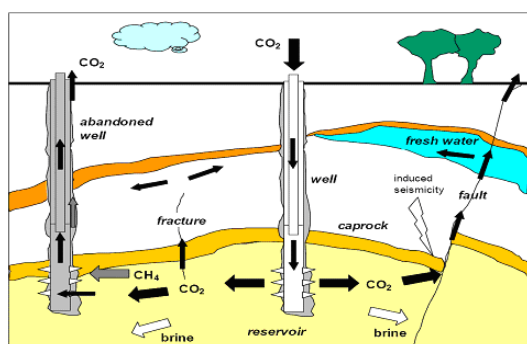


Fig 1. Underground CO₂ leakage risk; Black arrows represent CO₂ migration while white arrows indicate brine displacement due to CO₂ injection.

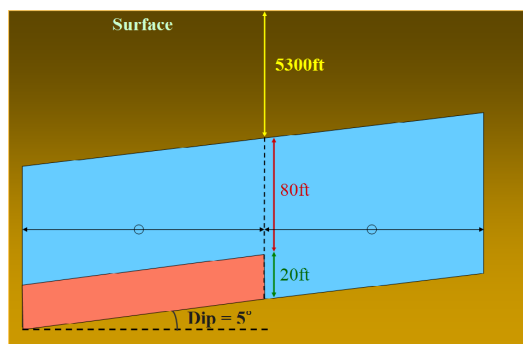


Fig 2. Schematic illustration for 2D base case model; the red portion represents CO₂-saturated zone while the blue part is occupied by brine phase.

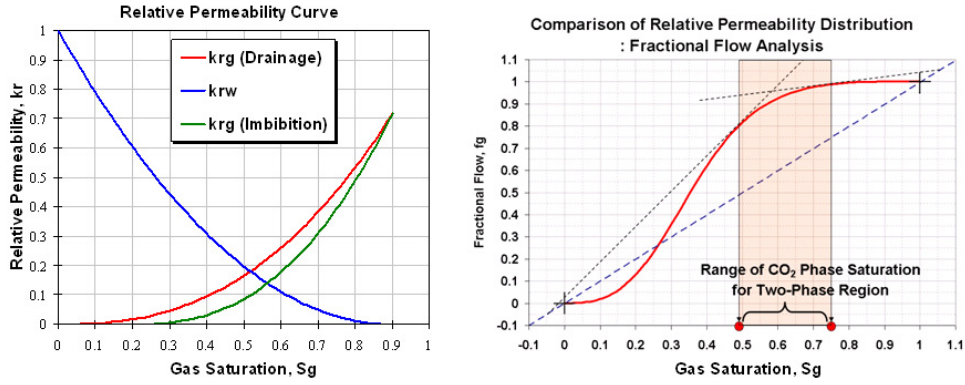


Fig 3. (a) Artificial relative permeability curve including hysteresis; here, we have residual gas saturation ($S_{gr} = 0.2$), which applies to grid blocks in which the CO₂ saturation approaches the end-point saturation ($S_{gr} = 0.9$); (b) Fractional flow curve for drainage curve accounting for mutual solubility, two phases (CO₂ and brine) can exist at the CO₂ phase saturation range of 0.49 (k_r of CO₂ = 0.16) to 0.74 (k_r of CO₂ = 0.43)

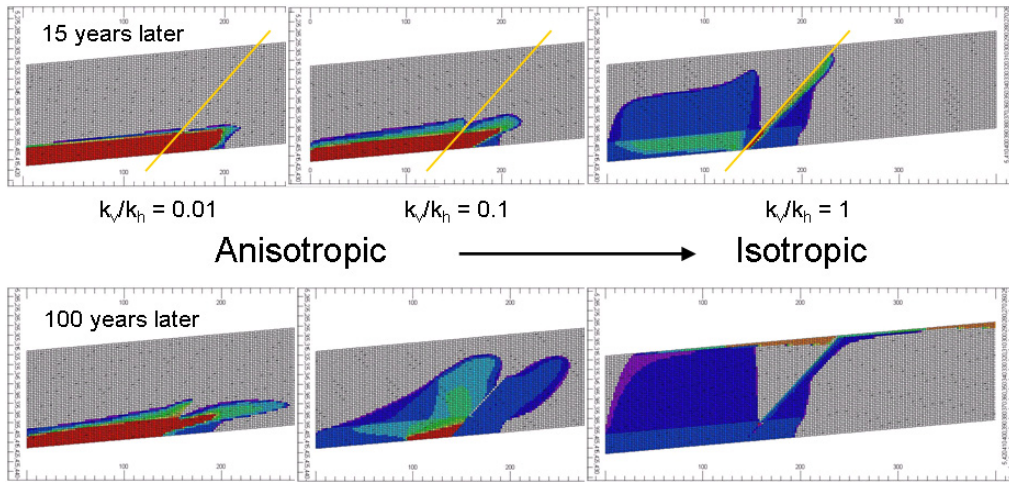


Fig 4. The comparison of CO₂ plume behaviors from anisotropy and isotropy of reservoir permeabilities with residual gas saturation ($S_{gr} = 0.2$); as permeability anisotropy is larger, the preferential flow of CO₂ tends to be more parallel to the bedding plane. Thus, more anisotropy will allow less probability that CO₂ can approach the surface or underground water zone.

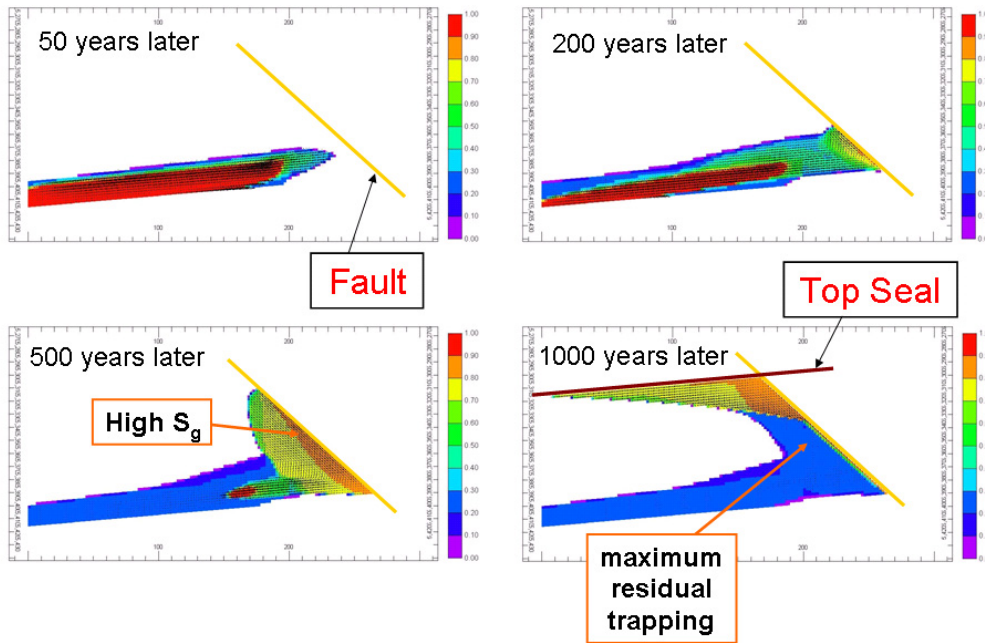


Fig 5. Declined and sealing fault's effect on CO₂ plume behaviour; The fault can act as another seal boundary for CO₂ trapping. By redirecting the plume movement (from updip to along the fault), the fault also causes CO₂ to build up to end-point phase saturation along the fault. This maximizes residual saturation trapping.

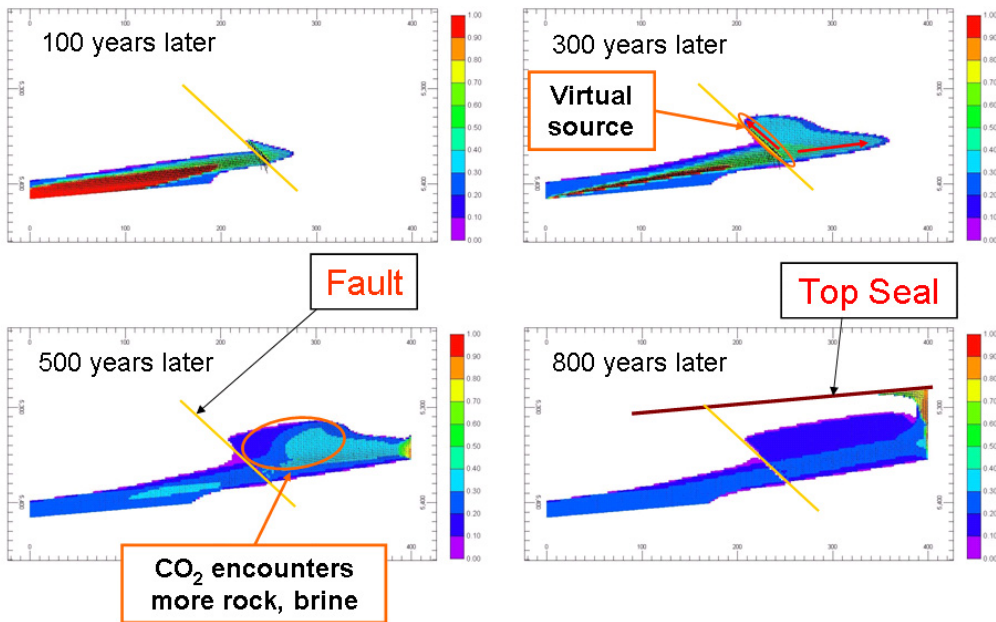


Fig 6. Declined and conductive fault's effect on CO₂ plume behavior. Before approaching the fault, CO₂ plume shows the similar behavior with other cases. After encountering the fault, CO₂ plume has two kinds of behaviors: along the fault and across the fault. The main migration is parallel to the bedding plane since anisotropy and dipping of the reservoir determine the preferential flow of CO₂ phase. The migration of CO₂ upward along the conductive fault creates a virtual source, from which CO₂ migrates updip into permeable strata. This increases the contact area of the CO₂ plume with the reservoir resulting in more residual saturation trapping.

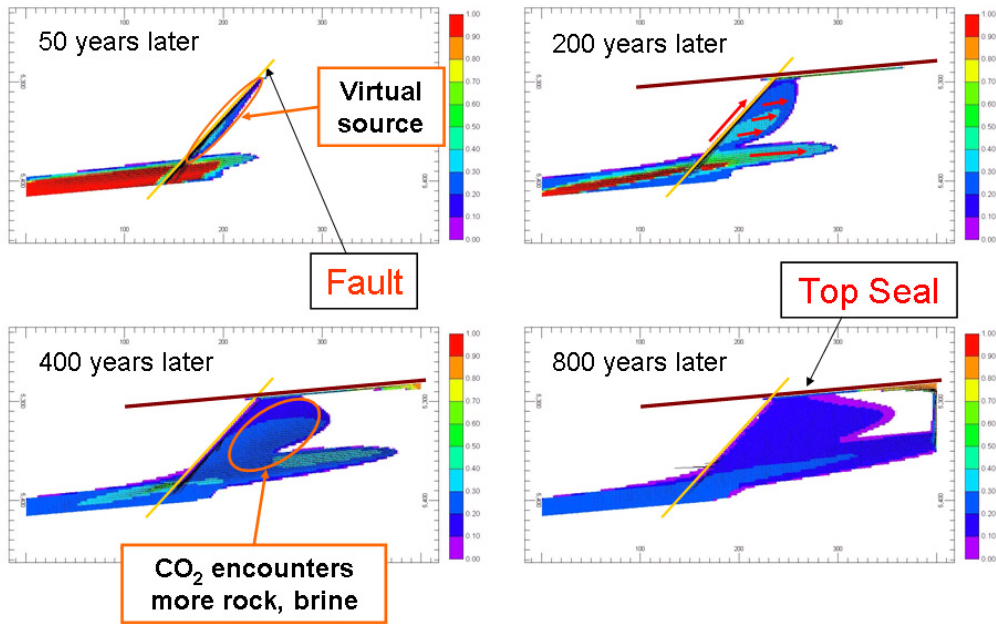


Fig 7. Inclined and conductive fault's effect on CO₂ plume behavior. Large amount of CO₂ leaks into the fault then below the top seal. However, the fault also creates a virtual source for updip migration into the permeable bed. This attenuates the leakage and results in significant additional residual saturation trapping.

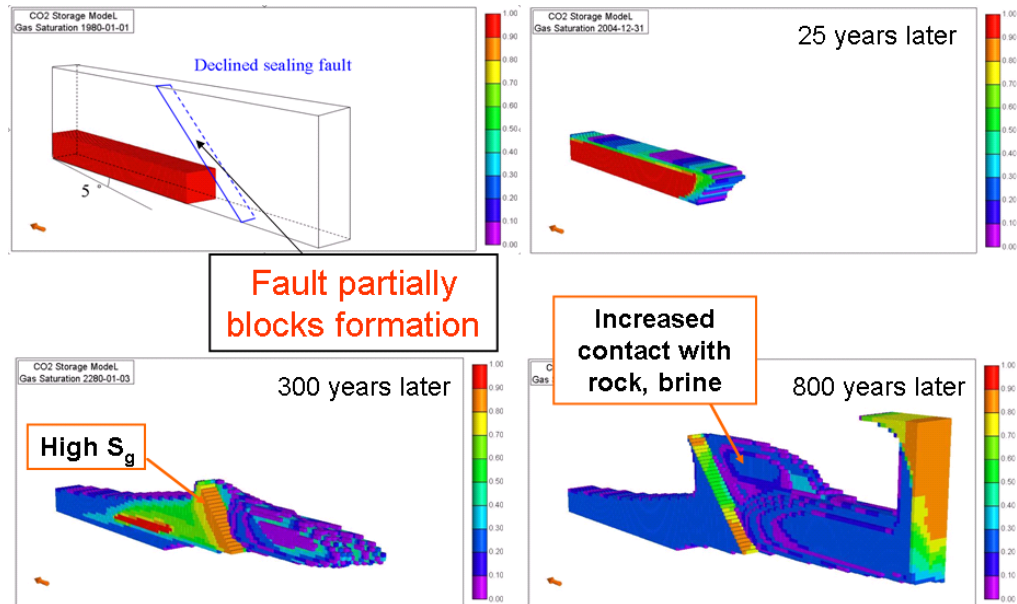


Fig 8. 3D results for the effect of declined and sealing fault in the complicated geological formation (fault seals only part of formation). At first, the stored CO₂ migrates laterally because dip and permeability anisotropy controls the plume behavior. But build-up of CO₂ saturation along the fault acts as a virtual source that greatly increases the cross-section through which CO₂ migrates updip. This increases the amount of residual saturation trapping in the formation.