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GHGT-12

## The Effect of Aquifer/Caprock Interface on Geological Storage of CO<sub>2</sub>

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### Abstract

The migration of CO<sub>2</sub> stored in deep saline aquifers depends on the morphology of the top of the aquifer. Topographical highs, such as anticlines, may trap CO<sub>2</sub> and limit the distance migrated, or elevated ridges may provide pathways enabling CO<sub>2</sub> to migrate further from the injector. For example, seismic data of the Utsira formation at the Sleipner storage site indicates that a branch of the CO<sub>2</sub> plume is moving to the north [1]. It is therefore important to study the interface between the aquifer and the caprock when assessing risk as CO<sub>2</sub> storage sites.

Undulations in the top surface of an aquifer may either be caused by sedimentary structures [2], or by folding. In addition, irregularities may be generated by faulting [2]. Large-scale features are detected using seismic data (i.e. structures with amplitudes greater than 10 m), and such structures will generally be included in reservoir or aquifer models. However, smaller-scale features could also have an effect on a CO<sub>2</sub> plume migration, and this is the topic of our study. We have conducted simulations in models with a range of top-surface morphology, and have examined the distance migrated and the amount of dissolution.

The results from this study suggest that the effects of sub-seismic variations in the topography of the aquifer/caprock interface are unlikely to have a significant impact on the migration and dissolution of CO<sub>2</sub> in a saline aquifer, compared with tilt or permeability anisotropy. The results were most sensitive to the  $k_v/k_h$  ratio during the injection period.

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**Keywords:** CO<sub>2</sub> storage; interface between caprock and storage formation

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## 1. Introduction

Carbon Capture and Storage (CCS) is one of several possible options for the reduction of CO<sub>2</sub> emissions to the atmosphere and it has the possibility to allow a huge decrease in CO<sub>2</sub> emissions arising from large point sources of CO<sub>2</sub> emissions [3].

Often simulations assume a distinct and smoothly undulating boundary between the aquifer and the caprock [4]. However studies of outcrops show that a variety of types of interface may arise in nature, depending on the depositional setting. For example, [5] have shown that there may be a gradual transition from sand-rich facies in the aquifer to mud-rich facies in the caprock. [2] have investigated the impact of top-seal morphology on CO<sub>2</sub> storage capacity and migration patterns, and concluded that it is important to model geological details in order to predict CO<sub>2</sub> migration. Therefore, when appraising any reservoir or aquifer for CO<sub>2</sub> storage, it is important to characterise the interface and to ensure that it is modelled adequately.

In this study the interface between caprock and storage formation is examined.

## 2. Model Specifications

This section describes a systematic study of the effect of parallel and perpendicular ridges to determine their effect on up-dip and lateral CO<sub>2</sub> migration. A set of numerical simulations was conducted to investigate the impacts of the transition zone, top morphology, tilt and  $k_V/k_H$  on the CO<sub>2</sub> storage. For this reason two types of models were created. The first type was created to study the impact of aquifer/caprock morphology. The second type was created to study the impact of transition zone (referred to as “*trans*”). In the former two main scenarios were considered. In the first one, ridges are perpendicular to the tilt (“*perp*” models). In the second one ridges are parallel to the tilt (it is called “*para*”).

Equation (1) was used to make top surfaces for the ridges. A simple model was chosen for the top surface, so that the properties could be studied methodically.

$$Z = Z_0 + A \left( \sin \left( \frac{2\pi x}{\lambda} \right) \right) + x(\tan \theta) \quad (1)$$

where,

$A$  refers to amplitude of the ridges (m)

$x$  denotes distance along the X (horizontal) direction (m)

$\lambda$  refers to wavelength which is 1000m here

$\theta$  refers to tilt angle.

As depicted in Fig. 1 the sizes of all the models are  $8 \text{ km} \times 8 \text{ km} \times 100 \text{ m}$ . One injector was placed on the left hand side of model and  $\text{CO}_2$  was injected through perforations at the bottom of the aquifer (bottom 50 layers). The models represented part of a larger aquifer, and the pore volume of the outer column of cells on the opposite side of where injector was placed, was multiplied by a factor of  $10\text{E}+9$ , to take account of this.

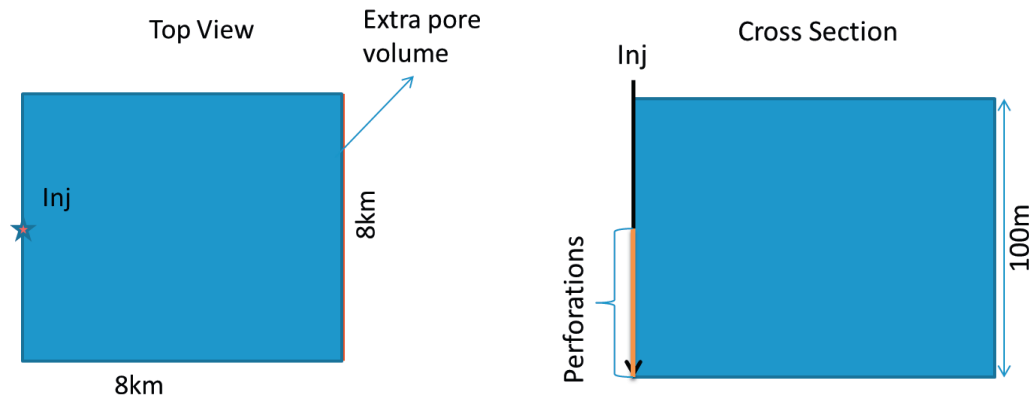


Fig.1. Schematic top view (left picture) and cross section (right picture) of model. The injector is placed at the edge of models on the left side.

Table 1 shows all the scenarios (144 models) that were used in this study. All models have the same dimensions and the same grid cell sizes ( $100 \text{ m} \times 100 \text{ m} \times 1 \text{ m}$ ). In all the models, the sandstone was homogeneous with constant porosity (0.2) and constant permeability (500 mD) and the shale (or mudstone) layers in the *trans* models were impermeable. The datum depth was set to 1500 m to ensure that none of the tilted models rose above 800 m, in order to keep injected  $\text{CO}_2$  in the supercritical phase.

Table 1: Model Specifications

<i>Perp/Para/Trans</i>	Amplitude (m)	Angle ( $\theta$ )	$k_V/k_H$
	0	0	0.01
	3	1	0.1
	6	2	1
	9	5	

It should be noted that amplitude in the *trans* models refers to the half of thickness of the transition zone. Sequential Gaussian simulation was used to generate the facies distribution and the permeability and porosity were correlated with that.

The CO<sub>2</sub> injection rate was chosen to be half of the CO<sub>2</sub> emissions of a 500 MW coal-fired power plant which is around 2 million tons of CO<sub>2</sub> per year. The well was controlled by surface rate with a maximum pressure limit of 220 bars. However, in all models studied here the same amount of CO<sub>2</sub> was injected into the models, as the pressure did not reach the maximum bottom-hole pressure. The injector was shut in after 6 years and the simulation was continued for 100 years. (This injection period is shorter than a typical project to limit the time simulation time.)

The models are described by four parameters:

The first part is the type of the model, which could be *para*, *perp* or *trans*.

The second one is the amplitude (A).

The third one is the tilt (D).

The forth one is  $k_V/k_H$  ratio (K).

For instance, Model Perp-A9-D5-K001 refers to a simulation with perpendicular ridges, amplitude of 9 m, a tilt of 5 degrees and a  $k_V/k_H$  ratio of 0.01. Fig. 2 shows the top morphology of models with amplitudes equal to 9 metres and different tilts (0-5, degrees).

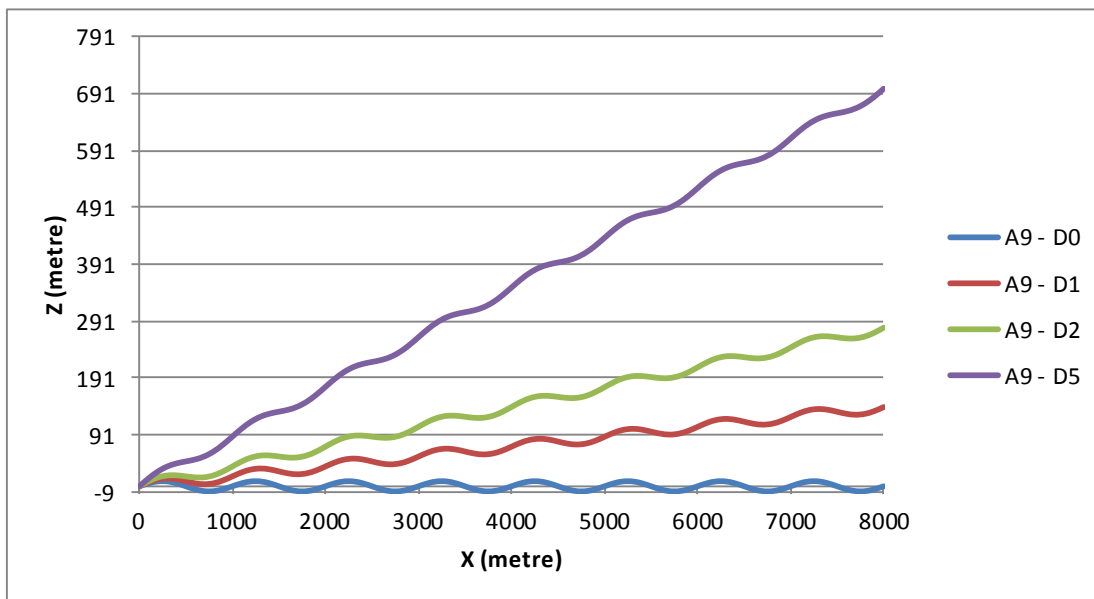


Fig.2. Top morphology of perp models with amplitudes equal to 9 metres and different tilts (D0-D5).

### 3. Results

#### 3.1. Para Models, Injection Period

Fig. 3 demonstrates the relation between the amounts of dissolved CO<sub>2</sub> (in percentage) at the end of injection period with  $k_V/k_H$  ratio, amplitude and tilt. It is very clear that the results are more sensitive to the  $k_V/k_H$  ratio than the other parameters.

The lower the  $k_V/k_H$  ratio the higher the amount of dissolved CO<sub>2</sub>. This is because the low permeability is preventing the rise of CO<sub>2</sub> therefore more CO<sub>2</sub> spreads laterally during the injection. Thus, more free CO<sub>2</sub> phase is in contact with fresh brine resulting in more CO<sub>2</sub> dissolution in the model with lower  $k_V/k_H$  ratio.

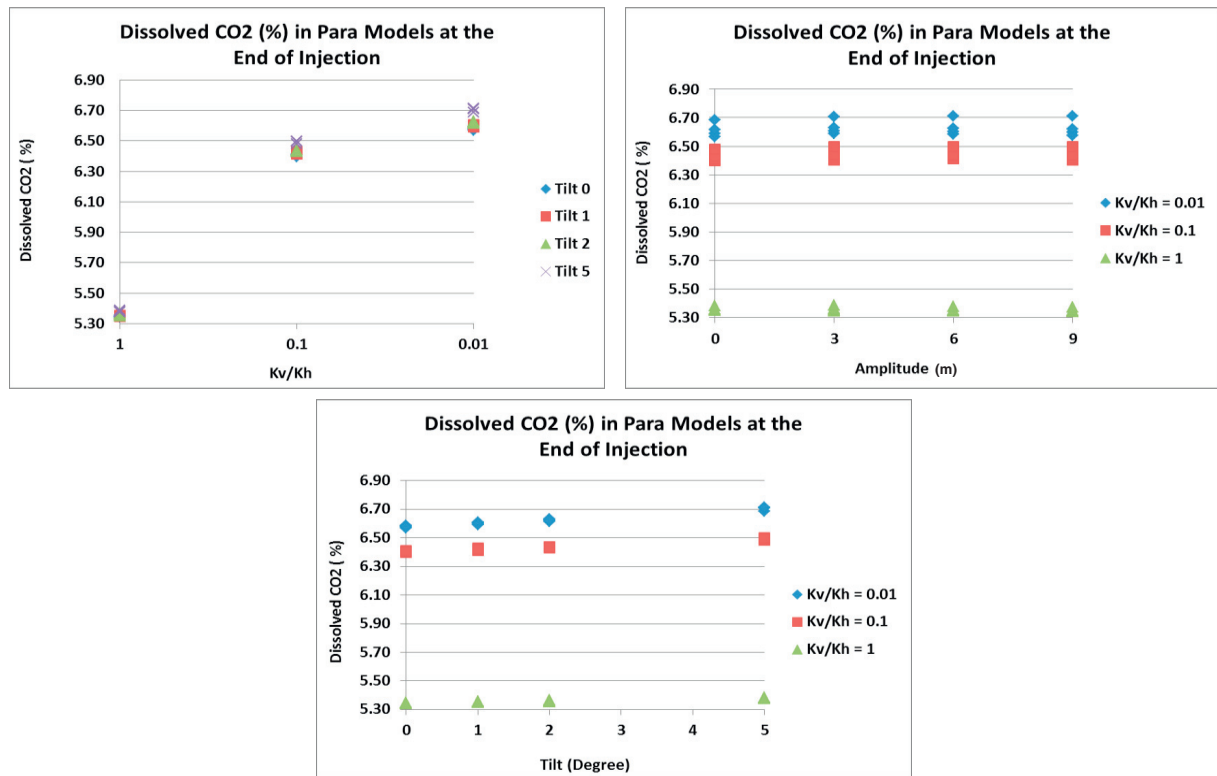


Fig.3. The amount of dissolved CO<sub>2</sub> in the *para* models at the end of injection comparing:  $k_V/k_H$  ratio and tilt (top right), amplitude and  $k_V/k_H$  ratio (top right), tilt and  $k_V/k_H$  ratio (bottom).

### 3.2. Para Models, Post Injection Period

Fig. 4 shows percentage of injected gas which exists as dissolved gas in all *para* models with respect to tilt,  $k_V/k_H$  ratio and amplitude 100 years post injection. During this period the amount of dissolved CO<sub>2</sub> is sensitive to the tilt and  $k_V/k_H$  ratio whereas the effect of amplitude is negligible. The effect of tilt is more important as the higher the tilt the more CO<sub>2</sub> migrates up-dip and therefore more CO<sub>2</sub> is in contact with fresh brine resulting in more CO<sub>2</sub> dissolved in models with higher tilt. From 0 to 2 degrees tilt approximately 1% more CO<sub>2</sub> is dissolved per 1 degree tilt. However, this change is more than 1% when tilt is increased to 5 degree.

The higher the tilt angle the more segregation between results of models with high and intermediate  $k_V/k_H$  ratio. If the models are flat, most CO<sub>2</sub> is dissolved in the models with the intermediate  $k_V/k_H$  ratio, next the models with lowest  $k_V/k_H$  ratio and the least CO<sub>2</sub> is dissolved in the isotropic models ( $k_V/k_H=1$ ). By increasing the tilt angle to 5 degrees, more CO<sub>2</sub> is dissolved in the isotropic models. This is because greater CO<sub>2</sub> migrates upwards resulting in more CO<sub>2</sub> in contact with fresh brine. Results show that despite increasing the amplitude from 0 to 9 m, approximately the same amount of CO<sub>2</sub> is dissolved 100 years post injection period in all models. This is due to the fact that when the CO<sub>2</sub> reaches the top sand layer, it starts to fill and migrate along the closest ridge. If the thickness of the plume is more than the amplitude, CO<sub>2</sub> moves laterally to the next ridges and fills them while migrating parallel to them. Therefore there is no obstacle to prevent CO<sub>2</sub> migration. Therefore amplitude does not have a significant effect on the amount of CO<sub>2</sub> dissolution in the *para* models.

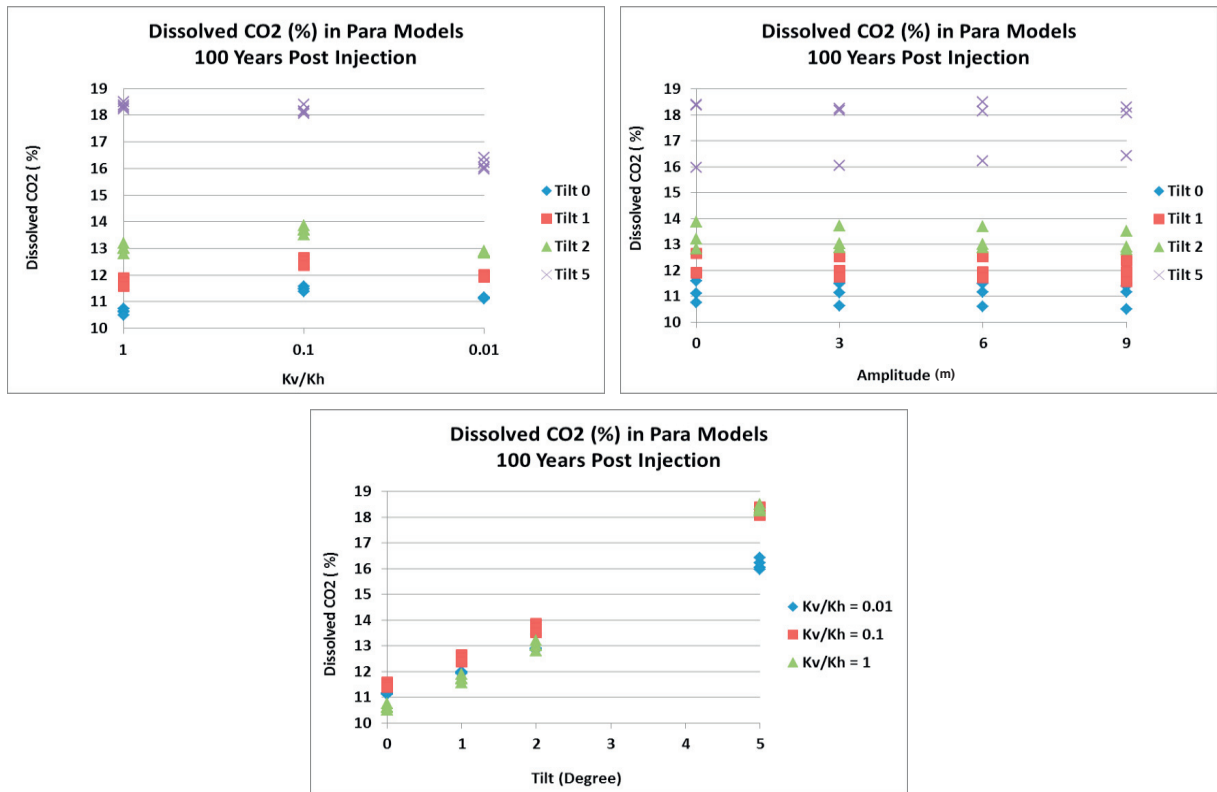


Fig. 4. The amount of dissolved CO<sub>2</sub> in the *para* models 100 years post injection comparing:  $k_v/k_h$  ratio and tilt (top left), amplitude and  $k_v/k_h$  ratio (top right), tilt and  $k_v/k_h$  ratio (bottom).

### 3.3. *Perp* Models

Results show that the effect of the  $k_v/k_h$  ratio and tilt on the amount of CO<sub>2</sub> dissolution during the injection period and 100 years post injection in *perp* models is the same as for the *para* models. However, amplitude has a slight effect on the amount of CO<sub>2</sub> dissolution in *perp* models whereas this was negligible in *para* models. This is because of the structural trapping that occurs in *perp* models. The bigger the amplitude, the more CO<sub>2</sub> is trapped structurally, and therefore less CO<sub>2</sub> migrates along the tilt direction, resulting in less CO<sub>2</sub> dissolution.



#### 4. Plume migration in trans models

Three models were chosen to investigate plume migration in the *trans* models with respect to tilt and  $k_V/k_H$  ratio. Fig. 5 shows plume migration in the three *trans* models (Trans-A6-D5-K1, Trans-A6-D1-K1, Trans-A6-D1-K001) 100 years after post injection period. The pictures on the left demonstrate the CO<sub>2</sub> plume in the top-most layer and pictures in right show the length and the width of migrated CO<sub>2</sub> through different layers.

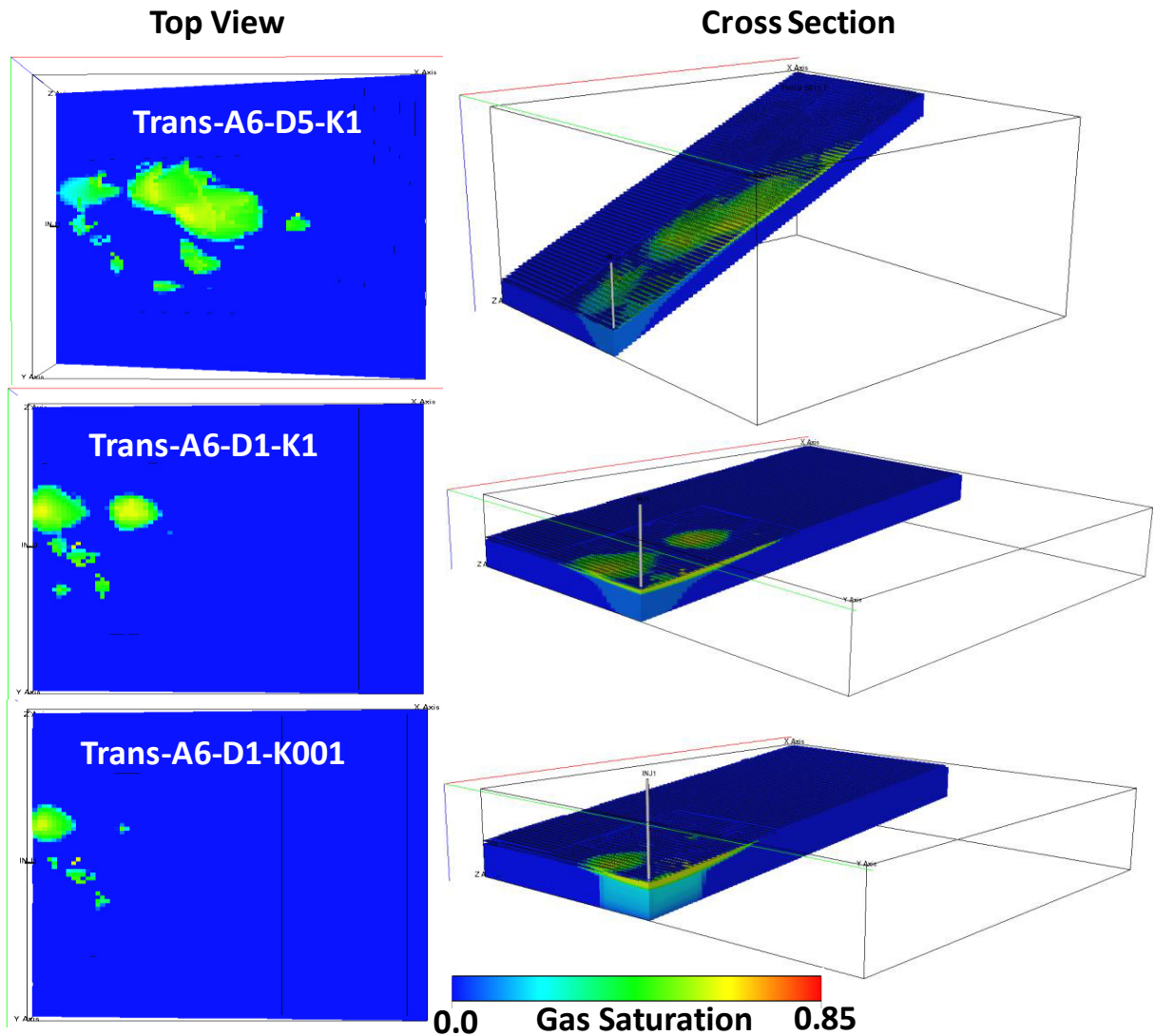


Fig. 5. Gas saturation 100 years post injection period in three *trans* models. All three models are tilted and have the same amplitude. However, top one and middle one have the same  $k_V/k_H$  ratio but the former one has 5 degrees inclination and the later one 1 degree. The bottom one which also is tilted (1 degree) however has a low  $k_V/k_H$  ratio (0.01). More CO<sub>2</sub> reaches the top layer due to higher tilt angle and higher  $k_V/k_H$  ratio (top picture) whereas the least upwards migration happened in the model with lower tilt angle and lower  $k_V/k_H$  ratio (bottom picture).

Fig. 5 shows that more CO<sub>2</sub> can reach the top of the storage formation by increasing tilt and  $k_V/k_H$  ratio. The plume at the top of the aquifer will have a patchy form depending on the permeability distribution. In addition, it can be concluded that the length of the plume is sensitive to the tilt and then  $k_V/k_H$  ratio. By increasing these two factors more CO<sub>2</sub> migrates up-dip resulting in the plume having a smaller width. On the other hand, more CO<sub>2</sub> spreads out laterally at the lower tilt angle and higher  $k_V/k_H$  ratio (Trans-A6-D1-K1). In the model with the small tilt and low  $k_V/k_H$  ratio (Trans-A6-D1-K001) more CO<sub>2</sub> accumulates above the injector and gives the highest thickness of the CO<sub>2</sub> plume amongst these models. Therefore less CO<sub>2</sub> migrates resulting in having the smallest length.

## 5. Discussion on numerical simulation results

The results of all 144 models are discussed in this section.

### 5.1. The effect of top morphology and transition zone on the amount of CO<sub>2</sub> dissolved

The amount of CO<sub>2</sub> dissolved at the end of the injection period and 100 years post injection period in all *trans*, *para* and *perp* models was chosen to investigate the effect of the amplitude of the ridges (thickness of transition zone in *trans* models), tilt and  $k_V/k_H$  ratio. Fig. 6 and Fig. 7 demonstrate amount of dissolved CO<sub>2</sub> in percentage at the end of injection and 100 years post injection with  $k_V/k_H$  ratio (Z axis), tilt (X axis), and amplitude (Y axis) for *trans* models (top values), *para* models (middle values) and *perp* models (bottom values) respectively.

### 5.2. End of Injection

Results show that the most sensitive parameter at the end of the injection period is  $k_V/k_H$  ratio (Fig. 6).

The lower the  $k_V/k_H$  ratio the more CO<sub>2</sub> is dissolved. This is due the fact that more CO<sub>2</sub> spreads out when the  $k_V/k_H$  ratio is low therefore more CO<sub>2</sub> will be in contact with fresh brine resulting in more CO<sub>2</sub> dissolution (Fig. 6). In other words, in models with high  $k_V/k_H$  ratio the effect of viscous force on the lateral migration is less than the model with low  $k_V/k_H$  ratio.

### 5.3. 100 Years Post Injection Period

Results show that the most sensitive parameter is tilt (Fig. 7). As the tilt increases from the left hand side of graph to the right side of the graph from 0 to 5 degrees more CO<sub>2</sub> dissolved in the models regardless the amplitude of the model.

The second most sensitive parameter is  $k_V/k_H$  ratio. The gas migration during post injection period is governed by buoyancy therefore the higher the  $k_V/k_H$  ratio the more CO<sub>2</sub> migrated upwards. Thus more CO<sub>2</sub> is in contact with fresh brine therefore more CO<sub>2</sub> is dissolved in brine (Fig. 7).

The effect of amplitude is not significant in *para* models due the fact that there is no obstacle for CO<sub>2</sub> migration.

However, in *perp* models by increasing the amplitude, especially for the high  $k_V/k_H$  and high tilt models, the amount of dissolved  $\text{CO}_2$  falls (Fig. 7).

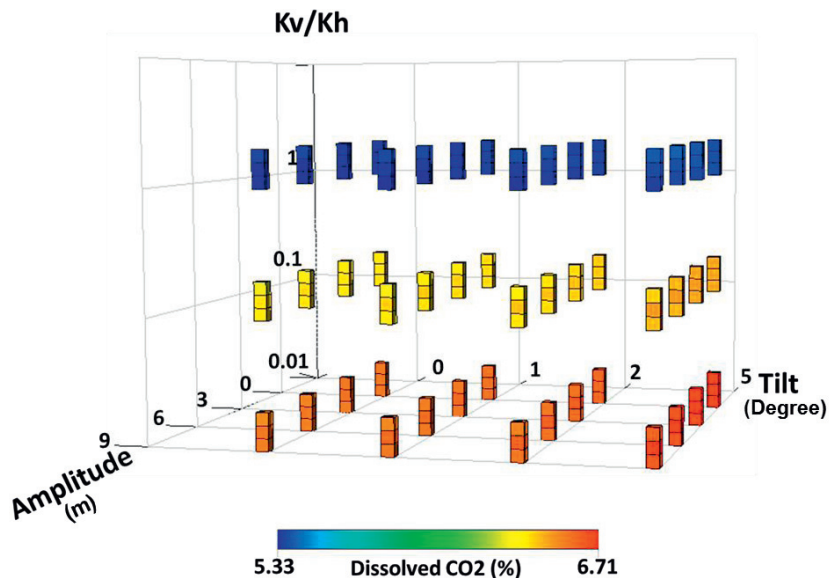


Fig. 6. Dissolved  $\text{CO}_2$  at the end of injection period for *Trans*, *para* and *perp* models. The top value at each point refers to *Trans* Model, the middle one refers to the *Para* Model and the bottom one refers to the *Perp* Model. Models with lowest  $k_V/k_H$  ratio have the highest amount of dissolved  $\text{CO}_2$  at the end of injection period.

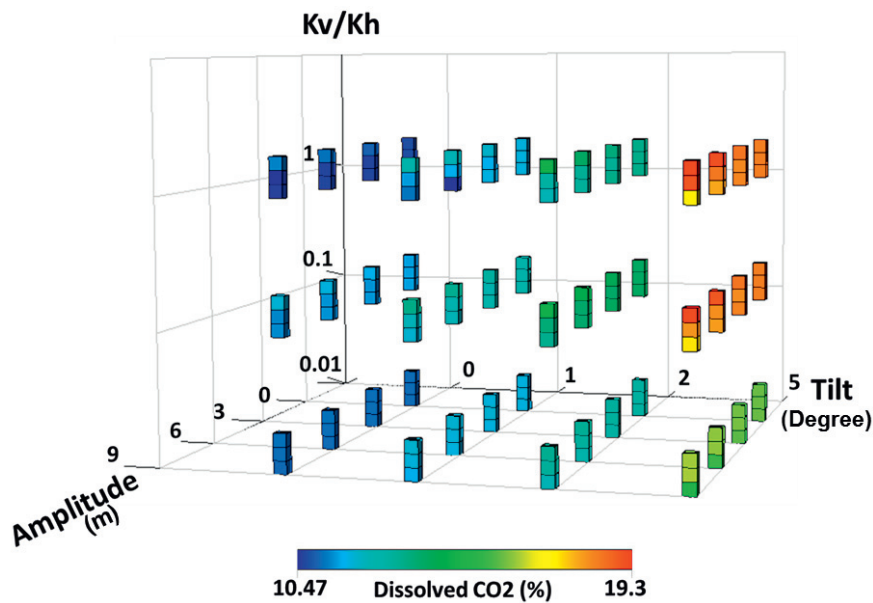


Fig. 7. Dissolved  $\text{CO}_2$  100 years post injection period for *Trans*, *para* and *perp* models. The top value at each point refers to *Trans* Model, the middle one refers to the *Para* Model and the bottom one refers to the *Perp* Model.

## 6. Conclusions

One noticeable result of this study is that during injection the effect of the  $k_V/k_H$  ratio was dominant. In other words, it was not just the caprock morphology that was affecting the results (dissolution and plume migration), it was the structure of the aquifer as a whole (The  $k_V/k_H$  ratio is used to take account of small-scale structure, which tends to be approximately horizontal). Lateral plume migration has been extensively studied [6]. However, the effect of the combination of tilt,  $k_V/k_H$  ratio, and amplitude during injection and post injection period has not previously been addressed.

In addition, the transition zone has a positive effect on the CO<sub>2</sub> storage as more CO<sub>2</sub> dissolved and the CO<sub>2</sub> vertical migration is limited too. In order to study the effect of top morphology on the CO<sub>2</sub> storage the amplitude of ridges and the orientations of ridges to the tilt was varied systematically, which has not been addressed in any work previously. Ridges with higher amplitude (bigger than plume thickness) provided more structural trapping if they were perpendicular to the tilt. However, ridges parallel to the tilt provide a pathway for rapid CO<sub>2</sub> up-dip migration. Although this may increase the risk of CO<sub>2</sub> leakage as it migrates further away from the injection point, more CO<sub>2</sub> is dissolved due to more migration.

In general, it can be concluded that the amount of CO<sub>2</sub> dissolution in saline aquifers is not strongly dependent on the direction of sub-seismic ridges at the top of aquifer or thickness of the transition zone (allowing a few percent differences). The effect of amplitude on plume migration is more important for the cases with small tilt angle than large tilt angle models.

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