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The Effect of Aquifer/Caprock Interface on Geological Storage of CO_2

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Abstract

The migration of CO_2 stored in deep saline aquifers depends on the morphology of the top of the aquifer. Topographical highs, such as anticlines, may trap CO_2 and limit the distance migrated, or elevated ridges may provide pathways enabling CO_2 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_2 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_2 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_2 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_2 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_2 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_2 emissions to the atmosphere and it has the possibility to allow a huge decrease in CO_2 emissions arising from large point sources of CO_2 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_2 storage capacity and migration patterns, and concluded that it is important to model geological details in order to predict CO_2 migration. Therefore, when appraising any reservoir or aquifer for CO_2 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_2 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_2 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 (refered 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.

$$Z = Z_0 + A(Sin(\frac{2\pi x}{\lambda})) + x(\tan\theta) \qquad (1)$$

where,

A refers to amplitude of the ridges (m)

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

λ refers to wavelength which is 1000m here

θ refers to tilt angle.

As depicted in Fig. 1 the sizes of all the models are 8 km × 8 km × 100 m. One injector was placed on the left hand side of model and 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 10E+9, to take account of this.

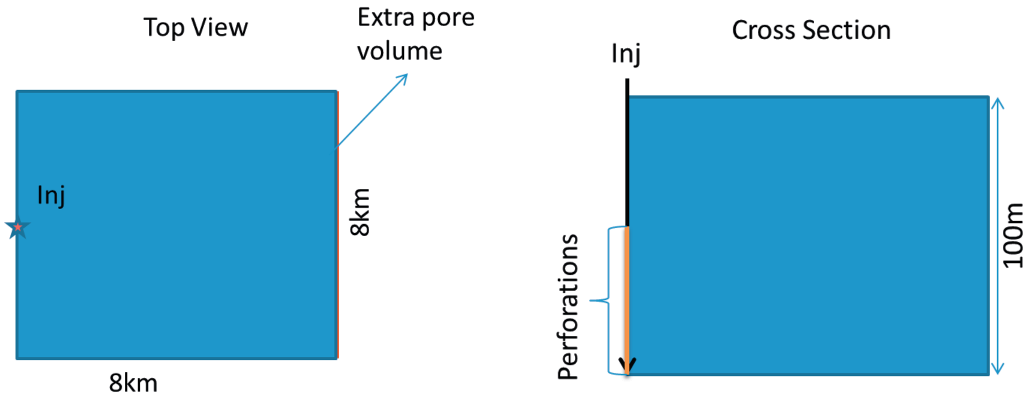

Fig.1. Schematic top view (left picture) and cross section (right picture) of model. The injector is placed at the edge of models on the left side.

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 m × 100 m × 1 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 CO_2 in the supercritical phase.

Table 1: Model Specifications

Perp/Para/Trans	Amplitude (m)	Angle (θ)	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_2 injection rate was chosen to be half of the CO_2 emissions of a 500 MW coal-fired power plant which is around 2 million tons of CO_2 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_2 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).

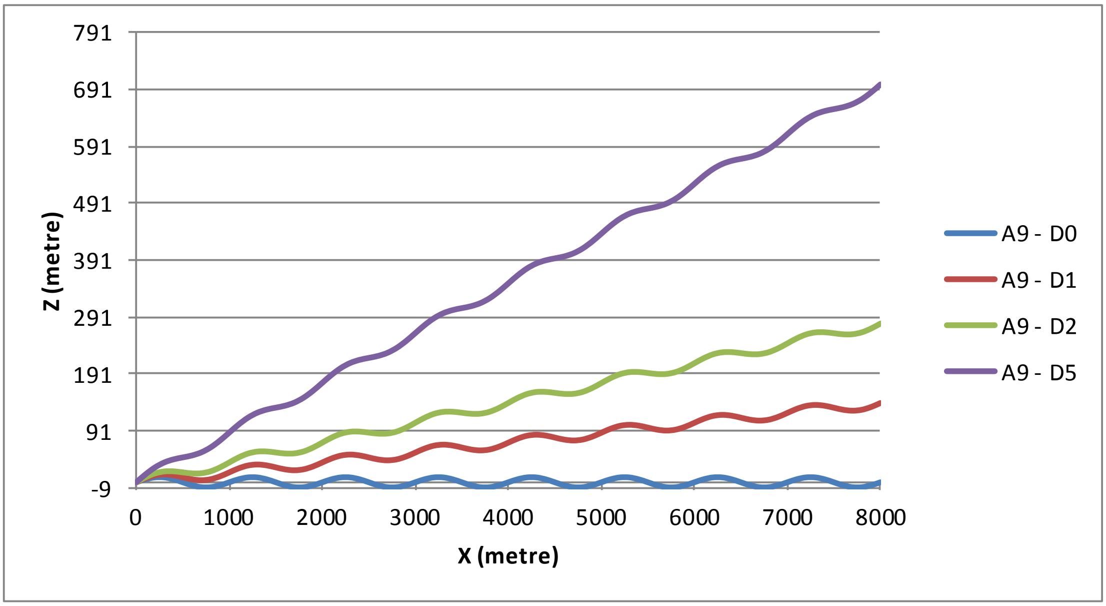

Fig.2. Top morphology of perp models with amplitudes equal to 9 metres and different tilts (D0-D5).

3. Results

3.1. Para Models, Injection Period

Fig. 3 demonstrates the relation between the amounts of dissolved CO_2 (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_2. This is because the low permeability is preventing the rise of CO_2 therefore more CO_2 spreads laterally during the injection. Thus, more free CO_2 phase is in contact with fresh brine resulting in more CO_2 dissolution in the model with lower k_V/k_H ratio.

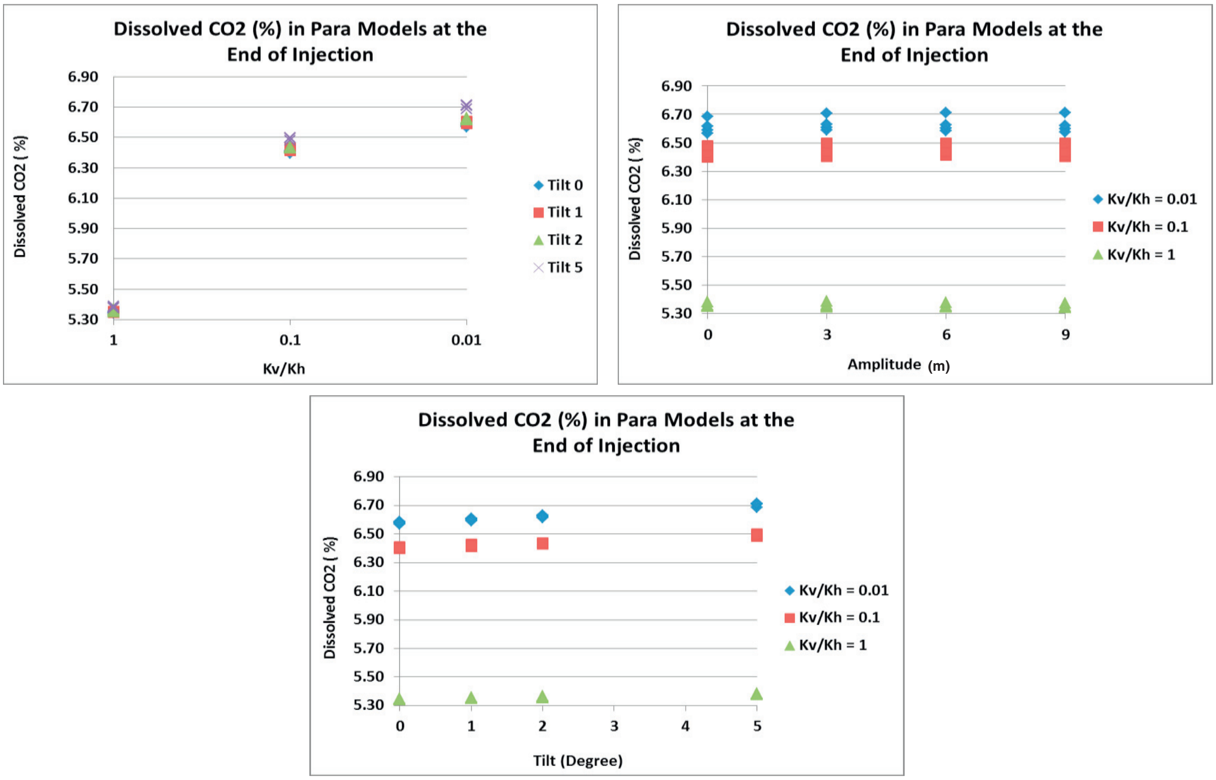

Fig.3. The amount of dissolved CO_2 in the *para* models at the end of injection comparing: k_V/k_H ratio and tilt (top right), amplitude and k_V/k_H ratio (top right), tilt and k_V/k_H ratio (bottom).

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_2 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_2 migrates up-dip and therefore more CO_2 is in contact with fresh brine resulting in more CO_2 dissolved in models with higher tilt. From 0 to 2 degrees tilt approximately 1% more CO_2 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_2 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_2 is dissolved in the isotropic models (k_V/k_H=1). By increasing the tilt angle to 5 degrees, more CO_2 is dissolved in the isotropic models. This is because greater CO_2 migrates upwards resulting in more CO_2 in contact with fresh brine. Results show that despite increasing the amplitude from 0 to 9 m, approximately the same amount of CO_2 is dissolved 100 years post injection period in all models. This is due to the fact that when the CO_2 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_2 moves laterally to the next ridges and fills them while migrating parallel to them. Therefore there is no obstacle to prevent CO_2 migration. Therefore amplitude does not have a significant effect on the amount of CO_2 dissolution in the *para* models.

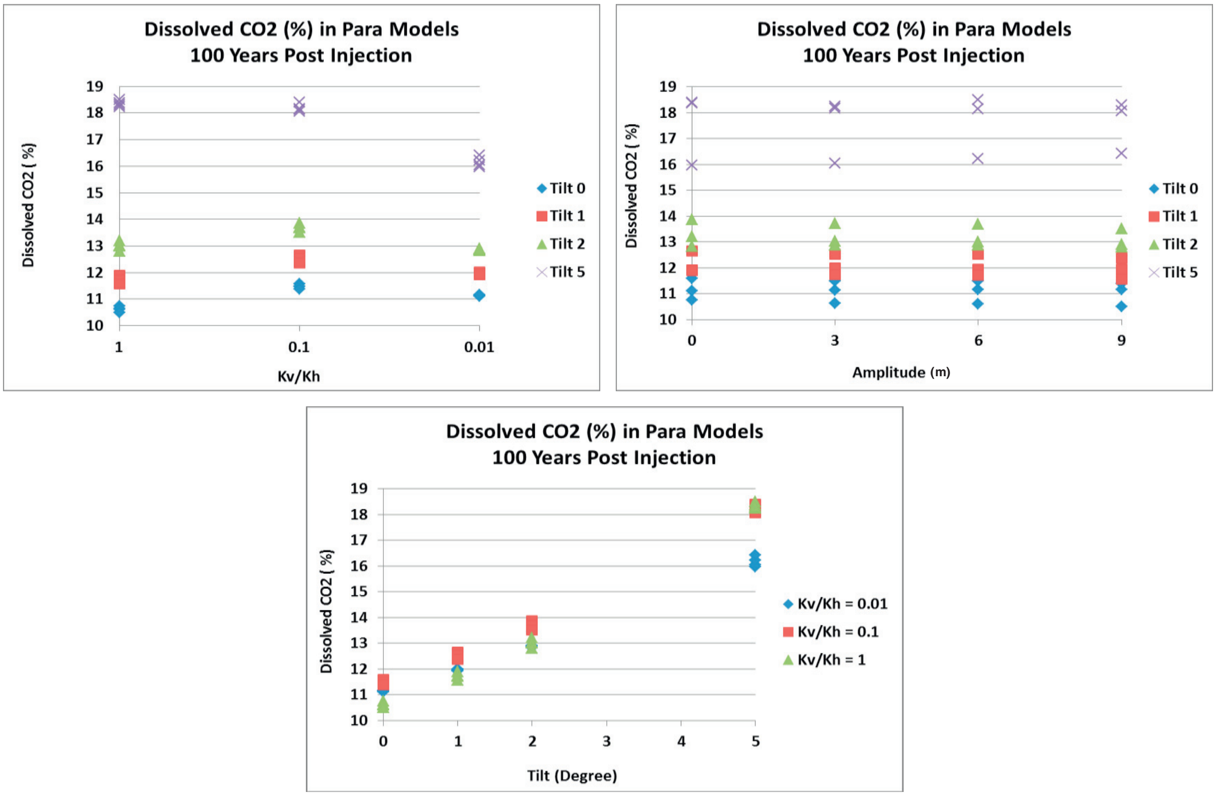

Fig. 4. The amount of dissolved CO_2 in the *para* models 100 years post injection comparing: k_V/k_H ratio and tilt (top right), amplitude and k_V/k_H ratio (top right), tilt and k_V/k_H ratio (bottom).

3.3. Perp Models

Results show that the effect of the k_V/k_H ratio and tilt on the amount of CO_2 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_2 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_2 is trapped structurally, and therefore less CO_2 migrates along the tilt direction, resulting in less CO_2 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_2 plume in the top-most layer and pictures in right show the length and the width of migrated CO_2 through different layers.

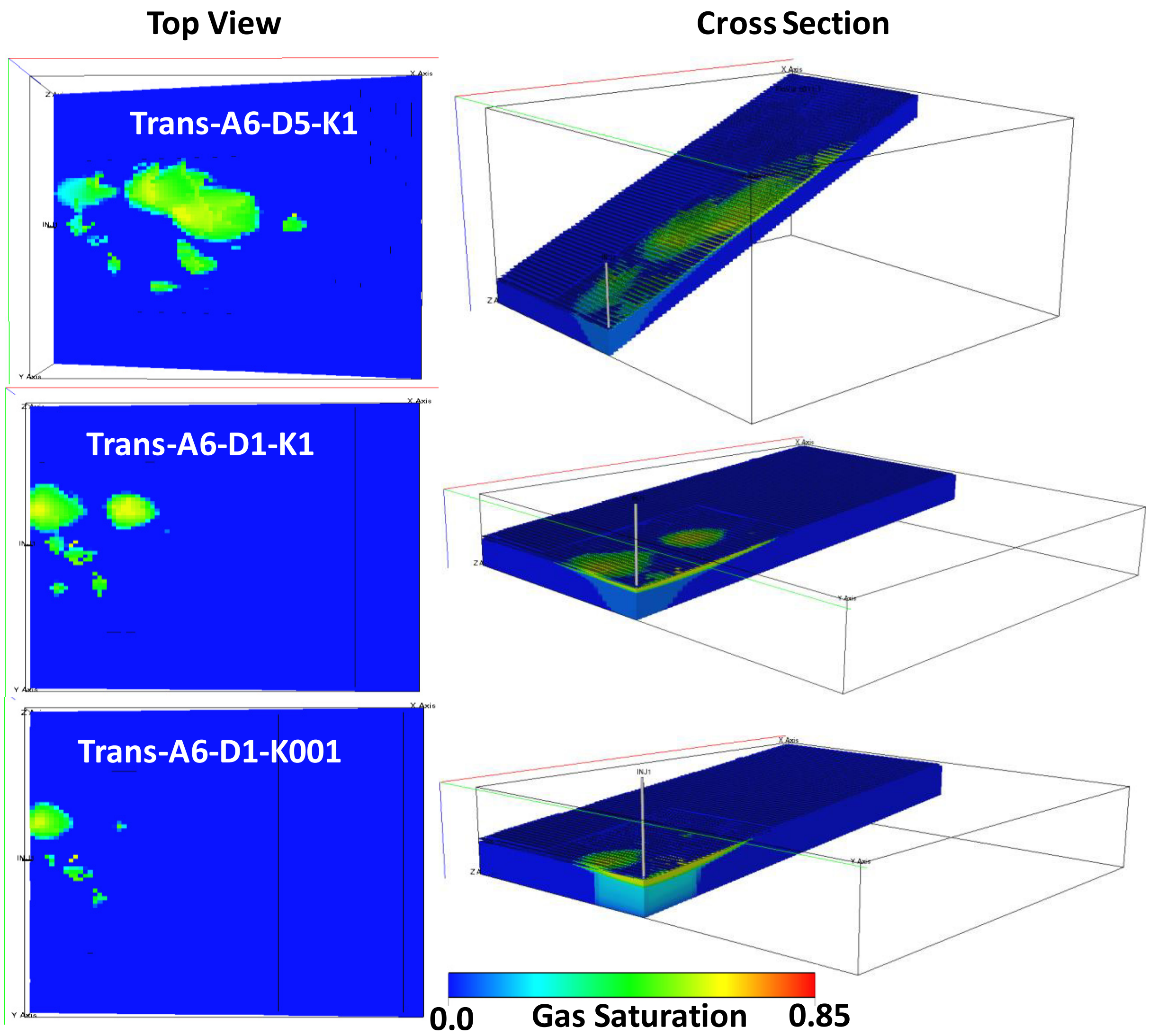

Fig. 5. Gas saturation 100 years post injection period in three *trans* models. All three models are tilted and have the same amplitude. However, top one and middle one have the same k_V/k_H ratio but the former one has 5 degrees inclination and the later one 1 degree. The bottom one which also is tilted (1 degree) however has a low k_V/k_H ratio (o.o1). More CO_2 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_2 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_2 migrates up-dip resulting in the plume having a smaller width. On the other hand, more CO_2 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_2 accumulates above the injector and gives the highest thickness of the CO_2 plume amongst these models. Therefore less CO_2 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_2 dissolved

The amount of CO_2 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_2 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_2 is dissolved. This is due the fact that more CO_2 spreads out when the k_V/k_H ratio is low therefore more CO_2 will be in contact with fresh brine resulting in more CO_2 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_2 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_2 migrated upwards. Thus more CO_2 is in contact with fresh brine therefore more CO_2 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_2 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 CO_2 falls (Fig. 7).

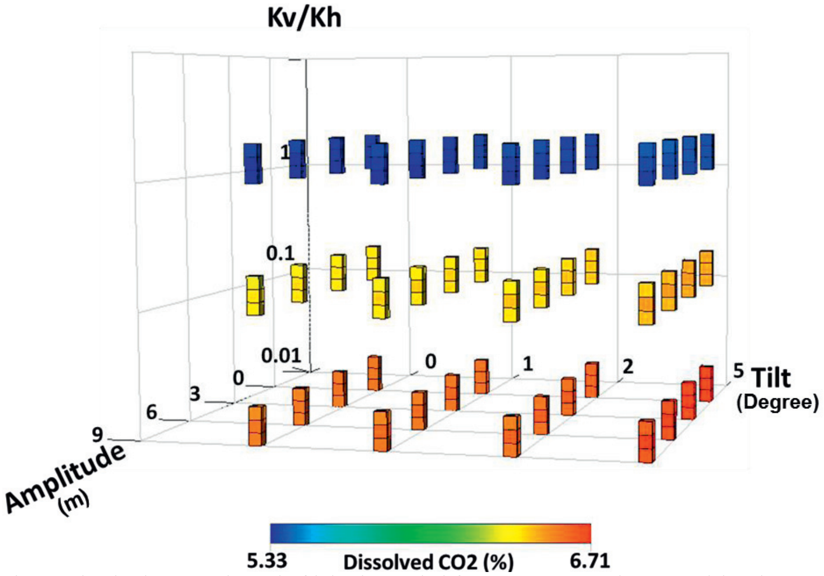

Fig. 6. Dissolved CO_2 at the end of injection period for *Trans*, *para* and *perp* models. The top value at each point refers to *Trans* Model, the middle one refers to the *Para* Model and the bottom one refers to the *Perp* Model. Models with lowest k_V/k_H ratio have the highest amount of dissolved CO_2 at the end of injection period.

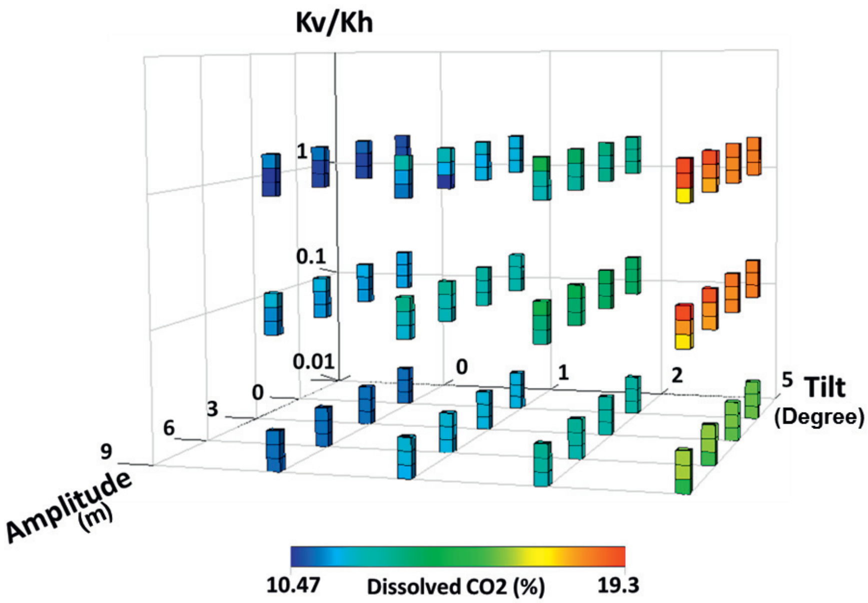

Fig. 7. Dissolved CO_2 100 years post injection period for *Trans, para* and *perp* models. The top value at each point refers to *Trans* Model, the middle one refers to the *Para* Model and the bottom one refers to the *Perp* Model.

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_2 storage as more CO_2 dissolved and the CO_2 vertical migration is limited too. In order to study the effect of top morphology on the CO_2 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_2 up-dip migration. Although this may increase the risk of CO_2 leakage as it migrates further away from the injection point, more CO_2 is dissolved due to more migration.

In general, it can be concluded that the amount of CO_2 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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