

Dipping open aquifers—The effect of top-surface topography and heterogeneity on CO₂ storage efficiency[☆]

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ABSTRACT

The Forties aquifer underlying the North Sea is used as an exemplar base case to provide a quantitative framework for assessing the CO₂ storage efficiency of dipping open aquifer storage units. Storage under a set of putative regulatory constraints is considered: pressure, migration distance and migration velocity. The effects of permeability, heterogeneity, aquifer dip and top-surface topography are all assessed and the results presented in terms of quantitative storage regimes. Permeability and aquifer dip are key determinants of storage efficiency, since they control the flow speed of the CO₂ and the amount of pressure build-up. Heterogeneity reduces storage efficiency due to localised pressure build-up, if this is a constraint. However, where pressure does not limit capacity, vertical heterogeneity improves storage efficiency through boosting the lateral sweep of CO₂. Top-surface topography introduces structural closures, regions of higher and lower dip than the model average, and channels. When compared to smooth models, structural closures increase efficiency and channels generally decrease efficiency. The net effect of all the competing topographical effects depends on which storage regime describes the smooth model. Overall, it is demonstrated that the storage regime and topography play important roles in determining storage capacity.

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1. Introduction

The estimation of CO₂ storage capacity is used to assess the economic and geological viability of CO₂ storage at different scales from individual sites to national assessments (Gammer et al., 2011; Norwegian Petroleum Directorate, 2012; US Department of Energy, 2010). The storage capacity of potential storage sites can depend upon many characteristics. Accounting for varying levels of complexity, numerous methodologies have been applied to estimate CO₂ storage capacity (Bradshaw et al., 2011; CSLF, 2008; Gammer et al., 2011; Goodman et al., 2011; Gorecki et al., 2009; Holloway et al., 2009; Jin et al., 2010; Kopp et al., 2009; Mathias et al., 2011; Norwegian Petroleum Directorate, 2012; Szulczewski et al., 2012; Vangkilde-Pedersen et al., 2009). The number of characteristics or levels of complexity accounted for is generally scale dependent with larger scale estimates, such as national capacity estimates, often including less complexity.

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Volumetric estimation methodologies, e.g. CSLF, (2008), Vangkilde-Pedersen et al. (2009), provide a simple and easily applicable storage capacity estimation method. These methods do not directly take into account any temporally or many spatially varying effects that may affect storage capacity, but simply assess the CO₂ storage capacity as the mass of CO₂ that could be stored, as a fraction of the aquifer pore volume. A number of national capacity estimation studies (e.g. Radoslaw et al. (2009), Lewis et al. (2009), Ogawa et al. (2011)) have used these volumetric estimation methodologies.

Other studies have accounted for spatial variation in aquifer properties as well as dynamic effects. This provides wide ranges in estimated storage capacities, from less than 1% to over 10% of pore volume dependent on the reservoir fluid and rock properties, structure and injection strategy. See, for example, Gammer et al. (2011), Goodman et al. (2011), Gorecki et al. (2009), Jin et al. (2010), Kopp et al. (2009), Qi et al. (2009), Szulczewski et al. (2012) and van der Meer and Yavuz (2009).

Dynamic and spatially varying effects are especially important when assessing the capacity of open as opposed to closed aquifers. In open aquifers the flow dynamics control when and how CO₂ reaches a storage boundary. For example, the viscosity ratio controls the vertical sweep and therefore the efficiency of residual trapping (Hesse et al., 2008), as can the background flow (Juanes et al., 2010), and there is interplay between residual and dissolution trapping (Gasda et al., 2011; MacMinn et al., 2011). In contrast, in

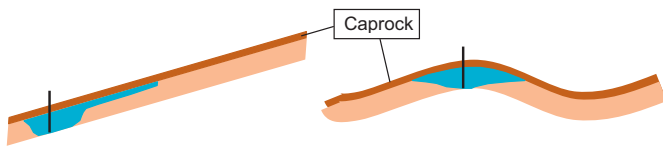


Fig. 1. Sketch of CO₂ injection into a dipping open aquifer (left) compared to an open aquifer with a large-scale structural closure (right). Both aquifers are open to flow at the lateral boundaries. The focus of this paper will be on dipping open aquifers.

closed aquifers, it is typically the pressure build-up that constrains storage capacity (Mathias et al., 2011).

This paper will consider the impact of dynamic and spatially varying effects upon flow in open aquifers that do not have significant large-scale structural closure (such as domes or fault sealing traps), which we will call dipping open aquifers. Fig. 1 shows a simple sketch of a dipping open aquifer compared to an open aquifer with a large-scale structural closure. Dipping open aquifers represent a significant proportion of storage capacity in the UK and worldwide (Holloway, 2009; Ogawa et al., 2011). Further, a number of national scale storage capacity estimation studies (Gammer et al., 2011; Ogawa et al., 2011) have found it useful to implement separate capacity estimation methodologies for dipping open aquifers and large-scale open structural closures. Large scale structural closures tend to be significantly more efficient at storing CO₂ than dipping open aquifers, but generally have less volume at the regional scale. In addition the sensitivity of storage efficiency to certain characteristics may be different in each case, making the design of a universal method difficult. Thus a separate understanding of both aquifer types is important; the focus here will be on dipping open aquifers.

There have been several dynamic modelling studies of CO₂ storage in dipping open aquifers (Doughty et al., 2001; Flett et al., 2007; Gammer et al., 2011; Goodman et al., 2011; Gorecki et al., 2009; Jin et al., 2010; Juanes et al., 2010; Kopp et al., 2009; Kuuskraa et al., 2009; Lengler et al., 2010; Obi and Blunt, 2006). However, only recently (Gammer et al., 2011; Szulczewski et al., 2012) have these studies investigated parameter sensitivity under the combined effects of plume migration over longer time scales and pressure build-up on storage capacity. The UK Storage Appraisal Project – UKSAP (Gammer et al., 2011), considered the sensitivity of capacity in dipping open aquifers with a smooth top surface to various characteristics that influence flow. The work assumed that capacity was constrained to meet a set of practical regulatory guidelines and economic limits. Based upon these assumptions UKSAP (Gammer et al., 2011) showed that aquifer top-surface dip and permeability had the strongest influences on storage efficiency, since this controlled the rate at which the injected CO₂ migrates. Three storage regimes were identified, shown in Fig. 2, which summarised the effect of the two key parameters – average dip and permeability – by assigning different probability density functions for the storage efficiency of each regime. Storage efficiencies within the migration velocity limited regime were constrained by a limitation on CO₂ migration velocities 1000 years after injection. In the poor injectivity regime storage efficiency was constrained by a requirement for the aquifer pressure to remain below 90% of the estimated fracture pressure limit.

Most studies have not considered the sensitivity of storage capacity to aquifer geology – top-surface topography and heterogeneity. Where work has, it has mainly focussed on the effects of heterogeneity (Flett et al., 2007; Kuuskraa et al., 2009; Lengler et al., 2010), although not under the combined constraints of plume migration and pressure build-up. Chadwick and Noy (2010), Jin et al. (2010) and Pickup et al. (2011) have included top-surface topography in their simulation work and commented on the significant effect of top-surface topography upon the characteristics

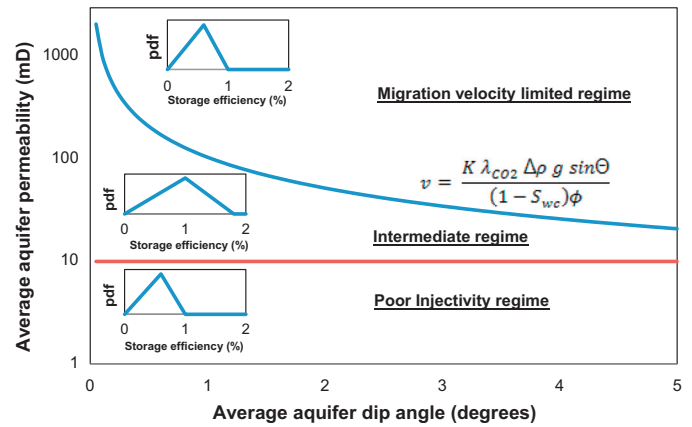


Fig. 2. Open aquifer storage regimes after Gammer et al. (2011). The intermediate and migration velocity limited regimes are separated by a boundary where the characteristic migration velocity $v = 10$ m/year. v is estimated using the equation indicated. K is permeability, λ_{CO_2} the CO₂ mobility, $\Delta \rho$ the density difference between brine and CO₂, Θ the average aquifer dip, ϕ porosity and S_{wc} the connate water saturation. The intermediate and poor injectivity regimes were separated notionally by a 10 mD cut-off. PDF stands for probability density function.

of the CO₂ plume. However, they do not systematically analyse the effect of top-surface topography. Nilsen et al. (2012) presented an analysis of trapping in the top structure of dipping open aquifers, using a semi-analytical spill-point analysis and vertical equilibrium modelling, to quantify storage capacity. However, the combined effects of permeability, dip, top-surface topography, variable injection, migration speed and pressure were not investigated.

Therefore the objectives of this work are to:

- Investigate whether the storage regimes shown in Fig. 2 from Gammer et al. (2011), which summarise the impact of permeability and aquifer dip, are good approximations when top-surface topography and aquifer heterogeneity are present.
- Investigate how top-surface topography and heterogeneity can affect storage efficiency in a dipping open aquifer. We shall consider top-surface topography that is large enough to be resolved by seismic, but smaller than would be considered as a single CO₂ storage trap. We will use an exemplar model based on the Forties aquifer for our studies.

The paper outline is as follows. The modelling methods are described in Section 2. In Section 3 the storage results from the Forties base case model are presented. To investigate objective (a) the sensitivity of storage efficiency to permeability and aquifer dip are presented in Section 4. To assess objective (b) sensitivity to top-surface topography and heterogeneity are presented in Section 5. Sections 6 and 7 present the discussion and conclusions.

2. Modelling methods

2.1. Geocellular model of the Forties base case storage unit

A section of the Forties sandstone member of the Sele Formation was chosen for the Forties base case geological model. This area avoided hydrocarbon fields, significant structural closures, known faulting and communication with overlying formations. Its scale was chosen as representative of a potential licensable open aquifer storage unit: smaller than the basin scale ~ 100 km $\times$ 100 km, but larger in areal extent than most oil and gas fields. The area of interest – shown in Fig. 3 – was 21.4 km $\times$ 36 km. The model was orientated northwest to southeast and spans several blocks in Quadrant 22 of the Central North Sea with an average aquifer thickness of 170 m.

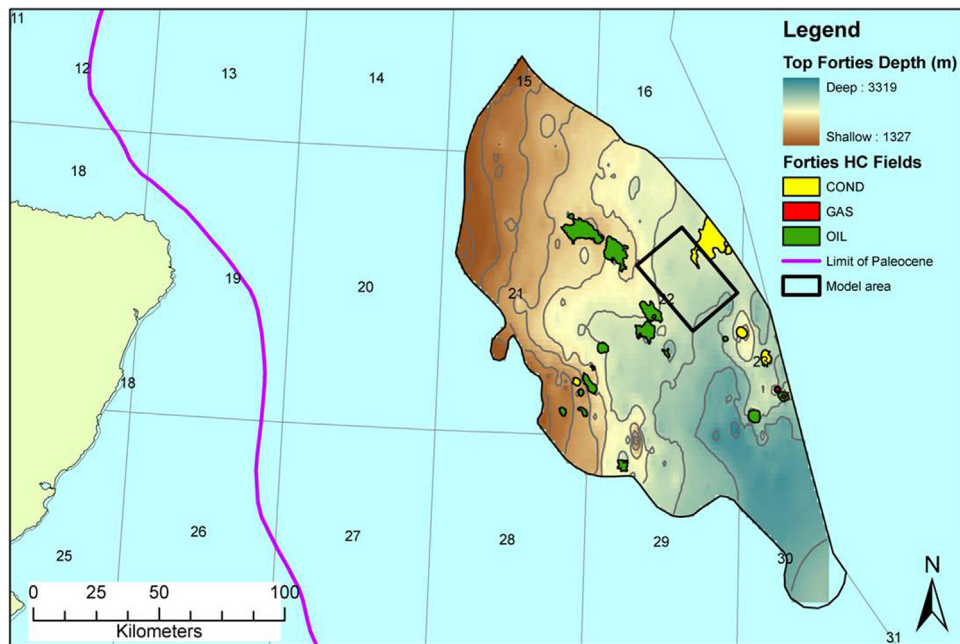


Fig. 3. Location of the Forties Sandstone member and the Forties geological model (black rectangle).

The grid dimensions of the geological model were $55 \times 91 \times 90$ giving a total of 450,450 grid cells. This was reduced from an original 1,733,400 cell model using horizontal upscaling to achieve feasible simulation runtimes. The topographical framework of the model was based on a seismic interpretation of the Top Forties and well tops of the underlying unit. To capture thin CO_2 tongues at the top of the storage unit, the vertical resolution is between 0.5 m to 1 m

towards the top of the Forties interval increasing to 3 m at the base. This also allowed the intra-reservoir shales to be captured in the geological model, thus preserving vertical heterogeneity.

The porosity and permeability models (e.g. Fig. 4a and b) were based upon a facies model describing cells as either channel or shale, derived using data from the 10 wells located in the Forties Sandstone Member. Permeability and porosity distributions for the

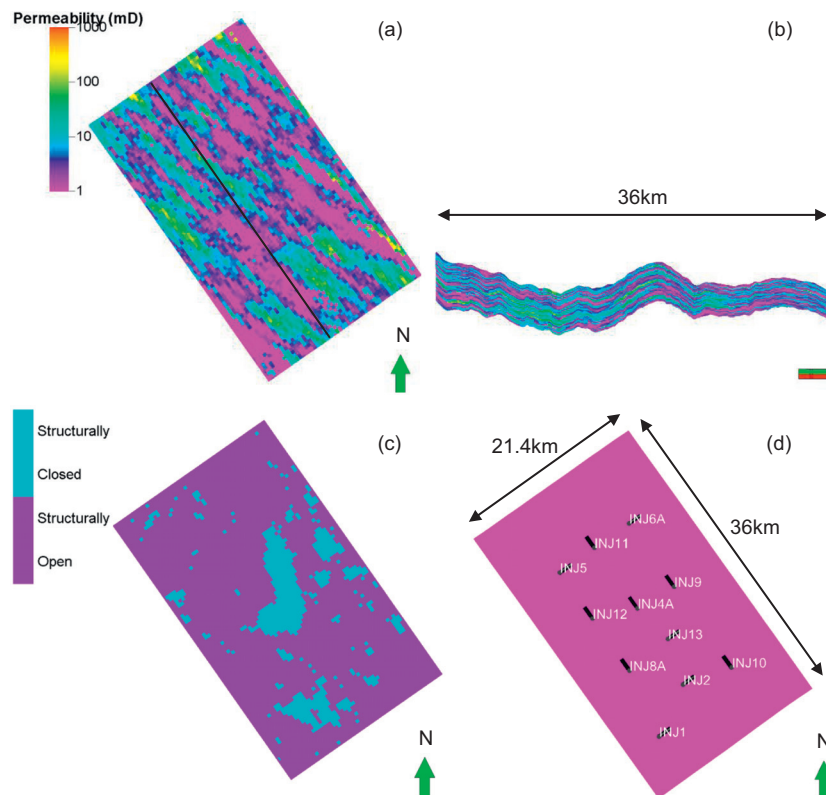


Fig. 4. The Forties geological model and well pattern. (a) The permeability model at the top of the Forties geological model. (b) A vertical cross section of permeability shown corresponding to the black line in (a). (c) The map of cells on the top layer of the Forties base case, which are structurally closed. (d) The locations of the eleven horizontal wells used for the Forties base case and sensitivity scenarios.

Table 1
Initial conditions and parameters for the Forties base case simulation.

Parameter	Value	Source
Aquifer datum depth (below sea level)	2800 m below	Geological model
Brine salinity	100,000 ppm	Gluyas and Hichens (2002)
Temperature	105 °C	Evans et al. (2003)
Pressure at datum	32 MPa	Calculated using brine density
CO ₂ density at datum	660 kg/m ³	TOUGH2 TM PVT data
CO ₂ viscosity at datum	0.0000546 Pa s ⁻¹	TOUGH2 TM PVT data
Brine density at datum	1006 kg/m ³	TOUGH2 TM PVT data
Brine viscosity at datum	0.000345 Pa s ⁻¹	TOUGH2 TM PVT data
Rock compressibility	0.0000489 MPa ⁻¹	Data from UKSAP
Porosity (arithmetic average)	0.16	Geological model
Permeability (arithmetic average)	11 mD	Geological model
Volume of storage unit	2 × 10 ¹⁰ m ³	Geological model
Volume of Forties sandstone member	3 × 10 ¹¹ m ³	Data from UKSAP
Fracture pressure gradient	0.0181 MPa/m	Data from UKSAP
CO ₂ and water relative permeability functions (drainage and imbibition)	Viking 2 dataset	Bennion and Bachu (2008)
Maximum residual CO ₂ saturation	0.297	Bennion and Bachu (2008)
Capillary pressure function	Viking 2 dataset	Bennion and Bachu (2006)
Relative permeability hysteresis model	Carlson model	Carlson (1981)

channel facies were based on published data and local core analyses. These distributions were used to assign permeability and porosity values within the channel facies. Values were assigned so that the centre of the channels had the highest permeability and porosity, decreasing towards the edges. The shales were modelled with near-zero porosity and permeability.

2.2. Dynamic model setup

The dynamic model was constructed in ECLIPSE 100TM. This allowed for accurate comparison with previous work on the assessment of the storage regimes (Gammer et al., 2011). A summary of initial fluid and rock properties used is given in Table 1. Initial pressures in the aquifer were calculated assuming hydrostatic equilibrium and a datum pressure and temperature were calculated using a geothermal gradient of 35 °C/km and seabed temperature of 8 °C, with rounding to the nearest 5 °C to coincide with the availability of PVT data. Brine salinity was estimated as 89,000 ppm but rounded to 100,000 ppm for the same reason.

Dissolution of CO₂ into the brine phase and vaporisation of water into the gas phase were both modelled, with density changes on mixing. All density, viscosity and phase partitioning values used during simulation were calculated using black oil PVT tables generated using the TOUGH-2TM ECO2N module (Pruess, 2005); the maximum mobility ratio between the CO₂ and brine is around 4. Isothermal conditions were assumed.

To represent the pressure response from the volume of the Forties sandstone connected to the Forties geological model, additional pore volume was added around the boundaries of the grid to make the total pore volume match the 3 × 10¹¹ m³ volume of the Forties sandstone member. The aquifer is believed to be open to flow beyond some of these boundaries, but this was not accounted for. Sensitivity to this and other boundary conditions was tested and found to have a limited effect (up to 5%) upon the injected CO₂ volume under a maximum pressure constraint. This was considered acceptably small compared to the other model sensitivities. The sensitivity of results from the upscaled 450,450 cell model to horizontal grid resolution was also tested and found to have little impact on the results. However, it is possible that through failing to capture the details of convective dissolution, the degree of trapping is under-estimated (see, for instance, MacMinn et al., 2011).

The local groundwater flow of 0.04–0.4 m/year was estimated using pressure data from GeoPressure Technology Ltd. and its inclusion in the model was considered. However over 1000 years this results in a migration distance of 0.1–1 cell in our model; therefore

groundwater flow was neglected. We note that groundwater flows may not be this slow everywhere.

2.3. Constraints on CO₂ injection and storage capacity

Injection was simulated for 50 years and the post injection period for a further 950 years. Injection rate and the calculated capacity were constrained by the following three conditions set out by Gammer et al. (2011), which interprets current EU guidelines (European Commission, 2011) and discussion in IPCC (2005):

- 99% of injected CO₂ must remain within the storage boundary after 1000 years – to be referred to as the ‘boundary constraint’.
- CO₂ migration velocities at 1000 years must be less than 10 m/year and declining – the ‘migration velocity constraint’.
- Pressures must remain less than 90% of the estimated fracture pressure limit – the ‘pressure constraint’.

In addition a minimum well injection rate of 0.1 Mt/year was also applied on economic grounds.

The boundary constraint was motivated by discussion in IPCC (2005) which considered that it is likely that, in appropriately selected and managed stores, at least 99% of injected CO₂ will be retained after 1000 years. The migration velocity constraint interpreted EU guidelines (European Commission, 2011) that suggest that CO₂ migration of several metres/year could be acceptable, provided that the migration rate is declining and there is no significant risk of leakage.

2.4. Measures of storage security and trapping

The key measures of storage security and trapping were defined and calculated as follows.

- *Escaped CO₂*: Any CO₂ that reached the ‘boundary cells’ at the side of the model. This CO₂ remains in the Forties sandstone member, but lies outside the region defined by the simulation model.
- *Dissolved CO₂*: All dissolved CO₂ within the model, but not within the ‘boundary cells’.
- *Structurally trapped CO₂*: Any gas phase CO₂ that was situated within a structural closure; this is CO₂ that cannot migrate further under gravity. An algorithm was written to calculate which cells were structurally closed (Fig. 4c).
- *Residually trapped CO₂*: Estimated using the Land (1968) trapping model with maximum residual CO₂ saturation shown in Table 1.

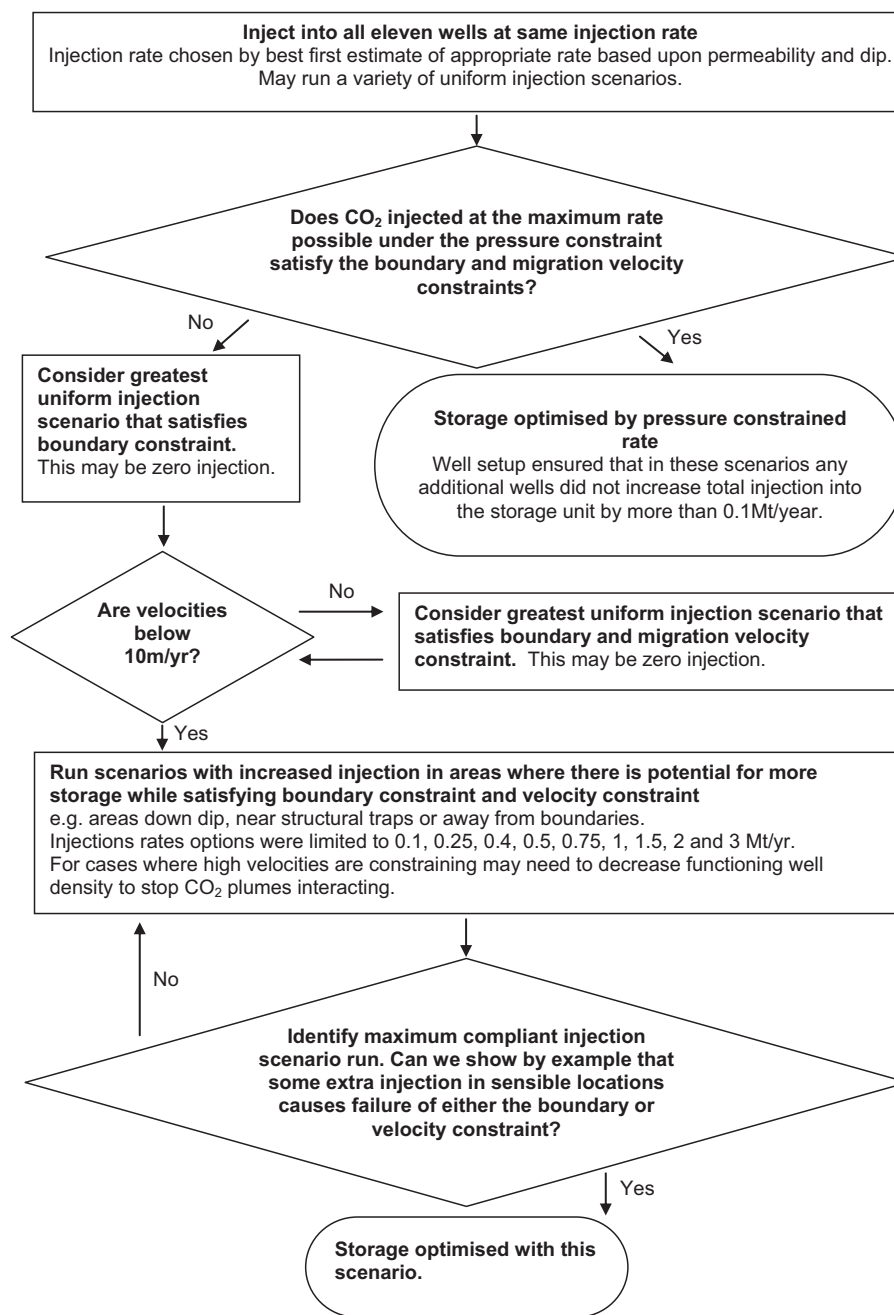


Fig. 5. General methodology for calculating the capacity of each model.

CO₂ within structurally closed cells was not counted to avoid double counting.

- **Low migration velocity storage:** Any CO₂ that was still within the boundaries of the model at 1000 years; satisfied the velocity constraint at 1000 years and was not trapped structurally, residually or by dissolution, we refer to as *low velocity CO₂*. We shall refer to the storage mechanism as *low migration velocity storage*. Over time the low velocity CO₂ must eventually become either structurally or residually trapped, dissolved or escape the model boundaries.

2.5. Methodology for calculating storage capacity – optimising injection and well location

A single set of well placements was used to keep the optimisation process feasible. Well locations were designed to:

- have a reasonably even distribution;
- where possible be located preferentially down-dip;
- be located to avoid injection into shales in heterogeneous models;
- provide high enough well density to maximise injection in the cases with poorest injectivity.

The exact placement of these wells was chosen by eye aided by detailed visualisation of the permeability field and the local dip. The locations were optimised by gradually increasing or relocating wells in order to optimise injection into the Forties base case. This involved particular effort to increase the number of wells so that any additional well increased total injection by at least 0.1 Mt/year. The final well pattern from this process, which was used for all models, is shown in Fig. 4d. 2 km long horizontal wells were used to avoid injection near shale layers and to assist with an improved areal spread of the CO₂ plume.

Table 2

Sensitivity matrix showing the 15 sensitivity models studied. Storage regime key: PI – poor injectivity regime, I – intermediate regime, MVL – migration velocity limited regime. The analytic migration velocity is approximately equal to $5.5K\sin\theta$ where K is permeability and θ aquifer dip. The shaded boxes are not modelled.

Average aquifer permeability (mD)	Average aquifer dip	Analytic migration velocity (m/year)	Storage regime	Homogenous smooth	Homogeneous with top-surface topography	Heterogeneous with top-surface topography
11	0.27°	0.3	I	✓	✓	✓
145	0.27°	3.8	I	✓	✓	✓
1000	0.27°	26	MVL	✓	✓	✓
145	1°	14	MVL	✓	✓	X
145	3°	42	MVL	✓	✓	X
11	1°	1.1	I	X	X	✓
11	3°	3.2	I	X	X	✓

The storage capacity in each sensitivity model was estimated by running dynamic simulations and increasing or reducing injection rates to meet the storage constraints. This was achieved through an iterative process shown in Fig. 5. In this process the escaped CO₂ and CO₂ velocity at 1000 years were measured so that potential injection rate scenarios could be accepted or rejected according to the boundary and migration velocity constraints. The pressure constraint was applied directly at the well.

Once the storage capacity had been optimised the storage efficiency S_{eff} was calculated according to the definition of Vangkilde-Pedersen et al. (2009):

$$S_{eff} = \frac{\text{Volume CO}_2 \text{ in place}}{\text{net-to-gross} \times \text{Total Pore Volume}} \quad (1)$$

where the net pore volume was estimated by extracting the pore volume of the sand facies in the geological model.

2.6. Sensitivity models

The range of sensitivities studied is shown by the boxes in Table 2. The Forties base case model had an average dip of 0.27° in the SE to NW direction and arithmetic average permeability 11 mD. Permeability and dip sensitivities were created by simply multiplying by a constant factor or shift throughout the model. Each sensitivity model was categorised into the Gammer et al. (2011) storage regimes using the diagrammatic method shown in Fig. 2. This required the calculation of characteristic velocities, shown in Table 2, using the equation embedded in the diagram, the average permeabilities and aquifer dips from Table 2 and data from Table 1. The categorisation is shown in Table 2. The following sections describe how these sensitivities were used to achieve the objectives outlined in Section 1.

2.6.1. Verifying the UKSAP storage regimes in geologically heterogeneous scenarios

To verify the Gammer et al. (2011) storage regimes in geologically heterogeneous scenarios, the 11 mD, 0.27° Forties base case model was used to test sensitivity to changes in average

permeability and aquifer dip. The permeability and aquifer dip sensitivity models considered are shown in the right-hand column in Table 2. These sensitivities allowed us to look at results representative of each of the Gammer et al. (2011) storage regimes. A poor injectivity storage regime case, as shown in Fig. 2, was not modelled. However, the Forties base case capacity was injectivity limited and this is representative of an adapted ‘pressure limited regime’ that is proposed in Section 4.3.

In addition, the application of dip and permeability sensitivities to the models without heterogeneity and/or top-surface topography was used to further evaluate the storage regimes. These cases were used to test the storage regimes for smooth models as described in Gammer et al. (2011). In particular this meant we could further evaluate the aquifer characteristics controlling storage efficiency on simpler cases.

2.6.2. Evaluating the sensitivity of storage efficiency to the presence of top-surface topography and heterogeneity

Models with and without aquifer heterogeneity and then with the top-surface topography removed, were considered (Fig. 6).

Since the capacity of the storage regimes is constrained by distinct mechanisms it was also considered whether the effects of top-surface and heterogeneity were different, depending upon storage regime. Thus the sensitivity of storage capacity to the presence of top-surface topography was tested under five dip-permeability combinations, shown by the top five rows of Table 2. The sensitivity to heterogeneity was tested under three dip-permeability combinations, shown by the top three rows of Table 2.

In the homogeneous sensitivity models the vertical to horizontal permeability ratio was set to 0.1. Porosities and permeabilities for the homogenous models were set to the arithmetic average of the heterogeneous model. In the smooth models, aquifer dip was taken as the average dip from the models with top-surface topography.

3. Forties model base case storage appraisal

Using the setup of Sections 2.1–2.5, the storage capacity of the Forties base case model was estimated. The final distribution of CO₂

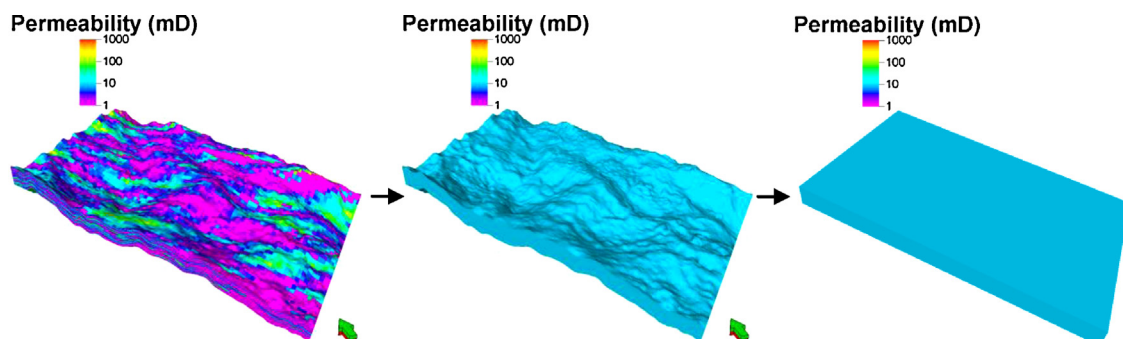


Fig. 6. Simplification of Forties base case model by successively removing heterogeneity and top-surface topography (vertical exaggeration 15×).

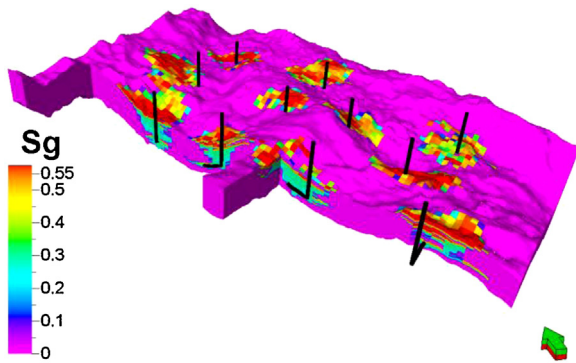


Fig. 7. CO₂ saturation in the Forties base case model at 1000 years. The maximum gas saturation is 0.577. The model is vertically exaggerated by a factor of 15. The wells are shown in black.

saturation at 1000 years is shown in Fig. 7. Its capacity was estimated as 471 Mt representing a storage efficiency of 3.5%, a high efficiency compared to the UKSAP storage results in Fig. 2. This was because the low permeability kept the CO₂ within the model and below the migration velocity, while only slightly constraining injection due to the pressure constraint. The magnitude of the storage efficiency is discussed further in Section 4.1.1. 18% of our injected CO₂ was ‘low migration velocity stored’ as shown in Fig. 8. Structural closures formed 0.9% of the pore volume. However, only 0.07% of the pore volume was used for structural trapping, occupied by 2% of the injected CO₂. 60% of the CO₂ was residually trapped, making this the dominant trapping mechanism in this case.

4. Verifying the UKSAP storage regimes – sensitivity of storage efficiency to aquifer dip and permeability

4.1. Verification of storage regimes with smooth homogeneous models

The regimes were first evaluated by summarising which mechanisms were found to limit capacity in each of our smooth homogeneous models and comparing the results to regime predictions. Table 3 shows that for the homogeneous smooth cases, the models generally behaved as predicted. The three cases categorised as migration velocity limited had their capacity limited by the migration velocity constraint. The two intermediate storage regime cases were not limited by migration velocity or *particularly poor* injectivity, satisfying the general definition of the intermediate regime. Although the models generally satisfied the regime definitions, two points were noted.

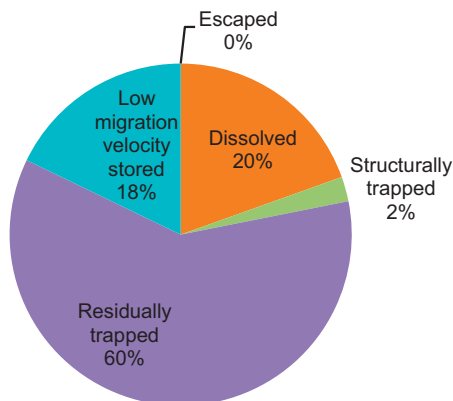


Fig. 8. Proportion of CO₂ trapped or stored by different mechanisms in the Forties base case model at 1000 years.

Table 3
The limiting factor upon storage capacity for each sensitivity model. Comments with underline and italic are not as predicted by their storage regime. Storage regime key: I – intermediate regime, MVL – migration velocity limited regime.

Average aquifer permeability (mD)	Average aquifer dip	Storage regime	Limiting factor	
			Homogeneous smooth	Heterogeneous with top-surface topography
11	0.27°	I	Injectivity (but not particularly poor injectivity)	Injectivity (but not particularly poor injectivity)
145	0.27°	I	Boundary	Migration velocity locally
1000	0.27°	MVL	Migration velocity	Migration velocity in most areas
145	1°	MVL	Migration velocity	Migration velocity in most areas
145	3°	MVL	Migration velocity	Migration velocity in most areas
11	1°	I		Injectivity (but not particularly poor injectivity)
11	3°	I		Migration velocity locally

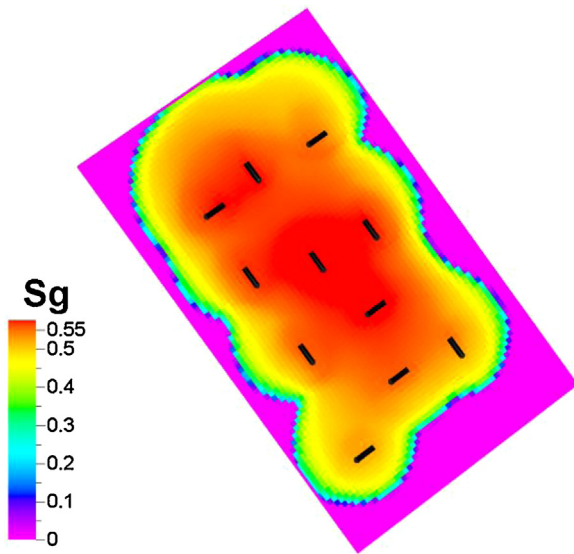


Fig. 9. CO₂ saturation profile in the top layer of the 0.27° dip, 145 mD permeability, smooth, homogeneous model at 1000 years. The black lines show well placements.

Firstly, in the 11 mD, 0.27° intermediate storage regime case, injectivity – although reasonable – was the limiting factor. This is not inconsistent with the regime definitions from Gammer et al. (2011) as the poor injectivity regime is not defined to include all models where the capacity is injectivity limited. However, this does lead to a fairly nominal definition of the boundary and injectivity limited models sitting within the intermediate regime. In addition, injectivity varies with depth but the border of the poor injectivity regime does not. We discuss these points and potential adaptations in Section 4.3.

Secondly in the 145 mD 0.27° case shown in Fig. 9, which was classified in the intermediate storage regime, it was noted that migration velocity was above that predicted in Table 2. This is accounted for in Section 4.1.2.

In addition to the difference in mechanism limiting capacity in each of the regions, an important motivation for creating the Gammer et al. (2011) regimes was the difference in storage efficiency. We also looked to verify this and our sensitivity results supported this by the segregation in magnitude of storage efficiencies shown in Fig. 10.

Further our results also explicitly explain the cause of the difference in storage efficiencies between the migration velocity limited

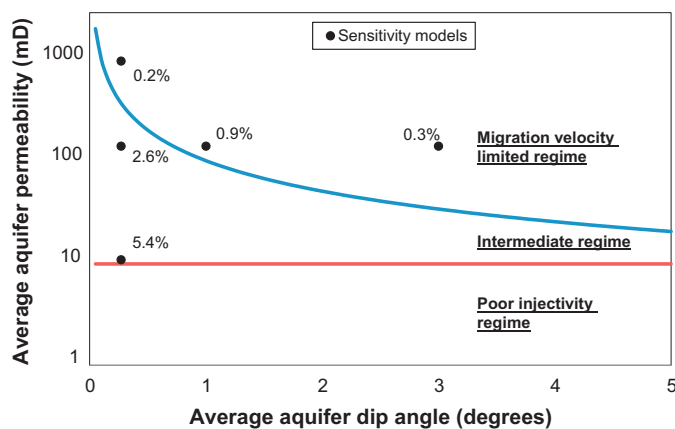


Fig. 10. Sensitivities applied to homogeneous smooth models. Storage efficiency of five different average permeability and aquifer dip scenarios. Results are shown against the three storage regimes.

regime and intermediate regime. Storage units categorised in the intermediate regime can store high-saturation CO₂ as low-velocity mobile CO₂, whereas storage units in the migration velocity limited regime cannot. Fig. 11 shows the percentage of the pore volume containing low velocity CO₂ is over 1% for an 11 mD permeability case and 0.5% for a 145 mD permeability case. In contrast, the 1 Darcy case effectively stores no ‘low velocity CO₂’; the only CO₂ which does meet the definition is very near residual, where it is practically immobile. This means that less can be injected, reducing the amount of dissolution and residual trapping and ultimately reducing storage efficiency. Overall, these results support the qualitative description of the factors limiting storage capacity in each regime, and the segregation in storage efficiencies between the regimes (Fig. 2).

4.1.1. Explaining high storage efficiencies

In Section 3 our storage efficiencies were observed to fall significantly outside the 0–1.8% storage efficiency range for intermediate regime models shown within Fig. 2. A simple comparison of the results showed this was largely accounted for by the difference in average depth of the Forties model (2800 m) compared to the standard UKSAP average depth (2000 m). This difference resulted in a difference in pressure capacity of the models due to the increasing difference between fracture pressure and hydrostatic pressure with depth. In addition, this work optimised well placement and injection, further increasing efficiency results compared to UKSAP results of Fig. 2.

4.1.2. Estimation of migration velocity and implications for storage regime boundary

In Section 4.1 the migration velocity in the 145 mD 0.27° case at 1000 years was found to be higher than expected. The migration velocity seen was 5.5 m/year rather than 3.8 m/year predicted using the analytic equation in Fig. 2. This was in part due to using maximum local velocities and the combined effects of discretisation approximations from the calculation of migration velocity using volumetric flow rates. Further, a more thorough analytic analysis of the velocity of spreading of the buoyant CO₂ plume (e.g. Vella and Huppert, 2006) shows an additional term to the component of flow up-dip due to gravity. Using this, the velocity of CO₂ migration is estimated as

$$v = \frac{K\lambda_{CO_2}\Delta\rho g}{(1-S_{wc})\phi} \left(\sin\theta + \frac{dh}{dx} \cos\theta \right) \quad (2)$$

where $\Delta\rho = \rho_{water} - \rho_{CO_2}$, K is the permeability, λ_{CO_2} is the mobility of CO₂, g is the gravitational constant, S_{wc} is the connate water saturation, ϕ is the porosity, h is the connected height of CO₂ in the direction perpendicular to the top-surface and x is the distance along the top-surface, and θ is the dip angle. The second term in this expression accounts for the buoyant spreading of CO₂. The main significance of this result is that we may observe some cases just below the intermediate/migration velocity limited storage regime divide that are limited by migration velocity. In flat aquifers the second term becomes the only term. In these cases the migration velocity constraint will only be broken after an amount of CO₂ large enough to increase dh/dx , is injected. In contrast, within the migration velocity limited regime any mobile CO₂ should move at speeds above 10 m/year.

4.2. Verification of storage regimes with heterogeneous models

Here we investigate the storage regimes when top-surface topography and aquifer heterogeneity are present. In particular, whether the regime categorisations still describe the mechanisms limiting capacity and whether there is still segregation in efficiencies between regimes.

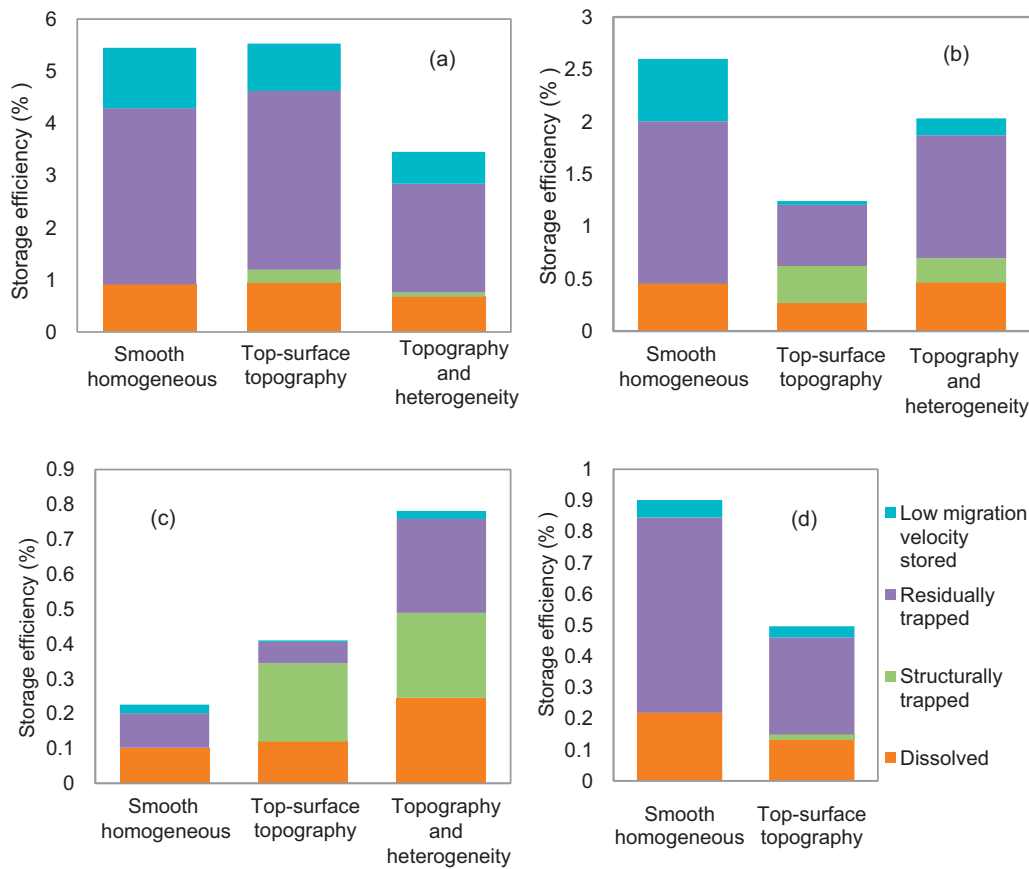


Fig. 11. Change in storage efficiency and storage mechanisms due to the introduction of top-surface topography and aquifer heterogeneity to the following smooth homogeneous cases: (a) 11mD 0.27° – pressure limited regime, (b) 145mD 0.27° intermediate regime, (c) 1 Darcy, 0.27° – migration velocity limited regime and (d) 145mD, 1° – migration velocity limited regime.

The right hand column of Table 3 shows that the predicted limiting mechanisms still limit capacity in our examples, but locally there are some changes. The migration velocity constraint becomes a limiting factor in some areas where locally higher dip or higher permeability is introduced. Conversely the migration velocity constraint is no longer limiting locally in areas of the heterogeneous model where there is locally lower dip, structural closure or lower permeability.

Considering the storage efficiencies in Fig. 12 provides us with some assessment of the extension of the segregation in magnitude

of storage efficiencies. We see that there is still a difference in storage efficiencies broadly agreeing with the idea of regimes. The implication of this result is that for our top-surface topography and aquifer heterogeneity, the average permeability and average aquifer dip are not significantly misrepresented by local effects. However, we note that for this model the efficiencies of the intermediate and migration velocity limited regimes have converged to some extent. Section 5 shall help to highlight that this is because some areas of each model have taken on characteristics more similar to that of the other regime.

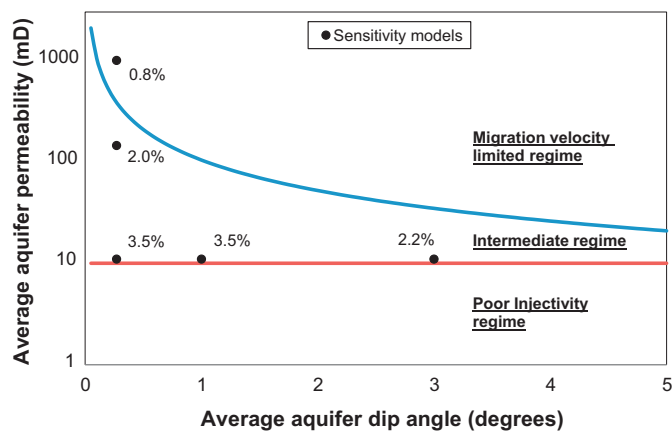


Fig. 12. Sensitivities applied to heterogeneous models with top-surface topography. Storage efficiency of five different average permeability and aquifer dip scenarios. Results are shown against the three storage regimes.

4.3. Potential adaptations to the storage regimes

Based on our results we have identified potential ways to adapt the regimes. These are shown in Fig. 13 and are described as follows:

- The regimes could be adapted to include a pressure limited regime and uneconomic injectivity regime as shown in Fig. 13.
- In the pressure limited regime the storage efficiency would be constant determined by the pressure capacity (or compressibility) of the system. This assumes that well numbers and density can be increased to meet this storage efficiency, independent of permeability. This maximum efficiency may be estimated conservatively using Mathias et al. (2011). The storage efficiency in the pressure limited regime would also be depth dependent. The boundary between the pressure limited regime and intermediate regime indicates where the increasing efficiency in the intermediate regime reaches the pressure limited maximum efficiency.
- The top boundary of the uneconomic injectivity regime would be defined by the permeability where economically too many wells

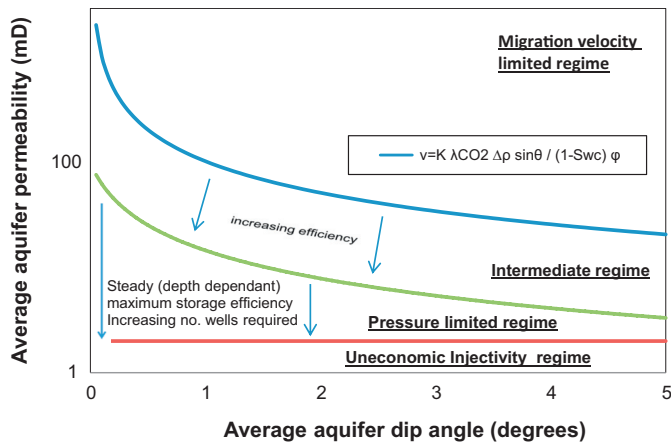


Fig. 13. Potential adapted version of dipping open aquifer storage efficiency regimes. The dashed boundary between the pressure limited regime and intermediate regime indicates a maximum efficiency, where the line is dependent upon efficiencies in the intermediate regime and the maximum efficiency.

at too low injectivity are required to inject the pressure limited storage efficiency. Thus, in the uneconomic injectivity regime storage efficiency is 0. The permeability level of the boundary to this regime would vary based upon depth. An estimate of this permeability could be calculated analytically using Mathias et al. (2009) or Mathias et al. (2011). We would also expect a narrow transition area between the pressure limited regime and uneconomic injectivity regime, but do not include this in Fig. 13.

In addition to these points it may also be possible to use analytical solutions in the intermediate and migration velocity limited regimes to define storage efficiencies for different permeability and dip. These may also have the advantage of accounting for thickness and porosity. Using analytic estimates of migration distance of mobile CO₂ at 1000 years, we expect increasing storage efficiencies with decreasing migration velocity in the intermediate regime, as shown in Fig. 13.

5. Evaluating the sensitivity of storage efficiency to top-surface topography and heterogeneity

Fig. 14 shows an overview of the storage efficiency results, using Fig. 11 and Table 3. The storage regimes provide a clear description of the key factors limiting storage efficiency, which

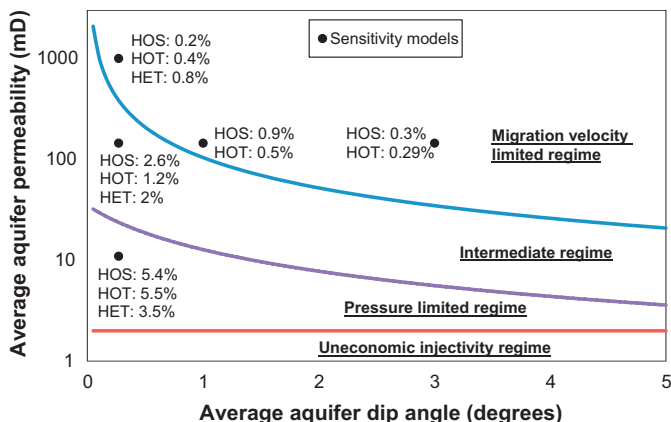


Fig. 14. Storage efficiency results in various regimes with and without heterogeneity and top-surface topography. Results for homogeneous smooth cases, homogeneous with top-surface topography and heterogeneous cases with top-surface topography are labelled HOS, HOT and HET respectively.

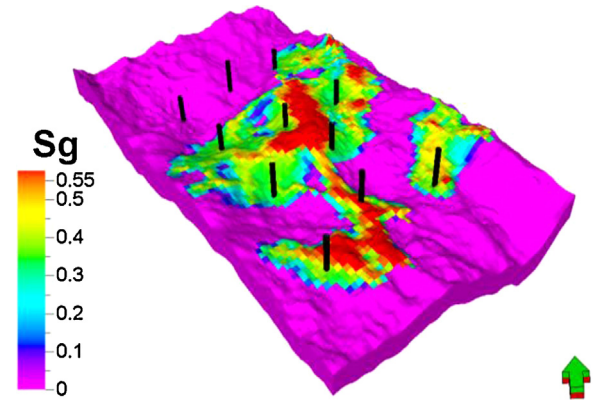


Fig. 15. CO₂ saturation in the homogeneous 145 mD, 0.27° dip model with top-surface topography at 1000 years. Model viewed from south and exaggerated by factor 15 in the vertical direction.

differ between the regimes. The effect of top-surface topography and heterogeneity was evaluated using cases from three storage regimes to see if they affect these models differently. The 11 mD 0.27° case is now categorised as a pressure limited regime model as its smooth homogeneous model capacity is limited by the pressure constraint.

5.1. Effect of top-surface topography upon storage capacity

The effect upon storage capacity of introducing top-surface topography in the pressure limited storage regime was minimal. In the intermediate storage regime, more significant effects are seen; there is a drop in storage efficiency from 2.6% to 1.2% for the 145 mD model. This was caused by the need to reduce injection rates into and stop wells in regions with locally higher dip to comply with both the boundary constraint and the migration velocity constraint. Fig. 15 shows that it was necessary to shut-in two wells in the north-west (upper left) to meet the migration velocity constraint. In addition channelling led to poorer coverage of the top-surface. Despite this reduction in storage efficiency Fig. 11(b) shows that the introduction of structural trapping due to top-surface topography stored 29% of the injected CO₂. This is visualised in Fig. 15 by the red high saturation patches.

The additional structural trapping along with the less secure high dip regions introduced two features with competing effects upon the storage capacity. First, structural trapping locally increased capacity. Second, high dip regions locally reduced capacity as they increased migration velocities and distances. The combined effect of the two impacts is subtle. If the structural closures alone were placed above the smooth model there could be a 48 Mt increase in storage. However, in this realistic example, where the geology has created structural closures there are associated regions that dip away from the structure. Also in other areas full closure is not formed and even worse, some partial closures form routes that can either lead to escape or prohibited high velocity migration. The result was that large portions of the remaining top-surface area outside the structural closures became less efficient at storage than in the smooth model. Effectively large portions of this area gained characteristics of the migration velocity limited storage regime. In the migration velocity limited regime where less CO₂ is low migration velocity stored, less is injected and therefore there is less dissolved or residually trapped CO₂ at 1000 years. This ultimately led to the lower storage efficiency in this case.

For migration velocity limited cases we first consider the 1 D, 0.27° case. Migration velocity was still the main constraint on capacity when top-surface topography was introduced. Fig. 14 shows that the introduction of top-surface topography increased

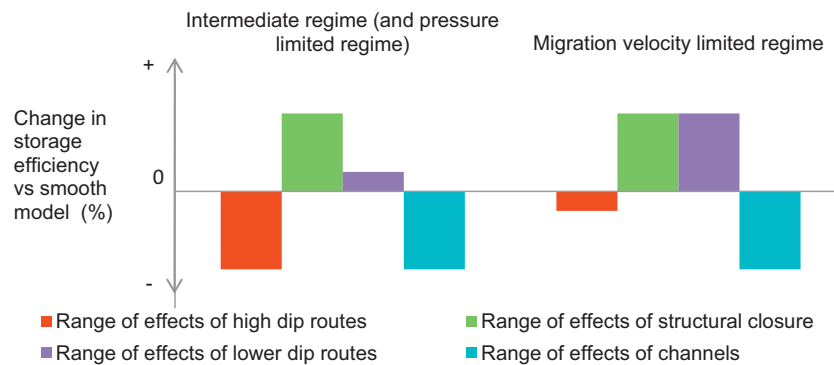


Fig. 16. Conceptual range of potential effects of the introduction of top-surface topography to the storage regime models.

the storage efficiency from 0.2% to 0.4%. Fig. 11(c) shows the increase almost directly corresponds to the increase in storage from the CO₂ stored in structural closures in the top-surface topography.

For the 145 mD 3° case, in contrast, the introduction of top-surface topography into the smooth model failed to produce any structural closure due to the large angle of dip. Fig. 14 shows a very small reduction in storage efficiency to 0.29%. Higher dip regions have little effect on storage efficiency if there is no low velocity CO₂ in the smooth model. However, we did see some channelling of CO₂ which led to poorer coverage of the top-surface and the small reduction in storage efficiency.

Finally we consider the 145 mD 1° case. Table 2 shows that the characteristic migration velocity of this model only just crossed the 10 m/year threshold and thus was able to store modest amounts of low velocity CO₂ at gas saturations a little below maximum gas saturation. This gave the model some characteristics similar to the intermediate storage regime and also led to the slightly more favourable 0.9% storage efficiency shown in Fig. 14. The dip eliminates most of the possible increased storage capacity from structural closure.

In summary, the introduction of top-surface topography introduces structural closures, regions of higher and lower dip than the model average, and channels. In models where capacity is pressure limited, these topographical features are seen to have little effect on storage efficiency. However, in intermediate regime and migration velocity limited models the introduction of top-surface topography to smooth models can affect storage efficiency by at least a factor of two.

The key effect of each of the four features is summarised as follows:

Structural Closure: the addition of localised structural closure allows immobilisation of high saturation CO₂ thus increasing storage efficiency. This is dependent upon CO₂ being able to access the correct regions though.

Higher dip routes to escape: These cause higher migration velocities which can affect the storage capacity – most significantly due to the migration velocity constraint. In particular they can stop the storage of high saturation, low velocity CO₂. The effect is thus regime dependent so that high dip routes will:

- Significantly decrease storage efficiency when low migration velocity storage is high in the equivalent smooth model (intermediate regime).
- Make significantly less difference to storage efficiency if there was little low migration velocity storage in the smooth model (migration velocity limited regime).

Lower dip routes to escape: The opposite to higher dip routes – so lower dip routes will

- Significantly increase storage efficiency when low migration velocity storage is low in the equivalent smooth model (migration velocity limited regime).
- Make significantly less difference to storage efficiency if there was a large amount of low migration velocity storage in the smooth model (intermediate regime).

Top-surface channels: Locally reduce the areal coverage of CO₂. Based on the assumption that the high areal coverage would be achieved on a smooth topography, channelling reduces storage efficiency.

The effects of these features compete to increase or decrease storage efficiency as demonstrated graphically in Fig. 16. This conceptual level picture of the balance of competing effects of the geological features suggests that migration velocity limited models are more likely to underestimate capacity than the other regimes. However, all three of the regimes here may see either increases or decreases in storage as a result of including top-surface topography. In general this will depend upon the geological occurrence of each feature that any particular top-surface topography introduces.

For the Forties top-surface topography considered in this work the most influential features were the structural closure and high dip routes. Introducing top-surface topography to our smooth homogeneous models induced the following effects:

- Our pressure limited model (11 mD 0.27°) showed little change.
- Our intermediate storage regime models (145 mD 0.27°) saw a decrease in storage efficiency as the effect of higher dip routes was more significant than the addition of structural closures. One model (145 mD 1°) categorised as migration velocity limited, but sitting very close to the transition also behaved similarly.
- Our remaining two migration velocity limited storage regime models either saw increases due to structural closure (1 D, 0.27°) or minimal change in storage efficiency (145 mD 3°).

These conclusions fit with those from the recent work of Nilsen et al. (2012), who demonstrated that morphology can have a significant impact on estimates of structural closures upon structural and residual trapping. However, while we considered a number of smooth homogeneous cases but introduced just one top-surface topography, Nilsen et al. (2012) treated just one smooth model but with multiple synthetic realisations of the top-surface topography.

5.2. Effect of heterogeneity upon storage capacity

The introduction of heterogeneity into the 11 mD 0.27° pressure limited storage regime model caused a drop in storage efficiency from 5.5% to 3.5% as shown in Fig. 14. Table 3 shows the capacity was still constrained by the pressure constraint at the lower

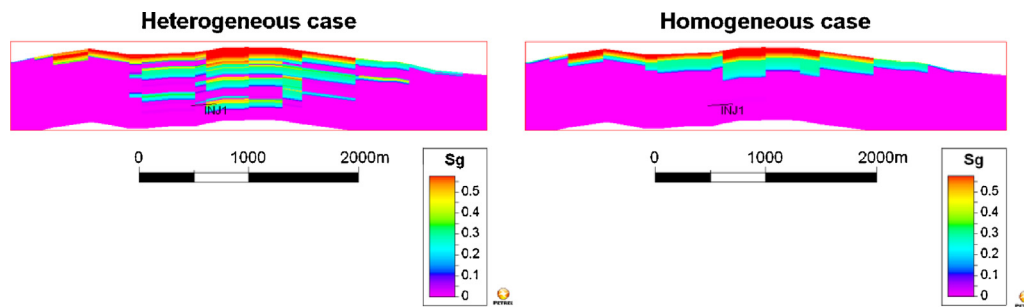


Fig. 17. Gas saturation profiles to show wider lateral migration under shales in the heterogeneous model (left) compared to the homogeneous model (right) at 1000 years. Both models have 145 mD permeability and 0.27° dip.

injection rate, because of localised pressure build-up in the heterogeneous case. These localised pressures can be seen to occur in regions surrounded by low permeability volumes such as shales. Heterogeneity also introduces uneconomic injectivity regions and therefore lower storage efficiency.

The effect of heterogeneity upon storage efficiency in the 145 mD 0.27° intermediate and 1 D 0.27° migration velocity limited storage regimes is considered together as the results are similar. In both cases the introduction of heterogeneity increases storage, from 1.2% to 2.0% and 0.4% to 0.8% respectively as shown in Fig. 14. Fig. 11(b and c) shows a rise in residual trapping and dissolution. This is explained by heterogeneity, such as shale layers within the model, which boosted the lateral migration of the CO₂ after injection. This led to greater reservoir contact and as predicted by Juanes et al. (2006) this resulted in more residual trapping and dissolution. This is demonstrated in Fig. 17 where far more extensive lateral migration and sweep is seen in the heterogeneous case. Although extending this result beyond cases with shale layers is not certain, it is supported by Lengler et al. (2010), who show that the time taken for CO₂ to spread is increased by heterogeneity.

An increase in storage is also seen for low migration velocities. This was mainly a result of trapping under thin shale layers deeper within the aquifer.

The introduction of heterogeneity has two major effects upon storage efficiency and the effect of heterogeneity depends upon the characteristics of comparable homogeneous model. In models with pressure limited storage efficiency, heterogeneity reduced storage efficiency due to partial compartmentalisation. In models where either the boundary constraint or migration velocity constrained storage efficiency, vertical heterogeneity improved storage efficiency by increasing the lateral sweep of CO₂.

6. Discussion

A key set of assumptions made in this work were the constraints used to assess the capacity of storage units. These are the assumptions made in Gammer et al. (2011) in which current regulation and guidance were interpreted. However, regulation can change and current guidance (European Commission, 2011) could be interpreted differently. The results of this work would have sensitivity to this; in particular if full residual trapping of CO₂ was required rather than permitting the storage of mobile but very slowly migrating CO₂ at 1000 years. This is demonstrated by Goater and Chadwick (2013), who showed the strong sensitivity to regulatory assumptions. If full residual trapping were required the CO₂ migration velocity would not be a key constraint. Areas where regulatory assumptions may affect our results include the time at which CO₂ stability is required, the acceptable migration velocity at that time and the proportion of injected CO₂ that must remain within the storage unit. Szulczewski et al. (2012) showed that under the assumption of full trapping, storage efficiency is less sensitive

to permeability and aquifer dip and more sensitive to the aquifer dimensions.

A number of other assumptions were also required. Firstly, only one top-surface topography and aquifer heterogeneity was employed. This has been successful for identifying mechanisms. More robust estimates of the average effect of top-surface structure and heterogeneity upon capacity would be obtained from consideration of an ensemble of putative aquifer models. In addition, to provide practical storage capacity estimates, a probabilistic approach to uncertainty in other parameters, such as permeability, should be taken. For instance, a probabilistic approach was taken by the UK Storage Appraisal Project (Gammer et al., 2011) to account for parameter uncertainty.

Secondly, our evaluation was undertaken at the scale of a storage unit that may be considered for licensing, rather than the entire basin scale, as regulation could apply directly to the storage unit alone. At the basin scale, the balance of some effects considered in this work may be slightly different. For example, the effect of high dip routes in the centre of a basin may be considered less important than at the edge of a storage unit. In addition, we have considered open boundaries over a storage unit scale, when potentially other adjacent units could change the nature of the boundary condition. This was assumed as, given the significant scale of a storage unit, it is not clear how often operation of neighbouring storage units would coincide.

7. Conclusions

A quantitative framework for assessing the CO₂ storage efficiency of dipping open aquifer storage units, as developed in Gammer et al. (2011), has been considered. This evaluates efficiency under a realistic set of regulations and places different storage sites into a number of regimes dependent upon their characteristics. The storage efficiency in each regime is limited by different constraints: pressure, migration distance, and migration velocity, with injection optimised within these. Potential adaptations to the regimes have also been considered. These account more explicitly for the limiting pressure capacity and the level of uneconomic injection.

The storage regimes identify permeability and aquifer dip as key determinants of storage efficiency due to their control on the velocity of mobile CO₂ and pressure. Open aquifers of modest permeability and dip can be favourable storage sites with large storage capacities. These aquifers limit the speed with which the CO₂ migrates, while the extensive open pore volume dissipates pressure.

The effect of introducing top-surface topography and heterogeneity was investigated. The effect of heterogeneity was shown to depend upon characteristics of comparable homogeneous model. When introduced to homogeneous models where pressure build-up limits storage efficiency, heterogeneity reduced storage efficiency due to localised pressure build-up. For homogeneous

models where pressure was not a constraint, vertical heterogeneity was seen to improve storage efficiency by improving the lateral sweep of CO₂.

Top-surface topography introduces structural closures, regions of higher and lower dip than the model average, and channels. When introduced to smooth models, structural closures increase efficiency and channels generally decrease efficiency. The effect of higher and lower dip routes upon efficiency is dependent upon the regime categorisation of the equivalent smooth model. The introduction of high dip routes significantly decreases storage efficiency when CO₂ in the equivalent smooth model is not limited by the migration velocity of CO₂ or pressure. Lower dip areas significantly increase storage efficiency if the equivalent smooth model is limited by the migration velocity of CO₂. Otherwise the higher and lower dip routes have little effect.

The effects of these four topographical features compete to increase or decrease storage efficiency. For the North Sea top-surface topography used in this work the balance of effects was dominated by structural closure and high dip routes. In general the balance will depend upon the geological occurrence of each feature that any particular top-surface topography introduces. However, the difference in effects of high and low dip regions upon different smooth models suggests that smooth models where the migration velocity of CO₂ limits efficiency are more likely to underestimate capacity than other models.

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