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Chimneys And Channels: History Matching The Growing CO2 Plume At The Sleipner Storage Site

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Summary

A revised analysis of seismic data at Sleipner has revealed large-scale, roughly north-trending, channels at a range of levels in the Utsira Sand. The seismic data also reveal localised chimneys within the reservoir and overburden, some of which show evidence of having provided vertical conduits for earlier natural gas flow. Reservoir flow models were set up with flow properties constrained by the observed levels of CO2 accumulation in the reservoir and the arrival time of CO2 at the reservoir top just prior to the first repeat survey in 1999. The initial model with laterally homogeneous sand units separated by thin semi-permeable mudstones achieved a moderate match to the observed time-lapse seismics. Subsequent flow models, progressively incorporating higher permeability vertical chimneys through the mudstones and large-scale channelling within the reservoir sands, yielded a progressive and marked improvement in the history-match of key CO2 layers within the plume. The preferred plume simulation flow model was converted into a seismic property model using Gassmann fluid substitution with an empirical Brie mixing law. Synthetic seismograms generated from this show a striking resemblance to the observed time-lapse data, both in terms of plume layer reflectivity and also of time-shifts within and beneath the CO2 plume.

Introduction

CO_2 separated from natural gas produced at the Sleipner field in the North Sea is being injected into the Utsira Sand, a regional saline aquifer of late Cenozoic age. Injection commenced in 1996 with around 18 million tonnes stored by 2018. The storage aquifer comprises mostly unconsolidated sand of high porosity (> 30%) and high permeability (> 1 Darcy) and is generally in excess of 200 m thick. A number of thin intra-reservoir mudstones, typically 1 – 2 m thick, are evident from geophysical logs acquired in wells around Sleipner (Figure 1a). Time-lapse seismic 3D data suggest the CO_2 has accumulated in the reservoir as a multi-tiered plume comprising up to 9 individual layers of CO_2 trapped beneath the mudstones (Figure 1b) that have acted as partial baffles to the upward flow of CO_2.

The key processes controlling fluid flow in the reservoir as a whole, both horizontal and vertical, remain poorly understood. It is evident that flow through the mudstones is via at least one high permeability chimney (chimney 1 in Figure 1b), but the exact mudstone by-pass mechanisms are currently unknown. The purpose of this study is to combine 3D simulations of the whole CO_2 plume with synthetic seismic modelling, to provide insights into the mechanisms by which CO_2 has migrated through the layered reservoir. In particular the models have been designed to investigate the geometry and evolution of enigmatic chimney features observed on 3D seismic data (Figure 1b). In addition, we have investigated the possible influence of high permeability channels developed within individual reservoir sands (Figure 1c).

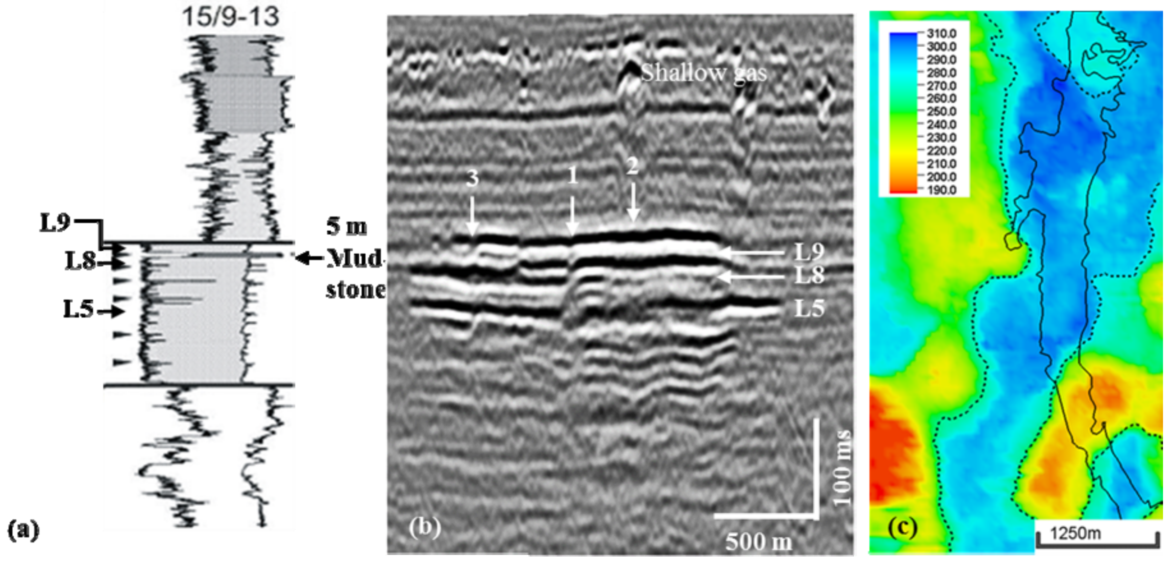

__Figure 1__ (a) representative geophysical well logs showing reservoir heterogeneity (γ-ray logs on the left tracks and resistivity logs on the right tracks). The reservoir sand has characteristically low γ-ray and resistivity readings so peaks within the sand denote thin mudstones. The approximate location of key CO_2 layers in the reservoir are shown, together with the 5-metre mudstone separating an upper sand wedge from the rest of the Utsira reservoir. (b) 2010 vintage seismic inline through the Sleipner CO_2 injection site showing three putative 'chimneys' (arrowed). Reflections from three key CO_2 layers (5, 8 and 9) discussed in the text are also labelled. (c) Utsira sand isopach map showing the location of the main Utsira channel (stippled black line) and the top sand wedge channel (solid black line) incorporated into the reservoir model.

3D reservoir model

A 3D geological model of the Utsira Sand reservoir was built from seismic picks depth-converted using a uniform mean overburden velocity of 1845 m/s and a reservoir velocity of 2050 m/s. The model was discretised using 60 50 x 50 m cells along the X axis and 111 50 x 50 m cells along the Y axis. The reservoir was divided vertically into 132 cells with a mean cell height of 2 m. No-flow boundary conditions were placed at the top and base of the reservoir, while the lateral boundary domains were maintained at near hydrostatic pressure conditions. The reservoir was sub-divided into a series of sand layers separated by thin laterally impersistent mudstone horizons: permeability information for each model is included in Table 1.

Model	Mst. 1 (mD)	Mst. 2 (mD)	Mst.3 (mD)	Mst. 4 (mD)	Mst. 5 (mD)	Mst. 7 (mD)	Mst. 8 (mD)	Number of chimneys	Chimney permeability (mD)
1	100	100	100	100	100	100	100	0	100
2	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	1	100
3	100	100	100	100	0.0001	0.0001	0.0001	1	100
4	100	100	100	100	100	100	0.0001	1	100
5	100	100	100	100	0.0001	0.0001	0.0001	2	100/100
6	100	100	100	100	0.0001	0.0001	0.0001	2	100/100
7	100	100	100	100	0.0001	0.0001	0.0001	2	100/100
8	100	100	100	100	0.0001	0.0001	0.0001	3	100/100/100
9	100	100	100	100	0.0001	0.0001	0.0001	3	100/100/2000[1]
10	100	100	100	100	0.0001	0.0001	0.0001	3	100/100/2000[2]

Table 1 *Key permeabilities (in milli-Darcy (mD)) for each model run. Models 7-10 introduce two high permeability N-S channels in the Utsira Sand. [1]In Model 9 Chimney 3 was assigned reservoir sand properties [2]In Model 10 Chimney 3 was assigned reservoir sand properties at the level of Mudstone 5 and semi-permeable mudstone properties above this layer.*

The simulations were designed to investigate the distribution and role of vertical (chimneys) and horizontal (channels) permeability pathways on the evolution of the plume. The location and geometries of the chimneys (Figure 1b) and channels (Figure 1c) included in the models were based on seismic observations (Williams & Chadwick, 2017; Cowton *et al*., 2018). In the first six simulations the height, number and flow properties of chimney conduits through the mudstones were systematically varied (Table 1). In these models the reservoir sands were assigned a uniform porosity of 0.37 and anisotropic permeability of 2 Darcy in the east-west direction and 8 Darcy in the north-south direction throughout the grid. Each intra-reservoir mudstone was assigned a uniform porosity of 0.34 and permeability of either 100 mD (semi-permeable) or 0.0001 mD (low permeability) depending on the model. The semi-permeable mudstone value was derived from a series of initial runs of simulation Model 1 (Table 1) in which an assumed uniform permeability of the mudstone layers was adjusted to allow a small amount of CO_2 to reach the top of the reservoir just prior to the 1999 time-lapse repeat seismic survey. The final four models (Models 7-10) introduce two high permeability N-S channels: one in the main Utsira reservoir and one in the topmost sand unit (Figure 1c). The sands within these channels were again assigned a permeability of 2 Darcy in the east-west direction and 8 Darcy in the north south direction.

Results

Results were constrained and calibrated by two key controls on model fidelity: the growth of the topmost CO_2 layer as measured on time lapse seismic data (Figure 2) and the horizontal distribution of the 3 largest CO_2 layers in the plume (Layers 5, 8 and 9 in Figure 1b). The simulations showed that a combination of chimneys and channels are required to match the growth of the CO_2 plume at Sleipner. Uniform semi-permeable mudstones (Model 1) result in a very high and rapidly increasing flux of CO_2 into the top reservoir sand (Figure 2). Models with a single vertical chimney (Models 2-4) trap most of the gas within the deeper CO_2 layers and are unable to match either the volumetric growth of the top layer (Figure 2) or the CO_2-Water Contacts (CWC) of the largest CO_2 layers observed on seismic data. Incorporating additional chimneys into the reservoir model (Models 5 and 6) increase the flux of CO_2 to the top of the plume and result in an improved fit to the volumetric growth of the top layer (Figure 2). These models cannot, however, reproduce the observed CWC's of Layers 5, 8 and 9 without incorporating high permeability channels into the model (Models 7-10). The best fit to the data is obtained using two high permeability channels together with 3 enhanced permeability chimneys. This combination provides a reasonable fit to the volumetric growth of the top layer (Model 10 in Figure 2) and an excellent fit to the observed CWC's (Figure 3a). Synthetic seismic modelling using the CO_2 distribution from Model 10 and a Brie patch mixing model gives a good match to observed reflectivity (Figure 3b) and measured pushdown (Figure 3c) at the time of the 1999 time-lapse monitor survey.

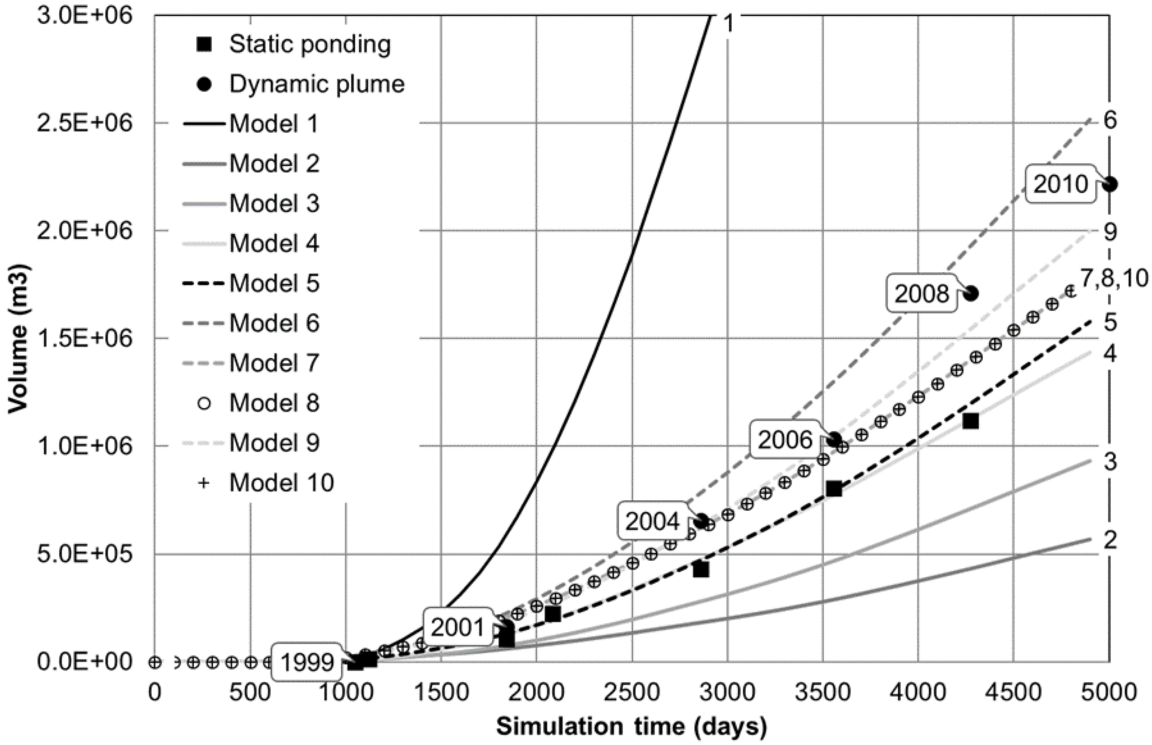

Figure 2 *Volumetric growth of the topmost CO_2 layer for each of the model scenarios in Table 1. Volumetric growth curves for each modelled scenario are numbered for clarity. Estimates of top layer volume from time lapse seismic data assuming static ponding of CO_2 beneath the reservoir topseal are shown as solid black squares. Solid black circles show the growth of the top CO_2 layer assuming a dynamic plume (based on methodology of Chadwick and Noy, 2010).*

Conclusions

Baseline seismic observations on reservoir structure and heterogeneity have been used to develop an improved 3D reservoir model of the Utsira Sand at Sleipner. Numerical flow simulations using the revised reservoir model show markedly improved history-matches for key CO_2 layers within the CO_2 plume compared with models that have laterally homogeneous sand properties, and without any need for detailed layer shape tuning. Synthetic seismograms of the preferred plume flow model provide a good match to the observed time-lapse seismic datasets, in terms both of reflectivity and time-shifts. Again, without any manual tuning of layer shapes or thicknesses.

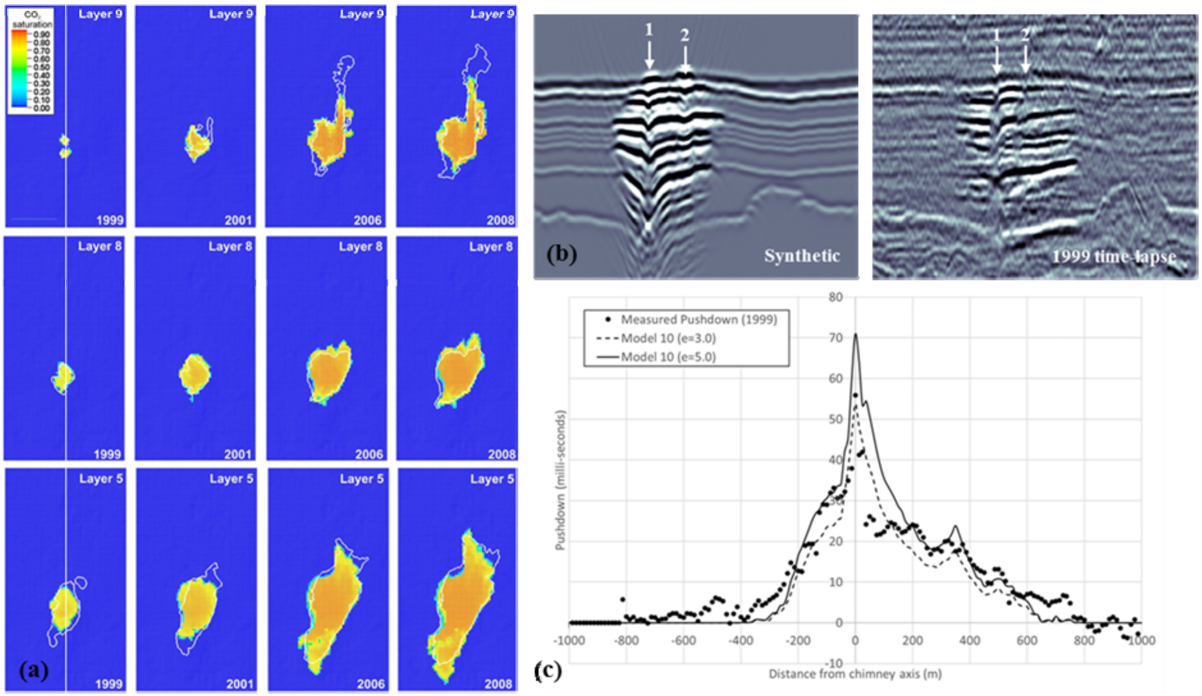

Figure 3 *(a) Evolution of key layers 9, 8 and 5 in the CO_2 plume for the best fit reservoir model (Model 10 in Table 1). White polygons delimit the CWC observed on time-lapse seismic data. (b) Comparison of a synthetic seismic section computed from Model 10 along the white line of section in (a) and a nearby inline from the 1999 seismic survey. (c) Comparison of pushdown of the Base Utsira reflection measured on the 1999 time-lapse data (solid black circles) and the synthetic seismic section assuming a patchy Brie mixing model with e=3 (stippled black line) and e=5 (solid black line).*

Acknowledgements

We acknowledge funding from NERC Grant NE/N016386/1 and EPSRC Grant EP/P026214/1 and also Equinor and the Sleipner partners for access to seismic datasets. The authors publish with permission of the Executive Director, British Geological Survey (NERC).

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