Optimising CO_2 storage in geological formations; a case study offshore Scotland

CO_2MultiStore project

September 2015

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A collaborative study published by Scottish Carbon Capture & Storage

Print managed by GMP Print Solutions.
The text and cover are printed on Cocoon 50% Silk FSC Recycled Credit
with the cover gloss laminated with a biodegradable laminate.

ISBN: 978-085272-852-9 printed version
ISBN: 978-085272-853-6 online version

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CO$_2$MultiStore study area showing national sectors of the North Sea

Foreword

The UK's targets to reduce greenhouse gas emissions are both ambitious and challenging. They cannot be achieved without taking every option to reduce the release of carbon dioxide (CO_2) into the atmosphere. The CO_2 released by burning fossil fuels and from industrial processes can be captured and permanently sequestered in deeply buried, offshore geological formations around the UK in a process known as carbon capture and storage (CCS). Knowledge of the geological formations gained during the exploration and production of oil and gas, and industry and research expertise, have all contributed to the recognition of the potential CO_2 storage around the UK, whether in exhausted hydrocarbon fields or in saline aquifers — ancient porous sandstones saturated with salt water.

Whilst the UK is at the forefront of the implementation of CCS in Europe, with four projects proposed to capture CO_2 at power plants and store it in rocks beneath the UK North Sea, there remain challenges for investors, companies and governments. One key challenge relates to improving understanding of the geological storage resource itself, something that cannot happen unless investment is combined with the UK's substantial technical capability. The research described in this report represents an important step along the road towards that aim, having brought together a unique industry partnership of academia, government and industry, and having made use of data collected as a result of oil and gas industry operations and data generated through early stages of the UK's CCS commercialisation competition.

The project illustrates how the Captain Sandstone, the storage formation proposed for the Peterhead CCS commercialisation competition project, is predicted to respond if it were developed with more than one CO_2 injection site. It provides vital insights and learning for the CO_2 storage sector — regulators and operators alike — to help optimise the management and the operation of CO_2 injection into large saline geological formations such as the Captain Sandstone at a regional scale utilising more than one location. It also sets a benchmark for best practice in the way to analyse and assess CO_2 storage prospects, having investigated methods of simplifying and reducing costs of that process along the way.

CO_2 storage has been in operation in a large saline formation associated with the Sleipner Gas Field in the Norwegian sector of the North Sea since 1999. The learning captured in this research is therefore relevant for exploiting the immense storage resource in all regions of the North Sea. In particular, the generic learning on the use of multiple injection sites in the development of large storage formations can be applied to projects following on from demonstration sites both in the North Sea and in CO_2 storage formations worldwide.

Experience gained by developing CCS in the North Sea will give the companies involved, whether in hardware development or in the practicalities of implementation, the credibility and experience needed to do well in an expanding overseas market.

Lord E R Oxburgh KBE

Sleipner Field CO_2 injection project, Norwegian North Sea.
Photograph: Harald Pettersen/Statoil.

Executive summary

Carbon capture, transport and storage (CCS) is considered a key technology to provide a secure, low-carbon energy supply and reduce the greenhouse gas emissions (DECC, 2014) that contribute to the adverse effects of climatic change (IPCC, 2014). Commercialisation projects for the permanent storage of carbon dioxide (CO_2) captured at power plants are currently in the design stage for the Peterhead, White Rose, Caledonia Clean Energy (DECC, 2013, 2015) and Don Valley projects. Storage of the CO_2 captured by these projects is planned in strata deep beneath the North Sea in depleted hydrocarbon fields or regionally extensive sandstones containing brine (saline aquifer sandstones).

The vast majority of the UK and Scotland's potential storage resource, which is of European significance (SCCS, 2009), is within brine-saturated sandstone formations. The sandstone formations are each hundreds to thousands of square kilometres in extent and underlie all sectors of the North Sea. The immense potential to store CO_2 in these rocks can only be fully achieved by the operation of more than one injection site within each formation.

Government, university and research institutes, industry, and stakeholder organisations have anticipated the need to inform a second phase of CCS developments following on from a commercialisation project in Scotland. The CO_2MultiStore study, led by Scottish Carbon Capture and Storage (SCCS), investigates the operation of more than one injection site within a storage formation using a North Sea case study. The Captain Sandstone, within the mature oil and gas province offshore Scotland, contains the Goldeneye Field, which is the planned storage site for the Peterhead CCS project. Previous research (SCCS, 2011) was augmented by data from offshore hydrocarbon exploration and detailed investigation of the Goldeneye Field for CO_2 storage (Shell, 2011a-i).

The research was targeted to increase understanding and confidence in the operation of two or more sites within the Captain Sandstone. Methods were implemented to reduce the effort and resources needed to characterise the sandstone, and increase understanding of its stability and performance during operation of more than one injection site. Generic learning was captured throughout the CO_2MultiStore project relevant to the characterisation of the extensive storage sandstones, management of the planned injection operations and monitoring of CO_2 injection at two (or more) sites within any sandstone formation.

The storage of CO_2 can be optimised by the operation of more than one injection site in a geological formation by taking a regional-scale approach to site assessment. The study concludes that at least 360 million tonnes of CO_2 captured over the coming 35 years could be permanently stored using two injection sites in the Captain Sandstone. Confidence in the planned operation of two or more injection sites in a storage formation is greatly increased by the use of existing information, knowledge and data acquired during hydrocarbon exploitation.

Widespread pressure changes should be expected by the injection of CO_2 at more than one site. Assessment, management and monitoring of pressure changes on a regional scale will optimise the storage capacity, ensure security of storage and prevent adverse effects to existing storage and hydrocarbon operations.

The vast offshore potential across all sectors of the North Sea could be made accessible and practical for storage of CO_2 captured from European sources by the operation of two or more sites in a storage formation by following the approach taken in CO_2MultiStore.

Key conclusions

1. The potential capacity for subsurface CO_2 storage identified by previous studies can be optimised by the operation of more than one injection site within a geological formation, based on this investigation by research scientists and prospective site operators.

2. The predicted performance of two reasonable and realistic CO_2 injection sites in the Captain Sandstone illustrates how security of storage can be maintained for the simultaneous operation of two sites.

3. Stakeholders can have increased confidence that at least 360 million tonnes of CO_2 captured over the coming 35 years could be permanently stored, at a rate of between 6 and 12 million tonnes per year, using two injection sites in the store assessed in CO_2MultiStore.

4. The availability of historical information, knowledge and data acquired during decades of UK offshore hydrocarbon exploration and production increases understanding and confidence for two or more prospective CO_2 injection sites in a storage formation. This research has greatly benefited from the re-use of historical information and expert input from industry participants, and access to data vital to increase confidence in storage prediction.

5. Storage of CO_2 at more than one injection site will create widespread interacting pressure changes within the storage formation, which will determine the total amount of CO_2 that can be stored. Effective appraisal of stores must include assessment of the regional changes in pressure generated by CO_2 injection over the lifetime of two or more sites.

6. The maximum acceptable pressure for all injection sites in a regional storage formation is ultimately defined at the location with the lowest acceptable maximum pressure limit to ensure security of storage throughout the formation. This location may be distant from an injection site.

7. The pressure changes generated at one site will interact with another site and also affect any nearby hydrocarbon fields within a storage formation. Pressure changes should be monitored at each of the injection sites and at hydrocarbon fields in the vicinity. Interaction of pressure changes from injecting CO_2 at a later time may be detrimental to a pre-existing site, which the second operator would address during project design. After the start-up of a second site, transmission of pressure changes can take years to significantly affect the first. In the scenario explored in CO_2MultiStore the delay is five years for sites that are 45 km apart.

8. CO_2MultiStore has implemented methods to reduce the effort and resources needed to predict the performance of additional prospective sites in the Captain Sandstone case study, validated by the industry data, by:

- Targeted simplification of extensive geological and flow simulation models
- Initial resource-effective fluid modelling before resource-intensive predictive modelling
- Grouping formations of similar geomechanical properties
- Defining a mathematical formula to evaluate the geomechanical stability of the injection sites
- Combining simpler calculations and detailed analyses; initial regional-scale calculations followed by site-specific geomechanical assessments and construction of simplified models for flow simulation of the regional pressure response before detailed modelling

9. CO_2MultiStore methods are expected to reduce the cost and increase investor confidence by resource-effective characterisation, to create a good storage reservoir model as recommended by the CCS Cost Reduction Task Force (CRTF, 2013). The CO_2MultiStore methods streamline the predictive process and can give a ‘first pass’ assessment of the suitability of a prospective site before embarking on costly detailed investigations. The methods tested are generic and can be applied worldwide.

10. If development of a store with more than one injection site is planned, a regional approach should be followed to establish the maximum operating pressure at individual sites. The maximum acceptable pressure would be defined to prevent adverse effects to the store, including nearby operational hydrocarbon fields. Mandatory monitoring will

demonstrate the sites are operating as predicted and to provide an early 'flag' should additional pressure management activities be needed.

11. Monitoring should distinguish the pressure effects from injection at the operator's own site, the effects of injection from another site in a storage formation, and pressure management activities. Additional monitoring by later storage sites may be required to ensure they do not adversely affect existing storage operations.

12. A pro-active regional approach to management of storage has the potential to optimise the resource, increases confidence in the 'security of provision' of storage capacity and increases certainty in the relationship with other users of the storage formation.

13. Managed changes in pressure due to CO_2 storage operations may be beneficial to oil and gas fields in a mature hydrocarbon province. The cost of pressure management or increased pressure for a hydrocarbon field operator may be reduced by managed CO_2 storage operations.

14. Insights gained from this research, essential to the effective characterisation and appraisal of any CO_2 storage resource with injection at more than one site, are:

- Early and continuous dialogue between geologists and engineers is vital to reliably predict performance to inform design and operation of more than one injection site within a storage formation
- The value of a storage formation model is increased by merging more than one existing geological model and re-using established knowledge and experience contained within the models gained from hydrocarbon field exploration and production
- The character of fluids and the properties of rocks at nearby hydrocarbon fields are essential data, acquired by field operators, to inform prediction of CO_2 storage operations
- Records of operations throughout the lifetime of a hydrocarbon field are a key source of information to validate predictions of storage performance. The detailed history of pressure changes and concurrent well flow rates, from initiation to depletion of a field, is very important and significantly increases confidence in the prediction of the performance of injection sites

15. Understanding of the Captain Sandstone storage resource has been substantially matured by integration of the expertise and knowledge of research scientists and industry in the CO_2MultiStore study investigations. Injection of 360 million tonnes of CO_2 modelled at the two sites is stored within one sixth of the total Captain Sandstone area. Storage of 360 million tonnes of CO_2, the previous estimated minimum theoretical capacity for the sandstone (SCCS, 2009) and total calculated at twelve possible injection points (SCCS, 2011), is predicted using hydrocarbon field data at two feasible and practical injection sites.

16. The CO_2MultiStore findings are important in a European context as they illustrate an approach to make the vast potential, in all sectors of the North Sea, accessible and practical for CO_2 storage. The methods developed in CO_2MultiStore can be applied to optimise CO_2 storage and give greater confidence to prediction of site performance worldwide.

Next steps to accelerate North Sea CO_2 storage

Considerable progress towards the implementation of CO_2 storage has been made by industry, Scottish and UK Governments, regulators and academia, contributing individually and in collaboration, since 2011 by:

- Selection of two prospective demonstrator storage sites in the UK North Sea (DECC, 2013)
- Recognition of the need and ability of the sector to reduce costs for 'next of a kind' second phase storage projects (CRTF, 2013)
- Presentation of options for a Central North Sea Storage Hub (Element Energy, 2014)
- Support for a strategic appraisal of UK CCS storage for follow-on projects (ETI, 2014)

Investigation of the development of multi-user stores in depleted hydrocarbon fields and offshore sandstones by CO_2MultiStore illustrates how the offshore storage resource could be used to permanently store captured CO_2. The research has also highlighted how use of existing knowledge and data can be extended to further increase confidence for investment in commercial-scale CO_2 storage in multi-user stores and in the Captain Sandstone.

Activities are proposed to increase confidence in storage site performance prediction by enhancing access to existing data, to assess benefit to existing hydrocarbon fields and inform pressure management of offshore formations.

1. Information, knowledge and data from hydrocarbon production should be made accessible for the assessment of offshore CO_2 storage resources. Agreements should be made for access to data held as 'commercial-in-confidence' by the operators of hydrocarbon fields that are, or near, prospective carbon stores.

Information to inform and validate the prediction of storage site behaviour is to include:

- Models of the hydrocarbon field geology, geomechanical stability and fluid flow
- Data on the physical character, composition and properties of the reservoir, cap rock, underlying strata and contained fluids
- Detailed history of pressure variations and well flow rates
- Well infrastructure and monitoring data

2. Operational hydrocarbon fields that are within prospective multi-user storage formations should be identified and assessed for the impact of storage site development. The pressure changes due to CO_2 storage operations as part of strategic development of a multi-user store should be predicted, to determine whether or not they are potentially beneficial to hydrocarbon production.

3. Options to optimise storage capacity by development of two or more injection sites in a regional storage formation by different pressure management strategies should be assessed and compared. For each option, the implications to the storage capacity for the entire storage resource and individual sites within it, as well as the operational responsibilities and cost implications, should be considered.

4. Opportunities to optimise geological storage of CO_2 and hydrocarbon recovery by assessing the operation of an integrated multi-user CO_2 store and enhanced oil recovery project should be studied. The potential for mutual benefit, to both the CO_2 storage and the hydrocarbon field components, should include economic and technical factors.

5. Historical information from hydrocarbon fields along the Captain Sandstone 'fairway' should be used to refine geomechanical stability modelling of CO_2 injection to maximise storage capacity in the Captain Sandstone.

1 Introduction

Demonstrator projects to reduce emissions of greenhouse gases from power and industrial plants by capture, transport and geological storage of carbon dioxide (CO_2) have proposed to contain the captured gas in deeply buried strata. Estimates of offshore CO_2 storage capacity for many nations around the North Sea hydrocarbon province include storage in suitable depleted oil and gas fields and also within sandstones that contain brine (Norwegian Petroleum Directorate, 2011; Bentham et al., 2014). Brine-saturated (saline aquifer) sandstones are very extensive and the potential storage capacity within them is estimated to be of much greater magnitude (thousands of millions tonnes CO_2) than in depleted oil and gas fields (tens to hundreds of millions tonnes CO_2) (SCCS, 2009; Bentham et al., 2014).

Exploitation of the potential storage resource within regional formations will be required to provide sites of sufficient capacity to accommodate commercial-scale storage of CO_2 to meet greenhouse gas emissions reduction targets (UK Government, 2008; Scottish Government, 2009). To maximise use of this resource, two or more injection sites will be required within any given storage formation. The large extent of individual sandstones, the number of hydrocarbon fields and the CO_2 injection sites anticipated within each present challenges to and implications for the licensing, operation and integrity of the storage formation.

This document presents the results, recommendations and key messages from the CO_2MultiStore project. The study builds on previous work by Scottish Carbon Capture and Storage (comprised of British Geological Survey (BGS); Heriot-Watt University; University of Edinburgh). The CO_2MultiStore project investigates a case study of two injection sites within a single multi-user storage formation, the Captain Sandstone (Figure 1). This report identifies generic learning from the CO_2MultiStore project case study of the key questions asked, learning from the process and technical knowledge gained relevant to any multi-user storage formation.

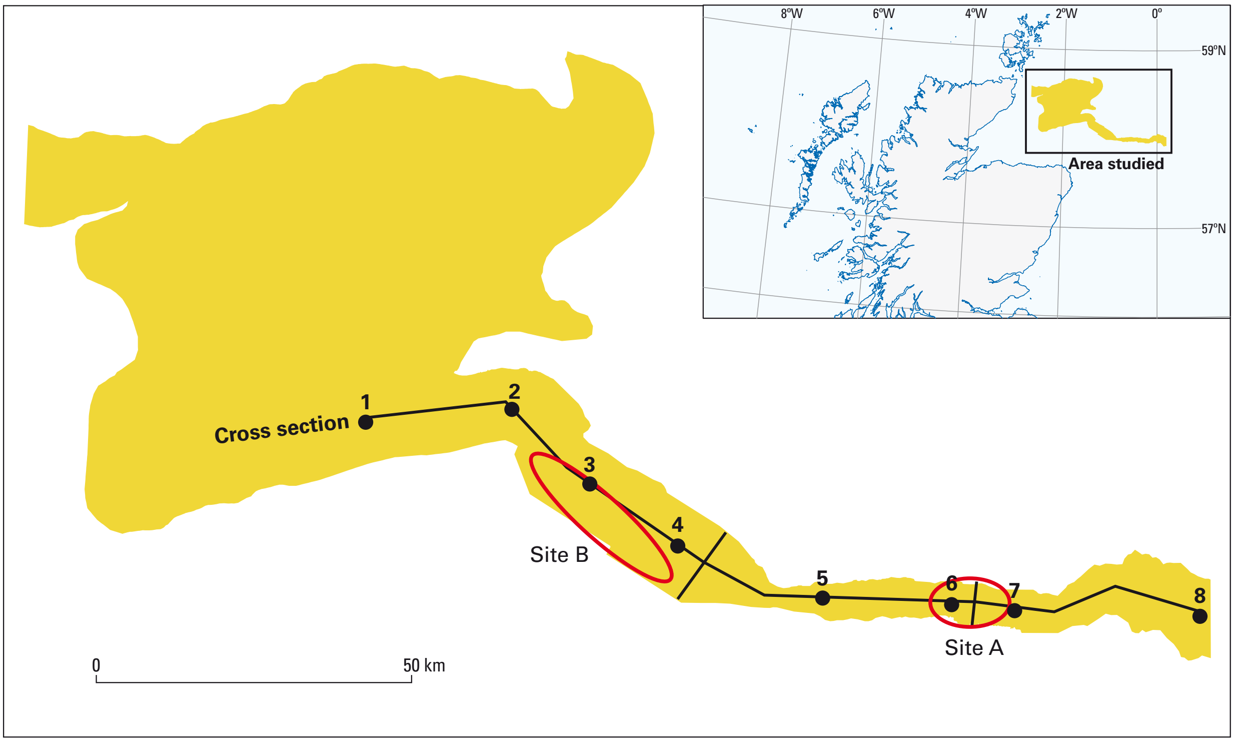
Prediction of the performance of firstly a demonstrator and secondly a 'follow-on' injection site within a regional storage formation is essential to anticipate and mitigate any adverse effects from the possible interaction with existing users of the pore space. Prediction of storage site performance is also required to assess any impact on existing uses of the pore space for hydrocarbon production or groundwater supply (EC, 2009 and 2011).

This study has:

- Investigated the subsurface storage of CO_2 by prediction of the operation, interaction and cumulative effect of two reasonable and realistic injection sites (an initial demonstrator and a subsequent 'follow-on' CCS project), within the same regional formation as a 'multi-user' CO_2 store
- Targeted investigation by predictive modelling to address the most highly ranked technical issues, raised by experts with industry experience in CO_2 storage, to increase understanding and certainty about the operation of more than one injection site
- Constructed a regional-scale, three-dimensional computer model of the storage strata, assessed the impact of pressure changes generated by CO_2 injection and simulated operation of the two injection sites

- Modelled the effect of the individual injection sites and the regional storage formation that will cumulatively maintain store integrity, predicted the extent of CO$_2$ migration at each injection site and assessed the effect on nearby hydrocarbon fields
- Determined the maximum injection rate and predicted duration and pressure constraints for CO$_2$ injection at both sites that cumulatively will not threaten the integrity of the regional storage formation
- Measured the effect of increased understanding and certainty of store performance and subsurface containment for the injection sites in CO$_2$MultiStore
- Implemented methods to reduce the effort and resources needed to model and predict storage performance over the large area needed for assessment of a regional multi-user storage formation
- Identified the constraints and requirements for site monitoring specific to a multi-user storage formation with two or more injection sites that would be included in the design of a monitoring plan
- Presented the generic learning from the North Sea case study on geological model construction, assessment of mechanical stability, prediction of injection site performance and the monitoring requirements, relevant to any multi-user storage formation

Figure 1 The extent of the CO$_2$MultiStore Captain Sandstone case study area, offshore Scotland, UK North Sea (inset) and position of the injection sites and lines of cross section



The CO$_2$MultiStore project investigates a case study of two injection sites within a single multi-user storage formation, the Captain Sandstone (Figure 1). This report identifies generic learning from the CO$_2$MultiStore project case study of the key questions asked, learning from the process and technical knowledge gained relevant to any multi-user storage formation.

2 Investigation of a multi-user storage formation: a North Sea case study

Much of the UK's CO_2 storage capacity is in extensive saline aquifer sandstones. However, research into optimising the storage capacity, taking into consideration leasing, permitting, operation and other subsurface users, is still in its relatively early stages.

The CO_2MultiStore project aims to reduce uncertainties thus increasing confidence in the business case for the development of multi-user CO_2 storage sites. The project investigates the interaction and cumulative effect of two CO_2 injection sites and their effect on nearby hydrocarbon fields. This approach assumes a first storage site within a depleted hydrocarbon field and surrounding aquifer sandstone and introduction of a second (or more) storage site within the same sandstone at a later date. Both sites are envisaged to benefit from re-use of existing oil and gas field infrastructure.

The definition of the two case study injection sites is intended to be both technically reasonable and realistic. The investigations of the North Sea exemplar case study address issues raised by the perceived effect of one storage site on another, as opposed to seeking to identify best practice associated with storage appraisal.

Technical activities are focused to increase understanding of the character of the multi-user store and reduce uncertainties arising from the interaction of the injection sites with other users of the pore space. The predictive model investigations were completed within the resources of a research project and targeted to address technical issues of greatest potential concern to the industry technical experts and researchers. No attempt has been made to present predictive models that are sufficiently comprehensive or detailed to support an application for a CO_2 storage permit without considerable additional investigations.

Injection Site A ('Site A') is positioned within the Goldeneye Gas Condensate Field incorporating the adjacent Captain Sandstone saline aquifer (Figure 2). The rate of injection is modelled as six million tonnes of CO_2 per year with a duration of 30 years, starting in 2016 until 2046.

Injection Site B ('Site B') assumes a second CO_2 injection site within the Captain Sandstone as a later follow-on project, anticipating the additional storage capacity required with the development of an established CCS industry. The reservoir is the saline aquifer Captain Sandstone west of the Goldeneye Field (Figure 2) with the position of the injection site informed by the results of initial predictive modelling activities in CO_2MultiStore. The position anticipates close interaction with nearby hydrocarbon fields, proximity to existing offshore infrastructure and pressure dissipation westwards in the Captain Sandstone (Figure 2). The rate of injection is also modelled as six million tonnes of CO_2 per year, to achieve an anticipated combined annual rate of storage needed of 12 million tonnes (SCCS, 2009). The duration of injection at Site B is also 30 years but starting in 2021 (five years after injection commences in Site A) until 2051.

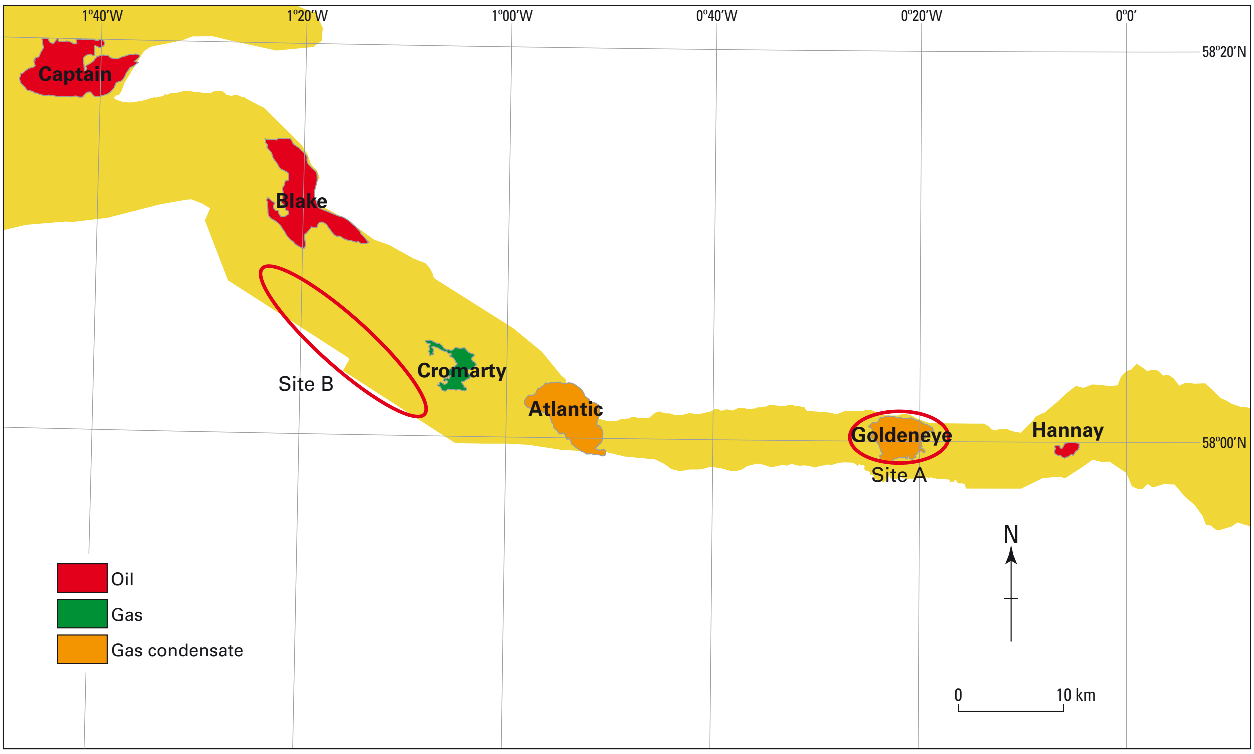


Figure 2 Hydrocarbon fields within the Captain Sandstone and positions of Site A and Site B for dynamic simulation of CO_2 injection modelled by CO_2MultiStore. Oil fields, red; gas fields, green; gas condensate fields, orange

The injection scenario was selected by the CO_2MultiStore project members to investigate interaction between two injection sites and hydrocarbon fields within the Captain Sandstone and is summarised in Table 1.

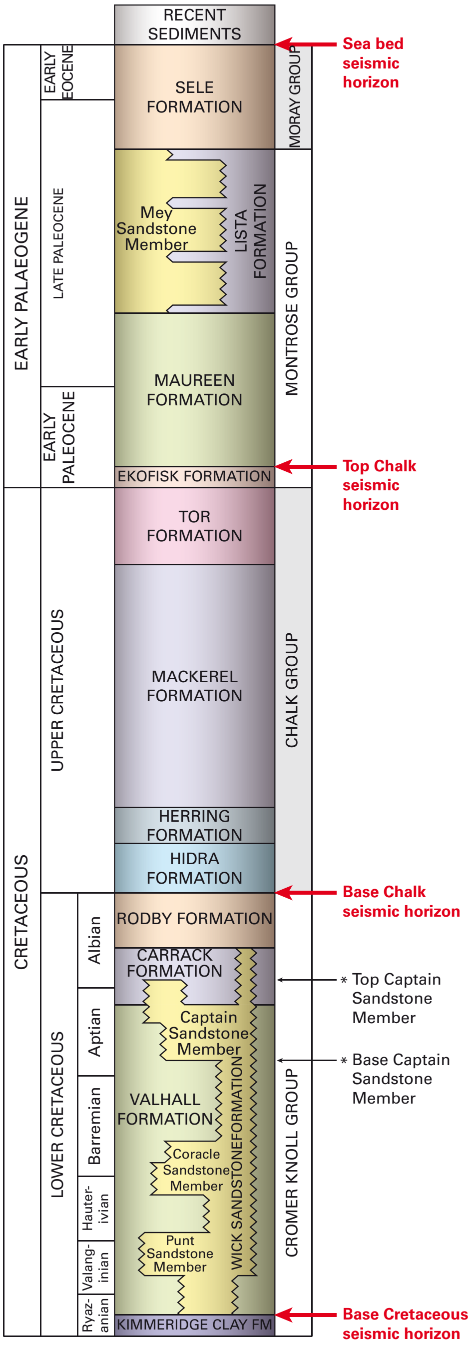
Table 1 Multi-user store injection scenario for investigation and analysis in CO_2MultiStore

	Site A	Site B
Location of the potential CO_2 storage site	Goldeneye Field	Captain Sandstone west of the Goldeneye Field
Existing infrastructure	Goldeneye Field platform and Goldeneye pipeline	Atlantic-Cromarty pipeline
Host site/structure for the storage strata	Goldeneye Field and Captain Sandstone	Captain Sandstone
Total volume to be injected	180 Mt	180 Mt
Annual rate of CO_2 injection	6 Mt per year	6 Mt per year
Number of injection wells	4 or 5 wells	5 wells
Type of wells (vertical or deviated)	Existing injection wells proposed (combination of vertical/inclined wells)	Optimised for CO_2 injection (likely to be inclined wells)
Timing of CO_2 injection (start date and anticipated completion date)	2016 to 2046	2021 to 2051
Maximum well head pressure	110 bar (11 MPa), which is the maximum allowed on the Goldeneye Field platform	As for Site A
Timing of injection relative to hydrocarbon production	After field depletion	Not applicable
Constraints for migration of the injected CO_2 gas	Site A and Site B to have no significant impact on other resource users. Hydrocarbon production assumed to take priority over CO_2 storage.	
Duration of modelled predictions after completion of injection	Site A and Site B 1000 years or longer	
Sensitivities to injection site parameters to be investigated	Storage formation boundaries either open or closed to flow. Base case is closed to flow.	

2.1 GEOLOGY OF THE CAPTAIN SANDSTONE MULTI-USER STORE

The geology of the Captain Sandstone multi-user store is summarised in Figure 3. Unconsolidated sediments below the sea bed overlie strata of the Moray Group and the Montrose Group. These are variably interbedded cohesive and non-cohesive units, with a thickness in the CO_2MultiStore study area of several hundreds of metres. At the base of the Montrose Group is the youngest chalk interval known as the Ekofisk Formation.

Figure 3 Generalised geological stratigraphy profile of the CO_2MultiStore study area (Johnson and Lott, 1993; Knox and Holloway, 1992)



The Captain Sandstone is within rocks of Cretaceous age. The Upper Cretaceous succession comprises the Tor, Mackerel and Herring formations. Within this group there are occasional mudstone units, which are considered to be sealing in terms of fluid flow. These mudstone intervals have a thickness of around 500 m where the Captain Sandstone forms a narrow 'fairway' (Figure 1) although they may be absent further to the west. Within the base of the Herring Formation is the Plenus Marl, which overlies the Hidra Formation. The Plenus Marl and the Hidra Formation are composed of relatively ductile shale and marl. They form part of the primary seal (cap rock) to the Captain Sandstone in conjunction with the underlying Rodby and Carrack formations. The total thickness of these strata can be about 200 m. However, in some areas it is known that the Rodby and Carrack formations are not present.

The Captain Sandstone (a member of the Wick Sandstone Formation) lies beneath the low permeability cap rock strata. The sandstone is informally subdivided into the Upper Captain Sandstone, the Mid Captain Shale, and the Lower Captain Sandstone (Table 5). The Lower Captain Sandstone is present throughout the CO_2MultiStore study area; the Upper Captain Sandstone is absent to the west of the area. The total thickness of the Captain Sandstone units is usually approximately 100 m. However, locally the Lower Captain Sandstone can be two or three times this thickness.

The Captain Sandstone is laterally equivalent to the Valhall Formation, which is underlain by the Humber, Fladen and Heron groups (Figure 3). The Humber and Heron groups comprise various sedimentary strata and the Fladen Group comprises volcanic deposits forming the Jurassic and Triassic succession.

The underlying Zechstein Group marks the top of Permian strata and an impermeable base to the storage sequence including a number of evaporite deposits. The combined thickness of the Humber and Heron groups is of the order of several kilometres.

2.1.1 Methods used to investigate the Captain Sandstone multi-user store

To ensure confidence in prediction of CO_2 store performance three important steps were taken: geological or 'static' modelling; geomechanical modelling to study rock behaviour, and simulation or 'dynamic modelling' of CO_2 injection at the two sites.

Dynamic three-dimensional (3D) simulation of CO_2 injection within a multi-user store is informed by realistic and practical injection scenarios at both sites; knowledge of the fluids within the storage strata, and an initial two-dimensional (2D) prediction of the behaviour of fluids within the sites. It is extremely advantageous to have information from wells within the subsurface, such as that gathered during the exploration, operation and depletion of a hydrocarbon field. Of particular importance are the initial pressure within the reservoir prior to hydrocarbon production and the history of pressure changes during depletion of the field. In general, understanding of the reservoir, subsurface conditions and the fluid properties of a prospective storage site can be extrapolated from a hydrocarbon field, where there is a good understanding and knowledge of the surrounding brine-saturated host sandstone, when knowledge is sparse.

Where two or more injection sites are assessed within a multi-user CO_2 storage formation, rather than at a single injection site, there are several key differences:

- The geological and dynamic simulation models will be more extensive
- Two or more hydrocarbon fields may be included within the models, each containing differing proportions of oil, gas and brine
- All strata that are affected by changes in pressure due to CO_2 injection must be encompassed within the multi-user store model

Rocks in which the pore spaces and contained fluids are connected and so can transmit a change in pressure between them are described as 'hydraulically connected'. Those rocks that are hydraulically connected will determine how far the changes in pressure will extend and so also the required extent of the predictive models. Knowledge of pore fluids within the rocks of a prospective storage site and their behaviour at the elevated pressures and temperatures deep within the subsurface is critical to reliably predict storage site performance.

2.2 ASSESSING THE CHARACTER AND TARGETING INVESTIGATION OF A MULTI-USER STORE

CO_2MultiStore investigated the operation of two reasonable and realistic injection sites as a multi-user store. The injection sites' characterisation and store performance activities addressed issues only associated with the planning and predicted operation of a multi-user store, rather than a single CO_2 injection site.

Characterisation and predictive modelling was targeted by the advice of technical experts with experience of CO_2 geological storage. The experts identified perceived issues and possible areas of concern arising from the operation of a multi-user CO_2 store. They also discussed each issue and assessed how likely it was, and the possible impact on the multi-user store if it did actually happen. A list (register) of the issues and perceived concerns identified by the technical and CO_2MultiStore experts was prepared. The assessments of likelihood and impact of possible effects were used to order the list from most to least importance. Technical investigations in CO_2MultiStore were targeted to address those issues ranked as most important, i.e. most likely and with potentially the greatest effect.

A rating of confidence on each of the likelihood and impact assessments was also documented. It was recognised that changes in the ratings of confidence would be used to measure the results of the technical investigations. The confidence ratings were re-assessed at agreed stages during the progress of CO_2MultiStore characterisation and predictive modelling of multi-user store.

Assessment to target CO_2MultiStore technical investigations was primarily achieved via a series of workshops held throughout the project's duration. Participants were project members with technical research, industry, regulatory, and storage lease holder expertise, and independent industry technical experts. The purpose of the workshops was to:

- Create and record a list of perceived issues and possible concerns relevant to the cumulative effect and interaction between two specified injection sites (specific injection scenarios for each of the two sites had been defined prior to the first workshop, Table 1)
- Assess, discuss, agree and record values for the likelihood (Table 2) and impact (Table 3) for each item listed. Confidence ratings for each value were also recorded (Table 4). The values were used to calculate a ranking to order the issues and concerns from most to least important
- Use the ranked list to guide the subsequent modelling work to allow the most highly ranked items to be investigated by data collation and predictive modelling activities
- Reassess the likelihood and impact of the issues addressed and level of confidence for each, after completion of phases of the technical investigations. The data collation and modelling results and draft reassessments were recorded
- Primarily, measure the increase in confidence on the likelihood and impact values assigned to each issue listed. Secondarily, reduce the likelihood and impact values and so lower the ranking of importance for each issue or concern towards a level regarded as acceptable
- Discuss in more detail where issues investigated by both dynamic simulation of CO_2 injection and geomechanical modelling had disparate ratings. The parameters or values generating the disparity and possible further investigations were identified and recorded
- Make decisions during the reassessment as to whether the investigations had reduced the concern to an acceptable level such that no further effort was required to investigate and mitigate the issue prior to development of the modelled injection site
- Discuss and record potential mitigating actions (preventative measures) to reduce the likelihood and impact values, and so the importance ranking, of those issues and concerns that remained

above a perceived acceptable level. Corrective measures that could be implemented during future operation of the modelled injection site were also noted

- Implementation of some of the mitigating actions was possible through additional data collation and predictive modelling by CO_2MultiStore. The implications of the results were discussed and recorded in a second reassessment workshop

Issues and concerns that remained above a perceived acceptable level were identified to be addressed by monitoring planning (see Section 2.6). The evolution of the likelihood and impact values, confidence ratings and importance rankings for issues and concerns during the progress of CO_2MultiStore investigations was also analysed. Figure 4 provides an overview of the assessment process to target investigations by CO_2MultiStore.

Figure 4 Overview of the assessment steps followed in CO_2MultiStore to target data collation and predictive modelling investigations

Expert workshop 1	**Preparation of a register of issues and concerns for the operation of a multi-user CO_2 store** **Assessment of likelihood, impact and confidence for each register item**
CO_2MultiStore activities	**Ranking of issues and concerns by importance, based on likelihood and perceived impact** **Assignment of most important issues and concerns for technical investigation** **Predictive modelling to investigate issues and concerns** **Re-ranking of register from the results of investigations**
Expert workshop 2	**Presentation of the results of modelling investigations** **Re-assessment of issues and concerns by experts** **Disparity in assessment highlights need for additional investigations**
CO_2MultiStore activities	**Data collation** **Additional predictive modelling investigations**
Expert workshop 3	**Presentation of the results of additional modelling investigations** **Re-assessment of issues and concerns by experts** **Identification of further preventative measures** **Discussion of corrective measures for future injection site development**
CO_2MultiStore activities	**Identification of issues to be addressed by monitoring planning activity**

Table 2 Example values for likelihood used in CO_2MultiStore (based on CO_2Qualstore (2009))

Description	Likelihood				
	Very low	Low	Medium	High	Very high
	1	2	3	4	5
Event	Unlikely to occur during the next 5000 years	Unlikely to occur during injection operations	Might occur during injection operations	Might occur several times during injection operations	Might occur often during injection operations
Frequency	About once per 10 000 years or less	About once per 1000 years	About once per 100 years	About once per 10 years	More than once per year

Table 3 Example of values for impact used in CO_2MultiStore (based on CO_2Qualstore, 2009)

Description	Impact				
	Very low	Low	Medium	High	Very high
	1	2	3	4	5
Impact on storage integrity	None	Unexpected migration of CO_2 inside the storage complex	Unexpected migration of CO_2 outside the storage complex	Migration of CO_2 to the sea bed	Significant leakage of CO_2 at the sea bed
Impact on local environment	Minor or no damage	Local damage of short duration for less than 1 year	Time of remediation of ecological resource for less than 2 years	Time of remediation of ecological resource for more than 2 years	No possible remediation of ecological resource
Impact on other resources	Minor or no impact	Slight performance loss for less than 1 week	Performance reduced for less than 1 month	Operation halted temporarily for less than 1 month	Operation halted for more than 1 month or permanently

Table 4 Example ratings for confidence in likelihood and impact developed and used in CO_2MultiStore

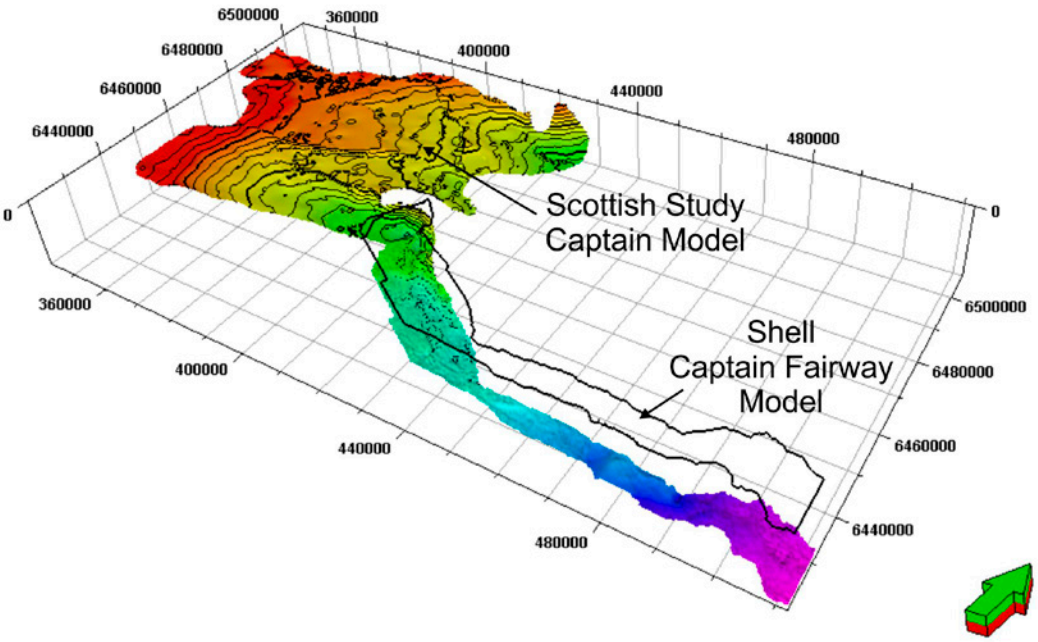
Description	Confidence				
	Very high	High	Medium	Low	Very low
	1	2	3	4	5
Event	Known	Some knowledge	Limited knowledge	Informed estimate	Not known
Examples	Well established and documented	Commonly experienced	Occasional evidence or experience	Limited evidence or experience from analogous practice	No evidence or examples in relevant practice

2.3 DEVELOPMENT OF A GEOLOGICAL MODEL FOR A MULTI-USER STORE

The geological ‘static’ model constructed of the storage strata provides a basis for the ‘dynamic simulation’ of CO_2 injection. The better the representation of the storage site geology by the 3D geological model the greater the confidence in the prediction of performance, interaction and cumulative effect of two or more sites in a multi-user storage formation. Output from the geological model also informs modelling of geomechanical stability.

Two existing geological models have been integrated (Figure 5): the Scottish Study Captain Sandstone Model (SCCS, 2011; Jin et al., 2012) and the Shell Captain Fairway Model (Shell, 2011a). The integrated model, developed using Schlumberger's proprietary PETREL software platform, was attributed with porosity, permeability and proportion of sandstone in the storage strata.

Figure 5 3D image of the upper surface of the CO_2MultiStore Captain Model from the merged Scottish Study Captain Sandstone Model (SCCS, 2011) and the Shell Captain Fairway model (Shell, 2011a, outline shown with black polygon)



Understanding fluid flow within a geological formation as a response to the injection of CO_2 is the primary objective of geological modelling. The CO_2MultiStore Captain Model is a reasonable approximation of the likely structure and variation in rock material within the Captain Sandstone for the purpose of investigating the interaction between two injection sites. It is a generic model of a potential multi-user storage formation that honours all data available to and sufficient for research study, based on a series of geologically reasoned assumptions. The model does not support the level of accurate predictions needed for characterisation of a planned injection site and as underlying technical work for a CO_2 storage permit application.

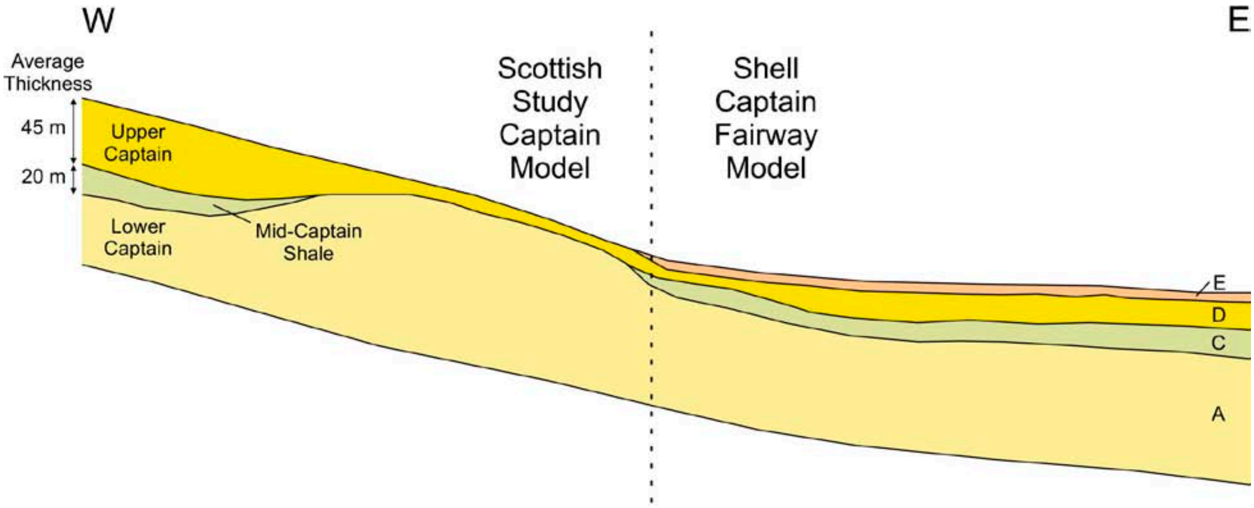
The Captain Sandstone is sub-divided in the Shell Captain Fairway Model (Figure 5) into Captain units E, D, C and A. These are correlated to the Upper and Lower Captain Sandstone, and Mid-Captain Shale divisions used in the Scottish Study Captain Model (Table 5). The Scottish Study Captain Model consists of the entire Cretaceous to sea bed succession, whereas the Shell Captain Fairway Model compromises only the Captain Sandstone interval. The CO_2MultiStore Captain Model therefore honours the divisions of the Scottish Study Captain Model, yet additional detail within the Captain Sandstone interval is incorporated from the Shell Captain Fairway Model.

Table 5 Summary of geological surfaces (blue rows) and volumes used in the CO_2MultiStore Captain Model

Scottish Study Captain Model surfaces	Scottish Study Captain Model volumes	Shell Captain Fairway Model (Shell, 2011a)	CO_2MultiStore Captain Model
Sea bed			Sea bed
	Cenozoic (sea bed to top Chalk surface)		Cenozoic
Top Chalk surface — picked from seismic data		Top Chalk surface — amalgamated regional surfaces	Top Chalk
	Chalk Group	Limited number of well data points used to isopach from base Chalk	Chalk
	Plenus Marl-Hidra Formation was not differentiated from the Chalk Group		Plenus Marl — Hidra Formation
Base Chalk surface — picked from seismic data		Base Chalk surface — amalgamated regional surfaces	Base Chalk surface
	Rodby and Carrack formations (from base Chalk to top Captain surfaces)		Rodby and Carrack formations
Top Captain surface — isochore values beneath the base Chalk surface		Top Captain Sandstone — picked from seismic data	Top Captain Sandstone surface
	Upper Captain Sandstone — assumed to be 45 m thick	Captain E (laterally variable, thin, heterogeneous) from isochore data	Captain E unit
		Captain D (laterally extensive massive sandstone unit) from isochore data	Captain D unit
	Mid-Captain Shale — constant 20 m thickness	Captain C (laterally extensive, mudstone-rich heterogenous unit) from isochore data	Captain C unit
	Lower Captain Sandstone	Captain A (laterally restricted, sandstone-rich unit) from isochore data	Captain A unit
Base Captain — isochore beneath the top Captain surface		Base Captain Sandstone surface picked from seismic data	Base Captain Sandstone surface
	Valhall Formation (from base Captain Sandstone surface to base Cretaceous strata surface)		Valhall Formation
Base Cretaceous strata surface — picked from seismic data			Base or near base Cretaceous strata surface

Due to lack of detailed well correlations at the time of modelling, the Upper Captain Sandstone was assigned a constant thickness of 45 m in the Scottish Study Captain Model, and where the overall Captain Sandstone thickness allowed, the Mid-Captain Shale was given a thickness of 20 m. During the integration of the models it was found that the upper three units in the Shell Captain Fairway Model considerably thinned towards the western margin of the model. The Captain E unit was not extended further westwards into the Scottish Study Captain Model. Interpolation of well data suggests that the Captain E unit would terminate in the area where the two models overlap, and no data were available to identify a re-emergence further to the west. The relationship between the Captain Sandstone sub-divisions in the two models and their interpreted integration is shown in Figure 6.

Figure 6 Diagrammatic profile illustrating the correlation of units across the area where the Scottish Study Captain Model and Shell Captain Fairway Model are joined



2.3.1 Fault modelling

A total of 43 faults were previously interpreted within the Captain Sandstone (SCCS, 2011), of which 28 were incorporated into the Scottish Study Captain Model. Many of the faults intersect only the base Cretaceous strata surface and are extended vertically beyond their true depth limits during the 3D grid construction. The result is the unreasonable crossing of some faults as they are artificially extended upwards to the top of the model. Several iterations were required to generate a 3D grid suitable for dynamic simulation of CO_2 injection (SCCS, 2011).

The fault geometries were much simplified to develop a suitable 3D model, as those derived from existing data interpretation were highly variable. Many iterative attempts to preserve the fault geometries during the 3D model construction were attempted, but it was found through visual inspection and statistical interrogation that many of thin intervals became distorted near faults. These geometries could severely impact the performance of the model during dynamic modelling to simulate CO_2 flow. A compromise was reached with regards to the detailed geometry of problematic faults, while preserving as closely as possible the contact of the faults with the Captain Sandstone surfaces.

The number of faults within the CO_2Multistore Captain Model was therefore reduced to 12, of which three terminate at the level of the top Chalk surface, while the others are interpreted and modelled to extend to the top surface of bedrock beneath sea bed sediments (rockhead). No major faults affect the Captain Sandstone within the Shell Captain Fairway Model (Figure 5).

The horizontal dimensions of the 3D model grid of the Shell Captain Fairway Model are 200 m by 200 m. At this detailed scale the regional model needed to assess a multi-user store would contain too many cells to readily complete the calculations to simulate CO_2 injection. Fewer, larger cells were used for the CO_2MultiStore study. The horizontal grid dimensions were increased to 400 m by 400 m. Although the resolution is reduced, the coarser-scale grid also reduces the number of cells in the extensive CO_2MultiStore model. The increase in horizontal grid size was judged not to cause detrimental smoothing of the topography on the top Captain Sandstone surface.

Porosity and permeability properties were not assigned to fault surfaces in the geological model. The flow properties of the faults are dependent upon the properties of the model cells lying to either side of a fault. Faults that define the boundary of the Captain Sandstone model were considered as closed to fluid flow (impermeable flow barriers) and so assuming the most restrictive conditions.

2.3.2 Geological model surfaces

Captain Sandstone surfaces

The top Captain Sandstone surface is the most important in terms of the dynamic simulation studies as the injected CO_2 is less dense than other fluids within the sandstone. The expected migration of CO_2 will be driven by buoyancy effects and migrate up to the top Captain Sandstone surface. For the Scottish Study Captain Model, the surface was modelled using contours of stratal thickness for the interval between the base of the Chalk Group and the top of the Captain Sandstone recorded in wells drilled for oil and gas (SCCS, 2011). This method ensures the Captain Sandstone can be mapped even where it is poorly resolved by imaging using seismic reflection data (Law et al., 2000). The top and base Captain Sandstone surfaces have been successfully interpreted over the Shell Captain Fairway Model area (Shell, 2011a, b, c). Greater confidence is therefore credited to the Shell Captain Fairway Model surfaces, so these were given priority in the area where the two models overlap. Additionally, a greater degree of confidence is attributed to the Shell Captain Fairway Model surfaces, due to the superior data quality available for the depth conversion. The surfaces extracted from the Scottish Study Captain Model were therefore disregarded in the area of overlap, and a single surface was derived from both datasets.

Base Cretaceous strata surface

The base Cretaceous strata surface was constructed from the interpretation of seismic reflection data and converted into depth below sea level for the Scottish Study Captain Model (SCCS, 2011). This surface was used as the primary input to the integrated base Cretaceous surface over the main part of the model area. To the east of the Scottish Study Captain Model, contours for a surface 'near the base of the Cretaceous' succession were incorporated from the Millennium Atlas (Fig 11.3 of Fraser et al., 2002). The depth of the contours was constrained by data from several key wells along the length of the 'fairway' to ensure gridding is correct. To facilitate a smooth transition between the two surfaces, the Scottish Study Captain Model surface was cropped where there is an acceptable match between the modelled and the contoured surface data.

Chalk Group surfaces

The Scottish Study Captain Model includes modelled horizons for the top and base Chalk surfaces, interpreted from seismic data and converted to depth below sea level. Consistent surfaces from the interpretation of seismic survey datasets with greatest coverage over the fairway were selected for the top and base Chalk Group surfaces for the integrated CO_2MultiStore geological model. The surfaces were constrained by depths to the geological formations recorded in oil and gas wells.

West of the CO_2MultiStore Captain Model area the Chalk Group strata crop out at or near to the sea bed. They are absent to the south west of the model where the Carrack and Rodby formations crop out at the sea bed.

Sea bed surface

The sea bed surface was derived from bathymetric contour data over the entire CO_2MultiStore study area (http://www.bgs.ac.uk/products/DigBath250/home.html). This data was gridded at a fairly coarse resolution to be used as the upper bounding surface in the geological model.

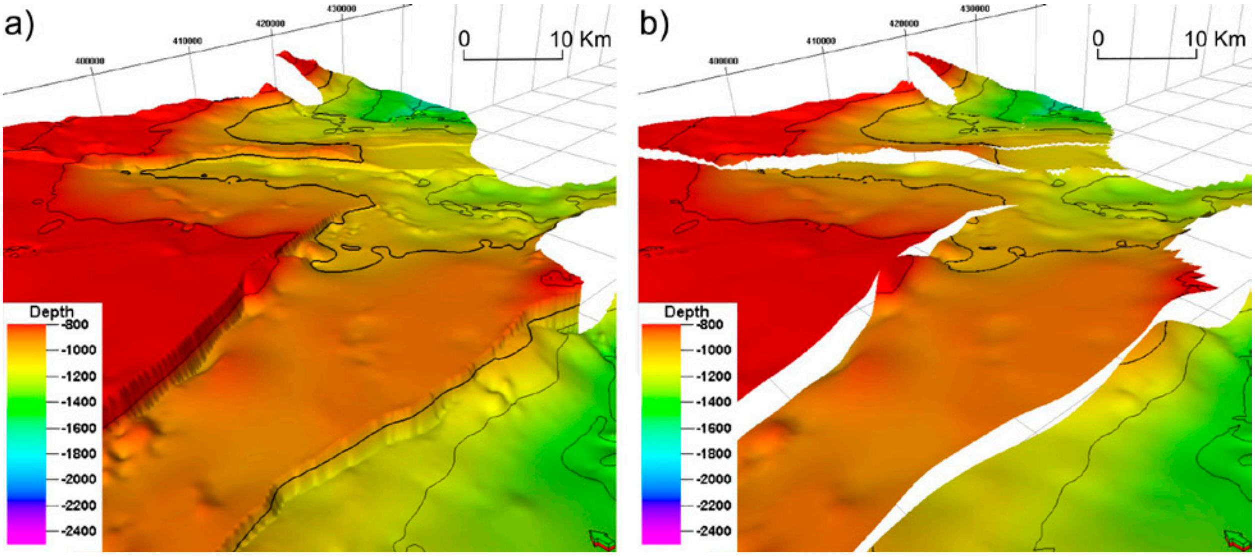
2.3.3 Implementation of surfaces in a 3D model

Each of the model surfaces (Table 5) was used as the main input data to build the model using Schlumberger's PETREL software. Oil and gas well records of the depth to the top and base of the Captain Sandstone were also incorporated; the modelled horizons within and to the west of the fairway are tied exactly with the well information. A radius of influence around each well, measuring two kilometres, was applied as a 'well correction'. This ensures that differences between the well data, the input surfaces and the final model surfaces are not unreasonably extrapolated to areas where accurate well data are not available.

The 'behaviour' of each fault with respect to each surface was specified so that small artificial offsets would not be introduced into the model grid. All faults were deactivated at the sea bed surface so as not to offset the sea bed topography, which is constrained by the bathymetry data.

A clean truncation of the modelled geological surfaces by fault planes is achieved within the model by terminating the surfaces at a fault (Figure 7). The distance at which the surfaces were terminated was specified for all faults as 400 m, the equivalent of one grid cell width. For the base Cretaceous surface, the distance was extended up to 2 km for faults around which the sparse data density caused the surface to unrealistically ramp either down to or up towards the fault planes.

Figure 7 a) Faulted input data surface, and b) same surface shown as expressed in the 3D model grid



2.3.4 Achievements of the 3D geological modelling

The CO_2MultiStore Captain Model integration activity has demonstrated the advantage of combining knowledge gained from two storage characterisation projects to benefit assessment for a potential multi-user store. The geologically 'best' model obtained from both projects confirms a correlation and attribution scheme common to both sites. Construction of a coherent, integrated geological model has demonstrated increased certainty in the understanding of the geology of the Captain Sandstone and surrounding strata for a multi-user store.

Geological modelling has also provided information on the possible range of geological variations in the character of the storage sandstone and their distribution. Three modelled predictions of sandstone characteristics give an indication of possible variations in sandstone quality that all honour the available data. The sensitivity of injection site performance to these geological variations can be tested by dynamic modelling, to reduce the likelihood of an unexpected pressure increase during storage operations.

The assessment that the CO_2 injected at the two sites is likely to migrate to more permeable rocks has been reduced by the geological modelling. The storage sites chosen for dynamic simulation of CO_2 injection in CO_2MultiStore are overlain by sealing cap rocks (Rodby–Carrack and Plenus Marl–Hidra units, Table 5). Together these primary cap rocks are tens to hundreds of metres thick with low permeability. Statistical modelling of the primary cap rocks using input information from both models indicates a uniformly low permeability throughout the model.

Beyond the extent of the CO_2MultiStore model, there are areas where the primary cap rock is known, from oil and gas exploration and production, to be thin or absent to the south west of the model area and north of the West Bank Fault. The likelihood of the CO_2 injected at the two sites migrating to an area of thin or absent cap rock is assessed by dynamic modelling (Section 2.5). Greater confidence in understanding the likelihood and possible impact could be gained by additional geological modelling work on the cap rock strata:

- Model the cap rock as its component formations, the Rodby, Carrack, Hidra formations and Plenus Marl unit, and secondary seal rocks within the Cenozoic strata (Table 5). Subdivide the cap rock strata from interpretation of additional constraining seismic and well data

- Obtain more information on cap rock properties, porosity, permeability and proportion of sandstone, over the entire model area

- Extend the model boundary to incorporate the sealing strata to the side and immediately above, beyond the Captain Sandstone

- Investigate and model in greater detail the geology in those key areas where the injected CO_2 plume is predicted to migrate by the dynamic modelling of CO_2 injection (Section 2.5.3.6)

2.3.5 Concluding remarks for the 3D static geological model

Ideally, the need to integrate two or more geological models prepared for different purposes and modelling processes would not be required. Given the best circumstances, sufficient resources would be available to construct a fully integrated model using source data consistently interpreted across the entire region of interest. The resources required to undertake such a study are seldom available, and a model integration exercise as detailed here may be necessary.

Re-use of existing geological models requires careful understanding of the methods used and the limitations of the initial models, and compromises are commonly required. Constraining data points, such as well data and seismic interpretations, should always accompany model data. This is particularly important in the zone of model overlap, to allow decisions to be made on model integration.

There may be instances when integrating models where geological surfaces where the models join are markedly different and the modeller would have to return to the original source data and perform some re-interpretation.

Information used for assessment of CO_2 storage (seismic interpretation, well correlations and geological property information) has generally been collected and/or interpreted for the purposes of hydrocarbon exploration and is thus focused on the oil and gas reservoir rocks. More information and interpretation of the cap rock is required for the purposes of CO_2 storage to assess store integrity, and this should be included at an early stage in the project.

2.4 INCREASING CERTAINTY IN THE GEOMECHANICAL STABILITY OF A MULTI-USER STORE

Pressure on rocks and the fluids contained within them increases with depth beneath the Earth's surface. Management of pressure within geological strata containing oil and gas is the long-established expertise of hydrocarbon reservoir engineers. Optimisation of oil and gas production may require the reservoir fluid pressure to be increased, decreased or maintained at a set value. Injection of CO_2 into storage strata increases the fluid pressure within the rock. Geomechanical modelling in CO_2MultiStore investigates and establishes the maximum acceptable fluid pressure value for the injection sites in the multi-user store. Maintaining pressure below the maximum acceptable value ensures the integrity of the sealing cap rock and that any faults present within the strata will be stable during operation of a multi-user store. In CO_2MultiStore, geomechanical modelling also investigates the transmission of pressure changes between Site A and Site B and any temperature effects caused by injecting CO_2 that is cooler than the deeply buried storage strata.

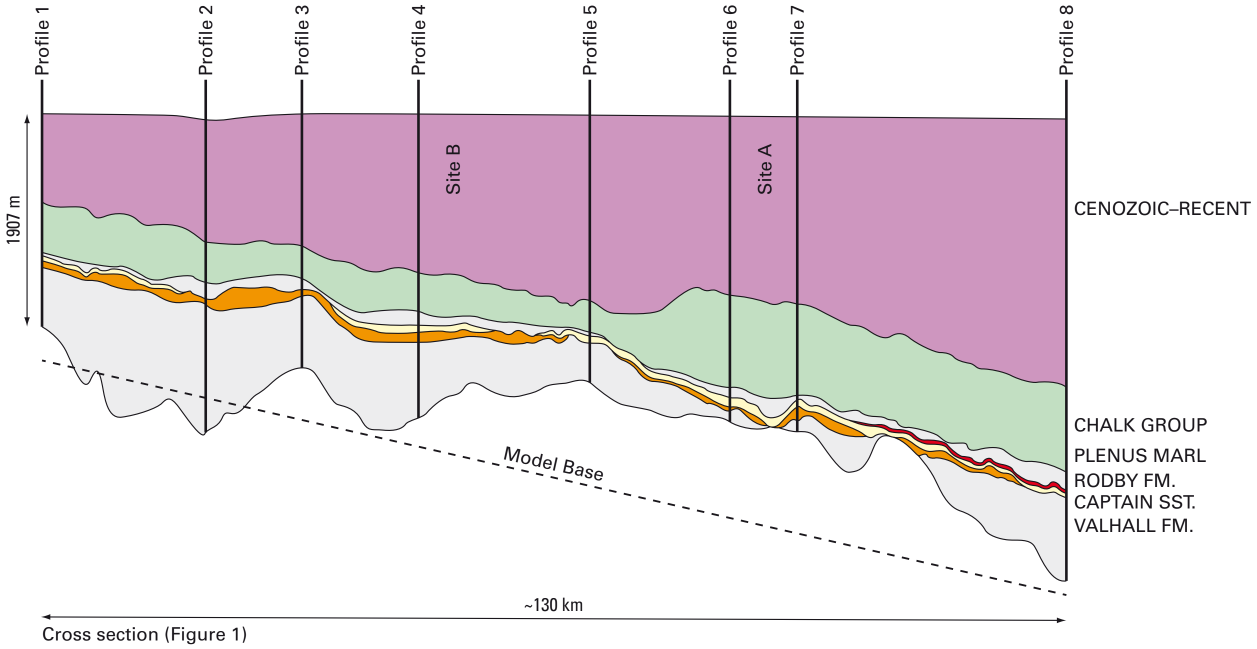
The objective of geomechanical modelling in CO_2MultiStore is to investigate the effect of pressure and temperature changes by the operation of a multi-user CO_2 store in the Captain Sandstone on the mechanical behaviour of the rock. The changes are predicted both in the immediate vicinity of each of the CO_2 injection sites and across the wider regional scale from the interaction and cumulative effect of both sites.

Investigations were targeted to possible areas of concern raised by technical experts (Section 2.2). Two methods were used: a generic approach to establish the maximum possible pressure for the Captain Sandstone at any depth along the fairway, and detailed analyses to address specific stability questions.

2.4.1 Input from the geological 'static' model for geomechanical stability modelling

The geomechanical model uses information derived from the geological 'static' model. Geological characteristics and mechanical parameters determine the geomechanical behaviour of different strata in response to CO_2 storage operations. Eight profile lines were selected along the Captain fairway from the CO_2Multistore Captain Model to construct the 3D geomechanical model (Figure 8).

Figure 8 Geological cross-section along the fairway from the geological CO_2MultiStore Captain Model showing numbered profiles selected for construction of the 3D geomechanical model. The position of the profiles is shown in Figure 1



2.4.2 Grouping of strata with similar geomechanical characteristics

Geological intervals that comprise the geological static model were grouped together according to their geomechanical characteristics (Table 6). For each group the rocks and contained fluids have a similar role and respond in similar ways in the stability assessment for CO_2 storage. The geological intervals are grouped into 'passive' overlying strata, 'active' (sealing) overlying strata divided into primary and secondary sealing cap rocks, the storage reservoir sandstone and the underlying strata (Table 6).

Table 6 Grouping of geological intervals with similar geomechanical characteristics. Darker greyed out intervals were 'inactive' for the geomechanical prediction calculations. Different intervals are 'inactive' for dynamic geomechanical modelling. Geological intervals are shown in Figure 2

Geomechanical groups		Geological intervals
'Passive' overlying strata		Recent sediments and formations of the Moray Group and Montrose Group.
'Active' overlying strata	Secondary Seal	Formations of the Chalk Group, excluding the Plenus Marl at the base (Ekofisk Hod. Mackerel and Herring formations).
	Primary Seal 2	Plenus Marl.
	Primary Seal 1	Hidra, Rodby, and Carrack formations.
Storage sandstone		Captain Sandstone units A,C,D and E.
Underlying strata		Valhall Formation, the Humber, Fladen and Heron groups and extending down to the Permian Zechstein Group.

The weight of the 'passive' overlying strata contributes to the downward pressure acting on the sealing rocks and storage sandstone.

The 'active' overlying strata, including the seal or cap rock, provide mechanical containment of fluids within the underlying storage sandstone for thousands of years. The sealing cap rocks can also contain the increase in pressure from the injection of CO_2. In this study two 'primary seal' rocks and a shallower 'secondary seal' are identified.

The 'storage formation' comprises porous and permeable geological strata, into which the CO_2 is injected and permanently stored. In these investigations this is the Captain Sandstone. The difference in permeability between the storage sandstone and the primary seal rock in the CO_2MultiStore model is considerable (Table 4.2).

The underlying strata forming the lowermost interval of the geomechanical model are commonly modelled as 'passive' in terms of investigation of the storage site.

The character of the surface between the storage formation and the underlying strata influences the predicted increase in pressure generated by CO_2 injection. Two alternatives were modelled, where the lower surface of the Captain Sandstone was either open or impermeable to flow of fluids into the underlying strata (Section 2.4.5.2).

2.4.3 Data sources for geomechanical stability modelling

Assignment of appropriate temperature, pressure, fluid and mechanical property values for the storage strata in the immediate vicinity of an injection well is very important. Varying these values can generate marked changes in the resulting pressure predicted by geomechanical stability modelling of CO_2 injection. Appropriate sets of values for the characteristics are needed to model the thermal, fluid and mechanical response of the Captain Sandstone to CO_2 injection. Values were drawn from published data from the Goldeneye Field (Shell, 2011h) and also the wider scientific literature.

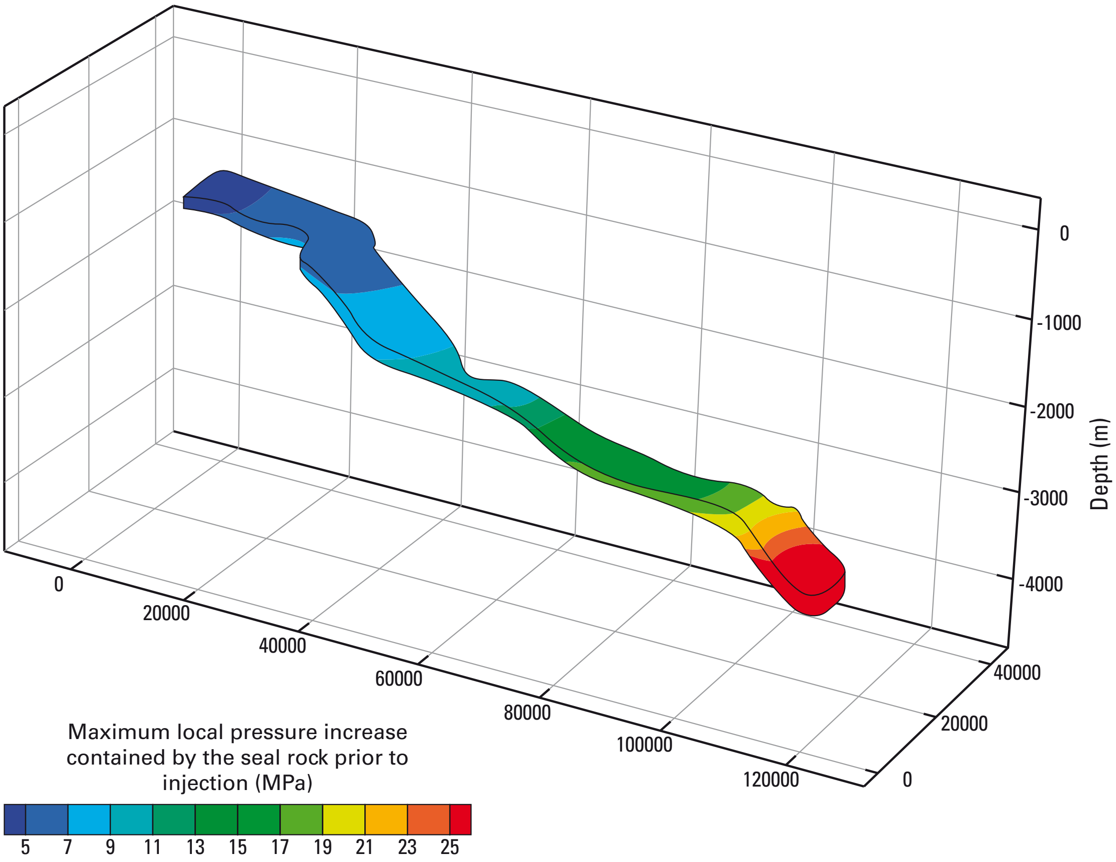
Pressure and temperature increase with depth beneath the Earth's surface. The rate of increase of fluid pressure and temperature with depth used for geomechanical modelling in CO_2MultiStore is based on measurements at the Goldeneye Field (Shell, 2011i).

2.4.4 Regional-scale determination of the maximum pressure contained by the primary seal rock

Initial regional-scale geomechanical modelling studied the stability of the Captain Sandstone along the fairway including the positions of Site A and Site B. A generic approach determined the maximum pressure contained by the primary seal rock of the Captain Sandstone at any depth in the area studied. The values representing the characteristics of each of the geomechanical groups of formations (Table 6) were used to determine a factor to calculate the maximum contained pressure. The factor was used to calculate the maximum pressure at any given depth based on input of values for the fluid pressure and horizontal and vertical forces at that point before CO_2 is injected. The maximum contained pressure values were calculated with different orientations for the horizontal forces, with only the lowest value deemed as suitable.

The calculated maximum pressure increases contained by the primary seal rock within the Captain Sandstone are illustrated along the fairway in Figure 15. These values were further refined from the results of the detailed geomechanical analyses to define the maximum acceptable pressure at each site after significant injection of CO_2 (Section 2.4.6). A standard engineering approach to define a factor of safety for maximum pressure values was followed in CO_2MultiStore.

Figure 9 3D model of the Captain Sandstone fairway showing the maximum increase in pressure contained by the seal rock calculated prior to widespread injection. Horizontal axes are distance in metres. The maximum acceptable pressure for each site is set at lower values using the results of the detailed dynamic geomechanical modelling (Section 2.4.6)



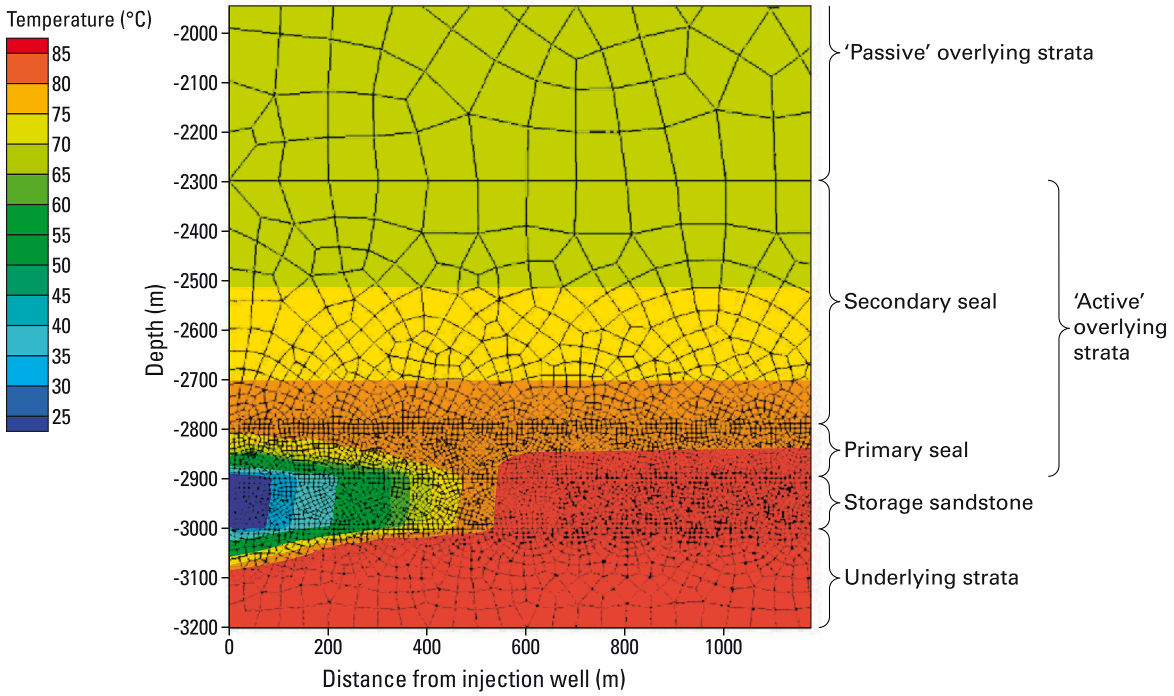
2.4.5 Detailed analysis of specific stability questions

Two-dimensional and three-dimensional models, each with different grid dimensions and cell shapes, were constructed to target the geomechanical investigations and address specific questions on the operation of a multi-user store. The multi-user store injection scenario in Table 1 was followed for the geomechanical modelling, although a more stringent setting was used for the number of wells. Injection at Site A and Site B is modelled at a rate of six million tonnes per year by one well at each of the two sites. The impact of injection in the immediate vicinity of each well predicted by the geomechanical modelling would be reduced by injection using multiple wells (Table 1). The predicted regional pressure response is unchanged by modelling of a single injection well at each site.

2.4.5.1 Effect of temperature change during CO_2 injection

The temperature profile after 30 years of injection (Figure 10) shows the cooling effect of the injection of CO_2, superimposed on the gradient of increasing temperature with depth across the groups of strata in the Captain Sandstone fairway.

Figure 10 Temperature profile after 30 years CO_2 injection into the groups of strata modelled in the Captain Sandstone 'fairway'. The injection well is modelled as the left-hand margin of the illustrated 2D model



Cooling by the injected CO_2 causes contraction of the strata and changes the horizontal forces acting on the deeply buried strata (Figure 11). Stiffer formations are capable of carrying more of the rock pressure changes than softer formations. Softer formations deform more readily to accommodate the changed forces while maintaining their sealing capability as the primary seal rock investigated in CO_2MultiStore. The presence of stronger formations reduces the amount of pressure change ‘felt’ by softer formations. The orientations of the horizontal forces are changed by the cooling effect of the CO_2, as seen by comparing the response modelled with and without temperature change (Figure 12). Rotation of the horizontal forces is important if there are any existing fractures within the geological sequence.

The distance over which the cooling by the injection of CO_2 has a significant geomechanical effect has been found to be confined to the immediate vicinity (500 m) of the injection well. The extent of effect due to the increase in fluid pressure is much more widespread (Figure 12a). The geomechanical effects due to temperature change are varied (positive and negative values in Figure 12b) and within 500 m of the injection well. The effects caused solely by injection of CO_2 are extensive and the fluid pressure changes measured over distances of tens of kilometres away from the injection well. The geomechanical effects are specific to the site that is being investigated. The modelled response to changes in fluid pressure and temperature during CO_2 injection are determined by the nature of interaction between the geomechanical groups of strata, the characteristics of each group and their relative position in the geological sequence.

Figure 11 Change in horizontal forces due to the cooling effect of injection of CO_2. An increase (positive values) is shown is colours from pale green to red

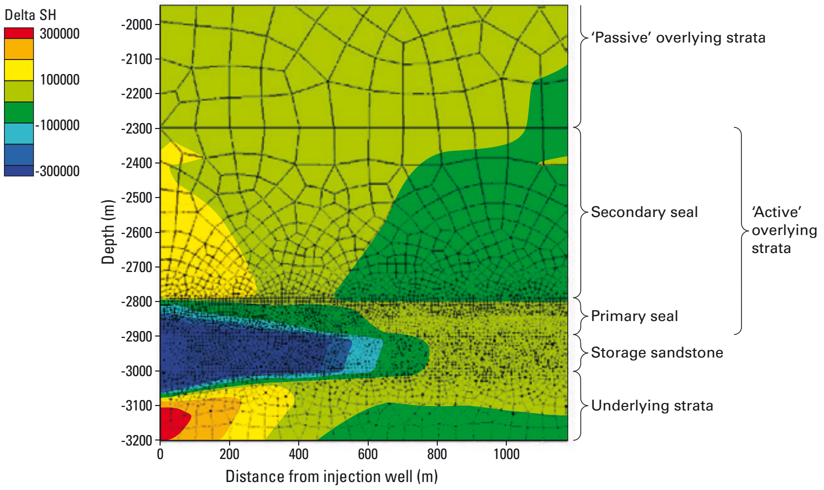
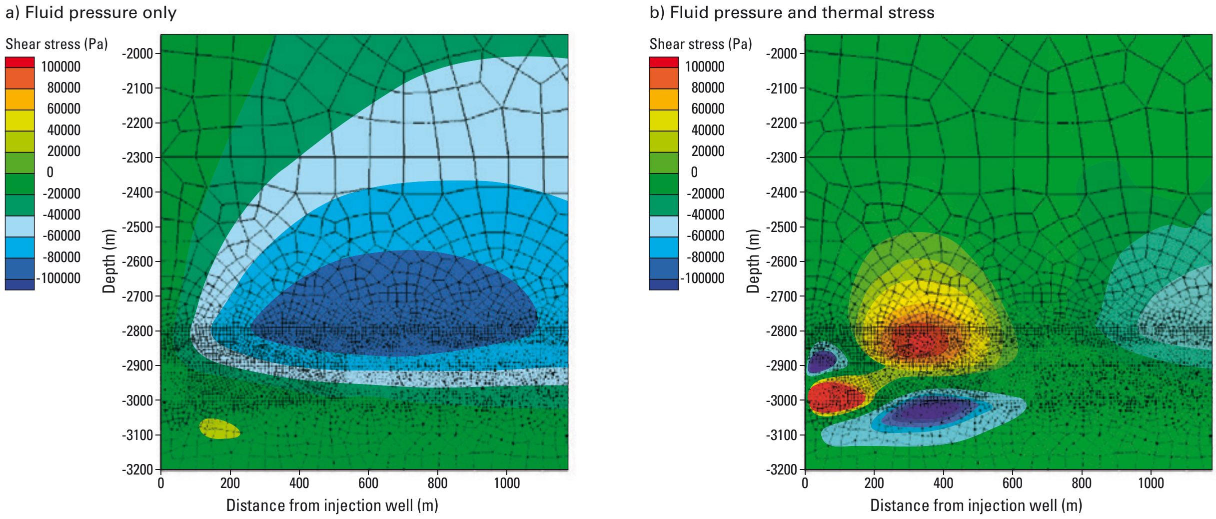


Figure 12 Changes to the orientation of horizontal forces a) caused solely by pressure changes due to injection of CO_2 and b) caused by both the increased pressure of CO_2 injection and decrease in temperature


a) Fluid pressure only

b) Fluid pressure and thermal stress

2.4.5.2 Three-dimensional geomechanical stability model of the Captain Sandstone fairway

A 3D geomechanical model of the Captain Sandstone fairway was constructed using profiles from the geological model (Figure 8) and informed by the results of the initial generic geomechanical modelling (Section 2.4.4). It was validated by comparison of the geomechanical stability predictions from the CO_2MultiStore model with published modelling results from the Captain Sandstone fairway (Shell, 2011h). The 3D geomechanical model calculated an estimate for the deformation of the sea floor expected due to combined injection into Site A and Site B. It was also used to investigate the pressure connection between the two sites during CO_2 injection.

Sea floor deformation from the operation of the Goldeneye Field

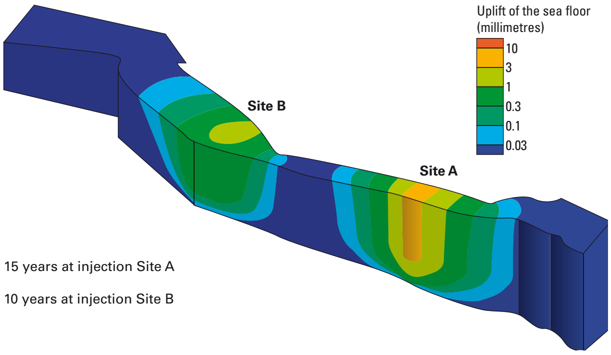
A published 3D model of part of the Shell Captain Sandstone Fairway Model calculates subsidence of the sea floor by approximately five centimetres during the production of natural gas from the Goldeneye Gas Condensate Field (Shell, 2011a). Deformation of three centimetres of subsidence predicted by the CO_2MultiStore Captain Sandstone fairway result is very similar, despite the model having different geometry and geomechanical properties. The similarity in the amount and extent of deformation predicted by the two models validates the CO_2MultiStore Captain Model and gives increased confidence in the predicted responses for the simulation of CO_2 injection in a multi-user store.

Sea floor deformation during CO_2 injection at Site A and Site B

Sea floor deformation during CO_2 injection at Site A and Site B was predicted using two alternative settings for the 3D geomechanical model. In one calculation the lower boundary of the model, including the underlying strata 800 m below the Captain Sandstone (Figure 8), was assumed to be completely open to flow of fluids into the underlying strata. A second calculation assumed the lower boundary of the model was closed to fluid flow. The two alternative characteristics are end-members in a possible range of properties for the lower boundary of the geomechanical model. The actual value will be between these two end-member values.

Where the lower boundary was modelled as open to fluid flow, the sea floor deformation predicted as a consequence of CO_2 injection at both Site A (for 15 years) and Site B (for 10 years) is shown in Figure 13. The sea floor is raised by a maximum of ten millimetres over Site A and three millimetres over Site B. The deformation does not have a widespread effect at either site. The effect from injection at one site does not extend to the other site (Figure 13).

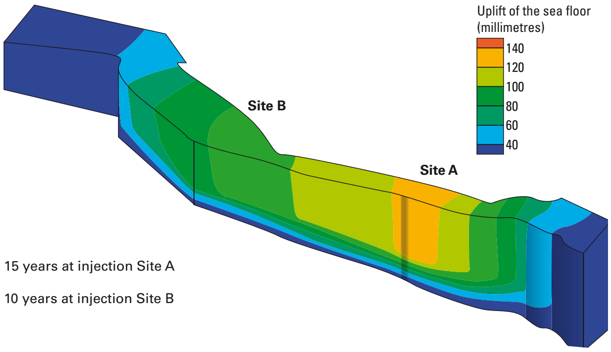
Figure 13 Sea floor deformation after 15 years CO_2 injection at Site A and 10 years injection at Site B, at an annual rate of 6 Mt per year at both sites with the lower boundary of the model open to fluid flow



Where the lower boundary of the modelled strata is represented as closed to fluid flow, the predicted sea floor deformation is significantly more than where the lower boundary is open to flow (Figure 14).

The sea floor is raised by a maximum of 140 millimetres over Site A and 100 millimetres over Site B as a consequence of CO_2 injection at both Site A (for 15 years) and Site B (for 10 years). The effect at each site is more extensive and overlaps with the effect due to the other site.

Figure 14 Sea floor deformation after 15 years CO_2 injection at Site A and 10 years injection at Site B, at an annual rate of 6 Mt per year at both sites with the lower boundary of the model closed to fluid flow



2.4.5.3 Pressure connection between Site A and Site B

The extent of changes in fluid pressure caused by injection of CO_2 is extensive and 'felt' over distances of tens of kilometres from the injection well (Figure 12a). Detailed 2D geomechanical modelling investigated the degree of the connection of pressure changes between Site A and Site B. The two alternative examples of the lower boundary either open or closed to fluid flow were calculated. Where the lower boundary of the geomechanical model is open to fluid flow (Figure 15) the increase in pressure at Site A due to injection at Site B is minimal (the scale is in Pascal not megaPascal).

Where the lower boundary of the modelled strata is represented as closed to fluid flow there is a significant increase in pressure (Figure 16). The cumulative effect after 30 years of CO_2 injection at Site A and Site B is a 0.9 MPa increase indicating a notable pressure connection between the two sites.

Figure 15 Predicted increase in pressure (Pa) at Site A due to CO_2 injection at Site B, with the lower boundary of the model open to fluid flow. Pressure is Pa not MPa, as in Figure 16

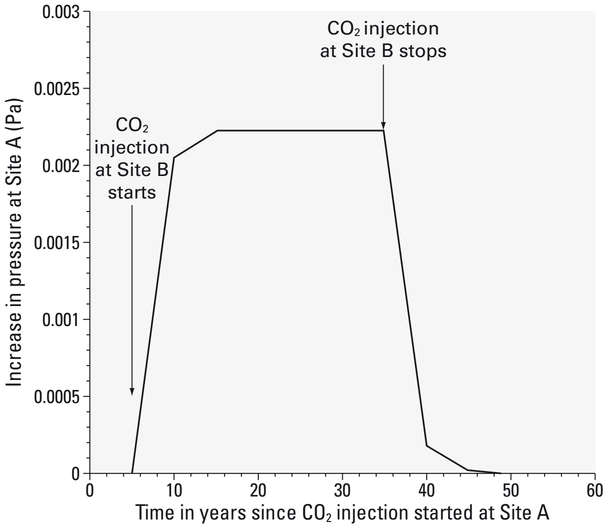
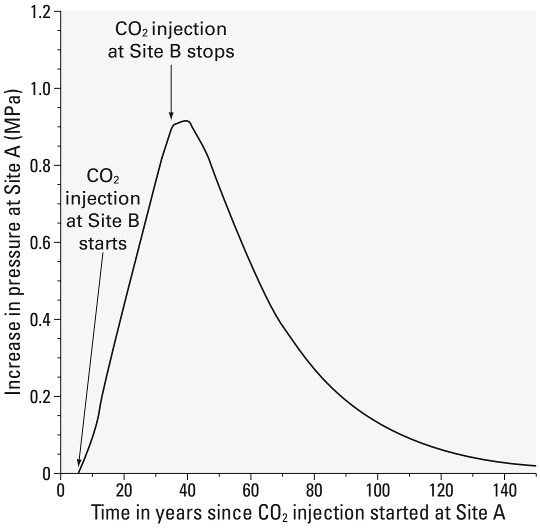


Figure 16 Predicted increase in pressure (MPa) at Site A due to CO_2 injection at Site B, with the lower boundary of the model closed to fluid flow



2.4.6 Results of the detailed geomechanical modelling

The 3D geomechanical model predicted changes in fluid pressure due to operation of a multi-user CO_2 store where the base of the model is considered either open or closed to fluid flow.

Sea floor deformation immediately above the injection wells during simultaneous injection at Sites A and B was predicted as one centimetre and 14 centimetres with the lower boundary open or closed, respectively. Deformation was much more widespread when the boundary was simulated as closed than when it was modelled as open to flow. Minimal pressure connection between the sites is indicated where the boundary is open to flow, whereas a pressure connection of 0.9 MPa is predicted when the boundary is closed.

The increase in pressure predicted by the 3D model was used to evaluate the generic assessment of geomechanical stability and the detailed 2D models for Site A and Site B. Key results of the pressure increase predicted by the geomechanical modelling methods with the lower model boundary either open or closed to fluid flow are presented in Table 7 and Table 8, respectively.

Table 7 Increase in pressure at Site A and Site B modelled for the multi-user store with the lower boundary open to fluid flow

	Pressure increase calculated by the initial 3D model (open lower boundary)	Pressure increase simulated by the detailed 2D model (open lower boundary)
Site A	1.27 MPa	3.0 MPa
Site B	1.23 MPa	1.65 MPa

Table 8 Increase in pressure at Site A and Site B modelled for the multi-user store with the lower boundary closed to fluid flow

	Pressure increase calculated by the initial 3D model (closed lower boundary)	Pressure increase simulated by the detailed 2D model (closed lower boundary)
Site A	5.8 MPa	6.3 MPa
Site B	6.0 MPa	6.6 MPa

2.4.7 Combining the generic and detailed geomechanical modelling results

2.4.7.1 Evaluation of maximum safe fluid pressures

The initial geomechanical modelling used a generic approach and characteristics of the geological strata to estimate the maximum increase in pressure contained by the primary seal rock at any depth in the area studied (Table 9). The initial analysis did not take into account the change in the horizontal forces caused by the injection of fluid into the storage sandstone or changes in temperature.

The effects of the increase in fluid pressure and the temperature changes near to the injection wells were investigated by detailed modelling using geological data from the CO_2Multistore Captain Model.

The results of the initial regional-scale predictions in Table 9 can be compared to the results of the detailed analyses of the two different conditions for the lower boundary of the model (Table 7 and Table 8).

Table 9 Maximum increase in pressure contained by the seal rock at Site A and Site B from the initial regional-scale geomechanical modelling

	Site A		Site B	
	Depth (metres)	Maximum increase in pressure contained by the seal rock	Depth (metres)	Maximum increase in pressure contained by the seal rock
Lower surface of primary seal rock	2523 m	18 MPa	1912 m	10.4 MPa
Upper surface of primary seal rock	2304 m	15 MPa	1727 m	8.3 MPa
Integrity of storage sandstone	2304 m	7.3 MPa	1727 m	1.6 MPa

The detailed models evaluated the containment of CO_2 by the strata under injection conditions and presented the results as a factor of safety, the ratio of disturbing forces (fluid pressure) to containing forces. This is used to calculate the maximum acceptable increase in pressure to securely contain injected CO_2 at each site (Table 10).

Combining the initial regional-scale and the detailed modelling approaches allows a generic evaluation of the geomechanical stability of the Captain Sandstone multi-user store. Fitting the results of the generic modelling predictions prior to CO_2 injection into the formation to the results of the detailed modelling predictions after widespread CO_2 injection gives an overall difference between the two of 0.6. The initial maximum possible pressure values (Table 9) are multiplied by 0.6 to give a general maximum acceptable increase in pressure accommodating the results of the detailed modelling and introduce a safety margin into the calculations. The maximum acceptable pressures predicted for Site A and Site B are presented in Table 10. The maximum pressure values for the lower surface of the primary seal rock at each site is the constraint used for dynamic simulation of CO_2 injection (Section 2.5).

Table 10 Maximum acceptable pressure values for primary seal rock and storage sandstone at Site A and Site B calculated from the results of the generic and the detailed modelling approaches

	Site A		Site B	
	Depth	Maximum acceptable increase in pressure	Depth	Maximum acceptable increase in pressure
Lower surface of primary seal rock	2523 m	10.8 MPa	1912 m	6.24 MPa
Upper surface of primary seal rock	2304 m	9 MPa	1727 m	4.98 MPa
Integrity of storage sandstone	2523 m	6.36 MPa	1912 m	1.8 MPa

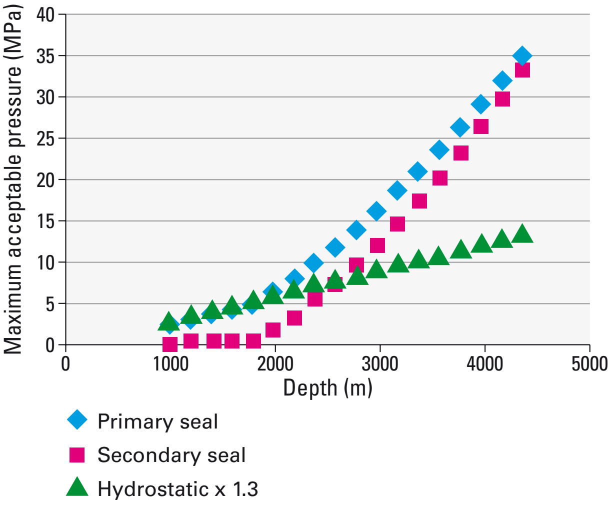
Operation of both sites, each injecting six million tonnes of CO_2 per year, can be sustained without concern for the containment of the CO_2 with the lower boundary of the model open to fluid flow. The maximum pressure increase simulated by detailed 2D modelling with an open lower boundary (3.0 MPa for Site A and 1.65 MPa for Site B, Table 7) are less than the maximum acceptable values for the lower surface of the primary seal rock (10.8 MPa and 6.24 MPa, respectively, Table 10).

Injection of six million tonnes of CO_2 per year can be sustained at Site A whether the lower boundary is open or closed to fluid flow because the maximum increase in pressure calculated by detailed 2D modelling (Table 7 and Table 8) is less than the maximum acceptable increase (Table 10). Operation of a multi-user store with both sites injecting at six million tonnes per year when the lower boundary is completely closed to fluid flow will increase the pressure at Site B (6.6 MPa, Table 8) to be too close to the maximum acceptable pressure for the seal rock (6.24 MPa, Table 10). The two alternatives for the character of the lower boundary of the model are end-members in a possible range of properties and the actual value will be between them.

2.4.7.2 Comparison of methods to assess maximum acceptable pressure

Evaluation of the maximum acceptable pressure for CO_2 storage in the Captain Sandstone based on a 'rule of thumb' multiplication of the hydrostatic pressure by 1.3 is shown in Figure 17. The estimated pressure values are compared with the calculated results for the primary and secondary seal rocks from CO_2MultiStore (Figure 17). At depths of less than 2500 m the estimated maximum value for the secondary seal rock is too high, the calculated maximum acceptable value is exceeded, and they would not contain CO_2 at the estimated pressures. At depths of less than 2000 m the primary seal rock would be close to failure and would rely on its inherent internal strength to prevent failure. At depths greater than 2500 m both the primary and secondary seal rocks would withstand the estimated maximum pressure and contain stored CO_2.

Figure 17 Comparison of the maximum acceptable pressure values calculated for the primary and secondary seal rocks in CO_2MultiStore with estimated values (hydrostatic pressure multiplied by 1.3)



The underestimate of the maximum increase in pressure the rocks could sustain at depths greater than 2300 m would artificially reduce the potential storage capacity at injection sites at these depths.

2.4.8 Conclusions from the modelling of geomechanical stability

Grouping of geological intervals with similar characteristics is effective to reduce the resources for modelling the thickness and extent of strata for the regional-scale geomechanical characterisation needed for a multi-user storage site. The Rodby and Carrack formations, the Plenus Marl and the Hidra Formation were modelled as the primary seal rocks in the strata overlying the Captain Sandstone to contain CO_2 injected into the Captain Sandstone. Validation of the geomechanical modelling results, by comparison with previously published results from part of the Captain Sandstone fairway, produced similar results, indicating the grouping of geological intervals was effective for regional-scale modelling.

Maximum acceptable pressures at each of the injection sites were derived by combining the results of initial regional-scale and detailed site-specific modelling of CO_2 injection (Table 10). The maximum pressure value for the lower surface of the primary seal rock at each site is the constraint used for dynamic simulation of CO_2 injection (Section 2.5). The characteristics of the grouped geological intervals were used to calculate the maximum pressure contained by the seal rocks, at any given depth before CO_2 is injected, for Site A and Site B (Table 9). The results of the detailed modelling and introduction of a safety margin were accommodated by multiplying the initial maximum containing pressure values by 0.6. If 'rule of thumb' methods were followed, the maximum acceptable pressure would be overestimated at shallower depths, threatening storage site integrity, or underestimated to reduce storage capacity.

The effect of temperature changes due to the cooling caused by the injection of CO_2 is predicted to be within one kilometre of the injection well after 30 years of CO_2 injection. There is no interaction of the effects caused by temperature changes between the two sites. Cooling does not significantly affect the ability of the strata of the Captain Sandstone fairway to contain the injected CO_2 due to their geological character, geometry and mechanical properties.

Selection of the fluid flow boundaries is critical to evaluating the pressure dissipation in the storage formation and the likely pressure the primary seal rock has to withstand during the injection phase. Detailed modelling of pressure increase and deformation of the sea floor during CO_2 injection illustrates the importance of understanding the character of the lower boundary of the model.

Injection rates similar to those expected for commercial-scale storage were applied at the two sites. Alternatives of either open or closed to fluid flow were used for the characterisation of the lower boundary of the modelled strata (including 800 m of strata underlying the storage sandstone). There is a marked contrast in the predicted performance of the multi-user store when using the end-member values of either open or closed to flow.

With an open lower boundary, the increase in pressure at both sites is below the maximum acceptable value, interaction between the sites is negligible and sea floor displacement is less than during natural gas production. The multi-user store will securely contain CO_2 injection at commercial-scale rates at both sites with an increase in pressure of around 1.5 MPa with the lower boundary open to flow. The values of increased pressure are also within the safety margin for containment of CO_2 by the overlying primary sealing cap rocks.

With a closed lower boundary the increase in pressure is just above 6 MPa using the commercial-scale injection rates at both sites. This is very close to the maximum possible pressure value at Site B and pressure management is expected to be needed to inject CO_2 at a rate of six million tonnes per year at Site B. Predicted displacement of the sea bed exceeds that during natural gas production and the pressure connection between the sites is notable with the lower model boundary closed to fluid flow. With the lower boundary closed to fluid flow the predicted interaction approximates 5% of injection pressure, 1 MPa, and could reduce the CO_2 storage capacity by 20% at Site B.

2.5 INCREASING CONFIDENCE IN PERFORMANCE PREDICTION FOR A MULTI-USER STORE

The dynamic simulation of CO_2 injection investigated the aspects identified during assessment of the planning and operation of a multi-user store by technical experts (Section 2.2). Predictive dynamic modelling was targeted to increase understanding of the Captain Sandstone and increase confidence in its operation as a prospective multi-user store. The investigations prioritised possible concerns that were rated as most likely to occur and with potentially the greatest effect. Firstly the geological model was refined to make it suitable for dynamic simulation of CO_2 injection. The dynamic modelling commenced with an initial phase of generic ‘box’ modelling to establish the suitability of the input data. The suitability of the initial results was validated by comparison with published results. The agreed input data were used in common by both the analysis of geomechanical stability (Section 2.4) and subsequent detailed dynamic simulations of CO_2 injection for a multi-user store (Section 2.5.3).

2.5.1 Refining the geological model for simulation of CO_2 injection at two sites

Nine intervals were modelled from the sea bed down to the rocks underlying the Captain Sandstone (Figure 18). The 3D geological model is about 163 km from west to east, 84 km wide from north to south (an area of approximately eight thousand square kilometres) and extends to a depth of 4340 m beneath the sea bed. The geological model was refined to be suitable for dynamic modelling by reducing the total number of cells in the dynamic model to a manageable number for the simulation calculations. During the reduction in the number of cells the detail of lateral or vertical variations should not be lost, so a horizontal cell size of 400 m by 400 m was selected. The vertical resolution varies according to each geological interval and the selected cell height takes into consideration the subsurface geology and the need for a model to appropriately represent the strata (Table 11). An illustration of the geological intervals, cell layers and heights is shown in Figure 19.

To improve the efficiency of the calculations and reduce the time needed to complete them, the analysis was confined to selected geological intervals in an area comprising the narrow fairway of the Captain Sandstone and its westward extension shown in Figure 23. The flow simulation focuses on the Captain Sandstone and the immediately over- and underlying geological units. The upper three geological intervals were not used for the fluid flow simulation (Table 11). The cap rock overlying the Captain Sandstone is characterised as having negligible permeability, whereas the underlying formation includes some permeable strata in which the pore space is connected with the Captain Sandstone as noted in the area of Site A (Table 12).

Figure 18 Geological intervals in the 3D CO_2MultiStore Captain model

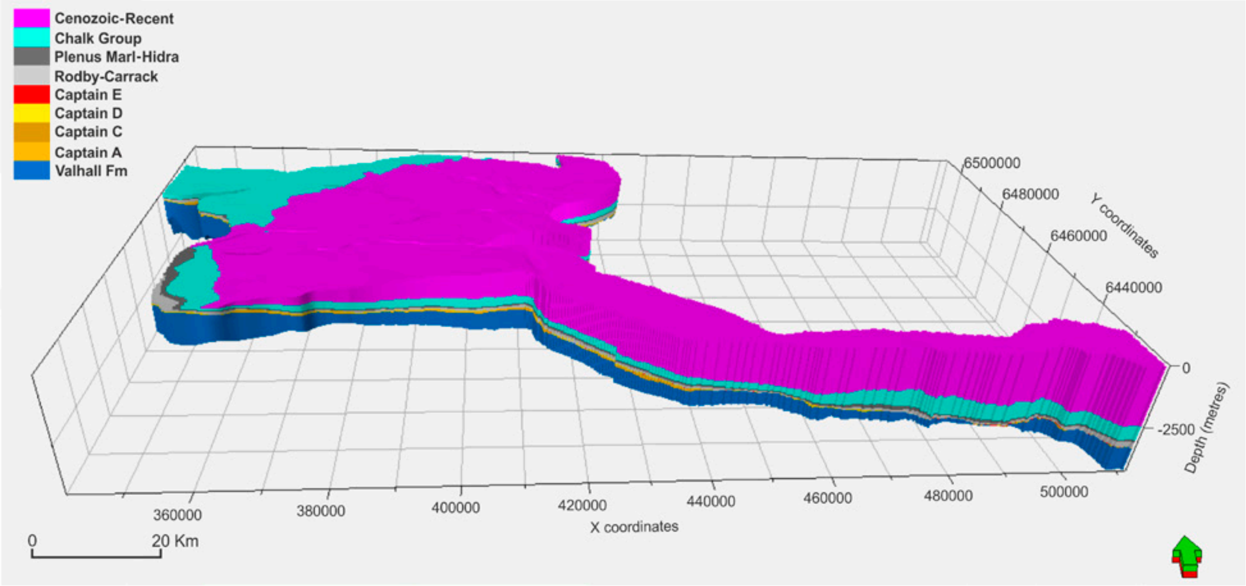
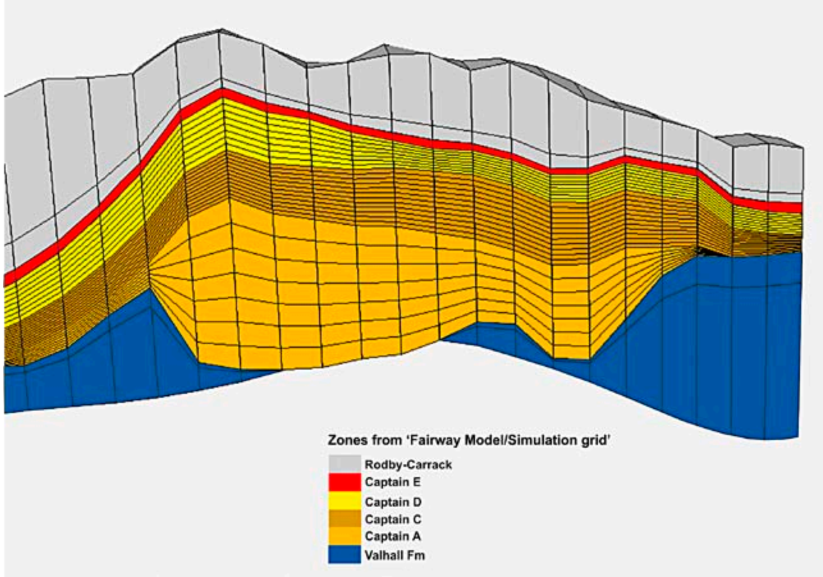


Table 11 Geological intervals, number of 3D cell layers, average cell heights and the total number of active cells in the model used to predict the effects of CO_2 injection. The dark greyed out intervals were 'inactive' for the dynamic modelling prediction calculations. Captain Sandstone unit B is not present in the CO_2MultiStore area. Different intervals are 'inactive' for the geomechanical modelling

		Geological model cell parameters	
Geological interval		Number of layers in interval	Average cell height in metres
Cenozoic rocks		1	715
Chalk Group strata		1	280
Plenus Marl and Hidra Formation		1	52
Rodby and Carrack formations		2	37
Captain Sandstone	Unit E	8	1.7
	Unit D	8	5.25
	Unit C	12	1.47
	Unit A	7	12.4
Valhall Formation		2	310
Total number of layers		42	
Total number of cells		4 239 570	
Total number of active cells		715 044	

Figure 19 A vertical profile through the geological model illustrates the geological intervals modelled at Site A, highly vertically exaggerated



The settings used to represent the multi-user storage strata by the CO_2MultiStore investigations are summarised in Table 12.

Table 12 Settings used for the simulation of CO_2 injection at Site A and Site B

Parameter	Values used
Porosity	Captain Sandstone 7% to 30%
Proportion of strata that is sandstone	40% to 90%
Average permeability in milliDarcy (mD)	Cap rock formations 0.005 mD Captain Sandstone 317 to 1037 mD Underlying formation 33 mD
Pressure gradient in megaPascal (MPa)	1.011 x 10^{-2} MPa per metre Values measured at the Goldeneye Field
Temperature gradient	30.4°C per kilometre

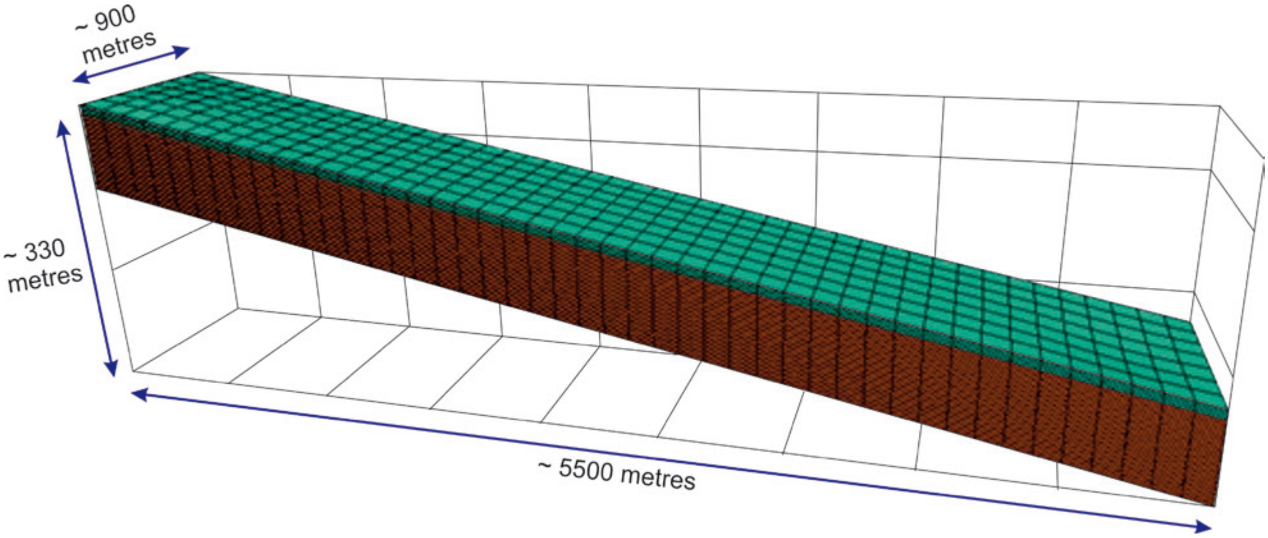
Connectivity within the Captain Sandstone is known to be very good from the experience of operating hydrocarbon fields. Communication of pressure changes between hydrocarbon fields within the Captain Sandstone has been observed by operators. It was assumed that, initially, none of the hydrocarbon fields were either under- or over-pressured relative to their depth below the sea bed.

The geological model cells were attributed with rock property values by statistical methods. Three statistical realisations of rock property attribution were generated, all honouring the input geological data, i.e. porosity and permeability. The effect of narrowing of the Captain Sandstone west of Site A (Section 2.3) and reduced continuity was rated as of 'low confidence' in the assessment by experts, so the realisation in which the property data has mid-case values of connectivity across the narrowed Captain Sandstone between Site A and Site B was selected. The other two realisations have lower and higher connectivity characteristics across the 'neck' between the two injection sites. They were used to test the sensitivity of the results to the input data.

2.5.2 Initial generic dynamic 'box' modelling

A generic 'box' model of homogeneous dipping strata was defined to test the input data to be used for the geomechanical stability analysis and the detailed dynamic simulation of CO_2 injection. The results of the generic box modelling were validated by comparison with a published box model of the Goldeneye Field. The validated parameters were input data to simulate the processes of fluid displacement during gas production and CO_2 injection for the Captain Sandstone in the vicinity of the Goldeneye Field. The CO_2MultiStore box model has the same dimensions, similar rock properties (Table 13) and angle of inclination as the Goldeneye Field 'box' model. The CO_2MultiStore box model was used to study and test possible variations in fluid property value, and their impact on predicted fluid movement. It was also used to examine the effect of different 3D grid sizes and so model resolutions. The results inform selection of the most appropriate parameters and options in the Schlumberger Eclipse (E300) dynamic modelling software used for the subsequent detailed dynamic simulations of multi-user storage CO_2 injection.

Figure 20 Geometry of the CO_2MultiStore box model of the Captain Sandstone units E (green) and D (brown)



The CO_2MultiStore box model is of the Captain Sandstone units E and D (Figure 20). The volume of strata portrayed by the model is 5486 m in length (represented by 45 grid cells), 914 m wide (represented by 7 grid cells) and 91 m high (represented by 40 grid cells). The total number of cells is 12 600.

The results from the CO_2MultiStore box modelling were compared with the published results of box modelling for the Goldeneye Field.

2.5.2.1 Goldeneye Field box model

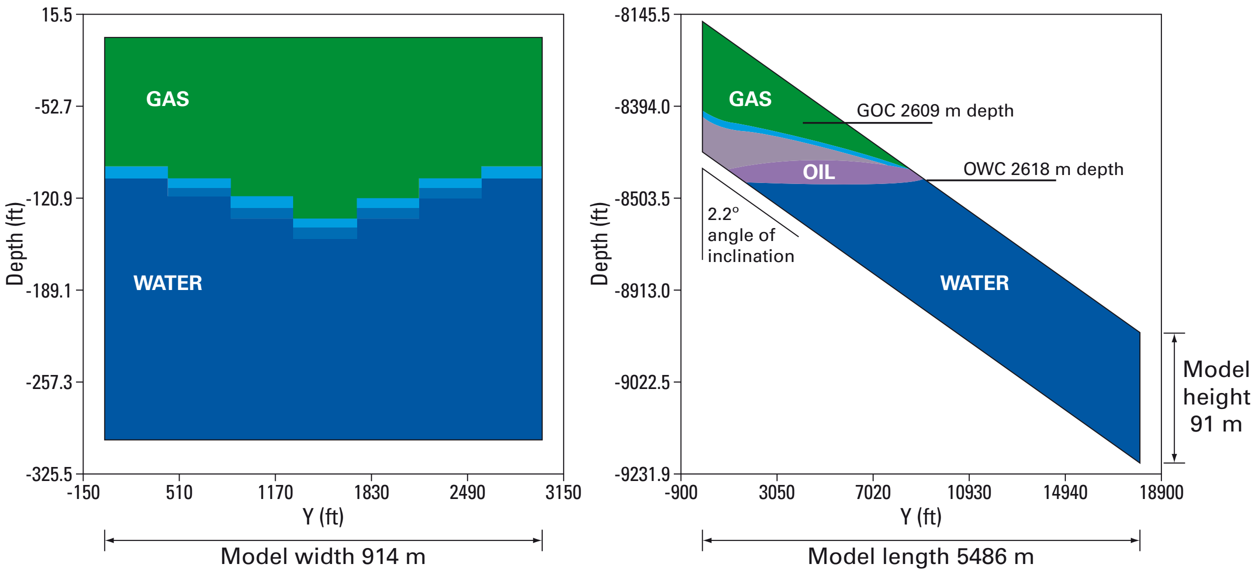
The dimensions of the published Goldeneye Field box model were mirrored in the CO_2MultiStore box model (Figure 21). This was ensured by working with engineers from Shell, the Goldeneye Field operator. The size and properties of the Goldeneye box model cell layers (Table 13) are constant, by geological interval. The dimensions of the model cells are 122 m in the two horizontal dimensions and 1.4 m in the vertical dimension. Captain Sandstone units E and D are represented by the model. The thickness of the sandstone units, cell layers and geological properties are summarised in Table 13.

Table 13 Cell size and geological properties for the Captain Sandstone units in the box modelling of the Goldeneye Field (from Shell, 2011b)

Geological interval	Interval thickness (m)	Number of cell layers	Proportion that is sandstone	Porosity	Permeability (mD)
Captain Unit E	9.1	4	61%	21%	7
Captain Unit D	82.3	36	94%	25%	790

The distribution of fluids within the Captain Sandstone at the Goldeneye Field (Figure 21) used for the CO_2MultiStore generic box modelling uses the same data as the published box model (Shell, 2011b).

Figure 21 Fluid distribution within the CO_2MultiStore Box model viewed 'end-on' (left) and 'side-on' (right) (Shell, 2011b). Distribution of fluids within the Captain Sandstone shown as water in blue, gas in green and oil in mauve. Measurements in metres, m; feet, ft. Oil-Water Contact, OWC. Gas-Oil Contact, GOC

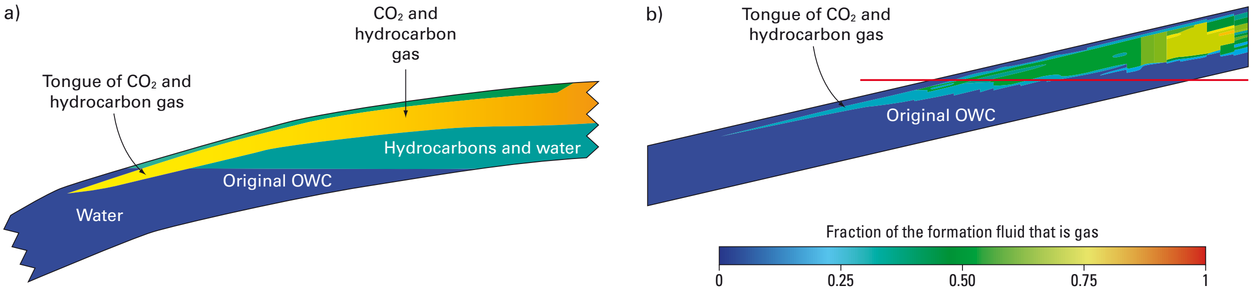


2.5.2.2 Validation of the CO_2MultiStore box modelling of the Goldeneye Field

The CO_2MultiStore box model was validated by comparison with the published results and data provided by Shell from box modelling of the Goldeneye Field (Shell, 2011f). All effort was made to incorporate as much of the Goldeneye Field data as was available into the CO_2MultiStore model to inform a direct comparison.

There was a good match between the generic box modelling in CO_2Multistore and the results of the operator for the Goldeneye Field (Shell, 2011f). One of main results replicated by the initial generic modelling was an effect caused by gravity-dominated flow at the end of the period of CO_2 injection, which was also identified in the published results. A 'tongue' of CO_2 and hydrocarbon gas was modelled as migrating downwards below the original contact between the hydrocarbon field and underlying water beneath the Goldeneye Field as illustrated in Figure 22a. The distribution of injected CO_2 by the generic box modelling by CO_2MultiStore also predicts formation of a tongue of CO_2 and hydrocarbon gas (Figure 22b). The tip of the CO_2 and hydrocarbon plume, migrating by gravity-dominated flow, also dips below the original oil-water contact.

Figure 22 Validation of the CO_2MultiStore generic box model by comparison of a) the published diagram of the distribution of fluids at the end of modelled CO_2 injection into the Goldeneye Field by Shell (2011e) and b) distribution of CO_2 saturation predicted by the CO_2MultiStore generic box model



The close match of the CO_2MultiStore generic box modelling results with the published model of the Goldeneye Field demonstrates the suitability of the properties assigned to both the fluids and rocks. The close match greatly increases confidence in the prediction of the performance of a multi-user store within the Captain Sandstone in the detailed dynamic simulations by CO_2MultiStore.

2.5.3 Detailed dynamic simulation of CO_2 injection

The detailed dynamic simulations of CO_2 injection at Site A and Site B did not use the entire CO_2MultiStore model shown in Figure 18. An area and geological intervals appropriate to predict the performance of the Captain Sandstone at Site A and Site B were selected to speed up the calculations and reduce the resources needed to complete them. The analysis was confined to selected geological intervals in an area comprising the narrow fairway of the Captain Sandstone and its westward extension shown in Figure 23. The flow simulation focuses on the Captain Sandstone and the immediately over- and underlying geological units. The upper three geological intervals in the model were not used for the fluid flow simulation (Table 11). The cap rock overlying the Captain Sandstone is characterised as having negligible permeability, whereas the underlying formation includes some permeable strata in which the pore space is connected with the Captain Sandstone as noted in the area of Site A (Table 12).

Figure 23 The outline of the area within the CO$_2$MultiStore geological model used to simulate the injection of CO$_2$ at Site A and Site B and position of oil (red), gas condensate (orange) and gas (green) fields within the model

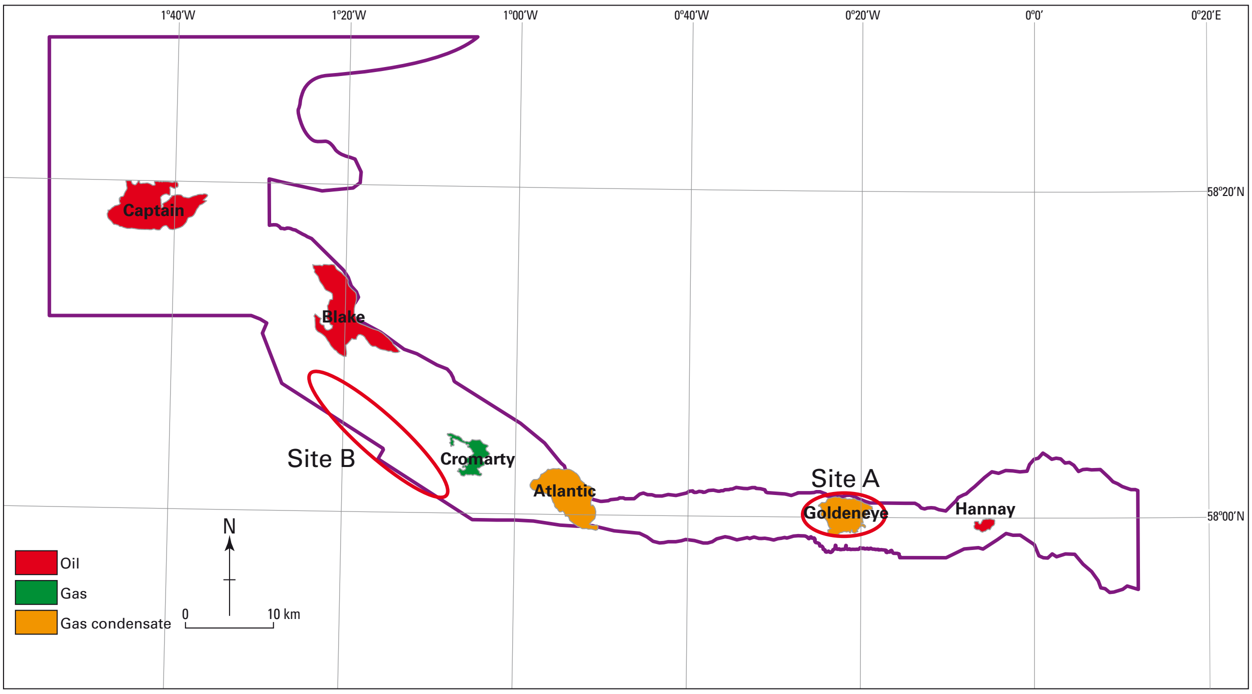


Table 14 Geological models merged and constructed in CO$_2$MultiStore

Name	Description	Published
Scottish Study Captain Sandstone Model	Captain Sandstone west of the Atlantic Field	SCCS (2011)
Shell Captain Fairway Model	Captain Sandstone eastward from and including the Blake Field	Shell (2011a)
CO$_2$MultiStore Captain Model	Merged Scottish Study Captain Sandstone and Shell Captain Fairway models	This report, Figure 5
CO$_2$MultiStore Dynamic Model	Subset of the CO$_2$MultiStore Captain Model eastward and including the Captain Field	This report, Figure 23

There are six hydrocarbon fields within the area of the Captain Sandstone investigated by the detailed dynamic modelling. Ideally, fluid properties would be assigned for each individual hydrocarbon field included within the model of a multi-user store. The CO$_2$MultiStore research uses data available from the Goldeneye Gas Condensate Field (Shell, 2011a-i). All the oil and gas fields are assigned the same fluid properties as the Goldeneye Field.

Reservoir pressure and well flow rate data are collected by a field operator throughout the lifetime of a hydrocarbon field. The history of data collected at the Goldeneye Field was used to validate the CO_2MultiStore model. The settings for the CO_2MultiStore model were adjusted to ensure a match of the results with real data history from the Goldeneye Field. Detailed production history data from all fields included within the multi-user store model, if available, should be used to validate the predictions of the performance of each CO_2 storage site.

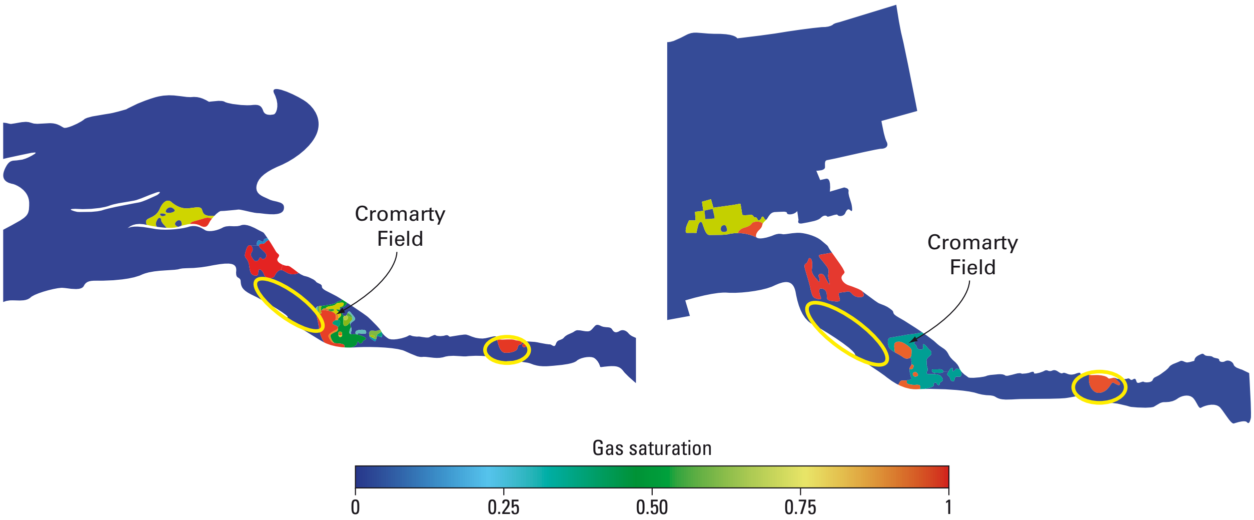
2.5.3.1 Upscaling to lower resolution models

The cell size is larger and so the resolution of the CO_2MultiStore Captain Sandstone Model is lower than is usual for the simulation of oil production by a field operator. 'Upscaling' to a coarser cell size may generate an artificial change in the volume of oil within each field. It may also smooth subtle irregularities in the roughness of the modelled surfaces and remove very thin geological intervals.

An extensive geological model suitable for simulation of a multi-user storage site is likely to contain one or more hydrocarbon fields. Validation of the model using data from any included hydrocarbon fields is required to correct the volume of oil or gas before the upscaled model is used to simulate injection of CO_2. Similarly, the upscaling activities will create a change in the extent of the field and so the shape of an oil or gas field within the model may not look the same as published field outlines.

The main differences to the shape of hydrocarbon fields within the CO_2MultiStore model are the changed boundaries of the Cromarty Gas and the Atlantic Gas Condensate fields (Figure 24, left). The loss of local irregularities on the coarser scale modelled surface may also artificially remove a hydrocarbon trapping structure and a manual modification was needed to contain hydrocarbons in the modelled field as illustrated for the Cromarty Field (Figure 24, right).

Figure 24 Extent of the Cromarty Gas Field (left) after upscaling to a coarser, low-resolution model and (right) after modification of the field boundary to correct artificial changes caused by the upscaling from a finer- to a coarser-scale model. The approximate positions of the injection sites are shown as yellow circles



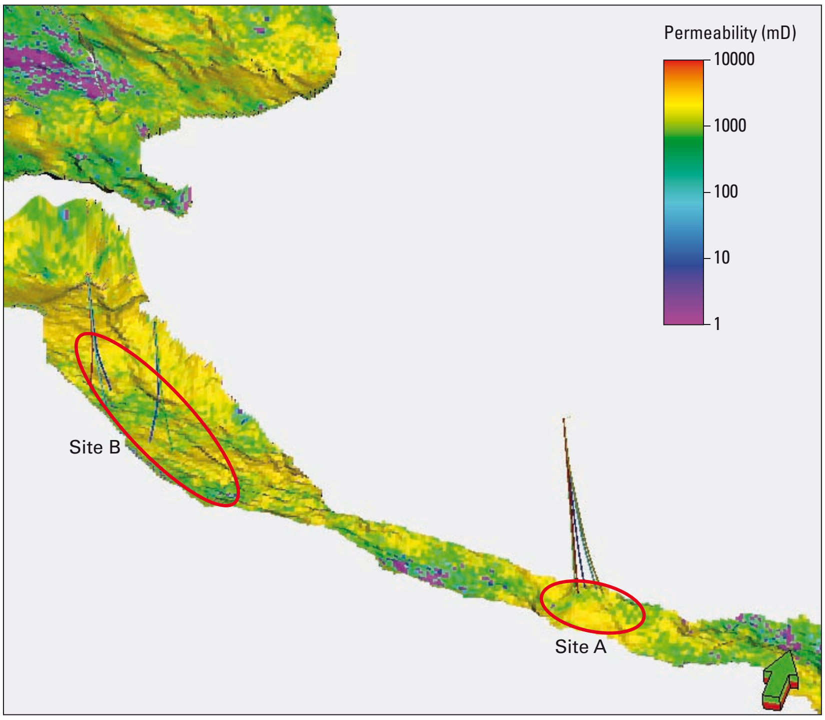
2.5.3.2 Positions of the modelled CO_2 injection wells at Site A and Site B and monitoring wells

Detailed hydrocarbon field production history data were available for seven wells within the CO_2MultiStore Captain Sandstone Model. The detailed production data, including daily hydrocarbon production and corresponding pressure values at the base of the well, were available from five producing hydrocarbon wells in the Goldeneye Field and two wells in the Hannay Oil Field. The pressure at the Blake Oil Field and the Captain Oil Field is maintained at a set value by the operator; one producing well in each of these fields was chosen as a monitoring well to show the pressure change during the entire hydrocarbon production and modelled CO_2 injection period.

The positions of the five CO_2 injection wells modelled at Site A for CO_2MultiStore are the same as the existing gas production wells at the Goldeneye Field and shown in Figure 25. The angle of inclination of the wells decreases with depth, becoming horizontal within the Captain Sandstone.

The positions of the five CO_2 injection wells modelled at Site B are shown in Figure 25. Three are toward the Blake Field, which lies to the north west, and two are toward the Cromarty Field, which lies to the south east of Site B. The wells become horizontal within the Captain Sandstone.

Figure 25 CO_2MultiStore Captain Sandstone permeability model showing the positions of storage Site A and Site B, and the positions and trajectories of the five modelled CO_2 injection wells at each site. Permeability values in milliDarcy, mD



2.5.3.3 Rate and timing of CO_2 injection

The annual rate of CO_2 injection is the total across all five injection wells at each site. Injection is constrained to a rate across all five wells equal to six million tonnes per year. The duration of CO_2 injection is for 30 years at each site. Injection at Site A is modelled to start in 2016, five years after hydrocarbon production stopped at the Goldeneye Field at the end of 2010. Site B starts CO_2 injection five years later than Site A. The timing of CO_2 injection for Site A and Site B are thus modelled as 2016 to 2046 and 2021 to 2051, respectively.

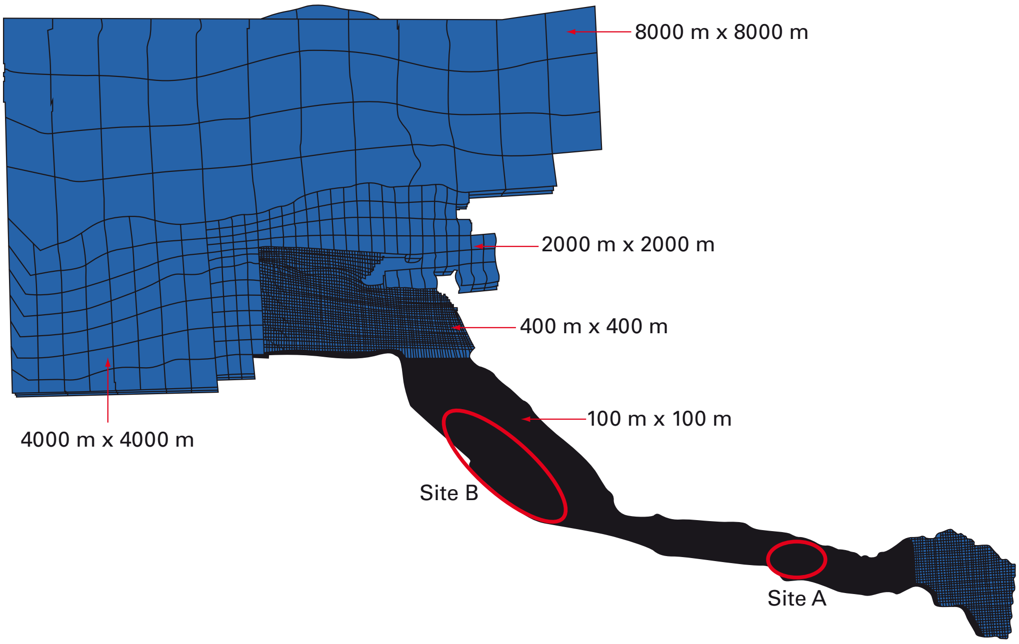
The maximum acceptable injection pressures, determined by geomechanical modelling of the multi-user store (Section 2.4.6.1), increases with the depth of the Captain Sandstone. Sites of existing wells within each of the hydrocarbon fields (Figure 23) were selected to monitor changes during CO_2 injection for the CO_2MultiStore predictive simulations. The objective for prediction of pressure changes is to ensure the maximum acceptable pressure is not exceeded in the immediate vicinity of the CO_2 injection points so the rocks will not fracture. In particular, for the shallower injection Site B the maximum acceptable pressure should not be exceeded by the cumulative effect of the operation of the multi-user store.

2.5.3.4 Local revision of the grid cells for dynamic modelling

The extent of the Captain Sandstone, the need to assess the pressure changes and the potential interaction from two sites require that the model should also cover a large area. However, the larger the total numbers of cells, the longer the simulation time, which is, in turn, dependent on the available computing resources. A compromise has to be made between the accuracy of the simulation and the affordability of time and cost.

To make the most effective use of resources, the CO_2MultiStore dynamic model structure was optimised. The number of geological layers was reduced, the number of model component cells was decreased (Table 12), and the area of each cell was varied (Figure 26). During construction of the geological 'static' model (Section 2.3) a uniform horizontal grid of cells 400 m by 400 m was used. A second phase of grid revision reflects the purpose of CO_2MultiStore dynamic modelling to investigate two injection sites. Coarsening of cells (upscaling) is appropriate in areas distant from the injection sites where the effect of injection will be a change in pressure, but to where CO_2 would not migrate. Around the storage sites, where the impact will be migration of the injected CO_2 as well as pressure changes, reduction of the cell area (refinement) is appropriate. The model will need to be most finely resolved around the storage sites to ensure greatest confidence in the prediction of the position of the migrated CO_2. Coarsening of the cell size away from the injection sites and reduction in the cell size in the vicinity of Site A and Site B in the CO_2MultiStore dynamic model is shown in Figure 26.

Figure 26 Horizontal dimensions of grid cells for the CO_2MultiStore dynamic model showing local cell-size reduction around the injection sites and cell size coarsening away from injection at Site A and Site B. Initial geological model cell size, before refinement, was 400m by 400m



2.5.3.5 Validation of the CO_2MultiStore dynamic model using hydrocarbon field data

The structure of the CO_2MultiStore dynamic model was validated by simulating the operation and closure of the Goldeneye Field from 2004 to 2012. The results were compared with historical hydrocarbon field production data from two wells, one each from the Goldeneye and Hannay fields. A good match was achieved, demonstrating that appropriate input data had been used for the CO_2MultiStore dynamic model increasing confidence in the prediction of multi-user storage site performance in CO_2MultiStore.

2.5.3.6 Detailed dynamic modelling of CO_2 injection at Site A and Site B

Migration of injected CO_2

The prediction of CO_2 migration addresses a concern raised by technical experts that the operation of a CO_2 storage site might adversely interact with other hydrocarbon fields within the Captain Sandstone.

After 30 years of injection at Site A the buoyant injected CO_2 migrates upwards. It is trapped below and spreads out beneath the upper surface of the Captain Sandstone (Figure 27). The CO_2 migrates laterally, extending beyond the boundary of the Goldeneye Field three kilometres eastwards. The injected CO_2 is predicted to migrate three kilometres westwards (Figure 27). The migrated CO_2 does not extend to either Site B or other hydrocarbon fields within the Captain Sandstone west of the Goldeneye Field.

The predicted distribution of CO_2 after 30 years' injection at Site A and 30 years' injection at Site B, commencing five years after Site A, is shown in Figure 28. The distribution and saturation of CO_2 only is illustrated. At Site A injection was into the Upper Captain Sandstone unit D (Figure 28a) with little or no migration into the Lower Captain Sandstone unit A (Figure 28b). At Site B the dynamic modelling simulates CO_2 injection into the Captain Sandstone unit A (Lower Captain Sandstone). At Site B, CO_2 was injected into the Lower Captain Sandstone unit A (Figure 28b). The CO_2 injected at Site B migrates outward from each injection well within Captain Sandstone unit D and in the north western part of the site the CO_2 coalesces and migrates towards the position of the Blake Field. Any encroachment by the CO_2 in the CO_2MultiStore scenario is modelled as occurring after 2030, when the Blake Field is expected to have long ceased production. The possible encroachment of CO_2 would be considered in the Blake Field well abandonment process.

Figure 27 View of the upper surface of the Captain Sandstone (top of Captain Sandstone Unit E) after 30 years of CO_2 injection at Site A (yellow circle) showing the distribution of CO_2 and hydrocarbon gas in red, oil in green, and water in blue. The hydrocarbon fields indicated on the illustrated model contain only hydrocarbons

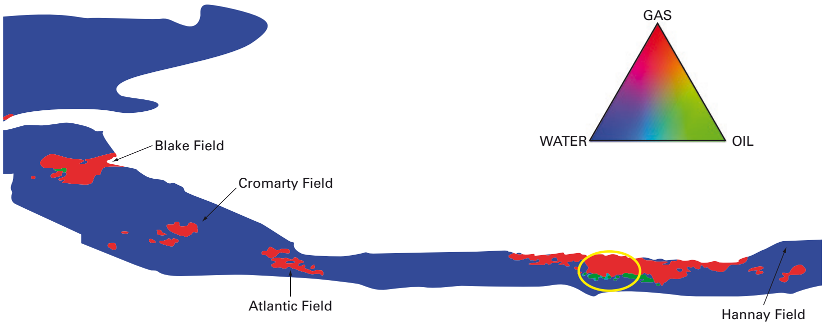
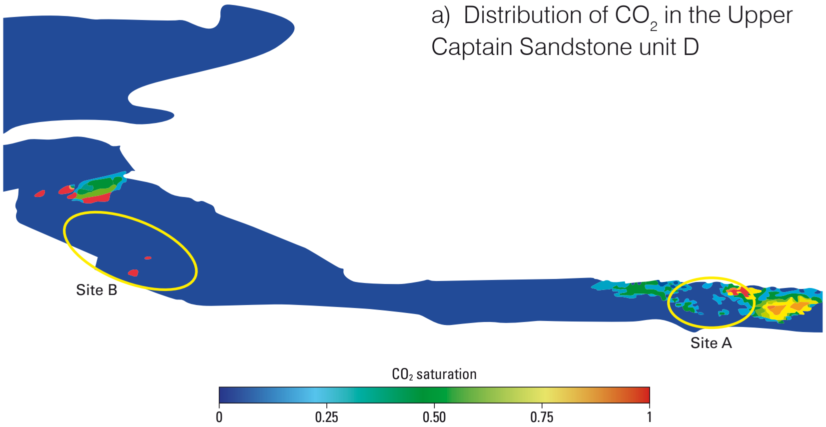
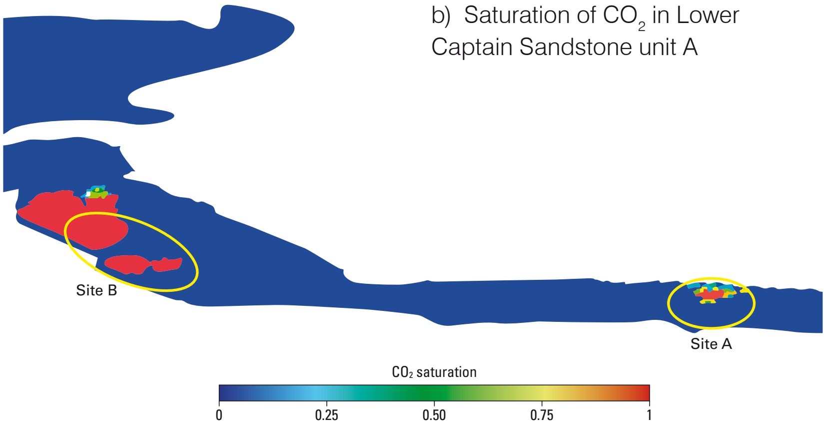


Figure 28 Distribution of CO_2 after 30 years of injection at both Site A also at Site B, starting five years after Site A a) in the upper Captain Sandstone unit D and b) in the lower Captain Sandstone unit A

a) Distribution of CO_2 in the Upper Captain Sandstone unit D



b) Saturation of CO_2 in Lower Captain Sandstone unit A

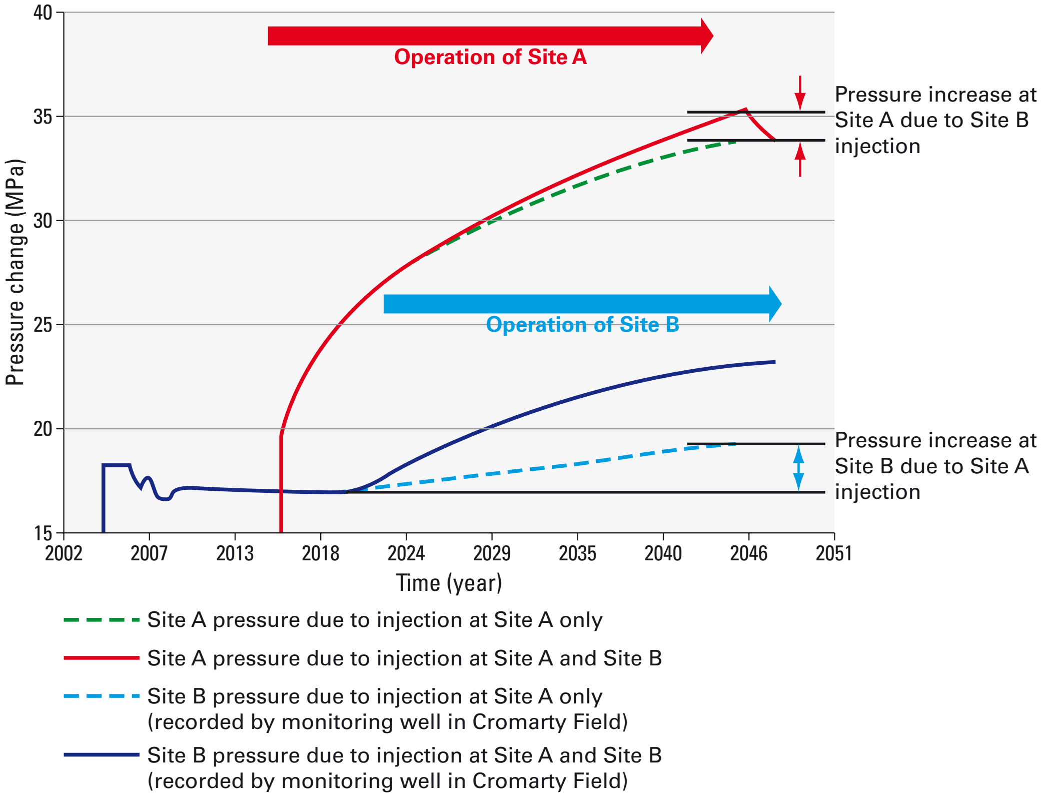


2.5.3.7 Pressure changes within the Captain Sandstone multi-user store

The extent of simulated changes in pressure within the Captain Sandstone due to CO_2 injection is widespread, as indicated by previous studies (SCCS, 2011, Akhurst et al., 2015). Dynamic modelling of CO_2 injection only at Site A for 30 years predicts there will be a measurable pressure change due to the operation of the first Site A at the position of Site B 50 km to the west and at a monitoring well within the Cromarty Field (Figure 29). Initial CO_2 injection at Site A generates a pressure increase of about 2 MPa at the position of Site B (blue arrows on Figure 29).

A second simulation of CO_2 injection predicts the pressure changes generated by injection at both Site A and Site B with operation of Site B starting five years after Site A (Figure 29). The impact on nearby hydrocarbon fields is assessed from the monitoring well positioned within the Cromarty Field (blue dashed line on Figure 29). There is an asymmetry in the pressure impacts of the two sites on each other. Injection operations at Site A cause a bigger increase in pressure at Site B (blue arrows on Figure 29) than the increase in pressure at Site A due to the injection operations at Site B (red arrows on Figure 29). This is due to the larger volume of the storage formation to the west of Site B, but much smaller storage formation volume to the east of Site A to dissipate an increase in pressure. This means that pressure due to injection at Site A will be forced to dissipate towards Site B more than pressure due to injection at Site B will be forced to dissipate towards Site A. The shallower depth of Site B means that this effect of injection at the neighbouring site will have an earlier impact at Site B because the cap rock strength is lower for shallower formations. The pressure increase at shallower Site B due to the existing operation of deeper

Figure 29 Pressure predicted at Site A, Site B and in a monitoring well in the Cromarty field due to CO_2 injection at two sites in the Captain Sandstone multi-user store



Site A will reduce the pressure increase available for accommodation of CO_2 injection at Site B.

Table 15 Pressure changes in nearby hydrocarbon fields during oil/gas production and CO_2 injection in Site A and Site B from 2016 to 2046

Hydrocarbon Field	Predicted pressure increase due to the operation of Site A and Site B
Hannay Oil Field	8 MPa
Goldeneye Gas Condensate Field	16 MPa
Atlantic Gas Condensate Field	6 MPa
Cromarty Gas Field	6 MPa
Blake Oil Field	5 Mpa

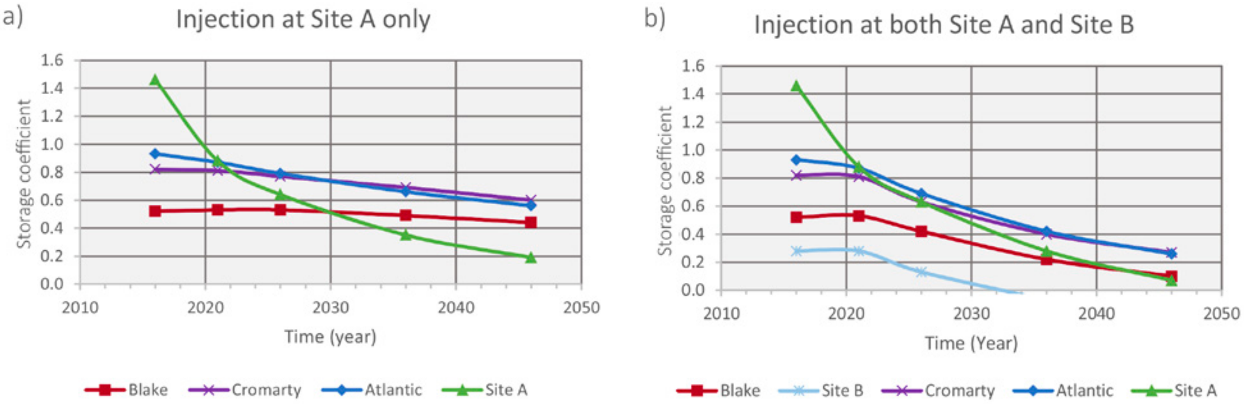
2.5.3.8 Pressure effect on nearby hydrocarbon fields

Increases in pressure due to the operation of two sites at nearby hydrocarbon fields were predicted by the detailed dynamic modelling in CO_2MultiStore. The pressure increases generated by the injection scenario of an initial demonstrator project and a subsequent follow-on CO_2 storage project are presented in Table 15. The pressure changes in each hydrocarbon field are due only to the operation of Site A and then Site B from 2016 to 2046. The relevance of the increase in pressure is dependent on the circumstances of the individual fields. Whether the increase is detrimental or beneficial differs for each field. A pressure increase at greater depth beneath the sea bed, e.g. Hannay and Goldeneye fields, is likely to have much less impact than one at shallower depth. Although the increase in the Blake, Cromarty, and Atlantic fields is 6 MPa or less, it is significant in comparison with the initial field pressure (15 MPa). Pressure management may be required to ensure the acceptable maximum pressure is not exceeded. However, increases in pressure may be beneficial, dependant on the relative timing of injection operations and hydrocarbon field development.

2.5.3.9 Pressure effects on the CO_2 storage capacity of nearby hydrocarbon fields

Hydrocarbon fields near Site A and Site B, once depleted, might be considered for CO_2 storage. The volume occupied by stored CO_2 is created by the compression of the fluids and rock and so influenced by pressure changes. The capacity of a prospective storage site is related to the increase in average pressure constrained by the maximum acceptable pressure, and the compressibility of the fluids and rock. The maximum acceptable pressure is determined individually for each site (Section 2.4.6) and the range of pressure increase up to that maximum. This maximum acceptable pressure is dependent on the initial pressure at each site and any subsequent pressure changes due to human use of the formation or to natural processes. Dynamic modelling can predict the pressure changes and so infer the storage capacity as a result of different prospective uses of the whole formation. In CO_2MultiStore, the operation of Site A alone, Site B alone, and the operation of both as a multi-user store was simulated. The change in storage capacity was assessed by calculating the pressure change over time at each site presented as storage efficiency values.

Figure 30 Predicted reduction of the storage co-efficient during multi-user storage operation when (a) Site A is injecting, and (b) Site A and Site B are injecting. Site A is 30km from Atlantic Field, 45km from Cromarty Field, and 55 km from Blake Field. Injection at Site A is modelled as starting in 2016



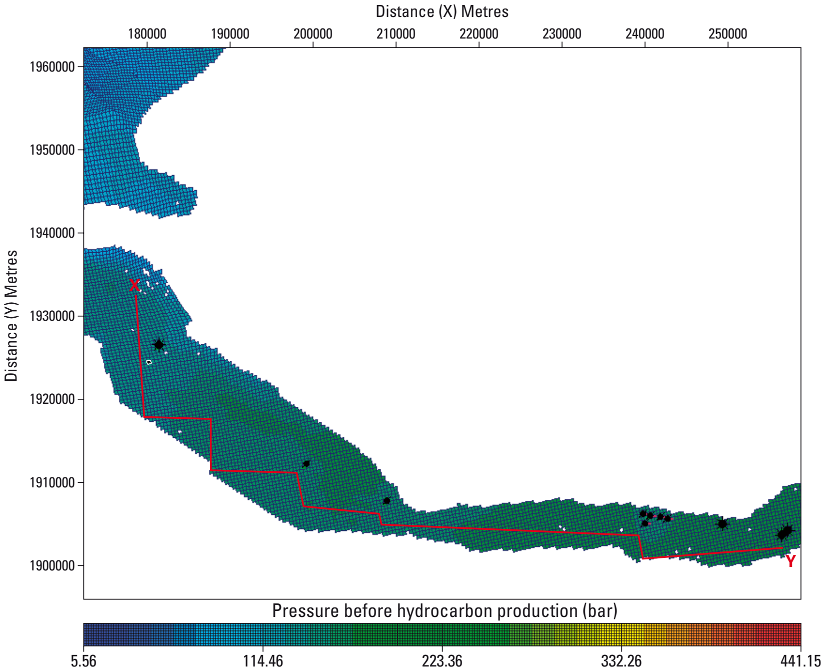
The changes in pressure were calculated at each injection site and also the monitoring well positions within nearby hydrocarbon fields. The maximum acceptable pressure was not exceeded at any of the injection wells modelled at Site A or Site B. Injection was discontinued as part of the multi-user store simulation at two wells in Site B to control the pressure increase, with the injection rate maintained across the remaining three wells to the end of the simulated operation of Site B.

The effect of pressure changes from Site A on Site B and on nearby hydrocarbon fields, if used for CO_2 storage, is illustrated by the predicted change in storage efficiency (Figure 30). The implication for storage efficiency, and therefore storage capacity, from the dynamic modelling is that the storage capacity of a second storage site decreases the closer it is to an existing Site A. The efficiency is also dependant on the relative depth of the two injection sites; the shallower the second injection site the greater the reduction in storage efficiency.

2.5.3.10 Predicted profile of pressure change due to the operation of a multi-user store

A profile of pressure change linking well positions in each field or each injection site used in CO_2MultiStore was plotted (Figure 31). The profile along the Captain Sandstone fairway starts at the Blake Field, passes through Site B, the Cromarty and Atlantic fields, and Site A to the Hannay Field.

Figure 31 Line of pressure profile along the Captain Sandstone fairway linking the well positions used in CO_2MultiStore



The pressure profile extends from west to east and shows pressure change along the length of the 'fairway' and over time (Figure 32). The small irregularities in the plotted lines are due to the stepped line of section that joins Site A and Site B with the hydrocarbon field positions. The pressure profiles at specified years during hydrocarbon production and CO_2 injection are plotted. Production of hydrocarbons from the Goldeneye Field from 2004 to 2010 reduced the pressure at the field and also along the fairway to the Atlantic Field (plot for 2011). After four years of natural pressure recovery due to influx of brine followed by a modelled five year period of CO_2 injection commencing in 2016, the pressure at the Goldeneye Field (Site A) in 2021 approaches its initial value. During this period hydrocarbons remaining in the Goldeneye reservoir are displaced by the injected CO_2. Once injection also commences in Site B, starting during 2021, pressure is predicted to increase all along the fairway (plot for 2026). The increase in pressure at Site A is greater than at Site B due to the shape of the fairway. The Captain Sandstone is relatively narrow at the position of Site A, which confines the pressure increase. The pressure increase propagates westwards along the fairway across its narrowest point, where it is also at its thinnest (Figure 6), toward Site B. The predicted increase in pressure is much reduced westwards as the width of the fairway increases and continues as the wider extent of the Captain Sandstone (Figure 32). Pressure increases at Site B are modelled as dissipating from the fairway into the extensive Captain Sandstone by westward displacement of brine.

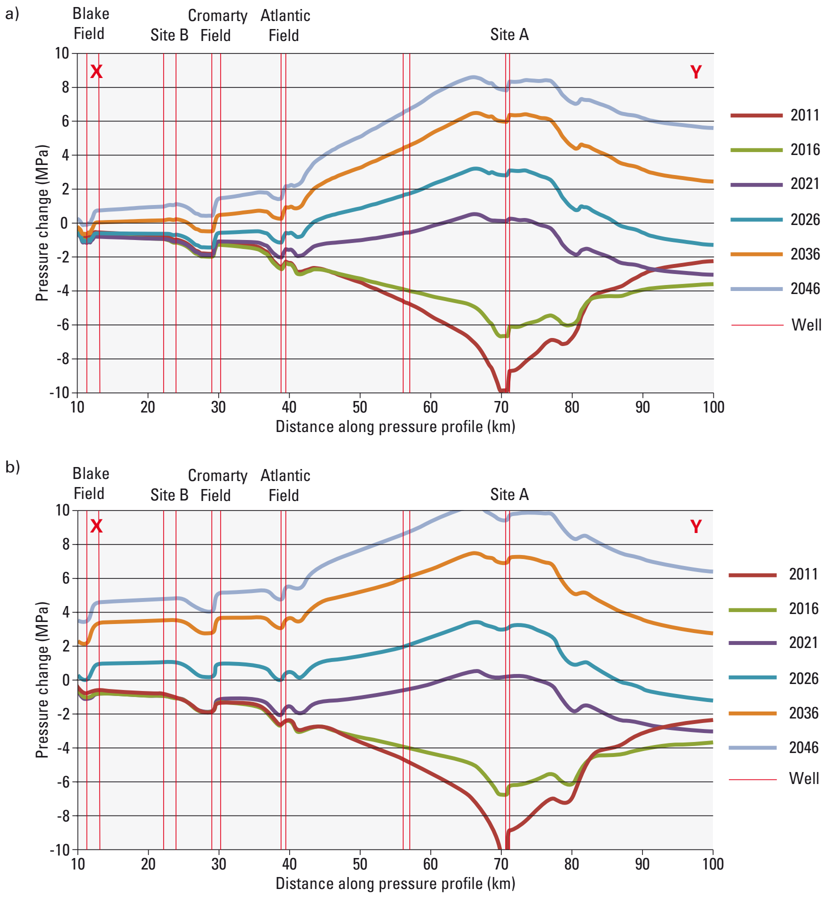


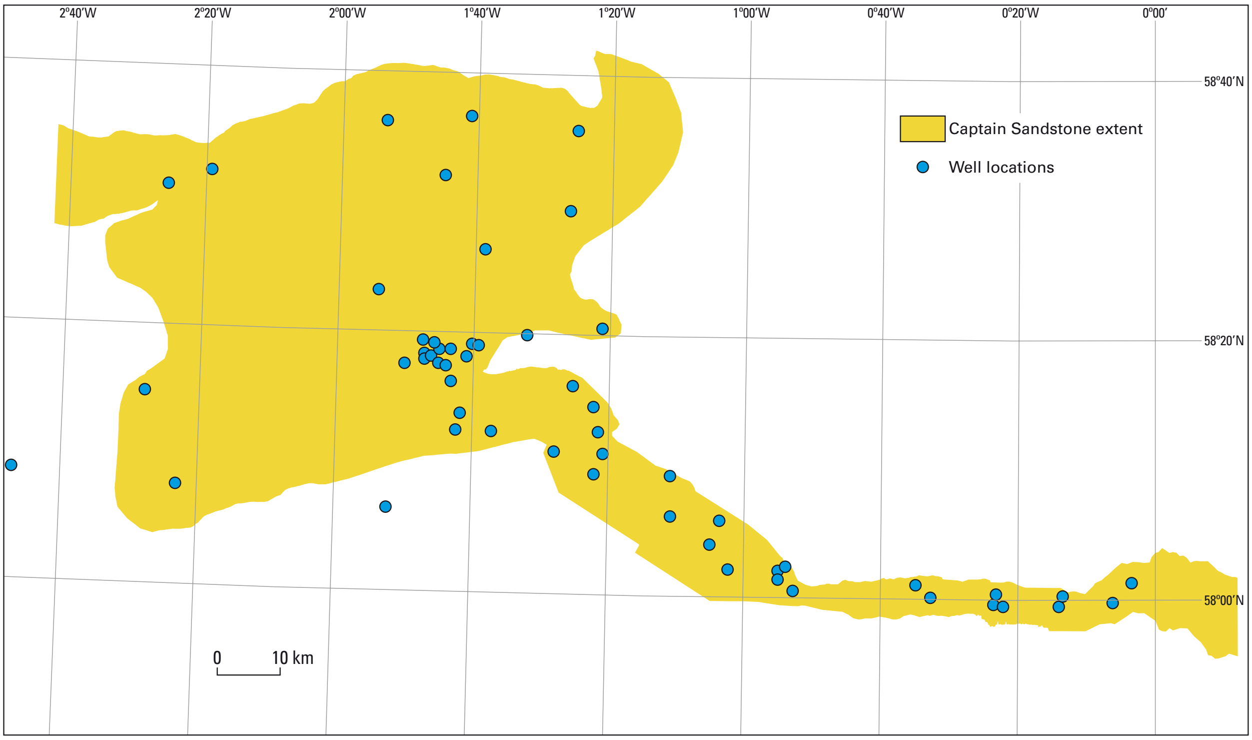
Figure 32 Profile of pressure difference along the Captain Sandstone fairway showing pressure change over time due to hydrocarbon production and CO_2 injection a) at Site A and b) at both Site A and Site B

Although injection is modelled for 30 years in Site A and 30 years in Site B, because the system is much narrower at Site A the pressure is dissipated much more at Site B.

2.5.4 Study of the effect of different properties for the underlying strata

Geological property data was compiled from selected hydrocarbon exploration and production wells for strata underlying the Captain Sandstone (Figure 33). The porosity, permeability, thickness and proportion of sandstone observed and measured in the wells by oil and gas companies were collated, down to rocks that are impermeable. The compiled geological information was used as input data to test the sensitivity of the pressure changes to the character of the lower boundary of the Captain Sandstone. Average values for the porosity and permeability, volume of the underlying rocks and the pore spaces within them were calculated for the Valhall Formation, which underlies the Captain Sandstone (Figure 3).

Figure 33 Position of well sites for geological data used to test the sensitivity of the detailed dynamic modelling to changes in the character of the strata underlying the Captain Sandstone

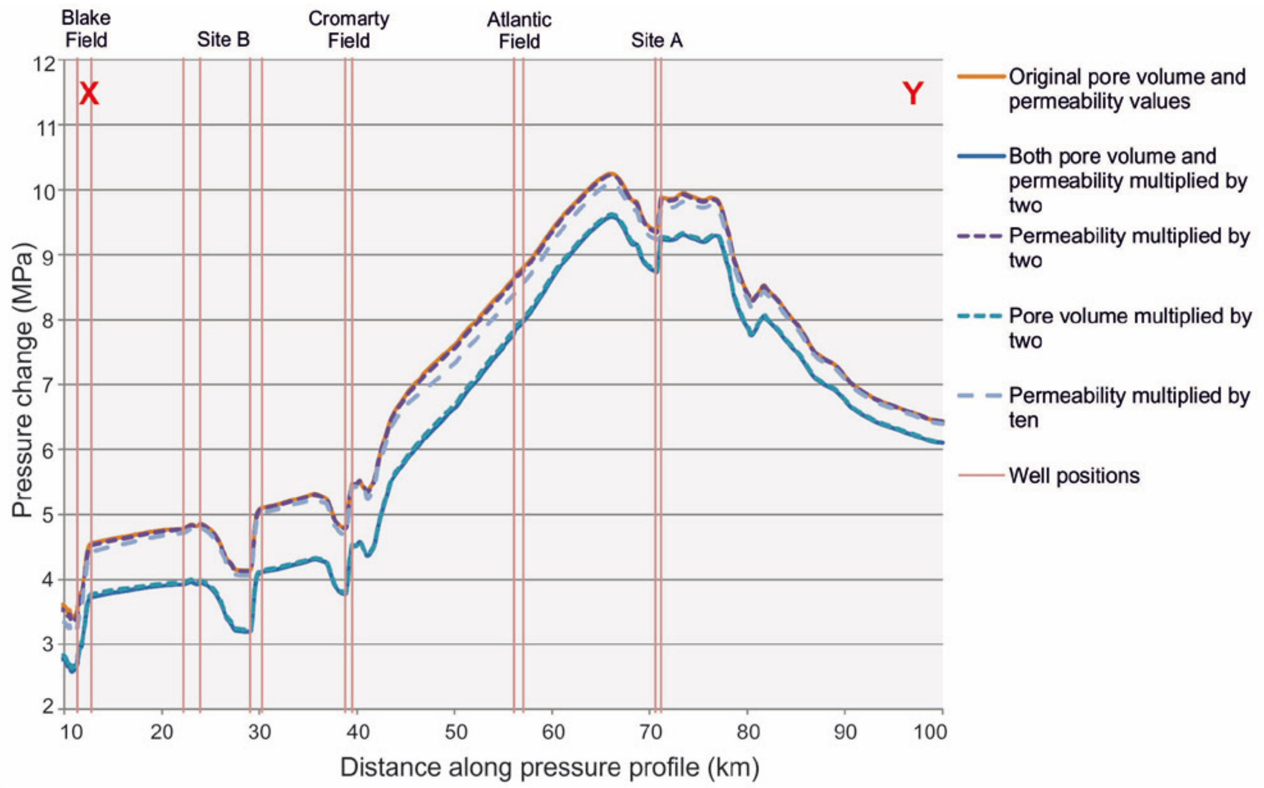


Four sensitivity simulations were calculated, with variations in pore volume and permeability for the underlying Valhall Formation (Table 16). Either the pore volume (0.22 km³) and average permeability (25 mD) values or multipliers of two or ten were used.

Table 16 Calculations used to investigate the sensitivity of the predictive pressure modelling to variations in the pore volume and permeability of the strata underlying the Captain Sandstone

Sensitivity calculation number	Pore volume multiplier	Average permeability multiplier
1	2	1
2	1	2
3	2	2
4	1	10

Figure 34 Profiles of pressure difference for the variations in the character of the strata underlying the Captain Sandstone used in the sensitivity studies (Table 16). The curves show the pressure response to changes in the characteristics of the underlying strata calculated in 2046 after 30 years of injection in Site A and 25 years of injection in Site B. The brown line shows the profile using the original pore volume (0.22 km³) and permeability (25 mD) values



Increasing the average permeability by a factor of two (from 25 mD to 50 mD), or even by a factor of 10 (250 mD), does not substantially reduce the increase in pressure generated by the injection of CO_2 (Figure 34). Varying the pore volume very significantly affects the pressure response and the performance of the storage strata. Doubling the pore volume of the underlying Valhall Formation reduces the pressure increase during simulation of the two CO_2MultiStore injection sites by 0.5 to 1.0 MPa. The wider range between the pressure at the start of CO_2 operations and the maximum acceptable pressure increases the potential CO_2 storage capacity at both injection sites. The implication for multi-user storage site appraisal in the Captain Sandstone is the importance of having a high level of confidence in the porosity and pore volume of the underlying strata as input data to the dynamic simulations of CO_2 injection.

Conclusions from the study of the properties of the underlying strata

It was found that, for simulation of the operation of a multi-user store in the Captain Sandstone, the permeability of strata underlying the injection sites had little impact on the overall system pressure response for the permeability values used. It is evident that an impermeable stratum would result in no pressure dissipation into that interval, but provided there is a finite permeability then pressure dissipation will take place. This is because the transmissibility between two strata is a function not only of the vertical permeability, but also of the cross-sectional area of the interface between these strata, and that is a very large number in this case.

The pore volume of the strata underlying the Captain Sandstone had a significant impact on the pressure response, with pressure changes of up to 1.0 MPa predicted due to a doubling of the pore volume in the Valhall Formation. Knowledge of the connected pore volume is important in assessing the pressure response. In general, pressure increase is inversely proportional to the volume of fluid and rock that is being compressed, and the greater the volume of the underlying intervals with which there is communication, the slower the increase in the system pressure will be.

2.5.5 Comparison of dynamic modelling results using a simplified version of the complex CO_2MultiStore Captain Model

An abundance of geological data is collected where there has been exploration and production of hydrocarbons. This is accompanied by knowledge gained of the performance of the hydrocarbon field reservoir rocks and a detailed understanding of the reservoir pressure and fluid flow over the lifetime of a field. Such data and information were available and used by CO_2MultiStore. Where a prospective multi-user storage site is a sandstone containing only brine (saline aquifer) and not also hydrocarbons, such rich datasets or existing knowledge is unlikely to be available. The CO_2MultiStore results were also used to assess the level of confidence with which a multi-user storage site within a saline aquifer can be assessed with fewer data and more sparse understanding of the strata. The complex CO_2MultiStore Captain Model was simplified, dynamic simulations of CO_2 injections were re-run, and the results compared.

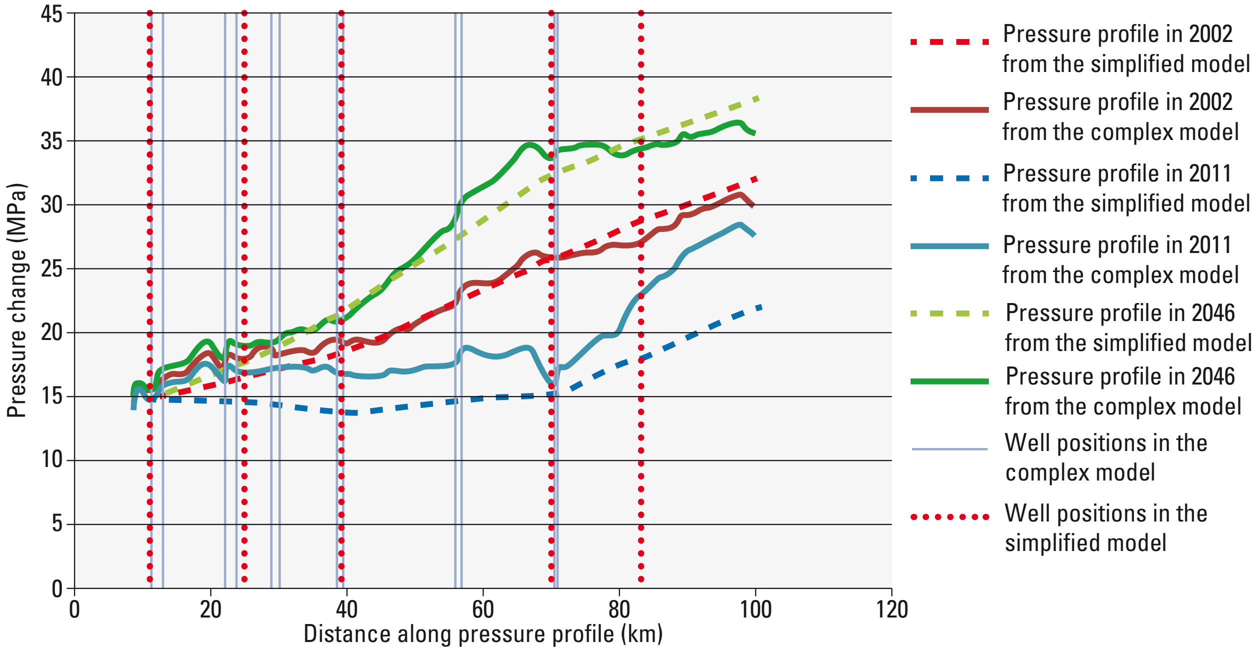
The simplified model combines a 3D model of the fairway with the Captain Sandstone further to the east and west represented as numerical values in the calculations. The total volume of pore space in the simplified 3D model and numerical values were sufficiently similar to the complex model to be fully acceptable. Hydrocarbon fields and properties of their contained fluids were retained but not represented in such great detail. The simplified 3D model is of a much smaller area, and the geological surfaces are smooth and uniformly inclined. The grid cells all have the same dimensions and are attributed with average values for porosity, permeability and proportion of sandstone for the strata within the fairway.

Dynamic modelling of the operation of a multi-user store in the Captain Sandstone was simulated using the same two injection sites, average angle of inclination of the strata, timing, duration and rates of injection and volumes of injected CO_2. Dynamic modelling predicted the pressure response for the Captain Sandstone multi-user store. The results were compared with the results from dynamic modelling using the complex model. Predicted migration of CO_2 at the two injection sites was not calculated.

Three pressure profiles were plotted, before hydrocarbon production in 2002 and after completion of hydrocarbon production in 2011 at the Goldeneye Field, and also after modelling of completion of multi-user store operations at CO_2 injection Site A and Site B in 2046 (Figure 35).

The regional response to pressure increases within the Captain Sandstone are replicated by simulation of injection using the simplified 3D model. There is a sufficiently close match, acceptable on the regional scale, of the solid and

Figure 35 Comparison of the pressure response by dynamic modelling of a complex and simplified 3D model of the Captain Sandstone. The profiles show the pressure response to operation of the multi-user store in 2002, 2011 and 2046



dashed lines on Figure 35. The much more rapid calculation, reduced from five days to four hours, is sufficient to assess the regional pressure response. The results are suitable to assess the suitability of a prospective multi-user site, and any requirement for pressure management and likely effect on existing nearby hydrocarbon fields. Comparison of the curves illustrates that, although sufficiently similar from the perspective of a regional variation, they do differ at the site-specific scale. There is insufficient match in the detailed prediction of pressure response. Definition of the maximum acceptable pressure at individual sites would not be appropriate from the predictions using a simplified dynamic model. The results would inform whether the resources needed for a more detailed assessment of maximum pressure are justified.

2.5.6 Conclusions from the dynamic simulation of CO_2 injection

A dynamic model of the Captain Sandstone was constructed by bringing together two separate static models. The dynamic model incorporates data from hydrocarbon exploration and production and for hydrocarbon fields within the Captain Sandstone.

Dynamic simulations have been performed on a generic box model of the system to validate the input data and to assess the impact of choices made for the input parameters with existing modelling. A good match was achieved, giving confidence that appropriate input data were being entered in the CO_2MultiStore Dynamic Model. This model was used to study the performance of the CO_2 injection sites, their interaction in a multi-user store, and the impact on hydrocarbon production activities in fields within the Captain Sandstone. The sensitivity of the results to the input data are assessed by comparing results when the input parameters are changed.

The following conclusions are drawn from analysis of the results of the dynamic simulation and sensitivity studies.

1. The pressure in each site affects any other injection sites and hydrocarbon fields in the dynamic model. The pressure changes are noted even though the highly porous and permeable sandstones (Captain A and D units) are partly separated by a low permeability layer (Captain C unit), and CO_2 was injected into different layers in Site A (Upper Captain Sandstone unit D) and Site B (Lower Captain Sandstone unit A).

2. There is a delay after the start of injection before the pressure response from one injection site is 'felt' at another in a multi-user store. The duration of the delay is dependent on the distance between the two sites. In CO_2MultiStore, the distance is approximately 45 km, and the delay is five years.

3. The storage capacity of a site in a multi-user store is constrained not only by the maximum acceptable pressure of its own site, but also by the initial reservoir pressure at the time the injection started. A depleted hydrocarbon field where there has been no water injection will have a higher storage capacity than an equivalent field at its initial pressure.

4. The share of the storage capacity that one site can use within a multi-user store is dependent on both spatial and geometrical factors (differences in depth and volume of storage formation in the vicinity of the sites, and distance between the sites) and the relative timing of the development of the sites.

    - The consequences of induced pressure increases, one site to another, are not equal as the depths and hence cap rock strength, of the two sites in CO_2MultiStore are different. The magnitude of induced pressure changes is also not symmetrical as one site is adjacent to a much larger volume of the storage formation than the other

    - Site A and Site B share the intervening part of the storage formation equally, but at either end Site B is in direct contact with a much greater volume of the overall Captain Sandstone than Site A. This means that injection in Site A has more of an impact on the pressure in the intervening region than does injection in Site B. Site A is much deeper than Site B and so can withstand a greater pressure increase. This pressure increase gradually dissipates along the intervening sandstone and affects the storage capacity in Site B more than the injection of a similar volume of CO_2 in Site B would affect the storage capacity in Site A

5. The impact of pressure increase on existing oil fields is significant, therefore the monitoring of pressure changes should be set not only in the two injection sites, but also in the locations where pressure changes may affect existing wells or the cap rock.

6. A long-term migration study is required for the optimisation of injection sites.

2.6 INCREASED UNDERSTANDING OF A MULTI-USER STORE

At the outset of the project, the investigations were targeted to increase confidence in the understanding of a multi-user store. It was recognised early on that it was possible to increase the rating of confidence through the CO_2MultiStore modelling work.

Ten issues were selected for consideration during the re-assessment process, from the register proposed when assessing the character in a multi-user storage site (Section 2.2). These were selected from perceived issues and potential concerns that had been addressed by the modelling:

- The most highly ranked issues in the draft revised rating
- Those with disparate ratings where they were investigated by both dynamic and geomechanical modelling, and
- Any other concerns that the modelling directly addressed

Three of these issues were discussed in more detail to finalise the draft rankings and decide whether confidence was at an acceptable level, or whether further mitigation (beyond CO_2MultiStore) would be expected at a real site and if so, what that might entail, and whether any (and what) corrective measures could be implemented if the issue occurred.

This process highlighted the need for further work, including gathering of additional data and re-running the models with the new input or model boundary parameters.

For the most part, it was considered that confidence in the top issues had increased, but given the limited additional data and modelling performed, overall confidence remained relatively low. Most of the measures suggested to increase confidence were not possible through a research project, but highlighted the following:

- Information sharing (pressure data in particular) between operators, the regulator(s) and/or an independent arbitrator will be key to understanding and mitigating perceived storage site interactions
- Information gained from actual testing will allow improved predictions from models based on updated parameters to update the perceived issues and rating of confidence

In a ‘real’ project, potential issues and their ratings need regular review as new information or technology (for mitigation or corrective measures) becomes available. Once all mitigation has been completed, any remaining ‘residual’ issues can inform the monitoring and corrective measures plans.

The CO_2MultiStore assessment work forms the early part of a storage site’s planning phase (left hand side of Figure 36, and Figure 37). This is based on data and evolution of understanding of a potential concern throughout the project. There is a general expectation that the knowledge gained through implementing a CO_2 storage project will incrementally increase confidence through time, as previously unknown parameters become apparent (Figure 36). Note that at the onset of injection from the second project, depending largely on the pressure connection between the sites, it may be some time before any interaction is seen and the nature of that increases confidence.

Confidence ratings have generally been increased through the CO_2MultiStore modelling and the re-assessment work for those issues addressed. The schematic in Figure 37 shows how certainty of the sites interacting with one another increases over time. However, one or two issues have remaining low confidence. This is considered to be normal for a research project, as in many cases this can only be increased by testing (or access to more data).

A general perception may be that confidence for CO_2 storage (site interaction) decreases through time, for example as pressure in a regional storage asset increases, unless this is managed, e.g. through water production or staged injection etc. As projects progress, however, knowledge from them will allow improved knowledge of and planning for site interaction. This in turn can allow for improved mitigation and hence a general increase in confidence levels through time. In either case, it is clear that having more than one storage site in a single storage asset requires careful management and a broad overview from custodians of the storage space, to be able to maximise its potential and ensure data sharing between stakeholders.

Based on the CO_2MultiStore research, it is clear that at least during the initial planning stages of a project, confidence ratings can change dramatically as the sensitivity studies highlight the important parameters, which may be unknown until more detailed testing takes place. Analysis of perceived issues at this early stage helps to identify these parameters and helps lead the whole project through logical steps to enable secure and efficient CO_2 storage. Mitigating actions beyond the research phase, implemented through site design, is expected to lead to a step change increase in both the confidence ratings and the certainty in the ratings.

Figure 36 Schematic diagram showing how perceived concerns relating to the interaction between two storage sites could be expected to change through time

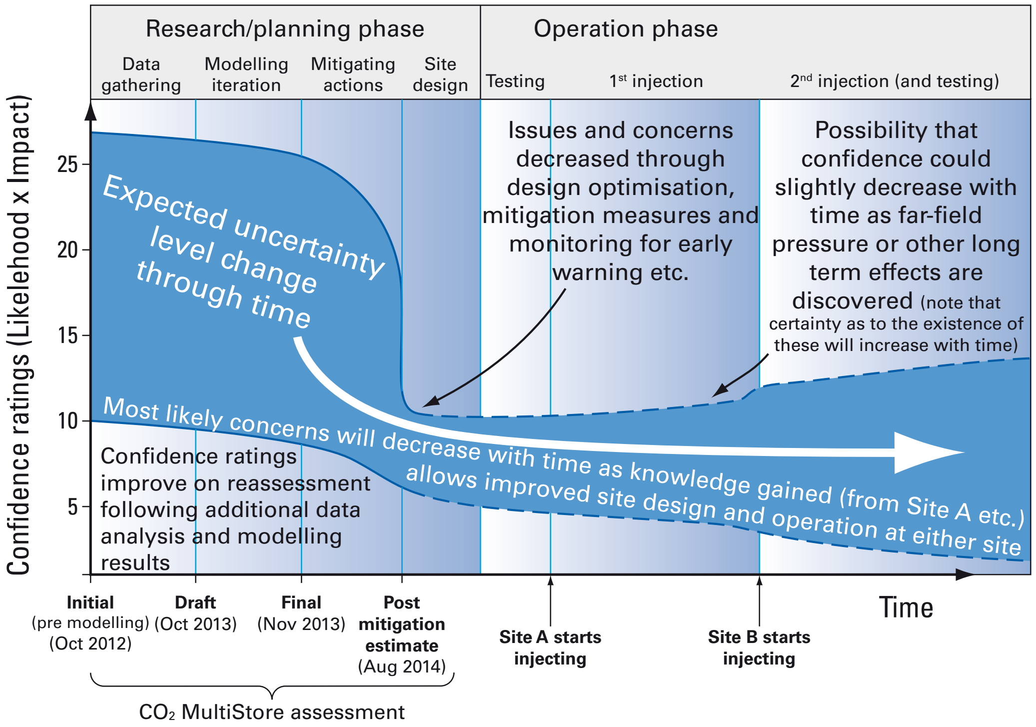
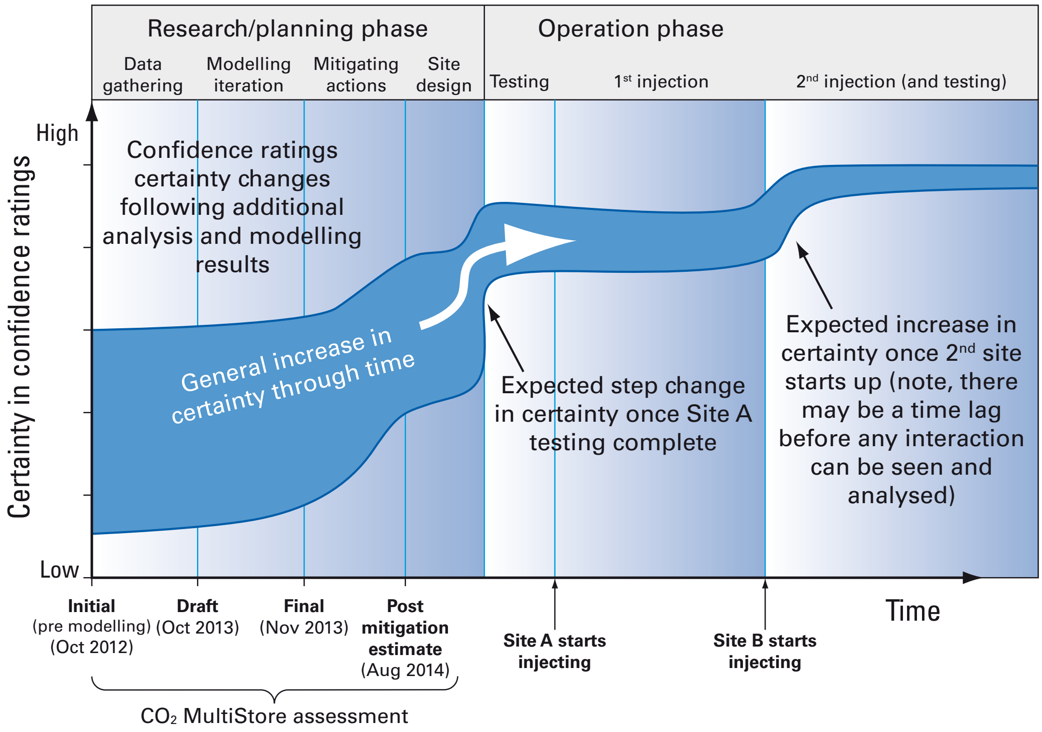


Figure 37 Schematic diagram showing how certainty in the confidence ratings based on interaction between two storage sites may be expected to increase through time



2.7 CONCLUSIONS ON THE DESIGN OF A PLAN FOR MONITORING MULTI-USER STORAGE OPERATIONS

An important first step in a monitoring plan is to carry out baseline studies, pre-injection of CO_2 into a storage site, of all the issues that might be expected to arise during injection and operation, e.g. current pressure conditions in the intended store. The plan should be designed to provide enough information to initiate site remediation of an unforeseen event and to demonstrate the site is performing according to predictions and providing continuing containment, and eventually enabling a satisfactory site closure strategy.

The monitoring plan must define the maximum operating pressures and enable careful observation of pressure changes during injection. Pressure monitoring would therefore be a key component of a site operator's monitoring plan and is also a regulatory requirement of the European Storage Directive (EC, 2009).

The principal objectives of the monitoring plan in a multi-user storage site would be to:

- Ensure cap rock integrity is maintained
- Verify the absence of detectable leakage above the cap rock
- Identify impacts from injection at the operator's site to the extent that this might be possible. The injection might be either at their own site injection or injection at the other site

- Assess the rate of the production of formation fluids. If necessary for the management of pressure, the rate of water production would be determined in response to the pressure monitoring

CO_2Multistore focused on the aspects of monitoring that would be required to specifically address any unforeseen events arising from a multiple injection scenario into the Captain Sandstone. Other aspects of the monitoring plan would address operational monitoring either required by regulations or to demonstrate conformance between the observed behaviour of the storage site and the predictions of behaviour from reservoir simulations in the geological model. The consequences of the potential problems identified in this project include potential for reduced storage capacity, reduced injectivity and reduced cap rock (primary seal) integrity. Unexpected and unacceptable pressure increases could lead to a need for changes to permit conditions, changes to leases, and possibly site closures in extreme cases.

A conclusion of the dynamic modelling work (Section 2.5) was that the monitoring of pressure changes should not only be undertaken at the injection sites, but also at the locations where pressure changes may impact other wells, hydrocarbon field operations or the cap rock.

Currently in the hydrocarbon industry, the potential impacts of additional production on pre-existing fields is not taken into consideration. Any impacts on existing fields by production at new fields may possibly require some commercial arrangement between operators, particularly if remedial action is required due to impacts of a nearby installation. However, storage regulations explicitly state that other uses of the subsurface can take precedence over CO_2 storage. In the UK, hydrocarbon production takes precedence and therefore any potential impacts on existing hydrocarbon production or on future production must be taken into account. The potential impacts of CO_2 storage could include an increase in pressure at a producing field, which may be considered a positive benefit to the producer, but may also result in increased water production in some wells.

Pressure monitoring in the storage formation and in overlying formations is therefore considered fundamental to provide the necessary data to manage the increases during injection. In addition to the design and monitoring of a multi-user store, additional actions that could be undertaken to mitigate possible problems include encouraging discussions between operators planning to inject into the same geological formation and sharing of data obtained on the formation to reduce issues during and arising from follow-on projects. Those operators that might be affected by new storage proposals could be asked to comment on the proposals to determine how the new project might affect existing operations. Furthermore, pre-competitive testing of the formation through injection tests and appraisal wells designed to establish the degree of connection between potential injection sites should be investigated.

Predicted issues would need to be addressed by the storage developer during project design and operation. Injection strategies would be designed to minimise unacceptable pressure increases, and monitoring plans would be designed to track pressure responses as a consequence of injection within the formation.

Later projects may be required to undertake additional monitoring to ensure their projects do not adversely affect existing operations. This additional monitoring may include establishing extended baseline data to determine the degree of pressure connectivity between sites, during injection at the first site but prior to injection at the second site. Furthermore, dedicated monitoring wells might be needed to provide observation points in the formation (and in overlying formations) where pressure increases may potentially affect cap rock integrity. Pressure management may also be necessary at follow-on sites to maintain pressures below minimum operating pressures and still maintain appropriate injection rates.

Coordination of injection operations may be needed in order to maximise the storage capacity of the formation as a whole. This may require strategic planning of the timing, location and total volumes stored at each site. Coordinated monitoring of the storage formation as an asset, including the possible construction of independent monitoring wells (outside storage complexes), could also be considered.

It is also considered very beneficial to take advantage of data on reservoir pressure responses acquired from hydrocarbon production operations. Hydrocarbon field operators have a wealth of data on producing fields and this data should be appropriately archived for the benefit of future storage developers.

3 Generic learning for the characterisation and operation of a multi-user store

CO_2MultiStore followed an 'assessment to target investigations' approach to the characterisation of two injection sites within a single extensive storage formation asset. The focus was those issues arising from the operation, interaction and cumulative effect of injection of CO_2 at two (or more) sites using the Captain Sandstone as a North Sea case study. The process of assessment to determine investigations and characterisation of prospective CO_2 storage sites complies with the EC Directive on the geological storage of CO_2 (EC 2009) and follows guidance for implementation of the directive (EC, 2011).

Capture of generic knowledge from the case study applicable to all UK storage sites was undertaken by:

- Facilitating study workshops with project members and invited industry participants with experience in CCS
- Collating knowledge capture sheets from meetings, discussions and activities during the progress of the project
- One-to-one discussions
- Consideration of the process
- Elucidation of key questions
- Recording of technical knowledge gained

Outputs from these knowledge capture activities were reviewed to identify decision making during the scenario selection, uncertainty identification, corrective measures application and consequences to the storage sites and asset. Common elements for injection sites were also identified arising from the management of a regional CO_2 storage asset including the key questions asked, the decisions made, the evolution of the process, and learning from the discussion and process relevant to all storage sites.

Generic learning from the CO_2MultiStore project is intended to be relevant to the definition of CO_2 stores, store management and store integrity for injection at two (or more) sites within any multi-user storage asset.

3.1 DEVELOPMENT OF A CONSISTENT GEOLOGICAL MODEL FOR A MULTI-USER STORE

Defining a 3D computer model, incorporating geological data and knowledge of the two prospective storage sites, is an essential step needed to predict how the sites will perform during the subsurface injection and geological storage of CO_2. The better the representation of the geology of the site by the geological model (also known as a 'static' model) the better the predictions of storage site behaviour will be. For European storage sites, the modelling of prospective sites is a specified requirement in the directive on the geological storage of CO_2 (EC, 2009, 2011).

Understanding of the subsurface geology at both sites in a multi-user store must be common, or at least consistent, for a confident prediction of the performance of both sites during injection and after injection has ceased, over periods of hundreds to thousands of years into the future. The geological model captures the 3D geometry of the sequence of strata, the geological structure (i.e. whether and how the strata are folded or faulted), the characteristics of the rock layers, geological faults and bounding surfaces, and how these attributes have been incorporated into the 3D grid or cells that comprise the model. Importantly, what data have been used and how they have been used to populate the cells with appropriate values to represent the geology at an injection site should be recorded.

3.1.1 Key questions

- **Should models be merged, or should a new integrated model be constructed from scratch? If merged, is the key information available for the model?**
  If models are available of one or both of the prospective injection sites in a multi-user store, merging of existing geological models should be considered to benefit from existing knowledge and an effective re-use of resources. Key information should be derived to determine if it is geologically reasonable before deciding to use and merge available models.

- **Is geological correlation possible between the models to be merged?**
  Understanding of the strata and geological structure becomes more refined as more finely resolved data become available to the interpreter. It should be possible to merge models where the geological surfaces can be correlated and the structural interpretation is consistent in existing interpretations.

- **How was the merged model constructed?**
  Re-use and merging of existing geological models for a multi-user store requires careful understanding of the methods used and initial model limitations. Compromises are commonly required. Constraining data points, such as well datasets and seismic interpretations, should always accompany model data. This is particularly important in the zone of model overlap, to allow decisions to be made on model integration.

- **Is the merged regional geological model sensible and suitable to predict multi-user store performance?**
  Effort should be concentrated in achieving the required level of detail in those areas proposed for simulated injection of CO_2. The grid size and number of cells in a geological model is important because the extent of a geological model to assess two prospective CO_2 injection sites will be significantly larger than a model of an oil or gas field. The system can be subsequently refined or coarsened within the simulation model if fine-scale resolution is needed.

- **What are the storage formation boundary conditions? What other data are needed for the multi-store geological model?**
  The character of storage formation boundaries, whether closed (low permeability) or open (high permeability) to fluid flow, is needed to predict the evolution of formation pressure during CO_2 injection. More information on the cap rock sealing the upper boundary of a

prospective CO_2 storage formation is required to assess store integrity than for the purposes of hydrocarbon exploration.

- **Does the geological model cover the full extent needed for a multi-user site? Are geological data available for all planned modelling activities?**
  The extent of a geological model to investigate and predict the performance and interaction for two or more sites will span the area between the prospective injection sites and also extend beyond them. The geological model of the injection sites must be sufficiently extensive to encompass the predicted migration of the injected CO_2 and the extent of the increase in formation pressure due to injection. Geomechanical modelling requires additional geological information which might not be included in the existing static geological models of the component sites.

3.1.2 Learning from the process

- Correlation is likely and models can be merged in an area within a well-established geological framework. If not, a new model would be needed
- Merging will be needed to create regional-scale models for multi-user stores
- Merging to create multi-user store models is likely to be the preferred outcome if it is technically possible
- Define data requirements early, start data transfer and access agreements early, and anticipate a lengthy duration before receipt
- The model merging process, settings, parameters and nomenclature need to be fully documented
- A defined mechanism is needed for access and exchange of information, e.g. pressure history data from hydrocarbon operators, to inform geological models
- The model merging process needs to include agreement of the stage at which the merged model output is complete
- For multi-user store modelling, the model checking process should be bespoke for CO_2 storage

3.1.3 Technical knowledge gained

- Integration of geological surfaces in adjacent and overlapping models
- Simplifying a fault model for prediction of the performance of a multi-user store
- Ensuring consistency of projections and other technical parameters for model merging.
- Resolution of disparities between geological surfaces in overlapping models.
- Subdividing the merged model into 3D cells and assigning cell-size values

- Method and scale of attribution
- Recording the method and understanding the implications of changes to model cell-size
- Ensuring the merged model surfaces are correct

3.1.4 Generic learning for construction of a geological 'static' model for a regional multi-user CO_2 store

1. Static geological models need to be constructed in an agreed, standard format and the details of model construction and design fully documented if they are to be re-used and merged.
2. If models are available of one or both of the prospective injection sites in a multi-user store, merging of existing geological models should be considered. This will enable benefit to be gained from existing knowledge entrained within existing models and an effective re-use of resources.
3. Ensure all model construction activities are documented. During construction of the static geological model, all technical steps should be recorded. This includes model merging, model prioritisation, correlation, attribution and manipulation, and will enable confident use and interrogation of the merged model.
4. Merging of static geological models captures the knowledge and understanding of the original modellers. However, the effort and resources needed to merge models will still be significant.
5. Where there is inheritance of two or more models, it is more likely that re-use of models will be an efficient process only if, or when, they can be sourced from the model originators with the accompanying knowledge or detailed documentation.
6. The additional cost and time taken for construction of a single integrated model of a multi-user store from scratch rather than merging of existing models, although significant, may be justified by considering whether the:
    - underlying data is available and readily accessible
    - model construction is well understood and documented
    - modelled geological surfaces can be correlated
    - structural interpretation is consistent in both models
7. Planning and so scheduling of sufficient time for static geological model construction is needed as the duration is likely to be longer than might reasonably be expected.
8. Static geological modelling for a regional-scale multi-user store needs to start as early as possible.
9. Preparatory modelling activities may need to start before all contracts are in place, and this might be achieved by initial non-disclosure agreements.

10. Additional model iterations to amend and adjust the merged models, which can be as time-consuming as initial model merging, should be anticipated and included in the schedule.

11. Knowledge of the storage site boundary conditions, and so the degree to which the increased pressure of injection can be dissipated by fluid flow across them, is crucial to the characterisation and increased understanding of the multi-user store.

12. The static geological model must take into account what will be needed for all predictive model activities. The extent of the geological model and provision of information on geological properties must be sufficient to inform geomechanical modelling and to predict pressure changes due to storage site operations by dynamic modelling.

13. It is essential that all geoscience modellers (geomechanical, dynamic and any other modelling activities) are included in development of the static model.

3.2 INCREASING CERTAINTY IN THE GEOMECHANICAL STABILITY OF A MULTI-USER STORE

It is essential to understand the interaction and cumulative effect of pressure changes from more than one injection site within a storage formation. This is to ensure the integrity of the initial and follow-on sites and also to correctly predict the ultimate storage capacity for the storage formation. The objective for predictive geomechanical modelling at two (or more) injection sites in a hydraulically connected multi-user store is to ensure the cap rock does not fracture from the cumulative effect of injection and so the integrity of the store maintained. The interaction and effects should be assessed over short, intermediate and long timescales.

3.2.1 Key questions

- **What is the depth to which the geomechanical model must be constructed?**
  A regional-scale geomechanical model will need to extend to the depth of those underlying strata that are closed to flow (impermeable). This may be much deeper and include strata that are not represented in the static geological model of the injection sites.

- **Do you have the required geological information on the underlying strata to inform geomechanical modelling?**
  Geological information is required for those strata that underlie the prospective storage sites and down to the strata that are closed to fluid flow. Property information, such as porosity, permeability, rock type and proportion that is sandstone is derived from oil and gas exploration well datasets. Data may need to be sought from beyond the extent of the storage site if exploration wells within it do not extend down to impermeable strata.

- **Do the injection scenarios modelled approximate what should be pragmatically expected at the sites?**
  When predicting the geomechanical response to injection at a second site, the rate of CO_2 injection at both sites is needed. The values used must be pragmatic, to neither significantly over- nor underestimate the anticipated rate because it will influence the nature of the pressure interaction between the two sites.

- **Are the properties of the cap rock known sufficiently to predict its response to cooling during CO_2 injection?**
  Cooling during CO_2 injection causes local contraction of the storage formation rock. Localised reduction and redistribution of the rock pressure is caused where contraction occurs. Redistribution of pressure is dependent on the uniformity of rock composition and therefore it is important to understand the associated range of properties within that rock.

3.2.2 Learning from the process

- The importance of engaging with the dynamic modellers very early in the multi-user store characterisation process should be realised
- Preliminary modelling work will establish agreed fluid pressure conditions before further geomechanical and dynamic modelling
- An integrated workflow is needed for resource-effective and consistent geomechanical, dynamic and static geological modelling of a multi-user store
- A technical overview role is needed to ensure the assumptions used, and the consequences of modelling results and their implications are fully understood

3.2.3 Technical knowledge gained

- More extensive geomechanical models and data are needed to characterise boundary conditions than traditionally used for static geological modelling or appraisal of a hydrocarbon field
- The effect of thermal stress is much less extensive than the fluid pressure increase associated with injection of CO_2
- Modelling confirms that the impact of adjacent injection sites increases the closer they are
- Interaction of ‘felt’ pressure effects should be anticipated between sites in a multi-user store
- The geometry of the storage formation will influence the interaction between sites and ultimately the storage capacity of a multi-user store
- Modelling indicates which parameters have the largest impact on the geomechanical integrity of a storage formation when pressure is increased

3.2.4 Generic learning to increase certainty in the geomechanical stability of a multi-user store

1. Geomechanical modellers need to work together with static modellers to define and include the requirements and extent of geological information needed for geomechanical modelling.
2. Geological information needs to be collected to enable definition of the nature of conditions across all boundaries for geomechanical and dynamic modelling.
3. The base of the regional-scale geomechanical model will be to the depth of those strata that are closed to flow (impermeable) and used in common for the dynamic modelling.
4. Knowledge or assumption of the nature of the lower boundary of the storage strata is essential as this is required to assess the impact at the injection sites.
5. Preliminary work by geomechanical and dynamic modellers should establish first-pass fluid pressure predictions. This is very important as the results of the geomechanical modelling determine constraints for cap rock integrity and fault reactivation at all sites in a multi-user store.
6. Validation of the geomechanical model and the dynamic model against each other should be undertaken where possible, e.g. by checking initial fluid pressure predictions are consistent.
7. Technical overview and active interaction is needed for modelling planning, iteration and results discussion, to understand the assumptions included within the respective models and their consequences.
8. We have shown by predictive modelling that the effect of the increased pressure of injection from one site on another is dependent on the proximity of the sites and the rate of propagation of the pressure increase.
9. The rate of pressure propagation between the two sites will be determined by the rate of CO_2 injection as well as the geometry, porosity, permeability and compressibility of the storage strata.
10. Where there are two injection sites within a hydraulically connected regional store, widespread pressure increases can occur across the store in a period of months from the start of injection and the increase will be less if pressure can dissipate beyond the storage site boundaries.
11. The geometry of the storage formation will influence the interaction between sites and ultimately the storage capacity of a multi-user store.
12. Cooling during CO_2 injection causes local contraction of the storage formation. Cap rock and overlying strata at each site need to be individually assessed for the impact of thermal stress.

13. The thermal impact of CO_2 injection is localised. The local radius of effect is in contrast to the impact from fluid pressure increase due to CO_2 injection, which is of regional extent.

14. Model parameters that have the largest impact on the geomechanical integrity when pressure is increased are: porosity and permeability of underlying strata; its connectivity with the storage formation, and the orientation of existing geological faults relative to the change in pressure.

3.3 INCREASING CONFIDENCE IN PERFORMANCE PREDICTION FOR A MULTI-USER STORE

Prediction of the performance of a second CO_2 injection site within a multi-user store is essential to anticipate and mitigate any adverse effects from the possible interaction with existing storage operations. Prediction of injection site performance is also required to assess any impact on existing uses of the pore space for hydrocarbon production or groundwater supply (EC, 2009 and 2011). The static geological model constructed of the storage strata is the basis for the dynamic simulation of CO_2 injection.

Dynamic 3D simulation of CO_2 injection within a multi-user store is informed by realistic and practical injection scenarios at both sites, knowledge of the fluids within the storage site strata, and an initial two-dimensional prediction of the behaviour of fluids within the sites.

Where two or more stores are assessed within a multi-user store there are several key differences from the simulation of injection at a single site:

- The dynamic model will be more extensive
- The model may include two or more hydrocarbon fields containing differing proportions of oil, gas and brine
- All strata that are affected by changes in pressure must be encompassed within the model

Rocks in which the pore spaces and contained fluids are connected and so can transmit a change in pressure between them are described as hydraulically connected.

3.3.1 Key questions

- **Is there a good understanding of the properties of fluids within the storage model?**
  Knowledge of pore fluids within the rock of a prospective injection site and their behaviour at elevated pressures and temperatures occurring at depth is critical to reliably predict storage site performance. Operators of depleted hydrocarbon fields being re-used as sites to contain injected CO_2 will have a good understanding of the fluids (oil, gas and brine) within the prospective site.

- **Does the dynamic modelling give an adequate representation of storage site fluid properties?**
  The 2D box model representing the storage site is informed by the physical properties of each of the fluids within the rocks, e.g. water, brine, oil, 'natural gas' or CO_2. Hydrocarbons compress more than water, allowing greater capacity to store CO_2, so their properties and

volume are very important model parameters. To validate whether the fluid properties for a merged model give an adequate representation of the contained fluids, the box model within the multi-user store can be compared with one from an adjacent hydrocarbon field.

- **Do you have the necessary pressure information to adequately assess a multi-user store?**
  Pressure information is essential to appraise sites within a multi-user store, and maximum acceptable pressure values determine the constraints for the operation of sites within the multi-user store. Due to the commercially sensitive nature of this data, detailed pressure history information for hydrocarbon fields is not publicly available but might be accessed by participation of the field operator in the storage project.

- **Does the model include enough of the regional geology for dynamic modelling of a multi-user store?**
  The objective for dynamic modelling is to represent those strata that are affected by the operation of a multi-user store. The entire connected pore volume is to be represented by the dynamic modelling, such as strata underlying the storage formation. These are to be included even if parts are judged unlikely to influence the CO_2 storage at the site(s) of interest.

- **Is the model resolution adequate to predict pressure change and CO_2 migration by dynamic modelling?**
  The wide extent of a dynamic model needed to predict the performance of two or more sites in a multi-user store will require some degree of upscaling to reduce the number of model cells. A coarse-scale (low resolution) grid more readily enables calculation of the extensive pressure footprint by upscaling to a regional-scale model. Care must be taken in upscaling as failure to adequately account for small zones of highly permeable rock may result in unpredicted rapid migration of CO_2 within small areas of the storage formation.

- **Can I extrapolate cap rock properties between sites in a multi-user store?**
  If the characteristics of the reservoir and cap rock between two depleted hydrocarbon fields is consistent (thickness, continuity and rock type) it might be assumed that the cap rock has sufficient sealing properties to retain CO_2. However, if local trapping structures within the brine-saturated parts of the prospective multi-user store do not contain hydrocarbons, the question has to be asked why. The regional model should be interrogated as to why hydrocarbons are not present. The answers may include that there were no hydrocarbon migration pathways that could have led to charging of structure, or that it is not a trap, in which case the sealing properties of the cap rock could be assumed to be sufficient for the multi-user store.

- **Are the injection scenarios realistic?**
  The injection scenarios simulated by dynamic simulation need to be realistic as each simulation, and associated consideration of sensitivities to settings within the model, is a significant commitment of resources. The scenarios should reflect what is likely to happen for capture and delivery of CO_2, availability of a depleted hydrocarbon field, position of injection wells relative to existing infrastructure, and rates of injection for that storage formation.

- **What is the optimal structure and operation of the modelling team?**
  The project team must include close and integrated working by the geological, dynamic flow simulation and geomechanical modellers to set up and predict the performance of a multi-user store. An oil company approach, with an integrated team of experts from all the predictive modelling disciplines, should be followed, allowing communication between the team at all stages of the process.

3.3.2 Learning from the process

- Proxy values may need to be used if property information for a storage formation is not available
- Injection scenarios simulated must be realistic, technically achievable and not exceed what is physically possible
- There are different intensities of interaction between the predictive modelling activities
- An operator of a hydrocarbon field will have an existing field model
- The computational resources needed for dynamic modelling may be exceeded if the static geological model is too detailed
- Validation of the predictive model against any field history data is crucial
- Access to any pressure data may be facilitated by a third party

3.3.3 Technical knowledge gained

- Representation of multiple variations in fluid properties
- Formation conditions at the point of injection
- Initial geomechanical modelling informs subsequent dynamic flow modelling
- Initial ‘resource-effective’ modelling of fluid properties
- Access to ‘lifetime’ pressure data for hydrocarbon fields
- Assessment of regional-scale performance prediction using a simplified model
- Representation of hydrocarbon fields in a simplified performance prediction model

3.3.4 Generic learning to increase confidence in performance prediction for a multi-user store

1. Dynamic models need to be newly developed to predict performance of multiple sites within a CO_2 store, with a wider range of fluid characteristics than traditionally used in hydrocarbon field modelling, in order to take account of the additional fluids and their properties.

2. Fluid property information may not be available so the use of proxy values or analogue data must be agreed between the modellers and fully documented.

3. Less complex and more rapid 2D box modelling or very coarse-scale 3D modelling of fluids within the regional-scale multi-user store should be validated by data from hydraulically connected hydrocarbon fields where possible. The results should be assessed and revised prior to any (more resource intensive) high-resolution 3D dynamic modelling.

4. Initial hydrocarbon field reservoir pressure information is essential to confidently appraise sites within a multi-user store and determine the maximum acceptable pressure. The lowest value that is calculated from the initial reservoir pressure for the sites assessed will be the eventual constraint for all.

5. Calibration of the predicted pressure results against records of pressure variation (pressure history) during hydrocarbon production is very important.

6. Pressure history should be used to validate the predicted performance of injection sites within the multi-user store, so access to pressure history from across a regional storage formation, if available, is crucial.

7. Hydrocarbon field pressure information is commercially sensitive and detailed data are not publicly available to either another hydrocarbon field operator or a prospective storage site operator. For multi-user storage assessment, access to pressure data and fluid property data may require an impartial third party with consequent requirement for legal agreements.

8. Dynamic modelling activities to assess a multi-user store by simulation of CO_2 injection need to be coupled with both static geological modelling and modelling of the geomechanical response to CO_2 injection in a multi-user store. A single integrated asset team is recommended.

9. Dynamic modelling must represent all geological strata that have hydraulically connected pore space and transmit pressure changes due to CO_2 injection at the prospective sites. For a multi-user store, this is at a regional scale.

10. Dynamic model iterations for multi-user stores need to be run for sufficient time, e.g. the lifetime of each of the proposed injection sites, in order to inform the performance and any possible interaction of the sites, and to refine a realistic injection scenario.

11. Operation of a later injection site will be affected by the pressure increase from an earlier licence to inject, and subsequent storage development should be anticipated when an earlier licence is awarded.

12. The impact of one injection site on another suggests that consideration should be given to optimal management of the entire connected pore volume, and not just individual sites in isolation. Regional-scale pressure management might be achieved in a variety of ways, e.g. multi-lateral agreements between storage site operators, integrated monitoring of injection sites and dialogue between operators to manage pressure.

13. Predictive modelling of the performance of a regional-scale multi-user site for regulation and leasing might want to use a single modelling team for all types of predictive modelling to minimise the risk of overlooking the consequences of the results of the differing modelling activities.

14. The results of upscaling must be carefully scrutinised to ensure subtleties that influence CO_2 migration, such as roughness of the upper storage formation surface or adequate representation of narrow zones of highly permeable rocks, are not reduced or lost during the process.

15. Because of the regional scale of the predictive modelling of a multi-user site, only one or two simulations may be possible due to the time taken and computer resources needed. Careful thought needs to be given to parameterisation of model layers as it is likely that only a few iterations will be carried out.

16. A regional-scale pressure response can be predicted using a simplified model in areas where data are sparse for a cost-effective indication of store performance. Hydrocarbon fields should be represented in a simplified model. More detailed modelling is needed to assess the pressure at the injection well, the maximum acceptable pressure, and to predict migration of the injected CO_2.

3.4 DESIGNING A PLAN FOR THE MONITORING OF A MULTI-USER STORE

3.4.1 Key questions

- **Is there potential for injection sites to interact? If so, how might they interact and what is the scale of the potential interaction?** Predictions of the performance of two or more sites, by simulation of CO_2 injection, geomechanical and other predictive modelling techniques, will indicate if there is potential for interaction. Propagation of an observable pressure change is widespread and so a regional approach to monitoring should be considered. Monitoring of pressure over the injection interval at each site in a multi-user store is therefore essential to ensure cap rock integrity is maintained and to avoid unexpected or unacceptable pressure increases should the alert level threshold pressure values be approached.

- **Is the degree of potential interaction avoidable, negligible or acceptable?**
  The effect of the increased pressure generated by injection at one site on another adjacent site was found in part to be dependent on the proximity of the sites. The pressure interaction may be deemed acceptable, since the impact of increased pressure of injection is likely to decrease the greater the distance, if injection sites are 100 km or more apart.

- **Can the effect of a second site on existing storage formation users be identified from baseline and monitoring observations?**
  An extended record of baseline monitoring may be required to establish any pressure interaction from an existing injection site or hydrocarbon field, and the likely variation due to expected storage or field operations. This baseline for a Site B proposed in a saline aquifer where there is no prior access to the storage formation may need to be derived from monitoring data obtained at Site A.

- **Would operation of a proposed multi-user store have an adverse effect on the integrity of one or other CO_2 storage sites? Will pressure need to be managed to operate a site without detrimental pressure changes on another existing site or field?**
  Pressure interactions between injection sites in a multi-user store should be expected. The implications for monitoring are that the maximum acceptable pressure threshold will be determined by the need to ensure integrity at all injection sites in a multi-user store. Pressure management may be deemed appropriate to ensure storage integrity or avoid an adverse effect on hydrocarbon operations. If so, monitoring of the pressure management method becomes a preventative measure.

- **Would operation of a proposed multi-user store have a beneficial or adverse effect on other existing pore space users?**
  The potential impacts of CO_2 storage would include a decrease in the rate of pressure reduction at a producing field, which may be considered a positive benefit to the producer, but may also result in increased water production in some wells. Monitoring of the regional-scale pressure increase due to CO_2 injection or pressure management by the operation of a multi-user store presents an opportunity to benefit existing and proposed operations. Consideration should be given to optimal management of the entire connected pore volume.

- **Can the CO_2 injected at one site be distinguished from that injected at another in a multi-user store?**
  Development of a multi-user store raises the unlikely possibility of a need to distinguish the source of any CO_2 gas in the shallow subsurface or at the sea bed in the area of the injection sites. In areas of multiple injections it would be prudent to use an inherent characteristic or introduce a co-injected tracer with the CO_2 that is unique to each operator. Monitoring to determine the source of any CO_2 by laboratory analysis of fluids collected at or near the sea bed would be a component of the monitoring plan.

3.4.2 Learning from the process

- The role of the prospective Site B operators is to assess the effect on other formation users
- Access to existing data is needed to inform monitoring planning

3.4.3 Technical knowledge gained

- Monitoring planning for a multi-user store by addition of an injection site
- Implications of inadequate monitoring of a multi-user store
- Obligation to monitor the pressure interaction
- Measuring of additional parameters to monitor the pressure interaction
- Definition of thresholds for monitoring of pressure in a multi-user store
- Extended monitoring and possible additional infrastructure for a multi-user store
- Anticipating and planning for a future multi-user store

3.4.4 Generic learning on the design of a plan for monitoring of multi-user storage operations

1. The principal concerns that arise from two or more injection sites in a multi-user store are related to unexpected and unacceptable pressure rises.
2. Pressure monitoring in the storage strata and in overlying formations is fundamental to mitigating these concerns and providing the necessary data to manage the concerns during injection.
3. Discussions between operators planning to inject into a potentially hydraulically connected formation and sharing of data obtained on the formation could mitigate potential concerns during and arising from follow-on projects.
4. Storage operators that might be affected by new storage proposals should expect to be asked to comment on the proposals (or some form of the proposals) to determine how the new project might affect existing operations.
5. Pre-competitive testing of the formation through injection tests and appraisal well design could establish the degree of connection between potential injection sites.
6. The effect of interactions on existing operations would need to be addressed by the prospective storage developer during project design and operation.

7. Later projects may be required to undertake additional monitoring to ensure their projects do not adversely affect existing operations.

8. Dedicated monitoring wells might be needed to provide observation points in the formation (and in overlying formations) where pressure increases may potentially affect cap rock integrity. The costs and resources needed for this are recognised as being significant.

9. Coordination of injection operations may be needed in order to maximise the storage capacity of the formation as a whole. This may require a strategic planning of the timing, location and total volumes stored at each site.

10. It is considered very beneficial to take advantage of data acquired on reservoir pressure responses from hydrocarbon production operations. Hydrocarbon field operators have a wealth of data on their fields and these data should be appropriately archived for the benefit of future storage developers.

3.5 OVERVIEW GENERIC LEARNING

1. Integration of existing models should be considered for assessment of a multi-user CO_2 store. The large extent of a model needed to appraise a multi-user store may encompass one or more hydrocarbon fields. Depleted oil and gas fields within a prospective storage formation are candidate injection sites. Where there are hydrocarbon fields, models will exist, prepared by their operators. The models capture understanding of the formations, the rock types, the fluids contained within them and the subsurface conditions, which are all appropriate for re-use to inform assessment for CO_2 storage.

    - Three-dimensional ‘static’ geological models of the injection sites may be merged and integrated to construct a regional-scale model suitable for multi-user store assessment, provided they are consistent, logical and well documented.

    - Fluid property data from a hydrocarbon field box model, either within or adjacent to a multi-user store, can be used to validate the representation of contained fluids in the multi-user store model.

    - Rock property and initial fluid pressure data would inform prediction of geomechanical stability of the prospective injection sites and pressure history information can be used to validate that the predictions are correct.

2. Access to field production data, where hydrocarbon fields are present within or adjacent to a multi-user store, is essential to validate the predictive site performance models. The initial reservoir pressure at the start of hydrocarbon production can be difficult to obtain and the pressure history and well flow data during production are regarded as confidential to the operator. Access to such data

by participation of the field operator in the storage project or via an independent third party might be arranged. Ideally, a field history database across all fields in a hydrocarbon province would inform the appraisal of fields for re-use as CO_2 stores.

3. Integrated working is essential when appraising a multi-user store. This is not solely best practice (initial fluid property modelling provides input data for geomechanical modelling that determines the maximum acceptable pressure, which, in turn, is a constraint for flow modelling), but considers the impact of one site on another and the implications of the results of one predictive modelling discipline on another. The effect of the 'footprint' of increased pressure from a later storage prospect on an existing site with the interaction and cumulative effect of two (or more) sites, for example, must remain within the maximum acceptable pressure at both.

4. A regional, basin-scale approach must be taken if a multi-user store is being assessed. All strata that have connected pore space and whether the contained fluids are in hydraulic communication must be considered. The connection, and so transmission of changes in pressure due to CO_2 injection site operations must be considered both in their extent and over time. In terms of a multi-user store the maximum acceptable pressure is defined by the lowest value for the two (or more) sites; a regional store (the parts in hydraulic communication) is only as strong as its weakest point. The duration and timing of the components of a multi-user store should also be assessed, as interactions from a later site may potentially be detrimental to an existing site.

5. Exploitation of a regional storage formation to optimise the CO_2 storage capacity of the resource as a multi-user store should be planned. Multiple iterations of storage scenarios should be modelled to optimise capacity by different injection scenarios (relative timing of development of sites, and varying injection rates, volume of CO_2 stored and well positions etc.). Resource-effective assessment of the predicted pressure effect for a multi-user store can be achieved using simplified basin-scale models. Comparison of predictions using a simplified and a complex model for the same storage prospect illustrates that a simplified model is acceptable for a regional-scale assessment of pressure change. Pressure prediction using a simplified regional-scale model would inform a prospective storage site operator and the permitting authorities of the overall performance of a formation for CO_2 injection before undertaking more detailed site characterisation modelling.

4 Next steps to accelerate North Sea CO_2 storage

Considerable progress toward the implementation of CO_2 storage has been made by industry, Scottish and UK Governments, regulators and academia, contributing individually and in collaboration, since the publication of *'Progressing Scotland's CO_2 Storage opportunities'* in 2011 by:

- Selection of two planned demonstrator CO_2 storage sites in the UK North Sea (DECC, 2013)
- Recognition of the need and ability of the sector to reduce costs for 'next of a kind' second phase storage projects (CRTF, 2013)
- Presentation of options for a Central North Sea Storage Hub (Element Energy, 2014)
- Support for a strategic appraisal of UK CCS storage for follow-on projects (ETI, 2014)

Investigation of the development of multi-user stores in depleted hydrocarbon fields and offshore sandstones by CO_2MultiStore illustrates how the offshore storage resource could be used to permanently store captured CO_2. The results of CO_2MultiStore research have also highlighted how use of existing knowledge and data can be extended to further increase confidence for investment in commercial-scale carbon storage in multi-user stores and in the Captain Sandstone. Maximising economic return from hydrocarbon resources around the UK, the objective of the Wood Review (Wood, 2014) may also be met by integration of pressure management for CO_2 storage with hydrocarbon production. Regional-scale pressure management for CO_2 storage operations has the potential to be beneficial to existing hydrocarbon fields as part of an integrated pressure management strategy. Coordinated and cooperative pressure management would demonstrate both competence and due diligence by users of offshore geological formations to maximise hydrocarbon production and optimise CO_2 storage operations.

Activities are proposed to increase confidence in storage site performance prediction by enhancing access to existing data, to assess benefit to existing hydrocarbon fields and inform pressure management of offshore formations.

1. **Information, knowledge and data from hydrocarbon production should be made accessible for the assessment of offshore CO_2 storage resources**. Agreements should be made for access to data held as 'commercial-in-confidence' by the operators of hydrocarbon fields that are, or near, prospective CO_2 stores. Data to inform and validate the prediction of storage site behaviour and input for monitoring planning are to include:
    - 3D computer models and documentation files of the hydrocarbon field geology
    - Information of the character and models of the fluids within the hydrocarbon fields
    - Data on the physical character and properties of the reservoir, cap rock and underlying strata
    - Detailed history of pressure variations and corresponding well flow rates by storage formation

- Data on the fluids analysed and pressures measured in hydrocarbon wells
- Well positions and the character of well casing and completion methods

Existing offshore hydrocarbon field data can provide the crucial information required to confidently assess and define the pressure thresholds and connectivity that determine the total amount of CO_2 stored in a multi-user store. Information that is particularly important is the reservoir pressure before hydrocarbon production started and the degree to which fluids within the reservoir rocks are connected with the underlying strata.

2. **Depleted hydrocarbon fields that are within prospective multi-user stores should be identified and assessed for the impact of storage site development**. The effect of CO_2 storage on hydrocarbon fields within a regional storage formation could be significant and whether the impact is beneficial or detrimental will be different for each individual field. The relative timing of possible storage operations to the stage of field development (initial production, secondary recovery phases and field depletion stages) should be assessed. The pressure changes due to CO_2 storage operations, as part of strategic development of a multi-user store, and whether or not they are potentially beneficial to hydrocarbon production should be predicted.

3. **Options to optimise storage capacity by development of two or more injection sites in a regional storage formation by different pressure management strategies should be assessed and compared**. For each option the implications to the storage capacity for the entire storage resource and individual sites within it, and the operational responsibilities and cost implications, should be considered.

4. **Opportunities to optimise geological storage of CO_2 and hydrocarbon recovery by assessing the operation of an integrated multi-user CO_2 store and enhanced oil recovery project should be studied**. The potential for mutual benefit to both the CO_2 storage and hydrocarbon field components should include economic and technical factors. CO_2 storage could gain by re-use of existing hydrocarbon field infrastructure, knowledge and expertise for supply, injection, pressure management and monitoring operations, and the financial support from enhanced oil recovery. Hydrocarbon production, for one or more fields, could benefit from a flexible CO_2 supply, use of the store to maintain stable injection rates, and pressure management without encroachment on field operations.

5. **Historical information from hydrocarbon fields along the Captain Sandstone fairway should be used to refine geomechanical stability modelling of CO_2 injection to maximise storage capacity in the Captain Sandstone**. Geomechanical modelling, complementing the CO_2MultiStore results, should increase confidence in understanding the boundary conditions and the mathematical calculation of maximum acceptable pressure within a future multi-user store. Integrated modelling of temperature and pressure changes during CO_2 injection and investigation of variations in the sandstone at prospective injection sites would refine knowledge of the pressure response within the store.

5 Concluding remarks

In recent decades the activities of humankind have been the dominant cause of climatic warming and there is evidence of the impacts of climatic change on natural and human systems around the world (IPCC, 2014). Carbon capture and storage (CCS), together with other emissions reduction activities, can contribute to the reduction in greenhouse gas emissions in a sustainable, low-carbon economy. To achieve cost-effective operation and widespread implementation of CCS and to mitigate emissions from power generation and industrial plants, economies must be made for deployment beyond demonstrator projects (CRTF, 2013).

The prospect of the construction of one or more demonstrator CCS projects in Scotland (DECC, 2013, 2015) gives an imperative for research to inform and so promote the development of second phase or ‘follow-on’ projects. The very substantial potential CO_2 storage resource in Scottish waters has been the focus of detailed characterisation by academic studies and investigation by industry. Despite a worldwide economic crisis, and slower than expected deployment of CCS projects, research has continued to develop Scotland’s offshore CO_2 storage resource, supported by both government and industry.

The collaborative research in this study demonstrates the willingness to co-operate by stakeholders in government, industry and academia, in order to inform and develop CCS as a growing industry in Scotland and the UK. Access to and re-use of technical and often historical data, knowledge and expertise acquired and gained during exploration and production of hydrocarbons has proved invaluable to the CO_2MultiStore project. Grounding of the research by the use of offshore datasets and a realistic and reasonable approach to the prospective development of CCS projects greatly enhances confidence in the practical application of the project findings.

Appraisal of a prospective multi-user store by the operation of two or more CO_2 injection sites requires a regional, basin-scale approach to understand and manage the effect of injection on existing hydrocarbon fields and CO_2 stores. Expertise and knowledge from decades of experience in hydrocarbon exploration and production data, techniques and methods have been used to understand the geology, stability and performance of a North Sea multi-user store. CO_2MultiStore illustrates how scaling-up from the size of a hydrocarbon field to a regional appraisal can be achieved to reduce the resources required yet maintain output fit for storage site appraisal.

The Captain Sandstone is the most investigated prospective North Sea storage formation and is capable of storing CO_2 injected at two or more sites. Appraisal of a multi-user store in the Captain Sandstone, host to a prospective demonstration CCS project, indicates how a second phase project or projects might be operated whilst maintaining security of storage. CO_2MultiStore findings offer insights and learning relevant to regional CO_2 storage formations all around the UK, and potentially to maximising economic recovery of hydrocarbons from the UK continental shelf by integrated pressure management. Monitoring and management of pressure and cooperation with existing offshore operations is the key to the successful wider deployment of CO_2 storage as a multi-user store. Regional-scale pressure management will ensure integrity of all operations in the store, optimise the storage resource, and has the potential to enhance oil recovery in cooperation with field operators. CO_2MultiStore has examined and tested a simplified method, suitable for strata without oil and gas field data, sufficient to give a first-pass regional-scale assessment of the pressure response.

Generic learning relevant to the appraisal of any other multi-user CO_2 store, gained from the activities, process and technical knowledge, is a very significant output from CO_2MultiStore. The approach taken illustrates how the European-scale potential storage resource of the North Sea might be achieved and securely store captured CO_2 from adjacent onshore power generation and industrial sources. The methods developed can be applied worldwide to optimise CO_2 storage capacity and give greater confidence to prediction of a site performance.

6 Project participants

This study was commissioned by Scottish Carbon Capture and Storage (British Geological Survey — Natural Environment Research Council, Heriot-Watt University, and University of Edinburgh), the Scottish Government and CCS stakeholders.

The study was supported and guided by:

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Scottish Government
The Crown Estate
Shell
Vattenfall

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BP
CO_2DeepStore
Progressive Energy
Senergy
Shell
Statoil
Vattenfall

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