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Assessing interactions between multiple geological CO_2 storage sites to optimize capacity in regionally extensive storage sandstones

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Abstract

The potential resource for carbon dioxide (CO_2) storage in strata underlying the North Sea is mostly within brine-saturated sandstone formations which are each many hundreds to thousands of square kilometres in extent. 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.
A UK North Sea case study anticipates the operation of two injection sites in the Captain Sandstone and assesses any interaction between the injection sites. Technical investigations to optimize the storage capacity in a regionally extensive North Sea sandstone by the operation of more than one injection site within a storage formation [1] are summarised: geological modelling; geomechanical modelling; simulation of CO_2 injection; monitoring planning. The UK case study includes the Goldeneye Field, the storage site investigated for the planned Peterhead CCS project. An injection scenario was examined that comprised an initial project storing within a depleted hydrocarbon field structure followed by a second injection site within the surrounding saline aquifer. The research investigations were targeted to identify and reduce any perceived concerns specific to the operation of two sites by a risk assessment-led process. Requirements for a monitoring plan specific to a multi-user storage formation, based on the prediction of storage site performance, were also developed. Generic learning applicable to any suitable multi-user storage sandstone was captured, from the process followed and the technical knowledge acquired, on the characterisation of extensive sandstone formations, management of the planned injection operations and monitoring planning.

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Keywords: Optimising CO_2 storage; multiple injection sites; North Sea; predictive modelling; monitoring planning; generic learning.

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1. Introduction

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 [2,3]. The brine-saturated (saline aquifer) sandstones are very extensive and their potential storage capacity is estimated to be of much greater magnitude (thousands of million tonnes CO_2) than in depleted oil and gas fields (tens to hundreds million tonnes CO_2) [3,4]. To optimize use of the extensive North Sea sandstone formations as a storage resource multiple injection sites will be required within any given storage formation. The large extent of individual sandstones, any included hydrocarbon fields and the multiple store sites anticipated within each, presents challenges to and implications for the licensing, operation and integrity of the storage asset.

A North Sea case study of two injection sites within a single multi-user storage sandstone was investigated by the CO_2MultiStore project. The study investigated the anticipated operation of a multi-user store within the Captain Sandstone (Fig.1). The Captain Sandstone contains the Goldeneye Gas Condensate Field, within the mature oil and gas province offshore Scotland, the storage site investigated for the planned Peterhead CCS project. Previous research on the Captain Sandstone [5] was augmented by data from offshore hydrocarbon exploration and detailed investigations of the Goldeneye Field for CO_2 storage [6].

Fig. 1 Map of the UK and adjacent waters showing the area of the Captain Sandstone investigated as a case study for the operation of a multi-user CO_2 storage site, international boundaries and lines of latitude and longitude.

The research investigation of the operation of two injection sites within the Captain Sandstone case study is both technically reasonable and realistic. The study benefited from the publicly available results from the UK CCS Competition [6] and also the advice of industry technical experts with experience of the practical appraisal and operation of CO_2 storage sites. The injection scenario anticipated an initial CO_2 storage site within the Captain Sandstone and a second follow-on injection project within the same geological formation.

Generic learning was captured throughout the research investigations relevant to the characterisation of extensive storage sandstones, management of the planned injection operations and monitoring of CO_2 injection and migration at two (or more) sites within any sandstone formation. The method followed and the learning presented here can be applied to suitable formations in all sectors of the North Sea, and beyond. The findings illustrate an approach to optimize the capacity of extensive storage formations by secure storage of CO_2 in two (or more) injection sites and make the vast storage potential in all sectors of the North Sea [2,3], accessible and practical for CO_2 storage.

This paper considers the rationale for the research investigation and summarises the risk assessment-led methodology followed. The North Sea case study is described and the modelling to predict and assess interactions between operations is outlined and the findings reviewed. An overview of generic learning on the characterisation of a multi-store site, anticipation of pressure changes due to interaction between sites, design of a monitoring plan and planning to optimize capacity by operation of a multi-store site is presented.

2. Rationale and methodology

2.1. Rationale for the investigation of a multi-user storage formation

The rationale for the research investigation is to examine the scenario of a multi-user storage formation to reduce uncertainties and increase understanding in their operation to optimise the CO_2 storage capacity of regionally extensive sandstones. Technical activities were targeted to increase understanding and reduce uncertainties arising from the interaction between the injection site(s) and with other users of the pore space by a risk assessment-led process.

The process of risk assessment to determine investigations and characterisation of prospective CO_2 storage sites complies with the EC Directive on the geological storage of carbon dioxide [7] and follows guidance for implementation of the directive [8]. For European storage sites the modelling of prospective sites is a specified requirement [7]. Prediction of injection site performance by modelling, as undertaken by technical activities in CO2MultiStore, is also required to assess any impact on existing uses of the pore space for hydrocarbon production or groundwater supply [7,8].

The predictive model investigations undertaken were sufficiently detailed to address technical issues of greatest potential concern to industry technical experts and researchers. No attempt was made to present predictive models that are comprehensive or sufficiently detailed to support a storage permit application.

2.2. Methodology

An injection scenario for two sites was selected to meet an anticipated combined annual rate of storage need of 12 million tonnes (Mt) [1,4] (Fig. 2). An initial injection Site A was positioned within the Goldeneye Gas Condensate Field, the storage site being the trapping structure that contains the Goldeneye Field and the adjacent saline aquifer Captain Sandstone. The rate of injection was modelled as 6 Mt of CO_2 per year for 30 years.

A second storage Site B within the Captain Sandstone was modelled as a later 'follow-on' project anticipating the additional storage capacity required for a developing CCS industry. Site B is within the saline aquifer Captain Sandstone, approximately 45 kilometres west of the Goldeneye Field, with the injection site positioned using the results of initial modelling. The choice of location of the injection site takes account of closer interaction with hydrocarbon fields in the vicinity and pressure dissipation into the wider Captain Sandstone to the west [9]. The rate of injection was also modelled as 6 Mt of CO_2 per year and the duration of injection also 30 years, but injection at Site B starting and continuing five years after injection at Site A.

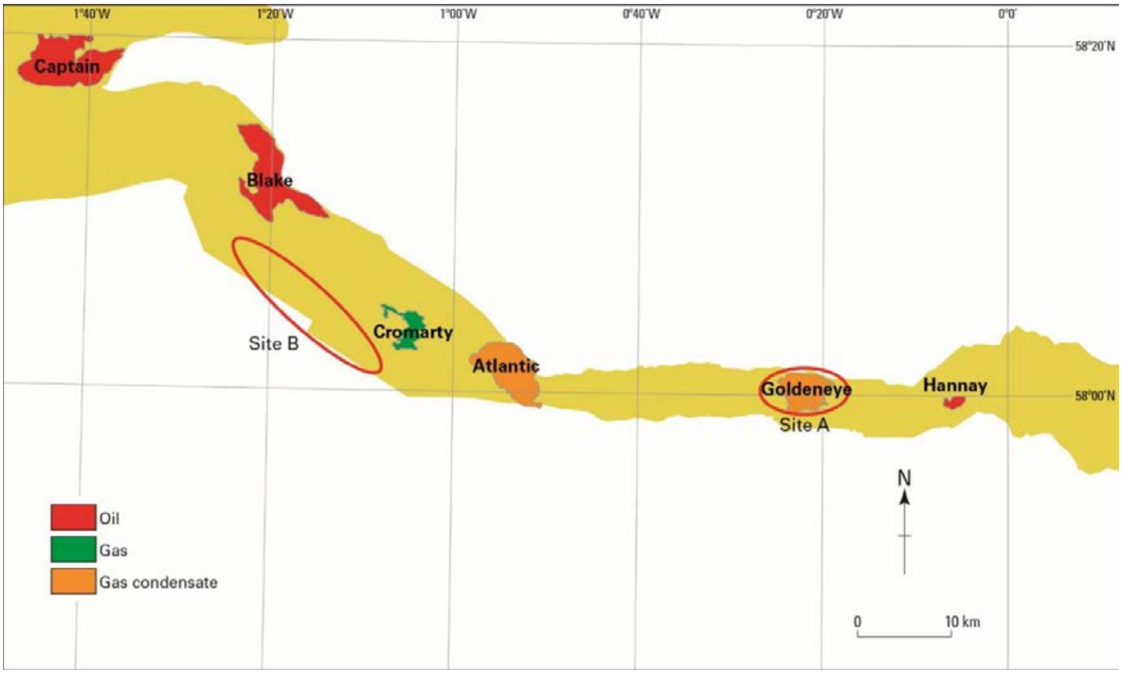

Fig. 2. The eastern part of the area of the Captain Sandstone shown in Fig. 1 investigated as a case study for the operation of a multi-user CO_2 storage formation showing the position of Site A and Site B for dynamic modelling of CO_2 injection, hydrocarbon fields within the Captain Sandstone, and lines of latitude and longitude.

A risk assessment process was followed solely targeted to identify, mitigate and reduce risks specific to the operation of two injection sites within a multi-user storage formation. External industry and research technical experts participated in an initial risk assessment and two subsequent reassessment workshops. Firstly, the experts considered the injection scenario of two sites in a multi-user store in the scenario defined by CO_2MultiStore project members. The experts then discussed and recorded possible risks associated with the operation of, and potential interaction between, the two sites.

Technical work was undertaken to predict the response to the injection scenario, forecast the performance of the two sites, identify any interaction between the sites and determine the nature of any interaction by: predictive geological modelling; geomechanical stability modelling; dynamic simulation of CO_2 injection. The risk assessment process was iterative. Two phases of technical investigations were undertaken and a risk reassessment workshop after each phase assessed the implications of the results of the modelling work. Risks that remained above an acceptable level after the technical investigations and assumed implementation of all suggested mitigating actions, termed residual risks, were targeted by the monitoring planning activity.

Generic knowledge on the process taken, questions addressed and technical knowledge gained from the North Sea case study was captured throughout the study. An overview of the generic learning is presented here. The context, learning and discussion of individual points on questions addressed, learning from the process and technical knowledge gained are detailed in [10].

3. North Sea case study of the Captain Sandstone

Prediction of the performance of an initial and a second CO_2 injection site within the Captain Sandstone to anticipate and mitigate any adverse effects from any interactions between injection sites and with existing users of the pore space was by:

- construction of a regional-scale ‘static’ geological model of the storage strata
- regional and detailed modelling of the geomechanical stability
- dynamic simulation of the operation of two injection sites
- identification of the constraints and requirements for monitoring specific to a multi-user storage formation

The case study investigations are summarised in the following text sections and further technical details are available in [1,11].

3.1. Construction of a regional-scale geological model

Where two or more injection sites are assessed within a multi-user CO_2 storage formation, rather than at a single injection site, the geological model will be more extensive. It will need to include all strata that are affected by changes in pressure and modelled by the geomechanical and CO_2 injection simulations. Two existing geological models [5,6] were integrated (Fig. 3). Understanding fluid flow within a geological formation as a response to the injection of CO_2 was the primary objective of geological modelling. The CO_2MultiStore Captain Model (Fig.4) 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 the research study [1].

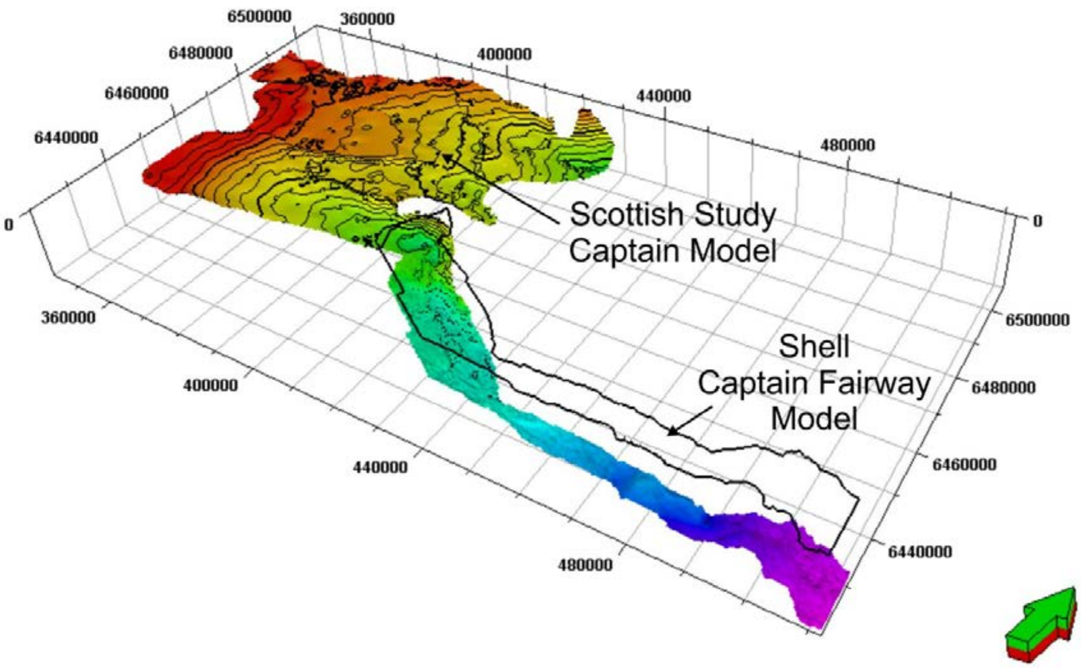

Fig. 3. Three-dimensional image of the upper surface of the CO_2MultiStore Captain Model from two existing merged geological models [5,6], outline of [6] shown with black polygon.

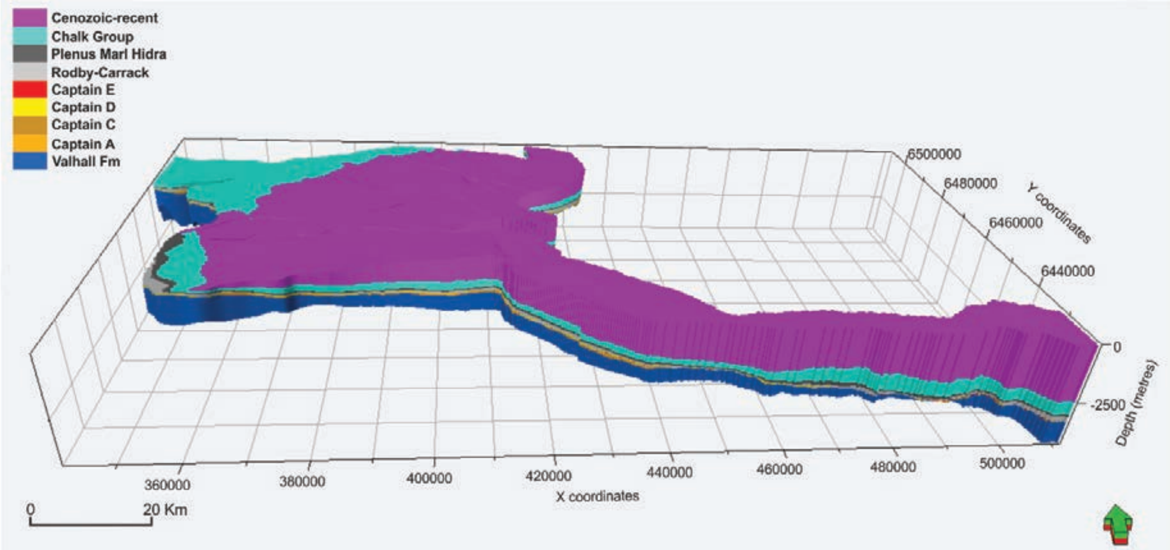

Fig. 4. Geological CO2MultiStore Captain Model (approximately 163 km from west to east, 84 km from north to south and with an area of approximately 8000 km2) illustrating the nine intervals modelled from the sea bed down to the rocks underlying the Captain Sandstone

Merging of the two models, construction of the geological surfaces, fault modelling and property attribution were successfully achieved to provide a consistent regional geological model for assessment of a multi-user storage formation [1]. Integration of the models has combined the knowledge gained from two storage characterisation projects, with the resultant model having 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.

3.2. Regional and detailed modelling of geomechanical stability

Geomechanical stability modelling of the Captain Sandstone investigated and established the maximum acceptable fluid pressure value for the injection sites in the multi-user store case study [1,11]. Maintaining pressure below the maximum acceptable value will ensure the integrity of the sealing cap rock and that any faults present within the strata will be stable during operation of the multi-user storage formation. The results of 3D regional-scale and 2D detailed geomechanical modelling were combined to investigate 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 native fluids in the deeply buried storage strata. The maximum acceptable pressures were derived using an empirical function for the regional coverage of the Captain Sandstone [11].

Maximum acceptable pressure values, including a safety margin, for the lower surface of the sealing cap rock obtained at each site were used to define a crucial constraint for the subsequent simulations of CO_2 injection. The effect of temperature changes due to the cooling caused by the injection of CO_2 was 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. By contrast the changes in fluid pressure caused by injection of CO_2 were predicted to be over distances of tens of kilometres from the injection well. It was found that the nature of the fluid flow boundaries is critical to evaluating the pressure dissipation in the storage formation during injection. There was a marked contrast in the predicted performance of the multi-user store when using the end-member values of either open or closed to fluid flow for the lower boundary of the modelled strata and including 800 metre-thickness of strata beneath the storage sandstone. Where the lower boundary is represented as open to fluid flow the increase in pressure at the first Site A due to the operation of the second Site B is minimal. Where the lower boundary is represented as closed to fluid flow there is a significant increase in pressure indicating a notable pressure connection between the two injection sites [1] not as evident when pressure is allowed to dissipate across the lower boundary. The maximum acceptable pressure value contained by the strata is determined by depth; the cap rock strength of deeper storage strata at Site A can securely contain a greater increase in pressure than shallower strata at Site B [11].

Operation of both sites, each injecting 6 Mt 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. Operation of both sites each injecting at 6 Mt per year with the lower boundary completely closed to fluid flow will increase the pressure at Site B to be above the maximum acceptable pressure; pressure management would be needed to inject CO_2 at a rate of 6 Mt per year at Site B if injection at a similar rate at Site A were also taking place. 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 character for the fluid flow properties will be an interim value that needs to be determined by further investigation.

3.3. Dynamic simulation of the operation of two injection sites

The dynamic simulation of CO_2 injection investigated perceived concerns identified during the risk assessment for the operation of a multi-user store and addressed risks that were rated as most likely to occur and with potentially the greatest effect. 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 [6,12,13]. The agreed input data were used in common by both the analysis of geomechanical stability and subsequent detailed dynamic simulations of CO_2 injection for a multi-user storage formation. Any interaction between the injection sites was assessed by simulating and comparing two scenarios: operation of only Site A; staged operation of both Site A and Site B as the injection scenario (as described in text section 2.2). The impact on nearby hydrocarbon fields (Fig. 2) was also assessed. The effect of the fluid flow character of the lower boundary of the modelled strata, and geological properties of the underlying strata (porosity, permeability, thickness and proportion of sandstone), as noted in the discussion on the geomechanical modelling, was also investigated. The detailed dynamic simulations of CO_2 injection at Site A and Site B used only the eastern extension of the Captain Sandstone (Fig. 5), although the pressure response of the entire system volume was modelled by use of appropriate boundary conditions at the western edge of the model. The investigations and analysis are described in detail in [1].

Where a prospective multi-user storage formation is a sandstone containing only brine (saline aquifer) and not also hydrocarbons, the rich datasets and existing knowledge used for the CO_2MultiStore research are unlikely to be available. The CO_2MultiStore Captain model was simplified and the dynamic simulations of the CO_2MultiStore injection scenario were re-run. The results from the full and simplified models were compared to assess the level of confidence with which a multi-user storage site within a saline aquifer formation can be assessed with fewer data and less detailed understanding of the strata.

Validation of the generic 'box' modelling of input data showed a good match with the data obtained by the operator of the Goldeneye Field [13]. The dynamic simulations were also validated using detailed production data collected at the Goldeneye Field. The simulations predicted that after thirty years of injection the buoyant injected CO_2 at Site A would migrate upwards and laterally, extending 3 km eastwards and 3 km westwards beyond the boundary of the Goldeneye Field. It did not predict migration of CO_2 from Site A either to Site B or to the hydrocarbon fields between the two injection sites. However, the extent of simulated changes in pressure within the Captain Sandstone due to CO_2 injection was widespread, as indicated by previous studies [5,14] and the geomechanical stability modelling. 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 later Site B. Simulation of the pressure changes generated by CO_2 injection at both sites, with operation of Site B starting five years after Site A, shows 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 than the increase in pressure at Site A due to the injection operations at Site B. The shallower depth of Site B means that this effect of injection at the neighbouring site will have a greater 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 Site A will reduce the pressure increase available for accommodation of CO_2 injection at Site B.

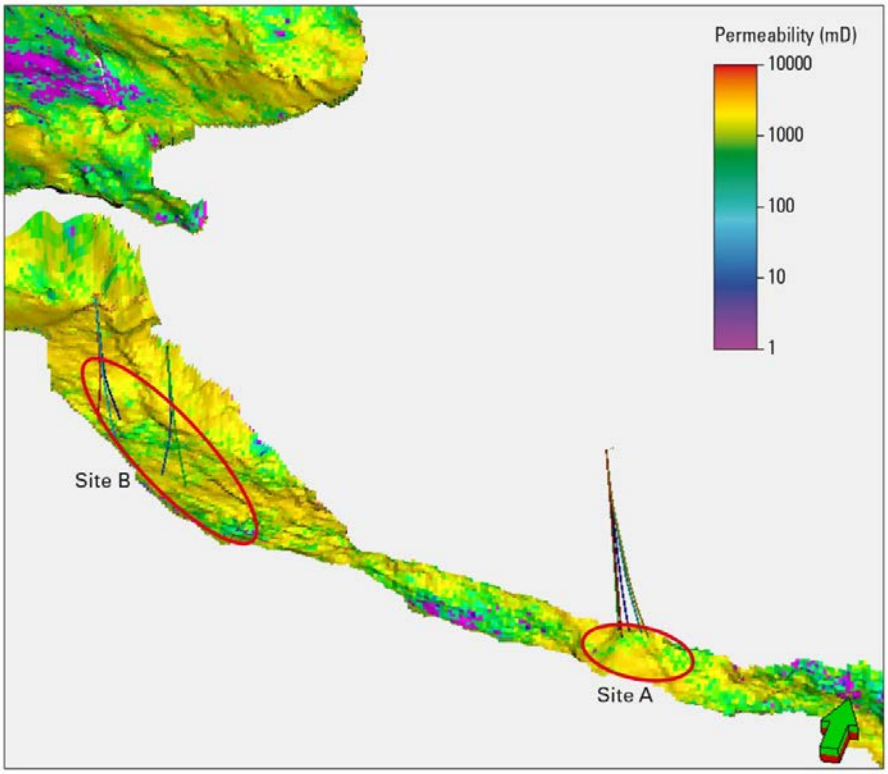

Fig. 5. Permeability model of the eastern extension of the CO2MultiStore Captain Model used for dynamic simulation of CO_2 injection showing the position of injection Site A and Site B, and the position and trajectory of the wells modelled for CO_2 injection at each site. Permeability values in milliDarcy, mD.

Increases in pressure at nearby hydrocarbon fields due to the operation of the two injection sites were predicted by the detailed dynamic modelling. However, increases in pressure may be beneficial dependent on the relative timing of injection operations and hydrocarbon field development, although pressure management may be required to ensure the acceptable maximum pressure is not exceeded. Study of the properties of the underlying strata on pressure changes during simulation of the operation of the Captain Sandstone multi-user store found that the pore volume had a significant impact on the pressure response. Doubling the pore volume of the underlying formation reduces the overall system pressure response, whereas the permeability of strata underlying the injection sites had little impact [1]. The regional response to pressure increases replicated by simulation of injection using the simplified three-dimensional CO_2MultiStore Captain Model was a sufficiently close match to assess the regional pressure response. The results are appropriate to assess the suitability of a prospective multi-user formation, any requirement for pressure management, and likely effect on existing nearby hydrocarbon fields, but are not sufficiently detailed to define maximum acceptable pressures at specific sites.

3.4. Constraints and requirements for monitoring specific to a multi-user storage formation

Monitoring of injection sites by the operator is an obligation, overseen by competent authorities, as explicitly specified in the European directive on the geological storage of carbon dioxide [7]. Monitoring of a multi-user storage formation must meet the requirements associated with the operation of an individual injection site as well as addressing potential interactions arising from multiple injection sites. The monitoring plan must define the maximum operating pressures and enable careful observation of pressure changes during injection and pressure monitoring is a regulatory requirement [7]. The principle objectives of the monitoring plan in a multi-user store would be to:

- Ensure cap rock integrity is maintained
- Verify the absence of detectable leakage above the cap rock
- Identify impacts from injection at an operator's site - either at their own site injection or injection at another site
- Assess the rate of the production of formation fluids. The rate of water production, if necessary for the management of pressure, 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. The consequences of the possible perceived problems include the potential for reduced storage capacity, reduced injectivity and reduced cap rock 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 [1] was that the monitoring of pressure change should not only be undertaken at the injection sites in a multi-user storage formation, but also at the locations where pressure change may impact other wells, hydrocarbon field operations or the cap rock. Pressure monitoring in the storage formation and in overlying formations is therefore considered fundamental to provide the necessary data to manage increases in pressure during injection. Actions to mitigate possible problems, in addition to the design and monitoring of a multi-user store, could be undertaken. Discussions between operators planning to inject into the same geological formation and sharing of data obtained on the formation could reduce issues during and arising from follow-on projects.

Later follow-on projects in a multi-user storage formation 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. Coordination of injection operations may be needed in order to optimise the storage capacity of the formation as a whole. Strategic planning of the timing, location and total volumes stored at each site in a multi-user storage formation may be required. Coordinated monitoring of the storage formation as an asset, including the possible construction of independent monitoring wells (outside storage complexes), could also be considered.

4. Overview of generic learning for the characterisation of a multi-user CO_2 storage formation

Generic learning applicable to any suitable regionally extensive sandstone formation was captured during the investigation of the North Sea case study of the Captain Sandstone to optimise capacity by operation of a multi-user CO_2 storage formation. Technical knowledge was gained on the characterisation of a multi-user storage site, anticipation of interaction between injection sites, design of a monitoring plan and planning to operate multiple CO_2 injection sites [1,10].

An overview of the generic learning is presented here, as numbered points,that highlight important findings obtained from across the research activities or that have a regional perspective.

1. Development of a single predictive model for both injection projects and integration of any existing hydrocarbon field or regional models should be considered to assess interactions within a multi-user CO_2 storage formation. 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 also candidate storage 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 subsurface conditions, which are all appropriate for re-use to inform assessment for CO_2 storage:

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

- Fluid property data from a hydrocarbon field 'box' model, either within or adjacent to an injection site, can be used to validate the representation of contained fluids in the multi-user storage formation 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 predictions are correct.

2. Access to field production data, where hydrocarbon fields are present within or adjacent to a multi-user storage formation, is essential to validate the predictive site performance models and to inform monitoring planning. Access to such data by participation of the field operator in the storage project or via an independent third party should be arranged. Ideally, a field history database across all fields in a hydrocarbon province would inform the appraisal of fields for re-use for CO_2 storage.
3. Integrated working between all of the disciplines, including geological 'static' and geomechanical stability modelling and 'dynamic' simulation of CO_2 injection, is essential when appraising a multi-user store. It is best practice, since the 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. Equally importantly, integrated working supports appraisal of any interaction of one site on another and to allow the implications of the results of one predictive modelling discipline to be assessed by other disciplines.
4. The effect of the 'footprint' of increased pressure from a later injection prospect on an existing injection site with the interaction and cumulative effect of two (or more) sites must remain within the maximum acceptable pressure at both sites. Interaction of pressure changes may occur even though the CO_2 may not migrate between injection sites. When characterising a multi-user storage formation the maximum acceptable pressure is defined by the lowest value for the two (or more) sites assessed; a regional storage formation, comprising all the strata in hydraulic communication, is only as strong as its weakest point.
5. A regional, basin-scale approach must be taken if a multi-user storage formation is being assessed and all strata that have connected pore space must be considered. Even very modest fluid conductivity in the underlying rock formations can have a beneficial cumulative impact over large areas, such as those assessed for the operation of multiple injection sites in a regionally extensive formation, in dissipating pressure.
6. Accurate prediction and active monitoring of the pressure response from multiple injections is identified as being the single most important tool for indicating site performance in the scenarios investigated by the case study. Extended baseline monitoring observations for a later-implemented site will be needed to define appropriate pressure thresholds which determine the storage capacity for follow-on injection sites in a multi-user store. Extended baseline monitoring observations for a later-implemented site will be needed to define appropriate pressure thresholds which determine the storage capacity for all injection sites in a multi-user store. Additional monitoring activities may be required and actions expected to mitigate unexpected and unpredicted increases in pressure.
7. Where there is more than one CO_2 injection site in a multi-user store the connection and transmission of changes in pressure due to site operations, must be considered both in their extent and over time. While pressure fluctuations travel quickly, measured in seconds over a distance of tens of kilometres, the full pressure impact of CO_2 injection in one site will not immediately be observed at another site. The delay between the onset of CO_2 injection at one site and the maximum pressure increase at another site may be several years over distances of tens of kilometres. The duration and timing of the components of a multi-user store must be fully anticipated, so that impacts of the follow-on injection site on an existing site can be predicted and assessed. Operators of second and subsequent sites should consider how soon they need to commence injection, after start of operation of the first site, to achieve their required maximum storage capacity. The consequence is that there is a significant time advantage to being the operator of the first site, and that operators of second and subsequent sites should aim to start CO_2 injection as early as possible to maximise storage capacity.
8. To optimise the CO_2 storage capacity of an extensive sandstone formation it is sensible to plan as a multi-user storage site. Additional monitoring infrastructure may be cost effective to optimise storage capacity if a regional approach is taken. Multiple iterations of storage scenarios should be modelled to optimise capacity by assessing different injection scenarios. The scenarios considered should examine the relative timing for the development of sites, and vary the rate of injection, volume of CO_2 stored and well positions etc. Resource-effective assessment of the predicted pressure effect for a multi-user storage formation can be achieved using simplified basin-scale 3D models. Pressure prediction using a simplified regional-scale model was found to be sufficient to 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.

5. Conclusions

Generic learning captured from the investigation of a North Sea case study is applicable to other regionally extensive formations to inform optimisation of the potential CO_2 storage capacity by operation of a multi-user storage formation.

Carbon dioxide can be securely contained within multiple (two or more) injection sites within a geological formation to optimise its potential storage capacity, following the approach investigated by the CO_2MultiStore project. The storage resource within an extensive formation must be assessed on a regional scale for its suitability to optimize its capacity by permanently containing CO_2 at two or more injection sites. The extent of the regional-scale geological model required to appraise multiple injection sites must encompass any existing uses of the formation and all hydraulically connected pore space, such as in strata underlying the storage formation. The regional-scale geological model should be consistent and incorporation of existing geological models should be considered, where possible and available. Fluid and rock property properties, initial fluid pressure and detailed hydrocarbon field production data, where available, are essential to validate and inform prediction of interactions between injection sites. Integrated working between all of the characterisation disciplines permits the interaction of one site on another to be appraised and the implications of the results of one predictive modelling discipline to be assessed by other disciplines.

Interactions between the injection sites due to temperature changes or migration of the injected CO_2 were not predicted by the case study. However, interactions were predicted due the increase in pressure of CO_2 injection although the injections sites were tens of kilometres apart. Possible interactions between injection sites should be assessed for each prospective multi-user CO_2 storage formation. A simplified regional 3D model was found to be sufficient to assess the pressure response in the case study but not adequate to determine site-specific maximum acceptable pressure values. When characterising a multi-user storage formation the maximum acceptable pressure is defined by the lowest acceptable value for the formation; however, the location of the lowest acceptable maximum pressure may be distant from an injection site.

The pressure connection within the regional storage sandstone, both between the injection sites and to the under- and overlying rocks was highlighted as a key parameter effecting the timing and any potential interaction between the sites. Pressure management may be needed to ensure integrity of the injection sites, as modelled in CO_2MultiStore. Pressure monitoring and management of a regional storage asset is an essential activity to facilitate secure CO_2 storage. However, storage management could also optimize the potential storage capacity in a regionally extensive formation.

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