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QICS Work Package 1: Migration and trapping of CO_2 from a reservoir to the seabed or land surface

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Abstract

Natural CO_2 seeps can be used as analogues for studies into surface flux and impact resulting from leaking engineered geological CO_2 reservoirs. However their long-lived nature often means that the local environment has either adapted or evolved around the seepage site. The 'Quantifying Impact of Carbon Storage' (QICS) experiment provides the solution to this issue by releasing CO_2 into an environment previously untouched by CO_2. Work Package 1 (WP1) of the QICS project is primarily concerned with the migration of CO_2 in the subsurface and how to relate the results of the relatively shallow experiment to a full storage scale setting in the UK North Sea. The main objectives of WP1 are to investigate potential leakage pathways from the reservoir to the surface, determine possible leakage rates and assess the potential volumes of leaked CO_2 that can reach the surface environment.

Keywords: CO_2, leakage, North Sea, QICS

1. QICS Project and Work Package 1

The UK Natural Environmental Research Council funded project 'Quantifying Impacts of Carbon Storage' (QICS) represents the World's first *in situ* CO_2 leakage experiment. The experiment is located 400m offshore near Benderloch on the west coast of Scotland and involves the release of a small volume of CO_2 from 12m below the seabed into a 'pristine' environment with a water depth of 10-12m. One of the main issues with using natural seeps as analogues for leakage of injected anthropogenic CO_2 is their typically long lived nature, which allows the local ecosystem to evolve with the seep through time.

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Investigation of CO_2 seepage in to a previously untouched environment is a key objective of the QICS experiment. The primary aims of the experiment are two-fold: 1) to investigate the environmental impact of CO_2 seeps into a seafloor environment; 2) to evaluate appropriate monitoring equipment and strategies for the characterisation of CO_2 seeps above prospective geological storage reservoirs.

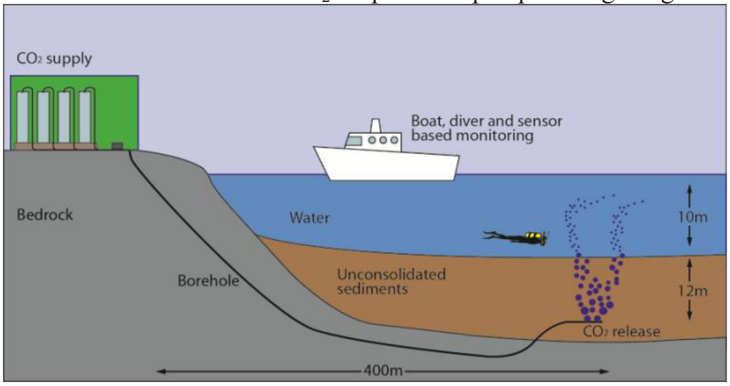

Fig. 1. Schematic of QICS experiment.

The major objective of WP1 is to relate the findings of the QICS experiment to demonstration scale for geological storage of CO_2 in the UK sector of the North Sea. In this paper we summarise work thus far completed and discuss future work plans for WP1: Migration and trapping of CO_2 from a reservoir to the seabed or land surface. We will evaluate potential leakage pathways through the geological overburden that connects the storage reservoir with the seabed environment for five representative North Sea geological and environmental settings. It is hoped that by determining the types of possible pathways through the overburden that we may be able to constrain possible types of CO_2 seepage at the seafloor and estimate their resultant range of flux into the local ecosystem.

Potential migrationary pathways through the geological overburden are often highly complicated. Ascending flow may be self-organizing in homogeneous strata or channeled into pathways by geological fabrics such as textural heterogeneities, fractures and faults. Migration is further complicated by change from dense to light phase as CO_2 ascends through the CO_2 saturation line [1]. The geology and formation waters of the overburden can also attenuate leakage via a range of reversible and irreversible trapping mechanisms such as dissolution, mineral, stratigraphic and residual saturation trapping which operate over a range of timescales [2].

The following section discuss a workflow of North Sea scenario site selection and investigation of potential leakage promotion factors, and is followed by a summary of a global review of terrestrial and offshore natural CO_2 seeps [3].

2. North Sea scenarios

The UK sector of the North Sea can be divided into three separate physiographic regions: the Northern North Sea (NNS), Central North Sea (CNS) and Southern North Sea (SNS). The NNS and SNS comprise extensional basins separated by the Mid North Sea High which spans the majority of the CNS. We base each of our five representative settings on areas that are realistic targets for geological storage of CO_2. For initial demonstration projects, abandoned hydrocarbon fields, rather than saline aquifers, will be the likely targets, due to abundant pre-existing geological information and proven caprock integrity. For each scenario we use local hydrocarbon fields to inform the type, lithology and depth of the storage reservoir. Rather than focusing on any particular or proposed storage reservoirs, our objective is to gain information on the typical ranges of features present in five different representative settings. In order to achieve this we have chosen to investigate areas of 40 x 40 km^2 using a range of data compiled into a GIS database.

2.1. Data sources

The GIS database is constructed from information from a range of sources (Table 1). Information from JNCC and DECC are freely available [4][5]. UK offshore data from EDINA, a Joint Information Systems Committee (JISC) designated national data center, is available to staff of universities, colleges and research institutes across the UK. Information from the BGS is available to purchase under license from their DigRock250 and DigBath250 digital map data portfolio. In addition, a suite of useful data on pock mark fields, open channels, hard rock substrate and salt tectonics provided by BGS under a QICS project partner agreement. Figure 2 shows examples of these data layers and the locations of the five representative settings under investigation.

Table 1. Data used in GIS database

Source	Availability	Information
British Geological Survey (BGS)	QICS project partner license agreement	Bathymetry, Quaternary Geology, Quaternary Structures, Open Channels, Pock Mark Fields, Hard Rock Substrate, Tectonic Geology, Tectonic Structures, Salt Tectonics.
Joint Nature Conservation Committee (JNCC)	Freely available [4]	Substrate, Biological Zones, Energy at Seabed, Predictive Habitat.
EDINA	Freely available to UK higher and further education institutes	Seabed Sediments, Bedrock Geology, Bedrock Structures.
UK Department of Energy & Climate Change (DECC)	Freely available [5]	Hydrocarbon Fields, Exploration Wells.

2.2. The five representative settings

We investigate five separate geological provinces in the UK sector of the North Sea (Table 2). One site is located in the CNS. Two of each of the other sites are located in the NNS and SNS (Fig. 2) so have a similar geological history. However these sites have different typical hydrocarbon traps, varieties of Pleistocene deposits and types of Holocene sediments, making for interesting comparisons. The representative setting locations are also realistic target areas for geological CO_2 storage primarily due to the presence of hydrocarbon fields which may be depleted or desirably targeted economically for enhanced oil recovery purposes.

Table 2. Representative setting information

Scenario	Location	Details
A	Inner Moray Firth Basin	Rotated fault block traps, Mid Jurassic cyclical sand reservoirs, ENE trending normal faults
B	Outer Moray Firth Basin	Fault bounded basins, Lower Cretaceous turbiditic reservoirs, E trending normal faults
C	Central Graben	Salt related traps, Paleocene turbiditic reservoirs, SES trending normal faults

D	Humber	Inverted basins, salt tectonics, Rotliegend aeolian reservoirs, SE trending faults & folds
E	Anglo-Dutch Basin	Salt related traps, Triassic fan sand reservoirs, SE trending faults & folds

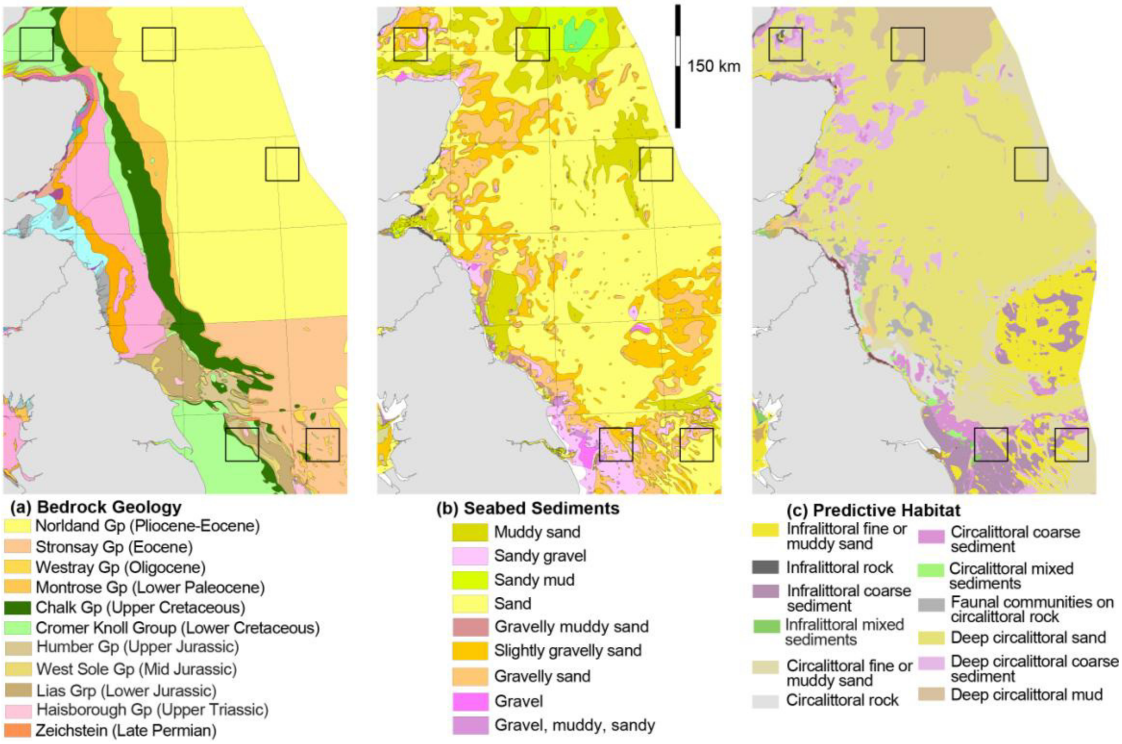

Fig. 2. Examples of GIS dataset. (a) Bedrock geology (b) Seabed sediments (c) Predictive habitat.

2.3. Leakage pathways

By pooling information from the various data sources we can evaluate a range of factors that can contribute to leakage pathways through the overburden (Table 3). The relative importance of these factors will vary between locations and we can use this information to estimate an overall leakage risk ranking for the five representative settings. Most of the factors are natural in origin.

In terms of hard rock geology, faulting and salt structures make up the major risks (Fig. 3a). The majority of faults in the North Sea have a normal displacement profile. Normal faults can potentially provide conduits for leaking CO_2 if they strike parallel to the local maximum principle stress direction [6]. Faults can also form permeable pathways if a migrating CO_2 plume drives an increase in pore pressure adequate enough to locally decrease effective stress at the base of the fault [7]. Salt bodies can cause deformation and fracturing of the overlying stratigraphy and also have a large influence on the salinity of formation waters. Solubility of CO_2 decreases with increasing pore water salinity.

Within unconsolidated Quaternary deposits leakage can be exacerbated by various factors (Fig. 3b). If there is little cohesion between unconsolidated sediments and bedrock, the contact between the two can provide a conduit for leakage. This is especially important to consider in locations where hard rock substrate is present. Pre-existing shallow gas can be an issue as it can be mobilized by migrating CO_2 to produce gas chimneys which generate high permeability pathways to the surface. Open channels can provide relatively deep (up to 130m) gaps in the seafloor up to 5km wide and 40km long. These depressions in the seafloor can provide leaking CO_2 with easier access to the seabed by reducing the length of subsurface escape pathways.

Anthropogenic pathways include hydrofractured reservoir cap rock and leaky completed hydrocarbon wells (Fig. 3c). Hydrofracture can occur in depleted hydrocarbon reservoirs if injection of CO_2 leads the reservoir pressure to exceed the initial discovery pressure of the reservoir. Hydrocarbon wells are common across the North Sea (Fig. 3c). Abandoned wells may provide conduits for flow due to completion and degradation issues, which are more common in older wells [8].

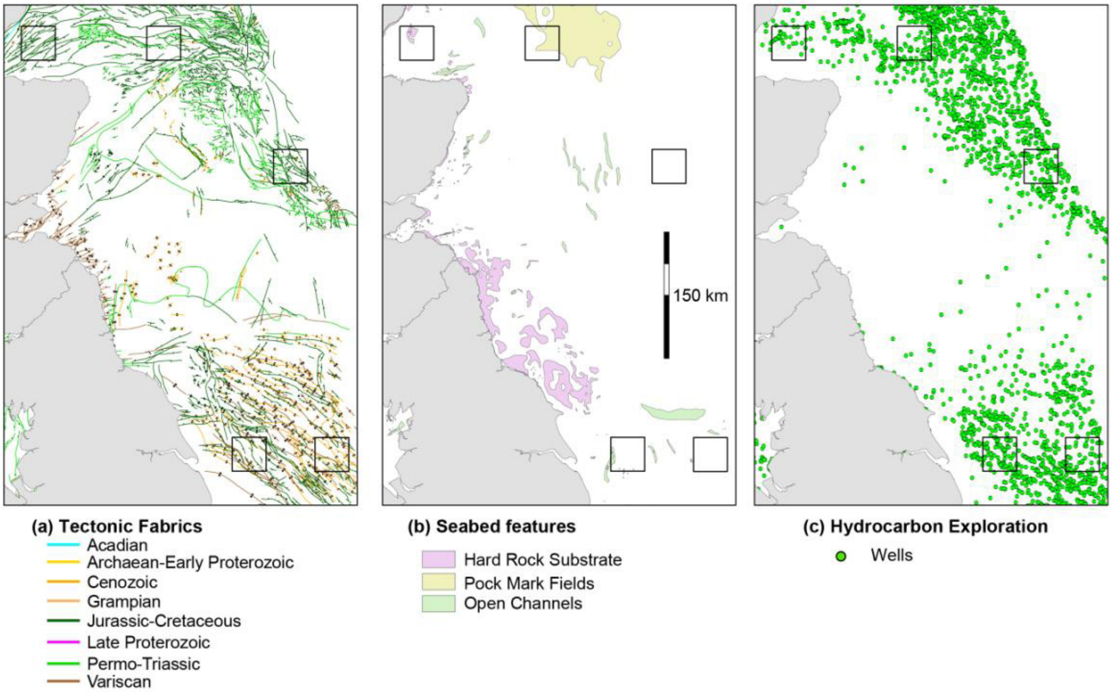

Fig. 3. Examples of GIS information on factors that can increase the risk of CO_2 migration; (a) Tectonic fabrics including faults, folds and basin edges; (b) Seabed features including hard rock substrate, pockmark fields and open channels; (c) Exploration well information for the UK sector of the North Sea.

Table 3. Possible factors that can promote CO_2 migration pathways

Factor	Mechanism
Faults	Can provide relatively high permeability vertical conduits under appropriate fault orientation, ambient principle stress direction and localized pressure field.
Salt Bodies	Halokinesis of salt can deform overlying strata leading to faults and fractures. Key effect on formation water salinity.
Unconsolidated Sediments	Reduced diagenic alteration, compaction and secondary mineralization can provide a better interconnected system of larger pores.
Shallow Gas	Natural gas may be mobilized by CO_2 and create gas chimneys.

Open Channels	Can be > 130m deep relative to local seafloor and provide shorter pathway s to seabed.
Hard Rock Substrate	Outcropping bedrock may be highly permeable. Contact between bedrock and unconsolidated sediments may provide conduits.
Exploration Wells	Existing wells, especially older examples, may have completion or degradation issues.

3. CO_2 seep review

To complement this study we are also reviewing our current understanding of natural CO_2 seeps. Sites of natural emissions of CO_2 and other gases from the geosphere provide analogues for surface release of CO_2 that has leaked from engineered geological CO_2 storage sites. Natural emissions can provide insights into the rates of CO_2 leakage and their impact on the local environment. This section is a short summary of the output produced thus far from this work which is presented in more detail in the Seep Review of Kirk (2011) [3].

The Kirk (2011) Seep Review [3] discusses the measurement of CO_2 flux, comparison of terrestrial and offshore flux rates, and the environmental impacts of leakage. Tables 4 and 5 represent a collection of measured values from both terrestrial and offshore seeps. It can be clearly seen that there is a numerical bias towards terrestrial seeps due to the relative ease of discovery, observation and measurement. Due to the challenge of measuring diffuse seepage of CO_2 in offshore environments it is difficult to make direct comparisons with terrestrial examples of diffuse seepage. The majority of known offshore CO_2 seeps are located in shallow marine settings due to the ease of observation. It is likely that the survey under-represents releases in deeper water settings as these are hard to identify due to the complete dissolution of CO_2 bubble plumes.

Table 4. Offshore fluxes from Kirk (2011), all references are detailed within report [3].

Site	Flux rate (x 10^6 L/day)	Flux rate (t/m^2/year)	CO_2 source	Gas composition	Water Depth (m)	Temp (°C)	Salinity (TDS mg/L)	pH	Reference
Panarea	7-9	1670 - 8500	Linear faults & vents aligned with the faults	CO_2 – 98% H_2S – 1.7%	Up to 30	46-135 (discharge temp)	37,600 – 54,500	3-8	Tassi et al. 2009; Caramanna, 2010; Lombardi, 2010; Etiope et al. 2007
Ischia, Italy	South side 1.4 (over $3000m^2$)	7.3	Mainly < 5 vents /m^{-2}	CO_2 – 90-95% N_2 – 3-6% No H_2S	Shallow <5 (warm water site in photic zone)	13-25 (sea water ambient seasonal fluctuations)	380,000	7.4 – 8.2	Lombardi et al. 2010; Hall-Spencer et al. 2008
	North side – 0.7 (over $2000m^2$)	5.5							Lombardi, 2010
Champagne site, Mariana arc	0.9 (over $10m^2$ as liquid droplets)	$8x10^8$ (moles/year as liquid droplets)	Vents	CO_2 - 90-98% H_2S – 1% Trace H_2 and CH_4	1600	47-103 (discharge temp)		3.4 – 4.8	Lupton et al. 2006
Hatoma Knoll, Okinawa Trough			Vents	CO_2 - 95-98% 2-3% - H_2S	682 - 1430	3.9 – 6.4 (bubble temp)	344,190	7 – 7.4	Shitashima et al. 2008
Salt Dome Juist, Southern German North Sea	1-10 (t/day)		Point source above dome			13-15		6.8	McGinnis et al. in press

Table 5. Terrestrial fluxes from Kirk (2011) , all references are detailed within report [3].

Natural analogue	CO_2 flux rate ($g/m^2/day$)	Flux rate equivalent in $t/m^2/yr$	CO_2 flux distribution	CO_2 concentration	CO_2 source	Reference
Laacher See caldera, Germany	Close to vent centres: 500-1200	0.18 - 0.44	2 conspicuous gas vents, some areas of diffuse flux	Close to vent centres: ~ 100%	Degassing from magma chamber in East Eiffel volcanic field	Jones et al, 2009
	Diffuse flux: 23-54	0.0084-0.020		Diffuse flux: 9.1%		
	Background: ~<30	0.011		Background: ~4%		
Ukinrek Maars, Alaska, USA	4 plant-kill zone mean flux: 689-1190 (estimated total 21-44t/day)	0.25-0.43	Diffuse emissions, 4 zones of plant-kill	Spring gas bubbles: 97.6% Soil gas 91.5%	Diffuse magmatic degassing (related to Ukinrek Maars basalt)	Evans et al, 2009
Furnas and Fogo volcanoes, Sao Miguel Island, Azores	Mean: 8-600 (range: 0-4605.4)	0.0029-0.22 (mean) (range: 0-1.7)	Diffuse volcanic emissions near fumarole fields	Up to 96.6% in soil. Up to 22.8% in dwelling	Diffuse volcanic	Viveiros et al, 2008
Latera caldera, Italy	Horizontal profile (site 5) mean: 131.1 (range: 3.25-3569.73)	0.048 (mean) (range: 0.0012-1.3)	4 vents (location controlled by permeable pathways within faults)	17.8% mean (range 0.42-85.92%)	Mainly metamorphic alteration of limestone at depth related to magma intrusion	Annunziatellis et al, 2008
	Background: <22	<0.0080		Background: <2.5%		
Horseshoe lake, Mammoth Mountain, California, USA	Mean: 1346 (range: 218-3500)	0.49 (mean) (range: 0.080-1.3)	Diffuse from tree-kill area	Not available	Diffuse volcanic	Lewicki et al, 2008
Pululahua caldera, Ecuador	Diffuse mean peak flux: 84.3 (range: non detectable to 141.7) Total CO2 emission: 270t/day, or 9.8t/km²/day	0.031 (mean) (range: non-detectable - 0.052)	SW-NW trend along east of inner caldera indicates structural control	Not available	Diffuse volcanic	Padrón et al, 2008
	Background: 8.4 (accounts for >90% of diffuse emission)	0.0031				
Rekjanes geothermal field	6849		Diffuse soil gas, steam vents, mud pools		Soil diffuse degassing	Fridriksson et al. 2006
Rapolano fault	2.3 - 3076	52,560 (total flux)	Vents, productions wells			Mörner et al. 2002
Mefite d'Ansanto, Italy	0.93 – 2 billion (total flux) (928 - 2000 t/day)	338,720 – 730,000 (Total flux calculated from daily rate)	Numerous gas vents	98.5%	Related to extensional tectonics uplift creating network of extensional fractures	Chiodini et al. 2010
	0.28 billion (total flux) (280 t/day)	102,200 (total flux)				Rogie et al.2000
		310,000 (total flux)				Italiano et al. 2000
Little Grand Wash fault, Paradox Basin, Utah, USA	18.8 ± 8.7 (Natural leakage)		Carbonated springs		Decarbonation of carbonates	Burnside et al. In Press
	1472 ± 677 (Crystal Geyser)		Abandoned exploration well			
Pannonian Basin, Hungary		1100 – 3670 (total flux)	Bubbling wells, local streams, strongly carbonated springs	Basement groundwaters: 10-15 m^3m^{-3} Subvolcanic groundwaters: 50% CO_2- rich gas: 95%	active tectonic zone	Pearce et al. 2004 Sherwood Lollar et al. 1997

When evaluating environmental impact, it is important to note that natural analogue studies suggest that concentration and duration of CO_2 exposure has a bigger impact on local ecosystem communities than the flux rate of a seep. For example, in terrestrial settings concentrated CO_2 build-ups may accumulate in low energy environments, such as topographic depressions, as the result of either high or low flux rates of CO_2. For offshore environments, dissolution of CO_2 can mediate the chemistry and lower the pH of local seawater. This can result in shell dissolution, reduced metabolism, reproductive issues, and have a big impact on organisms that produce calcareous skeletal structures [3].

Overall several questions were raised in the review with regards to understanding the effects of CO_2 seepage into an offshore environment;

- How much of the CO_2 being released is dissolving in the pore waters within the sediments immediately below the seabed?
- What pH and other geochemical changes result?
- What is the impact of a new seep on benthic marine organisms and communities?
- How much geochemical interaction is there between naturally seeping CO2 and sediments, and the shells of benthic marine organisms?
- What level of accuracy of seepage quantification can be achieved offshore, especially below easily diveable depths? For example, will it be possible to account for all of the CO2 potentially leaking from an offshore CO2 storage site by direct measurements (bubbles, dissolution etc.)?
- What would a comprehensive offshore seabed leakage detection and measurement system look like and cost?
- Is there any realistic prospect of remediating or mitigating a leak at the seabed from an offshore CO2 storage site?
- Would an offshore leak naturally decay and if so over what kind of time period?

Feld scale experiments like QICS, which can characterize the chemical and biological impacts of new seeps, enable us to overcome some of the limitations of the natural analogues, including their longevity, relatively steady state and the environmental adaptation around them. Linking the results of the field scale experiments with a review of deep water North Sea environments and scenario-modelling allows us evaluate potential storage and leakage pathways through the geological overburden.

4. Discussion and Conclusions

It is important to determine the potential environmental impacts in the event of leakage from a geological CO_2 storage site. The majority of countries looking to implement CCS are focusing on using geological reservoirs that are offshore, and thus it is particularly important to investigate the effects of CO_2 in marine settings. There are several examples of natural CO_2 seeps that can be used as analogues for the leakage of geologically stored CO_2 into the environment. However due to the long lived nature natural seeps, their local environment has adapted to the presence of CO_2. Studies of natural seeps also only present a snapshot in time that may not be representative of the conditions near the start of leakage or in the future. The QICS experiment addresses these issues by releasing CO_2 into a previously untouched environment and monitoring the environmental impact over time.

In order to relate the results of the QICS experiment to a full scale CO_2 geological storage project in the UK sector of the North Sea, we are investigating five separate representative settings that represent typical geological and environmental settings found within the North Sea. A wide range of information on geological, environmental and hydrological properties has been integrated by construction of a GIS database. Investigation of factors that can potentially promote leakage of CO_2 from a storage reservoir, such as faults and abandoned hydrocarbon wells, will give us an insight to the leakage risks within each of the scenarios. A global review of natural CO_2 seeps [3] has provided us with a range of flux rates for natural analogues.

Future work will involve building on the flux review [9] and constructing geological models of the five scenarios constrained by the collated GIS database. These geological models will be used to parameterize numerical simulations which will examine physical ascent, geochemical interaction and phase change of CO_2. Combining the results of these models with information on natural seeps will provide a picture of potential leakage pathways through the overburden from the storage reservoir to the surface environment. Taking into account geological trapping mechanisms [2], which can contribute to attenuation of leaked CO_2, we hope to gain an idea of how much CO_2 can escape from a reservoir in the event of leakage and estimate the volume of the leaked mass that could potentially reach the surface.

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