Feasibility of Geological Carbon Dioxide Storage; From Exploration to Implementation

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Feasibility of Geological Carbon Dioxide Storage;
From Exploration to Implementation

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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy at Durham University

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Abstract

This study utilises a range of techniques to investigate the feasibility of the geological storage of carbon dioxide. Three specific themes were addressed.

Saline aquifers have been proposed as an attractive geological storage medium due to the theoretical storage capacity they can offer, despite the poor quality and quantity of date available to appraise them. Numerous published methodologies attempt to refine the uncertainty by the introduction of capacity coefficients producing estimates with a variance of up to five orders of magnitude. In this thesis, the source of this uncertainty is investigated using Monte Carlo based sensitivity on a North Sea case study site. This shows the limitations and sources of error inherent in the application of such method. A new method is proposed to account for the limited available input data.

Injectivity of geological reservoirs has been highlighted as a potential setback for CO_2 storage. Reservoir hosted compartmentalising membrane seals are shown to permit CO_2 migration without compromising storage integrity in three North Sea examples. The presence of oil as a wetting fluid in the substrate significantly reduces the capillary entry pressure of a membrane seal as a product of CO_2 water contact angles of cos 85° to cos 90°. Cross fault flow rates are shown to be on operational timescales.

Despite technical and geological viability, CO_2 storage projects have been cancelled as a consequence of public objection. Public Engagement has been proven to affect the public’s perception of CCS in both positive and negative directions by facilitating informed decision making. The perception of trust and impartiality are demonstrated to outdo the perception of knowledge and experience. Furthermore the perceived benefits of CCS are evidenced to be tempered by person’s preordained perception either of the technology, or those who advocate it.

Declaration

The material contained in this thesis has not previously been submitted for a degree in this or any other institution. The work is entirely my own except where reference is made.

Contents

List of Figures

List of Tables

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Numerous people over the past years have helped me make this PhD what it is today and there are countless that I need to thank. Firstly, particular gratitude must go to all of my supervisors, Jon Gluyas and Richard Davies for all of the advice and discussion over the past years and help shaping this thesis into what is depicted here. Sandra Bell for all of her unwavering support and guidance in helping me understand and embrace the world and techniques of Anthropology; and to Simon Mathias for his help and patience while explaining mathematics. I am exceptionally grateful to Durham University, specifically The Centre for Doctoral Training in Energy, and its founders Phil Taylor, Douglas Halliday and Katie Daniels for funding and supporting this research. I am also grateful to my industry partners David Handstock and John Aldersey-Williams of Progressive Energy for allowing me to use their data, and for the discussion over the course of this PhD. The following companies are also thanked for making this research possible, specifically, SMT, Schlumberger and Halliburton for providing the Kingdom, Petrel and Landmark seismic software used in this study, and TGS Nopec for allowing me to publish the seismic lines included in this thesis.

From Durham University, I am grateful to all of the administrative staff; in particular April Furnal, Karen Atkinson, Janice Oakes and Paula Elliot for helping this PhD run smoothly. To the IT staff of Dave Stevenson, Gary Wilkinson and Matthew Hepburn for their help with seismic data and fixing my numerous IT breakdowns; and to the academic staff for help and discussion, in particular João Trabucho-Alexandre, Jonny Imber and Neil Goulty. A special mention must also go to Peter Stanley of ERC Equipoise for his help with cross platform transfer of seismic data, David Scott, formerly of GPT for his help in understanding overpressure, and Steve from Whistling Mule for filming the debate presented in Chapter 6.

A huge note of thanks goes to all of my friends and colleagues of who there are too many to mention. But in particular Mark I, Katie, Alex F, Amy, BJ, Amelie, Steve, Bansri, Sam and Clayton for making my time here fun and for your encouragement. A special mention must go to Rhian for all of the light-hearted chat, jazz and veggie food nights on my frequent trips to Edinburgh. Also thank you to Cat, Bob, Alex P and Mark B for keeping me sane during my write up with evening bike rides and lunchtime cycling and climbing chat!

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DEDICATION

This doctoral thesis is dedicated to my parents, Helen and Mike Hedley, and to my grandparents, Brenda and Cliff Thompson. Without their unwavering strength, support and encouragement, I would not have made it this far.

1. INTRODUCTION

1.1. RESEARCH CONTEXT

Carbon dioxide capture and storage (CCS) is the process of capturing CO_2 from a point source such as fossil fuel fired power station or industrial processing plant and subsequent transport to where it can be injected into a porous geological formation to be stored indefinitely. To be effective, the storage potential of the geological formations must be significant relative to annual global CO_2 emissions (IPCC, 2005).

This thesis differs from previously published research and encompasses three distinct aspects of CCS. These are geological exploration for, and appraisal of, storage prospects, containment risk and seal failure, and investigation into social challenges that if mishandled have proven to lead to delays and project failures.

1.2. THESIS OUTLINE

Chapter 1 addresses the fundamentals of geological CO_2 storage, along with the detailed geological setting and evolution for the geographical localities of the study sites. Chapter 2 introduces the primary methodologies for all of the geological investigation undertaken in the course of this research along with a description of the datasets utilised. In the following section, Chapters 3-7 are described individually and form the main data sections for this thesis. Chapters 3 and 4 contain the main geological investigations undertaken in this project and have been written and submitted as stand-alone publications; edited where appropriate. As such these chapters contain background reading, methodologies and conclusions specific to those studies. Theory critical to shaping research into the social context and acceptability is defined in Chapter 5, and the methodology of the implemented study, results and conclusions derived from this theory presented in Chapter 6.

Chapter 3 – Uncertainty in static CO_2 storage capacity estimate.

This chapter investigates the impact of uncertainty, caused by poor data availability, on static CO_2 storage capacity estimates in saline aquifers. Whilst offering, theoretically, an abundance of large capacity storage reservoirs, saline aquifers are often located on the margins of petroleum producing operations. As such, they are, for the most part ignored when collecting subsurface data which includes seismic reflection surveys and exploratory boreholes, with associated core and down hole measurement techniques.

This study investigates the role of uncertainty in geological parameters required by the mathematical solutions for calculating the storage potential of saline aquifers. These solutions have been analysed and are found to suffer numerous shortcomings inherent in the understanding of the reservoir system and attempts to derive a solution that is applicable to whole sedimentary basins over site specific prospects. Where possible, these methods were re-written and refined in an effort to correct for these shortcomings by redefining inputted terms to be more site appropriate in addition to removing superfluous and repetitive variables. Monte Carlo forecasting was used as a means of comparing the storage capacity estimates, derived from these solutions and, subsequently as means of investigating the sensitivity of geological input parameters.

Chapter 3 provides an in-depth analysis on the influence of uncertain geological information on static capacity estimates via the means of sensitivity analysis. As such, it is the first study to critically assess the validity of globally implemented published methodologies and identify limitations when applied to poorly understood saline aquifers. This paper has been published in the journal Greenhouse Gases: Science and Technology (Hedley et al., 2013). Prof. Davies, Prof. Gluyas and Dr. Mathias were co-authors and provided supervision and manuscript editing advice. Mr Handstock is also a co-author for providing access to commercially sensitive datasets, and manuscript editing advice.

Chapter 4 – Influence of capillary entry pressures on cross fault migration – implications for CO_2 injection.

Chapter 4 builds upon the theory that pressure and hydrocarbons maybe transferred across faults in situations where the hydrocarbon buoyancy pressure exceeds the capillary entry pressure for the fault rock material. For the purpose of CCS, it is proposed that when injecting down dip of a 4-way dip closed structure that possesses faulted compartments, a sufficient CO_2 plume buoyancy pressure should allow cross fault flow of CO_2 into adjoining compartments, allowing reservoir pressure to equilibrate thus reducing the risk of fracture or capillary leakage at the trap crest. This chapter is intended for publication and is being prepared for submission to AAPG Bulletin.

Chapter 5 – Theory of risk, the perception of risk and its role in Public Engagement.

When implementing new technology, it is critical that the social implications are considered prior to roll out. It is common for organisations to focus resources on solving the technical, scientific and engineering challenges new technologies presents. However, if work to gauge the perception of the public is ignored, objection can slow or even stop permanently the deployment of the technology.

Chapter 5 first considers the founding theories of public perceptions of risk and scrutinises its relationships with perceived danger, trust and blame. Secondly, with these theories in mind, this chapter examines the subject of public engagement from its primary definition and its connection with the public perceptions of risk. Thirdly, it explores examples of the use of public engagement practises in determining public opinion of emerging technologies, including CCS, and provides case studies illustrating when these practises have been undertaken both poorly and successfully.

This investigation is also applicable to aiding the estimation of CO_2 injectivity and the impact of sub-seismic compartmentalisation, such as that common in the Southern North Sea gas fields.

Chapter 6 – The effects of informed public engagement on the public perception of CCS.

Chapter 6 draws upon the hypothesis of both the perception of risk and public engagement considered in Chapter 5, and builds upon them in developing a methodology implemented in this study to examine the role of un-biased public engagement on the public perception of CCS in the North East of England.

This study is amongst the first of its kind to use a public debate format, where the participants' perception of CCS is polled before and after exposure to the debate allowing examination of the role of the debate on public opinion. Furthermore, whilst the debate panel was designed to be unbiased, the method allowed the theories of trust to be considered and assessed in a real world situation.

Chapter 7 – Discussion and conclusions.

Chapter 7 is a synthesis of the conclusions drawn from chapters 3, 4, 5 and 6. It discusses uncertainties and discourses with published literature in addition to areas for future study.

In chapter 3, pronouns referring to the author (myself) are stated in the plural form (i.e. we replaces I) throughout. This is in acknowledgement of the co-authors in the publication. This thesis only contains manuscripts for which I am the first author. The authors listed contributed to the development of ideas during discussion as stated previously (pg. 4).

1.3. FUNDAMENTALS OF CARBON CAPTURE AND STORAGE

This thesis is focused primarily on the processes pertaining to the geological storage of captured carbon, the fundamentals of which are described in this section. The social science investigation presented in chapters 5 and 6 makes reference to the onshore capture and transport aspects and as such, an overview of the technology and the current deployment status is included below.

1.3.1. BASIC PRINCIPLES OF CO_2 CAPTURE AND TRANSPORT

As previously stated, Carbon Capture and Storage (CCS) in its simplest definition is the capture of CO_2 gas at a point source, transportation and indefinite storage in a porous geological formation. There are numerous technologies that facilitate the stripping of CO_2 from point sources, three of which have been identified as suitable for commercial deployment, namely post-combustion amine-stripping, oxy-fuel combustion and calcium looping technology (MacDowell et al., 2010).

Amine stripping comprises contacting the CO_2 stream with an aqueous amine solution forming water-soluble salts. The reactive nature of the absorption makes this technology well suited for low-pressure streams, and consequently makes this technology applicable for retrofitting to existing point sources.

Oxyfuel combustion comprises the burning of combustible fuel in a mixture of pure (>95% O_2) and recycled flue gas, predominantly CO_2 to regulate temperature and make up the volume vacated by the missing N_2. This process results in waste gas emission comprising CO_2 and H_2O, which are easily captured and separated, allowing CO_2 to be compressed and transported to suitable storage mediums (Buhre et al., 2005).

Carbonate looping technology comprises use of calcium oxide (CaO) in fluidized reactor beds. The CO_2 in the flue gas reacts with the CaO at approximately 650 deg C forming calcium carbonate ($CaCO_3$). The formed $CaCO_3$ is then reacted at c. 900 deg C, releasing a stream of highly concentrated CO_2 suitable for subsequent storage, while the reformed CaO is transferred back to the reaction bed for further use (Strhöle et al., 2009). As is the case with amine stripping, carbonate looping is being considered for retrofitting to existing, non-CCS point sources.

To be transported, the captured CO_2 requires compression into either liquid or dense phase to avoid two phase flow. The thermodynamic properties of CO_2 are discussed later in this chapter, however, for these phases to be achieved, the pressure and temperature (P/T) must exceed c. 220 degrees kelvin and 0.80 MPa (800 pa) for liquid phase and c. 300 degrees Kelvin and 9 MPa for dense phase. The exact P/T required would vary dependant on the purity of the captured CO_2, where common contaminants include nitrogen & sulphur.

Furthermore, dense phase CO_2 is a highly effective solvent, the corrosiveness of which is enhanced by the impurities such as H_2O, H_2S, O_2, NO_3 and SO_3 (Carter, 2010) that may be found within the captured form depending on stripping efficiency. Should a separate aqueous phase form, it will be saturated with CO_2 and consequently have a pH of c. 3, via speciation of carbonic acid (Cole et al., 2011). Such phases have the potential to drastically increase the corrosion rate of steel transport infrastructure, especially when further N and S bearing compounds are present in association with acidified water, leading ultimately to formation of sulphuric and nitric acids.

Pipelines are the preferred method of transporting CO_2, and thus for safe operations, such pipelines should not be subjected to internal corrosion. For this reason, the materials required for transporting the captured CO_2 from its point source to the storage location requires careful engineering and more resistant materials than would be utilised in the transport of liquid natural gas (LNG). Present CO_2 pipelines uses primarily for Enhanced Oil Recovery (EOR) are shown to have suffered minimal corrosion over the past 20 years; however, such lines are operated under stringent regulations regarding water and contaminant concentrations in the CO_2 stream (Gale and Davison, 2004).

For use in CO_2 capture and storage projects it is imperative therefore, that water content in the CO_2 stream are kept extremely low, likely through a combination of cleaning technologies prior and post combustion. If such concentrations are kept low, then the lessons from EOR transportation suggests corrosion rates will also be low. However, for the contaminants that do remain in the CO_2 stream, further research is required to quantify corrosion under water free conditions. However, current literature indicates that Iron is the primary source of corrosion, and thus, use of low iron stainless steels may further reduce the impact of low pH solvents (Cole et al., 2011).

1.3.2. FUNDAMENTALS OF GEOLOGICAL CO_2 STORAGE

The practise of injecting carbon dioxide gas into the subsurface is not a new technology, having first been utilised in the 1970's in Texas, United States, for the purpose of improving oil recovery (Dicharry et al., 1973). However, injecting CO_2 for the sole purpose of preventing emissions to the atmosphere did not commence operations until 1992 with the Statoil operated Sleipner project, stripping CO_2 from produced oil and re-injecting it into the brine saturated Utsira Formation (Baklid et al., 1996; Korbøl and Kaddour, 1995). The number of pilot projects and small-scale operations has grown slowly since the commencement of the Sleipner operation with 17 projects currently active globally. Of these, eleven provide small tonnages of CO_2 for use in enhanced hydrocarbon recovery operations with just 6 opting for pure geological storage (Global CCS Institute Database).

Suitable geological storage formations primarily comprise either deep saline aquifers (also referred to as deep saline formations) or hydrocarbon fields, whether decommissioned for pure storage, or active for enhanced oil recovery. Other potential but rarely considered mediums include deep, un-mineable coal seams, use in coal bed methane activities in addition to conceivable geological formations such as fractured basalts, and carbonate cavities or artificially created salt caverns (IPCC, 2005).

Physical trapping structures are analogous to hydrocarbon traps that have formed an impermeable barrier to the migration of hydrocarbons and fluids. Such structures may form 4-way dip or antiformal closures, fault closures and stratigraphic trapping. Dome or 4-way dip closed traps represent a form of structural trap resulting from either folding via tectonic forces, or doming resulting from the growth of salt diapirs. Fault closures commonly rely on the juxtaposition of permeable reservoir material against impermeable fine grained shales, salt or igneous rocks. Stratigraphic trapping utilise geological phenomena such as stratigraphic pinch out of porous or permeable intervals, unconformities where erosional surfaces are sealed by overlaying younger strata, and sedimentary structures such as carbonate reefs and platforms overlain by finer grained impermeable lithologies (Fig.1.1).

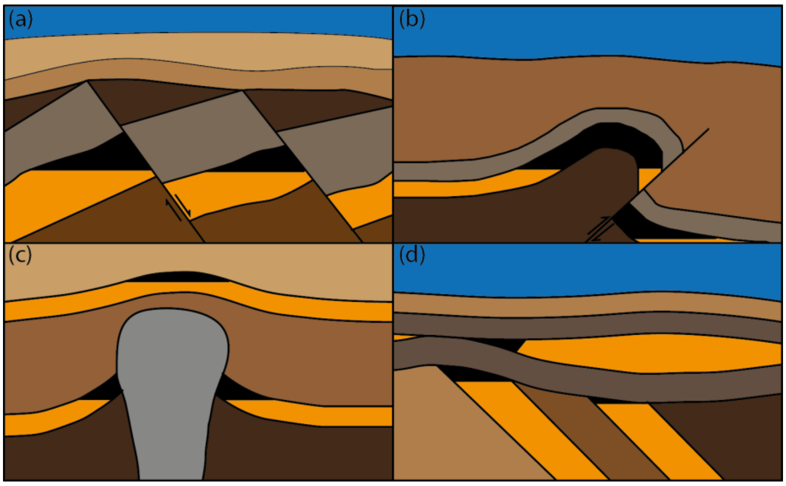

Fig. 1.1: Types of structural (a-c) and stratigraphic (d) geological traps suitable for CO_2 storage, specifically: (a) Tilted fault blocks in extensional basins. CO2 (black) is trapped by low permeability seals overlaying the reservoir unit, and juxtaposed in the hanging wall. (b) Accumulations in rollover antiforms in compressive, thrust fault settings. CO2 may be trapped in both the hanging and foot wall, where the hanging wall comprises a dip-closed structure and the foot wall requires a fault sealed structure. (c) Trapping via a 4-way dip closed antiformal trap above a penetrating salt diapir (grey) and trapping against the impermeable wall of the diapir. (d) Stratigraphic trapping due to bed pinchout, where deposition unconformably infills an eroded or folded topography; and erosional truncation of permeable units. (After Gluyas & Swarbrick, 2013)

Prior to injection into a suitable geological storage formation, the captured CO_2 is first compressed into the supercritical phase (Fig. 1.2). In supercritical form, the density of CO_2 is significantly increased, compared with the gaseous phase therefore requiring less space per given volume within the reservoir. Based on the common geothermal and formation pressure gradients, a storage prospect must be at a depth greater than 800m total vertical depth subsea (TVDSS) to maintain the supercritical phase (Fig. 1.2).

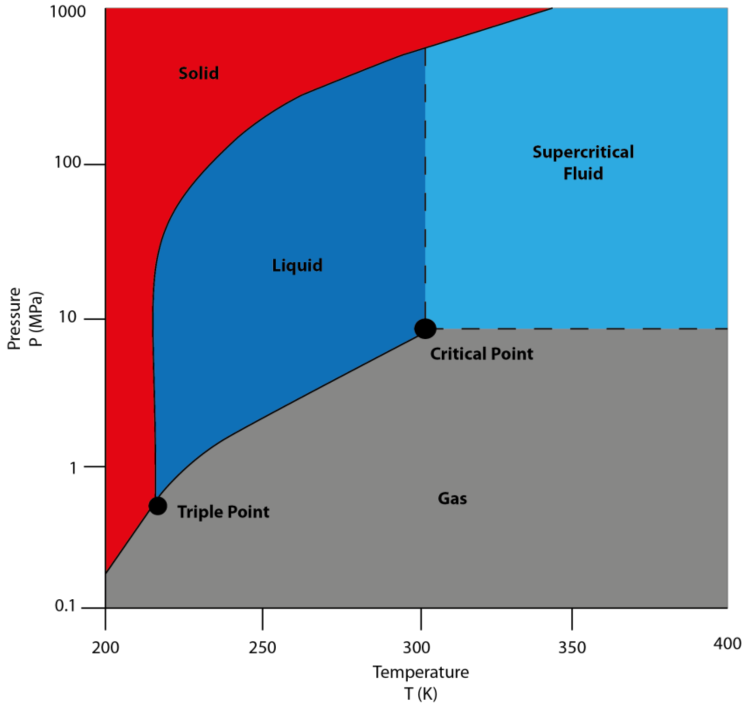

Fig. 1.2: Phase diagram for Carbon Dioxide indicating the critical temperature and pressure required for CO2 to remain as a supercritical fluid.

Once injected carbon dioxide may be trapped within a geological formation via any combination of five differing methods, dependent on the type of geological structure utilised, rate and volumes injected, and the time period of storage (Fig.1. 3 Table 1.1). Stratigraphic and structural trapping offers immediate storage potential and occurs in conjunction with hydrodynamic, free-phase and residual trapping. These trapping mechanisms, analogous with conventional trapping of hydrocarbons, represent the primary storage medium over human timescales.

Solubility trapping relies on the principal of Henry's law, which describes the relationship between the concentrations of gas dissolved in the fluid as a function of pressure, namely, the amount of gas in solution increases with an increase of pressure. Consequently, solubility trapping will offer both immediate and long term trapping solution, such that a proportion of the injected CO_2 will be immediately dissolved into the reservoir formation fluid, increasing as the reservoir pressure increases with injection. The CO_2 dissolved in solution will remain in place so long as reservoir pressure is maintained, as reductions in pressure will result in a de-gassing effect, analogous to un-capping a fizzy drinks container. The mass of CO_2 dissolved into the formation fluid is difficult to quantify in static models and as such omitted from studies presented in the literature and this thesis. Consequently, the storage volumes presented in such studies will represent a conservative underestimate of the maximum potential storage volume.

Mineral trapping represents the only ‘permanently’ secure storage solution. Mineral trapping relies upon the chemical reaction between CO_2 and water, resulting in subsequent precipitation of solid calcium carbonate ($CaCO_3$) within reservoir pore spaces.

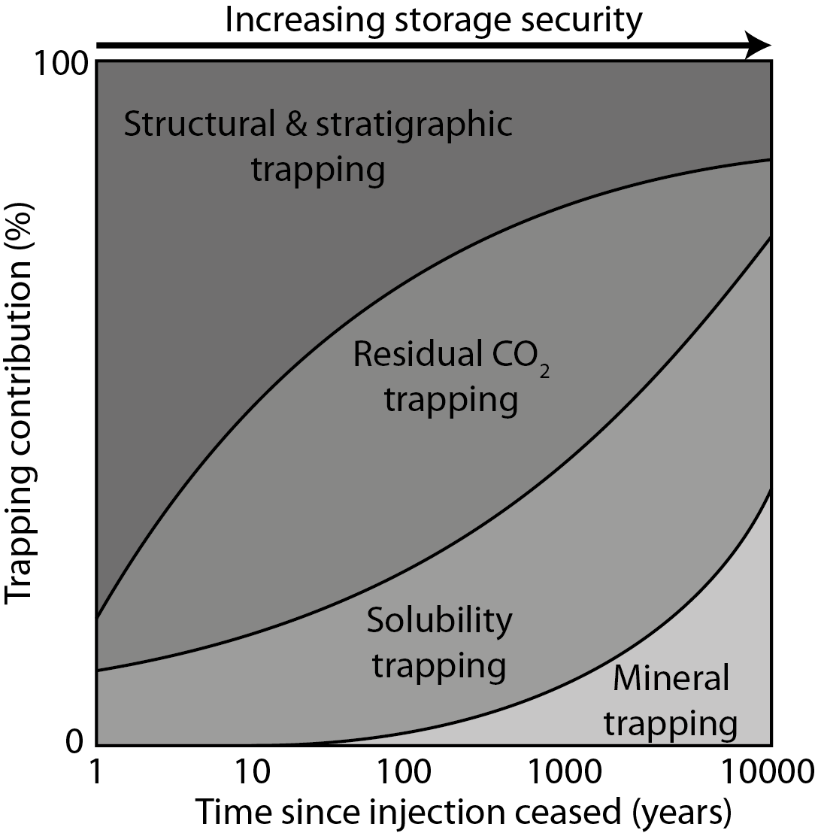

Fig. 1.3: Schematic diagram showing the increase in storage security over time as the physical trapping type changes from physical (structural) to geochemical (mineral precipitation) after IPCC, (2005).

Table 1.1: (Overleaf) Table summarising the main types of CO_2 trapping, the effective times scales and limitations (after Bachu, 2008).

Trapping mechanism	Nature of trapping	Effective time frame	Issues	Capacity limitation/benefits
Structural and stratigraphic	Bouyancy trapping within anticline, fold, fault block, pinch-out. CO2 remains as a fluid below physical trap (seal).	Immediate.	Faults may be sealed or open on stress regime, fault orientation and faults could be leak/spill points or compartmentalize trap.	If closed hydraulic system then limited by compression of fluid (few %) in reservoir. If open hydraulic system will displace formation fluid.
Residual gas	CO2 fills interestices between pores of the grains of the rocks.	Immediate to thousands of years.	Will have to displace water in pores. Dependent on CO2 sweeping through reservoir to trap large volumes.	Can equal 15 to 20% of reservoir volume. Eventually dissolves into formation water.
Dissolution/ solubility	CO2 migrates through reservoir beneath seal and eventually dissolves into formation fluid.	100 to 1000 s of years if migrating more than 1000 s of years if gas cap in structural trap and longer if reservoir is thin and has low permeability.	Dependent on rate of migration (faster better) and contact with unsaturated water and pre-existing water chemistry (less saline water better). Rate of migrations depends on dip, pressure, injection rate, permeability, fractures, etc.	Once dissolved, CO2 saturated water may migrate towards the basin center thus giving the very large capacity. The limitation is contact between CO2 and water and having highly permeable (vertical) and thick reservoirs.
Mineral precipitation	CO2 reacts with existing rock to form new stable minerals.	10 to 1000 s of years.	Dependent on presence of reactive minerals and formation water chemistry. Could precipitate or dissolve.	Rate of reaction slow. Precipitation could clog pore throats readucing injectivity. Approaches permanent trapping.
Hydrodynamic	CO2 migrates through reservoir beneath seal, moving with or against the regional ground water flow system whist other physical and chemical trapping mechanisms operate on the CO2.	Immediate.	Dependent on CO2 migration after the injection period<comma> being so slow that it will not reach the edges of the sedimentary basin where leakage could occur.	No physical trap may exist and thus totally reliant on slow transport mechanism and chemical processes. Can include all other trapping mechanisms along the migration pathway.

1.3.3. CURRENT STATUS OF CCS IMPLEMENTAION IN THE UK AND GLOBALLY

At present, there are two CCS demonstration studies in the Front End Engineering Design (FEED) study stage. These projects comprise the Peterhead CCS project, operated by Shell and SSE, and the White Rose CCS project operated by Alstom, Drax and BOC (DECC). The Peterhead project will store CO_2 from a currently operational Combined Cycle Gas Turbine Station captured via post combustion amine stripping, in the disused Goldeneye gas field 100 km offshore in the North Sea (Shell, 2013; CCSA 2013). The White Rose project will utilise a new build Oxyfuel supercritical coal fired power station on the Drax site, storing in an undisclosed location in the Southern North Sea (CCSA, 2013).

Globally, there are currently 8 commercial scale CCS plants in operation. These comprise:

1. Val Verde Natural Gas Plants (formerly Sharon Ridge) in Texas, U.S.A: operational since 1972 and capturing 1.3 million tonnes of CO_2 per year (Mtpa).
2. Enid Fertilizer in Oklahoma, U.S.A: operational since 1982 and capturing 0.7 Mtpa.
3. Shute Creek Gas Processing Facility in Wyoming, United States: operational since 1986 and capturing 7 Mtpa.
4. Sleipner is in the North Sea, about 160 miles west of Stavanger, Norway: operational since 1996 and injecting over 1 million tonnes of CO_2 annually.
5. The Great Plains Synfuels plant and Weyburn-Midale Project in Saskatchewan, Canada: operational since 2000 and capturing 3 million tonnes of CO_2 annually.

6. In Salah is in central Algeria: operational since 2004 and injecting over 1 Mtpa.
7. Snøvit, northern Norway: operational since 2008 and, at full production, the plant has a capture and storage capacity of 700,000 tpa.
8. Century Plant (formerly Occidental Gas Processing Plant) in Texas, U.S.A: operational since 2010 and capturing 8.5 Mtpa.

In addition to the above projects, there are currently 74 large scale CCS operations in planning, of which 14 are currently under construction or testing (CCSA, 2014)

1.4. GEOLOGICAL AND GEOGRAPHICAL SETTING

The geological and geographical focus of this thesis is the Central North Sea region of the UK Continental Shelf. Specifically, the southerly extent of UKCS quads 28 and 29 adjacent to the western edge of the Central Graben, the south easterly extent of UKCS quad 16 proximal to the intersection of the Viking, Central and Witch Ground Graben, and the south western extent of quad 14 on in the Halibut Basin on the edge of the outer Moray Firth (Fig. 1.4). The multiple phases of extension and rifting have been studied extensively, with a summary of the significant structural and stratigraphic developments included below. However for greater detail the reader is directed to the references herein.

The study into the social acceptability of CCS was conducted in Newcastle upon Tyne, North East England. A concise summary of the socio-economic setting of this region is included for context only as the assessment of such a setting is not a relevant variable in this study.

1.4.1. STRUCTURAL EVOLUTION OF THE CENTRAL NORTH SEA

The structural evolution of the Central North Sea is considered to have occurred as two major phases (Bartholomew et al., 1993). These comprise the initial development of a basin framework during the Early Palaeozoic (Coward, 1993), and subsequent repeated reactivation of pre-existing basement lineaments as a consequence of Mesozoic and Cenozoic deformation. This study focuses mostly on the Central Graben area of the North Sea, and as such the structural evolution of the Southern North Sea is largely omitted from this review.

The crystalline basement underlying much of the North Sea area consolidated during the Caledonian Orogeny between the late Cambrian and mid Devonian (Ziegler, 1990). A period of post-orogenic collapse followed during the Devonian accompanied by sinistral translation between the Laurentia-Greenland and Fenno-Scandian shield. This movement resulted in rapid subsidence of strike-slip basins, particularly in the Northern North Sea, providing the accommodation space for the deposition of several kilometres of Devonian Old Red Sandstone (Ziegler, 1988, 1989a).

Carboniferous basin development was controlled by tensional stresses producing several north-east trending Graben, visible onshore striking into the North Sea where they are poorly defined (Ziegler, 1988). During the Late Carboniferous, the Variscan foreland basin occupied the area of the Central and Southern North Sea and gave rise to the accumulation of a southward-expanding wedge of coal measures.

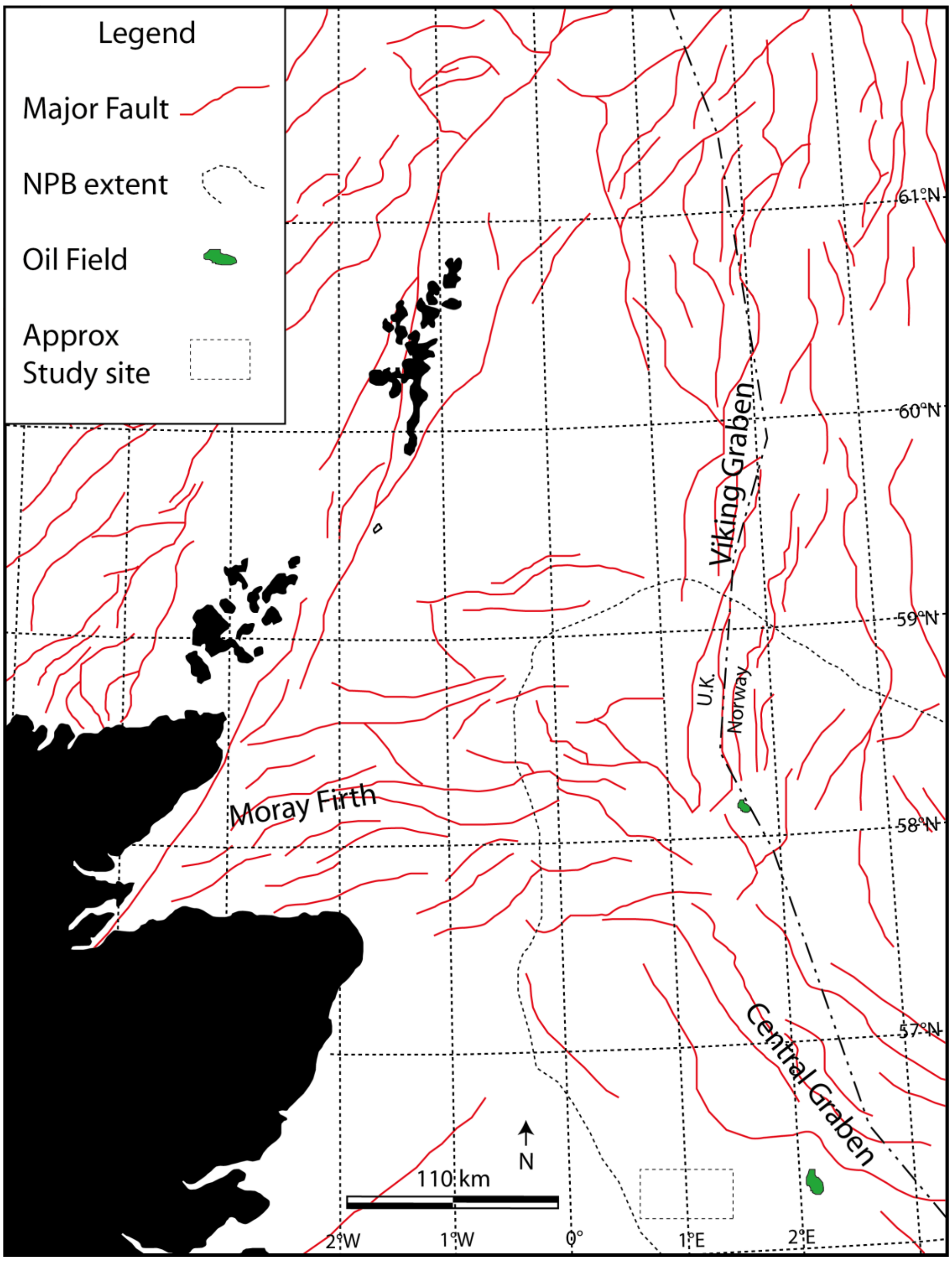

Fig. 1.4: Map showing the location of the major faults of the Central North Sea and the location of the trilete rift system with the 3 associated Graben. The outline of the Northern Permian basin marks the extent of the Lower Permian Rotliegend deposition, occurring to the west of the study site. The Auk and Maureen oilfields are included as these are referred to in this study as analogues (Adapted from Finlay et al, 2010).

The Carboniferous Graben were subsequently inverted during the late Westphalian phases of the Variscan orogeny as a consequence of a change from tensional to compressive stresses (Ziegler, 1975, 1988, 1989a, 1990).

A late Carboniferous – early Permian period of post Hercynian orogenic shear faulting followed associated with widespread magmatism and deformation of the Variscan foreland basins (Storetvedt, 1987).

Reconstruction of subcrop patterns of Palaeozoic geology beneath the Permian unconformity is tentative, although there is localised evidence for thick Devonian and Carboniferous successions beneath the base Permian and base Triassic unconformities. Consequently, such successions require a proportionate quantity of crustal thinning that cannot be defined. Therefore it is assumed that the North Sea comprises of mature continental crust of c. 35 km in thickness in areas devoid of Devonian Carboniferous sediment accumulation. However it must be noted that the widespread Carboniferous – Permian magmatism would have resulted in areas of thermal destabilisation (Ziegler, 1990).

Saxonian subsidence of both the Northern and Southern Permian basin coincided with the late Autunian abatement of magmatism and strike-slip tectonic, due likely to the decay of the crustal thermal anomalies that accompanied the Autunian strike-slip deformation (Ziegler, 1990). The east-west striking Northern Permian Basin stretching across the Central North Sea is more poorly defined than the larger Southern Permian Basin. The two Permian basins are separated by the Stephanian-Autunian series of highs, including the mid-North Sea, Ringkobing and Fyn Mons highs (Glennie and Underhill, 1998; Underhill, 2003; Ziegler, 1990). Further rifting occurred during the late Permian, originating from the Norwegian-Greenland area southwards into the Faero-Rockall Trough (Ziegler, 1990). The Permian basins continued to subside during this period as a consequence of thermal contraction of the lithosphere coupled with increased sedimentary loading (Ziegler, 1988).

The stratigraphy of the Permian deposits comprises the Lower Permian Rotliegend Group, a series of continental red beds including Aeolian and fluvial sandstones interbedded sabkhas; and the Upper Permian Zechstein Evaporitic sequence composed of halite, anhydrite and dolomite facies (Glennie, 1998; Glennie et al., 2003; Taylor, 1998).

The Triassic (248 – 206 Ma) comprised a significant period in the earth's structural history coinciding with the beginning of the break-up of Pangaea (Dietz and Holden, 1970), commencing with the crustal thinning and rifting along the axis of incipient Atlantic and the western edge of the Tethys (Stampfli, 2000; Ziegler, 1981, 1989b). Consequently, a new structural framework was established across north west Europe, controlling sedimentary deposition throughout the Mesozoic period (Ziegler, 1975, 1990). The extensional phase modified the pre-existing Permian structural framework, with Palaeozoic fault networks reactivated as extensional features contemporaneous with early Triassic extension driven rifting resulting in complex series of multidirectional basins (Fisher and Mudge, 1998). Indeed, the Triassic graben network of the Central North Sea is almost perpendicular to the axis of the Northern Permian basin (Ziegler, 1990).

Much of the evidence for Triassic rifting is located to the west of Britain, however it is widely accepted (Roberts and Yielding, 1991; Roberts et al., 1990; Roberts et al., 1995) that the Northern and Central North Sea basins were equally affected. This is despite subsequent deformation overprinting Triassic structures making the full extent of late Permian – Triassic extension, block rotation and graben infilling within these basins difficult to quantify (Platt, 1995; Roberts et al., 1995). Within sections of the Central and Southern North Sea away from main areas of post-rift subsidence, the major depocentres reflect phases of post-rift passive thermal subsidence as the Permian Margins became progressively overstepped (Fisher and Mudge, 1998).

Triassic sediments in general rest conformably upon the Zechstein despite the pronounced angular discordance between the Permian Rotliegend and Zechstein deposits, likely caused by a non-rotational late Permian – Early Triassic rifting phase (Cartwright, 1991). In all North Sea basins, Triassic sediments are dominated by clastic red beds comprising fluvial; inclusive of alluvial fan, aeolian dune, sabkha, lacustrine and shallow marine clastic facies, where the coarse grained clastic facies of the late Triassic dominate within the Central and Northern North Sea basins (Fisher and Mudge, 1998). The accumulation of such sediments coupled with syn-depositional faulting triggered episodes of Zechstein halokinesis during the mid to late Triassic (Ziegler, 1990).

Although early Jurassic sediments have been largely removed from the Central North Sea basins as a consequence of mid Jurassic erosion, it is assumed that the Central Graben continued to subside during this time (Ziegler, 1990). This preceded the uplift of the Central North Sea area, forming a broad arch transected by the Central Graben. This uplift was simultaneous with the interruption of the interconnection between the Arctic and Tethys oceans (Ziegler, 1981, 1988).

The collapse of Central North Sea rift dome during the mid to late Jurassic and continued subsidence of the central dome during the Oxfordian is marked by the transition from lacustrine and continental sediments to marine sediments. Thus indicating a widespread marine transgression into the Central North Sea and Viking Graben areas (Hamar et al., 1985; Ziegler, 1990).

It is generally accepted that the development and collapse of the Central North Sea thermal dome preceded the development of the North Sea trilete rift system (Fig.1.4) (Underhill and Partington, 1993; Ziegler, 1990), comprising the Viking and Central Graben and the Moray Firth (Davies et al., 1999; Erratt et al., 1999). Indeed it is proposed that the initial development of the trilete rift was directly caused by dome rise and decay (Underhill and Partington, 1993). The remaining evolution of the rift system was three-fold, comprising 1) east – west orientated extension during the Bathonian-Callovian resulting in north – south trending dip-slip faulting, 2) northwest – southeast extension forming northeast – southwest trending dip-slip faulting during the Oxfordian, and finally, 3) Early Volgian northeast – southwest trending extension resulting in northeast – southwest orientated faulting (Davies et al., 2001).

The tectonic system of the of the Cretaceous is poorly understood, where Jurassic extension is often extrapolated into the early Cretaceous, and Tertiary thermal subsidence and halokinesis models retroactively extended into the Chalk sequences. It has recently been accepted that plate wide compression and sub-basinal transpression dominated the Cretaceous tectonic evolution (Oakman and Partington, 2009). The transition between the late Jurassic and Early Cretaceous is easily identifiable across much of the North Sea by means of the strong seismic reflection, often termed the Base Cretaceous Unconformity (BCU) (Kyrkjebø et al., 2004), and more regionally in the UK sector as the Top Humber Group/Kimmerage Clay Formation (Oakman and Partington, 2009). The structural evolution throughout the Cretaceous is two-fold marked by the contrast between compressional and extensional stress regimes (Oakman and Partington, 2009). The lower most Cretaceous is characterised by northward orientated compression of the late Cimmerian resulting from onset of the Tethyan closure and associated Austrian orogeny (Oakman, 2005; Ziegler, 1990). The transition between the lower Cretaceous compression and extension occurred in the mid Austrian Orogeny during the mid Albian period resulting from further rifting in North Atlantic allied to the cessation of the Tethyan closure (Oakman, 2005).

The tectonic change is marked by the onset of mid Cretaceous global flooding swamping shelves and sediment source areas and deepening basins sufficiently to yield deposition of deep shelf to basinal marls, sufficiently enriched in carbonate resulting in extensive chalky limestones (Oakman and Partington, 2009). Chalk deposition continued for much of the Cretaceous, ceasing at the end of the Maastrichtian giving way to the development of condensed regional mudrocks that mark the transition across the Cretaceous – Tertiary boundary. Subsequent Tertiary turbiditic clastic influxes eroded and extinguished any remaining carbonate deposition in localised sub-basins (Megson, 1992; Oakman and Partington, 2009).

The early Tertiary saw both the Central and Northern North Sea heavily influence by significant plate activity (Anderton, 1993; Bott, 1987; Bowman, 2009; Galloway et al., 1993; Glennie and Underhill, 1998; Knott et al., 1993). Such authors have summarised these activities into five main events. Thermal doming centred above East Greenland relating to the formation of a mantle hotspot that resulted in hinterland rejuvenation during the Danian/Thanetian period. East-west extension triggered a period of volcanism during the early Palaeocene resulted in the formation of the British and Faeroe-Greenland Igneous Province, exemplified within the North Sea basins by the deposition of marker units such as the Andrew Tuff Formation. Further volcanism in the late Palaeocene connected to the onset of sea floor spreading in the Norway-Greenland Sea resulted in the widespread deposition of Tuff marker beds such as the Balder Tuff Formation. Development of a thermal dome caused the restriction of the Northern North Sea basin where consequently, the basin became anoxic during the late Palaeocene. This continued until a minor inversion occurred in the early Eocene, instigated by the final rupture of the North Atlantic Margin. Finally, subsequent passive subsidence led to the establishment of a clear marine connection between the North Sea and the North Atlantic.

The sedimentary deposition during the Tertiary was controlled by the interplay of tectonic, eustatic and hinterland characteristics, resulting in regionally variable clastic deposition (Bowman, 2009). Significant volumes of sediment were fed into the North Sea basin via the development of major submarine fan complexes, although differential uplift led to the development of geographically and lithologically separate depocentres (Morton et al., 1993). Early Palaeocene turbidites often caused reworking and erosion of the upper Cretaceous chalk units with subsequent deposition of coarse grained clastic materials, such as the Central

North Sea Maureen Formation (Galloway et al., 1993). Progressive uplift and tilting saw a gradational change from sand rich basin floors to progredational braided delta aprons (Milton et al., 1990). Volcanic activity led to subsequent deposition of tuffs and tuffaceous sand and mudstones recording a halt to the coarse grained sediment influx into the basin (Bowman, 2009). Further, and indeed the final deposition of aggrading submarine fan sandstones occurred in the late Palaeocene giving rise to the Forties Member (Knox and Holloway, 1992). The restriction of the North Sea Basins (described above) led to a period of deposition of fine grained anoxic sediments until sea level rise in the Eocene restored circulation and renewed mixed sand and mud successions.

1.3.2. STRATIGRAPHY AND GEOLOGY OF THE CENTRAL NORTH SEA AQUIFER SITE

The study presented in Chapter 3 utilises a lower Permian Rotliegend sandstone hosted saline formation, Zechstein salt sealed play fairway prospect as a potential carbon dioxide storage prospect. A full geological description is contained within Chapter 3, however a summary is included here for completeness.

The study site is located within the Northern Permian basin of the Central North Sea, approximately 200 km northeast of Teesside, northeast England (Fig.3.4). Geologically, the site comprises a porous reservoir interval consisting of Rotliegend sandstone. This lithology is composed of interbedded Aeolian, fluvial sheetflood and channel, and lacustrine facies deposited during the early Permian in the east-west striking Northern Permian Basin, described in the previous section. This unit is a proven reservoir interval, hosting hydrocarbons in the adjacent Auk and Ardmore oilfields in addition to the gas hosting equivalents in the Southern Permian Basin.

The porosity of the unit varies considerably depending on facies, ranging from 2% in the fluvial and lacustrine facies to >25% in the Aeolian dune facies. The reservoir interval is overlain and sealed by interbedded Halite and Anhydrite evaporates of the Upper Permian Zechstein Group deposited in subsiding basin conditions. The salt successions are proven to have very low permeability values of 2-3% coupled with exceptionally high fracture pressures providing excellent sealing ability. The Permian interval is overlain by a succession of Triassic, Jurassic and Tertiary clastic sand and mud units interrupted by a thin interval of Cretaceous Chalk.

1.3.3 GEOGRAPHY AND SOCIAL ECONOMICS OF NORTH EAST ENGLAND

The North East of England is the most northerly of the nine regions of England that are classified at the first level of the Nomenclature of Territorial Units for Statistics (NUTS). The region comprises the counties of Northumberland, County Durham, Tyne and Wear and Teesside, although the latter is split between the North East and North Yorkshire. The region is largely hilly topographically and consequently the significant population is focused in the three large conurbations, namely Teesside, Wearside and Tyneside, which include the cities of Middlesbrough, Sunderland and Newcastle respectively.

The North East is an example of a largely industrial region that has experienced a significant social and economic shift, from the boom linked to the industries of the steam age in the 19th Century, through the steal and coal mining driven economies of the mid to late 20th century, to the crash driven by the decline and closure of these industries by the end of the 20th Century (Tomaney, 2006). The region was subjected and indeed continues to be subjected to a series to governmental policies intended to halt the economic decline. However, none of these have proved successful and decline accelerated during the 1980’s and 1990’s (Benneworth and Tomaney, 2002). Consequently, the social structure is biased towards the lower income non-professional groups allied to high levels of unemployment (Tomaney and Ward, 2000).

Recent redevelopment, driven by regional development agencies such as ONE North East, created by the Labour government in 1999 (and closed in 2011 by the newly elected coalition), has led to significant improvements economically with growth in specialist manufacturing and processing, tourism and new business start-ups (ONE North East). Furthermore, the success of the science and technology sectors such as the renewable energy research facilities of Narec and CPI allied to the research facilities of Durham and Newcastle Universities have increased the number of skilled professional positions to the area in effort to address the social balance. However, despite these improvements and the re-opening of some of the heavy industries, the social and economic divide between the North and South East remains as wide as ever (Tomaney, 2006).

The industrial focus of the North East economy is responsible for relatively high levels of CO_2 emissions, despite the majority of the region being rural. Despite this, the region has seen a decrease in CO_2 emissions from 33 Million tonnes (Mt) in 2005 to 23 Mt in 2011, indeed the heavy industrial area of Redcar and Cleveland achieved a 61% decrease in emissions over this period (DECC, 2013). This industrial hub is the location of the proposed North East CCS cluster, comprising a pre-combustion CCS enabled power station with the ability to allow CO_2 feed in from heavy manufacturing such as steel and petrochemicals with pipeline connectivity to suitable geological storage and EOR activities in the Central North Sea (Progressive Energy Pers Comms). The Teesside Low Carbon CCS Project was shortlisted for the DECC CCS funding competition, but was not one of the two preferred proposals that share the £1b central funding (DECC 2012, 2013) and is currently on the reserve list should the two preferred project fail a FEED study.

REFERENCES

Anderton, R., 1993, Sedimentation and basin evolution in the Paleogene of the Northern North Sea and Faeroe–Shetland basins: Geological Society, London, Petroleum Geology Conference series, v. 4, p. 31.

Bachu, S., 2008, CO2 storage in geological media: Role, means, status and barriers to deployment: Progress in Energy and Combustion Science, v. 34, no. 2, p. 254-273.

Baklid, A., Korbol, R., and Owren, G., 1996, Sleipner Vest CO_2 Disposal, CO_2 Injection into a Shallow Underground Aquifer: SPE Journal of Petroleum Technology, p. 269.

Bartholomew, I. D., Peters, J. M., and Powell, C. M., 1993, Regional structural evolution of the North Sea: oblique slip and the reactivation of basement lineaments: Geological Society, London, Petroleum Geology Conference series, v. 4, p. 1109-1122.

Benneworth, P., and Tomaney, J., 2002, Regionalism in North East England: England: the State of the Regions, p. 137-146.

Bott, M. H. P., 1987, The continental margin of central East Greenland in relation to North Atlantic plate tectonic evolution: Journal of the Geological Society, v. 144, no. 4, p. 561-568.

Bowman, M. B. J., 2009, Cenozoic, Petroleum Geology of the North Sea, Blackwell Science Ltd, p. 350-375.

Buhre, B. J. P., Elliott, L. K., Sheng, C. D., Gupta, R. P., and Wall, T. F., 2005, Oxy-fuel combustion technology for coal-fired power generation: Progress in Energy and Combustion Science, v. 31, p.283 – 307.

Carter, L. D., 2010, Capture and storage of CO_2 and other air Pollutants. Report CCC/162. IEA Clean Coal Centre, London.

Cartwright, J., 1991, The kinematic evolution of the Coffee Soil Fault: Geological Society, London, Special Publications, v. 56, no. 1, p. 29-40.

Carbon Capture and Storage Association, 2013, CCS Project Proposals, http://www.ccsassociation.org/why-ccs/ccs-projects/current-projects/

Coward, M. P., 1993, The effect of Late Caledonian and Variscan continental escape tectonics on basement structure, Paleozoic basin kinematics and subsequent Mesozoic basin development in NW Europe: Geological Society, London, Petroleum Geology Conference series, v. 4, p. 1095-1108.

Cole, I. S., Corrigan, P., Sim, S., and Birbilis, N., 2011, Corrosion of pipelines used for CO_2 Transport: Is it a real problem?: International Journal of Greenhouse Gas Control, v.5, no. 4, p.749 – 756.

Davies, R. J., O'Donnell, D., Bentham, P. N., Gibson, J. P. C., Curry, M. R., Dunay, R. E., and Maynard, J. R., 1999, The origin and genesis of major Jurassic unconformities within the triple junction area of the North Sea, UK: Geological Society, London, Petroleum Geology Conference series, v. 5, p. 117-131.

Davies, R. J., Turner, J. D., and Underhill, J. R., 2001, Sequential dip-slip fault movement during rifting: a new model for the evolution of the Jurassic trilete North Sea rift system: Petroleum Geoscience, v. 7, no. 4, p. 371-388.

DECC, 2013, Local Authority CO_2 emissions estimates 2011; Statistical Summary and UK Maps, *in* Change, D. o. E. a. C., ed.: London, p. 1-38.

Dicharry, R. M., Perryman, T. L., and Ronquille, J. D., 1973, Evaluation and Design of a CO_2 Miscible Flood Project - SACROC Unit, Kelly-Snyder Field: SPE Journal of Petroleum Technology, p. 1310.

Dietz, R. S., and Holden, J. C., 1970, Reconstruction of Pangaea: Breakup and dispersion of continents, Permian to present: Journal of Geophysical Research, v. 75, no. 26, p. 4939-4956.

Erratt, D., Thomas, G. M., and Wall, G. R. T., 1999, The evolution of the Central North Sea Rift: Geological Society, London, Petroleum Geology Conference series, v. 5, p. 63-82.

Finlay, A. J., Selby, D., Osborne, M. J., and Finucane, D., 2010, Fault-charged mantle-fluid contamination of United Kingdom North Sea oils: Insights from Re-Os isotopes: Geology, v. 38, no. 11, p. 979-982.

Fisher, M., and Mudge, D., 1998, Triassic, *in* Glennie, K. W., ed., Petroleum Geology of the North Sea: Basic Concepts and Recent Advances, Fourth Edition: Oxford, Blackwell Science, p. 212-244.

Gale, J., and Davison, J., 2004, Transmission of CO_2 – safety and economic considerations: Energy, v. 29, p. 1319 – 1328.

Galloway, W. E., Garber, J. L., Liu, X., and Sloan, B. J., 1993, Sequence stratigraphic and depositional framework of the Cenozoic fill, Central and Northern North

Sea Basin: Geological Society, London, Petroleum Geology Conference series, v. 4, p. 33-43.

Glennie, K. W., 1998, Lower Permian - Rotliegend, *in* Glennie, K. W., ed., Petroleum Geology of the North Sea: Basic concepts and recent advances, Blackwell Science, p. 140.

Glennie, K. W., Higham, J., and Stemmerik, L., 2003, Permian, *in* Evans, D., Graham, C., Armour, A., and Brathust, P., eds., The Millenium Atlas: Petroleum Geology of the Central and Northern North Sea: London, Geological Society,, p. 318 - 322.

Glennie, K. W., and Underhill, J. R., 1998, Origin, Development and Evolution of Structural Styles, *in* Glennie, K. W., ed., Petroleum Geology of the North Sea: Basic concepts and recent advances, Volume 4, Blackwell Science, p. 54-58.

Gluyas, J., and Swarbrick, R., 2013, Petroleum Geoscience, Oxford, Wiley.

Hamar, G. P., Fjæran, T., and Hesjedal, A., 1985, Jurassic Stratigraphy and Tectonics of the South-Southeastern Norwegian Offshore, *in* Kaasschieter, J. P. H., and Reijers, T. J. A., eds., Petroleum Geology of the Southeastern North Sea and the Adjacent Onshore Areas, Springer Netherlands, p. 103-114.

Hedley, B. J., Davies, R. J., Mathias, S. A., Hanstock, D., and Gluyas, J. G., 2013, Uncertainty in static CO2 storage capacity estimates: Case study from the North Sea, UK: Greenhouse Gases: Science and Technology, v. 3, no. 3, p. 212-230.

IPCC, 2005, Special report on Carbon Dioxide Capture and Storage., *in* Metz, B., Davidson, O., de Coninck, H., Loos, M., and LA, M., eds., Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press.

Knott, S. D., Burchell, M. T., Jolley, E. J., and Fraser, A. J., 1993, Mesozoic to Cenozoic plate reconstructions of the North Atlantic and hydrocarbon plays of the Atlantic margins: Geological Society, London, Petroleum Geology Conference series, v. 4, p. 953-974.

Knox, R., and Holloway, S., 1992, 1. Paleogene of the central and northern North Sea, British Geological Survey Nottingham.

Korbøl, R., and Kaddour, A., 1995, Sleipner vest CO2 disposal - injection of removed CO2 into the utsira formation: Energy Conversion and Management, v. 36, no. 6-9, p. 509-512.

Kyrkjebø, R., Gabrielsen, R. H., and Faleide, J. I., 2004, Unconformities related to the Jurassic–Cretaceous synrift–post-rift transition of the northern North Sea: Journal of the Geological Society, v. 161, no. 1, p. 1-17.

MacDowell, N., Florin, N., Buchard, A., Hallett, J., Galindo, A., Jackson, G., Adjiman, C. S., Williams, C. K., Shah, N. and Fennell, P., 2010, An overview of CO_2 capture technologies. Energy & Environmental Science, v. 3 no. 11. p. 1645-1669.

Megson, J. B., 1992, The North Sea Chalk Play: examples from the Danish Central Graben: Geological Society, London, Special Publications, v. 67, no. 1, p. 247-282.

Milton, N. J., Bertram, G. T., and Vann, I. R., 1990, Early Palaeogene tectonics and sedimentation in the Central North Sea: Geological Society, London, Special Publications, v. 55, no. 1, p. 339-351.

Morton, A. C., Hallsworth, C. R., and Wilkinson, G. C., 1993, Stratigraphic evolution of sand provenance during Paleocene deposition in the Northern North Sea area: Geological Society, London, Petroleum Geology Conference series, v. 4, p. 73-84.

Oakman, C. D., 2005, The Lower Cretaceous plays of the Central and Northern North Sea: Atlantean drainage models and enhanced hydrocarbon potential: Geological Society, London, Petroleum Geology Conference series, v. 6, p. 187-198.

Oakman, C. D., and Partington, M. A., 2009, Cretaceous, Petroleum Geology of the North Sea, Blackwell Science Ltd, p. 294-349.

Platt, N. H., 1995, Structure and tectonics of the northern North Sea: new insights from deep penetration regional seismic data: Geological Society, London, Special Publications, v. 80, no. 1, p. 103-113.

Roberts, A. M., and Yielding, G., 1991, Deformation around basin-margin faults in the North Sea/mid-Norway rift: Geological Society, London, Special Publications, v. 56, no. 1, p. 61-78.

Roberts, A. M., Yielding, G., and Badley, M. E., 1990, A Kinematic model for the orthogonal opening of the late jurassic North Sea ruft system, Denmark - mid Norway, *in* Blundel, D. J., and Gibbs, A. D., eds., Tectonic Evolution of the North Sea Rifts: Oxford, Clarendon Press, p. 180-199.

Roberts, A. M., Yielding, G., Kusznir, N. J., Walker, I. M., and Dorn-Lopez, D., 1995, Quantitative analysis of Triassic extension in the northern Viking Graben: Journal of the Geological Society, v. 152, no. 1, p. 15-26.

Shell, 2013, Peterhead CCS Project, http://www.shell.co.uk/gbr/environment-society/environment-tpkg/peterhead-ccs-project.html.

Stampfli, G. M., 2000, Tethyan oceans: Geological Society, London, Special Publications, v. 173, no. 1, p. 1-23.

Storetvedt, K. M., 1987, Major late Caledonian and Hercynian shear movements on the Great Glen Fault: Tectonophysics, v. 143, no. 4, p. 253-267.

Ströhle, J., Galloy, A. and Epple, B., 2009, Feasibility study on carbonate looping process for post-combustion CO_2 capture from coal-fired power plants: Energy Procedia, no. 1, 1313 - 1320

Taylor, J. C. M., 1998, Upper Permian - Zechstein., *in* Glennie, K. W., ed., Petroleum Geology of the North Sea: Basic concepts and recent advances, Volume 4: London, Blackwell Science, p. 195.

Tomaney, J., 2006, North East England - A Brief Economic History, North East Research and Information Partnership Conference: Newcastle, Office for National Statistics, p. 1-40.

Tomaney, J., and Ward, N., 2000, England and the 'New Regionalism': Regional Studies, v. 34, no. 5, p. 471-478.

Underhill, J. R., 2003, The tectonic and stratigraphic framework of the United Kingdom's oil and gas fields: Geological Society, London, Memoirs, v. 20, no. 1, p. 17-59.

Underhill, J. R., and Partington, M. A., 1993, Jurassic thermal doming and deflation in the North Sea: implications of the sequence stratigraphic evidence: Geological Society, London, Petroleum Geology Conference series, v. 4, p. 337-345.

Ziegler, P. A., 1975, Geologic evolution of North Sea and its tectonic framework: AAPG Bulletin, v. 59, no. 7, p. 1073-1097.

-, 1981, Evolution of sedimentary basins in North-West Europe: Petroleum geology of the continental shelf of north-west Europe, v. 2, p. 3-39.

-, Laurussia - the Old Red continent, *in* Proceedings Devonian of the world: proceedings of the Second International Symposium on the Devonian System Calgary, Canada, 1988, Volume 14, Canadian Society of Petroleum Geologists, p. 15-48.

-, 1989a, Evolution of the Arctic — North Atlantic Rift System, Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound, Volume 266, Springer Netherlands, p. 37-38.

-, 1989b, Evolution of the North Atlantic—an overview: American Association of Petroleum Geologists Memoir, v. 46, p. 111-129.

-, 1990, Tectonic and palaeogeographic development of the North Sea rift system, *in* Blundel, D. J., and Gibbs, A. D., eds., Tectonic Evolution of the North Sea Rifts: Oxford, Clarendon Press, p. 1-36.

2. DATA AND METHODLOLOGY

2.1. INTRODUCTION

The research undertaken for this thesis is based upon interpretation of multiple subsurface datasets using a variety of geophysical and mathematical techniques. The source and specifics of such datasets will be discussed within this chapter in conjunction with the fundamental theory behind the methodologies employed in this research.

The literary theory and derivation of the methodology utilised for the anthropological research undertaken for this thesis is discussed separately in chapters 5 and 6.

2.2. SEISMIC REFLECTION DATA

Advances in geological understanding often coincide with the development of new geological and geophysical techniques. For the purposes of subsurface characterisation of sedimentary basins, the greatest impact may be due to the advent and development of seismic reflection technology (Cartwright, 2007). This began with basin mapping using 2D seismic data in the 1930’s, the quality of which improved rapidly throughout the 1970’s and 1980’s, and led to the development of systematic approaches to the seismic interpretation of sedimentary successions and applications to the development of chronostratigraphic and sequence stratigraphy (Posamentier et al., 2007).

Further advances occurred with the advent of 3D seismic technology (Sheriff and Geldart, 1995) that utilises dense survey grids to solve the spatial resolution limitations of 2D surveys allowing smaller and more discrete features to be investigated and understood (Fig. 2.1)

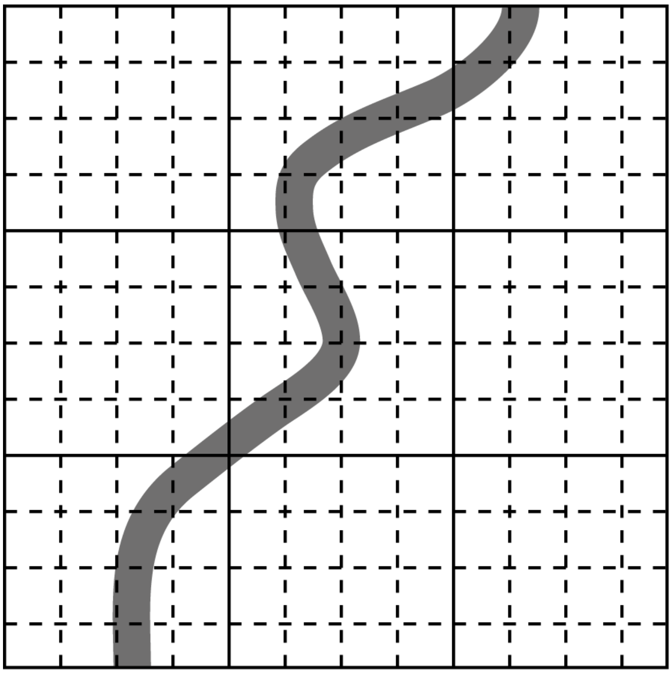

Fig. 2.1: The differences and advantages of 3D seismic (dashed lines) over 2D seismic (solid lines). In this case, the greater coverage allows a geological feature such as a channel (grey line) to be observed and mapped, which would otherwise have been missed in 2D seismic (after Brown, 2005). Not to scale.

The development of seismic reflection technology has, in general, been driven by the upstream oil and gas sector for reducing risks associated with hydrocarbon exploration and production (Brown, 2004). The high cost of obtaining such dense 3D surveys was restrictive and consequently the coverage was often limited to relatively small areas above producing fields rather for large scale basin reconnaissance. 3D seismic data have had a significant impact on the discovery, development and production of petroleum (Weimer and Davis, 1996). The cost base for seismic acquisition has dropped dramatically in recent decades resulting in ever increasing survey areas, where a single survey may now cover over 10 000 km^2 (Cartwright 1996). Furthermore, it is becoming increasingly common for such data to be shared with academic research institutions for the investigation of new sub-surface challenges (e.g. Ireland et al, 2011., Wright et al., 2011)

The similarities between hydrocarbon exploration and production (E&P) and geological CO_2 storage are many. Thus, the interpretation of seismic reflection data is of fundamental importance to the construction of detailed geological models of the storage complex. Specifically these models allow sub-surface stratigraphic units to be identified along with structural features such as faults that may aid or inhibit geological CO_2 storage. This thesis uses interpretation of both 2D and 3D seismic data in order to characterise prospective CO_2 storage complexes in the both the Permian and Tertiary of the UK Central North Sea.

2.2.1. THEORY OF SEISMIC REFLECTION IMAGING.

The primary purpose behind acquisition of seismic reflection data is to image sub-surface successions by the transmission and subsequent detection of compressional acoustic waves. The generation of acoustic waves must be repeatable to allow comparisons across the survey, have sufficient energy to propagate beyond the intended target and be safe, efficient and environmentally acceptable. Consequently, seismic sources often comprise air guns (offshore), vibroseis or small explosives (onshore) detonated at, or just below the earths’ surface (Kearey et al., 2009). The emitted waves propagate through the subsurface and some are reflected back to the surface by acoustic (geological) boundaries (reflection surfaces include bedding planes or unconformities). The remaining waves are refracted or attenuated. The proportions reflected to the surface are detected by geophone or hydrophone arrays where they may be subsequently processed for interpretation. While seismic reflection surveys may be conducted either on or offshore, the data utilised in thesis is collected solely in marine settings, as such only offshore methodologies will be referred to here. Consequently, when references herein are made to seismic wave velocity, this refers only to P-wave velocity as S (shear) waves are not transmitted through fluids.

The fundamental theory pertaining to seismic reflection surveys is the defining of the acoustic impedance (z) of a material. The impedance contrast between two materials determines the relative proportions of seismic energy that are either transmitted or reflected across the geological boundary. The acoustic impedance of a material is a product of its density (ρ) and its wave velocity (v) (Kearey et al., 2009); that is,

$$Z = \rho v \tag{2.1}$$

Contrasts in acoustic impedance across a geological boundary control the reflection coefficient (R) of such a boundary. The reflection coefficient is a numerical measure of the effects of an interface on the propagation of waves across it. Normally it is calculated as a ratio of the amplitude of the reflected wave to the amplitude of the incident ray (Kearey et al., 2009). However relating this principal to the physical properties of the interface materials requires the stress and strain of both materials to be considered. The formal solution to this relationship was derived by Zoeppritz (1919) but the widely accepted solution will be shown here (Bacon et al., 2003; Kearey et al., 2009); such that,

$$R = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1} \tag{2.2}$$

This simplifies to give,

$$R = \frac{z_2 - z_1}{z_2 + z_1} \tag{2.3}$$

The velocity of seismic P-waves through an isotropic, homogenous substance is controlled by the elastic properties and density of the material (Sheriff and Geldart, 1982). The subsurface is rarely either isotropic or homogenous, consequently, wave velocity will vary in three dimensions depending on rock or sediment composition, porosity, fluid saturation and pressure (Bacon et al., 2003). As such, seismic reflection data must be tied to calibrated velocity models derived from well bores before it can be used to estimate the true depth of a point of interest.

Seismic data may be collected in two, three or four (time lapse) dimensional surveys. The seismic data used in this study comprises predominantly 2D seismic surveys with additional use of 3D data. No 4D (time-lapse) seismic data has been used and as such is included in this section in reference to its use for post injection monitoring of CO_2 storage sites.

Two Dimensional seismic surveys are acquired as a series of parallel and orthogonal lines often kilometres apart that produce a cross section of the subsurface ((Kearey et al., 2009). The technology was first developed in the 1920's and was refined through to the 1950's. Interpretation of intersecting perpendicular lines allows basic models of the subsurface to be constructed by interpolation between lines. Models however are limited by the spacing of the seismic lines as these define the scale of resolvable structures. Thus, any structures, such as channels, antiformal domes and faults smaller than the grid spacing of the survey will not be imaged.

Three Dimensional seismic surveys utilise a regular grid of multiple 2D lines with an approximate 12.5 to 25m spacing. Such spacing results in a virtually continuous 3D data cube that is viewable from any orientation. The advances in 3D seismic resolution allow small-scale subsurface features, unresolvable in 2D, to be mapped with a high level of detail. Additionally, the advantages of the near continuous data cube allows key horizons to be interpreted quickly across a large geographical area.

Four Dimensional seismic surveys, also referred to as time-lapse seismic data comprise the study of two or more 3D seismic surveys over the same reservoir or target. This aims to observe changes over time, whether as an consequence of hydrocarbon production or to observe the impact of secondary recovery techniques. Most 4D seismic surveys utilise existing 3D surveys acquired at different times over the same or overlapping area and thus require very careful reprocessing to eliminate problems. In spite of improvements in reprocessing, these surveys require a large shift in reservoir acoustic properties to be observable. Recent surveys have used permanently positioned seabed receiver arrays, which significantly improves the survey repeatability and increases the detectability of subtle acoustic changes in the target reservoir or formation (Brown, 2004). Although not used in this study, 4D seismic surveys have been identified as an important potential monitoring tool to observe the migration of injected CO_2 plumes in sequestration projects as proven as proven by the Sleipner and Weyburn projects (Cairns et al., 2012; Chadwick et al., 2004, 2009; White, 2013). However, the high cost implications are seen as a barrier for large scale deployment.

2.2.1. ACQUISITION, PROCESSING AND INTERPRETATION OF SEISMIC REFLECTION SURVEYS.

Both 2D and 3D marine seismic reflection surveys are collected using a similar principal, towing streamers of hydrophones behind a survey vessel with an airgun source between the vessel and the streamer array. 2D seismic surveys utilise a single sources and streamer of multiple geophones. Conversely, 3D surveys utilise multiple source and receiver arrays, comprising between 6 and 12 streamers of between 6 and 12 km in length. Streamer arrays are positioned using paravanes at the head of the array, such that the position of the source relative the receiver is known at all times, critical when towing multiple arrays of several kilometres in length (Fig. 2.2).

Once obtained, raw seismic reflection surveys must be processed before they are ready for interpretation. The purpose of processing is refining the seismic data enhancing the acoustic signal, removing noise and filtering any physical effects that degrade the data (Sheriff and Geldart, 1995). Noise in the seismic data comprises components of the seismic waveform generated during the collection of the surveys but not relevant to geological interpretation (Kearey et al., 2009). This may be due to surface conditions, side scatted and refracted waves.

Seismic processing comprises three fundamental primary processes (Yilmaz and Doherty, 1987), namely;

Deconvolution; performed on a time axis to increase resolution via means of compressing the seismic wavelet to a spike supressing reverberating wave trains. This process removes distortion from the data increasing the signal to noise ratio and improving resolution.

Stacking; compressing the offset dimension hence reducing seismic data volume relative to the plane of the seismic section and furthermore increasing the signal to noise ratio.

Migration; performed on stacked sections to increase lateral resolution by means of collapsing diffractions and shifting dipping events to their true subsurface position. Other important processing phases include;

Static correction; comprises a bulk shift of a seismic trace to compensate for low seismic velocity material at or near to the earth’s surface, in particular heavily weathered that usually has altered acoustic properties in comparison to less affected deeper material. This correction also compensates for topography, heterogeneous lithologies and any external acoustic sources (Bacon et al., 2003)

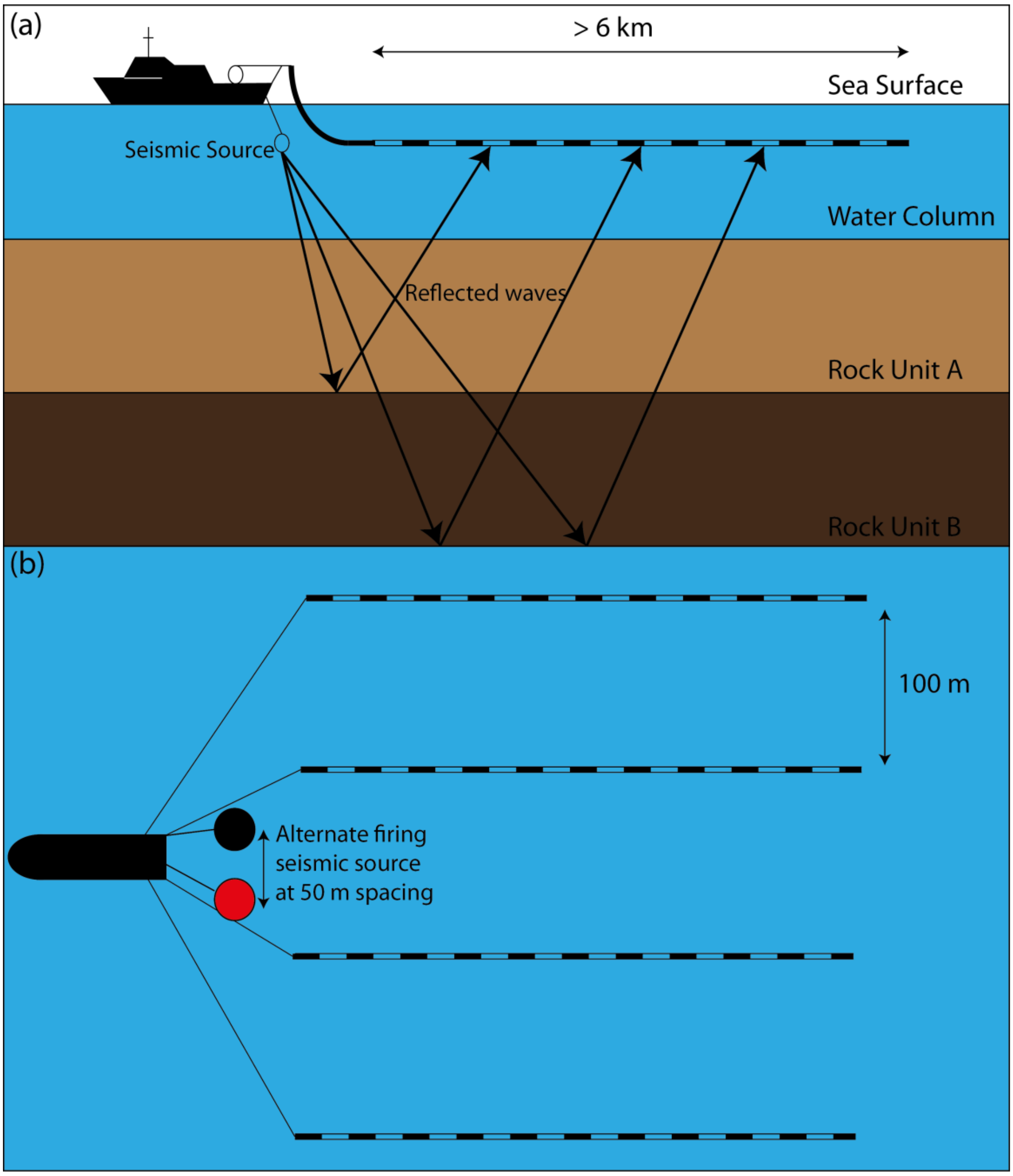

Fig. 2.2: Simplified cartoon of the basis of marine seismic acquisition. (a) As the boat travels along a pre-determined course, the air gun source is fired at known timings, emitting acoustic waves. These waves propagate through the water column and subsurface where they are reflected back of acoustic interfaces and recorded by the receivers towed behind the vessel. (b) For 3D acquisition a multi-source, multi-streamer system is used where the black and red sources fire alternately allowing multiple lines to be collected, in this case at 25m line spacing. Modern vessels are capable of deploying up to 12 streamers of 12km in length (after Bacon et al, 2003). Diagram is not to scale.

Normal moveout; compensates for the separation in travel time between the wave source and receivers for horizontal reflections (Sheriff and Geldart, 1995).

Dip moveout; compensates for the separation in travel time between the wave source and receiver for dipping reflectors (Yilmaz and Doherty, 1987).

The seismic data used in this thesis were supplied processed with no further processing required prior to interpretation. A full processing history of all of the seismic data was not available and consequently all details pertaining to the data parameters remain as either best estimates or where possible, measured using tools built into the interpretation software.

All seismic data in this thesis is displayed using the Society of Exploration Geophysicists (SEG) normal convention, or positive standard polarity. Thus an increase in acoustic impedance with depth is displayed as a positive wavelet as the seismic wave travels from a low velocity and low density medium to a high velocity and density medium. Inversely, a decrease in acoustic impedance with depth as the wave travels from a high velocity and density medium to a low velocity and density medium will result in a negative wavelet (Brown, 2004) (Fig. 2.3).

The size of the geological body that can be identified in seismic reflection data is dependent on the resolution of the data, and is limited by wave attenuation, signal to noise ratio and formation thicknesses (Bacon et al., 2003; Brown, 2004; Sheriff and Geldart, 1995).

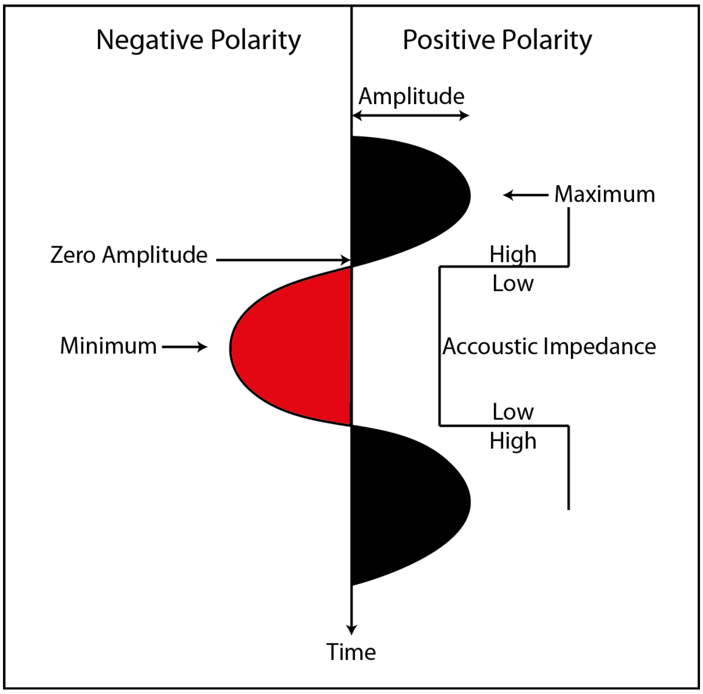

Fig. 2.3: Schematic diagram showing the polarity of seismic data and its relationship to the change in acoustic impedance across a geological feature. The polarity is recorded in SEG normal convention where black indicates a positive reflection and red a negative reflection (After Brown, 2005, Sheriff and Geldart, 1995)

A key parameter in the determination of seismic resolution is the frequency of the seismic wave that propagates through the subsurface. In general, frequency decreases with depth due to attenuation and as such seismic resolution tends to be higher at shallower depths (Kearey et al., 2009; Sheriff and Geldart, 1995). The dominant frequency and velocity of the seismic wave controls the wavelength, given by

$$\lambda = \frac{v}{f} \tag{2.4}$$

Where λ is the wavelength, v is the wave velocity through a geological medium and f is the frequency of the wave. The vertical resolution of seismic data is therefore given by:

$$vertical\ resolution = \frac{\lambda}{4} \tag{2.5}$$

And the horizontal resolution of seismic data given by:

$$horizontal\ resolution = \frac{\lambda}{2} \tag{2.6}$$

Horizontal resolution may be improved as a result of migration techniques, comprising three distinct functions, (1) the repositioning of out of plane reflections as a consequence of dip, (2) focusing of energy dispersed over a Fresnel zone and (3) collapsing of diffraction patterns from points and edges (Brown, 2004).

The seismic datasets used in this study were interpreted using SMT Kingdom Suite (Chapter 3), Schlumberger Petrel (Chapter 3) and Halliburton Landmark software (Chapter 4). The interpretation software chosen was defined by the format of the supplied seismic data. The 2D seismic surveys interpreted in Chapter 3 were supplied by Progressive Energy with permission from TGS Nopec. Surfaces created in this software were subsequently exported to the Schlumberger Petrel software to allow 3D visualisation. The 3D seismic survey viewed in Chapter 4 was supplied by Fairfield Energy as SGY data and was loaded and interpreted in the Decision Space Desktop module of the Landmark Suite.

The fundamental process of interpreting seismic data concerns the identification and mapping of specific seismic surfaces, either positive or negative, relating to a subsurface geological boundary or structure (Brown, 2004). The concept of using these reflections in order to interpret stratigraphic features, termed ‘seismic stratigraphy’ were described in depth by Vail et al. (1977). This concept is based upon the principle that seismic reflections relate to and follow the chronostratigraphic interfaces between geological units (Emery et al., 1996). Interpretation is conducted commencing with either a well pick in areas with well penetrations, or an easily definable strong continuous reflection which is then expanded to subsequent dip and strike sections. Structural features such as faults and folds are best interpreted from seismic sections perpendicular to the features strike direction (Bacon et al., 2003). In general, reflections should be conformable and not cross cut surrounding reflections. However, cross cutting reflections do occur, and are commonly caused by intrusive features such as diapirs (Koyi et al., 1995), digenesis (Davies et al., 2006), hydrates formation (Davies et al., 2012) (Taylor et al., 2000) or hydrocarbon indicators (Brown, 2004).

Specific properties pertaining to the identification of the mapped horizons discussed in the following chapters are described within those chapters and therefore will not be repeated here.

While a seismic section may closely resemble a geological cross section, it is important to note that it is only a visual representation of subsurface variations in both density and velocity. As such, seismic reflections will often comprise an amalgamation of the reflections produced from numerous individual interfaces (Sheriff and Geldart, 1995). Consequently, seismic reflection data provides a low-resolution representation the subsurface geology where the vertical component is given in time rather than depth.

2.3. WELL DATA

Seismic data alone cannot provide a complete picture of the subsurface, therefore to understand the nature and physical properties of the encountered geological formations. Therefore where available, well or borehole logs have been used for geological descriptions, core observations, petrophysical properties and measured unit thicknesses. Borehole drilling logs have also been interpreted to provide information on formation pressures and cap rock seal capacities.

The boreholes used in the study presented in Chapter 3 (Table 3.2), were obtained and viewed at the BGS borehole records archive, Gilmerton, Edinburgh (now housed at Keyworth, Nottingham) in paper and microfiche format. These logs were primarily viewed for the interpretation of reservoir facies identification, reservoir porosity and overburden and pressure profiling. The fundamental methods used employed in obtaining this information are summarised below.

Porosity was calculated from sonic velocities through the reservoir interval recorded on the composite borehole log and calculated using the following equation to give sonic porosity.

$$\varphi sonic = \frac{\Delta tlog - \Delta tma}{\Delta tf - \Delta tma} \tag{2.7}$$

Where ϕ_{sonic} is sonic porosity, Δt_{log} is the interval transit time of the formation, Δt_{ma} is the interval transit time of the formation and Δt_f is the interval transit time of the fluid in the well bore, in this case salt mud (Asquith and Gibson, 1982).

Reservoir pressure values were taken from both repeat formation testing (RFT) values, and inferred from drilling mud weights (see below).

Formation and fracture pressure profiles were calculated using the drilling mud weights plotted against depth and compared to standard values for both hydrostatic and lithostatic pressure gradients of 0.45 psi/ft and 1.00 psi/ft respectively (Fig. 2.4). Drilling mud weights, despite commonly being an overestimate of true formation pressure, can be converted from the standard unit of pounds per gallon (ppg) to psi/ft using the conversion 1 ppg is equal to 0.0511948 psi/ft, or 1.0 psi/ft is equal to 19.25 ppg.

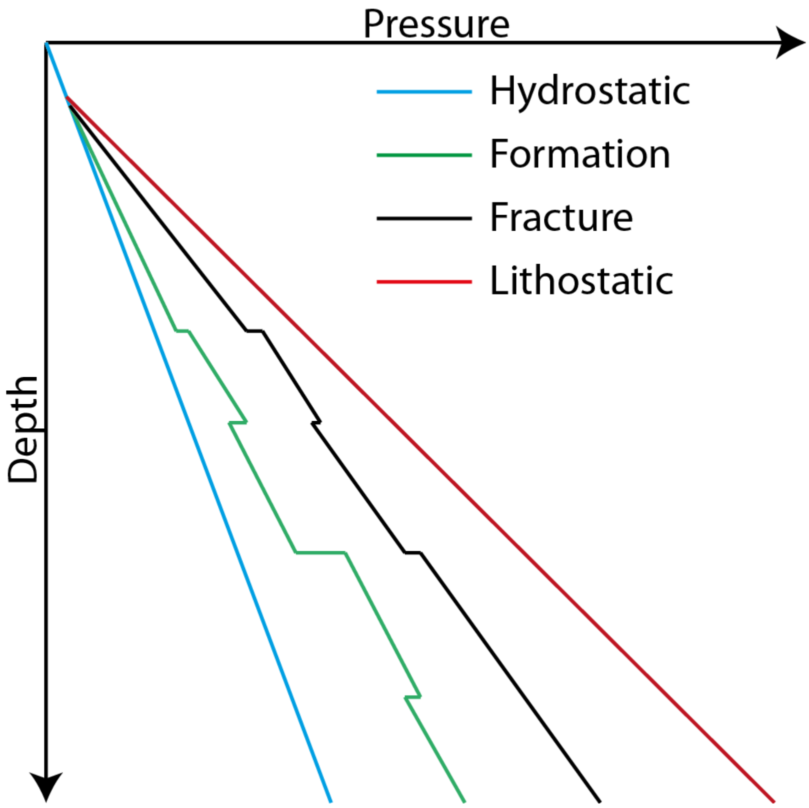

Fig. 2.4: Schematic pressure depth plot showing both hydrostatic and lithostatic pressure gradients (0.45 psi/ft and 1.00 psi/ft respectively). Formation and fracture pressure profiles may be plotted from measured values and gradients calculated from mud weight drilling profiles. The seal capacity, or maximum increase in reservoir pressure before the cap rock is compromised, may be estimated by the difference between the formation and fracture pressure plots at the depth of the reservoir cap rock interface.

Fracture pressure of a geological interval may be estimated from leak off testing results (LOT) where a well is shut in and the pressure increased by mud pumping until a decrease in downhole pressure is observed, interpreted to relate to the fracturing of the surrounding formation. The maximum mud pressure prior to fracturing is recorded as the leak of pressure in ppg, and may be converted to give and absolute pressure or a fracture gradient accordingly (Fig. 2.5) (Mouchet and Mitchell, 1989; Nguyen, 1996).

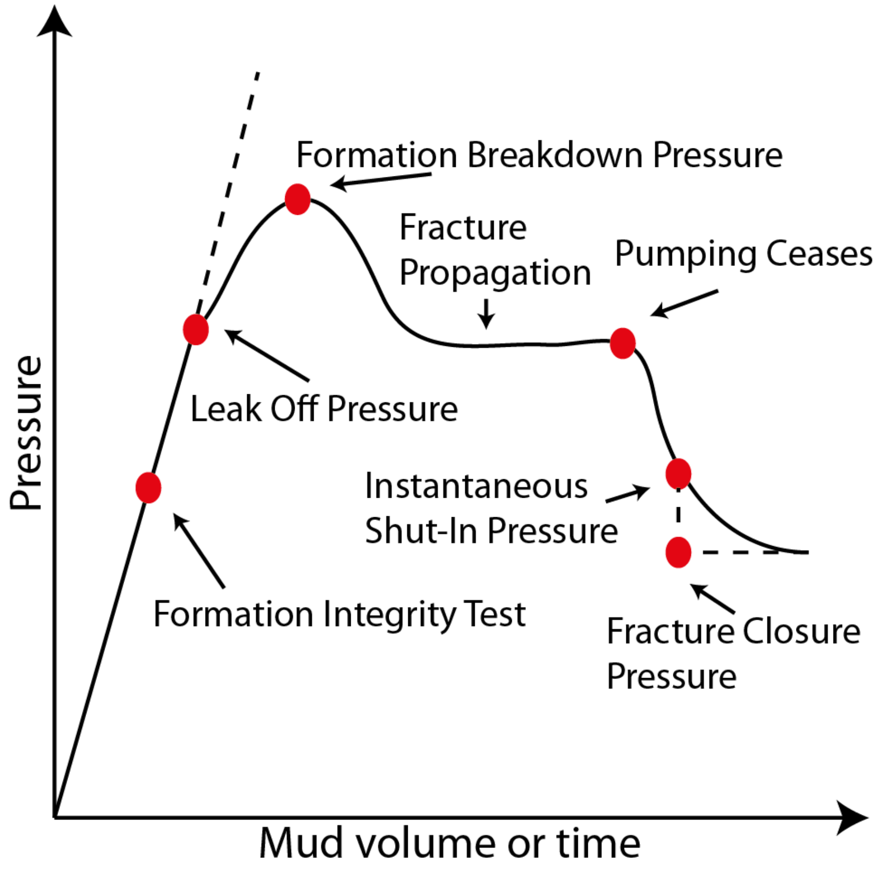

Fig. 2.5: Schematic profile of Leak Off Testing. The leak off pressure occurs when the pressure profile deviates away from a straight line gradient. This represents first development of fractures, which continues until the cessation of pumping, after which the well pressure decreases until the fracture closure pressure.

2.4. MONTE CARLO SIMULATIONS:

The study presented in Chapter 3 focuses on taking the geological information collected via the above methods, and making an assessment on the uncertainty in calculating potential CO_2 storage capacity derived from this information. For this purpose, Monte Carlo forecasting methods are employed to simulate capacity based upon a defined range of input values. Monte Carlo simulations are a commonly used method and are well documented in literature. As such, a brief summary will be presented here, however for further information the reader is directed to Metropolis (1987), Kroese et al. (2013) and Rubinstein and Kroese (2011).

2.4.1. THEORY AND HISTORY OF THE MONTE CARLO METHOD

The Monte Carlo method was conceived as a consequence of the Manhattan Project by mathematicians Stanislaw Ulam and Jon von Neumann as a statistical approach to solving the problem of neutron diffusion in fissionable materials (Metropolis, 1987; Metropolis and Ulam, 1949). At the centre of the Monte Carlo method is a statistical decisions based upon repeat random sampling in order to solve a mathematical or statistical problem (Sawilowsky, 2003). For geostatistical uses, the user may define end and or mid points for a specific function within the problem, and the random numbers will be generated based upon a probability distribution therein. For example, a normal distribution is a function that defines the probability of a number that occurs between two real numbers, such as measured minimum and maximum values (Davis, 1986).

The Monte Carlo simulations performed in this study were carried out using the Oracle Crystal Ball software. This software is a Microsoft Excel based suite of analytical tools capable of Monte Carlo simulation, forecasting and optimisation. The software is in common usage amongst the oil and gas sector for the forecasting of reserves and the assessment of risk, both technical and financial. Specific to this study is the software's ability to perform sensitivity analysis on the inputted data in order to determine which of the input variables drives the uncertainty of the reserve estimate models. These data are presented in the form of tornado diagrams, a style of bar chart that divides data categories vertically, and ordered such that the largest bar appears at the top, decreasing downwards to the smallest.

The simulations performed in this study utilised input data collated from a wider range of sources from published literature to measured downhole geological parameters. The lack of data availability directly over the study site required use of regional analogues, where geological variability necessitates the data to be presented as ranges rather than finite values. For use in Crystal Ball, these ranges must be assigned a suitable probability distribution, such that the generation of random numbers best fits the range and any skew in the data. The justifications behind the exact distributions used in this study are presented in Chapter 3, and the raw outputted report is included in Appendix 1b.

REFERENCES

Asquith, G. B., and Gibson, C. R., 1982, Basic Well Log Analysis for Geologists, Tulsa, Oklahoma, The American Association of Petroleum Geologists.

Bacon, M., Simm, R., and Redshaw, T., 2003, Three-D Seismic Interpretation, Cambridge University Press.

Brown, A. R., 2004, Interpretation of Three-dimensional Seismic Data, American Association of Petroleum Geologists and the Society of Exploration Geophysicists, v. no. 42.

Cairns, G., Jakubowicz, H., Lonergan, L., and Muggeridge, A., 2012, Using time-lapse seismic monitoring to identify trapping mechanisms during CO2 sequestration: International Journal of Greenhouse Gas Control, v. 11, no. 0, p. 316-325.

Cartwright, J., 2007, The impact of 3D seismic data on the understanding of compaction, fluid flow and diagenesis in sedimentary basins: Journal of the Geological Society, v. 164, no. 5, p. 881-893.

Chadwick, R. A., Noy, D., Arts, R., and Eiken, O., 2009, Latest time-lapse seismic data from Sleipner yield new insights into CO2 plume development: Energy Procedia, v. 1, no. 1, p. 2103-2110.

Chadwick, R. A., Zweigel, P., Gregersen, U., Kirby, G. A., Holloway, S., and Johannessen, P. N., 2004, Geological reservoir characterization of a CO2 storage site: The Utsira Sand, Sleipner, northern North Sea: Energy, v. 29, no. 9-10, p. 1371-1381.

Davies, R. J., Huuse, M., Hirst, P., Cartwright, J., and Yang, Y., 2006, Giant clastic intrusions primed by silica diagenesis: Geology, v. 34, no. 11, p. 917-920.

Davies, R. J., Thatcher, K. E., Armstrong, H., Yang, J., and Hunter, S., 2012, Tracking the relict bases of marine methane hydrates using their intersections with stratigraphic reflections: Geology, v. 40, no. 11, p. 1011-1014.

Davis, J. C., 1986, Statistics and Data Analysis in Geology, New York, John Wiley & Sons, Inc.

Emery, D., Myers, K., and Bertram, G. T., 1996, Sequence Stratigraphy, Wiley.

Ireland, M. T., Goulty, N. R., and Davies, R. J., 2011, Influence of stratigraphic setting and simple shear on layer-bound compaction faults offshore Mauritania: Journal of Structural Geology, v. 33, no. 4, p. 487-499.

Kearey, P., Brooks, M., and Hill, I., 2009, An Introduction to Geophysical Exploration, Wiley.

Koyi, H., Talbot, C. J., and Torudbakken, B. O., 1995, Analogue models of salt diapirs and seismic interpretation in the Nordkapp Basin, Norway: Petroleum Geoscience, v. 1, no. 2, p. 185-192.

Kroese, D. P., Taimre, T., and Botev, Z. I., 2013, Handbook of Monte Carlo Methods, Wiley.

Metropolis, N., 1987, The beginning of the Monte Carlo method: Los Alamos Science, v. 15, no. 584, p. 125-130.

Metropolis, N., and Ulam, S., 1949, The monte carlo method: Journal of the American statistical association, v. 44, no. 247, p. 335-341.

Mouchet, J.-P., and Mitchell, A., 1989, Abnormal pressures while drilling: Origins - Prediction - Dectection - Evaluation, elf aquitaine: manuels techniques.

Nguyen, J.-P., 1996, Drilling: Oil and Gas Field Development Techniques, Institut Francais du Petrole Publications: Editions Technip.

Posamentier, H. W., Davies, R. J., Cartwright, J. A., and Wood, L., 2007, Seismic geomorphology - an overview: Geological Society, London, Special Publications, v. 277, no. 1, p. 1-14.

Rubinstein, R. Y., and Kroese, D. P., 2011, Simulation and the Monte Carlo Method, Wiley.

Sawilowsky, S. S., 2003, You think you've got trivials: Journal of Modern Applied Statistical Methods, v. 2, no. 1, p. 218-225.

Sheriff, R. E., and Geldart, L. P., 1982, Exploration Seismology: History, theory, & data acquisition, Cambridge University Press, v. v. 1.

-, 1995, Exploration Seismology, Cambridge University Press.

Taylor, M. H., Dillon, W. P., and Pecher, I. A., 2000, Trapping and migration of methane associated with the gas hydrate stability zone at the Blake Ridge Diapir: new insights from seismic data: Marine Geology, v. 164, no. 1–2, p. 79-89.

Vail, P. R., Mitchum, R. M., and Thompson, S., 1977, Seismic stratigraphy and global changes of sea level, part 4: global cycles of

relative changes of sea level, *in* Payton, C. E., ed., Seismic Stratigraphy: Applications to Hydrocarbon Exploration, Volume 26: Tulsa, American Association of Petroleum Geologists, p. 83-97.

Weimer, P., and Davis, T., 1996, Applications of 3-D seismic data to exploration and production: AAPG Studies in Geology 42: SEG Geophysical Development Series, v. 5, p. 270.

White, D., 2013, Seismic characterization and time-lapse imaging during seven years of CO2 flood in the Weyburn field, Saskatchewan, Canada: International Journal of Greenhouse Gas Control, v. 16, Supplement 1, no. 0, p. S78-S94.

Wright, K. A., Davies, R. J., Jerram, D. A., Morris, J., and Fletcher, R., 2012, Application of seismic and sequence stratigraphic concepts to a lava-fed delta system in the Faroe-Shetland Basin, UK and Faroes: Basin Research, v. 24, no. 1, p. 91-106.

Yilmaz, Ö., and Doherty, S. M., 1987, Seismic Data Processing, Society of Exploration Geophysicists.

Zoeppritz, K., 1919, Erdbebenwellen VII. VIIb. Über Reflexion und Durchgang seismischer Wellen durch Unstetigkeitsflächen: Nachrichten von der Königlichen Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-physikalische Klasse, p. 66-84.

3. UNCERTAINTY IN STATIC CO_2 STORAGE CAPACITY ESTIMATES: CASE STUDY FROM THE NORTH SEA, UK.

ABSTRACT

We used a sub-salt Rotliegend Group sandstone saline aquifer in the North Sea as a case study site for Monte-Carlo based CO_2 geostorage capacity assessment. In the area of interest, this unit is characterised by sparse, low resolution, sub-surface data typical of the margins of global petroleum provinces, favoured for CO_2 storage. Such data scarcity leads to uncertainty regarding the complex trap geometries and ultimate CO_2 storage capacity. The Rotliegend reservoir, estimated to have porosity and permeability ranges of 11% - 27% and 0.2 mD- 125 mD respectively, is sealed by Zechstein salt. The salt, predominantly halite, is a proven hydrocarbon seal in the Central and Southern North Sea hosting oil and gas columns of >140 m (>450 ft.) and >150 m (>500 ft.). Utilising 2D-seismic data, boreholes and analogues, we estimate the pore volume of a 5 km^2 4-way dip-closed structure through Monte-Carlo based capacity simulations. We estimated storage capacity using published methodologies and compared this against a theoretical total storage calculation analogous to the gas in place equation used in the petroleum industry. We found that different methods yield a capacity range of $<10^4$ to $>10^9$ tonnes CO_2 where sensitivity analysis indicates variability in reservoir properties to be the dominant control. Thus static estimates based upon Monte-Carlo calculations present no advantage over theoretical pore volume estimations. This leaves 3D dynamic modelling of storage capacity populated by 3D seismic data and direct down-hole measurement of reservoir properties to improve confidence in capacity estimations as the recommended method.

3.1. INTRODUCTION

Optimal production from oil and gas reservoirs commonly benefits from high quality databases that include high resolution 3D seismic, borehole data and down hole production measurements, (Beardsley and Fore, 2009) allowing sub-surface geology to be characterised with a high degree of confidence (Fig. 3.1). The theoretical storage potential in deep saline aquifers is significantly greater than in oil and gas reservoirs (IPCC, 2005). However a significant proportion of this potential is in areas covered by low-resolution 2D seismic coverage with limited borehole calibration. These areas are typical of that found on the margins of global petroleum producing basins such as the southern and eastern margins of Australia,(Bradshaw et al., 2002) southwest India (Duggirala et al., 2008), margins of the Gulf of Cadiz (Lowrie et al.) and Irish Atlantic margin (Howard et al., 2009).

The development of CO_2 storage safety cases needs to provide sufficient confidence in reservoir assessment to satisfy both international and national regulatory requirements (e.g. EU Directive 2009/31/EC Annex 1). These require storage integrity and capacity, risk of leakage and the time period of storage to be assessed and quantified to a high degree of confidence before a site may be considered as a viable prospect for CO_2 storage and qualify for a storage permit.

Current literature presents two differing scenarios for calculating static storage capacity, based on whether the reservoir is closed (Chadwick et al., 2006; Ehlig-Economides and Economides, 2010) or open (Allinson et al., 2010; NETL, 2009) (Fig. 3.2).

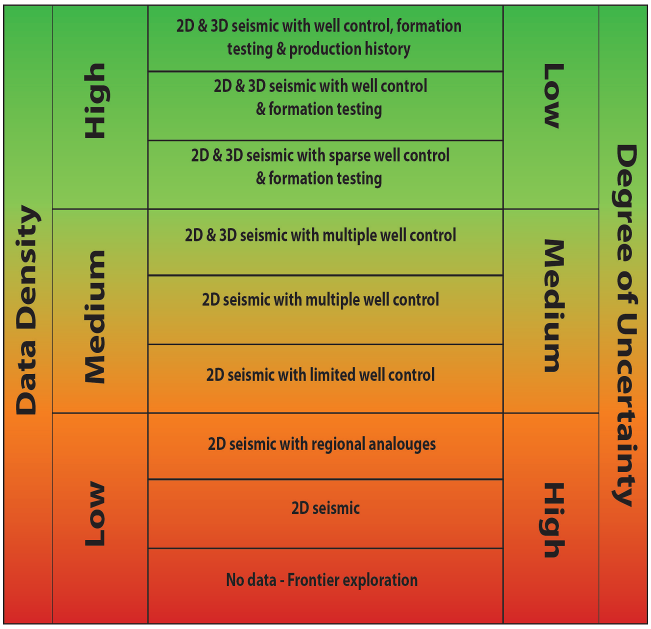

Fig. 3.1: Correlation between data density and degree of confidence in reservoir understanding. The case study site lies on the boundary between low and medium data density thus between a low and medium degree of confidence in reservoir understanding. Saline aquifer prospects for CO2 storage commonly lie in this lower region of the diagram when compared to abandoned hydrocarbon prospects that frequently rank in the high data density region. Consequently, hydrocarbon sites are often deemed more attractive despite offering less storage capacity than saline aquifers.

Where the open scenario is inferred, capacity calculations require the use of efficiency factors (NETL, 2009), a measure of what percentage of the total pore volume may be filled with CO_2 derived from the irreducible water saturation and net reservoir unit in gross rock volume. Additional parameters such as the density and gravitational effects of the injected fluid are also required.

Potential storage sites with low sub-surface data density and requiring parameters to be inferred from analogues mean uncertainties bring up the question as to whether efficiency factors are in fact a valid methodology. Whether their use is based on valid assumptions or will lead to capacity estimates outside of an acceptable range remains an open question. Where such low levels of data density and confidence co-exist (Fig. 3.1) with a significant (several orders of magnitude) range of storage capacity estimates, doubts are cast over the suitability of these sites. Thus, should these prospects be considered for immediate use for CO_2 storage? Should permit vendors demand acquisition of 3D seismic data and the drilling of test boreholes to reduce site uncertainty prior to consideration for a storage permit?

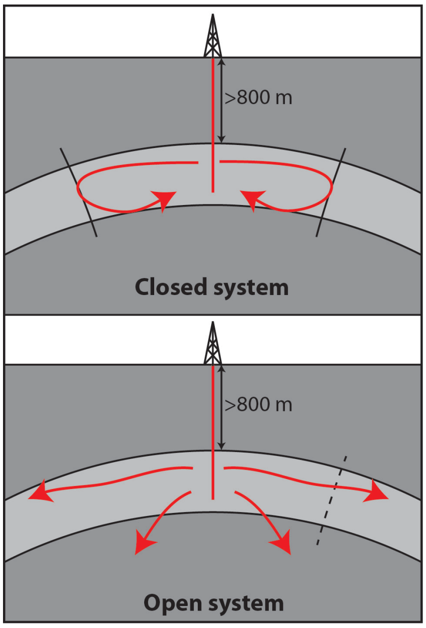

Fig. 3.2: Schematic illustrating differences between open and closed systems for CO_2 storage. Closed systems display impermeable boundaries on all sides with no potential for pressure pleading into connecting saline aquifers or formations. Open systems, despite being sealed to prevent CO_2 leakage display some permeable boundaries where pressure can bleed into adjoining formations (adapted from Zhou et al. (2008).

This study tackles the questions raised above by analysing a subsalt Rotliegend reservoir in the UK Central North Sea (Fig. 3.3) that is covered only by low resolution 2D marine seismic reflection data (typical of that found in other basin margins named above (Bradshaw et al., 2002; Duggirala et al., 2008; Howard et al., 2009; Lowrie et al.) and with scant knowledge of the size of the interconnected pore volume.

Whether the reservoir is in pressure communication or compartmentalised and thus fitting the closed (Ehlig-Economides and Economides, 2010) or open (NETL, 2009) system model is unknown. Furthermore, we investigate the suitability of current published methodologies in capacity calculations and compare these with the reserve calculations applied to conventional gas reservoirs.

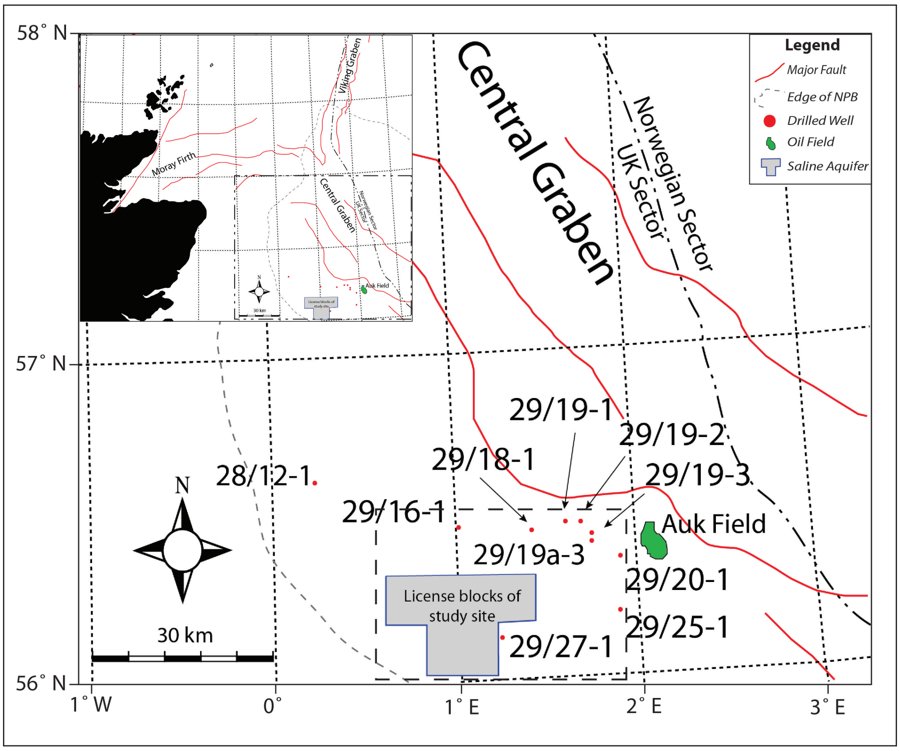

Fig. 3.3: Map indicating location of the study site within UKCS quads 28 and 29 correlated to approximate topographic extent of the Northern Permian Basin (NPB) indicated by the grey dashed line (adapted from Legler and Schneider (2008); and related to major faults (red lines) and graben of the Central North Sea. Well logs used in this study (Table 3.2) are indicated by red dots and well name. The Auk oilfield is included as an analogue for the reservoir and overburden sequence in the absence of porosity/permeability data from the study site.

The study site comprises a stratigraphic interval with numerous well penetrations within an extensively studied petroleum province. (Glennie et al., 2003). The particular interval comprises a successful play fairway couplet of reservoir horizon and overlying seal interval. We look to characterise the site in terms of suitability for CO_2 storage by assembling available data and estimating storage capacity. Key uncertainties inherent in the use of poorly explored and studied deep saline formations are highlighted and a first-pass screening workflow is developed that can be applied to other poorly understood geological formations that offer significant CO_2 storage potential.

3.2. BACKGROUND

Many methodologies for the purpose of estimating carbon dioxide storage capacity in a range of geological media have been proposed by a series of universities and governmental departments globally. Initial work undertaken by the US Department of Energy (NETL, 2009) devised a simple methodology for calculating storage capacity of regional scale saline aquifers by calculating the total aquifer volume and applying a series of Efficiency Factors that attempt to correct for the presence of geologic heterogeneity in the form of a probabilistic multiplicative sum of fractions. Significant work has been undertaken to refine and improve this approach by a number of authors (Allinson et al., 2010; Bachu, 2008; Bachu and Adams, 2003; Bradshaw et al., 2007; Chadwick et al., 2006; Goodman et al., 2011; Gorecki et al., 2009a; Gorecki et al., 2009b; Kopp et al., 2009; Zhou et al., 2008) specifically on refining the use of efficiency factors. Two commonly implemented methodologies have since been devised drawing upon the Department of Energy method (Goodman et al., 2011; NETL, 2009) and that of the Carbon Sequestration Leadership Forum (Bachu, 2008) that have been summarised by Kopp et al. (2009). A further controversial method was proposed by Ehlig-Economides and Economides

(2010) stating that geological formations acted like sealed containers and thus injection into such formations would result in a rapid pressure increase drastically reducing the potential storage volume.

While such work is necessary to shed light on the potential global storage volumes, all static capacity estimations use a series of equations that attempt to represent the complexities of geological heterogeneity and have led to wildly conflicting ranges of capacities, i.e. some national capacities exceed other global capacities (Bradshaw et al., 2007). Furthermore, all of the above methods have a focus based on basin scales. As such, the assumptions made within these methods are no longer valid or appropriate when studying an individual prospect. Put in the terms of the oil and gas sector, the published methodologies are comparable to a play fairway analysis of yet to find hydrocarbons, and conversely, this paper focuses on the site-specific prospect evaluation comparable to reserve in place estimation.

3.3. DATABASE

3.3.1. SEISMIC DATA

A total of 1208 km of two-dimensional marine seismic reflection data of various vintages (Table 3.1) were interpreted to identify potential storage sites and measure the distributions and thicknesses of key stratigraphic units. The seismic data properties vary depending on vintage, but have an inline spacing of between 1 km and 5 km and a cross line spacing of between 3 km and 10 km. The seismic dataset comprises an average vertical resolution of 35 m based upon an average sonic velocity for all lithologies of 2815 m s^{-1} calculated from the seabed to the top of the Rotliegend, and an average frequency for all surveys of 20 Hz. The data are zero phase migrated thus an increase in acoustic impedance is characterised by a red-black-red reflection combination in the seismic sections shown in this paper.

Survey	Shot date	Ownership	Coverage (approximate)
Vintage	1965 - 1992	Various	800 kms.
AH99-29	1999	Hess	500 kms.
WP-04	2004	Fugro	33 kms.
NSR-2007	2007	TGS Nopec	710 kms.

Table 3.1: 2D seismic survey vintages used in this study.

Seismic lines were interpreted using a series of key horizons and calibrated against available well control to identify stratigraphic boundaries, unconformities and reservoir and seal geometries, which define important stratigraphic and lithological units. Where possible the location of the base of the reservoir was estimated on the basis of an expected positive acoustic impedance contrast, however this was not possible on all lines due to the seismic signal attenuation sub-salt. Furthermore, it was not possible to tie this horizon against available well data and thus the base location of the reservoir cannot be treated with a great degree of confidence.

3.3.2. WELL DATA

Only one exploration well (29/27-1) has been drilled on the edge of the study site. Eleven adjacent wells (Table 3.2) are available around the site (Fig. 3.3) which allow for lithological, rock property and age calibration of the seismic data and key horizons. These wells all pre-date 1990 and are available in the public domain via micro-fiche well records. The well logs comprise stratigraphy derived from petrographic descriptions of recovered borehole rock cuttings allied to gamma ray, sonic and resistivity petrophysical logs. Limited pore pressure measurements were available from wells 29/16-1, 29/19-a3 and 29/27-1 comprising repeat formation testing (RFT) direct pressure measurements along with the pressure and density of drilling mud required to prevent an influx of pore fluid or gas into the wellbore. Pressure test data to determine the maximum allowable pressure before failure were included from wells 29/16-1 and 29/19a-3. No wells encountered oil or gas and therefore no production testing data were available. Core was available from well 29/27-1 but no other cores were accessible for analysis in this study. Where data such as porosity, permeability and other key parameters are not available, data from oil fields within 50km of the study site have been used providing they share similar stratigraphy.

Name	Year	Total Depth (m)	Base formation	Status
28/12-1	1971	2247	Rotliegend	Plugged & Abandoned
29/16-1	1973	3235	Rotliegend	Plugged & Abandoned
29/18-1	1976	3701	Rotliegend	Plugged & Abandoned
29-19-1a	1976	2352	Triassic	Plugged & Abandoned
29/19-2	1976	2951	Rotliegend	Plugged & Abandoned
29/19-3	1973	3048	Rotliegend	Plugged & Abandoned
29/19-a3	1986	3073	Rotliegend	Plugged & Abandoned
29/20-1	1973	2765	Rotliegend	Plugged & Abandoned
29/25-1	1970	3190	Devonian	Plugged & Abandoned
29/27-1	1987	2899	Rotliegend	Plugged & Abandoned
37/10-1	1969	2830	Carboniferous	Plugged & Abandoned

Table 3.2: Names and details of adjacent UKCS wells used in this study.

Data collected from wells 29/27-1 and 29/16-1 provided mud weights (the mass per unit volume of drilling fluid used to control the hydrostatic pressure whilst drilling) (Mouchet and Mitchell, 1989) used in drilling the Zechstein and Rotliegend intervals. The fracture pressure of the sealing Zechstein unit was taken from leak off test data (LOT - a test whereby the well is shut in and the pressure increased until a specific value is obtained or fractures are created within the formation (Nguyen, 1996) undertaken below the deepest set casing shoe. This maximum pressure can be estimated as the maximum allowable pressure for that formation during drilling but also as used in this case, a guide for the maximum CO_2 injection pressure that can be utilized without fracturing of the sealing unit (Nguyen, 1996).

3.4. GEOLOGICAL PERSPECTIVES

3.4.1. GEOLOGICAL SETTING

The study site is located offshore 200 km northeast of Teesside (NE England), on the southern edge of UK continental shelf quadrants 28 and 29 (Fig. 3.3). Geologically the site lies on the south-western edge of the Northern Permian Basin (Legler and Schneider, 2008). The geological evolution of the North Sea basin can be divided into five separate tectonic events (Ziegler, 1975). These comprise Caledonian and Variscan foreland basin phases, Permian and Triassic rifting stages and a Tertiary post rift phase of subsidence. It is accepted that the North Sea rift comprises a post-Caledonian graben system triggered by Devonian extension (Færseth, 1996) with active extension occurring during the Permo-Triassic and during the Middle and Late Jurassic (Davies et al., 2001; Roberts et al., 1995). The Lower Permian Rotliegend that forms the primary interest for this study was deposited in a broad east-west basin stretching from the UK onshore to Poland across the southern North Sea, and was formed as a result of thermal subsidence in the aftermath of the Variscan orogeny (Maynard and Gibson, 2001). The Rotliegend sandstones of the Central North Sea that form the reservoir for this study were deposited in a much smaller sub-basin (Northern Permian Basin) of similar orientation north of the fragmented Mid-North Sea High (Clark et al., 1998; Stemmerik et al., 2000). The thickness of these sandstones was controlled by the subsiding Danish-Norwegian basin creating accommodation space for deposition of sediment sourced from the uplifted Danish Central Graben (Stemmerik et al., 2000). Deposited of this Zechstein Group occurred within the connection between the Southern and Northern Permian Basin (Jenyon et al., 1984), to the southwest of the Central Graben.

The stratigraphy of the study site can be summarised as Devonian strata overlain by either Carboniferous Coal Measures, or directly and unconformably by the Lower Permian sandstones of the Rotliegend Group or its lateral equivalent the Silverpit Mudstone (lacustrine deposits) depending on position within the basin. This interval is overlain by the Upper Permian Zechstein Group strata comprising interbedded carbonates and evaporites. These are in turn overlain by Triassic silts and occasional sands, Cretaceous chalk and interbedded Tertiary silts and muds (Glennie et al., 2003),(Robson, 1991; Trewin et al., 2003) (Fig. 3.4).

3.4.2. CAPROCK INTERVAL

The Caprock interval for this case study comprises Upper Permian Zechstein salts with interbedded dolomites, deposited in subsiding basin conditions (Davison et al., 2000) and forming an extensive drape above the lower Permian Rotliegend Group. Adjacent well data and tied seismic data (Figs.3.6, 3.8) indicates that the Zechstein Group thickness ranges from approximately 100 m in the west and southwest, increasing to >1000 m in parts towards the east (Fig. 3.4). The low permeability Halite and Anhydrite facies is prevalent and comparable with facies observed as proven seals in adjacent oilfields, and as such provides strong evidence for a sealing caprock to the study site.

The salt shows evidence of early stage tectonic growth, due likely to burial depths of between 600 and 1000 m along with thinning of the overburden during Triassic extension (Taylor, 1998). Diapirs in the study area however are not as defined or extensive as those illustrated within the Banff Field to the north of the study area. Furthermore, such structures are not observed to penetrate further than the top of the Triassic strata reducing potential leakage pathways.

This displacement however causes adjacent localised thinning of the salt in some central and south-western sectors giving concerns over the quality of the seal in this area. Lack of well penetration within this area prevents direct identification of facies.

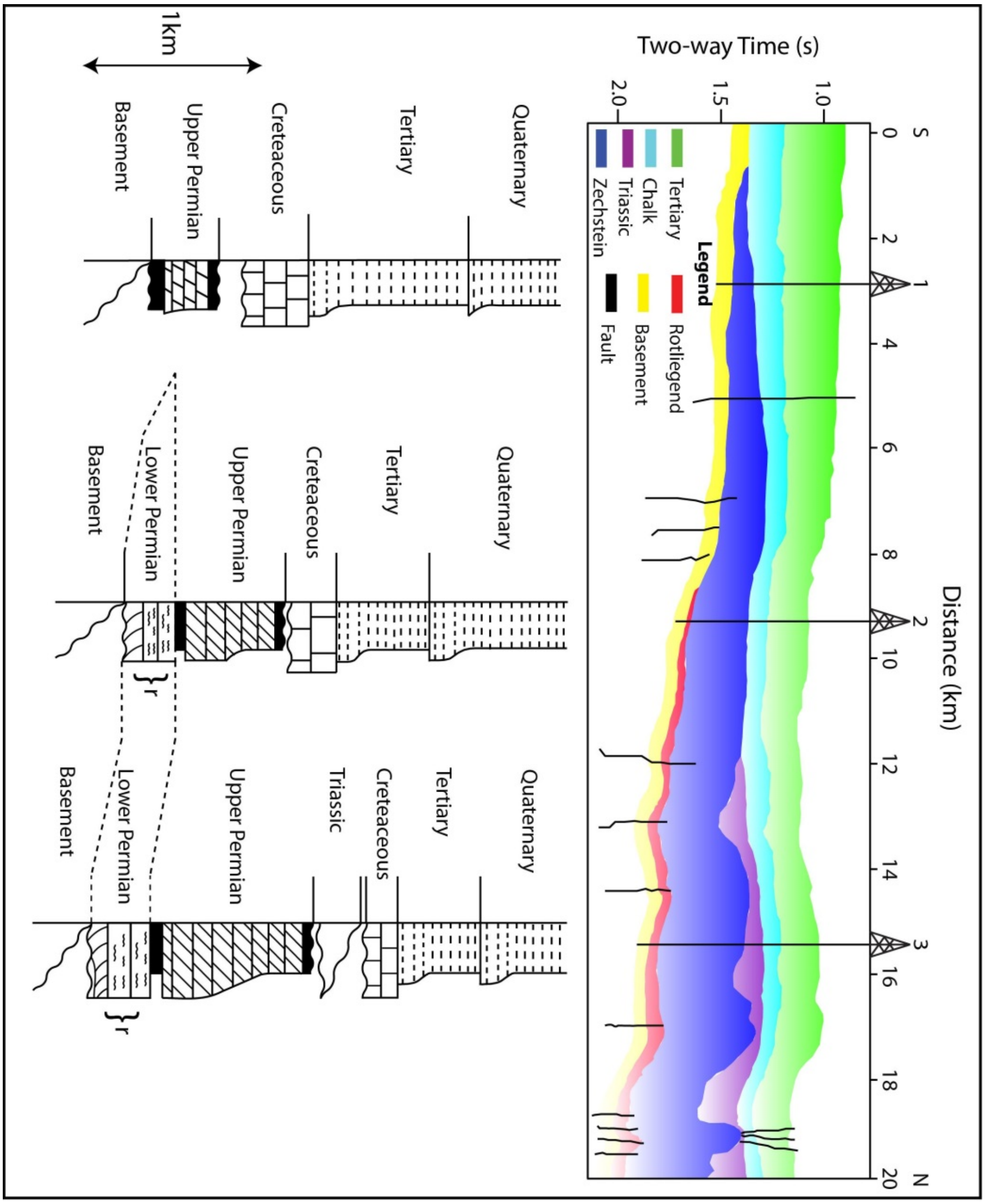

Fig. 3.4: Regional structure and stratigraphy based on regional 2D seismic line orientated south to north across the study sit. Schematic wells 1, 2 and 3 indicate the lateral variation in unit distribution and approximate variation in thicknesses. The blue Zechstein (Upper Permian) represents the cap rock succession and in observed to thin to pinch out in the south, beyond the stratigraphic pinch out of the red (Lower Permian) sandstone that represents the primary reservoir (r) for the study site.

Thus whether thickening and mobility of the salt has removed the halite/anhydrite phases from this portion of the seal leaving the dolomite exposed to potential CO_2 interaction and associated chemical reactions is impossible to directly quantify (Czernichowski-Lauriol et al., 2006). However, the chaotic nature of the seismic response and the lack of coherent seismic reflections would indicate likely presence of salt and thus these concerns are considered to be a low probability scenario.

Published sources (Glennie et al., 2003; Gluyas et al., 2005; Robson, 1991; Trewin et al., 2003) indicate Zechstein porosity at between 2% and 26% depending on sedimentary facies (generally 2 – 3% in the evaporite units and the higher 13 – 22% in the vuggy, fractured dolomite facies). Permeabilities range from 0.1 mD to 1 D again depending on facies. Drilling mud weights from well 29/27-1 indicate that fracture pressure through the Zechstein runs approximately equal to lithostatic pressure. A leak off test undertaken at the base Zechstein indicate leak off pressure of 48 MPa (7000 psi) and a seal capacity of 17 MPa (2500 psi) (Fig. 3.5).

Environment	Porosity Range (mean)	Permeability range (mD)
Aeolian Dune	12 to 25 (22)	80.00 to 1000
Fluvial sheetflood	9 to 19 (14)	1.00 to 100
Interdune sabkha	5 to 19 (15)	0.8 to 10
Fluvial channel	2 to 20 (6)	0.10 to 1.00

Table 3.3: Published Rotliegend porosity and permeability values (Selley, 1978) used in this paper in absence of measured values from drilled core in the study site. This table indicates the variation in porosity and permeability related to depositional facies. In the absence of well tie to accurately map the presence of each facies, a layered model was adopted using a most likely case scenario based on adjacent fields with similar stratigraphy.

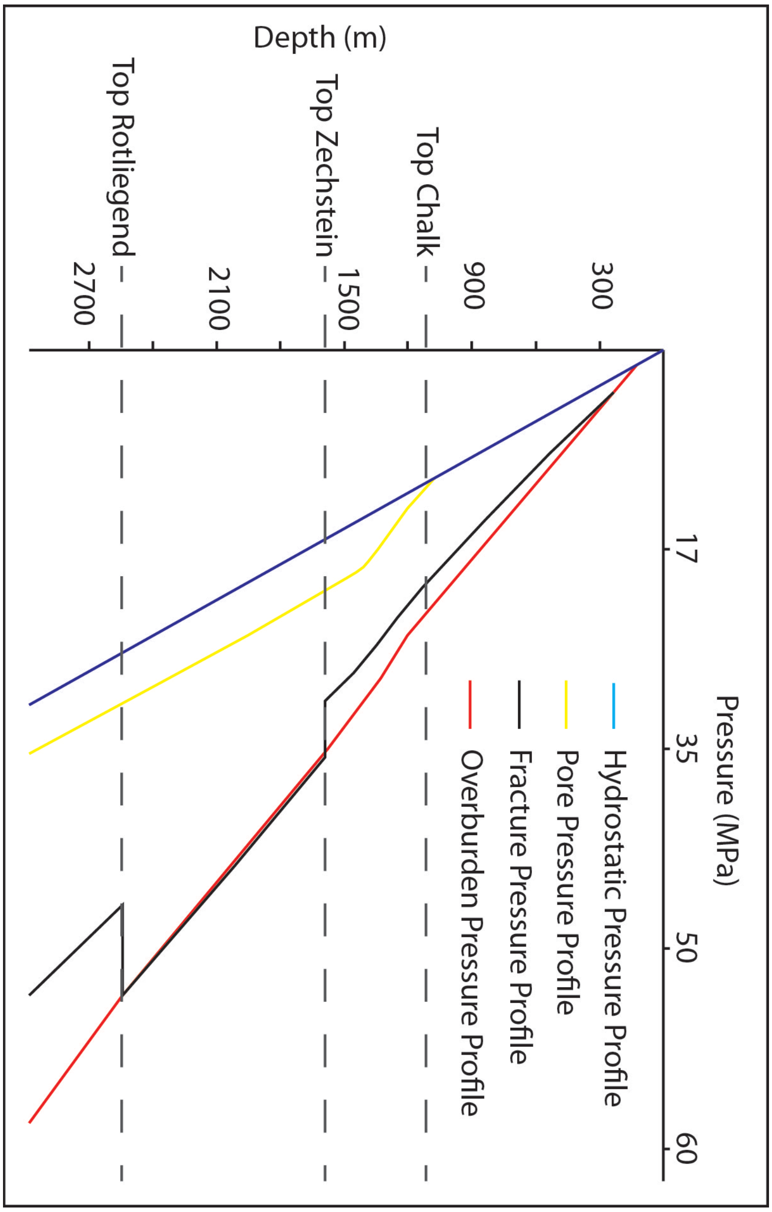

Fig. 3.5: Pressure plot using data from UKCS well log 29/19a-3 converted from PSI. Formation pressure plot is based upon pressure measurements and drilling mud weight profiles indicated that the reservoir is overpressured by c. 4 MPa (600 psi) on a hydrostatic gradient from the onset of overpressure within the Cretaceous Chalk unit. Fracture gradients calculated from leak off tests indicate a near lithostatic fracture pressure through the Zechstein salt, stepping back to c. 48 MPa (7000 psi) on entry into the top reservoir unit.

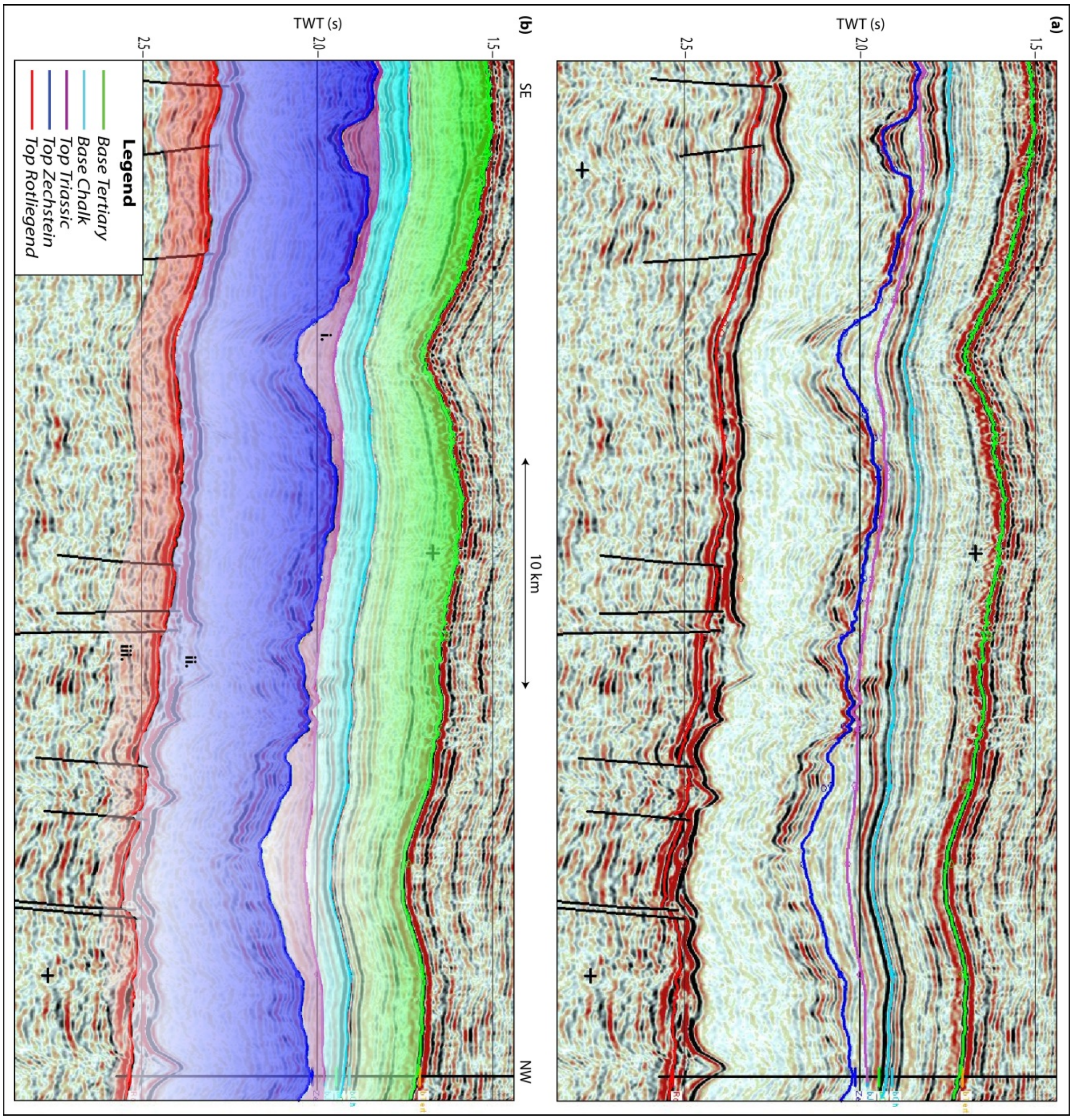

Fig. 3.6: a) seismic line trending south-east to north-west showing UKCS well 29/27-01 and well tied interpreted horizons derived from well cuttings. b) Seismic line showing variations in thickness across the study site including; i. localised thickening of the upper Zechstein halite facies, causing thinning and variable pinch out of the overlying Triassic sediments. ii. Semi-continuous high amplitude reflections caused by rafts of fractured dolomites set in the lower Zechstein halite and anhydrite facies. Iii. Attenuated basement of the lower Permian. The base reservoir is not resolvable in this survey.

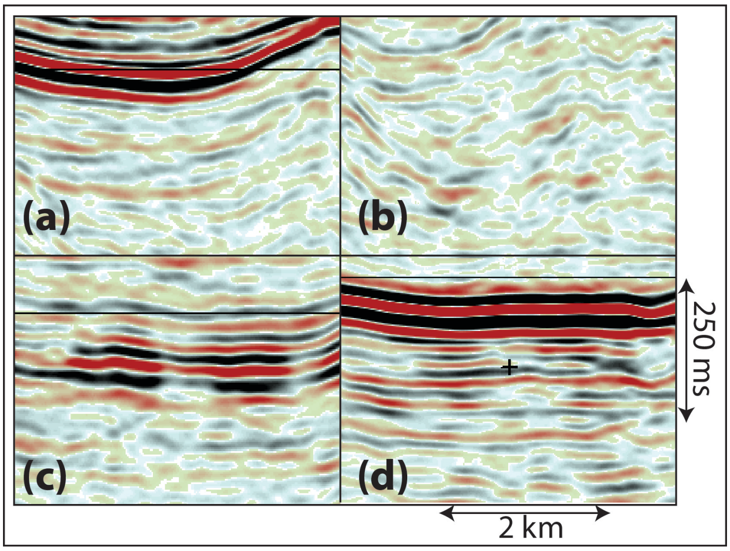

Figure 3.7: a) Seismic pick for the Top Zechstein indicated by the high amplitude continuous positive reflection above the moderate to low amplitude semi-continuous chaotic reflections. b) Seismic response through the Zechstein salt facies characterised by a series of chaotic, moderate amplitude, semi and non- continuous reflections. c) Seismic response through the Zechstein carbonate facies comprising moderate to high amplitude semi-continuous reflections set within the chaotic salt facies. This unit is often heavily fractured and deformed (Fig. 3.8.). d) Seismic pick for the Top Rotliegend unit indicated by the high amplitude continuous positive reflection above the attenuated moderate amplitude basement. The high amplitude reflections above represent the Zechstein carbonates described in c).

3.4.3. RESERVOIR INTERVAL

The reservoir interval for this study comprises sandstones of the Lower Permian Rotliegend Group. Seismic reflection profiles tied to stratigraphic formation tops derived from well log cutting descriptions (Fig. 3.6) indicate that the Rotliegend sandstone is represented by the first continuous positive reflection above the un-differentiated basement rather than the first negative reflection below the Zechstein as may be expected (Fig. 3.7(d)). Lithological descriptions from borehole logs that penetrate the Rotliegend Formation indicate that the sandstone is consistent with the dune and fluvial facies as found in the Auk reservoir and thus indicative of the presence of reservoir quality sandstone interval. These wells terminate within the Rotliegend and do not give an indication of maximum reservoir thickness. However the wells indicate that reservoir thickness must be in excess of 146 m in well 29/19-2 and in excess of 558 m in well 29/18-1. Core from well 29/19a-3 shows the reservoir rock to be reddish brown, medium to course grained, occasionally friable, laminated (~20º to bedding) sub-angular to sub-rounded, moderately sorted quartz arenite comprising >95% sub-angular milky translucent iron stained quartz consistent with that expected of the Aeolian dune facies of the Rotliegend. Localised anhydrite filling of pore and void spaces are present throughout the section (first 27 m) of the Rotliegend unit, with fracturing evident in some beds at approximately 20° – 25° to bedding. The rock is generally well cemented with some sections comprising loose sand and poorly cemented fragments of mostly <60 cm intervals.

The distribution of the Permian Rotliegend units is generally controlled by the presence of a topographic low accommodating sediments derived from adjacent upland areas (Maynard and Gibson, 2001); and thickness varies from <50 m (164 ft.) in parts of the Argyll field to >300 m (985 ft.) in the Auk field and in well logs used in this study. Pinch out of the Rotliegend is interpreted from well data to occur to the southwest of the study area, marking the edge of the Northern Permian basin (see dashed line Fig. 3.3). Data from adjacent wells and core data shows no evidence of small scale, permeability inhibiting deformation bands (Fowles and Burley, 1994 Crawford, 1998) within the Rotliegend sandstone and thus the impact of these structures has been omitted from the variables for this study.

Data collated from the adjacent Auk and Argyll oil fields in addition to porosities calculated from sonic well logs surrounding the study site indicate average porosities of 15 – 20%.

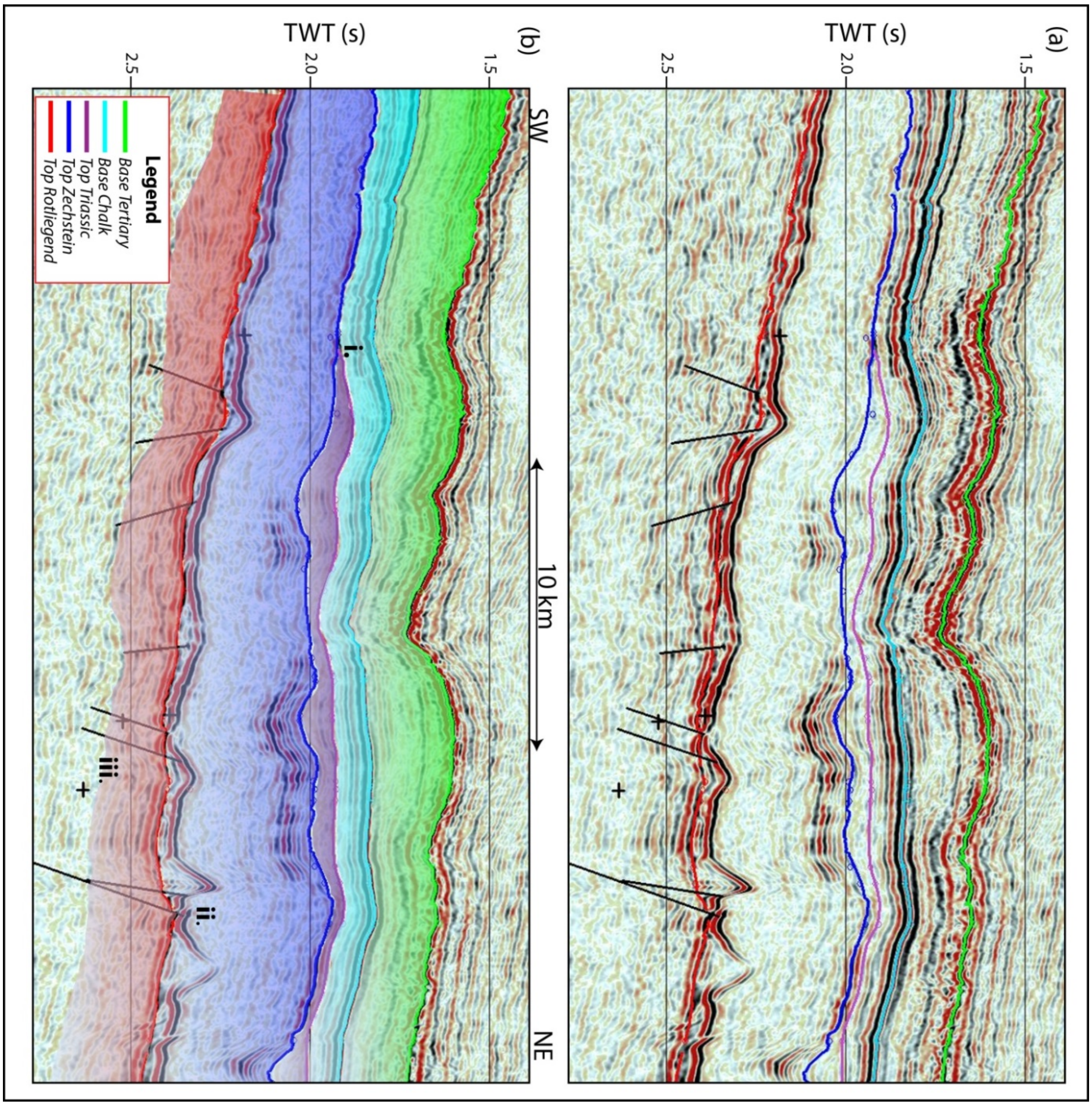

Fig. 3.8: a) Seismic line trending south-east to north-west showing UKCS well 29/27-01 and well tied interpreted horizons derived from well cuttings logs. b) Seismic line showing variations in thickness across the study site including; i. Localised thickening of the upper Zechstein halite facies causing thinning and variable pinch out of the overlying Triassic sediments. Ii. Semi-continuous high amplitude reflections caused by rafts of fractured dolomites set in the lower Zechstein halite and anhydrite facies. iii. Attenuated basement of the lower Permian. The base reservoir is not resolvable in this survey and has no proven well tie. Faulting in the lower Permian is small scale with limited offset and no sand/seal juxtaposition.

Average permeabilities for dune and sheetflood facies (Table 3.3) indicate values of 5mD (millidarcy) but range from as little as 0.1mD up to 1D (Darcy) depending on location within the Rotliegend succession (Robson, 1991; Selley, 1978; Trewin et al., 2003). Core flood data indicate permeabilities of 26 mD and 31 mD based on core samples (SCCC report C/O Progressive Energy).

3.4.4. TRAP STRUCTURE

This study focuses on three interconnected 4-way dip closed structures for preliminary injection of CO_2. These closures exist within a regional stratigraphically closed aquifer hosted within the Rotliegend Group sandstones. While the Zechstein Group represents a quantifiable caprock, it is difficult to predict the base seal for the reservoir. Regionally, Carboniferous shales and Coal Measures are present to the south of the prospect but Devonian sandstones underlay the target reservoir at this site. UKCS well 29/25-1 indicates Devonian Old Red Sandstone Formation is encountered unconformably below the Rotliegend Formation at 3106 m (10190ft) (Fig. 3.4). On condition that this observed unconformity is correct, the lack of hydrocarbons in surrounding exploration wells would suggest that, providing a stratigraphic sealing mechanism is in place, the site is underlain by Devonian strata rather than Carboniferous source rocks (Fig. 3.4). The low seismic resolution sub-salt and insufficient well penetration however makes this hypothesis difficult to quantify.

The initial phase of CO_2 injection would utilise the aforementioned 4-way dip closures where CO_2 would be trapped structurally in conjunction to residual and in solution. These structures are not thought to be sealed at the base and thus CO_2 migration beyond the spill point would flow into the larger stratigraphically closed Rotliegend Sandstone aquifer and undergo residual trapping during up dip migration offering a leakage fail safe. Moreover, the stratigraphically closed Rotliegend aquifer offers storage potential for further injection phases although the capacity of this structure has not been modelled in this study. As such, the lack of base seal quantification is not considered to be a critical uncertainty. Furthermore, access to this aquifer is considered to allow brine displacement and pressure dissipation out of the dip-closed structure, consequently reducing the impact of pressure build up within the structure.

The overburden comprises a sequence of Triassic and Jurassic clastic sediments overlain by chalk of Cretaceous age and Tertiary clastics. The Triassic strata generally comprise interbedded claystone and siltstone of Scythian age (Trewin et al., 2003) prior to mid Triassic period of erosion and subsequent unconformity. Jurassic Fulmar sandstones are observed in well logs resting on an erosional unconformity with the interbedded Triassic clay and siltstones despite not being present in the Auk or Argyll fields to the northeast. Cretaceous chalks conformably overlie the Jurassic which are in-turn overlain by an interbedded sequence of Tertiary sand and clays (Figs. 3.6 and 3.8).

3.5. METHODOLOGY

The above data were used to for the purpose of estimating the storage capacity of the storage site. Three main scenarios were highlighted for investigation using Monte-Carlo simulations. Scenario 1 investigates the total theoretical pore volume available within the reservoir and thus total theoretical capacity available for CO_2 storage; this is analogous to oil/gas in place calculations used in the upstream hydrocarbon industry.

The total theoretical pore volume may be calculated using the following equation (see Table 3.4 for definition of all variables):

$$V_{TP} = GRV.\Phi.(1 - S_{wiir}) \quad (1)$$

Multiplying the total theoretical storage volume by the density of CO_2 allows conversion from m^3 to tonnes. Thus the total theoretical CO_2 storage capacity may be calculated by:

$$SC_{TH} = GRV.\Phi.(1 - S_{wiir}).\ (\rho co_2) \quad (2)$$

Scenario 2 focused on a closed system that is confined on all sides (Ehlig-Economides and Economides, 2010) and does not allow either brine or pressure to migrate through these boundaries. As such, the storage capacity of a closed system is limited by the maximum allowable reservoir pressure increase before fracturing of the cap rock occurs (ΔP).

Term	Symbol	Unit	Description
Total Theoretical Pore Volume	V_{TP}	m^3	Volume of the total pore space of a reservoir rock theoretically available to be filled with CO_2 excluding that occupied with irriducible water saturation
Gross Rock Volume	GRV	m^3	Gross rock volume measured directly from seismic data or by multiplying the trap area by reservoir height and applying an appropriate shape factor (m^3) multiplied by the Net to Gross ratio (Fraction), the ratio of net sand within the reservoir.
Porosity	ϕ	Fraction	Pore volume within a rock expressed as a fraction of total rock volume.
Irriducible Water Saturation	Sw	Fraction	The lowest water saturation that can be achieved in a core plug under laboratory conditions. Expressed within equations a 1 minus irriducible water saturation to represent pore water that is theoretically able to be displaced.
Total Theoritical CO_2 Storage Capacity	SC_{th}	Tonnes (t)	Total storage capacity of a reservoir theoretically achievable if CO_2 occupied all theoretically avialble pore space.
CO_2 Density	ρCO_2	kg/m^3	Density of CO_2 at reservoir temperature and pressure.
Stored CO_2	SCO_2	t	Volume of CO_2 that can be stored in the reservoir.
Allowable Pressure Increase	ΔP	Mpa	Allowable pressure increase between background reservoir pressure and cap rock fracture pressure.
Total Compressibility	Ct	-	Compressibility of residual brine (Cw) and compressibility of the reservoir rock (Cr where Cr = (1/-2.141x10-2 + 4.064x10-2 (Ø)0ew.4652) x10-6 1/psi).[28] Ct = Cw + Cr.
Factor of Storage Efficiency	E	Fraction	Efficiency factor that represents the multiplicative combination of volumetric parametres reflecting the portion of a reservoirs pore volume that CO_2 is expected to contact.

Table 3.4: Nomenclature used in storage capacity calculation

Storage capacity of a closed system as defined by Chadwick et al. (2006) may be calculated by the following equation:

$$S_{co2} = GRV.\Phi.(\rho_{CO_2}).\Delta P.C_t \qquad (3)$$

Scenario 3 investigates open systems (NETL, 2009) where ΔP is omitted due to ability of the reservoir brine to be displaced outside of the primary reservoir (i.e. Fig. 3.2) removing the influence of the ‘sealed box’ pressure cell effect as demonstrated in Scenario 2. However, although pore scale displacement effects are incorporated into the efficiency factor (E), the dynamic effect of pressure increase around the wellbore is not modelled in the static solution. While pressure build up will occur in all formations on injection of a mass and thus potentially limit usable capacity, it is the purpose of these methods to assess the theoretical total static capacity of a porous formation. The injectivity of a formation, and thus the usable storage capacity has been studied extensively by Mathias et al., (2009a; 2009b; 2011; 2013), however requires input data not readily available in basin margin settings and as such is not modelled in this paper. As such, the storage capacity of an open system as defined by the United States Department of Energy can be calculated using:

$$S_{co2} = GRV.\Phi.(\rho_{CO_2}).E \qquad (4)$$

The efficiency factor (E), defined by the US Department of Energy (DoE) (NETL, 2009) as ‘the multiplicative combination of volumetric parameters that reflect the portion of a basin's or region's total pore volume that CO_2 is expected to actually contact. The terms defined for calculating efficiency by the DoE are generic and thus need modification prior to use in site specific capacity calculations to give a realistic representation of the expected formation. Detailed examination of the variables utilised by the US DoE indicates that the method of calculating efficiency (E) can be expanded to remove variables representing net to gross ratio and irreducible water saturation into a gross rock volume calculation.

Thus, the CO_2 storage capacity of an open saline formation can be calculated:

$$Sco2 = GRV.\Phi.(\rho_{CO_2}).(1 - S_{wirr}).E \qquad (5)$$

Using formulae 2, 3 and 5, Monte-Carlo simulations were run using the Oracle Crystal Ball forecasting simulator for each system type. An iterative process of Monte-Carlo trials was undertaken using 20 000 trials as a starting point increasing until no significant changes occurred. Consequently, a total of 1 million trials were used as an optimum between both accuracy and computational run time.

Areal extent and crest to spill depth were measured directly from the seismic data using the planimeter function within the SMT Kingdom software and measured depth to spill point to calculate reservoir volume (area x thickness). This was combined with net:gross values for the purpose of calculating gross rock volume. Values of net:gross were varied within the GRV calculation using a modal value of 80% based upon a regional average from adjacent oilfields with a minimum and maximum of 60% and 100% respectively. This was inputted into the Monte Carlo simulation via use of a triangular probability distribution, constrained by the minimum and maximum, and carried about a most likely value where a ≤ c ≤ b. This was chosen to represent to uncertainty and thus was preferable to a uniform distribution which implies all intervals are equally probably.

Porosity taken from published literature (Table 3.3) was varied around minimum and maximum values of 10% and 30% respectively using a normal distribution to account for the variability of average values plotting between 15% and 25%. A normal distribution was chosen over a log normal or stretched beta distribution to avoid skewing the distribution to either the negative or positive extent, reflecting the lack of an observed skew in the available analogue data.

Site-specific irreducible water saturation values were not available and thus a triangular distribution was used based upon published literature using minimum, maximum, and mode values (Table 3.5). A triangular distribution was used over a normal distribution to give a continuous range of values constrained by the two end members (a normal distribution may extend beyond the end members unless clipped) allied to a most likely outcome.

The closed storage scenario (eq 3) requires the maximum increase in pressure between fracture and reservoir pressure to be defined. An overpressure study performed as part of a commercial CCS feasibility study indicated a best, worst and most likely case scenario (Table 3.5). Pressure was calculated via a normal distribution, chosen over stretched beta/log normal and triangular as it avoids a positive or negative skewing of the input data.

The open storage scenario (eq 5) utilises the efficiency factor described previously but otherwise embodies the formula used in calculating total theoretical capacity. For efficiency factor, in place of the DOE sum of a series of multiplicative fractions for generic variables, this paper uses published values for effective reservoir sweep(2004; Richard G. Hughes, 2009) efficiency using a minimum and maximum value varied via a normal probability distribution (Table 3.5).

Input	Units	Min	Max	Mean	Mode	Distribution	Notes
ϕ	Fraction	0.07	0.30	-	-	Normal	Estimation of min and max porosity for all Rotliegned Facies collated from literature (Table 3)
GRV	m^3	4.43×10^8	6.65×10^8	5.54×10^8	-	Trianglar	Calculated GRV from reservoir areal extent, trap height & N:G ration varied from 60% to 100%
Swiir	Fraction	0.10	0.30	-	0.2	Trianglar	-
ΔP	Mpa	13	23	-	17	Normal	Minimum & maximum seal capacities representing minimum & maximum allowable pressure increase
E	Fraction	0.1	0.35	-	-	Normal	Estimated minimum and maximum published reservoir sweep efficiencies

Table 3.5: Input parameters, values, distribution and justifications for variables used in Monte-Carlo storage capacity simulations.

3.6. RESULTS

Results of the Monte-Carlo simulations indicate that the storage capacity varies greatly depending on whether the system is treated as closed or open. For a closed capacity system the results indicate tenth percentile (P10) base case of 1.3x 10^6 tonnes of CO_2 with dominant frequency results of 1.7 x 10^6 tonnes of CO_2. The 90th percentile (P90) for this system indicates a maximum storage capacity of 3 x 10^6 t of CO_2. When the system was treated as an open system, the results and thus storage capacity shifted significantly with a P10 value of 7.95 x 10^6 tonnes and a dominant frequency value 13 x 10^6 tonnes and P90 indicates storage capacity of 28 x 10^6 tonnes CO_2. Comparisons against the total theoretical storage shows results an order of magnitude greater than that of either the closed or open scenario, with P10 and P90 results of 42 and 112 x 10^6 tonnes, respectively (Fig. 3.9, Table 3.6).

The differences in calculated storage capacities between the three modelled scenarios were more substantial than expected. Further sensitivity analysis (Fig. 3.10) was employed to assess the impact of specific variables within the equations. Scenario one, the calculation of total theoretical storage, indicated that porosity variability has the greatest impact (93.1%) on reservoir capacity. It appears anomalous that porosity alone should have greater impact on storage capacity than gross rock volume (GRV). However, logically due to the high net:gross ratio of the reservoir and well constrained trap areal extent, GRV has a relatively minor variation and more certainty attached to input variables. Porosity conversely, is poorly constrained and as such less certain than GRV. As the key control of net poor volume, but separate to the GRV calculation (A.H.NTG), this uncertainty in input translates directly into total capacity estimation.

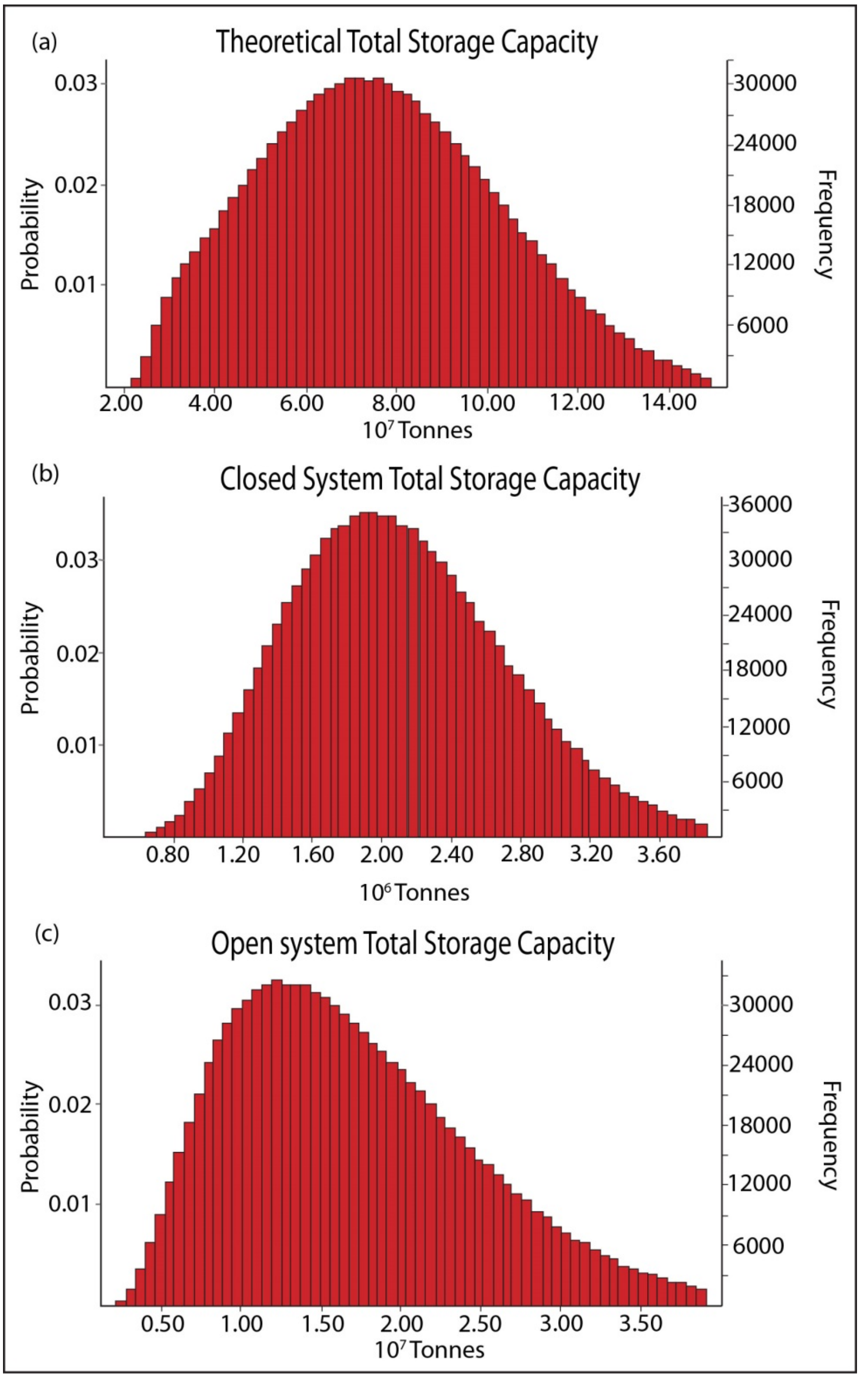

Fig. 3.9: a) Results graph from Monte Carlo simulations plotting theoretical CO_2 storage capacity against frequency. b) Results graph from Monte Carlo simulations plotting CO_2 storage capacity against frequency for a closed reservoir scenario. c) Results graph from Monte Carlo simulations plotting CO_2 storage capacity against frequency for and open reservoir scenario.

Sensitivity in closed storage scenarios indicates that although porosity remains the dominant control, impact is more evenly distributed between porosity and GRV (50.5% vs. 42.2% respectively). This contrast with regards to the previous scenario is deemed a result from the structuring of the two equations. Scenario one in essence calculates total available pore space that may be filled with CO_2 whilst Scenario 2, although still calculating volume of CO_2 able to be stored within that pore space, examines the effects of pressure and the ability of both rock and brine to be compressed directly impacting upon the bulk rock rather than pore space alone. It is surprising that allowable pressure increase does impact upon the sensitivity analysis despite common consensus and published literature (Chadwick et al., 2006; Ehlig-Economides and Economides, 2010) dictating that it is one of the key parameters.

The equation used in this paper calculates static capacity and therefore capacity at a randomly calculated reservoir pressure between natural reservoir and fracture pressure. As such, while the limitations of confining pressure are included and reservoir pressure exceeding fracture pressure is not allowable, this scenario investigates the whole reservoir and not isolated portions.

Short term dynamic effects such as isolated abnormal high pressure spikes around the well bore are not modelled as these constitute a reservoir engineering challenge that may be investigated statically (see Mathias et al., (2009a; 2009b; 2011; 2013), or dynamically on obtaining reliable downhole formation testing data.

System scenario results: Total Storage Capacity (10^6 tonnes)

Percentile	1: Theoretical	2: Closed	3: Open
P0	19.50	0.48	2.19
P10	42.50	1.30	7.95
P20	52.60	1.60	10.10
P30	60.80	1.70	12.10
P40	68.00	1.90	13.90
P50	75.00	2.10	15.90
P60	82.20	2.20	18.00
P70	89.90	2.40	20.50
P80	91.10	2.60	23.50
P90	112.00	3.00	28.00
P100	178.00	5.40	57.80

Table 3.6: Results in percentiles of Monte-Carlo based storage capacity estimations for theoretical, closed and open storage scenarios.

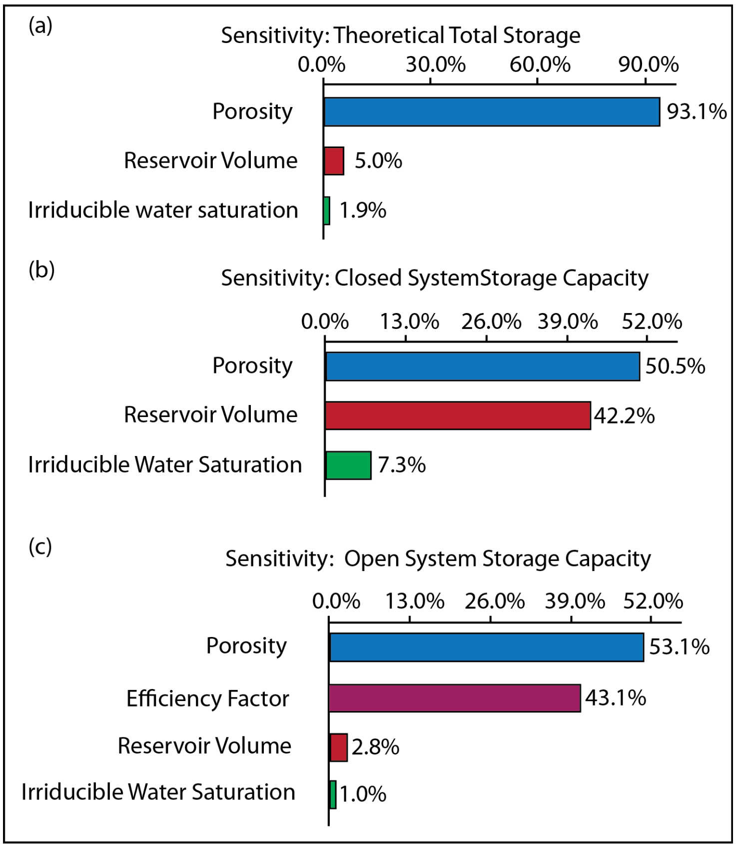

Fig. 3.10: Tornado charts showing relative impact of variables from sensitivity analysis undertaken on capacity estimation Monte Carlo simulations. Note that while all relevant variables stated in Table 3.5 were included, only those with an impact of >0% are displayed in this figure.

Furthermore, although having a confining effect on storage capacity, the seal capacity of the reservoir indicates that reservoir pressure may be increased by between 74% and 83% above initial reservoir pressure. In consequence, for this storage site, it is proposed that the confining effects of pressure build up are not as independently restrictive to total storage volume as factors that restrict the total effective pore volume. Nevertheless, the combined effect of these variables results in a reduction of storage capacity when compared to open or theoretical scenarios.

The above sensitivities are reflected in the shape of the outputted distributions for the three scenarios (Fig. 3.9). Although all curves are Gaussian in appearance, the distributions are log normal and skewed to the lower to mid-range of storage capacity estimates. It is likely that this represents the relatively low probability that of the modelled input values, all will be favourable.

Scenario 3 is structured in a form analogous to Scenario 1, where both porosity and sweep efficiency are used to calculate net pore volume available to be filled with $CO_{2.}$ Thus sensitivity analysis indicates that both porosity and efficiency factor rank as the most significant variables. GRV is not classed as significant, likely due to the relative lack of variability in areal extent and net:gross ratio.

3.7. DISCUSSION AND IMPLICATIONS

The importance of whether the reservoir unit is closed or open has significant implications for the storage capacity of this site. Results for the closed system indicate that the most probable capacity is likely to be in the region of 0.1 to 1 x 10^6

t of CO_2. Put in perspective of the required annual storage of 2.5 x 10^6 t CO_2 pa. from a midsized power station, a closed system would be unable to handle more than 6 months injection before the reservoir pressure exceeded the seal fracture pressure of 48 MPa. However, in the case of the open system, depending on exact physical properties such as porosity and thickness, using the same annual storage requirements, the site would be able to sequester between 30 and 250 years' worth of CO_2 from onshore CO_2 sources.

It is unlikely in the geological setting of the Central North Sea to have a completely open system in its most basic definition due to the structural history and the influence to the Central Graben fault network (Glennie and Underhill, 1998). Moreover, the assumptions in assuming a fully sealed closed system as proposed by Ehlig-Economides and Economides (2010) have since been widely discredited by a number of authors (Cavanagh et al., 2010; Chadwick et al., 2010). Comparable reservoir overpressure values taken from wells surrounding the study site indicate that the reservoir is in pressure communication at least over geological time; the storage capacity estimates based upon the closed system scenario are not deemed to be appropriate for this storage site and thus are considered to represent a 'worst case scenario'.

In this case, the lack of well data penetrating the reservoir and indeed the underlying base seal allied to poor seismic data quality, results in potentially significant inaccuracies in the required input parameters used for this study. While it is expected that further reservoir interval occurs below the spill point of the structure, should it be found that the system boundaries are of low permeability, pressure dissipation will be inhibited across them. Thus, pressure build up on injection around the well location by well number and design (Mathias et al., 2011) would require strict control resulting in a detrimental effect on injection rate and an increase in the number of wells required.

With regards to the equation for calculating closed storage capacity as defined by Chadwick et al., (2006) sensitivity analysis indicates that allowable pressure increase does not constitute a significant variable, a result at odds with numerous authors (Chadwick et al., 2006; Ehlig-Economides and Economides, 2010; Mathias et al., 2009b) due to the poorly constrained porosity and GRV data and the 74% to 83% allowable pressure increase. Whilst this is the case for this study where a seal capacity represents an allowable pressure increase of 74% to 83%, this may not be the case in tight gas or significantly overpressured reservoirs, which require further investigation. Furthermore, static methods pose significant shortcomings in that dynamic pressure spikes caused by injection are not modelled and as such represent only a total capacity per maximum pressure value and are not representative of injectivity.

Current methods of calculating static storage capacity in saline aquifers vary but all depend on capacity or efficiency factors, a numerical coefficient that converts theoretical storage capacity (i.e. 100% of available pore space) to probable capacity, analogous to a recovery factor deployed in oil and gas in place estimates. The US DoE NETL Atlas (NETL, 2009) utilises an E-factor of 2%, however it is based on capacity calculations for aquifer systems that cover hundreds of square kilometres and thus we consider such input values cannot be deemed accurate or appropriate on smaller scale prospects. For example, the parameter ‘fraction of total basin/region area that has a suitable formation present’ may be considered to be 100% on a prospect scale that has been thoroughly investigated, rather than the 20% – 80% range used by the Atlas.

Recent authors (Gorecki et al., 2009a; Kopp et al., 2009) have refined the input parameters over those used within the original methodology to remove these regional scale variables. Despite this modification, efficiency factors improve only by a value of 8% pointing to a flaw inherent in the method, i.e. multiplying a fraction by a further fraction resulting in an ever decreasing value. Where sufficient data are available, the method of calculating efficiency by relying on dynamic reservoir simulations requiring irreducible water saturation values as detailed by Gorecki et al. (2009a; 2009b) and Allinson et al. (2010) would appear to give more accurate results based upon a site-specific basis and result in estimated E factors of up to 16.5% for thin low permeability reservoirs, and up to 25% 4-way dip closed structures.

To quality control and contextualise the efficiency factors calculated both within this paper and previously published literature, the storage capacity equation was re-arranged with respect to the factor of efficiency, E_{geol}. Using published production data (Gluyas et al., 2005; McCrone, 2003; Robson, 1991; Stuart, 2003; Trewin and Bramwell, 1991; Trewin et al., 2003) from a range of North Sea oil and gas fields, E_{geol} was back-calculated by substituting total production of oil or gas and density of oil/gas for effective storage capacity and density of CO_2 respectively. This equation therefore calculates efficiency as the percentage of gross rock volume vacated by the produced hydrocarbons working on the hypothesis that pore fluid (oil, brine and gas) out must be less than or equal to the potential material injected. Although not a true representation for reservoirs with aquifer drive or where associated gas/water production is unknown, results indicate the value of efficiency varies considerably from <2% in tight oil reservoirs to >75% in gas reservoirs (Table 3.7).

Field	Field Type	Efficiency Factor (%)
Davey	Gas	70.67
Bessemer	Gas	71.03
Innes	Oil	11.5
Auk	Oil	0.57
Armada	Wet gas	7.68

Table 3.7: Efficiency factors, calculated as a percentage of gross rock volume vacated by produced reservoir fluids for a series of Rotliegend hosted North Sea gas, oil and gas condensate fields.

Complex published analytical methods for calculating static capacity may provide more accurate results due in part to non-reliance on efficiency factors. Application to low data density sites however requires further use of analogue data that does not account for lateral geological heterogeneity and thus is considered to only introduce further uncertainty and inaccuracies into already imprecise calculations.

The capacities presented in this study are relatively modest when compared to the total for the Central North Sea presented by the Energy Technologies Institute (ETI) (Total storage study PMax 178 Mt vs. ETI 40000 Mt). However, it is important to consider that this is based on one relatively small 4-way dip closure. The underlying stratigraphic trap within the study area indicates a PMax of c. 12000 Mt, representing over 30% of the total Central North Sea storage capacity.

3.8. CONCLUSIONS

The key uncertainty highlighted in this study is one of limited well and seismic data. The lack of well log data from within the storage site and indeed reservoir unit requires all static modelling input variables to be based on inferred assumptions from adjacent data. Sensitivity analysis indicates porosity to be the primary uncertainty in all capacity estimations. As such, site specific measurements allowing porosity to be constrained to 5% variation rather than 20% presented here would likely constrict the range of storage capacity estimates. Likewise, direct net:gross measurement in conjunction with 3D seismic data would restrict the variability of GRV.

Primary analysis of the storage capacity results detailed in this paper suggests that the most significant control on the storage capacity of deep saline formations is the ability to accurately classify the pressure system type present in the reservoir (i.e. Fig. 3.2). Whilst in a purely hypothetical model based scenario the closed pressure cell method has merit, experience of reservoir engineering techniques used in the oil and gas industry, drilling of pressure relief wells and formation water production (Jr., 2004; Malik and Islam, 2000) render this method unsuitable for storage capacity estimations in geological circumstances addressed in this paper.

When the more likely open system scenario is applied, further uncertainty is produced by the use of efficiency factors. It is proposed that this method is highly conservative and unsuitable for site specific calculations. Authors (Allinson et al., 2010; Kopp et al., 2009) have indicated that the variables relating to net area and net reservoir lithology may be omitted in site specific calculations where values equal 100%. Further to this we have shown that when dealing with 4-way dip closed reservoirs that may be filled to spill, buoyancy and gravity factors are invalid as the purpose is to calculate the total capacity and not at a given point during injection. Consequently is realistic that with brine production techniques, the available storage volume is equal to the total pore volume multiplied by one minus the irreducible water saturation. Under reservoir conditions, irreducible water saturation is unlikely to be obtained and thus an estimate of sweep efficiency is used to account for un-swept portions of the reservoir where geological heterogeneity may block internal reservoir connectivity. Back calculation from oil and gas field production data indicate that produced material may account for between 2% and 75% of total pore space leading to un-acceptable variation in storage capacity depending purely on which ‘best estimate’ of efficiency is implemented.

For sites afflicted by low data density, the uncertainty inherent in inferred input variables, shown in this case by sensitivity analysis to be porosity over reservoir volume, multiplied by the uncertainty intrinsic within efficiency factors results in an unacceptable range in storage capacity estimates.

Therefore we propose that for basin margin prospects with sparse data, a Monte-Carlo based P10, P50, P90 theoretical capacity estimation has less uncertainty than the efficiency based model. This figure may be refined by dynamically modelling the storage complex once the first stage of site appraisal has been completed, namely by obtaining at a minimum 3D seismic data and the drilling of one formation appraisal well allowing site specific measurements of reservoir pressure, porosity/permeability and temperature.

REFERENCES

2004, CO2 storage scenarios in North Germany. GESTCO project case studies: Bundesanstalt für Geowissenschaften und Rohstoffe.

Allinson, W. G., Kaldi, J. G., Cinar, Y., and Paterson, L., 2010, CO2 Storage Capacity â" Combining Geology, Engineering and Economics, SPE Asia Pacific Oil and Gas Conference and Exhibition: Brisbane, Queensland, Australia, Society of Petroleum Engineers.

Bachu, S., 2008, Comparison between Methodologies Recommended for Estimation of CO2 Storage Capacity in Geological Media: CSLF Task Force on CO2 Storage Capacity Estimation and the USDOE Capacity and Fairways Subgroup of the Regional Carbon Sequestration Partnerships Program.

Bachu, S., and Adams, J. J., 2003, Sequestration of CO2 in geological media in response to climate change: capacity of deep saline aquifers to sequester CO2 in solution: Energy Conversion and Management, v. 44, no. 20, p. 3151-3175.

Baklid, A., Korbol, R., and Owren, G., 1996, Sleipner Vest CO_2 Disposal, CO_2 Injection into a Shallow Underground Aquifer: SPE Journal of Petroleum Technology, p. 269.

Beardsley, R. H., and Fore, J. E., 2009, Exploration Prospect Interpretation and Risking Using Modern Geophysical Technology - A Methodology to Identify and Prioritize Exploration Focus Areas in GOM Using 3-Dimensional Volumes of Pressure, Temperature, and Other Subsurface Data.

Bradshaw, J., Bachu, S., Bonijoly, D., Burruss, R., Holloway, S., Christensen, N. P., and Mathiassen, O. M., 2007, CO2 storage capacity estimation: Issues and development of standards: International Journal of Greenhouse Gas Control, v. 1, no. 1, p. 62-68.

Bradshaw, M., Willcox, B., Struckmeyer, H., and Foster, C., 2002, Australia's Frontier Basins and Prospects for New Petroleum Provinces, 17th World Petroleum Congress: Rio de Janeiro, Brazil, World Petroleum Congress.

Cavanagh, A. J., Haszeldine, R. S., and Blunt, M. J., 2010, Open or closed? A discussion of the mistaken assumptions in the Economides pressure analysis of carbon sequestration: Journal of Petroleum Science and Engineering, v. 74, no. 1-2, p. 107-110.

Chadwick, R. A., Arts, R., Bernstone, C., May, F., Thibeau, S., and Zweigel, P., 2006, Best Practice for the Storage of CO2 in Saline Aquifers; Observations and guidelines from the SACS and CO2STORE projects, p. 19.

Chadwick, R. A., Smith, D., Hodrien, C., Hovorka, S., Mackay, E., Mathias, S. A., Lovell, B., Kalaydjia, F., Sweeney, G., Benson, S. M., Dooley, J. J., and Davidson, C., 2010, The realities of storing carbon dioxide - A response to CO2 capapcity issues raised by Ehlig-Economides & Economides. : Zero Emissions Platform.

Clark, J. A., Stewart, S. A., and Cartwright, J. A., 1998, Evolution of the NW margin of the North Permian Basin, UK North Sea: Journal of the Geological Society, v. 155, no. 4, p. 663-676.

Crawford, B. R., 1998, Experimental fault sealing: shear band permeability dependency on cataclastic fault gouge characteristics: Geological Society, London, Special Publications, v. 127, no. 1, p. 27-47.

Czernichowski-Lauriol, I., Rochelle, C., Gaus, I., Azaroual, M., Pearce, J., and Durst, P., 2006, Geochemical interactions Between CO_2, Pore-waters and Reservior Rocks, *in* Lombardi, S., Altunina, L. K., and Beaubien, S. E., eds., Advances in the Geological Storage of Carbon Dioxide, Springer, p. 157-174.

Davies, R. J., Turner, J. D., and Underhill, J. R., 2001, Sequential dip-slip fault movement during rifting: a new model for the evolution of the Jurassic trilete North Sea rift system: Petroleum Geoscience, v. 7, no. 4, p. 371-388.

Davison, I., Alsop, I., Birch, P., Elders, C., Evans, N., Nicholson, H., Rorison, P., Wade, D., Woodward, J., and Young, M., 2000, Geometry and late-stage structural evolution of Central Graben salt diapirs, North Sea: Marine and Petroleum Geology, v. 17, no. 4, p. 499-522.

Dicharry, R. M., Perryman, T. L., and Ronquille, J. D., 1973, Evaluation and Design of a CO_2 Miscible Flood Project - SACROC Unit, Kelly-Snyder Field: SPE Journal of Petroleum Technology, p. 1310.

Duggirala, M. N., Bastia, R., Tenepalli, S., Akella, M., Verma, R., and D'Silva, K., 2008, Mesozoics of the South Western Margin of India: A Frontier Exploration, 19th World Petroleum Congress: Madrid, Spain, World Petroleum Congress.

Ehlig-Economides, C., and Economides, M. J., 2010, Sequestering carbon dioxide in a closed underground volume: Journal of Petroleum Science and Engineering, v. 70, no. 1-2, p. 123-130.

Færseth, R. B., 1996, Interaction of Permo-Triassic and Jurassic extensional fault-blocks during the development of the northern North Sea: Journal of the Geological Society, v. 153, no. 6, p. 931-944.

Fowles, J., and Burley, S., 1994, Textural and permeability characteristics of faulted, high porosity sandstones: Marine and Petroleum Geology, v. 11, no. 5, p. 608-623.

Glennie, K. W., Higham, J., and Stemmerik, L., 2003, Permian, *in* Evans, D., Graham, C., Armour, A., and Brathust, P., eds., The Millenium Atlas: Petroleum Geology of the Central and Northern North Sea: London, Geological Society,, p. 318 - 322.

Glennie, K. W., and Underhill, J. R., 1998, Origin, Development and Evolution of Structural Styles, *in* Glennie, K. W., ed., Petroleum Geology of the North Sea: Basic concepts and recent advances, Volume 4, Blackwell Science, p. 54-58.

Gluyas, J. G., Mair, B., Schofield, P., Arkley, P., and McRae, D., 2005, Ardmore Field: rebirth of the first offshore oil field, UKCS: Geological Society, London, Petroleum Geology Conference series, v. 6, p. 367-388.

Goodman, A., Hakala, A., Bromhal, G., Deel, D., Rodosta, T., Frailey, S., Small, M., Allen, D., Romanov, V., Fazio, J., Huerta, N., McIntyre, D., Kutchko, B., and Guthrie, G., 2011, U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale: International Journal of Greenhouse Gas Control, v. 5, no. 4, p. 952-965.

Gorecki, C. D., Holubnyak, Y., Ayash, S., Bremer, J. M., Sorensen, J. A., Steadman, E. N., and Harju, J. A., 2009a, A New Classification System for Evaluating CO2 Storage Resource/Capacity Estimates, SPE International Conference on CO2 Capture, Storage, and Utilization: San Diego, California, USA, Society of Petroleum Engineers.

Gorecki, C. D., Sorensen, J. A., Bremer, J. M., Knudsen, D., Smith, S. A., Steadman, E. N., and Harju, J. A., 2009b, Development of Storage Coefficients for Determining the Effective CO2 Storage Resource in Deep Saline Formations, SPE International Conference on CO2 Capture, Storage, and Utilization: San Diego, California, USA, Society of Petroleum Engineers.

Howard, A., Beswetherick, S., and Miglio, G., 2009, Prospectivity on the Erris Ridge (Licence 7/97)â”High Risk/High Reward Frontier Exploration on the Irish Atlantic Margin, Offshore Europe: Aberdeen, UK, Society of Petroleum Engineers.

IPCC, 2005, Special report on Carbon Dioxide Capture and Storage., *in* Metz, B., Davidson, O., de Coninck, H., Loos, M., and LA, M., eds., Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press.

Jenyon, M. K., Cresswell, P. M., and Taylor, J. C. M., 1984, Nature of the connection between the Northern and Southern Zechstein Basins across the Mid North Sea High: Marine and Petroleum Geology, v. 1, no. 4, p. 355-363.

Jr., F. M. O., 2004, Storage of Carbon Dioxide in Geologic Formations: Journal of Petroleum Technology, v. 56, no. 9, p. 90-97.

Kopp, A., Class, H., and Helmig, R., 2009, Investigations on CO2 storage capacity in saline aquifers—Part 2: Estimation of storage capacity coefficients: International Journal of Greenhouse Gas Control, v. 3, no. 3, p. 277-287.

Korbøl, R., and Kaddour, A., 1995, Sleipner vest CO2 disposal - injection of removed CO2 into the utsira formation: Energy Conversion and Management, v. 36, no. 6-9, p. 509-512.

Legler, B., and Schneider, J. W., 2008, Marine ingressions into the Middle/Late Permian saline lake of the Southern Permian Basin (Rotliegend, Northern Germany) possibly linked to sea-level highstands in the Arctic rift system: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 267, no. 1-2, p. 102-114.

Lowrie, A., Somoza, L., Gardner, J. M., and Klekamp, T. L., Potential Hydrocarbon Plays of the Gulf of Mexico, Offshore Technology Conference: Houston, Texas.

Malik, Q. M., and Islam, M. R., 2000, CO2 Injection in the Weyburn Field of Canada: Optimization of Enhanced Oil Recovery and Greenhouse Gas Storage With Horizontal Wells, SPE/DOE Improved Oil Recovery Symposium: Tulsa, Oklahoma, 2000,. Society of Petroleum Engineers Inc.

Mathias, S., Hardisty, P., Trudell, M., and Zimmerman, R., 2009a, Approximate Solutions for Pressure Buildup During CO2 Injection in Brine Aquifers: Transport in Porous Media, v. 79, no. 2, p. 265-284.

Mathias, S. A., de Miguel, G., Thatcher, K. E., and Zimmerman, R. W., 2011, Pressure Buildup During CO_2 Injection into a Closed Brine Aquifer: Transport in Porous Media, v. 89, no. 3, p. 383-397.

Mathias, S. A., Gluyas, J. G., González Martínez de Miguel, G. J., Bryant, S. L., and Wilson, D., 2013, On relative permeability data uncertainty and CO2 injectivity estimation for brine aquifers: International Journal of Greenhouse Gas Control, v. 12, no. 0, p. 200-212.

Mathias, S. A., Hardisty, P. E., Trudell, M. R., and Zimmerman, R. W., 2009b, Screening and selection of sites for CO2 sequestration based on pressure buildup: International Journal of Greenhouse Gas Control, v. 3, no. 5, p. 577-585.

Maynard, J. R., and Gibson, J. P., 2001, Potential for subtle traps in the Permian Rotliegend of the UK Southern North Sea: Petroleum Geoscience, v. 7, no. 3, p. 301-314.

McCrone, C. W., 2003, The Davy, Bessemer, Beaufort and Brown Fields, Blocks 49/23, 49/30a, 49/30c, 53/5a, UK North Sea: Geological Society, London, Memoirs, v. 20, no. 1, p. 705-712.

Mouchet, J.-P., and Mitchell, A., 1989, Abnormal pressures while drilling: Origins - Prediction - Dectection - Evaluation, elf aquitaine: manuels techniques.

NETL, 2009, Carbon Sequestration Atlas of the United States and Canada: U.S. Department of Energy Office of Fossil Energy.

Nguyen, J.-P., 1996, Drilling: Oil and Gas Field Development Techniques, Institut Francais du Petrole Publications: Editions Technip.

Richard G. Hughes, 2009, Evaluation and Enhancement of Carbon Dioxide Flooding Through Sweep Improvement U.S. Department of Energy Office of Fossil Energy.

Roberts, A. M., Yielding, G., Kusznir, N. J., Walker, I. M., and Dorn-Lopez, D., 1995, Quantitative analysis of Triassic extension in the northern Viking Graben: Journal of the Geological Society, v. 152, no. 1, p. 15-26.

Robson, D., 1991, The Argyll, Duncan and Innes Fields, Block 30/24 and 30/25a, UK North Sea: Geological Society, London, Memoirs, v. 14, no. 1, p. 219-226.

Selley, R. C., 1978, Porosity gradients in North Sea oil-bearing sandstones: Journal of the Geological Society, v. 135, no. 1, p. 119-132.

Stemmerik, L., Ineson, J. R., and Mitchell, J. G., 2000, Stratigraphy of the Rotliegend Group in the Danish part of the Northern Permian Basin, North Sea: Journal of the Geological Society, v. 157, no. 6, p. 1127-1136.

Stuart, I. A., 2003, The Armada development, UK Central North Sea: The Fleming, Drake and Hawkins Gas-Condensate Fields: Geological Society, London, Memoirs, v. 20, no. 1, p. 139-151.

Taylor, J. C. M., 1998, Upper Permian - Zechstein., *in* Glennie, K. W., ed., Petroleum Geology of the North Sea: Basic concepts and recent advances, Volume 4: London, Blackwell Science, p. 195.

Trewin, N. H., and Bramwell, M. G., 1991, The Auk Field, Block 30/16, UK North Sea: Geological Society, London, Memoirs, v. 14, no. 1, p. 227-236.

Trewin, N. H., Fryberger, S. G., and Kreutz, H., 2003, The Auk Field, Block 30/16, UK North Sea, *in* Gluyas, J. G., and Hitchens, H. M., eds., United Kingdom Oil and

Gas Fields; Commermorative Millennium Volume., Volume 20: London, Geological Society, p. 12.

Zhou, Q., Birkholzer, J. T., Tsang, C.-F., and Rutqvist, J., 2008, A method for quick assessment of CO2 storage capacity in closed and semi-closed saline formations: International Journal of Greenhouse Gas Control, v. 2, no. 4, p. 626-639.

Ziegler, P. A., 1975, Geologic evolution of North Sea and its tectonic framework: AAPG Bulletin, v. 59, no. 7, p. 1073-1097.

4. PRESSURE TRANSFER ACROSS FAULTS VIA CAPILLARY FORCES; IMPLICATIONS FOR CO_2 INJECTION

4.1. INTRODUCTION

The movement of subsurface fluids via the capillary leaking of seals or cap rocks has been comprehensively studied in literature (Berg, 1975; Downey, 1984; Pittman, 1992; Watts, 1987) for the purpose of understanding the trapping and migration of hydrocarbons. Such seals or barriers can be divided genetically into two types, membrane seals that fail by capillary leakage (Fig. 4.1a, 4.1b), and hydraulic seals that fail via hydraulic fracturing (Watts, 1987). Fault seals may be categorised as either sealing faults, where the fault plane itself acts as a barrier to fluid flow (Fig. 4.2), or as juxtaposition faults (e.g. Fig. 4.1a), where the fluid pathway is impeded by a juxtaposed impermeable material (Watts, 1987; Yielding et al., 1997). However, it is generally accepted that both types of fault seal are analogous to membrane cap rocks that have been tilted to the angle of the fault plane (Watts, 1987). It has been proposed by authors (Downey, 1984; Fisher et al., 2001; Knipe, 1997; Schowalter, 1979; Watts, 1987) that capillary forces facilitate the movement of both pressure and hydrocarbons across faults in compartmentalised faulted reservoirs into adjoining compartments (Fig. 4.2). This is providing that the buoyancy pressure of the in place hydrocarbon column exceeds the capillary entry pressure of the fault core material (Fisher et al., 2001).

For the purposes of CCS, much of the work on capillary leakage has focused on predicting cap rock integrity, specifically ensuring that the CO_2 column buoyancy pressure does not exceed the cap rock capillary entry pressure.

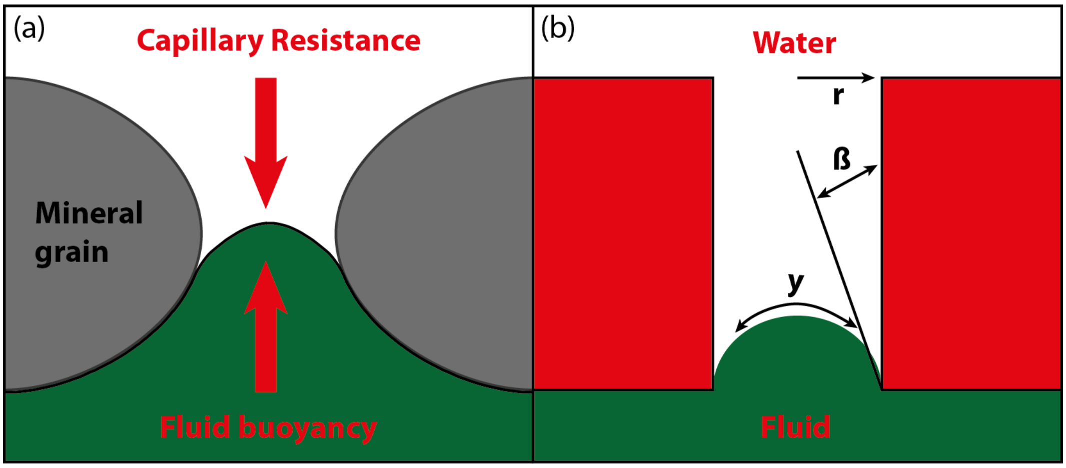

Fig. 4.1. Schematic diagram illustrating the fundamentals of capillary seals and an explanation of key terms used in this study, note for this example fluid may relate to hydrocarbons or CO_2. a) To enter a seal, the buoyancy pressure of the fluid and fluid column must be greater than the capillary resistance pressure opposing it. b) Illustration of key terms used in this study, r represents the radius of the pore throat, β is the contact angle of the fluid – water interface and the rock grain, and γ is the interfacial tension between the fluid and water. (Not to scale).

This is essential because when buoyancy pressure exceeds capillary pressure, leakage of CO_2 from the storage trap into the overburden sequence will occur via capillary pathways in the cap rock unit (e.g. Naylor et al., 2011). The study by Naylor et al., (2011) highlights the differences in interfacial tension (IFT) and wettability between CO_2 and other reservoir fluids act to reduce the threshold capillary entry pressure for CO_2 compared with hydrocarbons, such that seals secure for hydrocarbon columns may not be secure for equivalent CO_2 columns (Chiquet et al., 2007a, 2007b; Espinoza and Santamarina, 2010; Naylor et al., 2011). The study of cross fault migration of hydrocarbons described above has significant implications for CO_2 storage. Injection of CO_2 could lead to breakdown of the seals such that CO_2 will migrate into adjoining compartments (Fig. 4.2). This may aid the management of reservoir pressure and CO_2 diffusion and so limit the number of required injection wells.

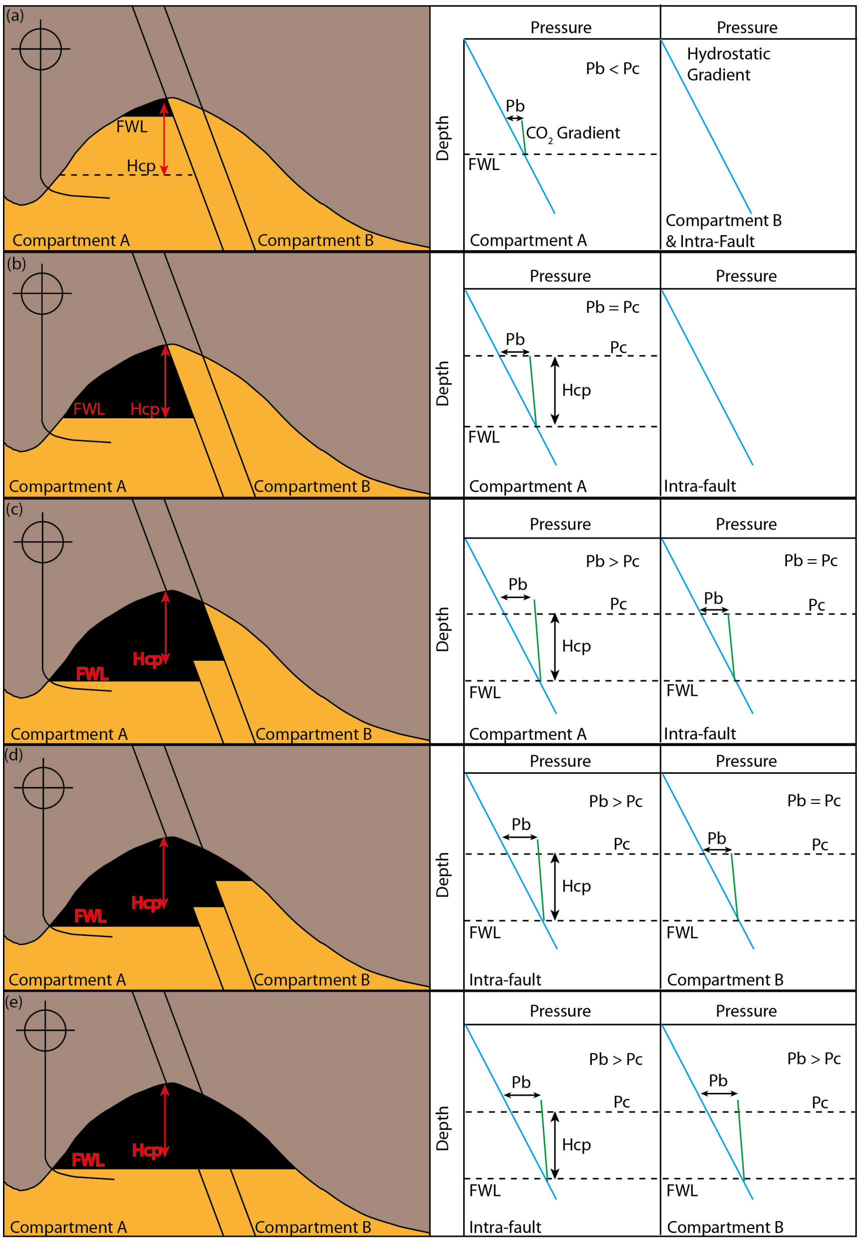

Fig. 4.2: Schematic representation (Not to scale) of CO_2 injection (Well bore represented by cross) into a faulted reservoir against the effects on reservoir pressure. The diagram illustrates CO_2 migration during continued injection relating to the changes in buoyancy pressure, maximum column height (Hcp)and capillary entry pressure (Cp). a) Gradual filling of compartment A, The buoyancy pressure (Pb) exerted upon the seal/fault interface by the CO_2 column (black) is less than the capillary entry pressure (Cp) of the fault, therefore CO_2 remains trapped. b) Continued injection increases the Hcp and similarly Pb. At the seal/fault interface, Pb is equal to Pc of the fault and CO_2 enters the fault. c) Injection continues and the CO_2 column exceeds the Hcp. Consequently the, Pb is now greater than Pc, increasing migration into the fault and increasing the pressure at the seal, compartment B and fault interface where Pb < Pc preventing migration into compartment B. d) In compartment A, Pb > Pc thus CO_2 migration continues. In the intra fault compartment, the CO_2 column increases such that Pb = Pc allowing capillary leakage of CO_2 into compartment B. e) Injection ceases, however the column height remains in excess of Hcp in compartment A, therefore migration continues. In the intra-fault compartment, the increase in column height exceeds Hcp, such that Pb > Pc and migration into compartment B continues. Pressure migration continues across all compartments until equilibrium is reached. Adapted from Fisher et al. (2001).

To avoid compromising containment integrity, two criteria must be met; 1. The capillary entry pressure of the fault plane must not exceed the brittle fracture pressure of the cap rock, and 2. The capillary entry pressure of the cap rock must exceed the entry pressure of the fault plane. Furthermore, for cross fault migration to be effective in aiding reservoir injectivity, the pressure must equilibrate across the fault in an operational, rather than geological timeframe.

This study summarises the current published methodologies for the calculation of the capillary entry pressure of a seal or fault plane, and maximum column heights that can be retained by such structures. The methodology is then adapted to be applicable for CO_2 injection scenarios in order to assess the likelihood of cross fault migration occurring without compromising the integrity of the cap rock unit. Finally, the methodology is applied to a selection of North Sea reservoirs (Fig. 4.3) of differing lithology and age, which have been identified as potential geological storage sites.

The sites used in this study were as follows:

Rotliegend Aquifer, Central North Sea: This example comprises a brine saturated Rotliegend sandstone reservoir sealed by the Upper Permian Zechstein salt (Chapter 3) targeted for CO_2 storage by the Teesside Low Carbon project. The reservoir facies comprises aeolian dunes and waterlain quartz arenites. Average porosity and permeability values of the reservoir interval are measured as 20% and 80 mD respectively. The seal comprises Zechstein evaporites, composed of interbedded facies of dolomite, anhydrite and halite. The average porosity and permeability values are estimated as 2% and <0.1 mD respectively.

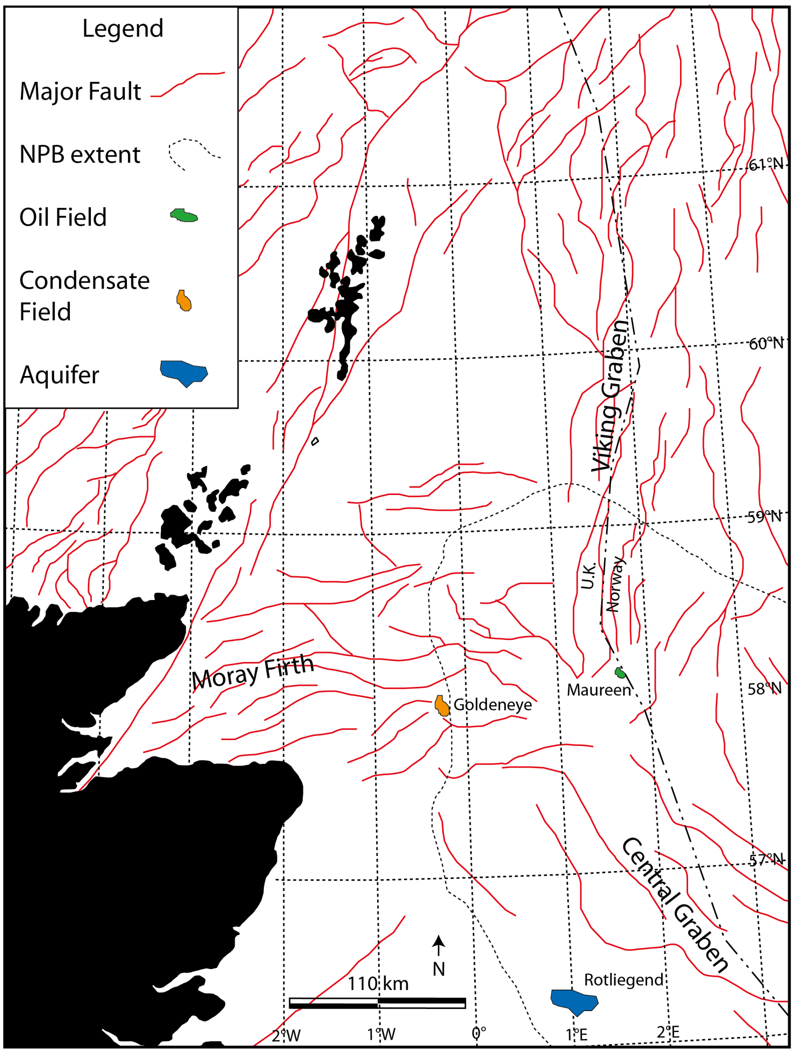

Fig. 4.3. Map showing the location and type of field for the three CO_2 storage prospects presented in this study. The three sites all use different stratigraphic intervals as the reservoir. The Lower Permian Rotliegend dune sandstone facies, Goldeneye is hosted in turbidite sandstones of the Lower Cretaceous and Maureen comprises turbidites of the Lower Palaeocene.

Maureen Field, Central North Sea: The Maureen Field is an abandoned oil field. It produced from a Palaeocene turbidite sandstone reservoir, sealed by mudstones of the Lista Formation. The Field was proposed for CO_2 storage and enhanced oil recovery activities as part of the Teesside Low Carbon project. The reservoir interval has average measured porosity and permeability values of 23% and 100 mD (Chandler and Dickinson, 2003; Cutts, 1991). The seal comprises hemipelagic mudstones with a porosity of 3% and permeability of 0.1 mD (Kilhams et al., 2012).

Goldeneye Field, Moray Firth: The Goldeneye field is the proposed site for the Peterhead CCS project, one of two winners of government funding for CCS demonstration projects. The field was discovered by Shell in 1996 as a gas condensate field that was producing from 2004 until abandonment in 2011. The reservoir comprises the mass turbidite sands of the Aptian Captain Sandstone Member, a division of the Lower Cretaceous Kopervik Sandstone Formation. The reservoir sands have a measured porosity of 25% and 1D permeability (Garrett et al., 2000; Wilson et al., 2005). The trap is sealed by Lower Cretaceous marls and mudstones of the Sola formation. These have average porosity and permeability values of 3.6% and 0.012 mD respectively (Jakobsen et al., 2004).

4.2. EXISTING THEORY

Calculation of fault sealing capacity in hydrocarbon reservoirs, at present, is mostly based on the analysis of Watts (1987). Using the assumption that faults are single planes with uniform capillary entry pressures. This implies that once a fault that separates reservoir rocks experiences capillary failure, the hydrocarbon column height difference maintained between fault blocks is equal to the maximum hydrocarbon column height that could be supported prior to leakage. This methodology has gone mostly unchallenged with the exception of the re-examination of the methodology and assumptions by Fisher et al., (2001). The Fisher et al. (2001) re-examination of the pre-existing Watts, (1987) methodology, proposes the amendment that column heights and fluid pressures can equilibrate without maintaining a column height difference equal to the maximum sealing capacity of the fault. This is providing that the buoyancy force of the column exceeds the entry pressure of the fault. Furthermore, the Fisher et al. (2001) study highlights the potential shortcomings of the Watts (1987) methodology, in that it is assumed that faults are single planes comprising of uniform capillary entry pressure extending across the fault. This does not account for the variability in capillary entry pressures for the fault plane, and the fault rock, whether that be cataclasite, clay smear or relatively un-deformed host rock.

The methodology for calculating the capillary entry pressures of fault seals presented below is a combination of that proposed by Berg (1975), Fisher et al. (2001) and Watts (1987) and is refined to be applicable for CO_2 systems. For consistency with published methods and available data, the calculations are performed in field units. The resulting values are subsequently converted and reported here using SI units, as is modern convention[*]. Results in field units are given in parenthesis for comparisons to published literature. All nomenclature used in the following equations is given in Table 4.1 below.

The differential in pressure due to the buoyancy forces exerted upon the seal is by the hydrocarbon or CO_2 column is related to the densities of the hydrocarbon/CO_2 and the density of the reservoir fluid, the vertical height of the column and the acceleration due to gravity, such that:

$$Pb = (\rho w - \rho h)gH \tag{4.1}$$

In the following equations, the subscripts h and co_2 are interchangeable to correspond to whether a hydrocarbon or CO_2 column is being considered. Equation

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[*] Conversion factors: 1ft = 0.3048 m, 1psi = 0.00689 MPa

4.1 is often re-written in terms of field units where 0.433 is a conversion constant that takes acceleration due to gravity into account, such that:

$$Pb = 0.433(\rho w - \rho h)H \tag{4.2}$$

In a water saturated reservoir, hydrocarbons or CO_2 can only migrate if the buoyancy pressure exceeds that of the capillary entry pressure of the fault in contact with the column.

The capillary entry pressure of such a fault is a function of the interfacial tension and the contact angle between fluid and rock, and the capillary radius given by:

$$Pc = \frac{2\,\gamma\, cos\beta}{r} \tag{4.3}$$

The capillary radius and pore throat diameter require measurements of physical samples or may be estimated via means of mercury (Hg) injection porosimetry according to the relationship:

$$Pc = \frac{\gamma h\; cos\beta h\; PHGef}{\gamma m\; cos\beta m} \tag{4.4}$$

The maximum column height (H = Hcp) that can be retained by the fault can be estimated by combining equations (4.2) and (4.4) for situations where buoyancy pressure is equal to capillary entry pressure (Pb = Pc). Therefore:

$$Hcp = \frac{\gamma h\; cos\beta h\; PHGef}{0.433\;(\rho w - \rho h)\gamma m\; cos\beta m} \tag{4.5}$$

Factor	Symbol	Units
Density of water	P_w	g cm^{-3}
Density of hydrocarbon	P_h	g cm^{-3}
Density of CO_2	P_{CO2}	g cm^{-3}
Gravitational acceleration	g	ms^{-1}
Column Height	H	m
Difference in Column Height	ΔH	m
Bouyancy Pressure	Pb	MPa
Bouyancy Pressure Differential	ΔPb	MPa i
Max Capillary Pressure	Pc	MPa
Mercury - Air IFT	γ_m	Dynes cm-1
Air - Water IFT	γ_a	Dynes cm-1
Oil - Water IFT	γ_h	Dynes cm-1
CO2 - Water IFT	γc	Dynes cm-1
Hg - Air contact angle	$\cos\beta_m$	Degrees
Air - Water Contact angle	$\cos\beta_w$	Degrees
Oil - Water Contact angle	$\cos\beta_h$	Degrees
CO2 - Water Contact Angle	$\cos\beta_C$	Degrees
Porethroat radius Seal	r_s	µm
Porethroat radius Reservoir	r_r	µm
Porethroat radius Fault	r_f	µm
Hg - Air Capillary Entry Pressure	P_{HGes}	MPa
Capillary Entry Pressure Seal	Pc_s	MPa
Reservoir Hg - Air Capillary Entry Pressure	P_{HGer}	MPa
Reservoir Capillary Entry Pressure	Pc_r	MPa
Fault Hg - Air Capillary Entry Pressure	P_{HGef}	MPa
Fault Capillary Entry Pressure	Pc_f	MPa
Max Hydrocarbon Height Seal	Hcp	m
Max Hydrocarbon Height Seal	H_hcp_s	m
Max Hydrocarbon Height Fault	H_hcp_f	m
Max CO_2 Height Seal	H_Ccp_s	m
Max CO_2 Height Fault	H_Ccp_f	m
Effective Grain Size	D	cm
Permeability	k	mD
Porosity	ϕ	%
Flow rate	q	m/s
Viscosity	µ	Pas
Relative Permeability	k_r	mD
Potential Gradient	∇ϕ	-

Table 4.1: Nomenclature used in the equations defined in this chapter.

However, if Hg – air data is not available, the effective capillary pressure can be estimated using the Berg (1975) solution for the estimation of the capillary radius from porosity and permeability data, given by:

$$D = [1.89k\emptyset^{-5.9}]^{0.5} \tag{4.6}$$

This can be resolved to give pore throat radius by:

$$r = 0.5(0.414D) \tag{4.7}$$

Using this relationship, maximum column height can be estimated in situations when no Hg- air data is available by combining equations (4.2) and (4.3). Such that:

$$Hcp = \frac{2\gamma h\ cos\beta h}{0.433\ (\rho w - \rho h)r} \tag{4.8}$$

Therefore, a fault will leak at the caprock/fault interface once the column height (H) reaches the maximum allowable column height (Hcp) such that the buoyancy pressure (Pb) becomes greater or equal to the capillary entry pressure (Pc).

4.3. APPLICATION TO CO_2 INJECTION AND STORAGE

For the case of CO_2 storage, once injection volume results in a CO_2 column and buoyancy pressure equal or exceeding the maximum column height of the fault (H_ccp_f) and buoyancy pressure (Pb), CO_2 will migrate across the fault into an adjoining reservoir compartment. Theoretically, analogous to the hydrocarbon example stated by Fisher et al. (2001), if injection continues such that the column height and buoyancy pressure remains greater than Hcp and Pb, cross fault migration will continue providing there is a column pressure differential across the fault. Such differentials will result in the CO_2 on either side of the fault being at different fluid pressures. This pressure differential modified from Fisher et al., (2001) may be resolved by:

$$\Delta Pb = 0.433(\rho w - \rho co_2)\Delta H \tag{4.9}$$

This differential will drive the flow of CO_2 across the fault, in accordance with Darcy's Law providing that CO_2 injection rate maintains a column height and buoyancy pressure exceeding $H_c cp_f$ allowing fluid pressure to equilibrate (i.e. $\Delta Pb = 0$). Once injection of CO_2 has ceased, cross fault flow will continue until $Pb < H_c cp_f$, at which point the fault will become impermeable to CO_2.

The rate of possible flow across a boundary feature can be calculated directly from the Darcy equation of fluid flow;

$$q = \frac{k_r}{\mu}\nabla\emptyset \tag{4.10}$$

Laboratory derived core measurements for relative permeability are not easily obtained, consequently, it is common for values to be estimated from porosity, pore throat radii and tortuosity values. Tortuosity is defined as the ratio of the actual fluid travel path to the shortest travel path, and is commonly given as √3 assuming spherical grains. Hence flow rate can be given by:

$$q = \frac{\varphi\, r^2}{8\vartheta^2\mu}\nabla\emptyset \tag{4.11}$$

The potential gradient, or driving force of the fluid may be calculated from the pressure differential, given by equation (4.9) and the thickness, such that;

$$\nabla\emptyset = \frac{\Delta Pb}{L} \tag{4.12}$$

The above method (Equations 4.1 – 4.5) was tested using published Hg –air data from the faulted reservoir (P_{Hgef}) and seal (P_{Hges}) units of Middle Bakkan Member, Saskatchewan (Ferdous, 2001). The methodology was then refined to allow characterisation of reservoirs and geological units identified as targets for CO_2 demonstration projects. For this purpose, equations (4.6) to (4.8) were applied using values for k and φ in order to estimate pore throat radii and subsequently maximum column height. Finally, an estimation of potential flow rate was given (Equations 4.9 to 4.12) to assess whether cross fault migration will occur over operational timescales rather than geological.

Validation of the contrasting methodologies between using Hg – air measured capillary entry pressures and porosity – permeability is given by comparable trends shown by both methods. It is not possible to validate this method against real world examples as direct replacement of hydrocarbon columns with CO_2 has not, and is unlikely to be undertaken. Current literature that compares differences between hydrocarbon and CO_2 columns (Naylor et al., 2011) for the purpose of cap rock integrity is also untested for this reason.

4.4. RESULTS

Inputting published values (Table 4.2) into the equations detailed above illustrates the variability in maximum allowable column heights for this scenario. Firstly, values for Hcp and Pc in hydrocarbon settings are significantly higher than when the same methodology is applied to CO_2 specific data. This variability is directly related to both the lower density of CO_2 in addition to the differences in contact angle and interfacial tension. Laboratory studies by Chiquet et al., (2007a, 2007b) and Espinoza and Santamarina, (2010) emphasises the influence of the geological substrate the CO_2 – water mix is in contact with on the contact angle. For both scenarios, quartz was used as a reference substrate due to its relative prevalence in sandstone reservoirs, the changing contact angles arising from whether the substrate was oil wet (hydrophobic) or water wet (hydrophilic) (Espinoza and Santamarina, 2010). In this scenario, hydrophobic substrates (oil wet quartz) reduce the capillary entry pressure and maximum column height by a factor of 40 when switching between hydrocarbon and CO_2 systems, reducing to 5 when considering hydrophilic substrates.

This significant decrease stems from the use of contact angle in equation (4.5), as the cosine of the contact angle. Under reservoir conditions in oil wet substrates, the contact angle of CO_2 – water is stated as 85° to 90°. Consequently the term $\cos\beta$ in this case ranges from 0.087 to 0.00 resulting in the significantly decreased capillary entry pressures (if $\cos\beta = 0$, H_{cp} and $P_c = 0$).

Applying the method to proposed CO_2 storage sites facilitates comparisons between idealised models calculated using Hg – air data (equation 4.5), to real world examples calculated using available porosity and permeability data (equations 4.6 to 4.8). The observed trends of differential entry pressures are maintained, as is the significant decrease in maximum allowable column heights when oil wet substrates are expected (Table 4.3) opposed to hydrophilic water wet substrates (Tables 4.4, 4.5).

Factor	Equation	Symbol	Units	Value
Density of water	-	P_w	g cm^{-3}	1.10
Density of hydrocarbon	-	P_h	g cm^{-3}	0.84
Density of CO_2	-	P_{CO2}	g cm^{-3}	0.46
Gravitational acceleration	-	g	ms^{-1}	9.81
Column height	-	T_h	m	780.00
Column height	-	H	ft	2559.06
Mercury - Air IFT	-	γ_m	Dynes cm-1	484.50
Mercuary - Air contact angle	-	$\cos\beta_m$	Degrees	140.00
Air - Water IFT	-	γ_w	Dynes cm-1	72.00
Air - Water Contact angle	-	$\cos\beta_w$	Degrees	0.00
Oil - Water IFT	-	γ_h	Dynes cm-1	48.00
Oil - Water Contact angle	-	$\cos\beta_h$	Degrees	30.00
CO2 - Water IFT oil wet	-	γ_c	Dynes cm-1	30.00
CO2 - Water Contact Angle oil wet	-	$\cos\beta_c$	Degrees	85.00
CO2 - Water IFT quartz	-	γ_c	Dynes cm-1	30.00
CO2 - Water Contact Angle quartz	-	$\cos\beta_c$	Degrees	40.00
Porethroat radius Seal	-	r_s	µm	3.28
Mercuary - Air Capillary Entry Pressure	-	P_{HGes}	MPa	6.89
Porethroat radius Reservoir	-	r_r	µm	3.69
Mercuary - Air Capillary Entry Pressure	-	P_{HGer}	MPa	1.39
Porethroat radius Fault	-	r_f	µm	7.93
Mercuary - Air Capillary Entry Pressure	-	P_{HGef}	MPa	2.76
Max Hydrocarbon Height Seal	4.5	H_hcp_s	m	303.64
Max Hydrocarbon Height Fault	4.5	H_hcp_f	m	121.46
Max CO_2 Height Seal oil wet	4.5	H_ccp_s	m	7.76
Max CO_2 Height Fault oil wet	4.5	H_ccp_f	m	3.10
Max CO_2 Height Seal quartz	4.5	H_ccp_s	m	67.36
Max CO_2 Height Fault quartz	4.5	H_ccp_f	m	27.06

Table 4.2: Table of input variables and solutions to maximum allowable column height estimations for cap rock and fault seals for both a hydrocarbon and CO_2 column. Input values are obtained from Ferdous (2001) and Espinoza and Santamarina (2010). The pressures given in Ferdous (2001) are listed as psi, but are erroneously low when compared to other literature. Therefore, it is considered that the values published are in bar, thus have been converted to psi for use in this study in keeping with comparable values.

Factor	Equation	Symbol	Units	Value
CO2 - Water IFT oil wet	-	γ_c	Dynes cm-1	30.00
CO2 - Water Contact Angle oil wet	-	$\cos\beta_c$	Degrees	85.00
CO2 - Water Contact Angle oil wet	-	$\cos\beta_c$	Cos	0.09
CO2 - Water IFT quartz	-	γ_c	Dynes cm-1	30.00
CO2 - Water Contact Angle quartz	-	$\cos\beta_c$	Degrees	40.00
CO2 - Water Contact Angle quartz	-	$\cos\beta_c$	Cos	0.76
Density of water	-	P_w	g cm^{-3}	1.10
Density of CO$_2$	-	P_{CO2}	g cm^{-3}	0.46
Reservoir Porosity	-	ɸ	%	23.00
Reservoir Permeability	-	k	mD	100.00
Reservoir Effective Grain Size	4.6	D	cm	1.32E-03
Reservoir Pore Throat Radius	4.7	r	µr	0.27
Max Reservoir CO$_2$ Column Height	4.8	H_ccp_f	m	0.64
Seal Porosity	-	ɸ	%	3.00
Seal Permeability	-	k	mD	0.10
Seal Effective Grain Size	4.6	D	cm	1.70E-02
Seal Pore Throat Radius	4.7	r	µm	3.52
Max Seal CO$_2$ Column Height	4.8	H_ccp_s	m	8.29

Table 4.3. Maximum CO$_2$ column heights for the Maureen oil field. The presence of hydrocarbons in the reservoir indicates the likely case of a hydrophobic oil wet substrate, consequently an oil wet CO$_2$ water contact angle is used.

Factor	Equation	Symbol	Units	Value
CO2 - Water IFT quartz	-	γ_c	Dynes cm-1	30.00
CO2 - Water Contact Angle quartz	-	$\cos\beta_c$	Degrees	40.00
CO2 - Water Contact Angle quartz	-	$\cos\beta_c$	Cos	0.76
Density of water	-	P_w	g cm^{-3}	1.10
Density of CO$_2$	-	P_{CO2}	g cm^{-3}	0.46
Reservoir Porosity	-	ɸ	%	20.00
Reservoir Permeability	-	k	mD	80.00
Reservoir Effective Grain Size	4.6	D	cm	1.79E-03
Reservoir Pore Throat Radius	4.7	r	µm	0.37
Max Reservoir CO$_2$ Column Height	4.8	H_ccp_f	m	7.59
Seal Porosity	-	ɸ	%	2.00
Seal Permeability	-	k	mD	1.00
Seal Effective Grain Size	4.6	D	cm	1.78E-01
Seal Pore Throat Radius	4.7	r	µr	36.83
Max Seal CO$_2$ Column Height	4.8	H_ccp_s	m	756.54

Table 4.4. Maximum CO$_2$ column heights for the Rotliegend sandstone prospect. The reservoir is fully water saturated, therefore a hydrophilic CO$_2$ water contact angle is applied. It is assumed for this care that the fault rock is derived directly from the host rock and no permeability correction is applied (Fisher and Knipe, 2001)

Factor	Equation	Symbol	Units	Value
CO2 - Water IFT quartz	-	γ_c	Dynes cm-1	30.00
CO2 - Water Contact Angle quartz	-	$\cos\beta_c$	Degrees	40.00
CO2 - Water Contact Angle quartz	-	$\cos\beta_c$	Cos	0.76
Density of water	-	P_w	g cm^{-3}	1.10
Density of CO_2	-	P_{CO2}	g cm^{-3}	0.46
Reservoir Porosity	-	ϕ	%	25.00
Reservoir Permeability	-	k	mD	1000.00
Reservoir Effective Grain Size	4.6	D	cm	3.27E-03
Reservoir Pore Throat Radius	4.7	r	μr	0.68
Max Reservoir CO_2 Column Height	4.8	H_ccp_f	ft	13.90
Seal Porosity	-	ϕ	%	3.60
Seal Permeability	-	k	mD	0.10
Seal Effective Grain Size	4.6	D	cm	9.93E-03
Seal Pore Throat Radius	4.7	r	μm	2.06
Max Seal CO_2 Column Height	4.8	H_ccp_s	ft	42.30

Table 4.5. Maximum CO_2 column heights for the Goldeneye field. The reservoir contains gas condensate with a density comparable with CO_2 at reservoir temperature and pressure, thus a CO_2 water contact angle is applied. It is assumed for this care that the fault rock is derived directly from the host rock and no permeability correction is applied (Fisher and Knipe, 2001)

As expected based on the results shown by the idealised scenario, the Maureen Field (Table 4.3) showed a marked decrease in maximum allowable column heights due to the expected oil wet substrate and the resultant effect on CO_2 water contact angle. Furthermore, this also signifies a significantly smaller window between the seal and fault capillary entry pressures of just 0.05 MPa (7 psi) versus the water wet prospects. Therefore, the injected CO_2 column may be increased by 7.62 m (25 ft.) after capillary leakage of the fault occurs before the containment integrity of the cap rock is compromised. This trend is continued in the Goldeneye prospect where the pressure differential in fault and cap rock capillary entry pressures is calculated as 0.17 MPa (25 psi) with an allowable column height difference of 28.3 m (93 ft.).

Conversely in the Rotliegend prospect, a pressure differential of 4.69 Mpa (680 psi), translating to a potential column height difference of 748.9 m (2457 ft.) is observed.

Factor	Equation	Symbol	Units	Value
Tortuosity	-	ϴ	-	3.00
Viscosity	-	µ	-	4.19E-05
Pressure difference	4.9	ΔPb	MPa	0.0041
Potential Gradient	4.12	∇ϕ	-	0.29
Flow Rate	4.11	q	m/s	2.38E-07

Table 4.6: Potential cross fault flow rate for the Maureen field. Rate assumes the pressure of compartment 1 is equal to Pc and the pressure of compartment 2 is equal to Pb with no CO_2 column present (Fig. 4.2b). Calculation of the Potential Gradient (equation 4.12), assumes a damage zone around the fault plane of 2m (Fisher et al., 2001)

Factor	Equation	Symbol	Units	Value
Tortuosity	-	ϴ	-	3.00
Viscosity	-	µ	-	4.19E-05
Pressure difference	4.9	ΔPb	MPa	0.048
Potential Gradient	4.12	∇ϕ	-	3.45
Flow Rate	4.11	q	m/s	4.45E-06

Table 4.7: Potential cross fault flow rate for the Rotliegend prospect. Rate assumes the pressure of compartment 1 is equal to Pc and the pressure of compartment 2 is equal to Pb with no CO_2 column present (Fig. 4.2b). Calculation of the Potential Gradient (equation 4.12), assumes a damage zone around the fault plane of 2m (Fisher et al., 2001)

Factor	Equation	Symbol	Units	Value
Tortuosity	-	ϴ	-	3.00
Viscosity	-	µ	-	4.19E-05
Pressure difference	4.9	ΔPb	MPa	0.09
Potential Gradient	4.12	∇ϕ	-	6.32
Flow Rate	4.11	q	m/s	3.41E-05

Table 4.8: Potential cross fault flow rate for the Goldeneye prospect. Rate assumes the pressure of compartment 1 is equal to Pc and the pressure of compartment 2 is equal to Pb with no CO_2 column present (Fig. 4.2b). Calculation of the Potential Gradient (equation 4.12), assumes a damage zone around the fault plane of 2m (Fisher et al., 2001)

The rate of flow (equation 4.11) is a function of the porosity, pore-throat radii, viscosity, tortuosity and potential gradient (equation 4.12). The potential gradient (equation 4.12) or driving force is defined by the difference in pressure between the two sides of the fault and associated damage zone where grain crushing, clay smear and cataclasite formation are likely to be present. This principal is analogous to the principles of diffusion, where particles in an area of high concentration preferentially migrate towards an area of low concentration in order to obtain equilibrium. The pressure differential is divided by the distance between those two points, in this case due to the lack of available data an average value of 2m has been used based after Fisher et al., (2001).

For this study, the flow rate was calculated for the onset of migration where the pressure in compartment 1 is equal to Cp as the maximum column height has been achieved, and zero CO_2 is present in compartment 2. Therefore the rate of flow is directly proportional to the magnitude of the column height at the initiation of leakage. This is illustrated by the relatively slow estimated flow rate the Maureen field of 2.38×10^{-7} m/s or 7.5 m/yr. Conversely, the higher pressures and porosities present in the Rotliegend and Goldeneye prospects results in faster flow rates of 4.45×10^{-6} m/s (140.3 m/yr) and 3.41×10^{-5} m/s (1075 m/yr) respectively.

It is important to consider however, that capillary leakage pressure is the pressure required for one molecule of substance to migrate across the reservoir/fault or reservoir/caprock interface, and not the total distance across the fault. The migration will continue as long as the buoyancy pressure in the reservoir remains above the capillary entry pressure of the interface, or until equilibrium has been achieved.

4.5. DISCUSSION

The methodology in this study is derived and adapted from that presented by previous authors (Berg, 1975; Fisher et al., 2001; Schowalter, 1979; Watts, 1987) to be applicable to CO_2 systems. The idealised scenario (Table 4.2) applies the revised method and proves its effectiveness for CO_2 containing systems. The subsequent application of the method to relevant real world potential CO_2 storage sites using easily available porosity and permeability data provided comparable results to those obtained using Hg – air techniques. This application proves that this method can be used as an effective screening tool when considering the sealing capacity of cap rocks, and the likely rate of cross fault CO_2 migration.

The results presented in this study indicate that there are clear differential between the maximum column heights for the caprock and fault unit. Furthermore, as the capillary entry pressure of the fault is less than that of the cap rock, cross fault migration will occur once the entry pressure of the fault has been exceeded. This migration will continue at a rate of “q” until either compartment fluids pressures equilibrate, or the buoyancy pressure of the column falls below fault capillary entry pressure. Consequently, it is proposed that for CO_2 injection purposes, this differential represents a sweet spot in the buoyancy pressure at the cap rock – fault interface where hydrocarbons or CO_2 migration across the fault is permissible without risk of capillary leakage through the cap rock.

However, it is important to consider that this model assumes a continuous capillary across the interface connecting the two compartments. In reality, this is unlikely and the pathway may be more convoluted due to the shape of rock grains, the orientation of clay particles that may be perpendicular to flow direction due to fault displacement direction, and fracture networks that may offer preferential pathways. Despite this caveat, this model still provides a useful estimation as to the rate of migration that may be expected, at least in terms of degrees of timescale (i.e. days, years, 10’s years).

The reduction in flow rate due to the above limiting factors may be offset however should solubility transport be an influencing mechanism. For solubility transport to occur, the capillary connection between the two compartments must first either be water saturated, or saturated with a CO_2 water solution. Such saturation would allow further CO_2 molecules to be transported within the aqueous solution resulting in a less resistant pathway than migration of CO_2 molecules through an unsaturated pore network.

The reduction in maximum column height observed between hydrocarbons and CO_2 columns is not without consequences. This reduction is both positive and negative for CO_2 injection, such that when dealing exclusively with CO_2 systems, the required pressure to facilitate cross-compartment migration is relatively low. However, the sealing capacity of the cap rock unit is also reduced reducing the safety window between allowing migration whilst maintaining storage integrity.

The lowest capillary pressures, occurring in oil wet hydrophobic substrates when $\cos\beta$ is near to zero resulting in exceptionally low maximum allowable column heights. This vastly increases the risk of containment failure via capillary leakage of the cap rock. This is discernible in the Maureen example where the maximum column height that could be retained by the cap rock reduced by a factor of 10 versus that of a hydrocarbon column.

It is therefore proposed that for CO_2 injection into depleted oil reservoirs, the wettability and nature of the cap rock substrate requires careful consideration when estimating storage volumes, such that the buoyancy pressure does not exceed the capillary pressure of the seal.

The CO_2 – water wet substrates predicted in both the Rotliegend and Goldeneye examples show an increase in the capillary entry pressures over that of the oil wet Maureen example. In spite of this, the pressure differential between the fault and seal entry pressures is 0.17 MPa (25 psi) in Goldeneye, 27 times less than observed in the Rotliegend example. Therefore, it is clear that the porosity and permeability values of the cap rock are of equal importance to that of the hydrophobic/hydrophilic nature of the substrates. A comparison between the three examples denotes that cap rock lithologies with low porosity possess greater sealing capacity than lithologies with higher porosity yet lower permeability.

The sealing capability of a fault is controlled by several factors. Primarily this focuses on the composition and the porosity - permeability relationship of the fault rock material (Bretan et al., 2003; Crawford, 1998; Engelder, 1974; Gibson, 1998). Specifically this is linked to the lithology within which the fault occurred, and thus the mineralogy of the deformed grains. In general, competent, clean clastic lithology with a high quartz content form disaggregation zones or granulation seams (Fisher and Knipe, 1998). Conversely, impure more clay rich clastics form phyllosilicate networks within the fault rock, despite limited grain fracturing (Knipe et al., 1997). Fine clay rich sediments result in significant clay smear (Bretan et al., 2003; Crawford, 1998; Gibson, 1994).

The examples used in this study do not directly account for these porosity and permeability relationships in fault rock. Analogies can still be drawn from the literature can allow conclusions to be drawn as to the validity of the observations made above. Furthermore, this can be used to estimate cross fault fluid location in specific storage targets. Specifically, the study undertaken by Fisher and Knipe (2001) quantifies the magnitude of the reduction in porosity and permeability. Consequently the increase in capillary entry pressure as a result of deformation can be estimated. The Fisher and Knipe, (2001) study indicates that clean sandstones (<5% clay) are found to suffer little or no grain fracturing and as such maintain porosity and permeability equivalent to the unreformed host rock. Impure clay rich clastics (15 -4 0% clay) suffer syn-deformational compaction and significant permeability reduction despite limited grain fracturing; and clay rich fine-grained sediments (>40% clay) produce extensive clay smear of very low permeability (<0.001 mD).

Using these relationships, predictions may be made as to the expected behaviour of faults within reservoirs frequently linked to potential CO_2 storage activities. For example, the quartz rich clean sandstones of the Rotliegend and Middle Jurassic (Olsen, 1987; Richards, 1992; Rieke et al., 2003) do not suffer significant grain fracturing and are likely to maintain fault permeability. Consequently cross fault migration in these reservoirs is more likely to occur than in the impure higher clay content sandstones of the Middle Jurassic, Triassic and Tertiary (Bowman, 2009; Dixon et al., 1995; Lonergan et al., 1998; Olsen, 1987).

It is important to note, that grain fracturing and porosity/permeability reductions is sometimes observed in clean sandstones, specifically the Rotliegend sandstones of the Southern North Sea (Leveille et al., 1997). Rotliegend sandstone facies containing >15% clay are uncommon in this formation, however cataclasites are frequently observed and show a broad distribution of grain size and magnitudes of permeability reductions. Cataclasites in quartz arenites (<5% clay) show a permeability reduction of <2 orders of magnitude over the undeformed reservoir, which increases up to 6 orders of magnitude in more clay rich wackes (5 - 15% clay) (Fisher and Knipe, 2001).

Based upon these observations, it is possible to predict that the dune facies of the Rotliegend is likely to suffer a reduction of <2 orders of magnitude. Conversely, the more clay and detrital grain rich turbidite derived sandstones of the Maureen and Goldeneye prospects are more likely to see a reduction of up to 6 orders of magnitude due to the formation of clay smear on the fault plane.

Application of these relationships to the three examples presented produces relatively insignificant effect. This supports the conclusion of Fisher and Knipe, (2001) that the permeability of >80% of faults is not sufficient to retard fluid flow at sufficient scales. It is more likely that such a reduction of permeability will have a greater effect on the flow rate. It is a shortcoming of the flow rate calculation presented in equation (4.11) that this reduction cannot be computed, and that relative permeability measurements would be required.

4.5.1: PROPOSED EXPERIMENTAL PROCEDURES FOR VALIDATING HYPOTHESIS

The lack of readily available data for capillary entry pressure, pore throat radii and fluid/matrix contact angle at present, prevents the direct calibration of the theory presented in this chapter to real world scenarios. This is compounded further as data, where available, is generally only collected from reservoir intervals. This focuses on courser grained clastic material, and not from the fine grained sealing lithologies present in the overburden, or across fault planes. Consequently, as described in this chapter, it is necessary to estimate such properties from the source of the material and the application of permeability reductions factors depending on the competency of the un-deformed material.

The lithological units presented in this thesis do however outcrop onshore and consequently calibration of the empirical theory described in this would be possible using targeted sampling and laboratory testing. Key to calculating the maximum column height that can be retained by a material (equation 4.5) are pore size and pore throat radii (equations 4.3, 4.4) and the mercury – air capillary entry pressure. These may be collected using mercury intrusion techniques based on the behaviour of non-wetting liquids in a capillary, in which a non-wetting fluid (any fluid with a contact angle of >90°, in this case mercury) cannot be spontaneously absorbed by the pores of a solid due to surface tension unless an external pressure is applied, i.e. the capillary entry pressures. When the pressure needed to force the non-wetting fluid into the pore space, the pore throat radii may be calculated using the relationship given by equation 4.3 (Watts, 1987).

Undertaking mercury intrusion procedures on representative samples of reservoir, fault and cap rock lithologies exposed in onshore outcrop would therefore allow calculation of the maximum column height that may be retained before membrane leakage occurs based upon validated physical data applied to a subsea reservoir setting (see equation 4.5).

Testing of the conclusions that the oil or water wet nature of the substrate has a key controlling impact on the sealing capacity and capillary entry pressure of a material may also be tested using laboratory fluid injection procedures. Gradually increasing the injection pressure of dense phase CO_2 into either water or oil saturated core in a pressure chamber at reservoir temperature and pressure should facilitate testing of the trend predicted in section 4.4 and 4.5. Should CO_2 enter the oil saturated core at a lower pressure than the water saturated core, this would confirm that hydrophilic (oil wet) substrates reduce the CO_2 water contact angle and interfacial tension resulting in a lower capillary entry pressure over that present in hydrophobic substrates. Should core not be available, or present unreasonably complexities, this observation could be tested by using glass micro models (see van Dijke et al., 2006). Such micro models would also allow reservoir/fault and reservoir/cap rock interfaces to be tested by simulating the transition from higher porosity and larger grained matrixes to finer grained, lower porosity matrixes.

4.6 CONCLUSIONS

This study shows that the standard procedure for estimating capillary entry pressures, maximum column heights and cross fault migration potential for hydrocarbon systems can be modified and applied to potential CO_2 injection sites. Furthermore, given suitable reservoir and caprock lithologies, a sweet spot between seal and fault capillary entry pressures is observed, facilitating cross fault migration of CO_2 while maintaining caprock integrity. Consequently, it is considered that with carefully controlled injection pressures and volumes, faulted compartmentalised reservoirs in clean sandstones should not present significant barriers to CO_2 migration.

Key controls on the magnitude of both the maximum column height and capillary entry pressures in CO_2 systems are shown to be the influence on hydrophobic and hydrophilic substrates on the CO_2 - water contact angle and interfacial tension. Specific concerns relate to the 40x reduction in maximum allowable column height when encountering oil-wet hydrophobic substrates, where contact angles approaching 90° result in entry pressures and max column heights proximal to zero. Thus, we propose that careful analysis of the caprock and likely fault material is critical when considering abandoned oil fields for CO_2 storage.

Published literature on the common porosity and permeability decreases in fault material helps inform prediction of likely cross fluid CO_2 migration in common North Sea sandstone reservoirs. However, the model in this and previous studies are based on limited available data and consequently cannot account for all geological heterogeneity. Nonetheless, the common North Sea reservoirs are often measureable in onshore analogues, therefore further study of Hg – air capillary entry pressure and pore throat radii in exposed fault cores and cataclasite would allow a more accurately constrained model to be produced to inform likely cross fault migration.

Based on the results generated in this study, allied to the published considerations discussed above, it is the Rotliegend prospect that shows the greatest potential for CO_2 injectivity. The reasons for this are as follows;

- The capillary entry pressure differential between the faults and caprock is significant allowing cross fault migration to occur without compromising cap rock integrity.
- Flow rate is sufficient that CO_2 migration will occur on operational rather than geological timescales.
- The clean, quartz rich nature of the upper dune facies indicates that permeability reduction due to faulting will be less than 2 orders of magnitude.

REFERENCES:

Berg, R. R., 1975, Capillary pressures in stratigraphic traps: AAPG Bulletin, v. 59, no. 6, p. 939-956.

Bowman, M. B. J., 2009, Cenozoic, Petroleum Geology of the North Sea, Blackwell Science Ltd, p. 350-375.

Bretan, P., Yielding, G., and Jones, H., 2003, Using calibrated shale gouge ratio to estimate hydrocarbon column heights: AAPG Bulletin, v. 87, no. 3, p. 397-413.

Chandler, P. M., and Dickinson, B., 2003, The Maureen Field, Block 16/29a, UK Central North Sea: Geological Society, London, Memoirs, v. 20, no. 1, p. 587-601.

Chiquet, P., Broseta, D., and Thibeau, S., 2007a, Wettability alteration of caprock minerals by carbon dioxide: Geofluids, v. 7, no. 2, p. 112-122.

Chiquet, P., Daridon, J.-L., Broseta, D., and Thibeau, S., 2007b, CO_2 - water interfacial tensions under pressure and temperature conditions of CO_2 geological storage: Energy Conversion and Management, v. 48, no. 3, p. 736-744.

Crawford, B. R., 1998, Experimental fault sealing: shear band permeability dependency on cataclastic fault gouge characteristics: Geological Society, London, Special Publications, v. 127, no. 1, p. 27-47.

Cutts, P. L., 1991, The Maureen Field, Block 16/29a, UK North Sea: Geological Society, London, Memoirs, v. 14, no. 1, p. 347-352.

Dixon, R. J., Schofield, K., Anderton, R., Reynolds, A. D., Alexander, R. W. S., Williams, M. C., and Davies, K. G., 1995, Sandstone diapirism and clastic intrusion in the Tertiary submarine fans of the Bruce-Beryl Embayment, Quadrant 9, UKCS: Geological Society, London, Special Publications, v. 94, no. 1, p. 77-94.

Downey, M. W., 1984, Evaluating seals for hydrocarbon accumulations: AAPG Bulletin, v. 68, no. 11, p. 1752-1763.

Engelder, J. T., 1974, Cataclasis and the generation of fault gouge: Geological Society of America Bulletin, v. 85, no. 10, p. 1515-1522.

Espinoza, D. N., and Santamarina, J. C., 2010, Water-CO2-mineral systems: Interfacial tension, contact angle, and diffusion—Implications to CO2 geological storage: Water resources research, v. 46, no. 7, p. W07537.

Ferdous, H., 2001, Regional sedimentology and diagenesis of the Middle Bakken Member: implications for reservoir rock distribution in southern Saskatchewan [Doctor of Philosophy: University of Saskatchewan, 467 p.

Fisher, Q., and Knipe, R. J., 1998, Fault sealing processes in siliciclastic sediments: Geological Society, London, Special Publications, v. 147, no. 1, p. 117-134.

Fisher, Q. J., Harris, S. D., McAllister, E., Knipe, R. J., and Bolton, A. J., 2001, Hydrocarbon flow across faults by capillary leakage revisited: Marine and Petroleum Geology, v. 18, no. 2, p. 251-257.

Fisher, Q. J., and Knipe, R. J., 2001, The permeability of faults within siliciclastic petroleum reservoirs of the North Sea and Norwegian Continental Shelf: Marine and Petroleum Geology, v. 18, no. 10, p. 1063-1081.

Garrett, S. W., Atherton, T., and Hurst, A., 2000, Lower Cretaceous deep-water sandstone reservoirs of the UK Central North Sea: Petroleum Geoscience, v. 6, no. 3, p. 231-240.

Gibson, R. G., 1994, Fault-zone seals in siliciclastic strata of the Columbus Basin, offshore Trinidad: AAPG Bulletin, v. 78, no. 9, p. 1372-1385.

-, 1998, Physical character and fluid-flow properties of sandstone-derived fault zones: Geological Society, London, Special Publications, v. 127, no. 1, p. 83-97.

Hedley, B. J., Davies, R. J., Mathias, S. A., Hanstock, D., and Gluyas, J. G., 2013, Uncertainty in static CO2 storage capacity estimates: Case study from the North Sea, UK: Greenhouse Gases: Science and Technology, v. 3, no. 3, p. 212-230.

Jakobsen, F., Ineson, J. R., Kristensen, L., and Stemmerik, L., 2004, Characterization and zonation of a marly chalk reservoir: the Lower Cretaceous Valdemar Field of the Danish Central Graben: Petroleum Geoscience, v. 10, no. 1, p. 21-33.

Knipe, R., Fisher, Q., Jones, G., Clennell, M., Farmer, A., Harrison, A., Kidd, B., McAllister, E., Porter, J., and White, E., 1997, Fault seal analysis: successful methodologies, application and future directions: Norwegian Petroleum Society Special Publications, v. 7, p. 15-38.

Knipe, R. J., 1997, Juxtaposition and seal diagrams to help analyze fault seals in hydrocarbon reservoirs: AAPG Bulletin, v. 81, no. 2, p. 187-195.

Kilhams, B., Hartley, A., Huuse, M., and Davis, C., 2012, Characterizing the Paleocene turbidites of the North Sea: the Mey Sandstone Member, Lista Formation, UK Central Graben: Petroleum Geoscience, v. 18, no. 3, p. 337-354.

Leveille, G. P., Knipe, R., More, C., Ellis, D., Dudley, G., Jones, G., Fisher, Q. J., and Allinson, G., 1997, Compartmentalization of Rotliegendes gas reservoirs by sealing faults, Jupiter Fields area, southern North Sea: Geological Society, London, Special Publications, v. 123, no. 1, p. 87-104.

Lonergan, L., Cartwright, J., Laver, R., and Staffurth, J., 1998, Polygonal faulting in the Tertiary of the central North Sea: implications for reservoir geology: Geological Society, London, Special Publications, v. 127, no. 1, p. 191-207.

Naylor, M., Wilkinson, M., and Haszeldine, R., 2011, Calculation of CO_2 column heights in depleted gas fields from known pre-production gas column heights: Marine and Petroleum Geology, v. 28, no. 5, p. 1083-1093.

Olsen, H., 1987, Ancient ephemeral stream deposits: a local terminal fan model from the Bunter Sandstone Formation (L. Triassic) in the Tønder-3, -4 and -5 wells, Denmark: Geological Society, London, Special Publications, v. 35, no. 1, p. 69-86.

Pittman, E. D., 1992, Relationship of Porosity and Permeability to Various Parameters Derived from Mercury Injection-Capillary Pressure Curves for Sandstone (1): AAPG Bulletin, v. 76, no. 2, p. 191-198.

Richards, P. C., 1992, An introduction to the Brent Group: a literature review: Geological Society, London, Special Publications, v. 61, no. 1, p. 15-26.

Rieke, H., Mccann, T., Krawczyk, C. M., and Negendank, J. F. W., 2003, Evaluation of controlling factors on facies distribution and evolution in an arid continental environment: an example from the Rotliegend of the NE German Basin: Geological Society, London, Special Publications, v. 208, no. 1, p. 71-94.

Schowalter, T. T., 1979, Mechanics of secondary hydrocarbon migration and entrapment: AAPG Bulletin, v. 63, no. 5, p. 723-760.

Van Dijke, M. I. J., Sorbie, K. S., Sohrabi Sendeh, M., and Danesh, A., 2006, Simulation of WAG floods in an oil wet micromodel using a 2D pore scale network model: Journal of Petroleum Science and Engineering, v. 52, no. 1-4, p. 71-86.

Watts, N. L., 1987, Theoretical aspects of cap-rock and fault seals for single- and two-phase hydrocarbon columns: Marine and Petroleum Geology, v. 4, no. 4, p. 274-307.

Wilson, J., Wall, G., Kloosterman, H. J., Coney, D., Cayley, G., Walker, R., J., and Linskaill, C., 2005, The discovery of Goldeneye: Kopervik prospect and play mapping in the South Halibut Basin of the Moray Firth: Geological Society, London, Petroleum Geology Conference series, v. 6, p. 199-216.

Yielding, G., Freeman, B., and Needham, D. T., 1997, Quantitative fault seal prediction: AAPG bulletin, v. 81, no. 6, p. 897-917.

5. ROLE OF PUBLIC ENGAGEMENT IN FORMULATING PUBLIC OPINION OF CCS TECHNOLOGY

5.1 INTRODUCTION

The previous chapters (i.e. Earth Science) have examined in detail the technical feasibility of Carbon Capture and Storage technology in terms of outright storage capacity of potential geological sites and the effects of capillary forces in the cross fault migration of CO_2 in the reservoir; in essence, an investigation of the process of CCS on a regional scale (km) decreasing through a reservoir scale (m) down to pore scale (mm).

The purpose of this chapter is to discuss the importance of keeping the social implications of this new and important technology in context throughout the development program. The following section discusses several examples where failure to consider the social acceptability of a technology has led to significant delays in project completion or its complete failure.

To understand and predict the social acceptability of a particular science, technology or project, it is important to first understand the social theory of risk, the way in which risk is perceived in the eyes of the public and indeed the stereotyping of the public; and subsequently how this defines the theory behind practical and effective public engagement.

5.2 THE THEORY OF RISK IN PUBLIC ENGAGEMENT

The concept of risk takes on numerous different connotations dependent upon the context in which it is evoked such as financial risk, risk to human health and risk to the environment. The perception of risk is widely acknowledged as a key step for human decision making based on an understanding of the consequences of an event or activity. For example, the consequences to human health of handling dangerous substances may be high; however the mitigation of dangers by working in a controlled environment and wearing suitable protective equipment means that the overall risk may be considered low. The word risk may be applied in numerous contexts, however perhaps the most fitting definition of how risk may be quantified and communicated is offered by Stern and Finebery (1996) "...to describe a potentially hazardous situation in as accurate, thorough, and decision-relevant a manner as possible, addressing the significant concerns of the interested and affected parties, and to make this information understandable and accessible to public officials and to the parties." This definition is not specific to a particular type of risk, but can be applied to all forms, whether it be financial or physical.

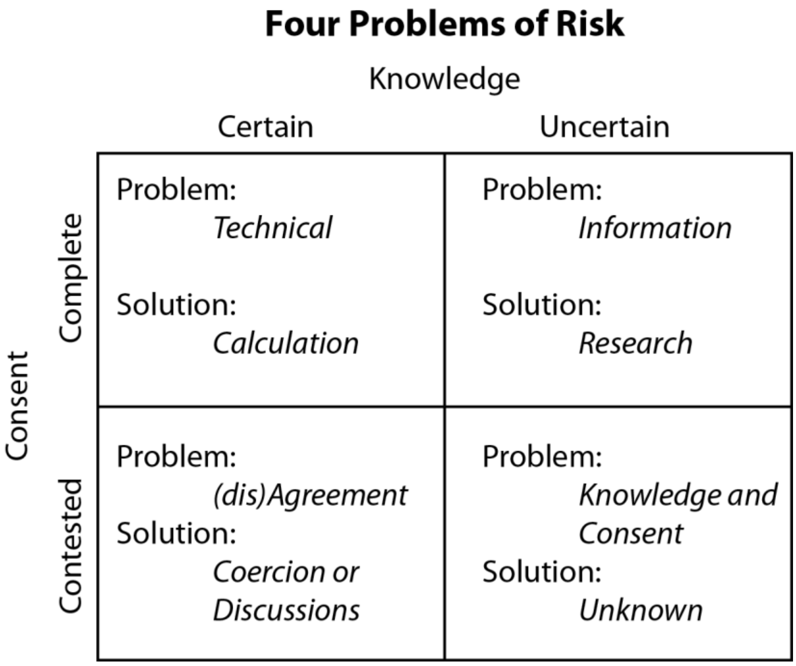
A concise explanation of risk is offered by Douglas and Wildavsky (1982) who assert "risk should be seen as a joint product of knowledge about the future and consent about the most desired prospects". Douglas and Wildavsky's (1982) ideas illustrate that when knowledge is complete and certain, objectives agreed, and alternatives considered it is possible to produce an acceptable solution. If the problem is technical, then the solution is further calculation and simulation. If the problem is lack of information then the solution is research (Fig.5.1). Problems arise either when there is disagreement over the nature of the problem and its definition, or when there are uncertainties over the level of knowledge and options pertaining to a project. In either case uncertainties are likely to prevail.

Deciding whether risks are acceptable or not requires human behaviour to be considered; specifically as to how people ignore most of the potential dangers that surround them and interact so as to concentrate only on selected aspects (Douglas and Wildavsky, 1982). Is the acceptance of risk derived from the perception of individual risks but subject to change when presented with a justifying argument? I.e. the risk of climate change is widely accepted as important but not worrying whereas the risks associated with nuclear power draw from previous examples of nuclear accident and thus are considered more serious and un-acceptable. However, when the individual is presented with the justification that Nuclear power is carbon neutral and thus help stop climate change, the acceptability of the risk increases even if the perception of the severity does not decrease (Bickerstaff et al., 2008).

To place this in the context of CCS, what may drive people to overlook the dangers of global warming and associated events to focus purely on the limited risk of underground CO_2 storage? Is the way in which acceptance is measured by addressing purely the opinion of CCS, and not the opinion of the role opf CCS in decarbonising power generation responsible for perhaps a more negative perception than renewable energy? Or is this driven by the actions of the stakeholders, (mis)information by the media, and distrust in the governing bodies and /or industry; or a combination of all these factors? A key element of understanding and predicting public perception and reaction to the risks to which they are to be exposed, is to effectively and accurately communicate the risks, implications and justifications fairly and openly.

The idea of a pure notion of risk that is unpolluted by interests and ideology arising from political bias, morals and emotions has been examined by Douglas (1992). This approach is commonly applied to professions such as law, which are ideally required to be politically and/or morally unbiased. The idealised notion of unpolluted risk is problematic as it fails to account for ways that lay-persons and experts perceive risk. Douglas comments frequently on the baffling behaviour of members of the public who fail to take note of attempts to educate them about risks, such as those inherent in failing to take out insurance against natural hazards or the dangers of driving un-roadworthy vehicles. Ideally people should adopt an unpolluted view of risk similar to that attempted by lawyers and actuaries who seek to follow logical arguments and avoid emotional influences in their assessments of risk. However, most commonly lay-people either exaggerate risk through the lens of fear or anger or underplay its potential often illustrated by unwillingness to invest in insurance schemes.

Because experts and lay-persons do not construct risks in the same way, risk perception varies greatly depending on context and can lead to conflicts of interest. A hypothetical example may be such as where government policy to solve public debt by radical reforms is deemed too risky by voters which results in a compromise. The method by which risk is communicated to the public has a significant role in how risk is perceived in general. It is a commonplace observation that people often treat Health and Safety regulations as unnecessary interference, evidenced by the expression ‘nanny state’ controls. Even though these regulations are often justifiable in reducing danger to life and limb they may be rejected by people who view them as confusing, infantilising or restrictive of their freedom of choice. Douglas (1985) characterises humans as generally over intrepid and difficult to persuade of the reality of dangers. It is likely that people, rather than taking responsibility personally, are often quick to hold others accountable for risk, in particular those who might already be held with suspicion.



Four Problems of Risk

		Knowledge: Certain	Knowledge: Uncertain
Consent	Complete	Problem: *Technical* Solution: *Calculation*	Problem: *Information* Solution: *Research*
	Contested	Problem: *(dis)Agreement* Solution: *Coercion or Discussions*	Problem: *Knowledge and Consent* Solution: *Unknown*

Fig.5.1. The four problems of risk defined by Douglas and Wildavsky's (1982) showing the perception of risk as a product of knowledge and consent.

Focusing on this statement in more detail, Douglas (1985) explains that public opinion generated from deciding whether or not risks/dangers inflicted on them by a higher power are fair, may in turn lead to rejection of these risks due to anger or indignation, perceived exploitation, lack of choice or confusions rather than fear alone. Thus the tendency to lay blame becomes an important factor in acceptability of any project. Perhaps therefore, the subject of blame has a more significant impact on the perception of risk than the danger presented by the situation itself? Or does the need to be held to account by law for all incidents make society on a whole more risk averse? Douglas (1992) comments on the language of probability becoming more frequent, where experts communicate risks measured as probabilities and leave the public to come to their own conclusions. She highlights the medical profession as a prime example, suggesting that potential litigation by patients against doctors for mistreatment and misleading advice has led to the latter becoming more formal and distant in their communication. Doctors are nowadays more likely to explain that procedure A has a 60% success rate as opposed to procedure B which has a 80% success rate, while the consequences of failure in procedure B are 70% more severe than procedure A. This kind of language forces the patient to choose the course of treatment based on their interpretation of the medical assessment of risk, thus transferring responsibility from doctors to patients. However Douglas considers the communication of facts in this manner increases the patients' perception of risk, leaving them confused and bereft of feelings of reassurance that result from close interpersonal communications.

Despite the best efforts of the experts, the assessment of the magnitude of the risk will always differ dependent on whether an organisation or demographic group is more risk adverse than another. Among the scientific community, risk and uncertainty are an accepted part of innovation and progress. Geology is a classic example as new measurements such as dating the age of the earth's crust comes with a significant uncertainty range comprising of millions of years, which is beyond the breadth of timescales that many members of the public can comprehend. These kind of disjunctions can lead to conflicting assessments of risk that inflate the risk perception amongst the non-experts and leads to the question of how the role of confusion and uncertainty within the theory of risk relates to theories of public engagement.

The UK National Co-ordinating Centre for Public Engagement (PE) draws attention to the link between risk and PE by stating: “Public engagement describes the myriad of ways in which the activity and benefits of higher education and research can be shared with the public. Engagement is by definition a two-way process, involving interaction and listening, with the goal of generating mutual benefit” (NCCPE, 2012). Although encouraging collaboration between university research and its communication to the non-specialist public, this statement is applicable to many aspects of communicating technical policy to non-experts. However, public engagement is not limited solely to transfer between research and the public but can cover a range of bodies and organisations be they governmental or commercial as well as different publics, as illustrated in Fig. 5.2 (Rowe and Frewer, 2005).

The hypothesis that confusion heightens perceptions of the magnitude of risk can be illustrated in Rowe and Frewer (2005) model of public communication (Fig. 5.2). Their model indicates a one-way flow of information from the experts to the public similar to that featured in the example of a doctor presenting a patient with scientific evidence of risks associated with a choice of procedures. Confusion arises due to the absence of a flow of information from the public back to experts: it is a one-way conversation. Simply being presented with facts and unable to seek clarification results in frightened publics and escalates people’s perceptions of risks.

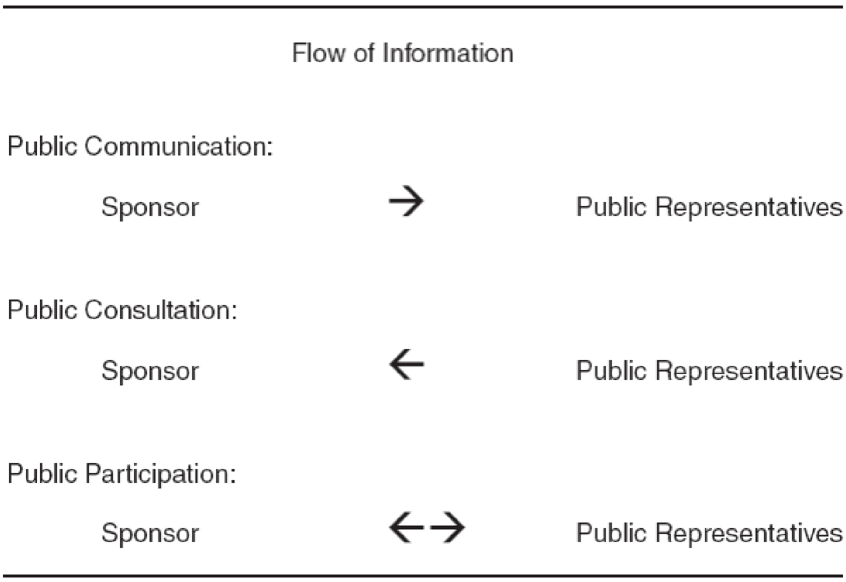


Fig.5.2. Differing types or Public Engagement based upon flow of information. After Rowe and Frewer (2005)

The two way flow of information between expert and public as presented by the engagement model allows for the non-experts to seek clarification on specific points that may alleviate confusion and lead to a more balanced risk perception between both parties. It is the idea of two way flow that inspired my investigation into whether a two way dialogue between experts and members of the public significantly alters perception of risk as opposed to the initial perceptions.

5.2 PUBLIC ENGAGEMENT THOERY IN PRACTICE

Public engagement techniques and examples have been applied to CCS technology and will be discussed in a later section. However, due to the novelty of the technology examples are not widespread. Thus it is necessary to turn to other examples of public engagement theory being used in practise. It should be noted that in normal use, the public often refers to “the ordinary people: in general or “the community”. However, when considering the behaviour or reactions of the public, it is important to consider that the public comprises a mixture of many differing backgrounds and demographics. For this reason, it is often necessary to consider the mixture and types of publics within the community as conclusions that refer to one specific demographic may not be valid or applicable to a hypothetical generalised population.

Public engagement practises are important in many ‘controversial’ industries, but it is necessary to understand the exact role that public engagement might play in order to avoid its misuse. Goven and Langer, (2009) warn that genuine public engagement cannot be used to simply gain acceptance for an already decided upon strategy, but rather public engagement should be deployed to open up the framing of a problem, acknowledge areas of uncertainty and aid informed technical decision making. In the case of nano-technologies (Rogers-Hayden and Pidgeon, 2008), public engagement may not always result in harmonious developments of a technology and may lead only to differences in visions between developers and consumers. However public engagement is still necessary if public participation is to consist of something more than mere dissemination of information. This view is in keeping with the point made by Rowe and Frewer (2005) about the need for a two-way flow of information in public engagement so that members of the public are fully integrated into decision making processes, rather than simply being presented with predetermined information.

With regard to climate change, (Lorenzoni et al., 2007) argue that public engagement is vital to the United Kingdom government being able to reach its 60% CO_2 emissions reduction targets. The (Lorenzoni et al., 2007) study indicates that public awareness of the dangers relating to climate change have increased significantly. But, barriers remain in place that prevent or decrease levels of public engagement on an individual and national scale, which if left unaddressed, are likely to impede the transition to more sustainable lifestyles.

A detailed study of public engagement in the climate change hypothesis was undertaken by Leiserowitz (2006). It affirmed the critical need for policy makers to understand public opinion as it represents the key context in which they operate. As a result, public opinion concerning climate change can fundamentally constrain political, economic or social actions to address climate risks. Leiserowitz (2006) gives the example that levels of opposition to climate initiatives depend on the perceived risks that climate change represents and indeed whether any such risks exist at all.

The examples discussed above echo the theory (Douglas, 1985, 1992) that government and corporations are not averse to risk, but they are averse to exposing others to risks. Thus a government may propose a series of climate initiatives such as imposing taxes on polluting commodities in an effort to reduce their attractiveness, but climate change sceptics who do not perceive there to be such risk are likely to oppose the measures especially if they affect a section of society to which they are affiliated. The knock on effect of these contrasting opinions may lead to a reduction in trust between the party proposing new policies, in this case the government, and those who deem themselves unfairly or unjustly penalised for their opinions. If breakdown of trust is allowed to escalate, it may lead to a cycle in which future policies face opposition based on distrust of the proposer. In short, the feeling of distrust outweighs the perceived risk of the consequence of not accepting new policies. The above examples provide an excellent background as to why it is critical to understand the state of public opinion prior to implementation of potentially controversial policies, planning of unpopular developments or the development of technologies that are generally poorly understood and perceived as risky.

In order to understand public opinion it must be carefully measured. Methods of investigation and measurement are well documented in literature (Bickerstaff et al., 2010; Li et al., 2006; Lorenzoni et al., 2007; Rowe and Frewer, 2005). Investigations that attempt to measure public opinion frequently comprise random anonymous surveys intended to capture and categorise opinions on a specific subject, such as government policies or local planning issues. These constraints however often cause such studies to overlook the diversities of publics. Other more qualitative methods are also deployed, alone or in combination with surveys, ranging from small scale ‘focus groups’ to larger scale town hall meetings. Such qualitative methods often focus on specific interest groups or stakeholders in an effort to avoid the overlooking of demographics inherent in random surveying. These methods will be discussed in greater detail in later sections of this chapter.

5.3 PUBLIC PARTICIPATION ACTIVITIES IN CCS

5.3.1 GENERAL PERCEPTIONS OF CCS:

Most objections to CCS relate to the fear of CO_2 leakage and the threat this might pose to the safety of local residents, property and the environment. Detailed research into the risk of leakage of CO_2 from sub-surface geological traps has been undertaken by both independent scientists and individual operators (Pawar et al., 2009; Pruess, 2008; Stenhouse et al., 2009; Stenhouse et al., 2006). However, this accumulated knowledge and detailed study tends to remain within the realm of geologists and other experts and is rarely disseminated to the wider public. Thus, local people may often be sceptical of this new technology as none of the detailed research is made available to them to help allay their fears or concerns despite it being widely available within the scientific community (Stangeland, 2009). As discussed in section 1 on perception of risk, people tend to be sceptical of politicians and representatives from industry, thus it is important to utilise effective public engagement in conjunction with collaboration projects between government, industry, local authorities, independent experts and environmental NGO's.

When investigating the social interaction and communication between policy makers or plan sponsors and different publics, analysis and media commentators have noted that major communication efforts by sponsors towards publics on the topic of CCS are universally lacking (Damian Carrington speech at the CCS institute, March 2011). Furthermore little effort has been made in developing a basic understanding of attitudes towards CCS (Reiner, 2008). A few examples of efforts to engage publics in advancing CCS technology are to be found in Canada (International Institute for Sustainable Development) but generally remain absent in Europe and the United States (Reiner, 2008).

Risks associated with CCS project are difficult to quantify, in part due to the numerous definitions of risk. The technical scientific risk of a CO2 storage project differs greatly from the social risk as perceived by those who might be affected. For example, a technical risk of CO2 leakage from an injection well can be assessed, modelled and mitigated appropriately. However, the perception of the risk that a project may present and public confidence in the risk assessment itself may be highly influenced by the credibility of the major stake-holder (Kasperson and Kasperson, 2005). Thus although the risk to public health may be scientifically assessed as negligible, the public distrust of a multinational organisation assumed to be in line for financial gain may result in the risk being perceived as high. Drawing a parallel with the nuclear example, if the wider publics reject or doubt the science of climate change and associated risks, the expense and potential risks to health of abatement technologies are deemed to be greater. However, if the risk of climate change is perceived to be greater than the singular risk involved in a CO_2 or nuclear accident then opposition to such technologies is likely to be lower (Bickerstaff et al., 2008).

Public perception and acceptance of CCS operations are not based purely around the views of the operators or locally affected populations, but incorporate wider audiences that may not be involved at a primary level. The perception that CCS can be responsible for a possible rise in energy bills maybe cause the technology to be viewed negatively, even by people not living near an active storage site (Shackley et al., 2009). Evidence from published reports such as Shackley et al. (2007b) indicates that overall there is a generally positive global perception of CCS. However to put this into its full perspective, it is necessary to analyse and identify specific groupings of opinion within a studied population. Once these groups are isolated, trends are evident, for example among members and representatives of environmental NGO's who have a particularly negative perception of CCS. They express concerns related to risks of pollution and other environmental dangers that are enhanced by arguments that CCS distracts funding away from fully renewable energy sources (Shackley et al., 2007a).

Furthermore, stakeholder opinions may differ depending on the current status of CCS in a particular country. For example, in Norway where CCS operations have been active for the past 13 years, there is evidence of a generally positive attitude among the populations. Conversely, countries such as Denmark that have effective low carbon energy infrastructure, there is overall a less positive attitude towards CCS which is seen to have potentially negative impact on development of renewable energy sources (Shackley et al., 2007b).

The deployment of CCS technology has been slow and difficult across the globe with demonstration projects are currently in operation in Norway, Canada, USA, Netherlands and France. Previously active projects now completed occurred in Norway and Australia, not including the Norwegian Mongstad project, recently cancelled due to spiralling costs. Several proposed project have met un-expected levels of opposition causing them to be suspended pending the outcome of enquiries and legal battles. A prime example is a joint plan between Shell and the Dutch government to sequester CO_2 in depleted gas reservoirs under the small Dutch town of Barendrecht. A series of errors in communication of plans and risk assessments led to fierce opposition from residents – town alderman Simon Zuurbier was recorded in the Financial Times as stating that “It’s become clear that there is no public acceptance for CCS in the boundaries of this community” (Cohen and Khermouch, 2009). The importance of public perception to CCS ambitions was summarised by Eric Drosin of the Zero Emission Platform Group “The greatest challenge facing CCS is not so much technological as it is one of perception,” and “The (CCS) technology is virtually unknown among the general public.”(Cohen and Khermouch, 2009).

Similar responses to planned operations have been encountered in Germany (Fischedick et al., 2009; Slavin and Jha, 2009), Denmark and the United States. Yet in Germany, a study undertaken by Fischedick et al. (2009) concludes that the perception of CCS related risks in Germany is virtually nil due to an almost total lack of knowledge relating to CCS. In general the German population are neither for nor against CCS. Therefore objections to CCS technology were initially assumed by policy makers to relate to NUMBY (Not Under My Back Yard) effects allied to other preconceptions that CCS is competing with renewable sources. However, the Fischedick et al. (2009) study added that media and NGO reporting of potential increases in energy costs and increased resource consumption as a result of CCS aids negative perception of the technology by the wider public. The study went on to highlight the need for a comprehensive description and explanation of all aspects of CCS implementation by the German media if the technology is to be considered viable.

Opinions of CCS may vary however, between an ‘in principle’ level and an ‘in reality’ level. A study into the acceptance of CCS technology in the Netherlands indicates that only 1.4 to 6.4% of respondents to a survey found the proposition of CCS technology so unacceptable that they would consider taking action against it to prevent implementation in the Netherlands (de Best-Waldhober and Daamen, 2006). The results of this study conflict with the mass objection witnessed at Barendrecht. It should be noted however that the reliability of such surveys conducted to gauge the acceptance of CCS has been questioned by some researchers who suggests that many of the responses are “pseudo-opinions”, representative of what the respondent feels the surveyor wants to hear. Such opinions are changeable in the presence of non-scientific information and may vary depending on the mood of the interviewee (de Best-Waldhober and Daamen, 2006). An alternative methodology proposed by de Best-Waldhober and Daamen (2006) is to use an informed choice questionnaire that provides respondents with material that assists them in providing an informed response. However, the difficulty of taking this approach is selecting what material is relevant and appropriate to inform while remaining neutral and non-leading.

A study of the perception of CCS in Great Britain concluded that many people have a good understanding of climate change and the risks it poses in addition to assessing which technologies increase or decrease CO_2 levels. However, when questioned about their level of knowledge of CCS technologies, only 5% of respondents had heard of or read about either carbon capture and/or storage in the past year. Furthermore only 2% of respondents saw CCS technologies as the best way of addressing global warming. This figure rose to 22% once technical and factual information was provided on how CCS works and the comparative costs of alternative technologies such as renewable energy. This research supports the view that positive public perceptions of technologies are strongly linked to levels of information and the type of knowledge possessed by the public (Curry et al., 2005).

Evidence suggests that stakeholders such as NGO's and commercial organisations with a vested interest in energy provision and climate change should be approached in the same manner as the other sectors of the public when considering opinions on CCS. Work undertaken by Johnsson et al. (2009) compared stakeholder attitudes on CCS between the USA, Europe and Japan and indicated all stakeholders believe climate change is a serious threat and that renewable power generation and CCS have a part to play in combating it. However, the majority of stakeholders put renewable energy sources above CCS in terms of attractiveness, consistent with views measured across the wider population. Additionally when considering perceived risk of CCS operations, it was found that leakage from reservoirs is stated as the primary concern among stakeholders and public opinion (Johnsson et al., 2009). Furthermore, Stephens et al. (2009) indicate that exposing stakeholders, i.e. individuals with a vested interest in a relevant project, to expert opinion and information increases levels of acceptance. This increase in knowledge however, does not cause the individuals perception of the risks to increase, mirroring the trends shown by the local public.

5.3.2 BARENDRECHT CASE STUDY

Much can be learned about the role of public engagement by a detailed analysis off the events at Barendrecht in the Netherlands. This case indicates the importance of high quality public collaboration in all stages of planning and development of the project. In this case Shell undertook a successful environmental impact assessment concluding that the site was the most reliable alternative with the lowest risk options. The project received the full backing of the Dutch government who agreed a contribution of £25 million and viewed it as the first in a series of steps for storing CO_2 (Chaffin, 2009). However, the government decided against opening a public debate and withheld a commissioned report relating to a review of the underlying geology from public access. Therefore, there was no pre-project understanding of the state of public opinion of CCS technology or bi-directional knowledge transfer between either the government or Shell and publics at national and local levels.

Opposition from local residents stemmed from their being alerted to the planned storage project via a Shell press release, rather than through communication from the government despite being a centrally financed project. Thus people perceived the project as a commercial enterprise contributing to Shell's profits without consideration for the safety of the local population. In fact, the site selection was the result of an extensive government funded study for the safest and most suitable sites for a pilot project. However, this fact was not openly communicated to the local population. As a result of this miscommunication the townspeople gathered legal representation in an effort to rebut the project (Webster, 2010). A visit and presentation by Shell representatives was praised by a local businessman as being “clear and convincing” but he went on to suggest that the damage had already been done and that “a lot of people are against it and won’t be convinced by any presentation” (Chaffin, 2009).

The government ignored public opposition and approved a small-scale demonstration facility for CCS at Barendrecht as a test site aimed towards a planned full-scale operation. The case was referred to the courts was subject to legal dispute as the townspeople continue a campaign to stop the project (Berrill, 2009) before the entire project was eventually cancelled (Terwel et al., 2012). Considering the model of public engagement (Fig. 5.2), it seems that the PE exercises implemented for the Barendrecht controversy were too little too late. In addition they were launched after a breakdown in trust, with the intention of gaining acceptance for an already planned and approved project. The developers did not discuss the townspeople’s concerns openly and with the appropriate degree of humility prior to decision making. The established flow of communication was unidirectional and failed to engage the local population.

In contrast to the Dutch example, positive results emerging from the ‘correct’ implementation of public engagement strategies are illustrated by the CCS project at Lacq, south-west France, owned and run by the French energy company Total. The project took 27 months from initial press release to permit with limited objection due in part to early efforts to engage local people in planning meetings (Ha-Duong, 2010; Ha-Duong et al., 2009). Three public meetings were arranged involving local people and experts invited to discuss topics such as risks, control and economics. These meetings led to the formation of a surveillance committee that comprised members of elected state and local government bodies, members of local associations, experts and Total representatives. This committee met eight times over the course of the permit application and all reports/documents relating to the projects were made publicly available to ensure a level of transparency that had been requested by the public. Ha-Duong (2010) summarised the important lessons for standards of PE as:

- Resources to be put in place early, perform analysis to map out stakeholders up front
- Utilise asymmetric decision making – All participants to public dialogue do not make final decision, but all participants in making the final decision must take part in public dialogue.
- Greater transparency and efficiency is gained by having technical experts answering questions directly.
- Public awareness of technical science must be improved.

To summarise the role of public perception and acceptance of CCS, we must draw on the conclusions of Tokushige et al. (2007) who outline several connected key factors in increasing the acceptability of CCS. They propose that an increase in the knowledge of benefits to the environment decreases risk perception thus improving public acceptance. Trust in information and its sources influence the acceptance of CCS indirectly via decreasing risk perception and enhancing benefit perception.

5.4 CONCLUSIONS

The conclusions drawn by Tokushige et al. (2007) suggest the public acceptance of CCS can be gained by means of educating different publics of the environmental benefits of the technology. However, this appears to be at odds with the founding principles of public engagement, specifically that its purpose is to communicate and inform, not to convince or persuade. It is for this reason that I felt it was necessary to investigate the role of public engagement on an individual's perception of CCS in a neutral manner removed from vested interests and maintaining the two way flow of information considered by Rowe and Frewer (2005) to be fundamental. For this bi-directional flow to be achieved, the study should impact both the knowledgeable professional and the individual seeking information. This may be that the individual benefits by an increased technical knowledge, and any preconceived notions of the public's perceptions by the professional either proven or disproven.

Furthermore, to examine public perceptions fairly and in an unbiased manner, unlike the informed choice questionnaires (de Best-Waldhober and Daamen, 2006), the research in the following chapter seeks to maintain a two-way flow of information. To achieve this, it is the public who should be given the opportunity to seek answers based on their individual perceived knowledge gaps and receive direct responses from a range of experts so that they may dray their own conclusions. This is preferable to being examined on topics deemed important by researchers that may ignore individuals particular concerns, potentially leading to biased or incomplete conclusions.

Therefore, based on the lessons learned from founding theories and published case studies, for the impact of public engagement on public perceptions of CCS to be fairly understood, an open two way dialogue is required between perceived experts and members on the public, who define an agenda based on their personal perceived gaps in knowledge.

REFERENCES

Berrill, P., 2009, Dutch ministers give OK for Barendrecht CCS plan.

Bickerstaff, K., Lorenzoni, I., Jones, M., and Pidgeon, N., 2010, Locating Scientific Citizenship: The Institutional Contexts and Cultures of Public Engagement: Science, Technology & Human Values, v. 35, no. 4, p. 474-500.

Bickerstaff, K., Lorenzoni, I., Pidgeon, N. F., Poortinga, W., and Simmons, P., 2008, Reframing nuclear power in the UK energy debate: nuclear power, climate change mitigation and radioactive waste: Public Understanding of Science, v. 17, no. 2, p. 145-169.

Chaffin, J., 2009, Public Wary of Carbon Capture, The Financial Times.

Cohen, R., and Khermouch, G., 2009, Carbon Sequestration Faces More than Just Technical Challenges: The Electricity Journal, v. 22, no. 8, p. 5-6.

Curry, T. E., Reiner, D., de Figueiredo, M. A., and Herzog, H., 2005, A Survey of Public Attitudes towards Energy and Environment in Great Britain: Laboratory for Energy and Environement: Massachusetts Institiute of Technology.

de Best-Waldhober, M., and Daamen, D., 2006, Public perceptions and preferences regarding large scale implementation of six CO_2 capture and storage technologies.

Douglas, M., 1985, Perception of Risk, Risk Acceptability according to the Social Sciences, Routledge, p. 29-40.

-, 1992, Risk and Blame, Risk and Blame: Essays in Cultural Theory: New York, Routledge, p. 3-19.

Douglas, M., and Wildavsky, A., 1982, Risk a Culture - An Essay on the Seclection of Technical and Environmental Dangers, University of California Press.

Fischedick, M., Pietzner, K., Supersberger, N., Esken, A., Kuckshinrichs, W., Zapp, P., Linßen, J., Schumann, D., Radgen, P., Cremer, C., Gruber, E., Schnepf, N., Roser, A., and Idrissova, F., 2009, Stakeholder acceptance of carbon capture and storage in Germany: Energy Procedia, v. 1, no. 1, p. 4783-4787.

Ha-Duong, M., 2010, Social aspects of carbon capture, transport and storage: Total's Lacq Project.

Ha-Duong, M., Nadaï, A., and Campos, A. S., 2009, A survey on the public perception of CCS in France: International Journal of Greenhouse Gas Control, v. 3, no. 5, p. 633-640.

Johnsson, F., Reiner, D., Itaoka, K., and Herzog, H., 2009, Stakeholder attitudes on carbon capture and storage -- An international comparison: Energy Procedia, v. 1, no. 1, p. 4819-4826.

Kasperson, J. X., and Kasperson, R. E., 2005, The Social Contours of Risk, Earthscan, 355 p.:

Leiserowitz, A., 2006, Climate Change Risk Perception and Policy Preferences: The Role of Affect, Imagery, and Values: Climatic Change, v. 77, no. 1-2, p. 45-72.

Li, Z., Dong, M., Li, S., and Huang, S., 2006, CO2 sequestration in depleted oil and gas reservoirs--caprock characterization and storage capacity: Energy Conversion and Management, v. 47, no. 11-12, p. 1372-1382.

Lorenzoni, I., Nicholson-Cole, S., and Whitmarsh, L., 2007, Barriers perceived to engaging with climate change among the UK public and their policy implications: Global Environmental Change, v. 17, no. 3–4, p. 445-459.

NCCPE, 2012, What Is Public Engagement.

Pawar, R. J., Watson, T. L., and Gable, C. W., 2009, Numerical Simulation of CO2 Leakage through Abandoned Wells: Model for an Abandoned Site with Observed Gas Migration in Alberta, Canada: Energy Procedia, v. 1, no. 1, p. 3625-3632.

Pruess, K., 2008, Leakage of CO2 from geologic storage: Role of secondary accumulation at shallow depth: International Journal of Greenhouse Gas Control, v. 2, no. 1, p. 37-46.

Reiner, D., 2008, A Looming Rhetorical Gap; A survey of Public Communications Activity for Carbon Dioxide Capture and Storage Technologies: Energy Policy Reserach Group.

Rogers-Hayden, T., and Pidgeon, N., 2008, Developments in nanotechnology public engagement in the UK: [`]upstream' towards sustainability?: Journal of Cleaner Production, v. 16, no. 8-9, p. 1010-1013.

Rowe, G., and Frewer, L. J., 2005, A Typology of Public Engagement Mechanisms: Science, Technology & Human Values, v. 30, no. 2, p. 251-290.

Shackley, S., Reiner, D., Upham, P., de Coninck, H., Sigurthorsson, G., and Anderson, J., 2009, The acceptability of CO2 capture and storage (CCS) in Europe: An assessment of the key determining factors: Part 2. The social acceptability of CCS and the wider impacts and repercussions of its implementation: International Journal of Greenhouse Gas Control, v. 3, no. 3, p. 344-356.

Shackley, S., Waterman, H., Godfroij, P., Reiner, D., Anderson, J., Draxlbauer, K., De Coninck, H., Heleen, G., Flach, T., and Sigurthorsson, G., 2007a, Stakeholder Perceptions of CO2 Capture and Storage in Europe: Results from the EU-funded ACCSEPT Survey.

Shackley, S., Waterman, H., Godfroij, P., Reiner, D., Anderson, J., Draxlbauer, K., and Flach, T., 2007b, Stakeholder perceptions of CO2 capture and storage in Europe: Results from a survey: Energy Policy, v. 35, no. 10, p. 5091-5108.

Slavin, T., and Jha, A., 2009, Not under our backyard, say Germans in blow to CO_2 plans, The Guardian, Guardian News and Media Limited.

Stangeland, A., 2009, The public lack of information about CCS - a serious bottleneck, Bellona.

Stenhouse, M. J., Gale, J., and Zhou, W., 2009, Current status of risk assessment and regulatory frameworks for geological CO2 storage: Energy Procedia, v. 1, no. 1, p. 2455-2462.

Stenhouse, M. J., Zhou, W., and Arthur, R., 2006, Assessment of the Long-term Fate of CO_2 Injected into the Weyburn Field, *in* Lombardi, S., Altunina, L. K., and Beaubien, S. E., eds., Advances in the Geological Storage of Carbon Dioxide, Springer, p. 231-242.

Stephens, J. C., Bielicki, J., and Rand, G. M., 2009, Learning about carbon capture and storage: Changing stakeholder perceptions with expert information: Energy Procedia, v. 1, no. 1, p. 4655-4663.

Stern, P. C., and Finebery, H. V., 1996, Understanding Risk: Informing Decisions in a Democratic Society, National Academy Press, p. 3-166.

Terwel, B. W., ter Mors, E., and Daamen, D. D. L., 2012, It's not only about safety: Beliefs and attitudes of 811 local residents regarding a CCS project in Barendrecht: International Journal of Greenhouse Gas Control, v. 9, no. 0, p. 41-51.

Tokushige, K., Akimoto, K., and Tomoda, T., 2007, Public perceptions on the acceptance of geological storage of carbon dioxide and information influencing the acceptance: International Journal of Greenhouse Gas Control, v. 1, no. 1, p. 101-112.

Webster, V., 2010, Public debate revisited on Barebdrecht CO_2 storage, Bellona.

6. ROLE OF PUBLIC ENGAGEMENT IN FORMULATING PUBLIC OPINION OF CCS TECHNOLOGY

6.1. INTRODUCTION

The previous chapter investigates the theory of the public perception of risk and its role in public opinion. This chapter builds upon this theory and describes the detailed methodology and method by which this investigation was conducted, the results obtained and the conclusions drawn from it. This chapter will also critically discuss the methodology drawing comparisons with other studies and comment upon improvements that could be made should the study be repeated.

6.2. METHODOLOGY

Drawing on the theories of risk, the perception of risk, and public engagement (Chapter 5), the question for this study is as follows:

Does public engagement, based upon open and informed debate with a free two way flow of dialogue between knowledgeable professionals and a self-selected audience influence that audiences opinions concerning CCS?

6.2.1 PLANNING

Review of published literature on public engagement practices (Chapter 5), allied to discussion within the Interdisciplinary Cluster on Energy Systems, Equity and Vulnerability (INCLUSEV) CCS working meeting in Edinburgh (March 2009) resulted in the first consideration of an open public dialogue event as a research tool. For the purposes of this study, I deemed a purely survey based investigation inappropriate due to the previously (Chapter 5.4) explained shortcomings expressed by de Best-Waldhober and Daamen (2006) and Malone et al. (2010), in addition to the critique of unidirectional flow of information (Rowe and Frewer, 2005). Therefore, I decided that a public debate format, comparable to the BBC Radio Four's current affairs programme 'Any Questions', was capable of producing the bi-directional flow of information between panel and audience critical for effective public participation (Rowe and Frewer, 2005). An interactive process was critical to my experiment as its purpose was to assess the significance of public engagement and not to convince or dissuade the public about the merits or demerits of carbon capture technology.

When planning the event, several issues had to be given careful consideration. For the venue, a city centre location was preferable due to ease of access by transport links and the potential it offered for demographic diversity in the recruitment of an audience. The Centre for Life venue in Newcastle was approached by virtue of its location. It also provided the option of including the debate in the official programme of the Newcastle Science Festival. The Science Festival is an annual event organised by the Centre for Life in collaboration with universities in the north east region as well as other organisations aimed at showcasing science to all levels and age groups. The benefits to my experiment of being part of the Science Festival were significant, primarily in terms of advertising the event to a more extensive and diverse audience than might be possible for a standalone event.

The selection of the debate panel and the chairperson were critical. It posed one of the significant variables that had the potential to skew the balance of the debate in a positive or negative direction. In mitigation of this, a balance between members who were for, against and undecided was desirable for the composition of the panel. It was also important that each panel member should come from a background that enabled them to be perceived as unbiased towards financial gain or to champion specific project. They needed to lack commercial ties and be sufficiently well informed to speak knowledgeably.

Taking account of the literature emphasising the role of trust in public participation, (Douglas, 1992) I decided that the candidate most likely to speak in favour of CCS technologies - the ‘for’ candidate, should be an academic rather than a representative of a commercial developer of CCS. In general, public trust in big corporations such as BP, Shell and other multinational oil corporations with expertise and interests in CCS is low. This perception is based on evidence an analysis from media coverage of oil related accidents which shows certain sectors of society are most likely to believe that corporations are more concerned with profit than safety, environmental protection and ethics (Bowman, 2010; Edman, 2013). Prof. Jon Gluyas, Chair of CCS Research at Durham University was selected as the candidate who would speak in favour of CCS due to his high level of expertise on the subject, and his intricate knowledge of the UK North Sea; the likely location for geological storage sites from operations in north east England, where the debate was taking place.

Finding a panel member to speak against CCS was difficult. Environmental NGO’s were an obvious choice as they are mostly campaigning against CCS. However, these organisations and the hard line protests that are undertaken in their name frequently polarise public opinion. Consequently the ideal candidate to voice the arguments against CCS needed to possess an accurate grasp of the subject with which to communicate their views against the technology, whilst at the same time being perceived as being trustworthy in the eyes of the public. The rationale behind the debate was to provide legitimate information delivered by a balanced panel as this was critical to the way in which the audience may be influenced when drawing their own conclusions. The Green Party for the North East and Newcastle was approached for a candidate and recommended Sandy Irvine. Mr Irvine has a background in education, a long-term interest in sustainability and climate change and a reputation for being well informed. His position on CCS is that it is the wrong method to combat climate change with unacceptable costs in comparison to more sustainable renewable methods.

Originally I envisaged that there should be one neutral candidate, but as a sufficiently well informed ‘neutral’ was hard to find, I decided instead that two pro CCS panel members with differing backgrounds and degrees of strength of commitment could be beneficial to the dynamic of the panel. Roberta Blackman-Woods was selected as a serving MP (Labour) for Durham City. She possesses an excellent knowledge of the current political standing of CCS, and holds a position of responsibility in the northeast region and is inclined to favour CCS as a means to boosting the local economy. The appointment of Mrs Blackman-Woods on the panel further added a well-known ‘name’ to assist in the advertising of the event. This generated interest from both the local and national press in addition to commercial organisations and associations. Mr Ross Weddle of the Community Renewable Energy (CoRE) Co-op was selected as a panellist for his credentials as a specialist in sustainable development at a community level. The CoRE Co-operative implement community run bio-digesters, solar, wind and micro-generation projects via a not for profit organisation. His position is that carbon reduction targets and energy targets can best be met by bringing responsibility into the local community. Despite this he believes that CCS has its place in the larger scale de-carbonisation of the energy sector. However he has reservations surrounding the costs and that CCS may interfere with investment in renewable technologies, but broadly accepts that renewable energy alone cannot currently meet energy demands. Consequently he regards CCS as a potentially important tool in the transition to a fully renewable energy future.

The selection of the chairperson presented significant challenges. Concerns for attracting an audience led me to consider inviting a well known name with social standing and a reputation for fairness. Primary targets were Radio 4’s Quentin Cooper, whose Material World programme had expressed some interest in covering a portion of the debate; and former Gladiator star Diane Youdale, presenter of a morning show on BBC Tees Radio. Diane Youdale had presented a radio interview on CCS and proven to be well briefed on the topic. Both possible candidates were approached but were unavailable. Further consideration and discussion with the science festival organisers, Prof. Paul Younger, Director of Newcastle Institute for Research on Sustainability at Newcastle University, was recommended as an suitable chairperson as he occupies a trusted position and due to his academic interests. Prof. Younger specialises in sustainability and is well known in the Newcastle and north east area for his work on coal mining, specifically the sustainable use of fossil fuels and the impact of mining on groundwater quality in addition to CCS and geothermal energy.

During the planning stages, it was decided to film the event as a means of accurately reviewing the proceedings in detail. A film would provide a precise record of the questions and topics that were covered and a verbatim account of the panellists' replies. Film evidence could also be used to investigate the tone of responses and make comments on the body language of both the panel and audience which simple voice recordings (the other considered method) would not allow. Following discussion with Mr Steve Wilson, a professional film maker with research interests in Anthropology, it was decided to produce a professional quality recording that could be broadcast live on the internet allowing a wider audience.

6.2.2 IMPLEMENTED METHODOLOGY

The data was collected using a BBC *Any Questions* and *Question Time* style public debate format as described above (Chapter 6.2.1). The format comprised a selected panel of experts with differing backgrounds and a chairperson. The desired panel comprised a diversity of opinions on carbon capture technologies to avoid too great a tendency for bias. On arrival the audience were requested to complete the first simple questionnaire (Fig. 6.1) as explained by an accompanying information leaflet and by instructions on the event title slide projected at the rear of the theatre. Audience members were asked to place the completed questionnaire in a sealed envelope for the remainder of the event.

The event began by the chair introducing and explaining the rationale and context behind the debate. The chair also introduced the members of the panel, who spoke briefly to give their background and opinions of CCS. The debate started with the chair inviting questions from the audience and directing them to specific members of the panel. The chair was responsible for ensuring each panel member received a relatively equal share of speaking time for balance and to keep the event moving. To promote debate, three known attendees were asked prior to the event to come prepared with questions should no other audience members raise their hands, although in the event this was not required. After one hour of debate, the chairman drew the proceedings to a close by inviting the audience to open the second sealed envelope and complete a second questionnaire before placing it in another sealed envelope. Both envelopes from the debate were kept together and handed in at the exit.

Following the event, envelopes containing the 1st and 2nd questionnaires were opened and answers inputted into a spread sheet to facilitate direct comparisons between answers. The results were grouped in ranges for both gender and age to compare whether differing sociological groups responded differently. Statistical analysis of the results was used to identify whether open dialogue causes the respondents to change their perceptions, and if so in what manner. Further analysis was undertaken with direct comparison with published comparable studies to examine whether there is any correlation between changes of opinion from informed decision making.

The whole event was professionally filmed with sound recorded directly from microphones to ensure a high quality recording. These were used to review the event in subsequent analysis to evaluate both the covered topics and answers and other details that might have been missed on the day.

The use of a public debate and targeted questionnaire for this study over random mailshot questionnaires presented control and neutrality challenges. However, the set of questionnaires collected before and after the debate offered the opportunity to examine the differences in answers between the survey population, rather than just examining data collected from random unrelated sources. The audience were directed to complete each questionnaire at a specific time before the debate started and at the close of the event. This ensures that the responses were either un-informed based upon the respondents baseline knowledge prior to the event, or informed based upon the respondents knowledge at the end of the debate and including the information they had received as a result.

Expanding upon the comments of de Best-Waldhober and Daamen (2006) on the reliability of random surveys, this study offers an interesting comparison as to whether the informed decision making process via open social dialogue produces different results from both the uninformed[*] and informed random questionnaires that she states are changeable based upon the mood of the respondent in the absence of un-scientific and relevant information.

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[*] An uninformed questionnaire comprises a survey where questions are posed with no accompanying information to guide the respondent. Informed choice questionnaires offer extra information specific to the topic or question being investigated to aid the respondent in making an ‘informed’ decision (de Best-Waldhober and Daamen, 2006).

The questionnaire was designed around the basic principle that it is a measure of opinion around four key areas of:

- Mitigating Climate Change
- Security of energy supply
- Risk
- Economic and social benefits to the North East of England.

The questionnaire (

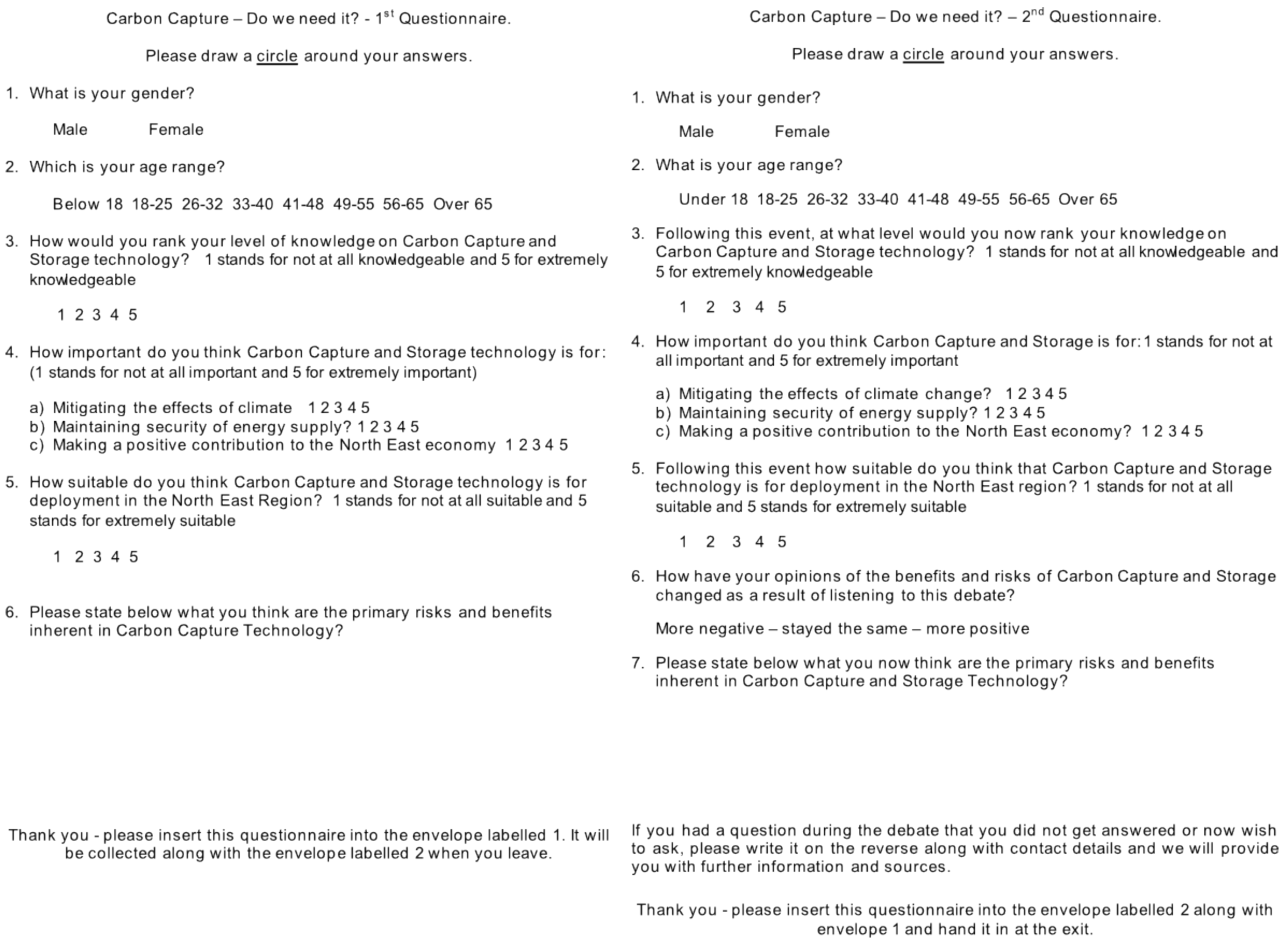
Fig. 6.1) was designed to be simple and straightforward and be possible to complete in less than two minutes. In order to do this a numerical scale was utilised for answers rather than time consuming written responses. The wording of the questionnaire was designed to be neutral and therefore not lead or suggest any particular answers.

Questions 1 and 2 of both questionnaires were to establish the gender and age range. These were included to allow social grouping of respondents in subsequent analysis. Question 3 asked the respondents to rank their degree of knowledge of CCS on a linear numerical scale between 1 and 5 where 1 stood for no knowledge, and 5 stood for extremely knowledgeable.

Question 4 of the first questionnaire was split into 3 parts focusing on the respondents' perceived role of CCS in the mitigation of the effects of climate change, securing the future energy supply and making a positive contribution to the local economy. The responses were measured on a numerical scale of 1 to 5 where 1 represented not at all important, and 5 represented extremely important.

Question 5 took this a step further by examining the respondents' perception on the suitability of CCS for local implementation. This again was measured on a numerical scale of 1 to 5 where 1 stood for not at all suitable and 5 stood for extremely suitable.

Question 6 of questionnaire 1 represented the only written answer on the questionnaire and examined the perception of both risk and benefits of the technology. It was deemed that due to the variety in potential answers, a multiple choice question with numerical answers was unsuitable in that it would lead the respondent to a particular answer rather than allowing free thought.



Carbon Capture – Do we need it? - 1st Questionnaire.

Please draw a circle around your answers.

1. What is your gender?

   Male Female

2. Which is your age range?

   Below 18 18-25 26-32 33-40 41-48 49-55 56-65 Over 65

3. How would you rank your level of knowledge on Carbon Capture and Storage technology? 1 stands for not at all knowledgeable and 5 for extremely knowledgeable

   1 2 3 4 5

4. How important do you think Carbon Capture and Storage technology is for: (1 stands for not at all important and 5 for extremely important)

   a) Mitigating the effects of climate 1 2 3 4 5
   b) Maintaining security of energy supply? 1 2 3 4 5
   c) Making a positive contribution to the North East economy 1 2 3 4 5

5. How suitable do you think Carbon Capture and Storage technology is for deployment in the North East Region? 1 stands for not at all suitable and 5 stands for extremely suitable

   1 2 3 4 5

6. Please state below what you think are the primary risks and benefits inherent in Carbon Capture Technology?

Thank you - please insert this questionnaire into the envelope labelled 1. It will be collected along with the envelope labelled 2 when you leave.

Carbon Capture – Do we need it? – 2nd Questionnaire.

Please draw a circle around your answers.

1. What is your gender?

   Male Female

2. What is your age range?

   Under 18 18-25 26-32 33-40 41-48 49-55 56-65 Over 65

3. Following this event, at what level would you now rank your knowledge on Carbon Capture and Storage technology? 1 stands for not at all knowledgeable and 5 for extremely knowledgeable

   1 2 3 4 5

4. How important do you think Carbon Capture and Storage is for: 1 stands for not at all important and 5 for extremely important

   a) Mitigating the effects of climate change? 1 2 3 4 5
   b) Maintaining security of energy supply? 1 2 3 4 5
   c) Making a positive contribution to the North East economy? 1 2 3 4 5

5. Following this event how suitable do you think that Carbon Capture and Storage technology is for deployment in the North East region? 1 stands for not at all suitable and 5 stands for extremely suitable

   1 2 3 4 5

6. How have your opinions of the benefits and risks of Carbon Capture and Storage changed as a result of listening to this debate?

   More negative – stayed the same – more positive

7. Please state below what you now think are the primary risks and benefits inherent in Carbon Capture and Storage Technology?

If you had a question during the debate that you did not get answered or now wish to ask, please write it on the reverse along with contact details and we will provide you with further information and sources.

Thank you - please insert this questionnaire into the envelope labelled 2 along with envelope 1 and hand it in at the exit.

Fig. 6.1: Example of questionnaires 1 and 2, as distributed to the audience for the debate

Questionnaire 2 mostly mirrored the questions posed in questionnaire 1. However, the purpose of the questions was to examine the respondents' perceptions DUE to the information they had gained. Thus the questions were worded extra carefully, e.g. 'Following this event, how suitable...' and 'Please state below what you NOW think...' An additional question was added to questionnaire 2 (question 6) directly examining whether or not the respondents' perception of CCS had changed as a result of the information they had received, and whether this change was more negative or positive. It was subsequently considered that this question could have been improved by requesting a measure of the magnitude of any perceived change. However at the time it was considered that this would overly increase the length and complexity of the questionnaire.

6.3. RESULTS

6.3.1. OVERVIEW OF RESULTS

Review of the responses indicated that all 31 attendees completed the two questionnaires. Of these 31 respondents, 71 % (22) were male and 29 % (9) female (Fig. 6.2). The event drew a diverse spread of age ranges (Fig. 6.3), however, it was noted that there was a relatively equal distribution of attendants from all age ranges with the exception of 49 – 55 group. There were no attendees under 18. When asked about their general perception of CCS after the debate, 32% were more positive about CCS, 19% less positive and 48% were neither more or less positive about CCS.

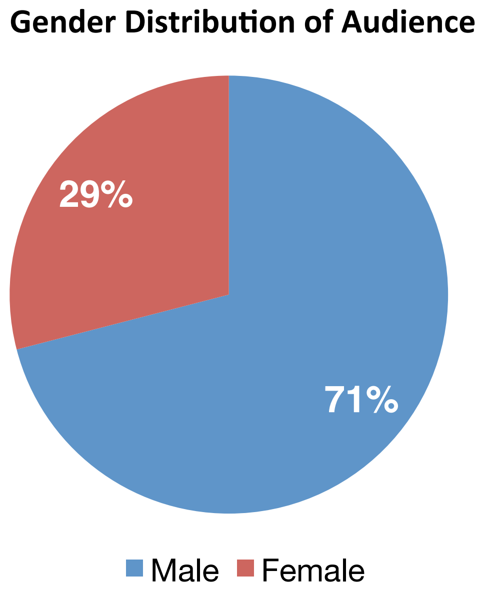


Fig. 6.2: Question 1 responses on gender expressed in percentage of total attendees.

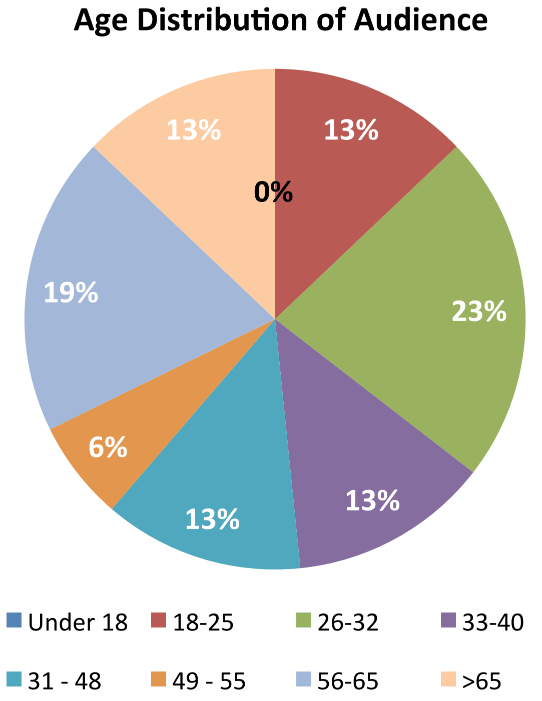


Fig. 6.3: Question 2 responses for age ranges expressed as a percentage of total attendees.

6.3.2. QUESTIONNAIRE RESULTS

Question 3

Question 3 of both questionnaires asked the respondent to rank their knowledge of CCS on a scale of 1 – 5 where 1 stood for 'not at all knowledgeable' and 5 stood for 'extremely knowledgeable'. The second questionnaire preceded the question with 'following this event' in order to investigate whether the public felt the debate had increased their level of understanding.

Question	Questionnaire 1			Questionnaire 2		
	Mean	St Dev	Mode	Mean	St Dev	Mode
3	2.55	1.09	2.00	3.32	0.70	3.00
4.a	3.84	1.00	4.00	3.65	1.14	4.00
4.b	3.06	1.34	3.00	3.00	1.39	3.00
4.c	3.32	1.11	4.00	3.10	1.27	3.00
5	3.26	1.06	3.00	3.29	1.12	4.00

Table 6.1: Table of mean and modal responses to all questions before and after the debate.

All 31 attendees returned a response for this question both before and after the debate. The modal value for this question was 2 with a mean response of 2.55 (Table 6.1) indicating that the audience had a little to no knowledge of CCS technology prior to the event. Although this increased to a mode and mean of 3 and 3.32 respectively in Questionnaire 2, the audience still felt they possessed only an average knowledge of CCS as a consequence of exposure to both the introduction and the debate.

The responses per attendee before and after the debate are expressed graphically in Fig. 6.4. A direct comparison in responses between questionnaires' 1 and 2 expressed as a percentage of total respondents is showing in Table 6.2.

Level of Understanding	% of Responses	
	Q1	Q2
1	16	0
2	39	10
3	23	52
4	19	35
5	3	3

Table 6.2: Table showing responses for question 3 expressed as a percentage of total attendees and the comparison before (Q1) and after (Q2) the debate. A rank of 1 equates to 'not at all knowledgeable' and 5 equates to 'extremely knowledgeable'.

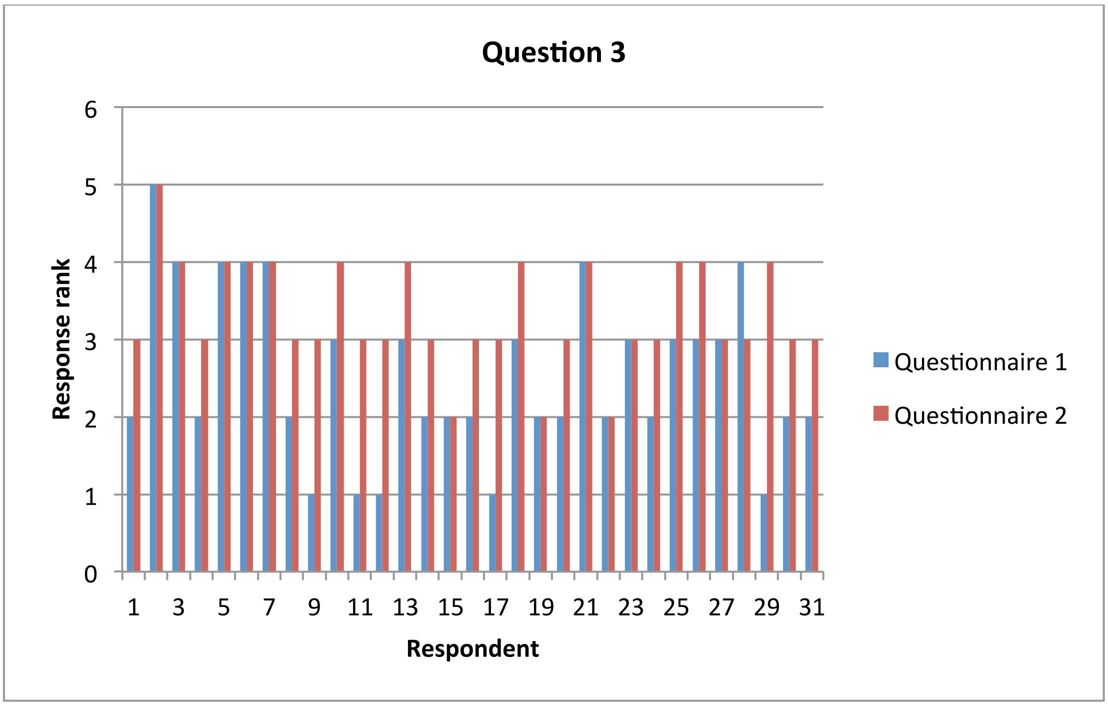


Fig. 6.4: Comparison of participant responses for question 3 from questionnaires' 1 and 2.

A total of 19 out of 31 (61.3%) respondents felt that their level of understanding had increased due to the event (Fig. 6.4), 11 (35.5%) felt the event had made no difference and one felt their understanding was worse than before. However, six of the 11 respondents who felt the event had no impact on their understanding had initially scored their knowledge as a ‘4’ or ‘5’ indicating they were already very knowledgeable about CCS technology. Therefore the technical level of the debate was unlikely to make any impact to these persons.

Of the 5 (16%) of respondents who scored their initial level of understanding as ‘1 not at all knowledgeable’ four felt that the debate had improved their understanding by 2 points, to an average level of ‘3’, with one feeling their understanding had increased to ‘4’. The respondent who deemed that the debate had reduced their knowledge offered no explanation as to why this was the case. However, as his initial ranking was a quite knowledgeable ‘4’ that subsequently dropped to an average ‘3’, it is plausible that he overstated his initial level of expertise and as a consequence of a debate, downgraded this accordingly.

Question 4.a

Question 4.a asked ‘how important do you think Carbon Capture and Storage is for mitigating the effects of climate change and ranked answers on a numerical scale of 1-5 where 1 stood for not at all important and 5 stood for extremely important. All 31 attendees returned a response for question 4.a for both questionnaires. The mean response prior to the debate was 3.84 with a mode of 4 (Table 6.1). This indicates that the audience believe that CCS is in important technology in the fight against climate change. However, the average response decreased to 3.65 after the event while the mode dropped one point to 3. Consequently, the debate made the audience feel that CCS may not be as important as they first thought. Despite this, the mean and mode remained above 3 (Fig. 6.5) and as such implies that CCS is perceived as an important mitigation technique, but not the most important.

Six of the 31 respondents deemed that CCS was more important for mitigating climate change after the event while 7 respondents concluded that CCS was less important following the event. Of the 7 respondents that decreased their rating, 4 reduced their ranking by 1 point, 2 by 3 points and 1 by 2 points. Of the two respondents who drastically reduced their ranking by 3 points, the rankings were reduced from 5 and 4 to 2 and 1 respectively. Overall, these two respondents felt more negatively about CCS as a result of this event and had a limited to moderate knowledge of CCS technology before the event began (Fig. 6.6). Demographic effects such as age range and gender were considered, however the data showed no correlations between change of opinions and demographic.

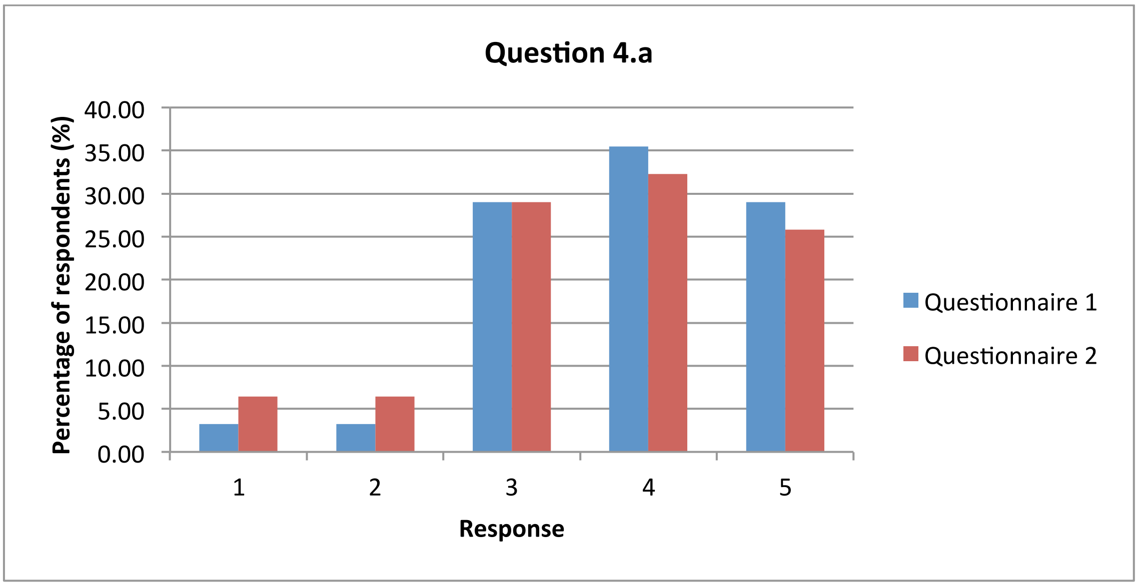


Fig. 6.5: Frequency of response ranking for question 4.a expressed as a percentage of the total attendees. Diagram shows the variation between before (Questionnaire 1) and after (Questionnaire 2) the debate.

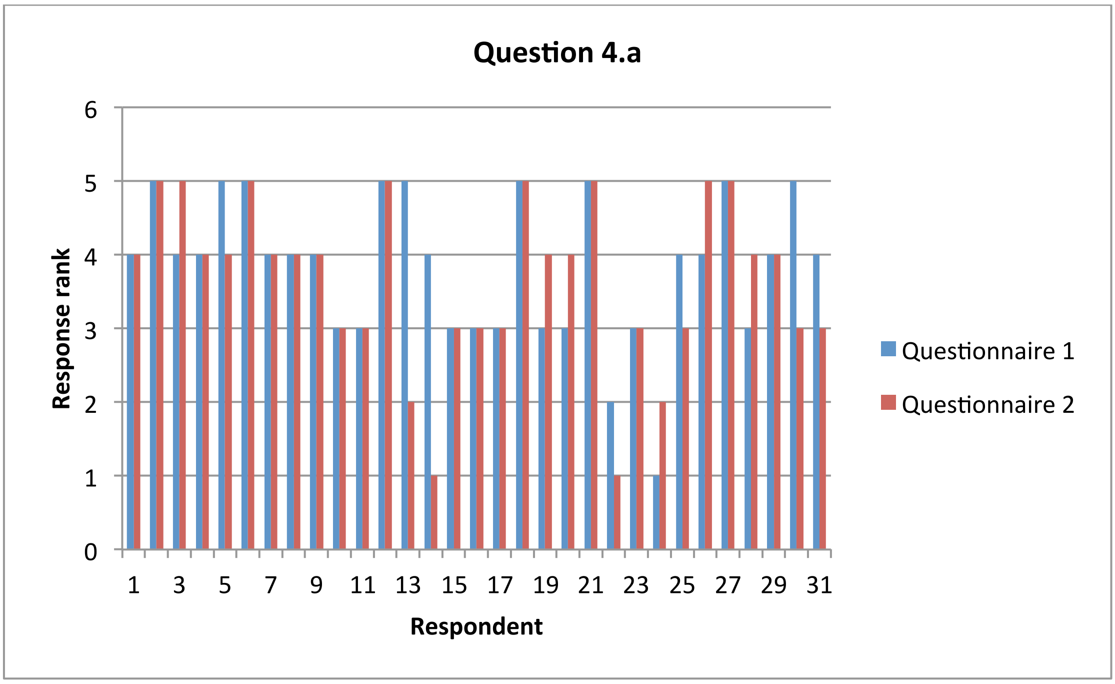


Fig. 6.6: Graph showing the individual perceptions of all participants both before (Questionnaire 1) and after (Questionnaire 2) the debate and the variations between the two responses.

Question 4.b

Question 4.b asked 'how important do you think Carbon Capture and Storage is for 'maintaining the security of energy supply' and ranked answers on a numerical scale of 1-5 where 1 stood for not at all important and 5 stood for extremely important. All 31 respondents offered an answer in both questionnaires. Answers prior to the onset of the introduction and debate returned a mean ranking of 3.06 and a mode of 3.00 indicating that the audience felt CCS was of average importance for maintaining energy supply (Table 6.1). Following exposure to the debate, responses were effectively unchanged with the mean falling by 0.06 to 3.00 and the mode remaining unmoved at 3. Consequently, it is considered that the debate did not significantly alter the audiences' general perceptions on the importance of CCS for maintaining energy security.

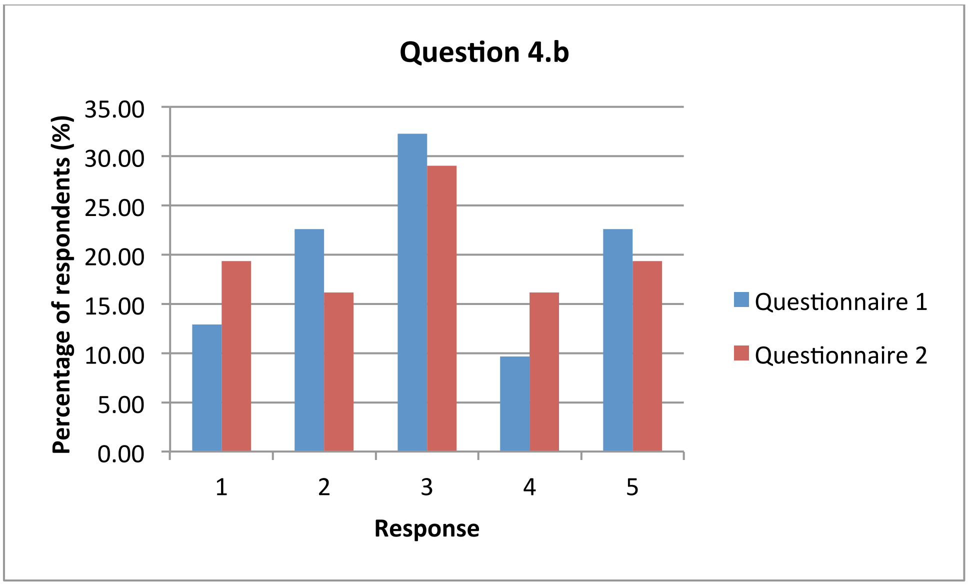


Fig. 6.7: Histogram showing the percentage of responses to question 4.b where a ranking of '3' proved the dominant response.

When analysis was expanded to individual respondents, 6 of the 31 stated that they felt CCS was more important for maintaining the security of energy supply as a result of the event whereas 6 felt that it would play a less important role than prior to the debate. The remaining 19 respondents were unchanged in their opinions. Equally, there was a relatively even spread of changes in ranking. Three respondents changed their opinions by an increase of both 2 and 1 points. Of the respondents that felt more negatively, two decreased their ranking by 2 points, three by 2 points and one by 3 points.

Furthermore, this question showed subtle patterns when analysed on a demographic basis. It was observed that three (50%) of the respondents who felt that CCS was more important for maintaining energy supply following the debate were of the 56 – 65 age range whilst no member of this age group felt more negatively. It is unclear why this may be as no explanation was offered in the comments section of the Questionnaire. A hypothesis is that while younger generations may be more idealistic in their views, older generations may be more conservative. As such, the value of maintaining a constant and reliable source of electricity may take precedent over drastic reductions in CO_2 emissions.

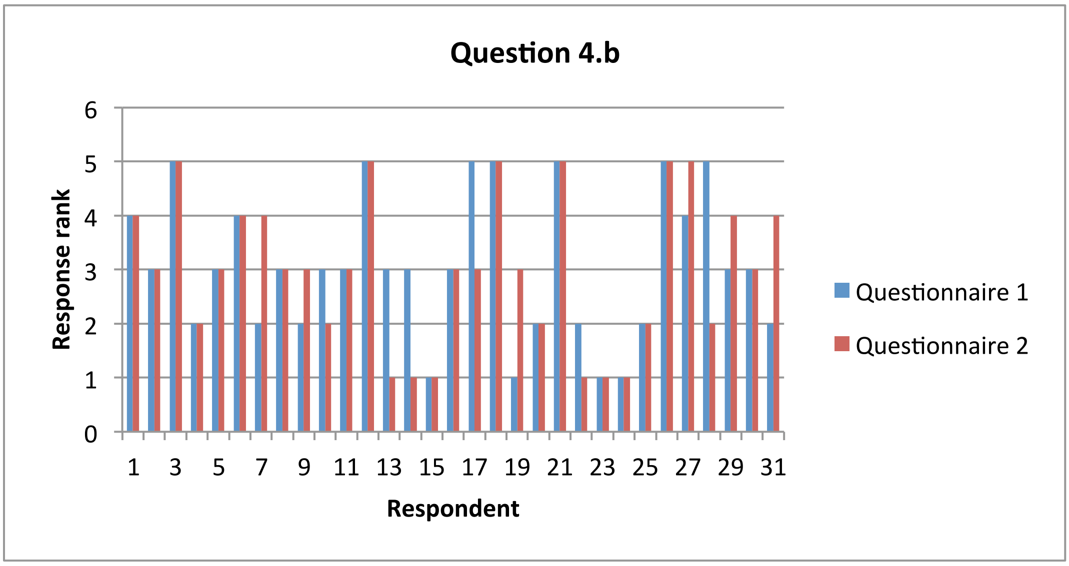


Fig. 6.8: Individual attendee responses to Question 4.b both before and after exposure to the introduction and debate session.

Question 4.c

Question 4.c asked ‘how important do you think Carbon Capture and Storage is for making a positive contribution to the North East Economy’ and ranked answers on a numerical scale of 1-5 where 1 stood for not at all important and 5 stood for extremely important. A 100% response rate was achieved for this question. Prior to the introduction and debate, the mean audience response was 3.32 and a mode of 4 (Table 6.1, Fig. 6.9) indicating that the attendees felt CCS was of above average importance to contributing to the local economy. This decreased as a consequence of the debate with the mean and mode decreasing to 3.10 and 3 respectively to an average importance.

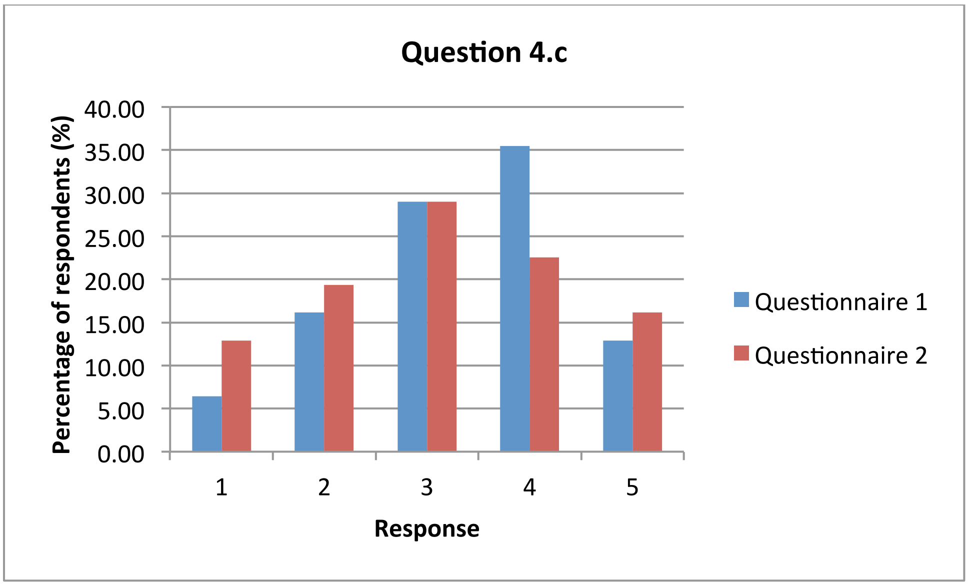


Fig. 6.9: Histogram showing the percentage of responses to question 4.c. The initial modal response of 4 fell significantly as a consequence of the debate and was replaced by 3 as the mode.

Of the 31 respondents, 5 stated that they felt CCS would play a more important role in boosting the north east economy as a result of the event whereas 10 felt that it would play a less important role than prior to the debate (Fig 6.10). The remaining 16 respondents were unchanged in their opinions. The respondents that felt more positively about CCS's role in contributing to the north east economy increased their ranking by 1 point. However, eight of the ten respondents that felt more negatively decreased their opinion ranking by one point and the remaining two by 2 points. It was observed that age grouping was significant in those who felt more negatively following the debate with 50% of the total being in the 26 to 32 age category.

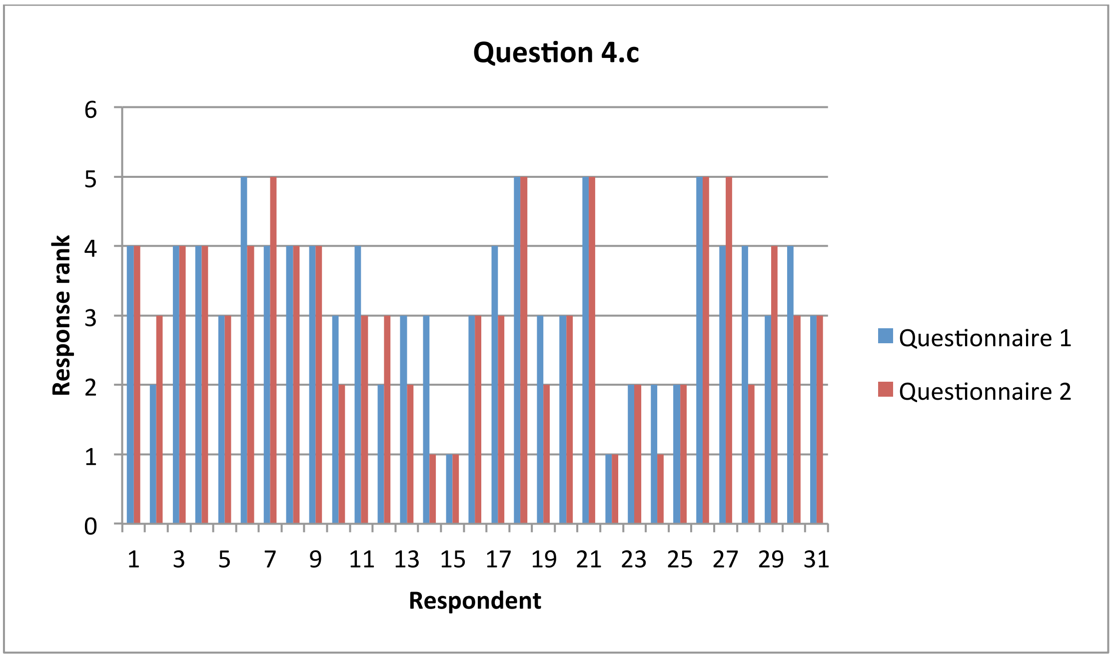


Fig. 6.10: Individual attendee responses to Question 4.c both before and after exposure to the introduction and debate session

Question 5

Question 5 investigated how suitable the audience felt CCS technology was to the north east region before and after the event and ranked answers on a numerical scale of 1-5 where 1 stood for not at all suitable and 5 stood for extremely suitable. Prior to the event all 31 attendees provided a rank for Question 5 with a mean and modal response of 3.26 and 3 respectively (Table 6.1Fig. 6.11). This is indicative of an average and mainly undecided response where the audience are neither for nor against CCS. Following the event, 9.8% (3) of the audience abstained from responding. Despite this, the mean increased to 3.29 and mode climbed one rank to 4 indicating that the audience felt CCS was more suitable to the North East as a consequence of exposure to the debate.

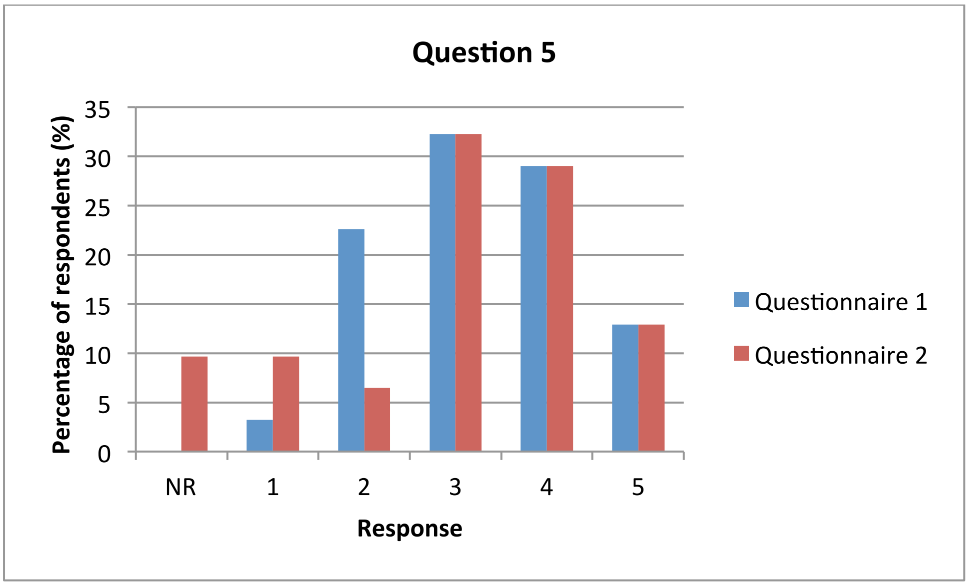


Fig. 6.11: Histogram showing the percentage of responses to question 5. The initial modal response of 3 remained unchanged after the debate. However the data indicate an almost bimodal response of both 3 and 4, both of which were unchanged.

Of the 31 respondents, 7 felt that CCS was more suitable for the North East region following the debate whereas 4 felt it less so. The remaining 20 respondents were unchanged in their opinions (Fig. 6.13).

Question 6

Question 6 asked whether the audiences opinions on CCS had changed, and if so whether they now felt more negative or more positive. As stated above (Figs. 6.2 and 6.3), predominantly the audience was unchanged in their opinions, but 10 felt more positive and 6 less so. In an attempt to further refine these variations in perceptions, it was attempted to group these changes by audience demographic

(Fig. 6.12 Table 6.3). Perception as a function of age grouping was mostly inconclusive. However, the 49 - 55 age range did prove the most negative where members were either more negative or unchanged with a 50:50 split. Although 50 % of the 41 – 47 group were also more negative, 25% were also more positive. No substantial conclusions could be made with regards to the sway in opinions as a function of gender.

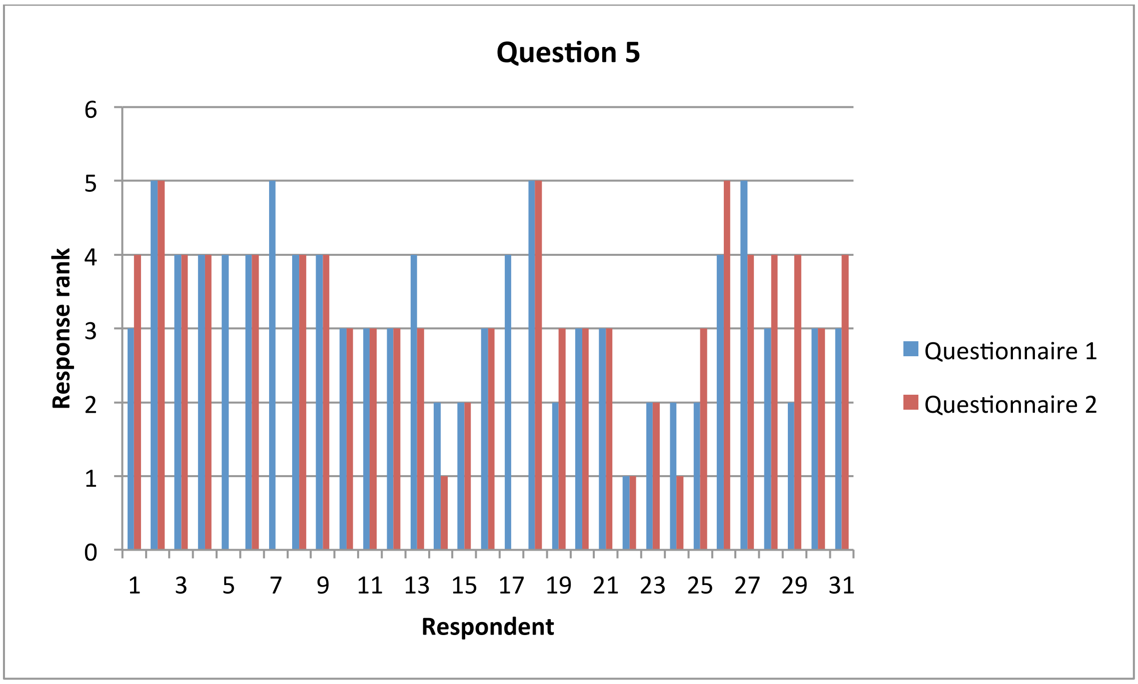


Fig. 6.12: Individual attendee responses to Question 5 both before and after exposure to the introduction and debate session

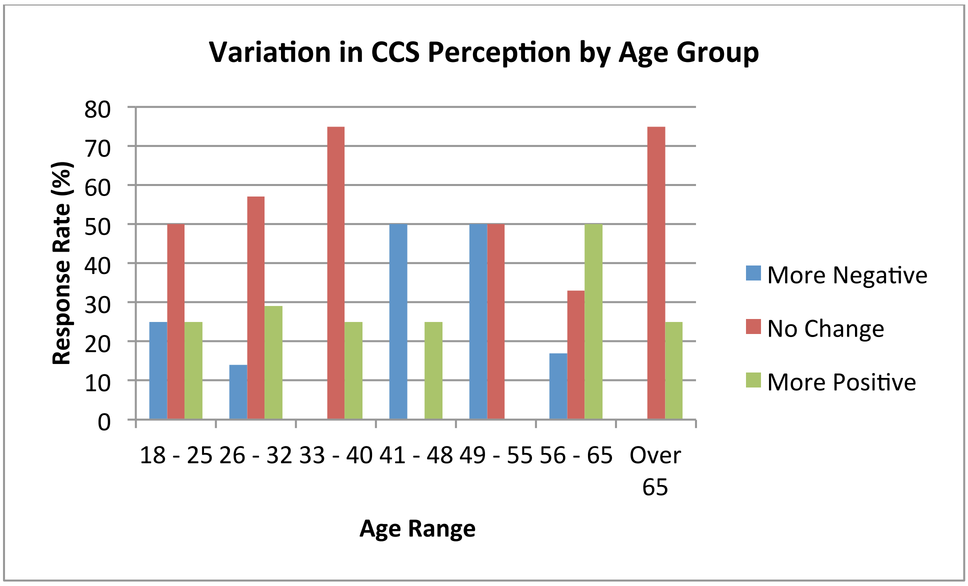


Fig. 6.13: Changes in respondents' opinions following the debate filtered into age groupings. Whilst no change is the dominant response, respondents aged 41 to 55 where the most negative whilst ages 26 to 32 and 56 to 65 where the most positive

Gender	Change of Opinion (%) More Negative	No Change	More Positive
Male (22)	13.64	54.55	31.82
Female (9)	33.33	33.33	33.33

Table 6.3: Changes in respondents opinions of CCS following the debate, separated into male and female demographics. The male group while predominantly unchanged, was slightly more positive following the debate. The female group although a smaller sample size, was evenly split between all three sways showing no polarization of opinions following the debate.

6.4. DISCUSSION OF RESULTS

It is important to reiterate that the purpose of this event was to investigate whether public engagement has an effect on the publics' perception of a specific topic, in this case CCS. It was not the purpose of this event to convince or persuade the public to be more positive about CCS. It is also critical to restate that the role of public engagement is to open a bi-directional dialogue between a party with a vested interest in a project and a party who are to be affected by such a project. Its purpose is to inform, address fears, concerns and opposition, and to allow the public to make an independent decision accordingly.

The results of this study indicated that overall, the audience did not alter their opinion on CCS as a consequence of the debate session. As such it would be simple to conclude that public engagement has little to no effect on people’s perceptions of a technology, however this would be incorrect. Whilst the respondents’ overall perception of CCS may have been unchanged, their perception of specific issues relating to its suitability and value did alter, in some cases significantly. As such, it is clear that this public engagement example has had an impact on the attendees’ perceptions, but in a more subtle manner that initially expected.

Furthermore, the disparities between responses relating to these sub-issues as a consequence of the debate allow conclusions to be drawn on the respondents’ reaction to the speakers, and any apparent bias in the panel. Overall, respondents often felt more negatively about issues such as the importance of CCS in maintaining energy supply, mitigating climate change and economic benefits. On review of the video, it is considered that the audience took more favourably to the responses by Sandy Irvine over and above the other speakers.

The video of the event exhibits results that were of greater interest than those provided by the questionnaire responses. While, as stated previously, it must be noted that the event was held during the escalating events of the Fukushima Nuclear accident, the topics covered during the debate were unexpected. The chair was instructed to ensure that the theme of the discussion was diverse and not to allow the debate to stall on one particular topic. It transpired that this was not required and the scope of the discussion was broader than anticipated. Perhaps the most significant and indeed surprising result was that the topic of safety was only discussed twice, once with regards the CCS' ability to cope with natural disasters, and once regarding the safety of the technology itself. This is at odds with recent surveys into CCS opinions that frequently cite the concerns surrounding leakage and safety as the foundation of most public opposition (see Curry et al. (2005), de Best-Waldhober and Daamen (2006), de Coninck et al. (2009), Ha-Duong et al. (2009), Miller et al. (2007), Shackley et al. (2007).

This discord may be, in part, due to the experience levels of the audience in attendance. Although the dominant response indicated an experience level of 2, 45% of the audience ranked their knowledge of CCS at 3 and above, including 19% of the audience with a ranking of 4. As such, it appears likely in this situation that the questions were voiced by the more knowledgeable members of the audience leading to a more social and economic theme of debate. The questionnaire did not require the respondents to state their occupation to maintain both anonymity and keep the questionnaire as concise as possible. Consequently it was not possible to group those with a high level of knowledge level to a particular type of technical or scientific occupation, therefore, any respondents who potentially work within the field or CCS were not able to be screened from the results.

The work undertaken by Roberts and Mander (2011) offers the best comparison to this study as it utilises similar methods such as before and after questionnaires, a panel of experts from a range of backgrounds and organisations, and was undertaken in a geographical locations that has been identified as a potential site for CCS operations. However, the methods diverge as Roberts and Mander (2011) utilised citizen panels, effectively a round table discussion, over a public debate format, and these discussions were repeated over three sessions. The findings of these citizen panels concluded that CCS has an initially low profile and that many of the respondents classed the consequences of leakage, either at capture point or storage, as their primary concern. Repeated exposure to the panel of experts did begin to indicate other concerns based upon whether the technology is in fact needed at all owing to its financial penalty. However, the authors felt that this was related to a lack of understanding on the magnitude of the required cuts in carbon emissions and that the attendees did not comprehend that renewable energy sources alone could not provide a direct replacement for fossil fuels. It should also be noted although possibly inconsequential, that the attendees to the Roberts and Mander (2011) meetings were paid the sum of £80 for 8 hours of attendance in direct contrast to this study where no financial incentive was offered to the audience.

Other published studies such as Bradbury et al. (2009) and Upham and Roberts (2011) that also use degrees of informed decision making, via the medium of focus groups or commissioned filmography respectively offer differing findings. Both of the aforementioned studies indicate that knowledge of CCS was low with few individuals possessing an average to detailed knowledge of the integral processes of CCS. The Bradbury et al. (2009) study concludes that the respondents felt that social risk was prevalent over technical risk, i.e. where past experiences left them more concerned with whether their objections would be heard, in addition to the potential mitigation of damage and compensation should failure occur rather than the failure of the technology itself. The Upham and Roberts (2011) study was repeated across 6 European countries and found that public opinion shared a high degree of commonality between all participating locations. This study was comparable to the one described in this thesis based on the use of pre and post discussion questionnaires with the objective of investigating the development of opinions on CCS via being exposed to new and additional information. However, the methods differ in that the Upham and Roberts (2011) study utilised a DVD to stimulate a focus group discussion while this study used a panel debate with an audience. With regards to results, the Upham and Roberts (2011) study differs in that much of the discussion and objection was related to storage uncertainties, at odds with the cost and position in the future energy mix presented here. However, the overall conclusions are similar in that the public, despite being from differing demographics, share a preference for renewable energy over CCS and lack trust in industry and government to make financially and environmentally suitable decisions regarding the future energy supply.

Although the Newcastle Science Festival debate focused on CCS in the north east of England, individual locations for infrastructure were no discussed in detail during the event. As such ‘NUMBY’ (not under my back yard) effects like those identified in the study by Wallquist et al. (2012) were not prevalent in the audience.

6.5. DISCUSSION OF METHOD

The choice of both host venue and geographical location for the event proved successful on both accounts in terms of ease of access and nearby demographics. Although hosting within the Newcastle science festival aided the event significantly in terms of access to venues, advertising and funding. Although the event sold out at 50 attendees, 19 failed to attend. The results may have been statistically improved if the full 50 had been present; however the 31 still offered a significant enough spread to be considered statistically valid.

The results of the level of knowledge question and the nature of the debate topics may suggest that a portion of the audience possessed an above average level of technical knowledge. This may be a consequence of hosting the event as part of the Science Festival. As such, it may be inaccurate to apply sweeping conclusions to the broader public based purely on the results of this debate.

Despite best intentions and efforts, it is impossible to conclude whether the opinions expressed by the respondents are their true inclinations or pseudo-opinions expressed as what the participant perceives the desired answer to be. It is a flaw and limitation inherent in using written anonymous surveys that has previously been studied in depth by de Best-Waldhober and Daamen (2006), Ha-Duong et al. (2009) and Malone et al. (2010) and authors within. Repeated surveying of the respondents may have given an indication of whether their opinions were valid, yet this still remains difficult to accurately determine and correct for.

Likewise, while previous work has indicated that CCS suffers from little exposure in the public domain, efforts to immediately inform prior to surveying are risky and easily lead to introductions of biases, both positive or negative, despite best intentions to be neutral (Ha-Duong et al., 2009; Malone et al., 2010). In the case of this study, best efforts were made to minimise any bias, both with the selection of the panel and the accompanying information pack. However, on review, the panel received a pro-bias due to the opinions expressed on the day by Jon Gluyas, Roberta Blackman-Woods and Ross Weddle.

In spite of this numerical imbalance, it was the negative panellist that appeared to gain the most attention from the audience. Research suggests (see Terwel et al. (2011) that frequently the public tend to side with the environmental or green groups over industrial or governmental groups. This is caused by the public perception of trust (comparable with the observations of Douglas (1992) in the impartiality of the groups' interest, coupled with the perception that environmental groups tend to be public serving, whilst industrial or governmental groups tend to serve the interests of organisations. Terwel et al. (2011) also observes that where trust is concerned, this perception takes precedence over the perception of organisational competence. The results of this thesis appear to concur with these observations as it is the anti-CCS representative of the Green Party, a small political organisation on the fringes of British politics, who takes precedence over those from a leading research institution and the dominant mainstream political party in the region.

It is a probable explanation therefore that in this study, despite the undesired pro-bias, the perceived public serving qualities of the anti-CCS panellist resulted in his responses gaining the most 'sympathy' from the audience.

6.6. REFLECTIONS AND FURTHER WORK

Reflecting on the evolution of this study from conception to completion, the implemented methodology complemented the primary hypothesis and succeeded in producing interesting results. However, on reflection this is not without flaws, shortcomings and room for improvements. Furthermore, the results and indeed raw data collected provides as many further questions as it does conclusions and consequently potential for future investigation that lay outside the primary remit of this study. In this section I will firstly highlight which, I feel, were the main shortcomings of the methodology and ways in which a repeated study could be improved. Secondly I will comment on the use of rhetoric in public debates, and its influence on a person's perception of risk, danger and consequently acceptability.

6.6.1 CRITIQUE OF METHOD

When the notion of using a public debate to test whether an open two directional flow of information affected a person's perception of CCS was first conceived, the choice of venue was open. As stated in section 6.2.1, a city centre location was desirable for its diversity in social demographics as well as ease of access. Inclusion within the Newcastle Science Festival allowed advertising to a wider audience and access a central venue. However, the questionnaire results indicated that the 45%

of the audience had an above average knowledge of CCS; potentially providing an explanation as to the discrepancies between this and other published studies (see section 6.4). This above average knowledge base may be a consequence of advertising the event as part of a science festival, signalling that it might not be of interest to members of non-science minded demographics. Without repeating the event at a neutral venue within the same geographical proximity, it is not possible to distinguish whether this discrepancy with published studies is indeed down to the more scientific nature of the audience or in fact a regional variation.

This inconsistency also revealed shortcomings in the design of the questionnaire. In order to maintain anonymity and keep the questionnaire as concise as possible for ease of completion, a question asking respondents to state their occupation was omitted. Should the study be repeated, inclusion of this question would further allow isolation of respondents with technical backgrounds and those with vested and or conflicts of interest compared to published studies.

Similarly, the questionnaire required compromises to be made between the optimum levels of detail that would allow fine grained analysis, yet be concise enough to be completed quickly: not take too much time out of the one hour 30 minute event. Furthermore, the relatively brief time span between completion of both questionnaires could result in the answers from the first still being fresh in the respondents mind while completing the second, potentially limiting its effectiveness. Should the study be repeated, the method could be improved and utilise an extended emailed or posted to the registered attendees prior to and post event. For this to be statistically viable, the sample size would require a significant increase based on expected return rates. With sample size in mind, the decision to broadcast the event live on the web was conceived relatively late in the planning stage when offered as a trial. Should this addition have been conceived earlier in the planning stages, it could have allowed the target demographic and dataset to be expanded by means of an online or interactive questionnaire. Furthermore, online webcasting would vary the geographical locations of the respondents, thus facilitating regional comparisons in initial and closing perceptions, and indeed the magnitude and polarity of any such variations.

Such webcasting methods would further allow the event to be repeated across a large geographical area, potentially even globally, with little logistical expense. Broadcasting would potentially remove the personal interaction element of the debate, although questions could be submitted via electronic forms to maintain two-way flow of information.

Subsequent discussions (Snape, Pers Comms), have expanded upon the theory briefly presented in Chapter 5 (Pg. 133), that gauging opinion of CCS as part of the whole energy system including carbon emissions, magnitude of power generation, security of supply and risk to the environment, in conjunction with other technologies such as nuclear and renewable, may return different perceptions than if a technology is considered separately. Such discrepancies have been observed by Bickerstaff et al, (2008) when investigating the public perception of the risks posed by nuclear power. Specifically that the perception of risk was based on the experiences of previous accidents and thus opinion was largely negative. However when framed in the context of the risks posed by climate change, and the role nuclear power may play as a low carbon power generation technology, then public opinion was found to be less negative, despite the risk perception still being high.

Therefore, if the study were to be repeated, running a parallel event taking the above question into consideration may lead to interesting comparisons. Such a parallel event would need considerable changes to the methodology; however, the overall format of using panel debates and post event questionnaires would remain consistent. The proposed methodology to test these hypotheses can be summarised as follows:

The panel would comprise experts on UK power supply and demand and climate change, in addition to expert advocates of renewable, CCS and nuclear technology. The debate would be introduced by the experts on power and climate providing background and context on the current state of play regarding power consumption, potential supply from the differing technologies, and the evolving risks of climate change. Following which, all three advocates would be allowed to introduce their respective technology and their opinions. The debate would be started by taking questions from the audience about the pros and cons of the relevant technologies including the opinions of all panel members. A chair would attempt to ensure that all technologies received relatively equal coverage in terms of time and questions.

Upon closing the debate, the audience would be polled on their opinions of all of the technologies presented. Unlike the methodology used in this study (section 6.2), the respondents would be asked to rank which of the technologies they felt offered the best solutions in terms of green credentials, amount of power supplied per generation unit (i.e. power generated per wind farm/PowerStation), security and reliability of such power supply, financial cost and long term risks. The final question would ask the respondents to rank in terms of percentages, how much of the future energy mix they would like to see assigned to each of the technologies. The responses would then be compared to the debate focusing purely on CCS technology to look for any changes in opinion that may or may not occur.

A similar methodology may be used if the study was to be standalone, i.e. not run in tandem with a purely CCS focused study, by using the before and after questionnaire model detailed in section 6.2 along with the debate structure detailed above. However, in a standalone debate, the technology advocates would open the debate by introducing their respective technology. The audience would then be polled on risks, suitability's and their personal opinion of each of the technologies, and these results would then be sealed. The debate would then explore the role of these technologies in the wider energy future where the advocates would be able to communicate their opinions, and the energy and climate experts frame the responses in the wider context. Upon the close of the debate, the audience would be polled using a copycat questionnaire, but gauging whether their opinion of the technology has changed due to its place in the wider context, in line with the Bickerstaff et al, (2008) study.

6.6.2. REFLECTIONS ON RESULTS

It was observed that the respondents felt more negatively about the issues raised in question 4 of both questionnaires (see section 6.4). This may be a consequence of the audience favouring the responses of the anti-CCS speaker, Sandy Irvine, over and above those of the three other panellists. This was despite total speaking times between all panellists being approximately equal. It is considered that there are two potential causes for this response, and the explanation is likely to be a combination of both.

Firstly, as inferred in section 6.5, this coalescence between public opinion and environmental groups over industrial or governmental organisations is common (Terwel et al., 2011). This reflects the theories of the public perceptions of trust examined in detail in chapter 5 and section 6.5, and therefore is likely to be partly responsible for the favourable responses to the negative panellist.

Secondly, when viewing the video, it is evident that Sandy Irvine used stronger imagery and rhetoric when emphasising his point, despite these images being tangential to the precise topic of CCS. Such an example would be his inference that a global enactment of CCS would result in gross energy wastage like that evident in Las Vegas becoming prevalent worldwide. Although scientifically incorrect, this inference directly linked the undesirable and negative image of Las Vegas to CCS, potentially altering the audience's perception of CCS to be more negative by association.

The use of rhetoric to emphasis a point and to persuade an audience to support your argument over and above those of others is common and difficult to account for or indeed counter. Consequently within the boundaries of this study, unless the panellists were permitted only to respond using facts and statistics with no anecdotal elaboration; an un-natural and stilted format, the true impact of rhetoric cannot be statistically quantified and therefore an observation.

The role of rhetoric in all forms of communication has been the subject of extensive study and publications (Billig, 1996; Carrithers, 2005, 2012; Dunbar and Dunbar, 1998). This study, although not within the remit of the working hypothesis or implemented methodology, observed the influences of rhetorical skill in swaying an audience to a particular point of view. For a statistically quantifiable measure of the magnitude of this influence, an in depth discourse analysis of the debate recording would be required.

Discourse analysis, specifically Critical Discourse Analysis (CDA), concerns the relationship of power and inequality inherent in language (Blommaert and Bulcaen, 2000) and is primarily used to analyse opaque and transparent structural relationships of dominance, discrimination, power and control manifested in language (Wodak, 1996). For application in this study, as mentioned above, comparison between the debate recording and questionnaire responses indicated a favouring of the anti-CCS speaker, due potentially to his rhetorical skill in invoking powerful imagery into his arguments. However, it is true that all panellists employed rhetoric, but not is appears as effectively as Sandy Irvine. Consequently further investigation is required as to why that of the Mr Irvine proved more persuasive than the combined reasoning of the three other panellists. Is the reason that he simply possessed better rhetorical skill than the other panellists, or that building on the public perception of trust elaborated on previously, his perceived public serving position gave him a greater social power or perceived importance (Van Dijk, 1993), such that his opinions carried more punch. However, it is equally likely that both of these factors played a part.

To solve this matter, a critical discourse analysis would be required on several common subject areas. These include,

- Power and dominance (Van Dijk, 1993). This subject investigates social power rather than individual power, and consequently the perceived importance of a group, or member of that group over and above that of an individual or indeed an opposing group. The concept of power and dominance much studied philosophical and social concept, however widely accepted descriptions are provided by Clegg (1989) and Lukes (1986).
- Conversationalisation. This subject explores the variety of discursive practises common in everyday public life, but is also applicable to political and technological fields. For instance, as the style of political address has changed from formal and rigid address to more casual styles that mimic ordinary conversation, attempts have been made to address the effects on society (Fairclough and Mauranen, 1997). Does this change in style, although allowing for more effective communication, blur the boundaries of information and persuasion and obscure the objectification of power relationships by suggesting equality in social standings (Blommaert and Bulcaen, 2000). Therefore for the purpose of this study, do the public respond more favourably to casual conversational styles over formal responses as they perceive the informant as an equal, or in fact is the opposite true where a more formal approach suggests a higher social power and consequently a more favourable reaction?

- Imagery. Discourse analysis remains largely a text or linguistically defined concept, although certain authors have begun emphasising the importance of visual media (e.g. Kress and Van Leeuwen (2006). However, of particular interest to this study in the invoking of mental imagery via linguistic means. Does the apparent favouring of the anti-CCS panellist stem from increased or more powerful descriptions of visual imagery over that used by other panellists.

The timescale required for a valid study of these points was not within the remit of this PhD, indeed a full and in-depth study on one of these categories could be the subject of an entire doctorate. However, for future post-doctoral study, the role of rhetoric and discourse and their relationships to public perceptions of trust provide an interesting and critical role in fully understanding the role of public engagement practises in the acceptance, or otherwise, of new and controversial technologies.

6.7. CONCLUSIONS

This study shows that whilst sweeping changes in opinion may not be prevalent, public engagement events do have an impact on public perceptions of certain aspects CCS technology. This is signified by the more negative or more positive sways to certain issues such as economic benefits or energy security whilst maintaining an unchanged opinion of the overall technology.

Comparisons to the results of other similar investigations show variations in both opinions and credentials of respondents. While this study indicates that public domain knowledge is still low, the audience for this debate proved more knowledgeable than all other referenced studies, likely due to its inclusion in a science festival.

As previously stated it is not the purpose of public engagement to convince or persuade, and in fact it would be wrong to use it as such a tool. However, a primary purpose is to convey information in an unbiased two directional manner. In this sense, this event succeeded in informing a varied demographic as the majority felt that their knowledge had increased as a consequence of their attendance.

Despite best efforts to obtain total neutrality with regards to the weighting of the panel, personalities and rhetorical skill will always tip the balance in one direction or another, as was the case in this study. Despite an apparent pro bias in the panel, it was the one anti-CCS speaker that appears to have tipped the balance in his favour in Question 4. As stated by Malone et al. (2010), all efforts to immediately inform are always likely to introduce apparent biases, despite best efforts to maintain neutrality.

This study indicates that public debate does have an influence on perceptions of a technology and allows participants to reach informed conclusions. However, of further interest would be an examination of the role of the use of rhetoric in skewing the results of such public engagement exercises. In this debate it was the anti-CCS advocate who displayed the most rhetorical skill, however, in a repeated study this may have been the opposite. As previously discussed, it is not possible or indeed plausible to undertake ‘pure’ risk assessment or cost-benefit analyses of CCS technology as people possess preordained orientations towards either CCS technology itself, or those who they perceive to be its advocates. The best that it is plausible to achieve is the fostering of increased trust both in and between the different stakeholders through medias such as debates and other forms of open discussion that support transparency such that areas of common ground may be revealed amongst disputants.

REFERENCES

Billig, M., 1996, Arguing and thinking: A rhetorical approach to social psychology, Cambridge University Press.

Blommaert, J., and Bulcaen, C., 2000, Critical Discourse Analysis: Annual Review of Anthropology, v. 29, p. 447-466.

Bowman, K., 2010, Tapping The Public View Of Big Oil, Forbes.

Bradbury, J., Ray, I., Peterson, T., Wade, S., Wong-Parodi, G., and Feldpausch, A., 2009, The Role of Social Factors in Shaping Public Perceptions of CCS: Results of Multi-State Focus Group Interviews in the U.S: Energy Procedia, v. 1, no. 1, p. 4665-4672.

Carrithers, M., 2005, Why Anthropologists should study rhetoric: Journal of the Royal Anthropological Institute, v. 11, no. 3, p. 577-583.

-, 2012, Seriousness, Irony, and the Mission of Hyperbole: Religion and Society: Advances in Research, v. 3, no. 1, p. 51-75.

Clegg, S., 1989, Frameworks of power, Sage.

Curry, T. E., Reiner, D., de Figueiredo, M. A., and Herzog, H., 2005, A Survey of Public Attitudes towards Energy and Environment in Great Britain: Laboratory for Energy and Environement: Massachusetts Instiituite of Technology.

de Best-Waldhober, M., and Daamen, D., 2006, Public perceptions and preferences regarding large scale implementation of six CO_2 capture and storage technologies.

de Coninck, H., Flach, T., Curnow, P., Richardson, P., Anderson, J., Shackley, S., Sigurthorsson, G., and Reiner, D., 2009, The acceptability of CO2 capture and storage (CCS) in Europe: An assessment of the key determining factors: Part 1. Scientific, technical and economic dimensions: International Journal of Greenhouse Gas Control, v. 3, no. 3, p. 333-343.

Douglas, M., 1985, Perception of Risk, Risk Acceptability according to the Social Sciences, Routledge, p. 29-40.

-, 1992, Risk and Blame, Risk and Blame: Essays in Cultural Theory: New York, Routledge, p. 3-19.

Douglas, M., and Wildavsky, A., 1982, Risk a Culture - An Essay on the Seclection of Technical and Environmental Dangers, University of California Press.

Dunbar, R., and Dunbar, R. I. M., 1998, Grooming, gossip and the evolution of language, Harvard University Press.

Edman, S., 2013, Public Perception of the Oil and Gas Industry: The Way Ahead, v. 9, no. 2, p. 3.

Fairclough, N., and Mauranen, A., 1997, The Conversationalisation of Political Discourse: A comparative view: Belgian Journal of Linguistics, v. 11, no. 1, p. 89-119.

Ha-Duong, M., Nadaï, A., and Campos, A. S., 2009, A survey on the public perception of CCS in France: International Journal of Greenhouse Gas Control, v. 3, no. 5, p. 633-640.

Kress, G. R., and Van Leeuwen, T., 2006, Reading Images: The Grammar Of Visual Design, Routledge.

Lukes, S., 1986, Power, New York University Press.

Malone, E. L., Dooley, J. J., and Bradbury, J. A., 2010, Moving from misinformation derived from public attitude surveys on carbon dioxide capture and storage towards realistic stakeholder involvement: International Journal of Greenhouse Gas Control, v. 4, no. 2, p. 419-425.

Miller, E., Bell, L. M., and Buys, L., 2007, Public understanding of carbon sequestration in australia: Socio-demographic predictors of knowledge, engagement and trust: International Journal of Emerging Technologies and Society, v. 5, no. 1, p. 15-33.

Roberts, T., and Mander, S., 2011, Assessing public perceptions of CCS: Benefits, challenges and methods: Energy Procedia, v. 4, no. 0, p. 6307-6314.

Rowe, G., and Frewer, L. J., 2005, A Typology of Public Engagement Mechanisms: Science, Technology & Human Values, v. 30, no. 2, p. 251-290.

Shackley, S., Waterman, H., Godfroij, P., Reiner, D., Anderson, J., Draxlbauer, K., and Flach, T., 2007, Stakeholder perceptions of CO2 capture and storage in Europe: Results from a survey: Energy Policy, v. 35, no. 10, p. 5091-5108.

Terwel, B. W., Harinck, F., Ellemers, N., and Daamen, D. D. L., 2011, Going beyond the properties of CO2 capture and storage (CCS) technology: How trust in stakeholders affects public acceptance of CCS: International Journal of Greenhouse Gas Control, v. 5, no. 2, p. 181-188.

Upham, P., and Roberts, T., 2011, Public perceptions of CCS: Emergent themes in pan-European focus groups and implications for communications: International Journal of Greenhouse Gas Control, v. 5, no. 5, p. 1359-1367.

Van Dijk, T. A., 1993, Principles of critical discourse analysis: Discourse & society, v. 4, no. 2, p. 249-283.

Wallquist, L., Seigo, S. L. O., Visschers, V. H. M., and Siegrist, M., 2012, Public acceptance of CCS system elements: A conjoint measurement: International Journal of Greenhouse Gas Control, v. 6, no. 0, p. 77-83.

Wodak, R., 1996, Disorders of discourse, Longman.

7. DISCUSSION & CONCLUSIONS

7.1. INTRODUCTION

This chapter summarises the principal findings of chapters 3 to 6 to in order to discuss results and uncertainties, and examine the main implications of these findings on the feasibility of geological CO_2 storage. Finally this chapter proposes opportunities for further work that are directly derived from this study in addition to some that are interest driven with further implications for CCS.

7.2. PRINCIPAL FINDINGS

This thesis has sought to examine the feasibility of geological carbon dioxide storage from an exploration for reservoir capacity stage, through to social barriers to implementation. To achieve this, interpretation of seismic reflection data, mathematical and statistical modelling and a public engagement study have been employed. Despite the divergent methods, it has been possible to construct a coherent theme focusing on highlighting and solving challenges considered to be fundamental to each stage of CCS implementation; namely understanding theoretical capacity during exploration for suitable storage sites, predicting injected CO_2 migration within faulted reservoirs, and the impact of public engagement techniques on public perception and acceptance of CCS.

Chapter 3 – Uncertainty in static CO_2 storage capacity estimate.

This chapter investigates the causes of uncertainty in static storage capacity estimates that causes a variance of five orders of magnitude. Monte Carlo based sensitivity analysis shows that poorly defined subsurface data is the root cause of this uncertainty. The data are derived from low resolution 2D seismic and sparse well control, thus critical factors such as porosity have to be inferred from regional analogues. In addition, the reservoir efficiency factors are shown to be over conservative and unsuitable for site specific application. These factors are not defined by real world data and consequently introduce further error, comparable to that introduced by geological uncertainty. As such, based on the sensitivity analysis, a Monte Carlo run theoretical total storage capacity based purely on inferred geological inputs results in less variance and uncertainty that the widely implemented efficiency factor method.

Chapter 4 – Influence of capillary entry pressures on cross fault migration – implications for CO_2 injection.

This chapter builds upon the theory that pressure and hydrocarbons may be transferred across faults in situations where the hydrocarbon buoyancy pressure exceeds the capillary entry pressure for the fault rock material. It is observed that CO_2 injection into faulted compartments, sufficient CO_2 plume buoyancy pressure will allow cross fault flow of CO_2 into adjoining compartments. This facilitates the equalising of reservoir pressure at a flow rate governed by the pressure difference across the fault and the porosity/pore throat radii of the fault rock. CO_2 is found to cause a significant decrease in the maximum column that can be retained by the cap rock and faults when compared to hydrocarbon systems. This is apparent when oil wet substrates are predicted over water wet substrates due to the cosine of the contact angle approaching zero.

Chapter 6 – The effects of informed public engagement on the public perception of CCS.

This chapter examines the role of un-biased public engagement on the public perception of CCS in the north East of England. A public debate format facilitates the impact of two-way open dialogue to be examined with significant findings at odds to convention. On an overall level, the opinion of CCS was mostly unchanged, however the opinions of specific aspects of CCS changed significantly as a result of the debate. Furthermore, the study highlighted that the perception and any preconceived notion of the panellist may unduly influence their opinion of the technology rather than their knowledge of the technology itself. In this study it was found that the audience reacted more positively to the negative panellist despite his relative lack of expertise on the subject. This is likely due to the perception of being public serving rather than the potential industry serving perception of the other panellists.

7.3. DISCUSSION

Chapter 3*:* Published literature on the static CO_2 storage capacity of aquifers has focused around whether a geological storage reservoir may be classed as closed (Chadwick et al., 2006; Ehlig-Economides and Economides, 2010) or open (Goodman et al., 2011; NETL, 2009).

Firstly, when considering the closed trap, the equation stated by Chadwick et al. (2006) implies that the only available storage volume in a closed trap is produced from the compressibility of both rock grain and the in situ brine. For a theoretical model this may be valid, however, it is shown in this study to be applicable in real world examples due to membrane leakage of boundaries and field engineering techniques. Therefore, the closed model is shown to be flawed and should therefore if considered at all; it must be treated as an upmost worst case scenario only.

Secondly, the proposed open system model relies heavily on the use of efficiency factors or capacity coefficients. Such factors are proposed by numerous authors (Bachu, 2008; Bradshaw et al., 2007; Gorecki et al., 2009a; Gorecki et al., 2009b; Kopp et al., 2009) to factorises the volume of reservoir that is available for CO_2 storage. These factors are based upon the multiplicative sum of variables defined as fraction. Designed to reflect the heterogeneity of the subsurface, such factors propose that between 1% and 4% of the reservoir is available for storage. When considering a specific prospect, much of the input variables used to formulate the factor become redundant. In short, the factors are designed for play fairway analysis over prospect scale investigation. Despite this, efficiency factors are widely and therefore inappropriately applied to storage sites in the literature resulting in highly conservative estimate.

As a consequence of the shortcomings of the methods explained above, CO_2 capacity estimates can suffer a 5 order of magnitude variance. Put in perspective, this may vary from 0.1 Mt to in excess of 100 Mt. Thus for an average power station, this variance is the difference between months of storage capacity to in excess of 100 years of capacity. The study presented in Chapter 3 used sensitivity analysis to assess the root cause of this uncertainty and proposed amendments to methods that minimises such a variance.

Saline aquifer storage prospects are poorly characterised and studied because unlike hydrocarbon fields, they offer no known economic resource. Consequently, they are not covered by high resolution seismic data and well penetrations are few and commonly limited to failed exploration wells from which few data were collected. Therefore geological properties such as porosity, permeability and reservoir pressure have to be estimated from best analogues. Usually this comprises onshore outcrops and producing hydrocarbon fields from the same or similar stratigraphic units. It was found by that this study, that poorly constrained porosity inputs when applied to a total theoretical capacity model, accounted for 93% of variance in volume. When applied to open system calculations, geological uncertainty was split more equally with the impact of the capacity coefficients (50.5% vs. 43.1% respectively). Therefore, it is evident that when considering poorly characterised aquifer prospects, the use of capacity coefficients adds significant uncertainty. This is in conflict to its intended purpose of correcting for geological heterogeneity.

To summarise, it is found that when studying poorly characterised saline aquifers, the geological uncertainty from poorly constrained data is exacerbated by the use of efficiency factors. Therefore, it is proposed that in this scenario, a theoretical total capacity equation should be used in order to minimise uncertainty. Furthermore, it is proposed that static capacity estimations should be used only as a screening tool for potential sites, not as a method for assessing injectivity or other reservoir engineering techniques. Should a prospect be deemed to have sufficient total theoretical capacity, subsequent phases of model refinement should be undertaken in conjunction with obtaining further, higher resolution data.

***Chapter 4**: T*he study of capillary flow across membrane baffles is based primarily on the works of Berg (1975), Schowalter (1979) and Watts (1987), with some more recent modification by Fisher et al. (2001). Much of the literature focuses on the capillary sealing capacity of the low permeability lithologies, for the purposes of retaining hydrocarbon accumulations. Fisher et al. (2001) built upon this theory for the application of migration of hydrocarbons across membrane faults in compartmentalised reservoirs.

For the purposes of CO_2 storage, the literature has focused purely on cap rock integrity (Naylor et al., 2011), i.e. ensuring that CO_2 cannot escape through the confining cap rock via capillary leakage. There is, at present, no published literature investigating the potential for cross fault CO_2 migration and its implications for injectivity. This study is therefore, to the best knowledge of the author, this first to apply an amended capillary methodology in order to quantify this potential.

Validation of the method is derived from comparison of published Hg – air capillary entry pressure and pore throat data to that predicted using the derived porosity permeability equation. Such comparisons show equivalent patters and trends, and as such, the method is deemed to be valid.

This findings show that maximum column heights and capillary entry pressures of both seals and faults decrease for a CO_2 system compared to an equivalent hydrocarbon system. This trend is emphasised in when oil wet hydrophobic substrates are predicted. This phenomenon is derived from the changes in CO_2 water contact angle compared with that of oil – water, in addition to variations in density. The reduced sealing capacity of the cap rock is comparable to the findings of Naylor et al. (2011). However, the reduced sealing capacity of membrane faults is advantageous for the purposes of CO_2 injection, as flow rates indicted migration on operational timescales.

Uncertainty in the findings of this study stems from the type of deformation and the composition of the fault rock. Deformation of reservoir sandstones has been shown in some cases to cause reduction of permeability and porosity. Efforts have been made to quantify this in the literature (Fisher and Knipe, 2001; Knipe et al., 1997). These effects are likely greater detrimental impact on flow rate over and above the capillary entry pressures of the fault rock itself. Lack of core derived capillary entry pressure data and relative permeabilities however make the true magnitude of this impact difficult to quantify. Furthermore, there is no direct geological comparison between maximum hydrocarbon and CO_2 heights that may be retained by the same seal. Thus, this method remains an estimate of the subsurface effect until supporting laboratory analogues may be obtained.

Chapter 6*:* It is important to reiterate that the purpose of public engagement is to inform and not to persuade or convince. There is clear evidence presented in chapter 5.3 that when public engagement is ignored, opposition to projects is more prevalent (Chapter 5.3). With this opposition in mind, it is necessary to consider the question 'what is the true effect of open two way public dialogue on the public perception of a technology?'

The results of the study reported in Chapter 6. demonstrate how an example of open informed debate had little effect on an audience's overall opinions of CCS. However, the study was able to demonstrate changes in people's opinions of related topics; namely the benefits of CCS to de-carbonising energy generation, maintaining the security of energy supply and enhancing the local economy. Furthermore, a significant percentage of the audience indicated that their knowledge had been increased as a consequence of participating in the debate. Therefore these results show that this particular public engagement exercise did have an effect on people's grasp of CCS, regardless of whether this was in a more positive or negative direction. Additionally, when considering the original remit of public engagement, which is to inform, this study shows that open two way dialogue is effective at imparting knowledge without adopting a preconceived agenda or intentional bias.

This particular study produced results that are at odds with published literature on similar themes (Roberts and Mander, 2011; Upham and Roberts, 2011), in as much as the results demonstrated that safely was of far less of concern to this audience than has been encountered elsewhere. This study also differs from previous research in that it is, to the best knowledge of the author, the only study to use an open debate format in preference to focus groups. Those who participated in the debate were able to define their own agenda by asking questions they felt represented the gaps or uncertainties in their knowledge. This differs from focus groups that explained the processes of CCS by using a syllabus defined by the researchers rather than the participants. It is therefore likely that participants in previously published studies reacted to the information provided by researchers rather than being able to request specific information and opinions of their own choosing.

It is worth noting that the audience appeared to favour the views expounded by the Green Party representative, who had less direct experience dealing with matters relating to CCS, than the other panellists, most of whom possessed greater technical knowledge of the subject. This outcome is primarily deemed to be a result of people's perceptions of the trustworthiness, and impartiality of environmental organisation, such as the Green Party (Douglas, 1992; Terwel et al., 2011, 2012). In this case, it is concluded that the Green Party panellist was perceived to be a representative of a "green" organisation dedicated to serving the public, despite the Green Party's place in the party political system, whereas the remaining panellists were perceived to have a greater interest in serving the interests of an organisation or profession – the official government opposition; geological corporations and renewable energy enterprise.

Other explanations for this apparent favouring of views are two-fold. Firstly, it is possible that the personal views of the audience were more aligned to the 'lifestyle change not technology change' message that was portrayed by Mr Irvine. Secondly, his use of rhetoric to emphasise his point was particularly persuasive for the audience than the rhetoric used by the other three panellists. This explanation is difficult to quantify accurately as rhetoric was widely employed by all individuals.

For this instance, an in depth critical discourse analysis would need be to be performed on the video in order to quantify the magnitude of this effect. In hindsight, it is likely that although the perception of trust is a significant explanation for the apparent negative sway of the audience, the true cause is likely to be a combination of all of the explanations described above.

All studies relying on quantifying the opinions of people are fraught with uncertainties inherent in the results and this study is no different. As with the comparable published studies mentioned above (Roberts and Mander, 2011; Upham and Roberts, 2011), the conclusions drawn from this debate are based on the opinions of the mixture of backgrounds and professions present in the audience on this particular day. As such it is dangerous to draw sweeping conclusions for the wider society, itself a blend of publics, from this single sample. Indeed repeating the event with the same audience is not guaranteed to return identical results such is the unpredictability of people (Douglas and Wildavsky, 1982).

Nonetheless, the method used in this study does show that open two way dialogue can have an impact upon a person’ perceptions of a specific technology. Furthermore, the benefits of such a method are two-fold: 1) a person may find that their initial concerns are altered as a result of access to further information on which to base their decision. And 2) the proposer of the debated project may find that the reason for opposition is unexpected and unrelated to reasons they have previously considered. Therefore they are able to structure their provision of information to the public to include material that enables the opposing party to reach a more informed conclusion, be that positive or negative.

7.4. CONCLUSIONS AND IMPLICATIONS OF FINDINGS

The conclusions of this thesis have several implications for the current methodologies used to assess the feasibility of CO_2 storage. These are summarised below.

- Current methodologies for estimating static storage capacity of saline aquifers contain a series uncertainties and shortcomings. This study shows that the poor data coverage of saline aquifers directly translates to poorly constrain geological input variables. This in turn leads to significant variance of capacity estimates. This uncertainty is exacerbated by the introduction of capacity coefficients. It is also observed that there is a widespread misuse of such coefficients in the literature for several reasons.
    - These coefficients are often employed to site specific prospects, outside of their original remit, with little to no consideration of the validity of the factors used to calculate them. Therefore, until the range of uncertainty and error can be constrained, a theoretical storage capacity estimates method induces less uncertainty than an efficiency factor based model.
    - Secondly, efforts to refine them to include reference to dynamic effects contribute further error and uncertainty, leading often to unfeasibly conservative estimates. This study proposes that a capacity coefficient, if used at all for screening purposes, should be

derived from reservoir sweep efficiency data observed in comparable hydrocarbon fields.

- This study shows that the presence of membrane faults in the storage reservoir will permit cross fault CO_2 migration. This is providing that a CO_2 column height equal to the capillary entry pressure is present. It has been observed that due to the influence of density and CO_2 water contact angles, the capillary entry pressures required for migration are significantly lower than those required in equivalent oil systems. This questions further the validity of the closed reservoir model proposed by Ehlig-Economides and Economides (2010) as it is unlikely that fully dealing boundary features will retard pressure or CO_2 migration at sufficient pressure. The lithology of the reservoir rock is important to predicting the likelihood of permeability decreases across the fault damage zone as a result of grain crushing and clay smear. Therefore it is proposed that clay deficient hosts such as Aeolian dune sandstones are less likely to impede flow compared to more clay rich, turbidites.
- The observations made in chapter 4, support the conclusions made by Naylor et al. (2011) that the maximum column height of CO_2 that can be retained by a seal is significantly decreased compared to an equivalent hydrocarbon system. This is exacerbated by the presence of oil as a wetting fluid in the substrate, which may reduce the capillary entry pressure of such a seal to near zero. This is of significance when considering CO_2 storage in abandoned hydrocarbon fields, such that the maximum pre-production

hydrocarbon column height is not a directly comparable to potential CO_2 column heights.

- The study undertaken in chapters 5 and 6 shows the importance of public opinion to the potential success or failure of a CCS project. Experience from the Netherlands and Germany illustrates how public opposition can cause the cancellation of CCS projects, even at the final stage, with significant cost to both government and operators. Conversely, the example of the French Lacq project shows that public opposition can be managed via public engagement. This study shows how open two way dialogue alters public perceptions of certain elements of a technology.
- Furthermore, this open two-way flow of information is beneficial to the operators. Engaging various publics allows their concerns and objections to be understood and addressed. Therefore it is proposed, that an open two way dialogue throughout the planning process of any controversial project, is likely to reduce potential objection and diminish the risk of late stage cancellations. This process should be implemented at the same time as any geological screening, such as that mentioned above, to minimise the financial risk. Nonetheless it should be noted that the purpose of public engagement is not to convince, and its implementation is not guaranteed to reduce opposition. Furthermore, preordained perceptions of a project, or those considered to be its advocates, play a significant role in governing the eventual outcome.

7.5. FUTURE RESEARCH

Though a number of conclusions have drawn through the methods employed in this thesis, there are still a number of unknowns and uncertainties. This may be mitigated by the following areas for future research.

- Capacity coefficients, although often misused, represent a useful theoretical tool for converting total theoretical storage capacity to usable storage capacity. This is akin to the conversion of total hydrocarbon reserves in place, to recoverable resource via a recovery factor. To this end, refining of the capacity coefficient method would lead to useful results. Defining the relationship between observed reservoir sweep efficiency to the horizontal and vertical permeability ratio and flow rates would aid removal of uncertainty derived from non-specific input variables.
- All of the reservoirs studied in in chapter 4 outcrop on land, leading to easily accessible reservoir analogues. As such, the porosity and permeability reductions caused through clay smear and grain crushing are visible. Laboratory Hg – Air capillary entry pressure and CO_2 flow experiments on such analogues would offer real world data that could be used to validate the observations derived from mathematical solutions.
- References to potential improvements to the method employed in chapter 6 are made in section 6.6. However, of key interest is the potential of the webcasting tool to allow simultaneous repeatability of the study in global locations. This would allow more detailed conclusions to drawn as to the key

concerns pertaining to CCS in addition to correlating of key concerns to specific audiences.

- To further investigate the reasons that the audience looked more favourably on the panellist who spoke against CCS in this study via undertaking a critical discourse analysis. Such as study would examine the use of rhetoric between all panellists and quantify why, if at all, the panellist least favourable to CCS proved more persuasive. The full theory of such a study is explained in section 6.6.2; however, the conclusions drawn would allow the role of rhetoric and discourse and their relationships to public perceptions of trust to be better understood.

REFERNCES

Bachu, S., 2008, Comparison between Methodologies Recommended for Estimation of CO2 Storage Capacity in Geological Media: CSLF Task Force on CO2 Storage Capacity Estimation and the USDOE Capacity and Fairways Subgroup of the Regional Carbon Sequestration Partnerships Program.

Berg, R. R., 1975, Capillary pressures in stratigraphic traps: AAPG Bulletin, v. 59, no. 6, p. 939-956.

Bradshaw, J., Bachu, S., Bonijoly, D., Burruss, R., Holloway, S., Christensen, N. P., and Mathiassen, O. M., 2007, CO2 storage capacity estimation: Issues and development of standards: International Journal of Greenhouse Gas Control, v. 1, no. 1, p. 62-68.

Chadwick, R. A., Arts, R., Bernstone, C., May, F., Thibeau, S., and Zweigel, P., 2006, Best Practice for the Storage of CO2 in Saline Aquifers; Observations and guidelines from the SACS and CO2STORE projects, p. 19.

Douglas, M., 1992, Risk and Blame, Risk and Blame: Essays in Cultural Theory: New York, Routledge, p. 3-19.

Douglas, M., and Wildavsky, A., 1982, Risk a Culture - An Essay on the Seclection of Technical and Environmental Dangers, University of California Press.

Ehlig-Economides, C., and Economides, M. J., 2010, Sequestering carbon dioxide in a closed underground volume: Journal of Petroleum Science and Engineering, v. 70, no. 1-2, p. 123-130.

Fisher, Q. J., Harris, S. D., McAllister, E., Knipe, R. J., and Bolton, A. J., 2001, Hydrocarbon flow across faults by capillary leakage revisited: Marine and Petroleum Geology, v. 18, no. 2, p. 251-257.

Fisher, Q. J., and Knipe, R. J., 2001, The permeability of faults within siliciclastic petroleum reservoirs of the North Sea and Norwegian Continental Shelf: Marine and Petroleum Geology, v. 18, no. 10, p. 1063-1081.

Goodman, A., Hakala, A., Bromhal, G., Deel, D., Rodosta, T., Frailey, S., Small, M., Allen, D., Romanov, V., Fazio, J., Huerta, N., McIntyre, D., Kutchko, B., and Guthrie, G., 2011, U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale: International Journal of Greenhouse Gas Control, v. 5, no. 4, p. 952-965.

Gorecki, C. D., Holubnyak, Y., Ayash, S., Bremer, J. M., Sorensen, J. A., Steadman, E. N., and Harju, J. A., 2009a, A New Classification System for Evaluating CO2 Storage Resource/Capacity Estimates, SPE International Conference on CO2 Capture, Storage, and Utilization: San Diego, California, USA, Society of Petroleum Engineers.

Gorecki, C. D., Sorensen, J. A., Bremer, J. M., Knudsen, D., Smith, S. A., Steadman, E. N., and Harju, J. A., 2009b, Development of Storage Coefficients for Determining the Effective CO2 Storage Resource in Deep Saline Formations, SPE International Conference on CO2 Capture, Storage, and Utilization: San Diego, California, USA, Society of Petroleum Engineers.

Knipe, R., Fisher, Q., Jones, G., Clennell, M., Farmer, A., Harrison, A., Kidd, B., McAllister, E., Porter, J., and White, E., 1997, Fault seal analysis: successful methodologies, application and future directions: Norwegian Petroleum Society Special Publications, v. 7, p. 15-38.

Kopp, A., Class, H., and Helmig, R., 2009, Investigations on CO2 storage capacity in saline aquifers—Part 2: Estimation of storage capacity coefficients: International Journal of Greenhouse Gas Control, v. 3, no. 3, p. 277-287.

Naylor, M., Wilkinson, M., and Haszeldine, R., 2011, Calculation of CO_2 column heights in depleted gas fields from known pre-production gas column heights: Marine and Petroleum Geology, v. 28, no. 5, p. 1083-1093.

NETL, 2009, Carbon Sequestration Atlas of the United States and Canada: U.S. Department of Energy Office of Fossil Energy.

Roberts, T., and Mander, S., 2011, Assessing public perceptions of CCS: Benefits, challenges and methods: Energy Procedia, v. 4, no. 0, p. 6307-6314.

Schowalter, T. T., 1979, Mechanics of secondary hydrocarbon migration and entrapment: AAPG Bulletin, v. 63, no. 5, p. 723-760.

Terwel, B. W., Harinck, F., Ellemers, N., and Daamen, D. D. L., 2011, Going beyond the properties of CO2 capture and storage (CCS) technology: How trust in stakeholders affects public acceptance of CCS: International Journal of Greenhouse Gas Control, v. 5, no. 2, p. 181-188.

Terwel, B. W., ter Mors, E., and Daamen, D. D. L., 2012, It's not only about safety: Beliefs and attitudes of 811 local residents regarding a CCS project in Barendrecht: International Journal of Greenhouse Gas Control, v. 9, no. 0, p. 41-51.

Upham, P., and Roberts, T., 2011, Public perceptions of CCS: Emergent themes in pan-European focus groups and implications for communications: International Journal of Greenhouse Gas Control, v. 5, no. 5, p. 1359-1367.

Watts, N. L., 1987, Theoretical aspects of cap-rock and fault seals for single- and two-phase hydrocarbon columns: Marine and Petroleum Geology, v. 4, no. 4, p. 274-307.

APPENDIX 1.A

UNCERTAINTY IN STATIC CO_2 STORAGE CAPACITY ESTIMATES: CASE STUDY FROM THE NORTH SEA, UK

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Modeling and Analysis

ghg GREENHOUSE GASES SCIENCE AND TECHNOLOGY

Uncertainty in static CO_2 storage capacity estimates: Case study from the North Sea, UK

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Abstract: We used a sub-salt Rotliegend Group sandstone saline aquifer in the North Sea as a case study site for Monte-Carlo-based CO_2 geostorage capacity assessment. In the area of interest, this unit is characterized by sparse, low resolution, subsurface data typical of the margins of global petroleum provinces, favored for CO_2 storage. Such data scarcity leads to uncertainty regarding the complex trap geometries and ultimate CO_2 storage capacity. The Rotliegend reservoir, estimated to have porosity and permeability ranges of 11–27% and 0.2 mD–125 mD, respectively, is sealed by Zechstein salt. The salt, predominantly halite, is a proven hydrocarbon seal in the central and southern North Sea hosting oil and gas columns of >140 m (>450 ft) and >150 m (>500 ft). Utilizing 2D-seismic data, boreholes and analogues, we estimate the pore volume of a 5-km^2 4-way dip-closed structure through Monte-Carlo-based capacity simulations. We estimated storage capacity using published methodologies and compared this against a theoretical total storage calculation analogous to the gas in place equation used in the petroleum industry. We found that different methods yield a capacity range of $<10^4$ to $>10^9$ tonnes CO_2 where sensitivity analysis indicates variability in reservoir properties to be the dominant control. Thus static estimates based upon Monte-Carlo calculations present no advantage over theoretical pore volume estimations. This leaves 3D dynamic modeling of storage capacity populated by 3D seismic data and direct down-hole measurement of reservoir properties to improve confidence in capacity estimations as the recommended method.

Key words: carbon capture and storage; efficiency factors; uncertainty; storage; capacity estimation

Introduction

Carbon dioxide capture and storage (CCS) is the process of stripping carbon dioxide (CO_2) from the waste gasses of combusted fossil fuels and subsequent storage in porous underground geological formations.[1] Although injecting dense phase CO_2 into rock strata has been demonstrated since 1972[2] for the purpose of enhanced oil recovery (EOR) projects, a near-industrial scale CCS project for pure storage of waste CO_2 did not commence operations until 1996 in the Sleipner field, Norwegian North Sea.[3,4]

Optimal production from oil and gas reservoirs commonly benefits from high-quality databases that

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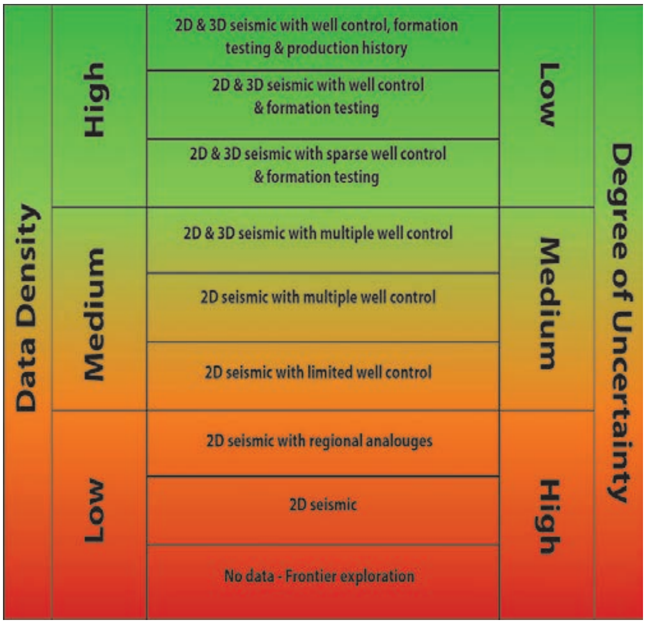

Figure 1. Correlation between data density and degree of confidence in reservoir understanding. The case study site lies on the boundary between low and medium data density thus between a medium and low degree of confidence in reservoir understanding. Saline aquifer prospects for CO_2 storage commonly lie in this lower region of the diagram when compared to abandoned hydrocarbon prospects that frequently rank in the high data density region making the hydrocarbon sites more attractive despite aquifers offering significantly higher storage volumes.

include high-resolution 3D seismic, borehole data, and down-hole production measurements,[5] allowing subsurface geology to be characterized with a high degree of confidence (Fig. 1). The theoretical storage potential in deep saline aquifers is significantly greater than in oil and gas reservoirs.[1] A significant proportion of this potential, however, is in areas covered by low-resolution 2D seismic coverage with limited borehole calibration. These areas are typical of those found on the margins of global petroleum producing basins such as the southern and eastern margins of Australia,[6] southwest India,[7] margins of the Gulf of Cadiz,[8] and the Irish Atlantic margin.[9] The development of CO_2 storage safety cases needs to provide sufficient confidence in reservoir assessment to satisfy both international and national regulatory requirements (e.g. EU Directive 2009/31/EC Annex 1). These require storage integrity and capacity, risk of leakage and the time period of storage to be assessed and quantified to a high degree of confidence before a site may be considered as a viable prospect for CO_2 storage and qualify for a storage permit. Current literature presents two differing scenarios for calculating static storage capacity, based on whether the reservoir is closed[10,11] or open[12,13] (Fig. 2). Where the open scenario is inferred, capacity calculations require the use of efficiency factors,[12] a measure of what percentage of the total pore volume may be filled with CO_2 derived from the irreducible water saturation and net reservoir unit in gross rock volume. Additional parameters such as the density and gravitational effects of the injected fluid are also

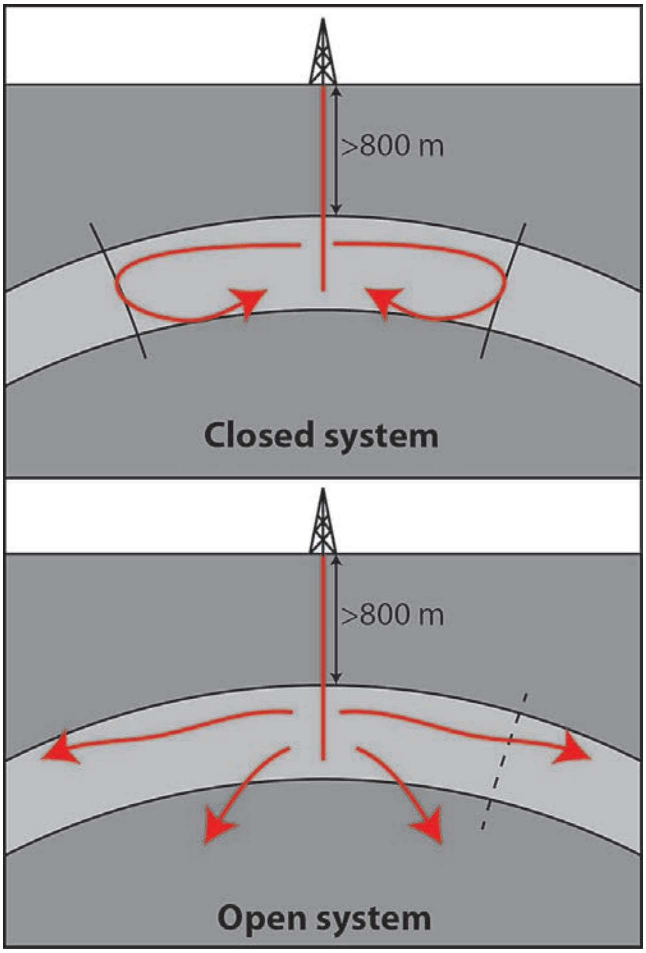

Figure 2. Schematic illustrating differences between open and closed systems for CO_2 storage. Closed system display impermeable boundaries on all sides with no potential for pressure bleeding into connecting saline aquifers or formations. Open (and semi-closed) systems despite being sealed to prevent CO_2 leakage display some permeable boundaries where pressure can bleed into adjoining formations (adapted from Zhou et al., 2009[15]).

required. Potential storage sites with low sub-surface data density and requiring parameters to be inferred from analogues mean uncertainties bring up the question as to whether efficiency factors are in fact a valid methodology. Whether their use is based on valid assumptions or will lead to capacity estimates outside of an acceptable range remains an open question. Where such low levels of data density and confidence co-exist (Fig. 1) with a significant (several orders of magnitude) range of storage capacity estimates, doubts are cast over the suitability of these sites. Thus, should these prospects be considered for immediate use for CO_2 storage? Should permit vendors demand acquisition of 3D seismic data and the drilling of test boreholes to reduce site uncertainty prior to consideration for a storage permit?

In this paper, we tackle the questions raised above by analyzing a subsalt Rotliegend reservoir in the UK Central North Sea (Fig. 3) that is covered only by low-resolution 2D marine seismic reflection data (typical of that found in other basin margins named above[6–9]) and with scant knowledge of the size of the interconnected pore volume. Whether the reservoir is in pressure communication or compartmentalized and thus fitting the closed[11] or open[12] system model is unknown. Furthermore, we investigate the suitability of current published methodologies in capacity calculations and compare these with the reserve calculations applied to conventional gas reservoirs.

The study site comprises a stratigraphic interval with numerous well penetrations within an extensively studied petroleum province.[14] The particular interval comprises a successful play fairway couplet of reservoir horizon and overlying seal interval. We look to characterize the site in terms of suitability for CO_2

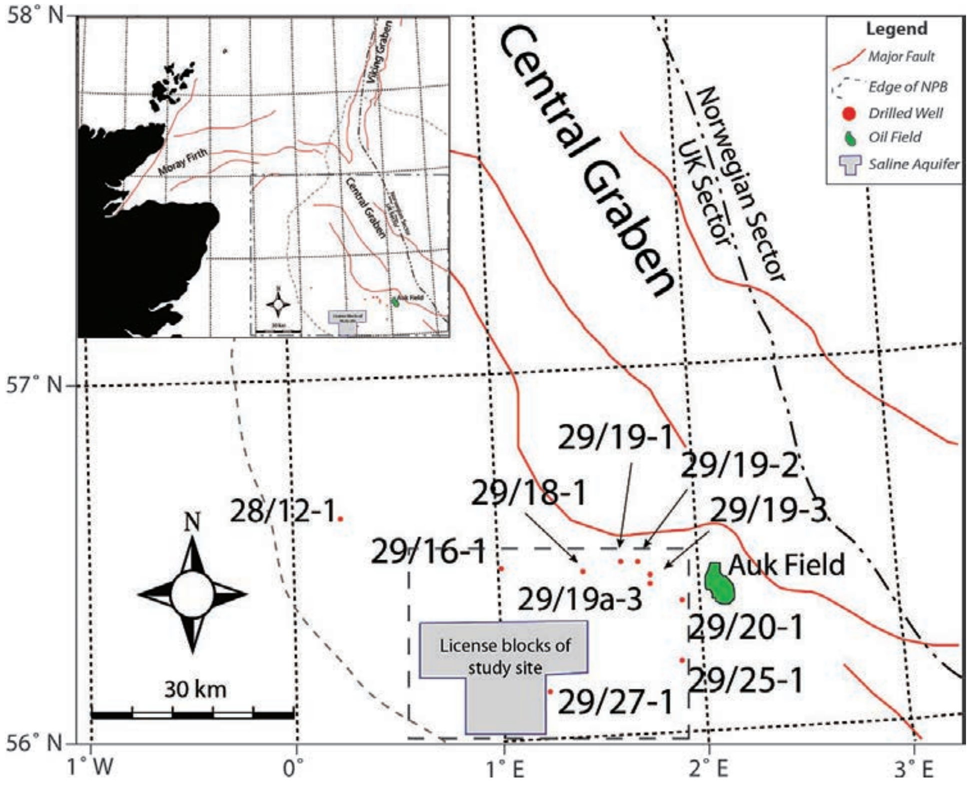

Figure 3. Map indicating location of study site within UKCS Quads 28 and 29 correlated to approximate topographical extent of the Northern Permian Basin (NPB) indicated by dashed grey line (adapted from Legler and Schneider, 2008[16]) and related to major faults (red line) and selected grabens of the Central North Sea. Well logs used in this study (Table 1) are indicated by red dots with well name. The Auk oilfield is included as an analogue for the reservoir and overburden sequence in the absence of porosity/permeability data from the study site.

storage by assembling available data and estimating storage capacity. We highlight the key uncertainties inherent in the use of poorly explored and studied deep saline formations and develop a first-pass screening workflow that can be applied to other poorly understood geological formations that offer significant CO_2 storage potential.

Background

Many methodologies for the purpose of estimating CO_2 storage capacity in a range of geological media have been proposed by a series of universities and governmental departments globally. Initial work undertaken by the US Department of Energy (DoE)[12] devised a simple methodology for calculating storage capacity of regional scale saline aquifers by calculating the total aquifer volume and applying a series of efficiency factors that attempt to correct for the presence of geologic heterogeneity in the form of a probabilistic multiplicative sum of fractions. Significant work has been undertaken to refine and improve this approach by a number of authors[10,13,15–22] specifically on refining the use of efficiency factors. Two commonly implemented methodologies have since been devised drawing upon the DoE method[12,21] and that of the Carbon Sequestration Leadership Forum[22] that have been summarized by Kopp *et al.*[15] A further controversial method was proposed by Ehlig-Economides and Economides[11] stating that geological formations acted like sealed containers and thus injection into such formations would result in a rapid pressure increase drastically reducing the potential storage volume.

While such work is necessary to shed light on the potential global storage volumes, all static capacity estimations use a series of equations that attempt to represent the complexities of geological heterogeneity and have led to wildly conflicting ranges of capacities, i.e. some national capacities exceed other global capacities.[19] Furthermore, all of these methods have a focus based on basin scales. As such, the assumptions made within these methods are no longer valid or appropriate when studying an individual prospect. Put in the terms of the oil and gas sector, the published methodologies are comparable to a play fairway analysis of yet to find hydrocarbons, and conversely, this paper focuses on the site specific prospect evaluation comparable to reserve in place estimation.

Table 1. 2D seismic survey vintages used in this study.

Survey	Shot date	Ownership	Coverage (approximate)
Vintage	1965–1992	Various	800 km
AH99-29	1999	Hess	500 km
WP-04	2004	Fugro	33 km
NSR-2007	2007	TGS Nopec	710 km

Database

Seismic data

A total of 1208 km of two-dimensional marine seismic reflection data of various vintages (Table 1) were interpreted to identify potential storage sites and measure the distributions and thicknesses of key stratigraphic units. The seismic data properties vary depending on vintage, but have an inline spacing of between 1 km and 5 km and a cross line spacing of between 3 km and 10 km. The seismic dataset comprises an average vertical resolution of 35 m based upon an average sonic velocity for all lithologies of 2815 m s^{-1} calculated from the seabed to the top of the Rotliegend, and an average frequency for all surveys of 20 Hz. The data are zero-phase migrated thus an increase in acoustic impedance is characterized by a red-black-red reflection combination in the seismic sections shown in this paper.

Seismic lines were interpreted using a series of key horizons and calibrated against available well control to identify stratigraphic boundaries, unconformities and reservoir and seal geometries, which define important stratigraphic and lithological units. Where possible, the location of the base of the reservoir was estimated on the basis of an expected positive acoustic impedance contrast; however this was not possible on all lines due to the seismic signal attenuation sub-salt. Furthermore, it was not possible to tie this horizon against available well data and thus the base location of the reservoir cannot be treated with a great degree of confidence.

Well data

Only one exploration well (29/27-1) has been drilled on the edge of the study site. Eleven adjacent wells (Table 2) are available around the site (Fig. 3) which allow for lithological, rock property and age

Table 2. Names and details of adjacent UKCS wells used in this study.

Name	Year	Total depth (m)	Base formation	Status
28/12-1	1971	2247	Rotliegend	Plugged & Abandoned
29/16-1	1973	3235	Rotliegend	Plugged & Abandoned
29/18-1	1976	3701	Rotliegend	Plugged & Abandoned
29-19-1a	1976	2352	Triassic	Plugged & Abandoned
29/19-2	1976	2951	Rotliegend	Plugged & Abandoned
29/19-3	1973	3048	Rotliegend	Plugged & Abandoned
29/19-a3	1986	3073	Rotliegend	Plugged & Abandoned
29/20-1	1973	2765	Rotliegend	Plugged & Abandoned
29/25-1	1970	3190	Devonian	Plugged & Abandoned
29/27-1	1987	2899	Rotliegend	Plugged & Abandoned
37/10-1	1969	2830	Carboniferous	Plugged & Abandoned

calibration of the seismic data and key horizons. These wells all pre-date 1990 and are available in the public domain via micro-fiche well records. The well logs comprise stratigraphy derived from petrographic descriptions of recovered borehole rock cuttings allied to gamma ray, sonic and resistivity petrophysical logs. Limited pore pressure measurements were available from wells 29/16-1, 29/19-a3 and 29/27-1 comprising repeat formation testing (RFT) direct pressure measurements along with the pressure and density of drilling mud required to prevent an influx of pore fluid or gas into the wellbore. Pressure test data to determine the maximum allowable pressure before failure were included from wells 29/16-1 and 29/19a-3. No wells encountered oil or gas and therefore no production testing data were available. Core was available from well 29/27-1 but no other cores were accessible for analysis in this study. Where data such as porosity, permeability and other key parameters are not available, data from oil fields within 50 km of the study site have been used providing they share similar stratigraphy.

Data collected from wells 29/27-1 and 29/16-1 provided mud weights (the mass per unit volume of drilling fluid used to control the hydrostatic pressure whilst drilling)[23] used in drilling the Zechstein and Rotliegend intervals. The fracture pressure of the sealing Zechstein unit was taken from leak off test data (LOT – a test whereby the well is shut in and the pressure increased until a specific value is obtained or fractures are created within the formation)[24] undertaken below the deepest set casing shoe. This maximum pressure can be estimated as the maximum allowable pressure for that formation during drilling but also as used in this case, a guide for the maximum CO_2 injection pressure that can be utilized without fracturing of the sealing unit.[24]

Geological perspectives

Geological setting

The study site is located offshore 200 km northeast of Teesside (NE England), on the southern edge of UK continental shelf quadrants 28 and 29 (Fig. 3). Geologically the site lies on the south-western edge of the Northern Permian Basin.[25] The geological evolution of the North Sea basin can be divided into five separate tectonic events.[26] These comprise Caledonian and Variscan foreland basin phases, Permian and Triassic rifting stages, and a Tertiary post-rift phase of subsidence. It is accepted that the North Sea rift comprises a post-Caledonian graben system triggered by Devonian extension[27] with active extension occurring during the Permo-Triassic and during the Middle and Late Jurassic.[28,29] The Lower Permian Rotliegend that forms the primary interest for this study was deposited in a broad east-west basin stretching from the UK onshore to Poland across the southern North Sea, and was formed as a result of thermal subsidence in the aftermath of the Variscan orogeny.[30] The Rotliegend sandstones of the Central North Sea that form the reservoir for this study were deposited in a much smaller sub-basin (Northern Permian Basin) of similar orientation north of the fragmented Mid-North Sea High.[31,32] The thickness of these sandstones was controlled by the subsiding Danish-Norwegian basin creating accommodation space for deposition of sediment sourced from the uplifted Danish Central Graben.[32] Deposited of this Zechstein Group occurred within the connection between the Southern and Northern Permian Basin,[33] to the southwest of the Central Graben.

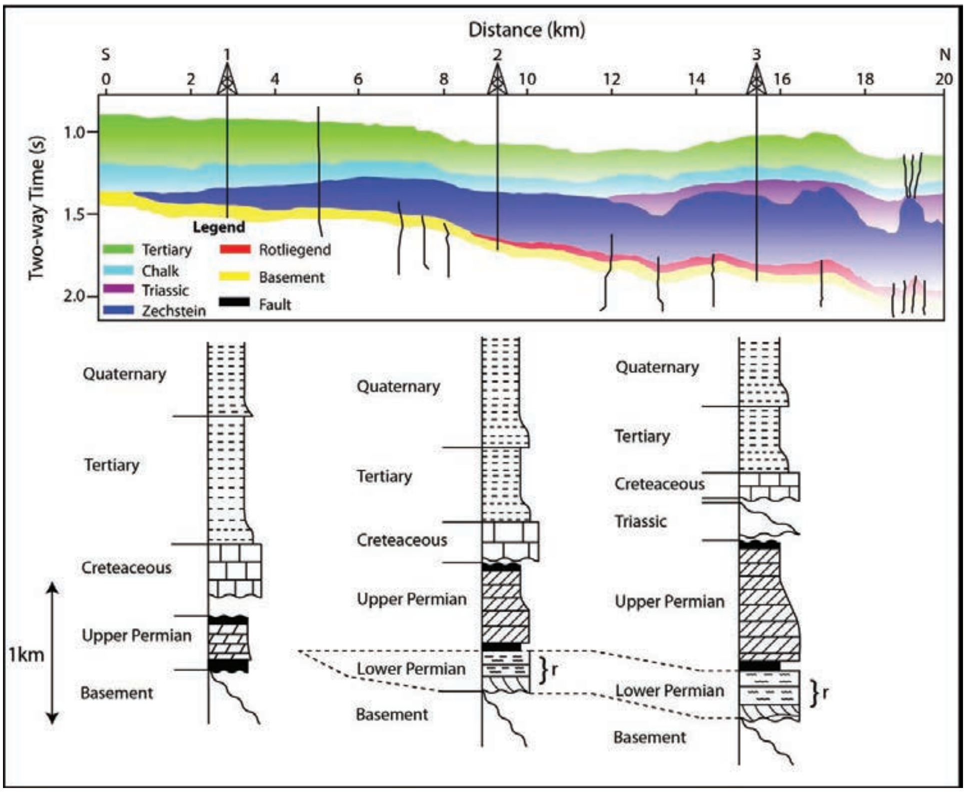

Figure 4. Regional structure and stratigraphy based on regional seismic line orientated south to north across the study site. Schematic wells 1, 2 and 3 included showing the lateral variation in unit distribution and approximate variation in thicknesses. The blue Zechstein (Upper Permian) represents the cap rock for the study site and is observed thinning to pinch out in the south beyond the stratigraphic pinch out of the red Lower Permian Rotliegend sandstones that represent the primary reservoir (r).

The stratigraphy of the study site can be summarized as Devonian strata overlain by either Carboniferous Coal Measures, or directly and unconformably by the Lower Permian sandstones of the Rotliegend Group or its lateral equivalent the Silverpit Mudstone (lacustrine deposits) depending on position within the basin. This interval is overlain by the Upper Permian Zechstein Group strata comprising interbedded carbonates and evaporites. These are in turn overlain by Triassic silts and occasional sands, Cretaceous chalk and interbedded Tertiary silts and muds[14,34,35] (Fig. 4).

Caprock interval

The Caprock interval for this case study comprises Upper Permian Zechstein salts with interbedded dolomites, deposited in subsiding basin conditions[36] and forming an extensive drape above the lower Permian Rotliegend Group. Adjacent well data and tied seismic data (Figs 6 and 8) indicates that the Zechstein Group thickness ranges from approximately 100 m in the west and southwest, increasing to >1000 m in parts towards the east (Fig. 4). The low permeability Halite and Anhydrite facies is prevalent and comparable with facies observed as proven seals in adjacent oilfields, and as such provides strong evidence for a sealing caprock to the study site.

The salt shows evidence of early stage tectonic growth, due likely to burial depths of between 600 and 1000 m along with thinning of the overburden during Triassic extension.[37] Diapirs in the study area, however, are not as defined or extensive as those illustrated within the Banff Field to the north of the study area. Furthermore, such structures are not observed to penetrate further than the top of the Triassic strata reducing potential leakage pathways.

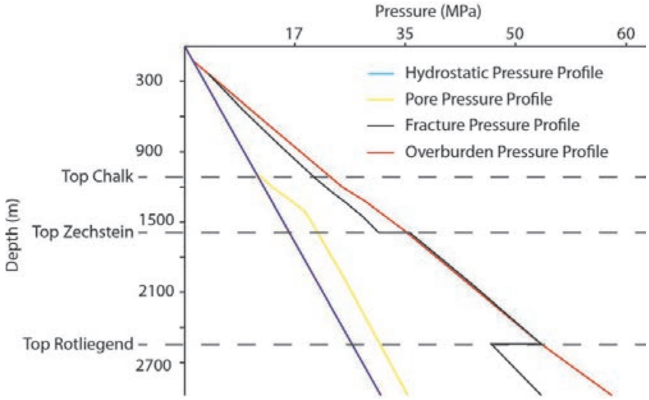

Figure 5. Pressure plot using data from UKCS well log 29/19a3 converted from psi. Formation pressure plot based upon pressure measurements and drilling mud weight profiles indicating that the reservoir is over pressured by c. 4 MPa (600 psi) on a hydrostatic gradient from the onset of overpressure within the cretaceous chalk. Fracture gradients inferred from leak off tests indicate a near lithostatic fracture pressure through the Zechstein salt, stepping back to c. 48 MPa (7000 psi) on entry into the top reservoir unit.

This displacement, however, causes adjacent localized thinning of the salt in some central and south-western sectors giving concerns over the quality of the seal in this area. Lack of well penetration within this area prevents direct identification of facies. Thus whether thickening and mobility of the salt has removed the halite/anhydrite phases from this portion of the seal leaving the dolomite exposed to potential CO_2 interaction and associated chemical reactions is impossible to directly quantify.[38] However, the chaotic nature of the seismic response and the lack of coherent seismic reflections would indicate likely presence of salt and thus these concerns are considered to be a low probability scenario.

Published sources[14,34,35,39] indicate Zechstein porosity at between 2% and 26% depending on sedimentary facies (generally 2–3% in the evaporite units and the higher 13–22% in the vuggy, fractured dolomite facies). Permeabilities range from 0.1 mD to 1 D again depending on facies. Drilling mud weights from well 29/27-1 indicate that fracture pressure through the Zechstein runs approximately equal to lithostatic pressure. A leak off test undertaken at the base Zechstein indicate leak off pressure of 48 MPa (7000 psi) and a seal capacity of 17 MPa (2500 psi) (Fig. 5).

Reservoir interval

The reservoir interval for this study comprises sandstones of the Lower Permian Rotliegend Group. Seismic reflection profiles tied to stratigraphic formation tops derived from well log cutting descriptions (Figs 6 and 8) indicate that the Rotliegend sandstone is represented by the first continuous positive reflection above the un-differentiated basement rather than the first negative reflection below the Zechstein as may be expected (Fig. 7(d)). Lithological descriptions from borehole logs that penetrate the Rotliegend Formation indicate that the sandstone is consistent with the dune and fluvial facies as found in the Auk reservoir and thus indicative of the presence of reservoir quality sandstone interval. These wells terminate within the Rotliegend and do not give an indication of maximum reservoir thickness. However the wells indicate that reservoir thickness must be in excess of 146 m in well 29/19-2 and in excess of 558 m in well 29/18-1. Core from well 29/19a-3 shows the reservoir rock to be reddish brown, medium to course grained, occasionally friable, laminated (~20° to bedding) sub-angular to sub-rounded, moderately sorted quartz arenite comprising >95% sub-angular milky translucent iron stained quartz consistent with that expected of the Aeolian dune facies of the Rotliegend. Localized anhydrite filling of pore and void spaces are present throughout the section (first 27 m) of the Rotliegend unit, with fracturing evident in some beds at approximately 20°–25° to bedding. The rock is generally well cemented with some sections comprising loose sand and poorly cemented fragments of mostly <60 cm intervals.

The distribution of the Permian Rotliegend units is generally controlled by the presence of a topographic low accommodating sediments derived from adjacent upland areas;[30] and thickness varies from 0 m (164 ft) in parts of the Argyll field[39] to >300 m (985 ft) in the Auk field and in well logs used in this study. Pinch out of the Rotliegend is interpreted from well data to occur to the southwest of the study area, marking the edge of the Northern Permian Basin (see dashed line Fig. 3). In this region, the top Rotliegend is expected to occur at a depth of c. 1500 m (Fig. 9), safely exceeding the minimum depth of 800 m recommended for CO_2 storage. Data from adjacent wells and core data shows no evidence of small scale, permeability inhibiting, deformation bands[40,41] within the Rotliegend sandstone and thus the impact

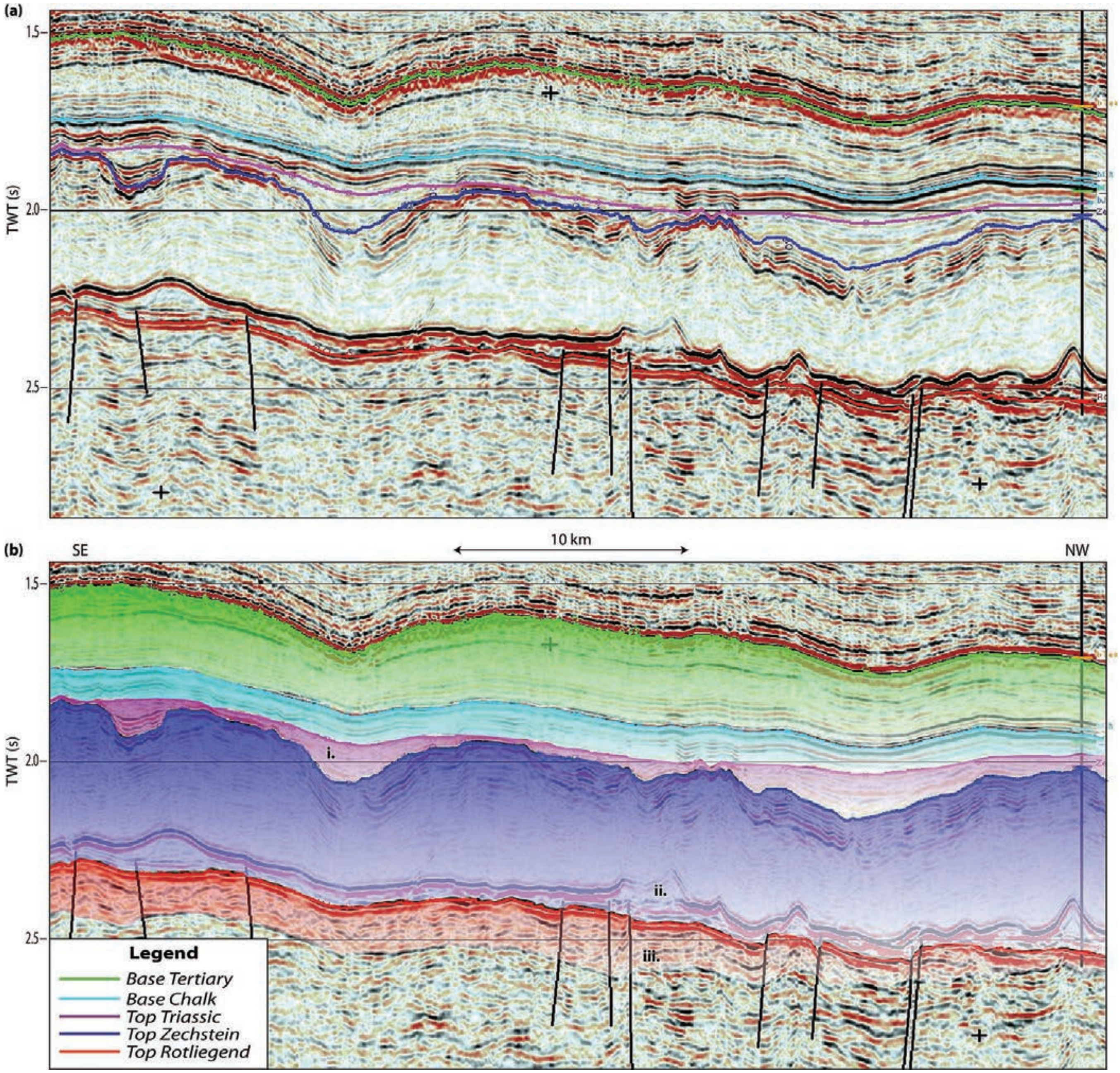

Figure 6. a) Seismic line trending south-east to north-west showing UKCS well 29/27-01 and well tied interpreted horizons derived from well cuttings logs. b) Seismic line showing variations in thickness across the study site including; i. Localised thickening of the upper Zechstein halite facies causing thinning and variable pinch out of the overlying Triassic sediments. ii. Semi-continuous high amplitude reflections caused by rafts of fractured dolomites set in the lower Zechstein halite and anhydrite facies. iii. Attenuated basement of the lower Permian. The base reservoir is not resolvable in this survey and has no proven well tie. Faulting in the lower Permian is small scale with limited offset and no sand/seal juxtaposition.

of these structures has been omitted from the variables for this study.

Data collated from the adjacent Auk and Argyll oil fields in addition to porosities calculated from sonic well logs surrounding the study site indicate average porosities of 15–20%. Average permeabilities for dune and sheetflood facies (Table 3) indicate values of 5mD (millidarcy) but range from as little as 0.1mD up to

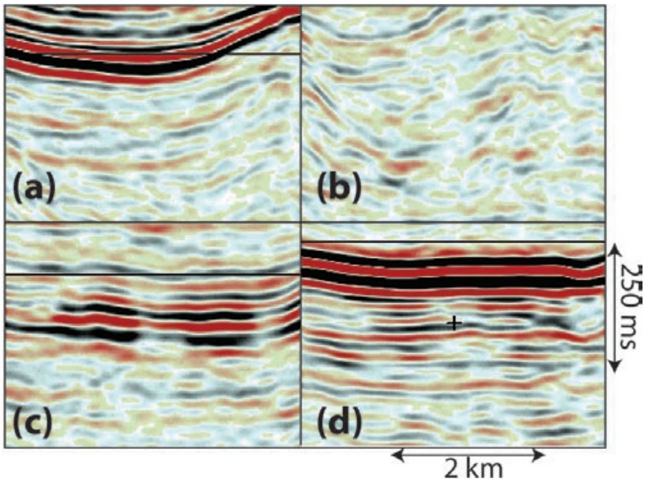

Figure 7. a) Seismic pick for the Top Zechstein indicated by the high amplitude continuous positive reflection above the moderate to low amplitude semi continuous chaotic reflections. b) Seismic response through the Zechstein salt facies characterised by a series of chaotic, moderate amplitude semi and non-continuous reflections. c) Seismic response through the Zechstein carbonate facies comprising moderate to high amplitude semi-continuous reflections set within the chaotic salt facies. This unit is often heavily fractured and deformed (Figures 8; 11). d) Seismic pick for the Top Rotliegend unit indicated by the high amplitude continuous positive reflection above the attenuated moderate amplitude basement. The high amplitude reflections above this represent the Zechstein carbonate facies described in c).

1D (Darcy) depending on location within the Rotliegend succession.[34,35,42] Core flood data indicate permeabilities of 26 mD and 31 mD based on core samples (SCCC report C/O Progressive Energy).

Table 3. Published Rotliegend porosity and permeability values[42] used in this paper in absence of measured values from drilled core in the study site. This table indicates the variation in porosity and permeability related to depositional facies. In the absence of well tie to accurately map the presence of each facies, a layered model was adopted using a most likely case scenario based on adjacent fields with similar stratigraphy.

Environment	Porosity range (mean)	Permeability range (mD)
Aeolian Dune	12 to 25 (22)	80.00 to 1000
Fluvial sheetflood	9 to 19 (14)	1.00 to 100
Interdune sabkha	5 to 19 (15)	0.8 to 10
Fluvial channel	2 to 20 (6)	0.10 to 1.00

Trap structure

This study focuses on three interconnected 4-way dip closed structures for preliminary injection of CO_2. These closures exist within a regional stratigraphically closed aquifer hosted within the Rotliegend Group sandstones. While the Zechstein Group represents a quantifiable caprock, it is difficult to predict the base seal for the reservoir. Regionally, carboniferous shales and coal measures are present to the south of the prospect but Devonian sandstones underlay the target reservoir at this site. UKCS well 29/25-1 indicates Devonian Old Red Sandstone Formation is encountered unconformably below the Rotliegend Formation at 3106 m (10190 ft) (Fig. 4). On condition that this observed unconformity is correct, the lack of hydrocarbons in surrounding exploration wells would suggest that, providing a stratigraphic sealing mechanism is in place, the site is underlain by Devonian strata rather than carboniferous source rocks (Fig. 4). The low seismic resolution sub-salt and insufficient well penetration however makes this hypothesis difficult to quantify.

The initial phase of CO_2 injection would utilize the aforementioned 4-way dip closures where CO_2 would be trapped structurally in conjunction to residual and in solution. These structures are not thought to be sealed at the base and thus CO_2 migration beyond the spill point would flow into the larger stratigraphically closed Rotliegend Sandstone aquifer and undergo residual trapping during up dip migration offering a leakage fail safe. Moreover, the stratigraphically closed Rotliegend aquifer offers storage potential for further injection phases although the capacity of this structure has not been modeled in this study. As such, the lack of base seal quantification is not considered to be a critical uncertainty. Furthermore, access to this aquifer is considered to allow brine displacement and pressure dissipation out of the dip-closed structure, consequently reducing the impact of pressure build up within the structure.

The overburden comprises a sequence of Triassic and Jurassic clastic sediments overlain by chalk of Cretaceous age and Tertiary clastics. The Triassic strata generally comprise interbedded claystone and siltstone of Scythian age[35] prior to mid Triassic period of erosion and subsequent unconformity. Jurassic Fulmar sandstones are observed in well logs resting on an erosional unconformity with the interbedded Triassic clay and siltstones despite not being present

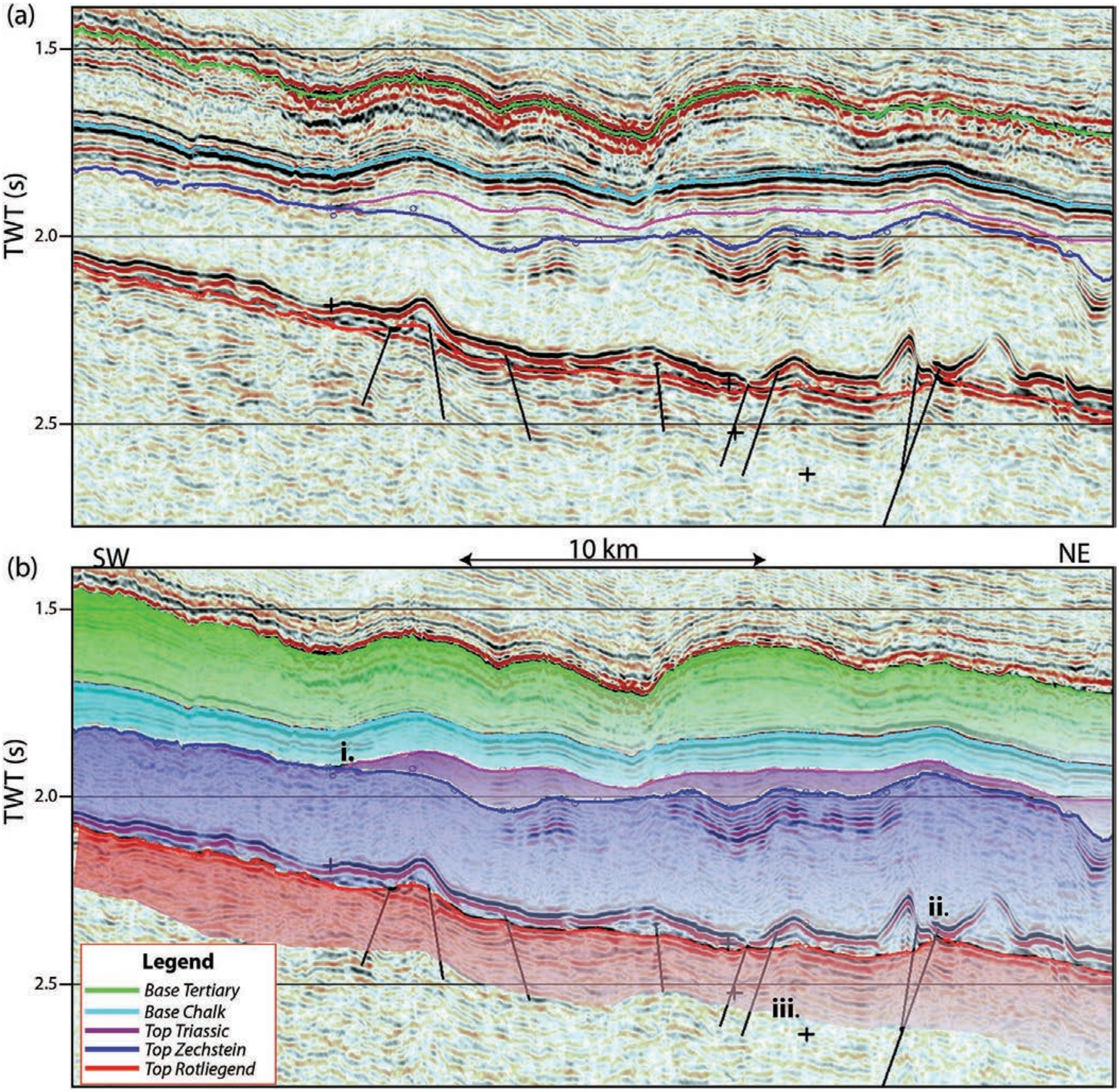

Figure 8. a) Seismic line trending south-west to north-showing general overview of subsurface structure and moderate relief fold structures in the upper chalk and Tertiary sediments. b) Seismic line showing variations in thickness across the study site including; i. Regional pinch out of the overlying Triassic sediments leaving an unconformable boundary between Cretaceous chalks and Upper Permian Zechstein evaporites. ii. Semi-continuous high amplitude reflections caused by rafts of fractured dolomites set in the lower Zechstein halite and anhydrite facies. iii. Attenuated basement of the lower Permian. The base reservoir is not resolvable in this survey and has no proven well tie. Faulting in the lower Permian is small scale with limited offset and no sand/seal juxtaposition.

in the Auk or Argyll fields to the northeast. Cretaceous chalks conformably overlie the Jurassic which are in-turn overlain by an interbedded sequence of Tertiary sand and clays (Figs 6 and 8).

Methodology

These data were used to for the purpose of estimating the storage capacity of the storage site. Three main

Table 4. Nomenclature used in storage capacity calculations

Term	Symbol	Unit	Description
Total Theoretical Pore Volume	VTP	m^3	Volume of the total pore space of a reservoir rock theoretically available to be filled with CO_2 excluding that occupied with irriducible water saturation
Gross Rock Volume	GRV	m^3	Gross rock volume measured directly from seismic data or by multiplying the trap area by reservoir height and applying an appropriate shape factor (m^3) multiplied by the Net to Gross ratio (Fraction), the ratio of net sand within the reservoir.
Porosity	φ	Fraction	Pore volume within a rock expressed as a fraction of total rock volume.
Irriducible Water Saturation	Sw	Fraction	The lowest water saturation that can be achieved in a core plug under laboratory conditions. Expressed within equations a 1 minus irriducible water saturation to represent pore water that is theoretically able to be displaced.
Total Theoritical CO_2 Storage Capacity	SC^{th}	Tonnes (t)	Total storage capacity of a reservoir theoretically achievable if CO_2 occupied all theoretically avialble pore space.
CO_2 Density	ρCO_2	kg/m^3	Density of CO_2 at reservoir temperature and pressure.
Stored CO_2	SCO_2	t	Volume of CO_2 that can be stored in the reservoir.
Allowable Pressure Increase	ΔP	Mpa	Allowable pressure increase between background reservoir pressure and cap rock fracture pressure.
Total Compressibility	Ct	–	Compressibility of residual brine (Cw) and compressibility of the reservoir rock (Cr where Cr = (1/-2.141 x 10^{-2} + 4.064 x 10^{-2} (Ø)0ew.4652) x10^{-6} 1/psi).28 Ct = Cw + Cr.
Factor of Storage Efficiency	E	Fraction	Efficiency factor that represents the multiplicative combination of volumetric parametres reflecting the portion of a reservoirs pore volume that CO_2 is expected to contact.

scenarios were highlighted for investigation using Monte-Carlo simulations. Scenario 1 investigates the total theoretical pore volume available within the reservoir and thus total theoretical capacity available for CO_2 storage; this is analogous to oil/gas in place calculations used in the upstream hydrocarbon industry.

The total theoretical pore volume may be calculated using the following equation (see Table 4 for definition of all variables):

$$V_{TP} = GRV \cdot \Phi \cdot (1 - S_{wiir}) \tag{1}$$

Multiplying the total theoretical storage volume by the density of CO_2 allows conversion from m^3 to tonnes. Thus the total theoretical CO_2 storage capacity may be calculated by:

$$SC_{TH} = GRV \cdot \Phi \cdot (1 - S_{wiir}) \cdot (\rho co_2) \tag{2}$$

Scenario 2 focused on a closed system that is confined on all sides (e.g. Ehlig-Economides and Economides.[11]) and does not allow either brine or pressure to migrate through these boundaries. As such, the storage capacity of a closed system is limited by the maximum allowable reservoir pressure increase before fracturing of the cap rock occurs (ΔP).

Storage capacity of a closed system as defined by Chadwick *et al.*[10] may be calculated by the following equation:

$$Sco2 = GRV \cdot \Phi \cdot (\rho CO_2) \cdot \Delta P \cdot Ct \tag{3}$$

Scenario 3 investigates open systems[12] where ΔP is omitted due to ability of the reservoir brine to be displaced outside of the primary reservoir (i.e. Fig. 2) removing the influence of the 'sealed box' pressure cell effect as demonstrated in Scenario 2. However, although pore scale displacement effects are incorporated into the efficiency factor (E), the dynamic effect of pressure increase around the wellbore is not modeled in the static solution. While pressure build-up will occur in all formations on injection of a

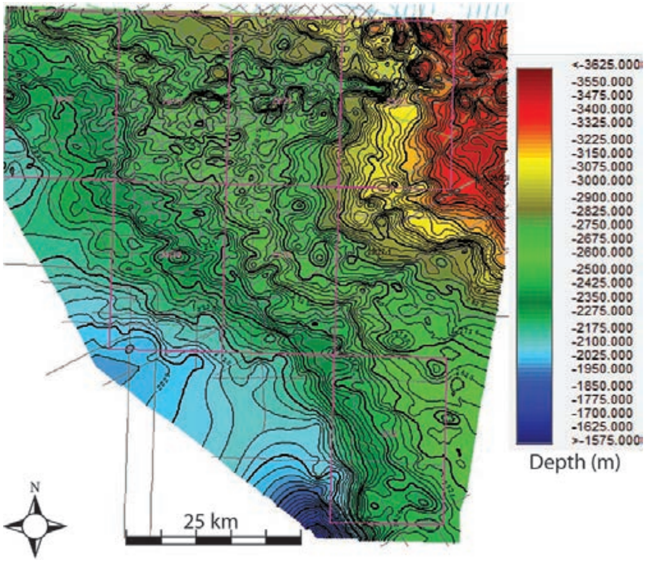

Figure 9. Depth converted contoured surface of the top Rotliegend reservoir unit over the study site.

mass and thus potentially limit usable capacity, it is the purpose of these methods to assess the theoretical total static capacity of a porous formation. The injectivity of a formation, and thus the usable storage capacity has been studied extensively by Mathias *et al.*;[43–46] however, it requires input data not readily available in basin margin settings and as such is not modeled in this paper. As such, the storage capacity of an open system as defined by the US DoE can be calculated using:

$$\mathrm{Sco2} = \mathrm{GRV}\cdot\Phi\cdot(\rho CO_2)\cdot E \qquad (4)$$

The efficiency factor (E), defined by the US DoE[12] as 'the multiplicative combination of volumetric parameters that reflect the portion of a basin's or region's total pore volume that CO_2 is expected to actually contact.'[13] The terms defined for calculating efficiency by the DoE are generic and thus need modification prior to use in site-specific capacity calculations to give a realistic representation of the expected formation. Detailed examination of the variables utilised by the US DoE indicates that the method of calculating efficiency (E) can be expanded to remove variables representing net to gross ratio and irreducible water saturation into a gross rock volume calculation.

Thus, the CO_2 storage capacity of an open saline formation can be calculated:

$$\mathrm{Sco2} = \mathrm{GRV}\cdot\Phi\cdot(\rho CO_2)\cdot(1 - S_{wirr})\cdot E \qquad (5)$$

Using formulas 2, 3 and 5, Monte-Carlo simulations were run using the Oracle Crystal Ball forecasting simulator for each system type. An iterative process of Monte-Carlo trials was undertaken using 20 000 trials as a starting point increasing until no significant changes occurred. Consequently, a total of 1 million trials were used as an optimum between both accuracy and computational run time.

Areal extent and crest to spill depth were measured directly from the seismic data using the planimeter function within the SMT Kingdom software and measured depth to spill point to calculate reservoir volume (area × thickness). This was combined with net:gross values for the purpose of calculating gross rock volume. Values of net:gross were varied within the GRV calculation using a modal value of 80% based on a regional average from adjacent oilfields with a minimum and maximum of 60% and 100%, respectively. Porosity taken from published literature (Table 3) varied around minimum and maximum values of 10% and 30%, respectively, using a normal distribution to account for the variability of average values plotting between 15% and 25%. Site-specific irreducible water saturation values were not available and thus a triangular distribution was used based upon published literature using minimum, maximum, and mode values (Table 5).

The closed storage scenario (Eqn (3)) requires the maximum increase in pressure between fracture and reservoir pressure to be defined. An overpressure study performed as part of a commercial CCS feasibility study indicated a best, worst and most likely case scenario (Table 5).

The open storage scenario (Eqn (5)) utilizes the efficiency factor described previously but otherwise embodies the formula used in calculating total theoretical capacity. For efficiency factor, in place of the DoE sum of a series of multiplicative fractions for generic variables, this paper uses published values for effective reservoir sweep[47,48] efficiency using a minimum and maximum value varied via a normal probability distribution (Table 5).

Results

Results of the Monte-Carlo simulations indicate that the storage capacity varies greatly depending on whether the system is treated as closed or open. For a closed capacity system the results indicate tenth percentile (P10) base case of 1.3×10^6 tonnes of CO_2

Table 5. Input parameters, values, distribution and justifications for variables used in Monte-Carlo storage capacity simulations.

Input	Units	Min	Max	Mean	Mode	Distribution	Notes
ϕ	Fraction	0.07	0.30	–	–	Normal	Estimation of min and max porosity for all Rotliegend Facies collated from literature (Table 3)
GRV	m^3	4.43×10^8	6.65×10^8	5.54×10^8	–	Triangular	Calculated GRV from reservoir areal extent, trap height & N:G ration varied from 60% to 100%
S_{wiir}	Fraction	0.10	0.30	–	0.2	Triangular	–
ΔP	MPa	13	23	–	17	Normal	Minimum and maximum seal capacities representing minimum & maximum allowable pressure increase
E	Fraction	0.1	0.35	–	–	Normal	Estimated minimum and maximum published reservoir sweep efficiencies.

with dominant frequency results of 1.7×10^6 tonnes of CO_2. The 90th percentile (P90) for this system indicates a maximum storage capacity of 3×10^6 t of CO_2. When the system was treated as an open system, the results and thus storage capacity shifted significantly with a P10 value of 7.95×10^6 tonnes and a dominant frequency value 13×10^6 tonnes and P90 indicates storage capacity of 28×10^6 tonnes CO_2. Comparisons against the total theoretical storage shows results an order of magnitude greater than that of either the closed or open scenario, with P10 and P90 results of 42 and 112×10^6 tonnes, respectively (Fig. 10 and Table 6).

The differences in calculated storage capacities between the three modeled scenarios were more substantial than expected. Further sensitivity analysis (Fig. 11) was employed to assess the impact of specific variables within the equations. Scenario 1, the calculation of total theoretical storage, indicated that porosity variability has the greatest impact (93.1%) on reservoir capacity. It appears anomalous that porosity alone should have greater impact on storage capacity than gross rock volume (GRV). However, logically due to the high net:gross ratio of the reservoir and well constrained trap areal extent, GRV has a relatively minor variation and more certainty attached to input variables. Porosity conversely, is poorly constrained and as such less certain than GRV. As the key control of net poor volume, but separate to the GRV calculation (A.H.NTG), this uncertainty in input translates directly into total capacity estimation.

Sensitivity in closed storage scenarios indicates that although porosity remains the dominant control, impact is more evenly distributed between porosity and GRV (50.5% *vs* 42.2%, respectively). This contrast with regards to the previous scenario is deemed a result from the structuring of the two equations. Scenario 1 in essence calculates total available pore space that may be filled with CO_2 whilst Scenario 2, although still calculating volume of CO_2 able to be stored within that pore space, examines the effects of pressure and the ability of both rock and brine to be compressed directly impacting upon the bulk rock rather than pore space alone. It is surprising that allowable pressure increase does impact upon the sensitivity analysis despite common consensus and published literature[10,11] dictating that it is one of the key parameters. The equation used in this paper calculates static capacity and therefore capacity at a randomly calculated reservoir pressure between natural reservoir and fracture pressure. As such, while the limitations of confining pressure are included and reservoir pressure exceeding fracture pressure is not allowable, this scenario investigates the whole reservoir and not isolated portions. Short term dynamic effects such as isolated abnormal high pressure spikes around the well bore are not modeled as these constitute a reservoir engineering challenge that may be investigated statically[43–46] or dynamically on obtaining reliable down-hole formation testing data. Furthermore, although having a confining effect on storage capacity, the seal capacity of the reservoir indicates that reservoir pressure may be increased by between 74% and 83% above initial reservoir pressure. Consequently, for this storage site, it is proposed that the confining effects of pressure build up are not as independently restrictive to total storage volume as factors that restrict the total effective pore volume.

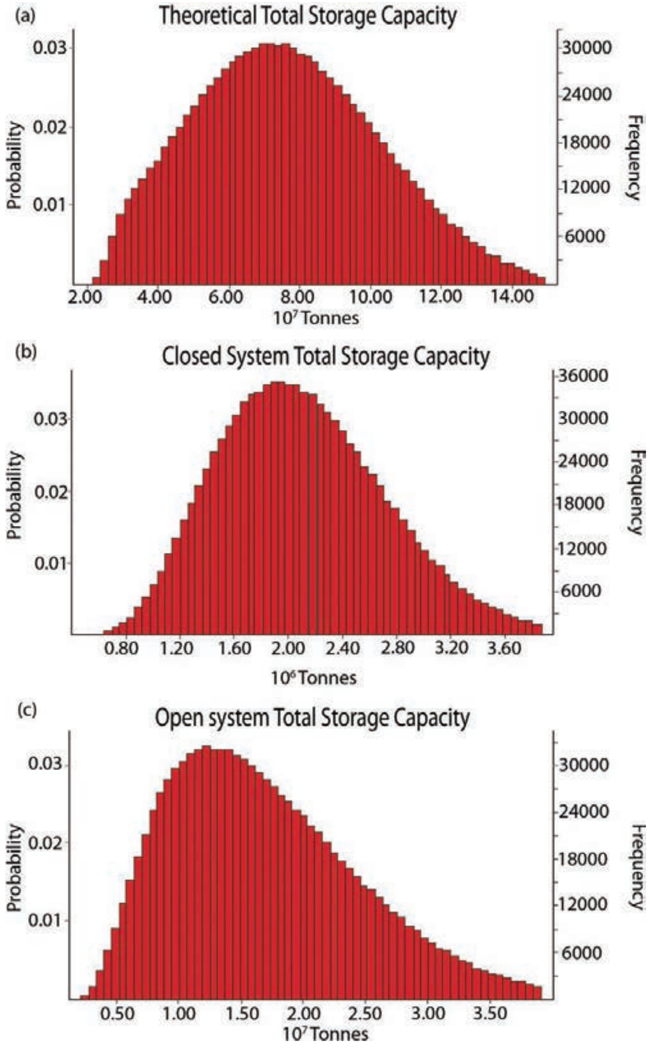

Figure 10. a) Results graph from Monte Carlo simulations plotting theoretical CO_2 Storage capacity in tonnes against frequency. b) Results graph from Monte Carlo simulations plotting CO_2 Storage capacity in tonnes against frequency for a closed reservoir scenario. c) Results graph from Monte Carlo simulations plotting CO_2 Storage capacity in tonnes against frequency for an open reservoir scenario.

Nevertheless, the combined effect of these variables results in a reduction of storage capacity when compared to open or theoretical scenarios.

The structure of the equation used in Scenario 3 is analogous to Scenario 1, where both porosity and sweep efficiency are used to calculate net pore volume available to be filled with $CO_{2.}$ Thus sensitivity analysis indicates that both porosity and efficiency factor rank as the most significant variables. GRV is not classed as significant, likely due to the relative lack of variability in areal extent and net:gross ratio.

Table 6. Results in percentiles of Monte-Carlo-based storage capacity estimations for theoretical, closed, and open storage scenarios.

System scenario results: Total Storage Capacity (10^6 tonnes)			
Percentile	1: Theoretical	2: Closed	3: Open
P0	19.50	0.48	2.19
P10	42.50	1.30	7.95
P20	52.60	1.60	10.10
P30	60.80	1.70	12.10
P40	68.00	1.90	13.90
P50	75.00	2.10	15.90
P60	82.20	2.20	18.00
P70	89.90	2.40	20.50
P80	91.10	2.60	23.50
P90	112.00	3.00	28.00
P100	178.00	5.40	57.80

Discussion and implications

The importance of whether the reservoir unit is closed or open has significant implications for the storage capacity of this site. Results for the closed system indicate that the most probable capacity is likely to be in the region of 0.1 to 1 × 10^6 t of CO_2. Put in perspective of the required annual storage of 2.5 × 10^6 t CO_2 pa. from a mid-sized power station, a closed system would be unable to handle more than 6 months injection before the reservoir pressure exceeded the seal fracture pressure of 48 MPa. However, in the case of the open system, depending on exact physical properties such as porosity and thickness, using the same annual storage requirements, the site would be able to sequester between 30 and 250 years' worth of CO_2 from onshore CO_2 sources.

It is unlikely in the geological setting of the central North Sea to have a completely open system in its most basic definition due to the structural history and the influence to the Central Graben fault network.[49] Moreover, the assumptions in assuming a fully sealed closed system as proposed by Ehlig-Economides and Economides[11] have since been widely discredited by a number of authors.[50,51] Comparable reservoir overpressure values taken from wells surrounding the study site indicate that the reservoir is in pressure communication at least over geological time; the storage capacity estimates based upon the closed

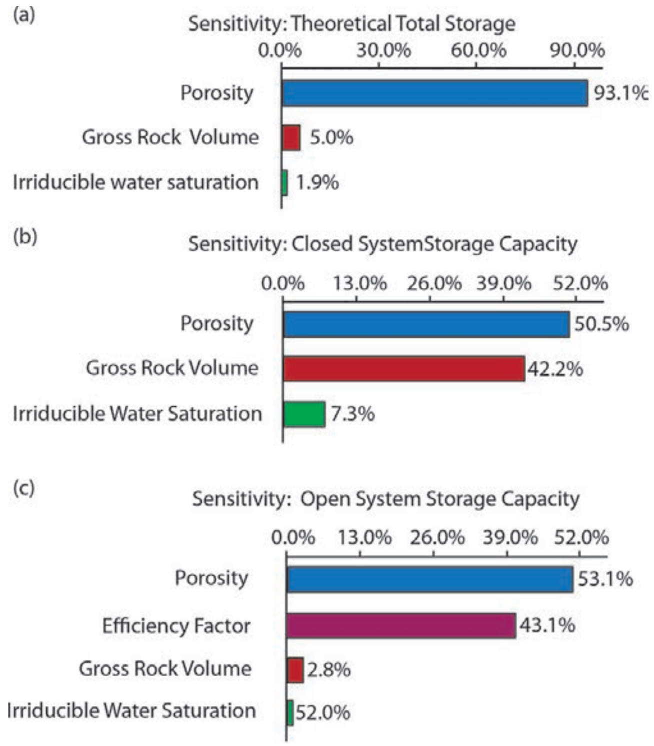

Figure 11. Tornado charts showing relative impact of variables from sensitivity analysis undertaken on capacity estimation Monte-Carlo simulations. Note that while all relevant variables stated in Table 5 were included in the simulations, only those with an impact >0% are displayed.

system scenario are not deemed to be appropriate for this storage site and thus are considered to represent a worst case scenario.

In this case, the lack of well data penetrating the reservoir and indeed the underlying base seal allied to poor seismic data quality, results in potentially significant inaccuracies in the required input parameters used for this study. While it is expected that further reservoir interval occurs below the spill point of the structure, should it be found that the system boundaries are of low permeability, pressure dissipation will be inhibited across them. Thus, pressure build up on injection around the well location by well number and design[44] would require strict control resulting in a detrimental effect on injection rate and an increase in the number of wells required.

With regards to the equation for calculating closed storage capacity as defined by Chadwick *et al.*,[10] sensitivity analysis indicates that allowable pressure increase does not constitute a significant variable, a result at odds with numerous authors[10,11,46] due to the poorly constrained porosity and GRV data and the 74% to 83% allowable pressure increase. Whilst this is the case for this study where a seal capacity represents an allowable pressure increase of 74% to 83%, this may not be the case in tight gas or significantly over-pressured reservoirs, which require further investigation. Furthermore, static methods pose significant shortcomings in that dynamic pressure spikes caused by injection are not modeled and as such represent only a total capacity per maximum pressure value and are not representative of injectivity.

Current methods of calculating static storage capacity in saline aquifers vary but all depend on capacity or efficiency factors, a numerical coefficient that converts theoretical storage capacity (i.e. 100% of available pore space) to probable capacity, analogous to a recovery factor deployed in oil and gas in place estimates. The US DoE NETL Atlas[12] utilizes an E-factor of 2%; however it is based on capacity calculations for aquifer systems that cover hundreds of square kilometers and thus we consider such input values cannot be deemed accurate or appropriate on smaller scale prospects. For example, the parameter ‘fraction of total basin/region area that has a suitable formation present’ may be considered to be 100% on a prospect scale that has been thoroughly investigated, rather than the 20–80% range used by the Atlas. Recent authors[15,16] have refined the input parameters over those used within the original methodology to remove these regional scale variables. Despite this modification, efficiency factors improve only by a value of 8% pointing to a flaw inherent in the method, i.e. multiplying a fraction by a further fraction resulting in an ever-decreasing value. Where sufficient data are available, the method of calculating efficiency by relying on dynamic reservoir simulations requiring irreducible water saturation values as detailed by Gorecki *et al.*[16,17] and Allinson *et al.*[10] would appear to give more accurate results based upon a site-specific basis and result in estimated E factors of up to 16.5% for thin low permeability reservoirs, and up to 25% 4-way dip closed structures.

To quality control and contextualize the efficiency factors calculated both within this paper and previously published literature, the storage capacity equation was re-arranged with respect to the factor of efficiency, E_{geol}. Using published production data[34,35,39,52–54] from a range of North Sea oil and gas fields, E_{geol} was back-calculated by substituting total

Table 7. Efficiency factors, calculated as a percentage of gross rock volume vacated by produced reservoir fluids for a series of Rotliegend hosted North Sea gas, oil and gas condensate fields.

Field	Field Type	Efficiency Factor (%)
Davey	Gas	70.67
Bessemer	Gas	71.03
Innes	Oil	11.5
Auk	Oil	0.57
Armada	Wet gas	7.68

production of oil or gas and density of oil/gas for effective storage capacity and density of CO_2, respectively. This equation therefore calculates efficiency as the percentage of gross rock volume vacated by the produced hydrocarbons working on the hypothesis that pore fluid (oil, brine, and gas) out must be less than or equal to the potential material injected. Although not a true representation for reservoirs with aquifer drive or where associated gas/water production is unknown, results indicate the value of efficiency varies considerably from <2% in tight oil reservoirs to >75% in gas reservoirs (Table 7).

Complex published analytical methods[15] for calculating static capacity may provide more accurate results due in part to non-reliance on efficiency factors. Application to low data density sites however requires further use of analog data that does not account for lateral geological heterogeneity and thus is considered to only introduce further uncertainty and inaccuracies into already imprecise calculations.

Conclusions

The key uncertainty highlighted in this study is one of limited well and seismic data. The lack of well log data from within the storage site and indeed reservoir unit requires all static modeling input variables to be based on inferred assumptions from adjacent data. Sensitivity analysis indicates porosity to be the primary uncertainty in all capacity estimations. As such, site-specific measurements allowing porosity to be constrained to 5% variation rather than 20% presented here would likely constrict the range of storage capacity estimates. Likewise, direct net:gross measurement in conjunction with 3D seismic data would restrict the variability of GRV.

Primary analysis of the storage capacity results detailed in this paper suggests that the most significant control on the storage capacity of deep saline formations is the ability to accurately classify the pressure system type present in the reservoir (Fig. 2). Whilst in a purely hypothetical model based scenario the closed pressure cell method has merit, experience of reservoir engineering techniques used in the oil and gas industry, drilling of pressure relief wells and formation water production[55,56] render this method unsuitable for storage capacity estimations in geological circumstances addressed in this paper.

When the more likely open system scenario is applied, further uncertainty is produced by the use of efficiency factors.[13] It is the opinion of this paper that this method is highly conservative and unsuitable for site specific calculations. Authors[13,15] have indicated that the variables relating to net area and net reservoir lithology may be omitted in site specific calculations where values equal 100%. Further to this we have shown that when dealing with 4-way dip closed reservoirs that may be filled to spill, buoyancy and gravity factors are invalid as the purpose is to calculate the total capacity and not at a given point during injection. Consequently is realistic that with brine production techniques, the available storage volume is equal to the total pore volume multiplied by one minus the irreducible water saturation. Under reservoir conditions, irreducible water saturation is unlikely to be obtained and thus an estimate of sweep efficiency is used to account for unswept portions of the reservoir where geological heterogeneity may block internal reservoir connectivity. Back calculation from oil and gas field production data indicate that produced material may account for between 2% and 75% of total pore space leading to un-acceptable variation in storage capacity depending purely on which 'best estimate' of efficiency is implemented.

For sites afflicted by low data density, the uncertainty inherent in inferred input variables, shown in this case by sensitivity analysis to be porosity over reservoir volume, multiplied by the uncertainty intrinsic within efficiency factors results in an unacceptable range in storage capacity estimates.

Therefore we propose that for basin margin prospects with sparse data, a Monte-Carlo-based P10, P50, P90 theoretical capacity estimation has less uncertainty than the efficiency based model. This figure may be refined by dynamically modelling the storage complex once the first stage of site appraisal has been completed, namely by obtaining at a minimum 3D seismic data and the drilling of one formation appraisal well allowing site specific measurements of reservoir pressure, porosity/permeability and temperature.

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References

1. IPCC, Working Group III of the Intergovernmental Panel on Climate Change, *Special report on Carbon Dioxide Capture and Storage,* ed by Metz B, Davidson O, de Coninck H, Loos M and LA M. Cambridge University Press, Cambridge (2005).
2. Dicharry RM, Perryman TL and Ronquille JD, Evaluation and design of a CO_2 miscible flood project – SACROC unit, Kelly-Snyder Field. *SPE J Petrol Technol* **25**:1309–1318 (1973).
3. Korbøl R and Kaddour A, Sleipner vest CO_2 disposal - injection of removed CO_2 into the utsira formation. *Energ Convers Manage* **36**(6/9):509–512 (1995).
4. Baklid A, Korbol R and Owren G, Sleipner vest CO_2 disposal, CO_2 injection into a shallow underground aquifer. SPE Annual Technical Conference and Exhibition, 6–9 October, 1996, Denver, Colorado (1996).
5. Beardsley RH and Fore JE, *Exploration Prospect Interpretation and Risking Using Modern Geophysical Technology - A Methodology to Identify and Prioritize Exploration Focus Areas in GOM Using 3-Dimensional Volumes of Pressure, Temperature, and Other Subsurface Data.* Offshore Technology Conference, 4–7 May, 2009, Houston, Texas.
6. Bradshaw M, Willcox B, Struckmeyer H and Foster C, *Australia's Fronteir Basins and Prospects for New Petroleum Provinces.* 17th World Petroleum Congress, 1 January, 2002. World Petroleum Congress, Rio de Janeiro, Brazil (2002).
7. Duggirala MN, Bastia R, Tenepalli S, Akella M, Verma R and D'silva K, *Mesozoics of the South Western Margin of India: A Frontier Exploration.* 19th World Petroleum Congress, 29 June–3 July, 2008 Madrid, Spain, (2008).
8. Lowrie A, Somoza L, Gardner JM and Klekamp TL, *Potential Hydrocarbon Plays of the Gulf of Mexico.* Offshore Technology Conference, 6–9 May, 2002 Houston, TX (2002).
9. Howard A, Beswetherick S and Miglio G, Prospectivity on the Erris Ridge (Licence 7/97)â, *High Risk/High Reward Frontier Exploration on the Irish Atlantic Margin. Offshore Europe,* January 1, 2009. Society of Petroleum Engineers, Aberdeen, UK (2009).
10. Chadwick RA, Arts R, Bernstone C, May F, Thibeau S and Zweigel P (eds), *Best Practice for the Storage of CO_2 in Saline Aquifers; Observations and guidelines from the SACS and CO2STORE projects*. British Geological Survey Occasional Publications, Nottingham, UK (2008).
11. Ehlig-Economides C and Economides MJ. Sequestering carbon dioxide in a closed underground volume. *J Petrol Sci Eng* **70**(1/2):123–130 (2010).
12. NETL, *Carbon Sequestration Atlas of the United States and Canada.* US Department of Energy, Office of Fossil Energy, Washington DC (2009).
13. Allinson WG, Kaldi JG, Cinar Y and Paterson L, *CO_2 Storage Capacity â Combining Geology, Engineering and Economics.* SPE Asia Pacific Oil and Gas Conference and Exhibition, Society of Petroleum Engineers, Brisbane, Queensland, Australia (2010).
14. Glennie KW, Higham J and Stemmerik L. Permian, In *The Millenium Atlas: Petroleum Geology of the Central and Northern North Sea,* ed by Evans D, Graham C, Armour A and Brathust P. Geological Society, London, pp. 318–322 (2003).
15. Kopp A, Class H and Helmig R, Investigations on CO_2 storage capacity in saline aquifers—Part 2: Estimation of storage capacity coefficients. *Int J Greenhouse Gas Cont* **3**(3):277–287 (2009).
16. Gorecki CD, Holubnyak Y, Ayash S, Bremer JM, Sorensen JA, Steadman EN *et al., A New Classification System for Evaluating CO_2 Storage Resource/Capacity Estimates.* SPE International Conference on CO_2 Capture, Storage, and Utilization, Society of Petroleum Engineers, San Diego, CAa, USA (2009).
17. Gorecki CD, Sorensen JA, Bremer JM, Knudsen D, Smith SA, Steadman EN *et al., Development of Storage Coefficients for Determining the Effective CO_2 Storage Resource in Deep Saline Formations.* SPE International Conference on CO_2 Capture, Storage, and Utilization, Society of Petroleum Engineers, San Diego, Ca, USA (2009).
18. Bachu S and Adams JJ, Sequestration of CO_2 in geological media in response to climate change: Capacity of deep saline aquifers to sequester CO_2 in solution. *Energ Convers Manage* **44**(20):3151–3175 (2003).
19. Bradshaw J, Bachu S, Bonijoly D, Burruss R, Holloway S, Christensen NP *et al.,* CO_2 storage capacity estimation: Issues and development of standards. *Int J Greenhouse Gas Cont* **1**(1):62–68 (2007).
20. Zhou Q, Birkholzer JT, Tsang C-F and Rutqvist J, A method for quick assessment of CO_2 storage capacity in closed and semi-closed saline formations. *Int J Greenhouse Gas Cont* **2**(4):626–639 (2008).
21. Goodman A, Hakala A, Bromhal G, Deel D, Rodosta T, Frailey S *et al.,* U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale. *Int J Greenhouse Gas Cont* **5**(4):952–965 (2011).
22. Bachu S, *Comparison between Methodologies Recommended for Estimation of CO_2 Storage Capacity in Geological Media*. CSLF Task Force on CO_2 Storage Capacity Estimation

and the USDOE Capacity and Fairways Subgroup of the Regional Carbon Sequestration Partnerships Program (2008).

23. Mouchet J-P and Mitchell A, Abnormal pressures while drilling: Origins - Prediction - Detection - Evaluation: Elf aquitaine: Manuels techniques. Société Notionale Elf Aquitaine, Boussens (1989).
24. Nguyen J-P, *Drilling: Oil and Gas Field Development Techniques*. Institut Francais du Petrole Publications, Editions Technip, Paris (1996).
25. Legler B and Schneider JW, Marine ingressions into the middle/late Permian saline lake of the Southern Permian Basin (Rotliegend, Northern Germany) possibly linked to sea-level highstands in the Arctic rift system. *Palaeogeogr Palaeocl* **267**(1/2):102–114 (2008).
26. Ziegler PA, Geologic evolution of North Sea and its tectonic framework. *AAPG Bull* **59**(7):1073–1097 (1975).
27. Færseth RB, Interaction of Permo-Triassic and Jurassic extensional fault-blocks during the development of the Northern North Sea. *J Geol Soc* **153**(6):931–944 (1996).
28. Davies RJ, Turner JD and Underhill JR, Sequential dip-slip fault movement during rifting: A new model for the evolution of the Jurassic trilete North Sea rift system. *Petrol Geosci* **7**(4):371–388 (2001).
29. Roberts AM, Yielding G, Kusznir NJ, Walker IM and Dorn-Lopez D, Quantitative analysis of Triassic extension in the northern Viking Graben. *J Geol Soc* **152**(1):15–26 (1995).
30. Maynard JR and Gibson JP, Potential for subtle traps in the Permian Rotliegend of the UK Southern North Sea. *Petrol Geosci* **7**(3):301–314 (2001).
31. Clark JA, Stewart SA and Cartwright JA, Evolution of the NW margin of the North Permian Basin, UK North Sea. *J Geol Soc* **155**(4):663–676 (1998).
32. Stemmerik L, Ineson JR and Mitchell JG, Stratigraphy of the Rotliegend group in the Danish part of the Northern Permian Basin, North Sea. *J Geol Soc* **157**(6):1127–1136 (2000).
33. Jenyon MK, Cresswell PM and Taylor JCM, Nature of the connection between the Northern and Southern Zechstein Basins across the Mid North Sea High. *Mar Petrol Geol* **1(4)**:355–363 (1984).
34. Robson D, The Argyll, Duncan and Innes Fields, Block 30/24 and 30/25a, UK North Sea. *Geol Soc London Mem* **14**(1):219–226 (1991).
35. Trewin NH, Fryberger SG and Kreutz H. The Auk Field, Block 30/16, UK North Sea, in *United Kingdom Oil and Gas Fields; Commermorative Millennium Volume*, ed by Gluyas JG, Hitchens HM. Geological Society, London, pp. 12 (2003).
36. Davison I, Alsop I, Birch P, Elders C, Evans N, Nicholson H *et al.,* Geometry and late-stage structural evolution of Central Graben salt diapirs, North Sea. *Mar Petrol Geol* **17**(4):499–522 (2000).
37. Taylor JCM, Upper Permian - Zechstein, in *Petroleum Geology of the North Sea: Basic Concepts and Recent Advances*, ed by Glennie KW. Blackwell Science, London (1998) pp. 195.
38. Czernichowski-Lauriol I, Rochelle C, Gaus I, Azaroual M, Pearce J and Durst P, Geochemical interactions between CO_2, pore-waters and reservior rocks, in *Advances in the Geological Storage of Carbon Dioxide*, ed by Lombardi S, Altunina LK and Beaubien SE. Springer, Netherlands, pp. 157–174 (2006).
39. Gluyas JG, Mair B, Schofield P, Arkley P and Mcrae D. Ardmore Field: Rebirth of the first offshore oil field, UKCS. *Geol Soc London Petrol Geol Conf Series* **6**:367–388 (2005).
40. Fowles J and Burley S, Textural and permeability characteristics of faulted, high porosity sandstones. *Mar Petrol Geol* **11**(5): 608–623 (1994).
41. Crawford BR, Experimental fault sealing: Shear band permeability dependency on cataclastic fault gouge characteristics. *Geol Soc London, Special Pub* **127**(1):27–47 (1998).
42. Selley RC, Porosity gradients in North Sea oil-bearing sandstones. *J Geol Soc* **135**(1):119–132 (1978).
43. Mathias S, Hardisty P, Trudell M and Zimmerman R, Approximate solutions for pressure buildup during CO_2 injection in brine aquifers. *Transport Porous Media* **79**(2):265–284 (2009).
44. Mathias SA, De Miguel G, Thatcher KE and Zimmerman RW, Pressure buildup during CO_2 injection into a closed brine aquifer. *Transport Porous Med* **89**(3):383–397 (2011).
45. Mathias SA, Gluyas JG, González Martínez De Miguel GJ, Bryant SL and Wilson D, On relative permeability data uncertainty and CO_2 injectivity estimation for brine aquifers. *Int J Greenhouse Gas Cont* **12**:200–212 (2013).
46. Mathias SA, Hardisty PE, Trudell MR and Zimmerman RW, Screening and selection of sites for CO2 sequestration based on pressure buildup. *Int J Greenhouse Gas Cont* **3**(5):577–585 (2009).
47. GESTCO, *CO_2 storage scenarios in North Germany. GESTCO project case studies.* Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover (2004).
48. Hughes RG, *Evaluation and Enhancement of Carbon Dioxide Flooding Through Sweep Improvement*. US Department of Energy Office of Fossil Energy, Washington DC (2009).
49. Glennie KW and Underhill JR, Origin, development and evolution of structural styles, in *Petroleum Geology of the North Sea: Basic Concepts and Recent Advances*, ed by Glennie KW. Blackwell Science, London, pp. 54–58 (1998).
50. Cavanagh AJ, Haszeldine RS and Blunt MJ, Open or closed? A discussion of the mistaken assumptions in the economides pressure analysis of carbon sequestration. *J Petrol Sci Eng* **74**(1/2):107–110 (2010).
51. Chadwick RA, Smith D, Hodrien C, Hovorka S, Mackay E, Mathias SA *et al., The realities of storing carbon dioxide - A response to CO_2 capapcity issues raised by Ehlig-Economides & Economides*. Zero Emissions Platform (2010). Available: http://dx.doi.org/10.1038/npre.2010.4500.1 [13 May 2013].
52. Mccrone CW, The Davy, Bessemer, Beaufort and Brown fields, blocks 49/23, 49/30a, 49/30c, 53/5a, UK North Sea. *Geol Soc London Mem* **20**(1):705–712 (2003).
53. Trewin NH and Bramwell MG, The Auk field, block 30/16, UK North Sea. *Geol Soc London Mem* **14**(1):227–236 (1991).
54. Stuart IA, The Armada development, UK Central North Sea: The Fleming, Drake and Hawkins Gas-Condensate Fields. *Geol Soc London Mem* **20**(1):139–151 (2003).
55. Malik QM and Islam MR, *CO_2 Injection in the Weyburn Field of Canada: Optimization of Enhanced Oil Recovery and Greenhouse Gas Storage with Horizontal Wells.* Society of Petroleum Engineers Inc, SPE/DOE Improved Oil Recovery Symposium, Tulsa, Oklahoma, 3–5 April (2000).
56. Orr FM Jr, Storage of Carbon Dioxide in geologic formations. *J Petrol Technol* **56**(9):90–97 (2004).

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APPENDIX 1.B

RAW CRYSTAL BALL OUTPUT REPORT IN SUPPORT OF THE MONTE CARLO SIMULATIONS PRESENTED IN CHAPTER 3 SECTION 3.6

Crystal Ball Report - Full

Simulation started on 27/09/2012 at 16:27
Simulation stopped on 27/09/2012 at 17:51

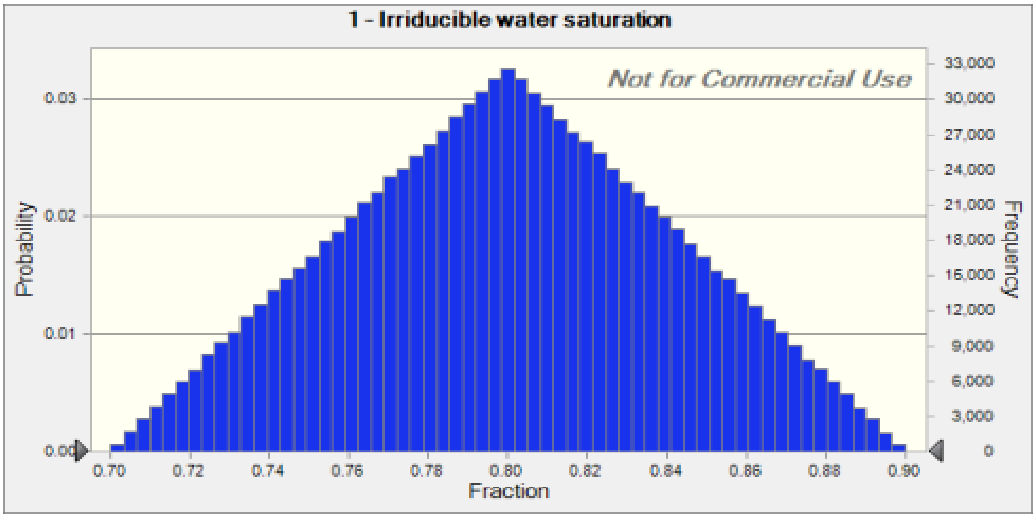
Run preferences:	
Number of trials run	1,000,000
Extreme speed	
Monte Carlo	
Random seed	
Precision control on	
Confidence level	95.00%
Run statistics:	
Total running time (sec)	5070.58
Trials/second (average)	197
Random numbers per sec	1,183
Crystal Ball data:	
Assumptions	6
Correlations	0
Correlated groups	0
Decision variables	0
Forecasts	15

Forecasts

Worksheet: [CCC xtal ball ache.xlsx]CCC

Forecast: 1 - Irriducible water saturation **Cell: D55**

Summary:
Entire range is from 0.70 to 0.90
Base case is 1.00
After 1,000,000 trials, the std. error of the mean is 0.00



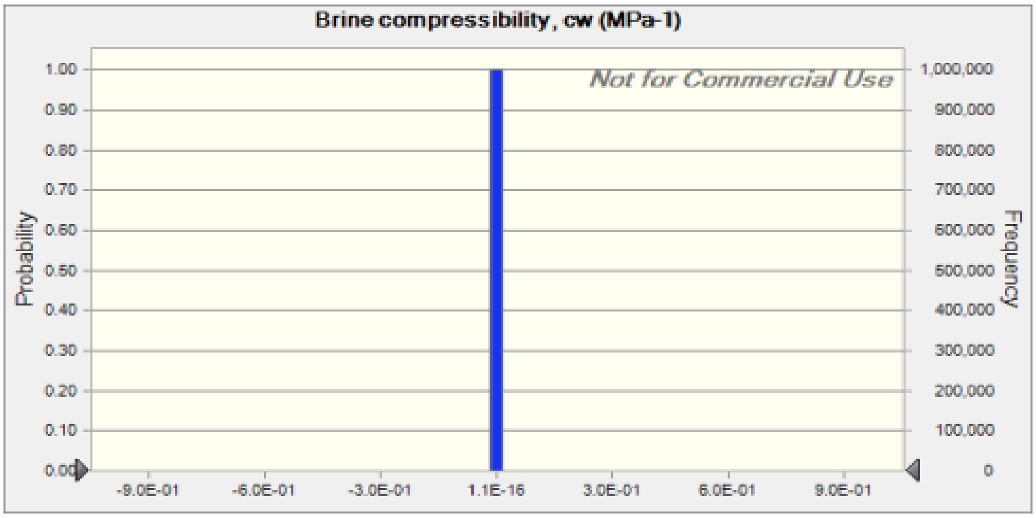
Statistics:	Forecast values
Trials	1,000,000
Base Case	1.00
Mean	0.80
Median	0.80
Mode	---
Standard Deviation	0.04
Variance	0.00
Skewness	0.0013
Kurtosis	2.40
Coeff. of Variability	0.0510
Minimum	0.70
Maximum	0.90
Range Width	0.20
Mean Std. Error	0.00

Forecast: 1 - Irriducible water saturation (cont'd) **Cell: D55**

Percentiles:	Forecast values
P0	0.70
P10	0.74
P20	0.76
P30	0.78
P40	0.79
P50	0.80
P60	0.81
P70	0.82
P80	0.84
P90	0.86
P100	0.90

Forecast: Brine compressibility, cw (MPa-1) **Cell: C16**

Summary:
Entire range is from 2.4E-04 to 2.4E-04
Base case is 2.4E-04
After 1,000,000 trials, the std. error of the mean is 0.0E+00



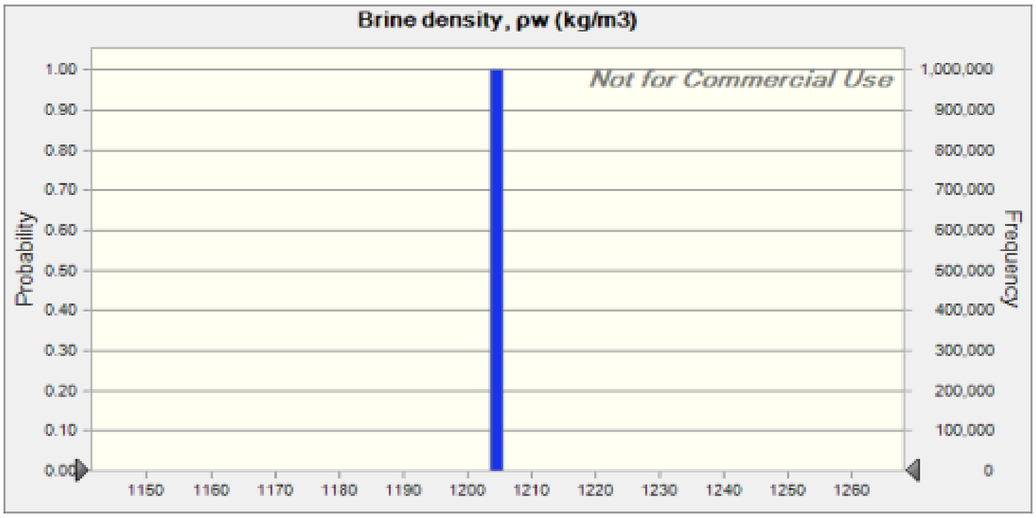
Statistics:	Forecast values
Trials	1,000,000
Base Case	2.4E-04
Mean	2.4E-04
Median	2.4E-04
Mode	2.4E-04
Standard Deviation	0.0E+00
Variance	0.0E+00
Skewness	---
Kurtosis	---
Coeff. of Variability	0.00
Minimum	2.4E-04
Maximum	2.4E-04
Range Width	0.0E+00
Mean Std. Error	0.0E+00

Forecast: Brine compressibility, cw (MPa-1) (cont'd) **Cell: C16**

Percentiles:	Forecast values
P0	2.4E-04
P10	2.4E-04
P20	2.4E-04
P30	2.4E-04
P40	2.4E-04
P50	2.4E-04
P60	2.4E-04
P70	2.4E-04
P80	2.4E-04
P90	2.4E-04
P100	2.4E-04

Forecast: Brine density, ρw (kg/m3) **Cell: C15**

Summary:
Entire range is from 1205 to 1205
Base case is 1205
After 1,000,000 trials, the std. error of the mean is 0



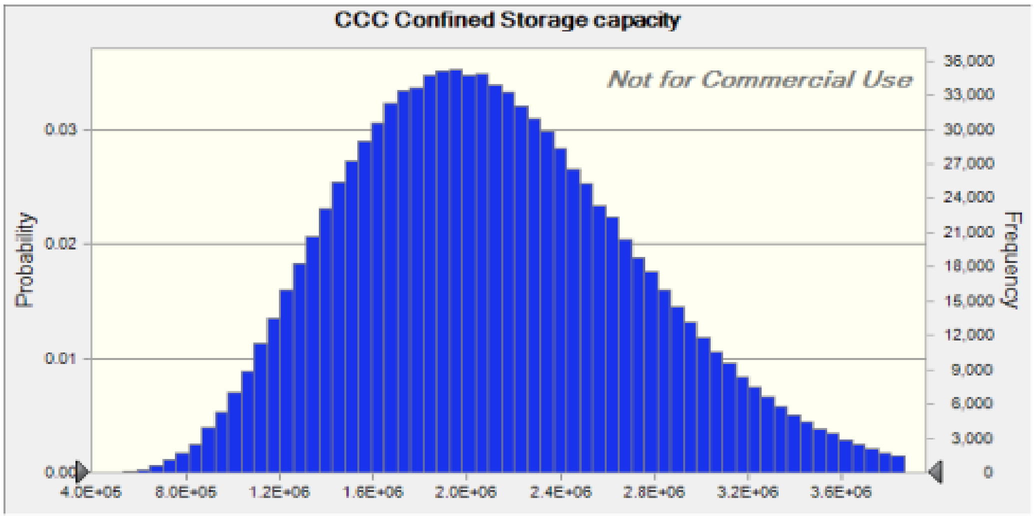
Statistics:	Forecast values
Trials	1,000,000
Base Case	1205
Mean	1205
Median	1205
Mode	1205
Standard Deviation	0
Variance	0
Skewness	---
Kurtosis	---
Coeff. of Variability	0.00
Minimum	1205
Maximum	1205
Range Width	0
Mean Std. Error	0

Forecast: Brine density, ρw (kg/m3) (cont'd) **Cell: C15**

Percentiles:	Forecast values
P0	1205
P10	1205
P20	1205
P30	1205
P40	1205
P50	1205
P60	1205
P70	1205
P80	1205
P90	1205
P100	1205

Forecast: CCC Confined Storage capacity **Cell: C29**

Summary:
Entire range is from 4.8E+05 to 5.4E+06
Base case is 0.0E+00
After 1,000,000 trials, the std. error of the mean is 6.3E+02



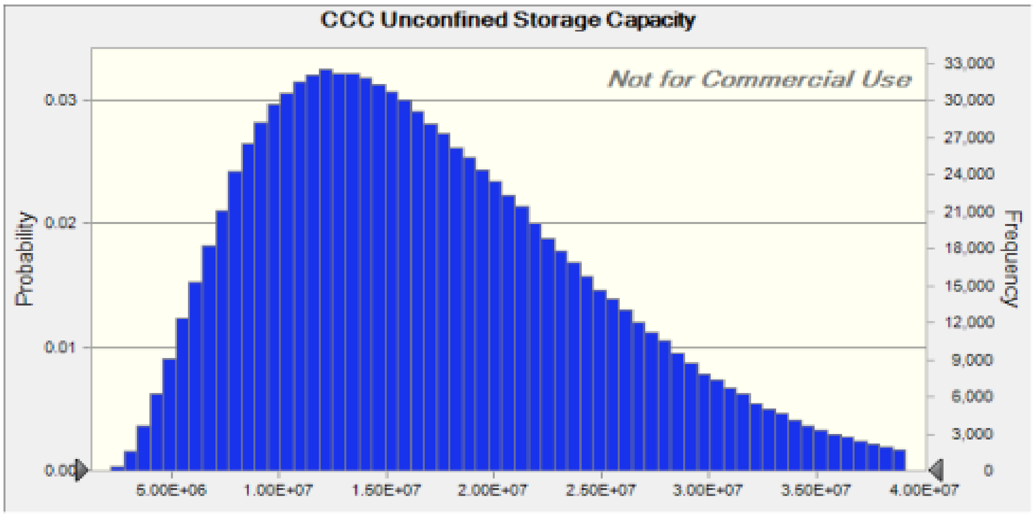
Statistics:	Forecast values
Trials	1,000,000
Base Case	0.0E+00
Mean	2.1E+06
Median	2.1E+06
Mode	---
Standard Deviation	6.3E+05
Variance	3.9E+11
Skewness	0.4672
Kurtosis	3.08
Coeff. of Variability	0.2965
Minimum	4.8E+05
Maximum	5.4E+06
Range Width	4.9E+06
Mean Std. Error	6.3E+02

Forecast: CCC Confined Storage capacity (cont'd) **Cell: C29**

Percentiles:	Forecast values
P0	4.8E+05
P10	1.3E+06
P20	1.6E+06
P30	1.7E+06
P40	1.9E+06
P50	2.1E+06
P60	2.2E+06
P70	2.4E+06
P80	2.6E+06
P90	3.0E+06
P100	5.4E+06

Forecast: CCC Unconfined Storage Capacity **Cell: C32**

Summary:
Entire range is from 2.19E+06 to 5.78E+07
Base case is 0.00E+00
After 1,000,000 trials, the std. error of the mean is 7.86E+03



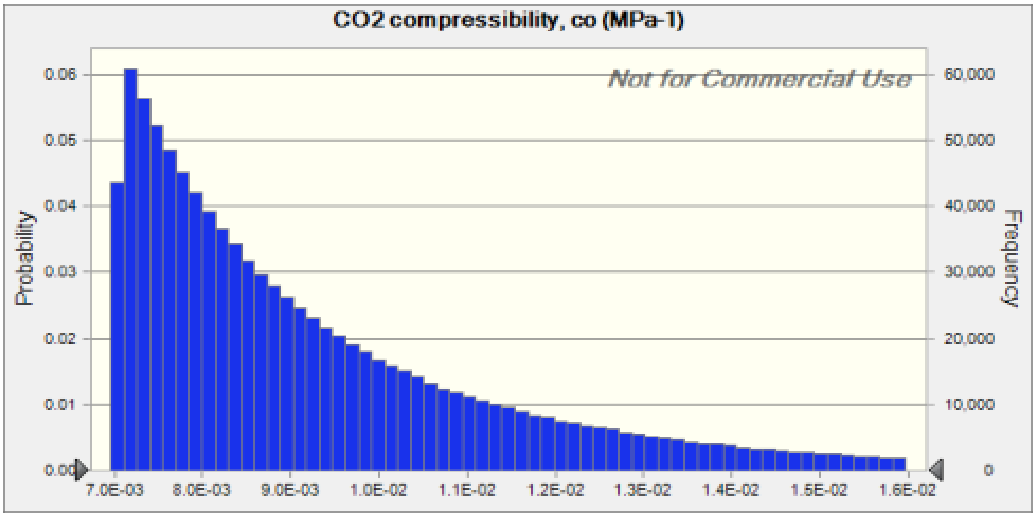
Statistics:	Forecast values
Trials	1,000,000
Base Case	0.00E+00
Mean	1.71E+07
Median	1.59E+07
Mode	---
Standard Deviation	7.86E+06
Variance	6.17E+13
Skewness	0.7532
Kurtosis	3.35
Coeff. of Variability	0.4595
Minimum	2.19E+06
Maximum	5.78E+07
Range Width	5.56E+07
Mean Std. Error	7.86E+03

Forecast: CCC Unconfined Storage Capacity (cont'd) **Cell: C32**

Percentiles:	Forecast values
P0	2.19E+06
P10	7.95E+06
P20	1.01E+07
P30	1.21E+07
P40	1.39E+07
P50	1.59E+07
P60	1.80E+07
P70	2.05E+07
P80	2.35E+07
P90	2.80E+07
P100	5.78E+07

Forecast: CO2 compressibility, co (MPa-1) **Cell: C20**

Summary:
Entire range is from 7.0E-03 to 2.1E-02
Base case is 7.1E-03
After 1,000,000 trials, the std. error of the mean is 2.3E-06



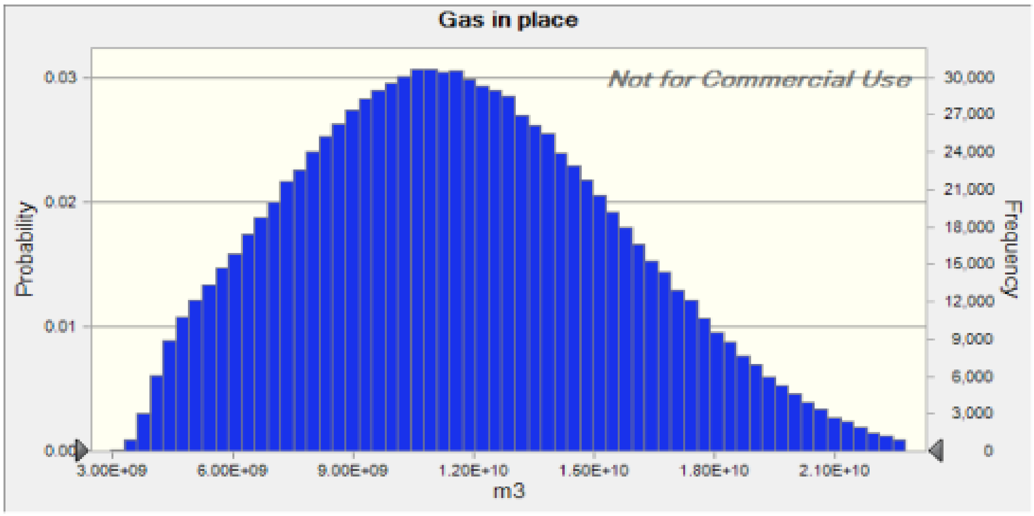
Statistics:	Forecast values
Trials	1,000,000
Base Case	7.1E-03
Mean	9.4E-03
Median	8.6E-03
Mode	---
Standard Deviation	2.3E-03
Variance	5.5E-06
Skewness	1.58
Kurtosis	5.52
Coeff. of Variability	0.2500
Minimum	7.0E-03
Maximum	2.1E-02
Range Width	1.4E-02
Mean Std. Error	2.3E-06

Forecast: CO2 compressibility, co (MPa-1) (cont'd) **Cell: C20**

Percentiles:	Forecast values
P0	7.0E-03
P10	7.2E-03
P20	7.5E-03
P30	7.8E-03
P40	8.2E-03
P50	8.6E-03
P60	9.2E-03
P70	9.9E-03
P80	1.1E-02
P90	1.3E-02
P100	2.1E-02

Forecast: Gas in place **Cell: D62**

Summary:
Entire range is from 2.97E+09 to 2.71E+10
Base case is 0.00E+00
After 1,000,000 trials, the std. error of the mean is 3.97E+06



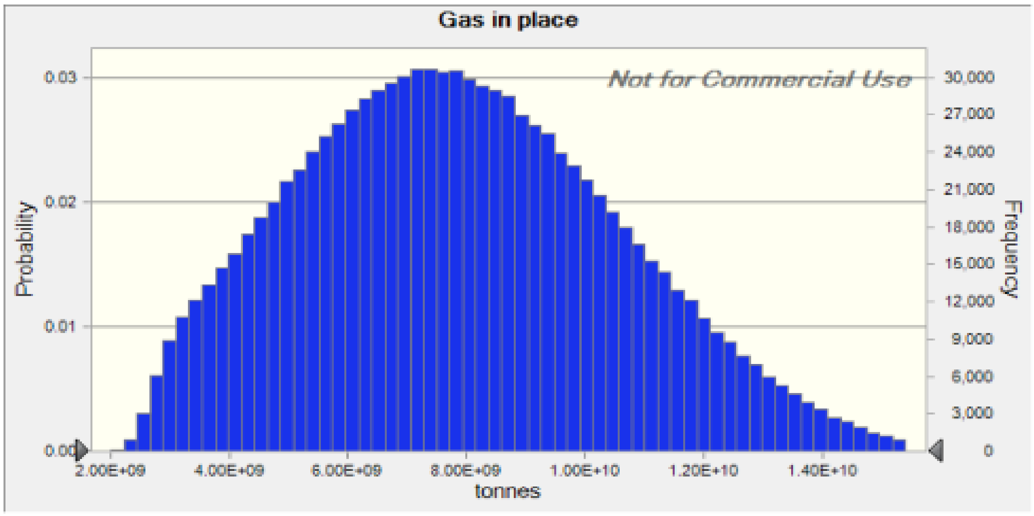
Statistics:	Forecast values
Trials	1,000,000
Base Case	0.00E+00
Mean	1.16E+10
Median	1.14E+10
Mode	---
Standard Deviation	3.97E+09
Variance	1.57E+19
Skewness	0.2872
Kurtosis	2.59
Coeff. of Variability	0.3411
Minimum	2.97E+09
Maximum	2.71E+10
Range Width	2.42E+10
Mean Std. Error	3.97E+06

Forecast: Gas in place (cont'd) **Cell: D62**

Percentiles:	Forecast values
P0	2.97E+09
P10	6.47E+09
P20	8.01E+09
P30	9.25E+09
P40	1.04E+10
P50	1.14E+10
P60	1.25E+10
P70	1.37E+10
P80	1.51E+10
P90	1.70E+10
P100	2.71E+10

Forecast: Gas in place **Cell: D63**

Summary:
Entire range is from 2.01E+09 to 1.84E+10
Base case is 0.00E+00
After 1,000,000 trials, the std. error of the mean is 2.68E+06



Statistics:	Forecast values
Trials	1,000,000
Base Case	0.00E+00
Mean	7.87E+09
Median	7.73E+09
Mode	---
Standard Deviation	2.68E+09
Variance	7.21E+18
Skewness	0.2872
Kurtosis	2.59
Coeff. of Variability	0.3411
Minimum	2.01E+09
Maximum	1.84E+10
Range Width	1.64E+10
Mean Std. Error	2.68E+06

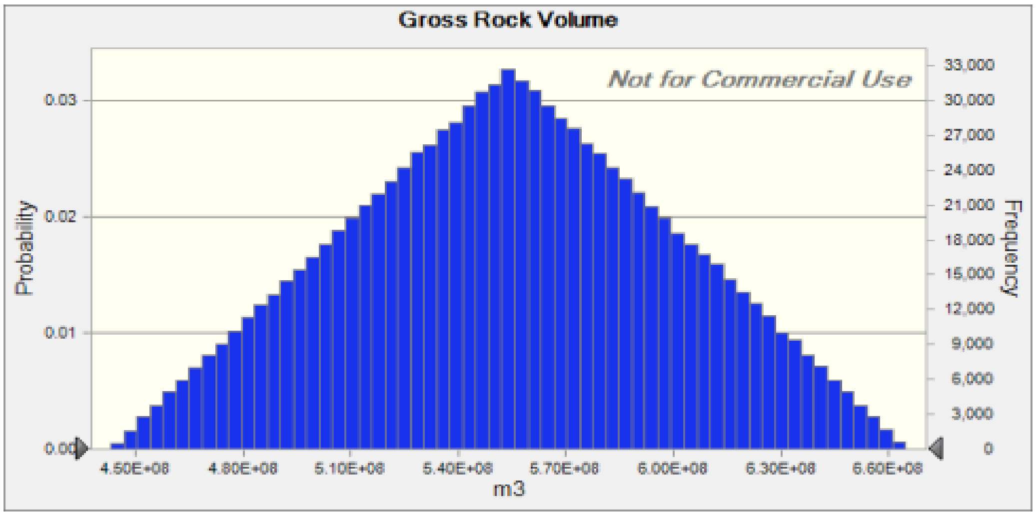
Forecast: Gas in place (cont'd) **Cell: D63**

Percentiles:	Forecast values
P0	2.01E+09
P10	4.38E+09
P20	5.42E+09
P30	6.26E+09
P40	7.01E+09
P50	7.73E+09
P60	8.47E+09
P70	9.27E+09
P80	1.02E+10
P90	1.15E+10
P100	1.84E+10

Forecast: Gross Rock Volume

Cell: D52

Summary:
Entire range is from 4.43E+08 to 6.65E+08
Base case is 0.00E+00
After 1,000,000 trials, the std. error of the mean is 4.52E+04



Statistics:	Forecast values
Trials	1,000,000
Base Case	0.00E+00
Mean	5.54E+08
Median	5.54E+08
Mode	---
Standard Deviation	4.52E+07
Variance	2.05E+15
Skewness	-0.0010
Kurtosis	2.40
Coeff. of Variability	0.0816
Minimum	4.43E+08
Maximum	6.65E+08
Range Width	2.21E+08
Mean Std. Error	4.52E+04

Forecast: Gross Rock Volume (cont'd) **Cell: D52**

Percentiles:	Forecast values
P0	4.43E+08
P10	4.93E+08
P20	5.13E+08
P30	5.29E+08
P40	5.42E+08
P50	5.54E+08
P60	5.66E+08
P70	5.79E+08
P80	5.95E+08
P90	6.15E+08
P100	6.65E+08

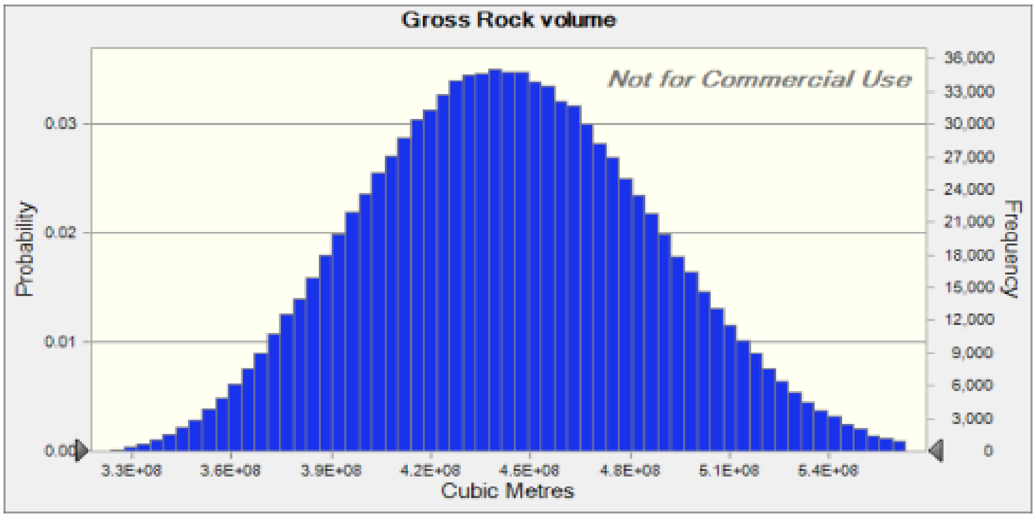
Forecast: Gross Rock volume **Cell: C23**

Summary:

Entire range is from 3.1E+08 to 5.9E+08

Base case is 0.0E+00

After 1,000,000 trials, the std. error of the mean is 4.3E+04



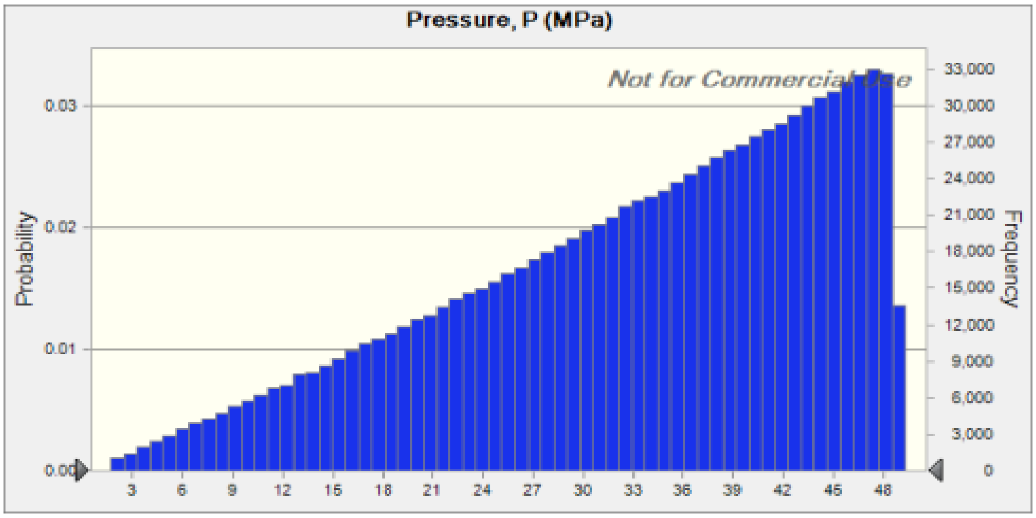
Statistics:	Forecast values
Trials	1,000,000
Base Case	0.0E+00
Mean	4.4E+08
Median	4.4E+08
Mode	---
Standard Deviation	4.3E+07
Variance	1.8E+15
Skewness	0.1165
Kurtosis	2.66
Coeff. of Variability	0.0963
Minimum	3.1E+08
Maximum	5.9E+08
Range Width	2.8E+08
Mean Std. Error	4.3E+04

Forecast: Gross Rock volume (cont'd) **Cell: C23**

Percentiles:	Forecast values
P0	3.1E+08
P10	3.9E+08
P20	4.1E+08
P30	4.2E+08
P40	4.3E+08
P50	4.4E+08
P60	4.5E+08
P70	4.7E+08
P80	4.8E+08
P90	5.0E+08
P100	5.9E+08

Forecast: Pressure, P (MPa) **Cell: C19**

Summary:
Entire range is from 0 to 49
Base case is 48
After 1,000,000 trials, the std. error of the mean is 0



Statistics:	Forecast values
Trials	1,000,000
Base Case	48
Mean	33
Median	35
Mode	---
Standard Deviation	11
Variance	127
Skewness	-0.6184
Kurtosis	2.49
Coeff. of Variability	0.3391
Minimum	0
Maximum	49
Range Width	49
Mean Std. Error	0

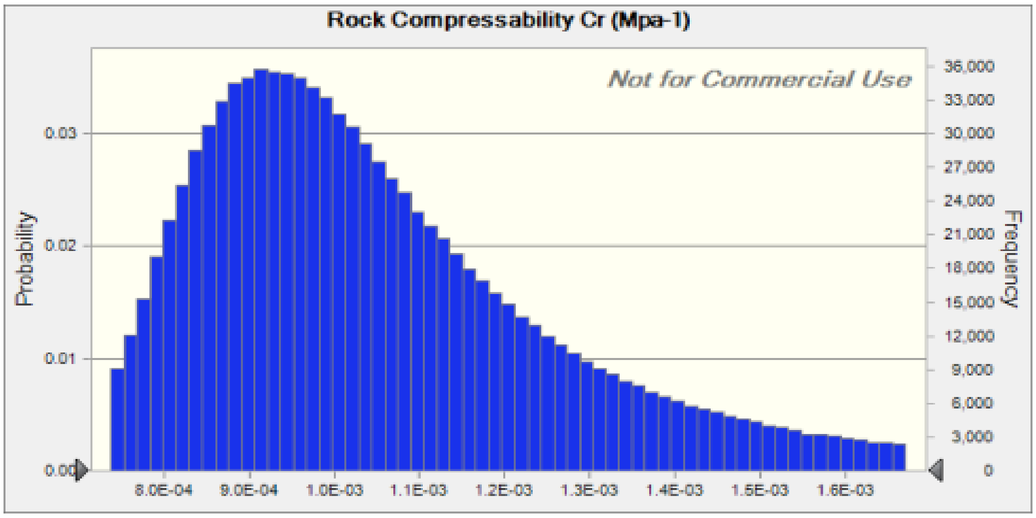
Forecast: Pressure, P (MPa) (cont'd) **Cell: C19**

Percentiles:	Forecast values
P0	0
P10	16
P20	23
P30	28
P40	32
P50	35
P60	38
P70	41
P80	44
P90	46
P100	49

Forecast: Rock Compressability Cr (Mpa-1) **Cell: C21**

Summary:

Entire range is from 7.4E-04 to 1.8E-03
Base case is 1.2E-03
After 1,000,000 trials, the std. error of the mean is 2.2E-07



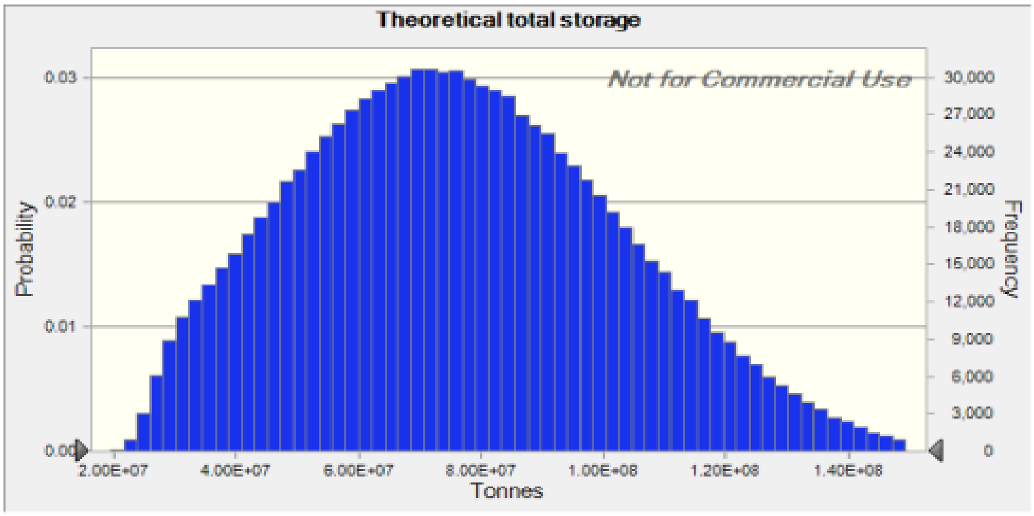
Statistics:	Forecast values
Trials	1,000,000
Base Case	1.2E-03
Mean	1.1E-03
Median	1.0E-03
Mode	---
Standard Deviation	2.2E-04
Variance	4.8E-08
Skewness	1.09
Kurtosis	3.95
Coeff. of Variability	0.2057
Minimum	7.4E-04
Maximum	1.8E-03
Range Width	1.1E-03
Mean Std. Error	2.2E-07

Forecast: Rock Compressability Cr (Mpa-1) (cont'd) **Cell: C21**

Percentiles:	Forecast values
P0	7.4E-04
P10	8.3E-04
P20	8.8E-04
P30	9.2E-04
P40	9.6E-04
P50	1.0E-03
P60	1.1E-03
P70	1.1E-03
P80	1.2E-03
P90	1.4E-03
P100	1.8E-03

Forecast: Theoretical total storage **Cell: C27**

Summary:
Entire range is from 1.95E+07 to 1.78E+08
Base case is 0.00E+00
After 1,000,000 trials, the std. error of the mean is 2.61E+04



Statistics:	Forecast values
Trials	1,000,000
Base Case	0.00E+00
Mean	7.64E+07
Median	7.50E+07
Mode	---
Standard Deviation	2.61E+07
Variance	6.79E+14
Skewness	0.2872
Kurtosis	2.59
Coeff. of Variability	0.3411
Minimum	1.95E+07
Maximum	1.78E+08
Range Width	1.59E+08
Mean Std. Error	2.61E+04

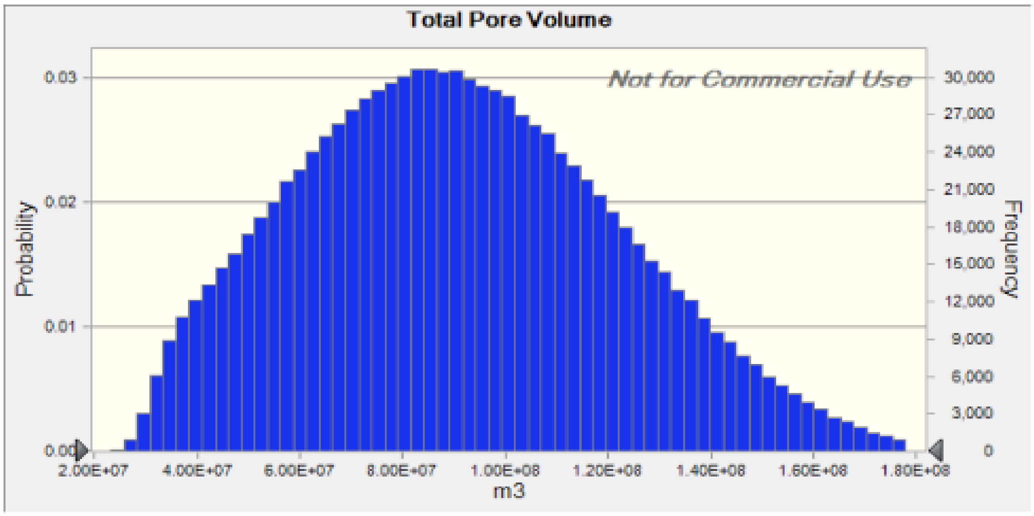
Forecast: Theoretical total storage (cont'd) **Cell: C27**

Percentiles:	Forecast values
P0	1.95E+07
P10	4.25E+07
P20	5.26E+07
P30	6.08E+07
P40	6.80E+07
P50	7.50E+07
P60	8.22E+07
P70	8.99E+07
P80	9.91E+07
P90	1.12E+08
P100	1.78E+08

Forecast: Total Pore Volume **Cell: C26**

Summary:

Entire range is from 2.32E+07 to 2.12E+08
Base case is 0.00E+00
After 1,000,000 trials, the std. error of the mean is 3.10E+04



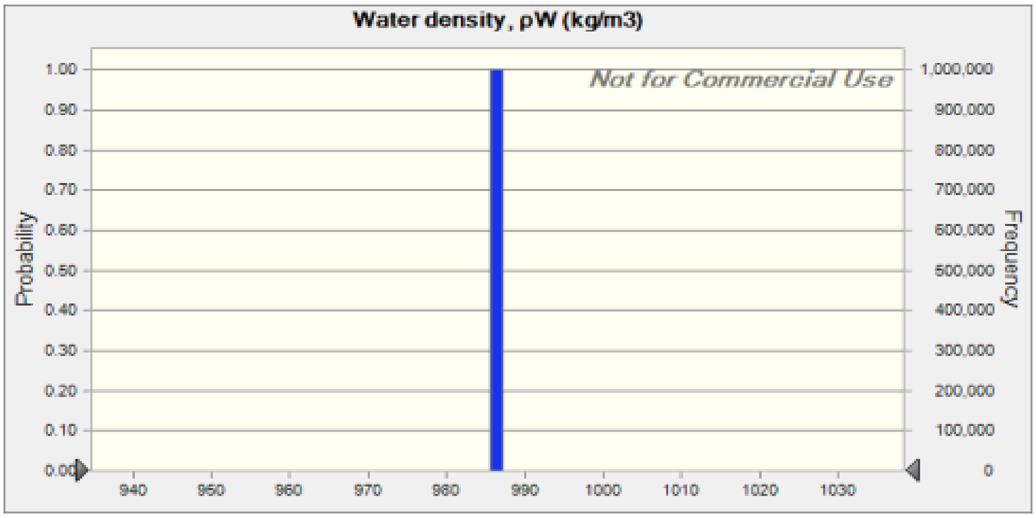
Statistics:	Forecast values
Trials	1,000,000
Base Case	0.00E+00
Mean	9.09E+07
Median	8.93E+07
Mode	---
Standard Deviation	3.10E+07
Variance	9.62E+14
Skewness	0.2872
Kurtosis	2.59
Coeff. of Variability	0.3411
Minimum	2.32E+07
Maximum	2.12E+08
Range Width	1.89E+08
Mean Std. Error	3.10E+04

Forecast: Total Pore Volume (cont'd) **Cell: C26**

Percentiles:	Forecast values
P0	2.32E+07
P10	5.06E+07
P20	6.27E+07
P30	7.23E+07
P40	8.10E+07
P50	8.93E+07
P60	9.78E+07
P70	1.07E+08
P80	1.18E+08
P90	1.33E+08
P100	2.12E+08

Forecast: Water density, ρW (kg/m3) **Cell: C14**

Summary:
Entire range is from 986 to 986
Base case is 986
After 1,000,000 trials, the std. error of the mean is 0



Statistics:	Forecast values
Trials	1,000,000
Base Case	986
Mean	986
Median	986
Mode	986
Standard Deviation	0
Variance	0
Skewness	---
Kurtosis	---
Coeff. of Variability	0.00
Minimum	986
Maximum	986
Range Width	0
Mean Std. Error	0

Forecast: Water density, ρW (kg/m3) (cont'd) **Cell: C14**

Percentiles:	Forecast values
P0	986
P10	986
P20	986
P30	986
P40	986
P50	986
P60	986
P70	986
P80	986
P90	986
P100	986

End of Forecasts

Assumptions

Worksheet: [CCC xtal ball ache.xlsx]CCC

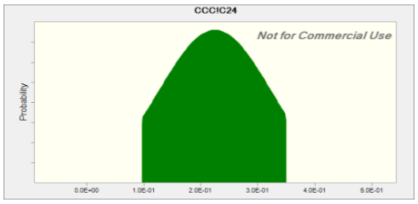
Assumption: C24

Cell: C24

Normal distribution with parameters:

P10	1.0E-01
P90	3.5E-01

Selected range is from 9.6E-02 to 3.5E-01



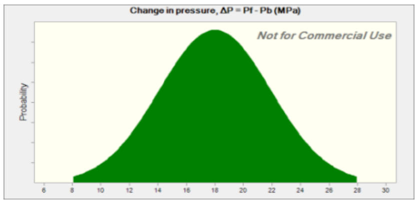
Assumption: Change in pressure, ΔP = Pf - Pb (MPa)

Cell: C9

Normal distribution with parameters:

P10	13
P90	23

Selected range is from 8 to 28

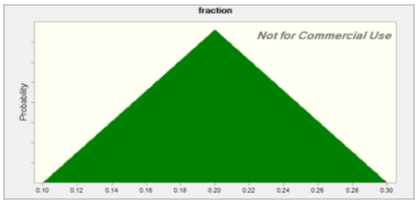


Assumption: fraction

Cell: D54

Triangular distribution with parameters:

Minimum	0.10
Likeliest	0.20
Maximum	0.30



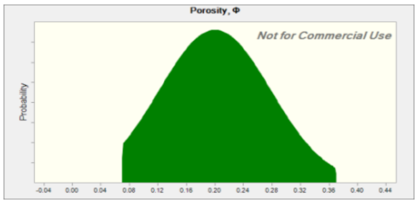
Assumption: Porosity, Φ

Cell: C8

Normal distribution with parameters:

P10	0.10
P90	0.30

Selected range is from 0.07 to 0.37

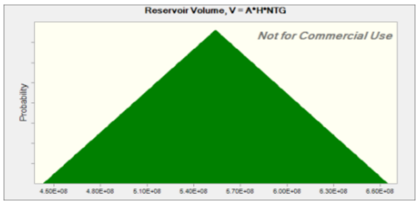


Assumption: Reservoir Volume, V = A*H*NTG

Cell: C6

Triangular distribution with parameters:

Minimum	4.43E+08	(=E6)
Likeliest	5.54E+08	(=G6)
Maximum	6.65E+08	(=F6)

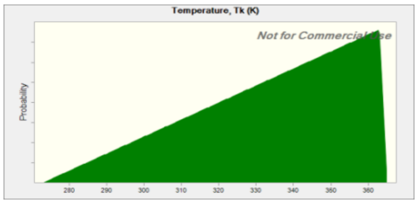


Assumption: Temperature, Tk (K)

Cell: C13

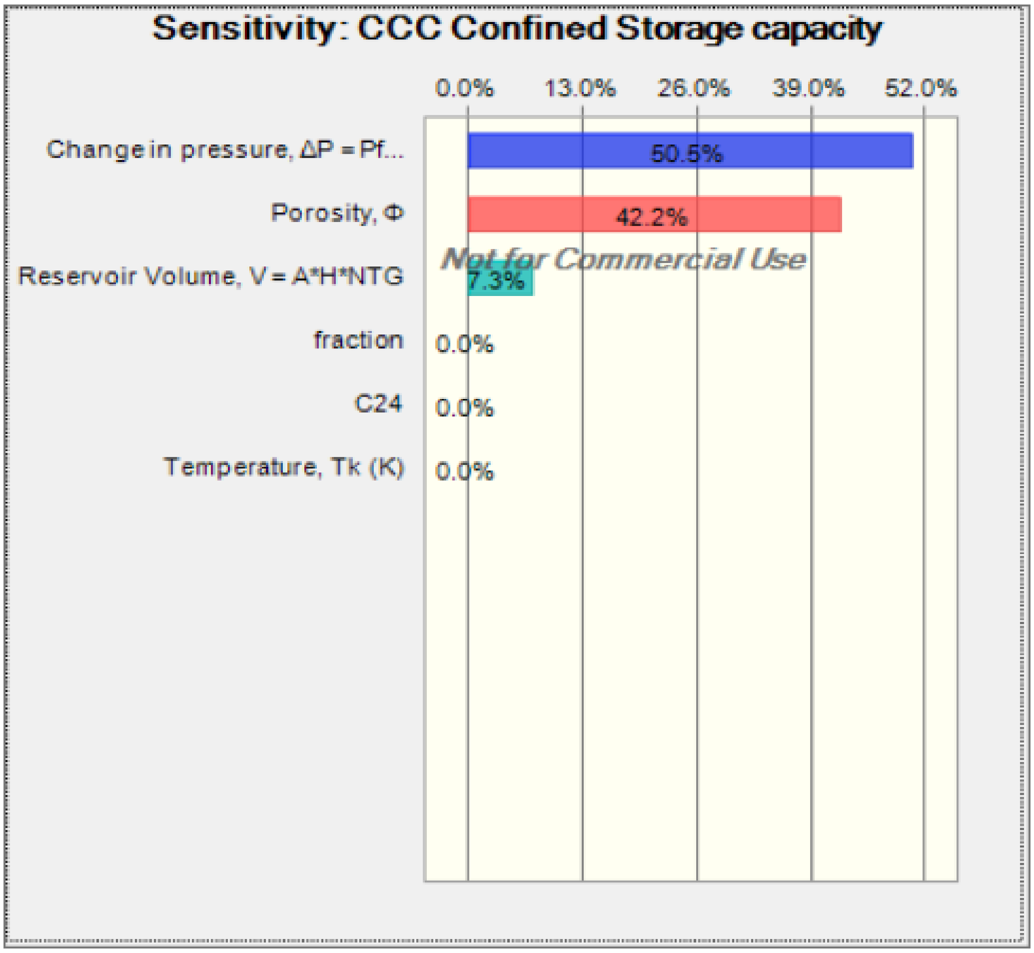
Triangular distribution with parameters:

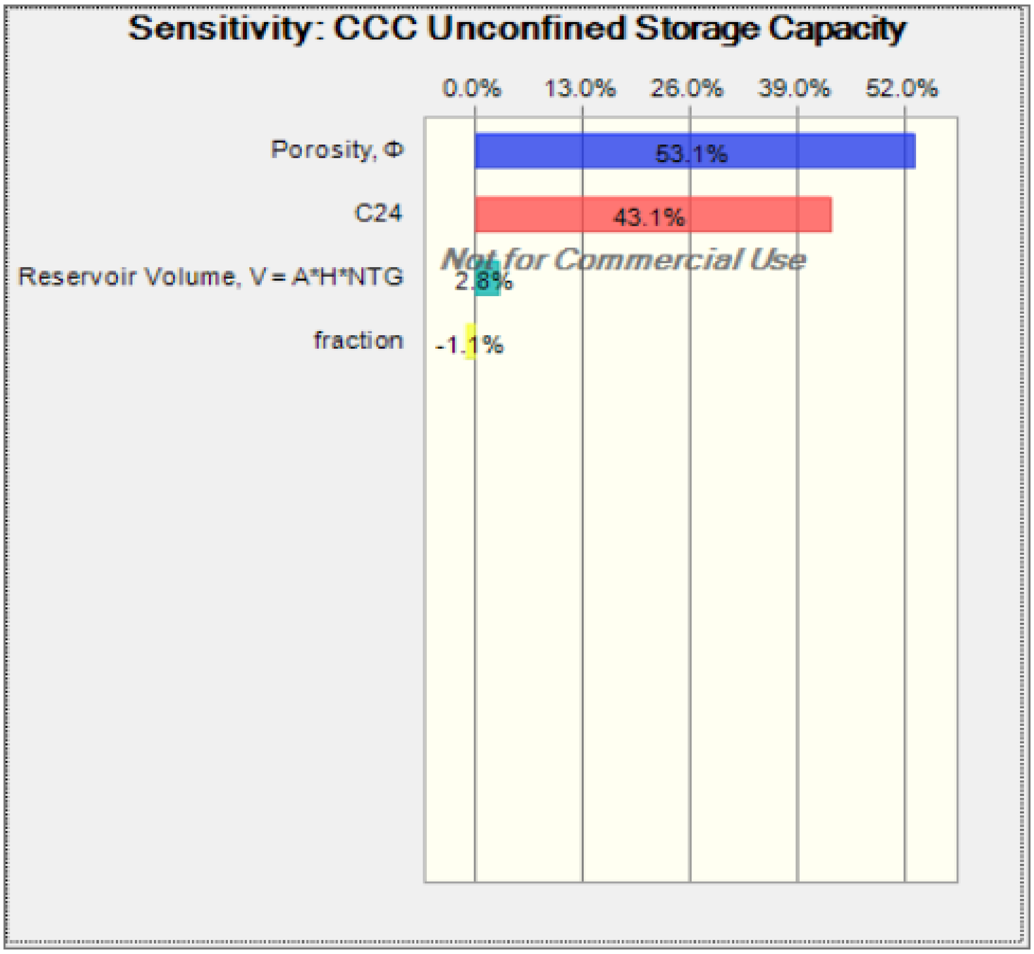
Minimum	273
Likeliest	363
Maximum	365

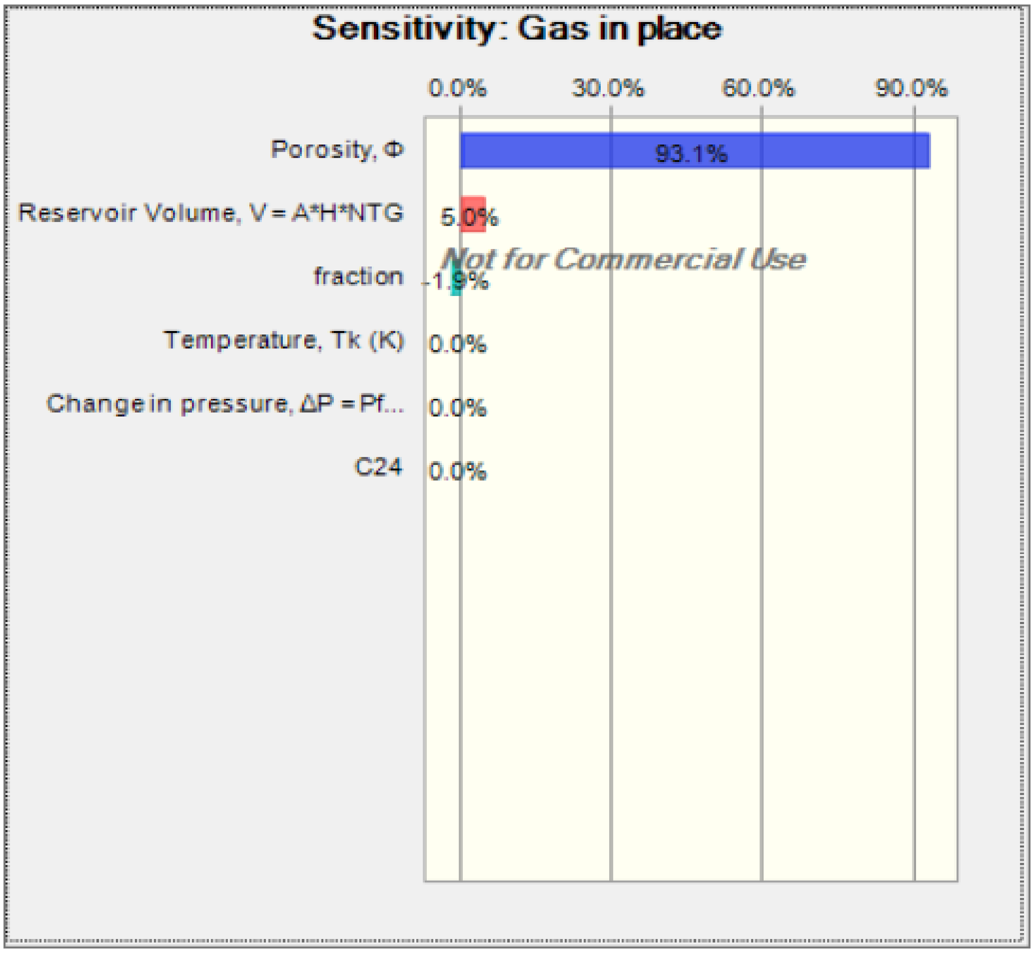


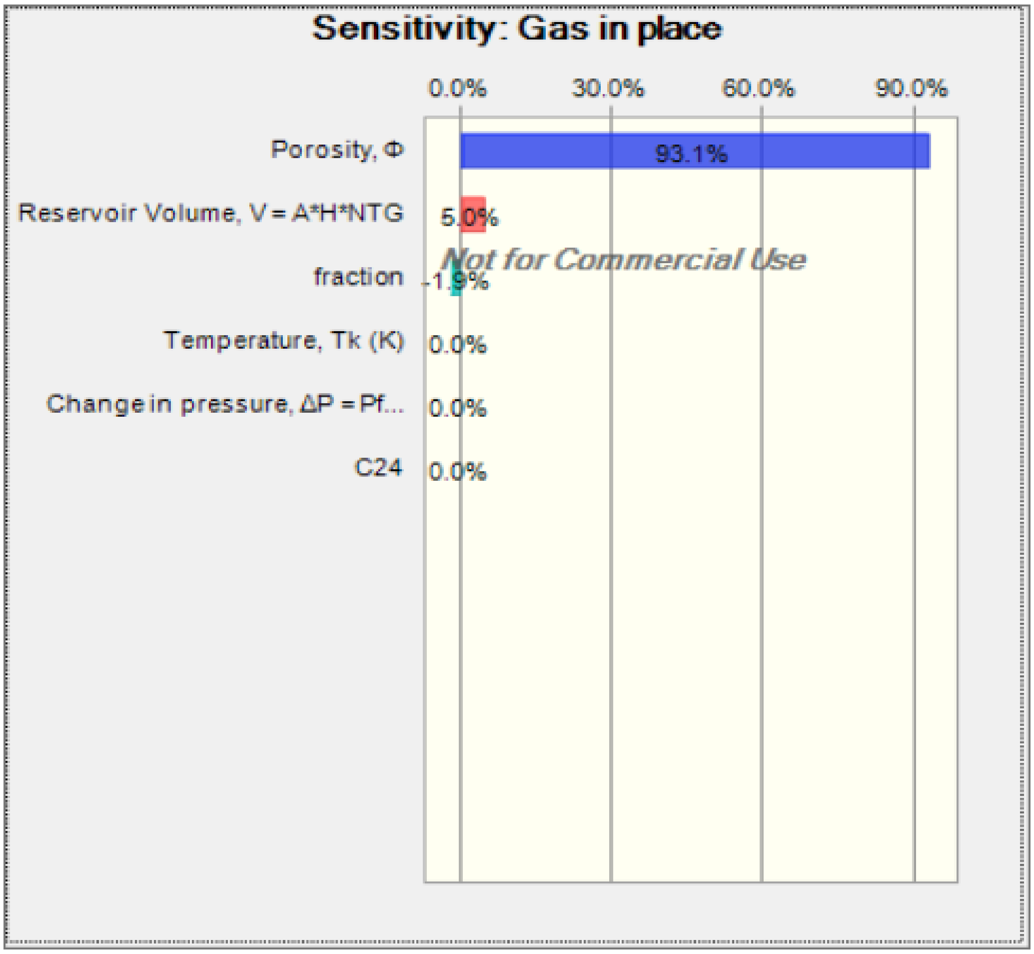
End of Assumptions

Sensitivity Charts




Sensitivity: CCC Unconfined Storage Capacity
0.0%
13.0%
26.0%
39.0%
52.0%
Porosity, Φ
C24
Reservoir Volume, V = A*H*NTG
fraction
53.1%
43.1%
2.8%
-1.1%
Not for Commercial Use

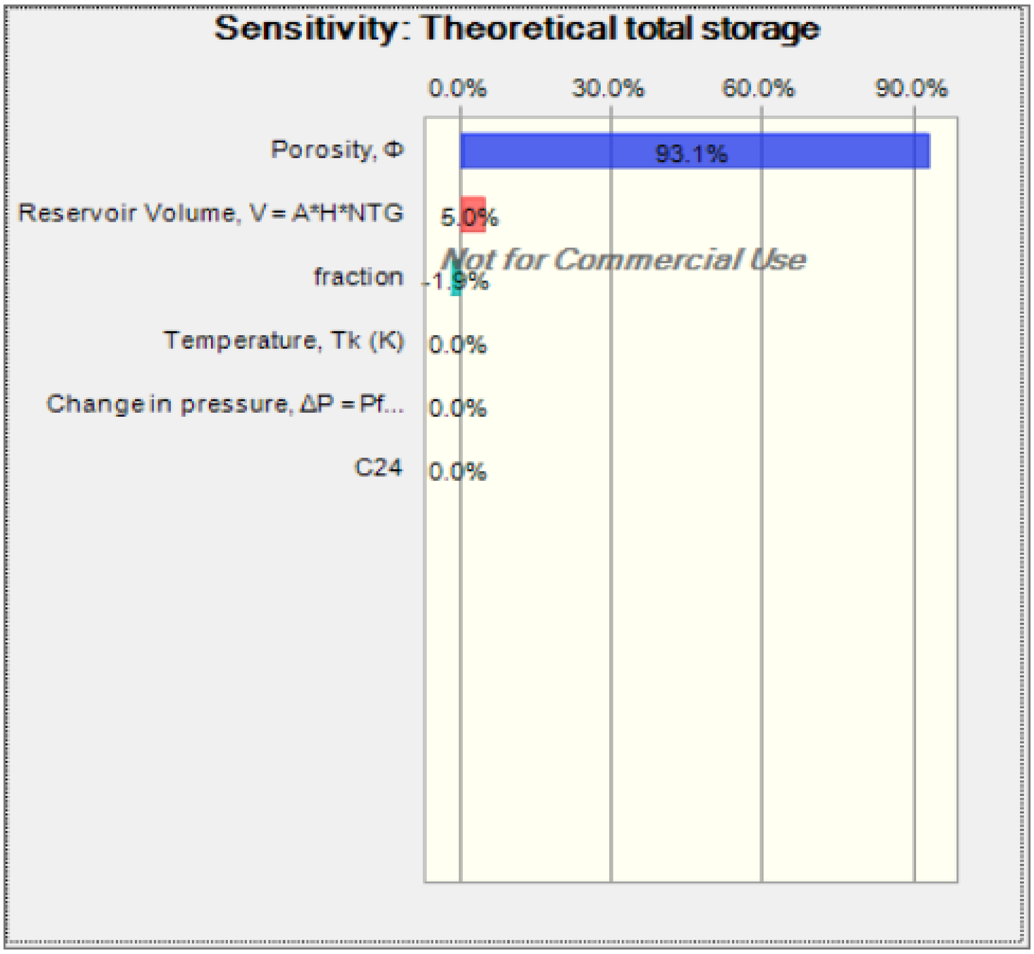

Sensitivity: Gas in place
0.0%
30.0%
60.0%
90.0%
Porosity, Φ
93.1%
Reservoir Volume, V = A*H*NTG
5.0%
fraction
-1.9%
Temperature, Tk (K)
0.0%
Change in pressure, ΔP = Pf...
0.0%
C24
0.0%


Sensitivity: Gas in place
0.0%
30.0%
60.0%
90.0%
Porosity, Φ
93.1%
Reservoir Volume, V = A*H*NTG
5.0%
fraction
-1.9%
Temperature, Tk (K)
0.0%
Change in pressure, ΔP = Pf...
0.0%
C24
0.0%

No target forecast has been specified

No target forecast has been specified

No target forecast has been specified



End of Sensitivity Charts

APPENDIX 2

TRANSCRIPT OF ‘CCS, DO WE NEED IT?’ DEBATE

A film of the full debate is available on line at https://vimeo.com/75970598

Transcript of debate:

During the hour long debate session, a total of 5 questions were discussed by the four panellists. The following section will state the question asked by a member of the audience along with a transcript of the response of the panellists Sandy Irvine (SI), Jon Gluyas (JG), Roberta Blackman-Woods (RBW) and Ross Weddle (RW). It should be noted that the event took place on the 18th March 2010, 7 days after the Japanese Tsunami of the 11th March 2010 and at the height of the escalating problems at the Fukushima nuclear power plant which may or may not have influenced the theme of the discussion.

Question 1:

With the recent events in Japan, what bearing will this have on the future of CCS?

RBW: Owing to recent events, the topic of nuclear will be re-examined in addition to careful consideration of other options including renewables and CCS and decisions have to be made as to the best energy mix. However, nations will continue to burn coal as a source of energy for the foreseeable future and thus CCS must therefore remain an option.

SI: Decision makers will remain committed to nuclear with the argument that the accident in Japan was the result of both a natural disaster and old technology. Meanwhile it is likely that public fear of nuclear will increase whether for rational or irrational reasons. In conclusion, there is a need to move away from the idea of failsafe technologies that are safe with proper human management or increased technology and transition towards fail-tolerant technologies i.e. Would the situation be different if wind rather than nuclear lined the Japanese Coastline?

RW: It is undesirable that waves lap at the concrete on most of our (the UK's) nuclear facilities. Whilst tsunamis are uncommon in the UK, with global sea level rise this could present future problems with flooding if not decommissioned in time. There needs to be some hard thinking before we continue down the nuclear avenue.

JG: Events in Japan will have global repercussions. UK media states that for UK nuclear reactors, the only threat comes from terrorism and not tsunamis/earthquakes but this is not the case. The UK suffers from seismic activity frequently although not to the same magnitude and tsunamis similar to those of Japan are recorded in the recent geological record resulting from slides off of the Canary Islands and offshore Norway. There is a need for development of fail-tolerant technologies but need to weight up the benefits vs. the risks, i.e., although wind is safe, it does not represent large scale generation.

Question 2:

The development of photovoltaic and wind technology is often undertaken abroad and local communities are suffering from closures of their pits, a lack of local level investment and job shortages. Therefore, is there scope for greater integration with Europe and the development of a super grid where investment will benefit local communities rather than developing CCS that only maintains the status quo unless technology is exported to China?

RW: The main issue surrounding super grids is that they are owned by multinational utilities companies who are not pro use of renewable unless the renewables are owned by the company. Thus the business model is vital i.e. where the investment is sourced from. Realistically it is only going to work with the introduction of a carbon price. Several attempts have been made but none so far are successful, and until this is resolved, it is unlikely that the super grid model will progress far.

RBW: The 2050 emissions targets are so far away from current levels, investment in cleaner energy technology is no longer either/or, it has to be across the board in all sectors. Europe has already started funds for development that all member states can bid into. Super grid idea makes politicians nervous due to reliance on other nations for energy. Situation between the Ukraine and Russia highlights potential energy shortages due to political disagreement. Therefore, current trend is to be self-sufficient in energy.

JG: Super grid is more and bigger of existing grids that cannot handle small scale community generation without implementation of smart grids. To meet growing energy demands and emissions targets, we need to do everything at both a large and small scale generation.

SI: Current mind set focuses on keeping business as usual rather than encouraging energy conservation and efficiency. The super grid model is just another method of maintaining the status quo but with one country or organisation holding the switch that can theoretically lead to energy shortages in other areas of Europe. Other problems with the super grid are that it creates a centralised society where if energy consumption is to be reduced, control needs to be brought down to a more community level where the consequences of wastefulness are more visible and thus mitigation more likely to occur. The downsides of the centralised society are shown in Las Vegas where local communities suffer energy and water shortages due to the wasteful excesses of the city of Las Vegas.

Question 3:

With regards to timescales, as CCS is being billed as a midterm solution that is a stop gap until renewable technology can be sufficiently developed to offer large scale generation technology, what are the timescales on implementing CCS should funding be a given?

JG: CCS could be implemented now; we are doing it now and have been pumping CO_2 underground in Texas USA since the 1970's. Most experience is with performing Enhanced Oil Recovery but the technology is there to do it now. What we cannot do now is multiply by 700 fold our photovoltaic output, let alone provide the raw materials to achieve that. Whilst efficiency is important, it is not the get out clause in an ultimate sense. Although CCS is seen as method of maintaining the status quo, without the carbon tax it cannot happen due to the cost of disposing of a waste material. Oil resource has been profitable ever since 1908. When you first find oil, you get the first oil almost for nothing and globally, nations have run wild with this free energy and now it is time to, as it were, come down off the drug and begin being more careful with energy resources.

RBW: Timescale that the (outgoing Labour) Government had in mind was for four demonstration projects to be online by 2020 and then being able to expand upon and sell the technology from 2020. There is currently a delay on three of the four demonstration projects and that the bidding process has been expanded thus the current timescales for implementation is unclear. MP's lobbying coalition government to progress this process as the technology is needed. Government not seeing CCS as a short term fix, but has a place in the whole energy mix. Efficiency is important but we have to remember third world countries that are developing will have an increased demand on energy. It is therefore unreasonable in a global context to expect that energy efficiency alone can fix the problem.

SI: CCS is like shovelling fuel on a run-away train where we need to put the brakes on and change directions. Coal mining is so devastating it needs to be wound down for that reason alone before carbon emissions are taken into the equation. Whilst global population is increasing and therefore it's widely talked about the ever increasing energy demand, you cannot always get what you want! We are unable to match that demand but the Chinese boom will deflate due to water shortages rather than energy shortages. Peak oil, and dwindling raw materials resources mean we cannot keep this path and must change direction. UK government hoping for feasibility projects operating by 2020 yet the quoted figures are six fold less than the emissions of one PowerStation. Therefore CCS is not operating at present as it is not operating at a commercially viable scale. Thus, the problem will have already happened by the time that CCS has been commissioned as we need to act within 10 years. Thus need to change lifestyles rather than just technologies, such as stopping 'Tesco town' models where large scale goods are transported on mass across huge distances and bring about change to a smaller scale, more locally sourced lifestyle. But all of this is an irrelevance with the ever increasing population issue is not addressed.

RW: Timescale that has not been discussed is the post injection timescale. Once CO2 has been injected if it works, it remains in the ground for thousands of years and thus is a solution unless it leaks. At the moment, global warming is threatening to release methane from tundra, and should that happen, CCS is an irrelevance. The current luxury of cheap energy has led to a large scale increase in population, but if the age of easy energy is over, that is likely to remove that spike. This is not a desirable situation however. We need to start working towards a better society where a few people are not making substantial amounts of money as that is not sustainable. Sustainability is looking at economics, social and economic outputs. Balancing those three variables may lead to a society that acknowledges that it is prolific in more ways than one.

Question 4:

Having just vaguely touched on the safely factor, could you expand on how safe is injecting compressed carbon underground? Is it safe or are we just making bombs underground? What is the safety factor of CCS?

JG: Everything we do has associated risks, but there are different levels of risks and contingencies that can be put in place. Carbon dioxide does not explode! Much is made of when a volcanic lake overturned in Cameroon where the resultant plume of gaseous CO_2 killed many people and animals. Geologically this was a natural and very rare event and bears little relation to what happens in the sub-surface. Yes there are risks and yes it may leak out again but consideration must be made as to how and where it is buried. Most diagrams show a huge power station and large pipelines storing CO_2 just under ground level. Scale is all important; CO_2 is buried at great depth well out of the human realms. The Earth deals with CO_2 on a geological timescale, when the atmosphere has a high CO_2 content, the Earth precipitates it as calcium carbonate (Limestone) and thus when storing CO_2 over geological timescales, it will precipitate in a solid mineral form. Monitoring is very important, and new methods are being developed at all times. But oil and gas stays buried for hundreds, thousands, millions and billions of years and thus is likely to stay put. (N.B. The chair addresses JG with the question: even if we could switch to a fully renewable energy source would you still advocate CCS? JG answers yes as CCS if used with biomass, it could create a fully carbon neutral energy source and begin to address the atmospheric co2 build up issues.)

RW: There are no specific concerns about the safety case for CO_2 – methane gas is a much bigger problem.

RBW: Politicians have been monitoring the safety case very closely which is why MP’s are keen for the demonstration projects to be online as soon as possible. Although it would be ideal for China and the developing world to overnight switch to renewable energy, the people of those countries are going to want to continue developing towards the lifestyle and quality of living of the west, and it is not for us to deny them that. Thus technologies such as CCS are important if they can help the developing world strive towards that but in a cleaner manner. The west needs to set an example in using

SI: Safety is not the biggest issue with CCS. Biggest issues with safety if CCS is to be commercial viable is insurance as cannot go ahead without insurance. Current demonstration projects have demonstrated at small scale for 15 years, but for commercial projects need to demonstrate security for >150 years. While leakage is often described as leakage from point of storage but leakage from pipelines also need to be considered. Scale is important as the energy needed to create the pipeline network may outweigh the energy benefits of the technology. But in general, safety case is not the biggest argument against CCS.

Question 5:

Regarding the carbon emission, is CCS carbon neutral, carbon negative or emits more carbon than the benefits? N.b. this was a 2 part question, unfortunately only the first part was audible on the event recording. JG was the only panellist who had a response to the first question and as such only his response is recorded below.

JG: whether CCS is carbon neutral or negative is difficult to quantify as it depends on how much CO2 is captured. CCS does suffer an energy penalty but at the moment we are emitting 100% of CO2, therefore even with a 20% energy penalty, an 80% reduction in emission is still a positive step forward towards mitigating climate change. It is possible for CCS to be carbon negative but would require the use of biomass and therefore probably unachievable.