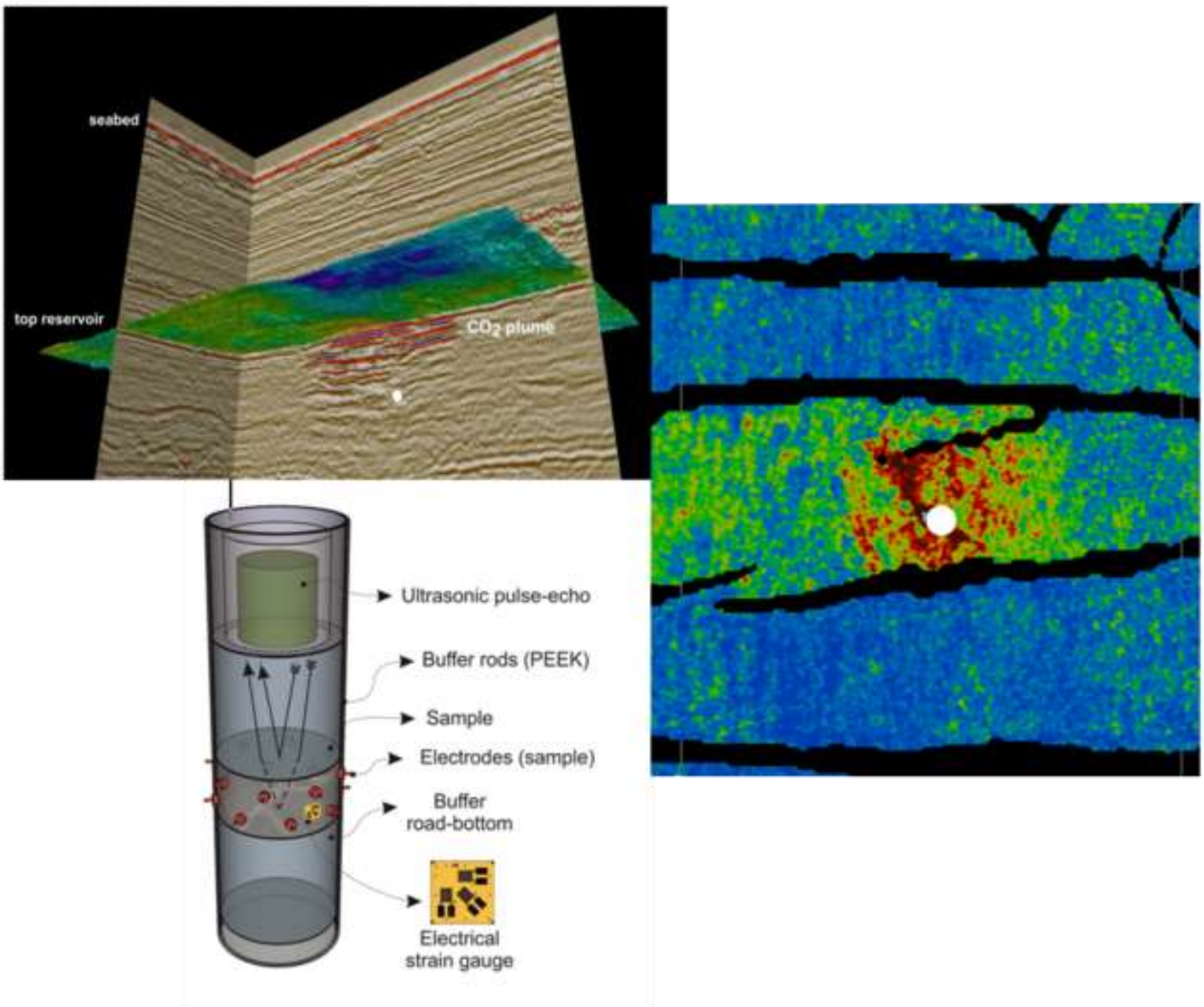
DiSECCS - Diagnostic Seismic Toolbox for Efficient Control of CO_2 Storage

Final Summary Report: Work Packages 1 - 4

BGS Energy Programme Report OR/17/002



DiSECCS http://www.bgs.ac.uk/diseccs/home.html

Diagnostic Seismic Toolbox for Efficient Control of CO_2 Storage:
DiSECCS

BRITISH GEOLOGICAL SURVEY

ENERGY PROGRAMME REPORT OR/17/002

DiSECCS - Final Summary Report Work Packages 1 - 4

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BRITISH GEOLOGICAL SURVEY

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Foreword

This document summarises findings of the main technical work packages 1 – 4 of the DiSECCS project (Diagnostic Seismic Toolbox for Efficient Control of CO_2 Storage).

Work Package 5 which integrates the research findings into a software toolbox and a 'recommendations and insights' document is the subject of two separate reports (BGS 2017a, b).

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Contents

Foreword 1

Acknowledgements 1

Contents 1

Executive Summary 2

1 Introduction 4

2 Work Package 1: Development of monitoring tools for the characterisation and measurement of induced pressure and geomechanical changes in the reservoir. 6

2.1 Seismic geomechanics (Tasks 1.1 and 1.2) 6

2.2 Application to real case-studies (Task 1.3) 9

3 Work Package 2: Monitoring to understand detailed flow processes and improve *in situ* quantification ... 13
3.1 Integrated very high resolution flow modelling and seismic analysis (Task 2.1) ... 13
3.2 novel methods for layer characterisation (Task 2.2) ... 21

4 Work Package 3: Experimental rock physics ... 28
4.1 Experimental methodology (Tasks 3.1 and 3.2) ... 28
4.2 Results (Tasks 3.3 and 3.4) ... 34
4.3 Conclusions ... 37

5 Work Package 4: Public Perceptions ... 38
5.1 Case-study analysis of analogues (Task 4.1) ... 39
5.2 Citizen focus groups (Task 4.2) ... 44
5.3 WP4 conclusions ... 47

6 Project outputs ... 50
6.1 Published Papers / REPORTS/Proceedings ... 50
6.2 Scientific Presentations ... 51
6.3 Public lectures / outreach ... 53
6.4 Influence on Policy/Practice/Training ... 53
6.5 Outputs in preparation / in press ... 54

7 References (non-DiSECCS) ... 55

Executive Summary

The DiSECCS project (Diagnostic Seismic Toolbox for Efficient Control of CO_2 Storage) has developed seismic monitoring tools and methodologies to identify and characterise injection-induced changes, whether of fluid saturation or pressure, in storage reservoirs. We have developed guidelines for the monitoring systems and protocols required to maintain the integrity of storage reservoirs suitable for large-scale CO_2 storage. The focus is on storage in saline aquifers (comprising the largest potential global storage resource), where considerable amounts of *in situ* water have to be displaced and both pressure and two-phase flow effects have consequences for storage integrity and storage capacity. Underground storage of CO_2 is associated with significant levels of public concern. A better understanding of this is a key element of establishing monitoring protocols to instil wider public confidence in CO_2 storage. DiSECCS draws on analogue activities, such as ‘fracking’ for shale gas, in conjunction with a discursive process involving lay participants, to gain insights into how people engage with similar underground activities and how controversies surrounding particular projects develop and evolve.

DiSECCS has five work packages, the first four carrying out the basic research and the fifth integrating findings into recommendations and tools. Datasets from the Sleipner, Snøhvit and Aquistore injection projects underpinned much of the applied seismic research, whilst the social research obtained data from online sources and from public interviews and focus groups.

Work Package 1 assessed the hydromechanical effects induced by CO_2 injection where pressure increase was significant. A sensitivity analysis was carried out to determine the sensitivity of geomechanical response to different reservoir parameters. Feasibility studies were carried out on the effectiveness of Amplitude versus offset (AVO) and amplitude versus offset and azimuth (AVOA) in anisotropy and fracture characterisation. Detailed assessments of CO_2 detectability in the presence of noise were carried out and noise reduction techniques investigated. Tools were tested on the time-lapse 4D datasets from the Aquistore pilot-site. In addition a coupled fluid flow-geomechanical model for Snøhvit has been built to study the seismic response to pressure and fluid saturation changes. This work is supported by a separate funding stream.

Work Package 2 focussed on the seismic characterisation and quantification of migrating thin layers of CO_2 in high quality reservoirs, utilising time-lapse datasets from Sleipner and Snøhvit. Techniques focussed on forensic interpretation of small reflection time-shifts integrated with numerical and analytical fluid flow models, novel spectral and dispersion analysis and theoretical rock physics.

Work Package 3 carried out advanced laboratory measurements of seismic changes in samples analogous to the Sleipner storage reservoir. Geophysical and geomechanical responses to changes in fluid saturation (brine / CO_2 mixtures) and fluid pressure were measured on both synthetic rock specimens and real core samples.

Work Package 4 conducted research into social attitudes to underground storage. Using fracking for shale gas as an analogue a media survey and social network analysis (of both online and offline networks) was carried out. A study was then undertaken to assess interested stakeholder responses to offshore CO_2 storage by means of interviews and citizen focus groups at two contrasting locations in northern England.

Work Package 5 integrated results from WPs 1 to 4 into a toolbox of seismic analysis software tools and a set of guidelines for optimal storage monitoring, and gaining social licence to operate. Results fromWP5 are reported separately.

1 Introduction

Seismic techniques comprise the key geophysical toolset for imaging and characterising induced changes in the subsurface associated with human activity. This ability to observe and quantify changes in fluid saturation, pressure and geological stress and strain using active and passive seismic techniques has critical application to the monitoring of geological CO_2 storage.

The DiSECCS project (Diagnostic Seismic Toolbox for Efficient Control of CO_2 Storage) has developed seismic monitoring tools and methodologies to identify and characterise injection-induced changes, whether of fluid saturation or pressure, in storage reservoirs. We have developed guidelines for the monitoring systems and protocols required to maintain the integrity of storage reservoirs suitable for large-scale CO_2 storage. The focus is on storage in saline aquifers (comprising the largest potential global storage resource), where considerable amounts of in situ water have to be displaced and both pressure and two-phase flow effects have consequences for storage integrity and storage capacity. Underground storage of CO_2 is associated with significant levels of public concern. A better understanding of this is a key element of establishing monitoring protocols to instil wider public confidence in CO_2 storage. DiSECCS draws on analogue activities, such as 'fracking' for shale gas, in conjunction with a discursive process involving lay participants, to gain insights into how people engage with similar underground activities and how controversies surrounding particular projects develop and evolve.

DiSECCS has five work packages, the first four carrying out the basic research and the fifth integrating findings into recommendations and tools:

Work Package 1: Development of monitoring tools for the characterisation and measurement of induced pressure and geomechanical changes in reservoirs
Task 1.1 Hydro-mechanical simulations
Task 1.2 Tool development and testing
Task 1.3 Application to real case-studies

Work Package 2: Monitoring to understand detailed flow processes and improve in situ quantification
Task 2.1 Integrated very high resolution flow modelling and seismic
Task 2.2 Novel methods for layer characterisation

Work Package 3: Experimental rock physics
Task 3.1 CO_2 rig development
Task 3.2 Manufacture of synthetic rocks
Task 3.3 Ultrasonic anisotropy measurements on synthetic rocks
Task 3.4 Ultrasonic anisotropy measurements on core samples
Task 3.5 Integration of the results with other Work Packages

Work Package 4: Public perceptions
Task 4.1 Case study analysis of analogues
Task 4.2 Citizen focus groups

Work Package 5: Guidelines and monitoring toolbox
Task 5.1 Guidelines and workflows
Task 5.2 Toolbox

To support the research DiSECCS has access to seismic and other datasets from three key storage sites, at Sleipner and Snøhvit in Norway and the Aquistore pilot-scale project in Canada. Numerical model data were also made available from the In Salah project in Algeria.

Sleipner

The Sleipner storage project is located offshore of southern Norway in the central North Sea in a water depth of around 80 m. Sleipner natural gas contains about 9% CO_2 and so needs CO_2 removal prior to sale. After separation at the platform CO_2 is injected via a deviated well into the Utsira Sand, a large saline aquifer, at a depth of just over 1000 m. Injection commenced in 1996 and, by the end of 2016, 16.55 million tonnes of CO_2 had been stored.

Snøhvit

The Snøhvit storage project is located offshore of northern Norway in the south-western Barents Sea in water depths ranging from 310 to 340 m. Snøhvit natural gas contains between 5% and 8% CO_2 and so needs CO_2 removal prior to sale. After separation at the Melkøya LNG plant near Hammerfest the CO_2 is piped back offshore for injection via a single injector well. Initial injection, starting in 2008, was into the Tubåen saline reservoir at a depth of about 2600 metres. Subsequently injection was switched to the slightly shallower Stø reservoir. By the end of 2016 4.34 million tonnes of CO_2 had been stored.

Aquistore

The Aquistore site in Saskatchewan is a research injection site attached to the Boundary Dam CCS project. Most of the captured CO_2 is used for enhanced oil recovery but episodic offtake is stored in a deep saline aquifer, comprising the Black Island and Deadwood units at a depth of about 3250 m. Injection started in 2015 with more than 35 thousand tonnes of CO_2 currently stored.

Background information and further results from DiSECCS can be found on the project website https://www.bgs.ac.uk/diseccs/

2 Work Package 1: Development of monitoring tools for the characterisation and measurement of induced pressure and geomechanical changes in the reservoir.

In this work package, we integrated hydromechanical simulation results with rock physics models and full-waveform seismic modelling to assess time-lapse seismic attributes for dynamic reservoir characterization and hydromechanical model calibration.

2.1 SEISMIC GEOMECHANICS (TASKS 1.1 AND 1.2)

2.1.1 Feasibility studies

A feasibility/sensitivity study was carried out to calculate time-lapse seismic responses from a dynamic elastic reservoir model based on a North Sea deep reservoir undergoing large pressure changes. The time-lapse seismic travel-time shifts and time strains calculated from the modelled and processed synthetic datasets (i.e. pre-stack and post-stack data) were in a reasonable agreement with the observations, and indicated the feasibility of using a 1-D strain rock physics transform and time-lapse seismic processing methodology. Estimated vertical travel-time shifts for the overburden and most of the reservoir were within ±1 ms of the observed values, indicating that the time-lapse technique is sufficiently accurate for predicting overburden velocity changes and hence geomechanical effects. Characterization of deeper structure below the overburden became less accurate, where more advanced time-lapse seismic processing and migration would be needed to handle the complex geometry and strong induced lateral velocity changes. Nevertheless, both migrated full-offset pre-stack and near-offset post-stack data imaged the general features of both the overburden and reservoir units. More importantly, results from the study indicated that integrated seismic and hydromechanical modelling can help constrain time-lapse uncertainty and hence reduce risk due to fluid extraction and injection (He et al. 2016).

Unlike reservoir models, which are commonly robustly calibrated with 4D seismic and fluids production data, geomechanical models are typically only loosely tied to available time-lapse seismic data, so we also undertook a study to assess what affect the uncertainty in typical input parameters has on modelled effective stress changes. Understanding how different modelling parameters affect stress change is extremely important for robust 4D seismic calibration. We used a Global Sensitivity Analysis technique on a sample of 1540 geomechanical models with parameters covering the range of typical of North Sea reservoirs, to assess the sensitivity of model inputs on the resultant vertical effective stress change. We successfully mapped each parameter to a sensitivity space and argue that by doing this we can reduce our initially considered ‘important’ inputs by 50%. Thus, reducing the number of calibration parameters and gaining a greater understanding of the model parameter sensitivity to stress and displacement allowed for a better understanding of what and how geomechanical models can be calibrated using time-lapse seismic data (Price et al. 2016a).

Anisotropy and fractures

Hydrocarbon production generally results in observable time-lapse changes within a compacting reservoir, but those physical property changes that lead to induced seismic effects, such as velocity increase, can be difficult to isolate uniquely. Thus, integrated hydro-mechanical simulation, stress-sensitive rock physics models and time-lapse seismic modelling workflows can be employed to study the effects of reservoir compaction on seismic velocity and seismic anisotropy. We studied the influence of reservoir compaction and compartmentalization on time-lapse reflection amplitude variation with offset (AVO) and with azimuth (AVOA). Specifically, the time-lapse AVO and AVOA responses were predicted for two reservoir models: a laterally homogeneous four-layer dipping model and a laterally heterogeneous graben. Seismic reflection coefficients for different offsets and azimuths were calculated for compressional (P–P) and converted shear (P–S) waves using an anisotropic ray-tracer as well as using approximate equations for AVO and AVOA. The simulations helped assess the feasibility of using time-lapse AVO and AVOA to evaluate induced stress anisotropy due to changes in the effective stress field. The results indicate that time-lapse AVO and AVOA analysis is a potential method for qualitatively and semi-quantitatively linking azimuthal anisotropy changes to pressure/stress change (He et al. 2015).

Fractures have a significant influence on the physical response of the subsurface. The presence of coherent fracture sets often leads to observable seismic anisotropy enabling seismic techniques to remotely locate and characterise fracture systems. We confirmed the general scale-dependence of seismic anisotropy and provided new results specific to shear-wave splitting (SWS). We found that SWS develops under conditions when the ratio of wavelength to fracture size ($\lambda S/d$) is greater than 3, where Rayleigh scattering from coherent fractures leads to an effective anisotropy such that effective medium model (EMM) theory is qualitatively valid. When $1 < \lambda S/d < 3$ there is a transition from Rayleigh to Mie scattering, where no effective anisotropy develops and the SWS measurements are unstable. When $\lambda S/d < 1$ we observed geometric scattering and began to see behaviour similar to transverse isotropy. We found that seismic anisotropy is more sensitive to fracture density than fracture compliance ratio. More importantly, we observed that the transition from scattering to an effective anisotropic regime occurs over a propagation distance between 1 and 2 wavelengths depending on the fracture density and compliance ratio. The existence of a transition zone means that inversion of seismic anisotropy parameters based on EMM will be fundamentally biased. More importantly, we observed that linear slip EMM commonly used in inverting fracture properties is inconsistent with our results and leads to errors of approximately 400% in fracture spacing (equivalent to fracture density) and 60% in fracture compliance. Although EMM representations can yield reliable estimates of fracture orientation and spatial location, our results showed that EMM representations will systematically fail in providing quantitatively accurate estimates of other physical fracture properties, such as fracture density and compliance. Thus more robust and accurate quantitative estimates of *in situ* fracture properties will require improvements to effective medium models as well as the incorporation of full-waveform inversion techniques (Yousef & Angus in review).

The presence of coherent fracture sets often leads to observable seismic scattering enabling seismic techniques to remotely locate and characterise fracture systems. We examined the widening effect of wavelets due to scattering within a fractured medium by using several different approaches. We used different methods including the RMS envelope analysis, shear-wave polarisation distortion, differential attenuation analysis and peak frequency shifting to assess the scattering behaviour of parametrised models in which the propagation direction is either normal or parallel to the fracture surfaces. The quantitative measures showed strong observable deviations for fractures of size in the order of, or greater than, the dominant seismic wavelength within the Mie and geometric scattering regimes for both propagation normal and parallel to fracture strike. The results suggest that strong scattering is symptomatic of fractures having size on the same order of the probing seismic wave (Yousef & Angus in review).

Based on the anisotropy and scattering analysis, we assessed the feasibility of inverting SWS measurements to quantitatively estimate fracture strike and fracture density assuming an effective medium fracture model. The results of the full waveform synthetics indicate that the source frequency of the induced microseismicity (or seismic source) is crucial in extracting reliable fracture parameters due to the relationship between scale length of the probing seismic wave and the fracture heterogeneity (i.e., size). Although the SWS results themselves were diagnostic of fracturing, the fracture inversion allowed placing constraints on the physical properties of the fracture system. For real microseismic datasets, the range in magnitude of microseismicity (i.e., frequency content), spatial distribution and variable source mechanisms suggested that derivation of fracture properties from SWS measurements is feasible. For the single seismic source case and optimum receiver array geometry, the inversion for strike had average errors of between 11% and 25%, whereas for density average errors were between 65% and 80% for the single fracture set and 30% and 90% for the double fracture sets. Improvements on resolving strike can be made by including more microseismic sources in the inversion process. Furthermore, the improvements in resolving fracture density (or stiffness) can be achieved using a more advanced inversion approach such as anisotropic tomography in which the medium can divided into different domains (Yousef & Angus 2016).

2.1.2 Noise reduction

Noise is a persistent feature in seismic data and poses challenges in optimising seismic images and physical interpretation of the subsurface. We analysed passive seismic data from the Aquistore storage pilot project permanent seismic array to characterise, classify and model seismic noise. We performed noise analysis for a three-month subset of passive seismic data from the array and provided conclusive evidence that the noise field is not white, stationary, or Gaussian; characteristics commonly assumed in most conventional noise models. We introduced a novel noise modelling method that provides a significantly more accurate characterisation of real seismic noise compared with conventional methods, which is quantified using the Mann–Whitney–White statistical test. This method is based on a statistical covariance modelling approach created through the modelling of individual noise signals. The identification of individual noise signals, broadly classified as stationary, pseudo-stationary and non-stationary, provided a basis on which to build an appropriate spatial and temporal noise field model. Furthermore, we have developed a workflow to incorporate realistic noise models within synthetic seismic data sets providing an opportunity to test and analyse detection and imaging algorithms under realistic noise conditions (Birnie et al. 2016).

Noise is particularly troublesome for passive seismic monitoring where it commonly masks microseismic events. We proposed a statistics-driven noise suppression technique that whitens the noise through the calculation and removal of the noise covariance. Noise whitening was shown to reduce noise energy by a factor of 3.5 resulting in microseismic events being observed and imaged at lower signal-to-noise ratios than originally possible, whilst having a negligible effect on the seismic wavelet. The procedure was shown to be highly resistant to most changes in the noise properties and has the flexibility of being used as a stand-alone technique or as a first step before standard random noise attenuation methods (Birnie et al. 2016).

2.1.3 Rock Physics

Here we studied the uncertainty of various rock physics models in accounting for the non-linear relationship between effective stress and seismic velocity and assessed the associated error in velocity prediction. We used a collection of over 200 core measurements of ultrasonic velocity versus stress to constrain four end-member models: empirical, first principle, microstructural and a third-order elasticity model. We found all models provide a relatively good fit to the observed data, but some failed to accurately fit simultaneously both P- and S-wave data due to their not accounting for an observed stress dependent V_P/V_S ratio. Based on Bayesian statistical analysis we found that all model parameters are very well constrained. Using global probability distributions, we estimated parameter errors to be less than 5% for all models which propagate to errors in typical velocity change estimates to be of the order of ~10%. However, we noted third-order elasticity parameter errors of 10 to 15% with associated velocity errors on the order of ~100%. These large errors resulted from an under-determined inverse problem caused by the simplification of the model for an isotropic rock. We attempted to correlate model parameters with core porosity, but found porosity alone is not enough to constrain unknown model parameters within a suitable accuracy. The results of this study showed that errors in estimated velocity caused by model constraints are potentially well below errors introduced by natural recorded noise or noise introduced by 4D acquisition and signal processing.

2.2 APPLICATION TO REAL CASE-STUDIES (TASK 1.3)

2.2.1 Snøhvit (Norway offshore)

A coupled fluid flow-geomechanical model for Snøhvit was built from data provided by Statoil, who also facilitated the model building process by providing direct feedback, clarification or updated data (i.e. depth converted horizons).The models were the focus of studies on the seismic response to pressure and fluid saturation changes.

2.2.2 Aquistore (Canada onshore)

The first post-CO_2-injection 3D time-lapse seismic survey at Aquistore was carried out following the injection of 36 kt of CO_2 within the selected reservoir units between 3170 m and 3370 m depth .

Limits on the detection of injected CO_2 in real noise conditions.
The objective was to assess the ability of time-lapse surface seismics to detect CO_2 in reservoir at ~3000 m depth after limited injection of CO_2. To simultaneously maximize repeatability and optimise subsurface imaging, particularly in the reservoir, a '4D-friendly simultaneous' processing flow was used. This is identical to that used for processing the pre-injection data and is divided into pre-stack and post-stack elements. The repeatability between the baseline and post-CO_2-injection survey was excellent with global normalised root-mean squar8e (NRMS) values of 1.13 for the raw pre-stack data. The global NRMS value, tracked over the processing sequence, decreased with each processing step to a global NRMS value of ~0.10 after the final cross-equalization step was applied (Roach et al. 2016a).

Based on the processing and time-lapse analysis of the baseline and post-injection datasets and comparison with two previous pre-injection surveys (Roach et al. 2017), the following can be concluded:

- Repeatability between the seismic surveys was excellent because of the use of permanent buried geophones and buried dynamite sources.

- There is no apparent progressive degradation of the repeatability of the dynamite shots between successive surveys, though variations in data amplitudes have been observed.

- Of the three distinct units of the reservoir, the Deadwood reservoir unit registered a significant amplitude difference above the background and was previously identified, through fluid replacement modelling, as being the region most sensitive to changes in CO_2 content.

- The Deadwood anomaly corresponds to ~18 kt of CO_2, half of the injected volume, and the extent of the plume compares reasonably with the area calculated based on porosity and 100% saturation.

- In the other two injection zones, the Black Island sand and the lower Deadwood unit, no significant amplitude anomalies were observed.

- For the Black Island sand, repeatability is excellent so the seismic data points to the presence of a small amount of CO_2 in the zone. For the lower Deadwood unit the repeatability is not as good as the other two units and so the quantity of CO_2 is not detectable above the noise.

- The ability to compare the post-injection time-lapse results to pre-injection results allowed for better interpretation of the data.

- These results validate the value of the permanent array of buried geophones as well as the repeated survey parameters. Also, the availability of the pre-injection analysis is invaluable.

The background time-lapse signal-to-noise level at the Aquistore storage site was characterised through the use of a pre-injection time-lapse analysis performed on two sparse 3D seismic datasets acquired at the site. The analysis revealed a lowest global NRMS of 0.07, computed on time-windows across the whole dataset. NRMS levels above this would be taken to indicate the presence of CO_2 in the reservoir.

Gassmann fluid substitution and 3D seismic forward modelling was used to investigate the conditions under which injected CO_2 can be detected above the defined minimum noise level. Noise-free synthetic seismograms were generated for the baseline model and for monitor models with the replacement of brine by CO_2 at various saturations within the reservoir. Wave Unix (Xu 2012) was used to generate the synthetic surface reflection seismic data from an explosive surface p-wave source using. Two sets of models were used: (i) a thickness-CO_2 saturation model; and (ii) a single-zone model. The thickness-CO_2 saturation model included CO_2 distribution through varying the thickness of the CO_2 filled layer within the reservoir. The thickness of the layer was varied in 1m increments up to 100% of the zone thickness. For the single-zone model the reservoir is treated as single 193 m thick layer where CO_2 replacement is within the entire layer. Synthetic datasets were created for a range of CO_2 saturations of the reservoir layer.

To assess the detection limits for the injected CO_2 in the reservoir under the background noise level at the site, the noise traces from the baseline and pre-injection monitor surveys were added to each of the synthetic datasets. NRMS values from the CO_2 model synthetics with noise added were compared with NRMS values derived by comparison of the baseline and pre-injection monitor surveys within the same region. The CO_2 was defined as detectable when the NRMS from the models exceeded the NRMS value (0.07) from the pre-injection surveys. It should be noted that the NRMS of the synthetic dataset with added noise increases with increasing CO_2 saturation up to 20%, but it remains unchanged for further increases in saturation. Thus, with this metric, datasets with CO_2 saturations above 20% cannot be distinguished from each other.

We found that the time-lapse repeatability is excellent and provides the ability to monitor the CO_2 induced changes in the reservoir at the Aquistore storage site. Specifically, the analysis of the global NRMS for two different types of synthetic datasets with real noise added suggests that:

- For the thin layers, CO_2 is detectable in all zones under noise conditions provided that at least 5 m of the aquifer in each zone is saturated with 5% CO_2
- For 193 metre thick fully saturated layer it is possible to detect the CO_2 using a time-lapse analysis providing that the CO_2 saturation is above 20%.

This work is presented in Roach et al. 2016b. Note that the analysis considered only changes in reflectivity as a detectability criterion. Induced time-shifts are also an important time-lapse effect, particularly where CO_2 accumulates as a thicker layer, and can be very powerful detection tool.

Fracture characterisation using singular value decomposition (SVD)

The optimal basis formalism of Varela et al. (2007) was employed for the inversion of fracture density from synthetic AVOA data from a caprock within a geological setting with large impedance and anisotropy contrasts. The method is case-specific and is very dependent on knowledge of the in situ rock properties. In this case-study, the method is particularly advantageous because it is independent of the impedance contrasts of the layers. The model-based approach thus allows for direct quantification of the magnitude of anisotropy from an inversion of the p-wave amplitudes along the interface of interest within the high contrast geological setting.

The first stage saw the analysis of synthetic data using the optimal basis inversion to determine the fracture density of a set of synthetic data having different fracture densities characterising the magnitudes of anisotropy. The rock properties of the media are from well logs obtained from the Aquistore injection well. The effective horizontal transverse isotropy (HTI) media were defined by the slip-interface model of Liu et al. (2000) which explicitly includes the fracture density of the medium. The exact reflection coefficients at the interface between the upper isotropic medium and the HTI medium (fractured caprock) constituted the modelled data and contained a complete AVOA response of the reservoir. Atrak, an anisotropic ray tracer (Guest & Kendall 1993), was used to generate the synthetic surface reflection seismograms from which the amplitudes to be analysed were formulated (the amplitudes picked along the horizon between the caprock and layer immediately above it).

Two sets of synthetic data were evaluated: (i) a simple two-layer geometry which was modelled with the upper layer being isotropic described by the rock properties of the layer directly above the caprock and the lower layer being HTI with background rock properties of the caprock; and (ii) a 14-layer simplified geological model where the caprock was the sole HTI medium.

The second stage was to apply the optimal basis method to real data acquired at the Aquistore site. Three geological units were analysed: (i) the Winnipeg Icebox (the caprock) so as to determine any potential risks of leakage at the site and to establish the pre-injection state of the caprock; (ii) the Prairie Evaporite, located above the caprock, forming the regional seal and expected to be free of fractures and (iii) the Birdbear which is the shallowest horizon and is known to be fractured. The Prairie Evaporite and the Birdbear results form end-members and so provide a basis for assessing results from the caprock.

The final stage of this analysis was the determination of the direction of anisotropy for a complete characterisation of the fractures at the caprock. The Grechka & Tsvankin (1998) ellipse method was used.

The model-based optimal basis inversion method, combined with the use of an azimuthally dependent Shuey-type equation for extending the range of offsets for the inclusion the anisotropy signature, is suitable for determining the magnitude of anisotropy in the strong contrast deep reservoir environment at the Aquistore storage site.The crucial elements and/or possible limitations of this approach for the inversion of real data are:

- The ability to select the correct variations of in situ rock parameters in establishing the modelled reflectivity matrix in order to optimise the basis functions.
- The ability to extract true amplitudes in the real data as a function of offset/incident angles since the method weighs heavily on the assumption that modelled data is representative of the real environment.

A first look at the results from the real Aquistore data indicates different average magnitudes of anisotropy of the end members as expected – the Prairie Evaporite has an average crack density of 0.01 while the Birdbear has an average crack density of 0.02.

2.2.3 In Salah (Algeria onshore)

AVOA analysis

Elastic models from BP’s geomechanical simulations at the In Salah injection site (by Rob Bissell and provided by James Verdon) were observed to have negative elastic tensor components were observed where they should only be positive. James Verdon was then asked to provide the geomechanical outputs so that we could generate the elastic models from our codes. Unfortunately, using the geomechanical output (stress, Young’s modulus, pressure, etc) with our rock physics model transforms also generated negative values where they should only be positive. Attempts were made to track down the source of this problem but without success. However, we do not believe the source of the problem is our rock physics model as this issue has not been encountered with other geomechanical models.

Generating seismic synthetic data for the saturation models was not done because seismic acquisition parameters were not obtainable from BP.

3 Work Package 2: Monitoring to understand detailed flow processes and improve in situ quantification

The seismic responses of different reservoirs to CO_2 injection involve a number of process-related trade-offs. High quality (thick, permeable and mechanically compliant) reservoirs tend to have a large seismic sensitivity and relatively high potential for the spatial and temporal resolution of thin, spreading CO_2 layers and the characterisation of layer properties. But they show rather small pressure increases, close to or beneath seismic detection limits. On the other hand, lower quality reservoirs tend to have a decreased seismic sensitivity with less potential for CO_2 layer characterisation but, conversely, with larger and more seismically tractable pressure increases.

DiSECCS had access to monitoring datasets which covered a range of reservoir quality: notably from the Utsira Sand at Sleipner, a thick homogeneous reservoir; the Stø Formation at Snøhvit also quite homogeneous; and the much more structurally and stratigraphically complex Tubåen reservoir at Snøhvit. Because of this we were able to address a number of different issues related to understanding injection processes, including characterisation of thin CO_2 layers, discrimination between fluid saturation and pressure effects and modelling layer flow.

3.1 INTEGRATED VERY HIGH RESOLUTION FLOW MODELLING AND SEISMIC ANALYSIS (TASK 2.1)

Work in Task 2.1 focussed on very accurate measurement of CO_2 layer morphology and temporal thickness, integrated with geological constraints and fluid flow modelling. The high-resolution 2010 seismic survey from Sleipner comprised the key dataset for this analysis, with the 2012 seismic data from Snøhvit also providing useful insights.

3.1.1 Morphology of thin CO_2 layers

Interpretation in DiSECCS focussed on the topmost CO_2 layer in the injected Sleipner plume which has accumulated beneath the reservoir topseal relief. The high-resolution 2010 seismic data have, in places, achieved explicit 3D imaging of the upper and lower reflective surfaces of the layer (Figure 3.1). It has been noted previously (Furre et al. 2015) that interference between the top and base layer reflections produces subtle time-shifts which can be strongly diagnostic of layer temporal thickness, and this approach to forensic interpretation of layer reflectivity and travel-times has been taken forward in DiSECCS.

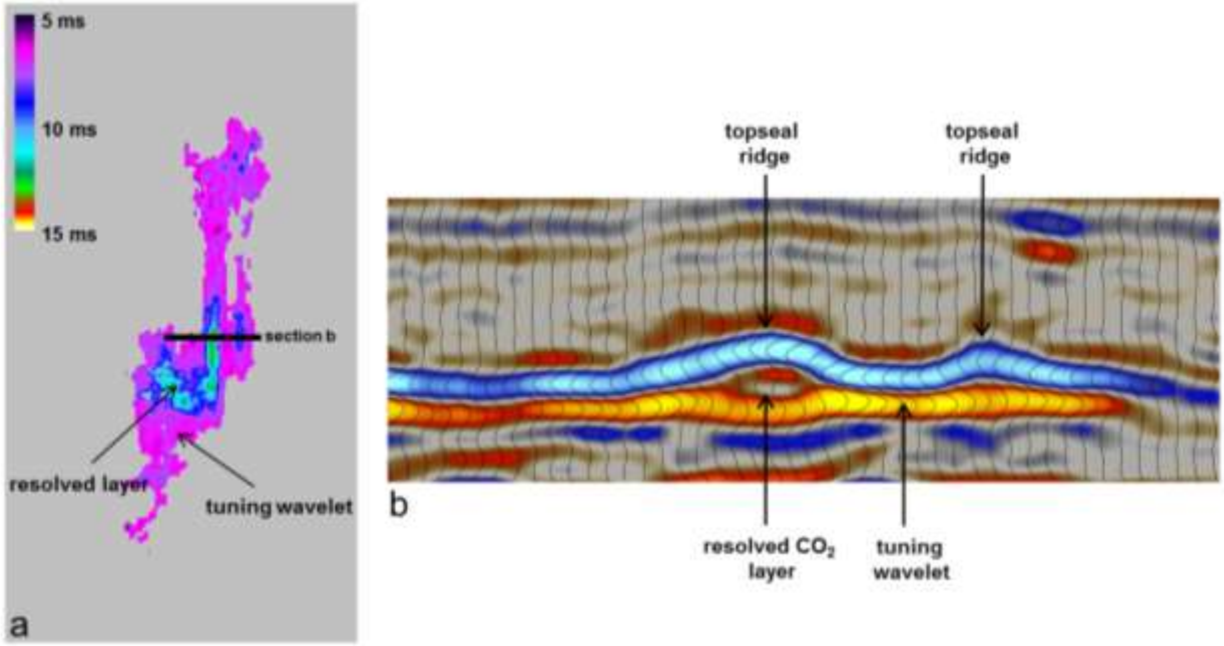

Figure 3.1 a) Map of the topmost CO_2 layer in 2010 showing temporal thicknesses and line of section b) section through topmost layer showing explicit resolution (separation) of top and base layer reflections (blue and orange respectively) beneath two north-trending ridges at the upper surface of the reservoir.

Layer velocity

CO_2 layer velocities at Sleipner can be estimated from rock physics (Figure 3.2), but they remain rather poorly-constrained. This is because only a single core is available which might not be representative of the reservoir as a whole, properties of the injected fluid (CO_2 plus minor CH_4) are uncertain, and, in particular, mixing scales (uniform or patchy) of the injected fluid and the aquifer brine are not well understood.

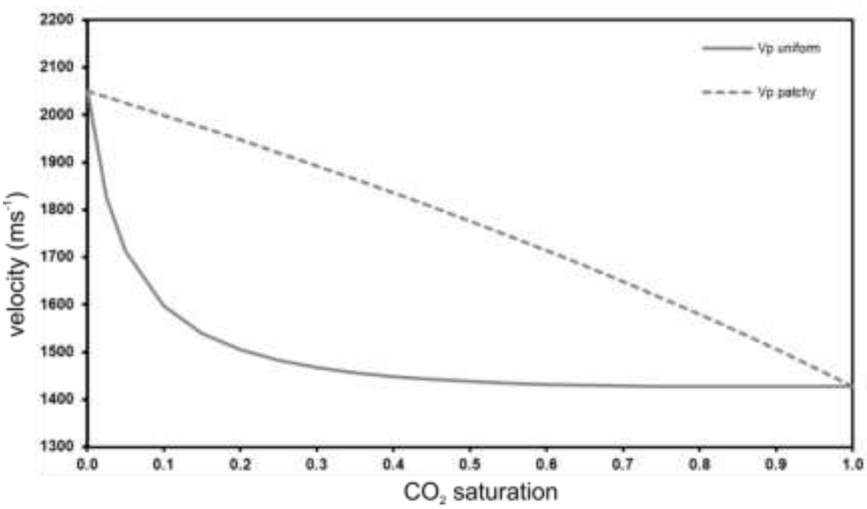

Figure 3.2 Seismic velocity for the Utsira Sand as a function of CO_2 saturation, for uniform (Reuss average) and patchy (Voigt average) fluid mixing scales.

Small time-shifts were used to obtain an empirical determination of the seismic velocity of the topmost CO_2 layer that is essentially independent of the rock physics and its associated uncertainties. Key to this is understanding the geometry of the CO_2-water contact. This forms the base layer reflection which is subject to small time-shifts depending on the topography of the overlying topseal and the thickness and velocity of the CO_2 layer (Figure 3.3).

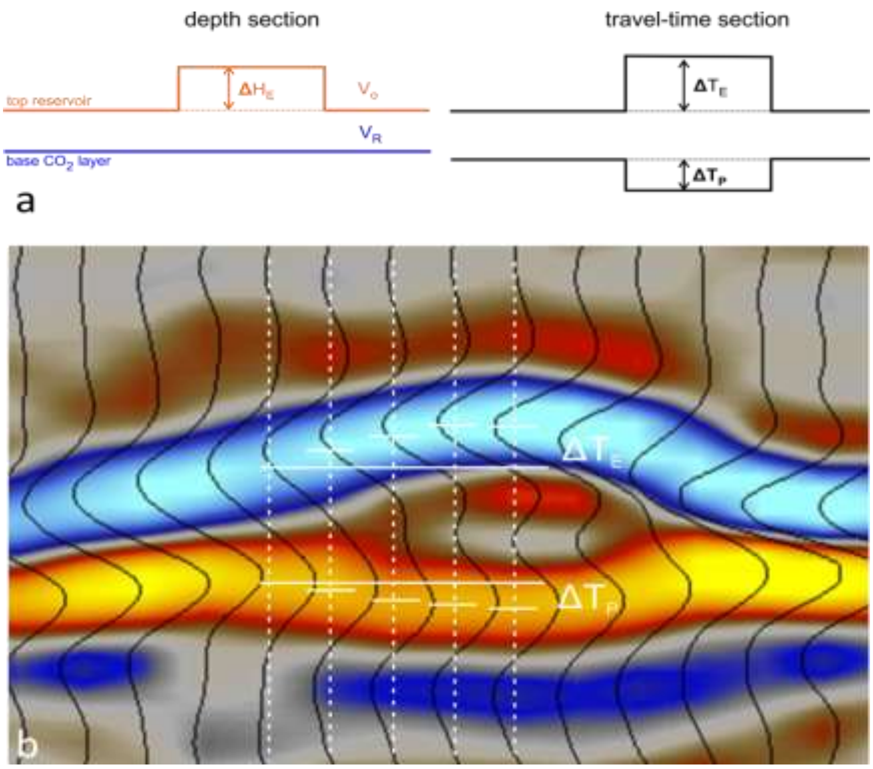

Figure 3.3 a) Relationship between top layer topography (ΔH_E, ΔT_E) and time-shifts of the base layer reflection (velocity pushdown ΔT_P) assuming a horizontal CO_2 – water contact and no wavelet interference effects. b) Seismic section through a ridge showing schematic measurement of ΔT_E and ΔT_P on five notional seismic traces (dashed lines).

With a perfectly resolved seismic image (i.e. for a seismic ‘spike’ with no interference between the top and base layer wavelets) there is a simple relationship between time-shifts due to topographic variation at the top layer reflection and time-shifts due to velocity pushdown at the base layer reflection:

$$\Delta T_P = \Delta T_E \left(\frac{V_O}{V_R} - 1 \right)$$

Equation 3.1

Where:
ΔT_E = time-shift at top layer reflection
ΔT_P = time-shift at base layer reflection
V_O = overburden velocity
V_R = CO_2 layer velocity

Rearranging Equation 3.1 gives an expression for V_R as a function of the overburden velocity and the time-shifts at the top and base of the CO_2 layer:

$$V_R = V_O \left(\frac{1}{\frac{\Delta T_p}{\Delta T_E} + 1} \right)$$

Equation 3.2

ΔT_E and ΔT_p can readily be measured from seismic data and V_o can be estimated from borehole and seismic processing velocities, so V_R can be calculated. Early results (Figure 3.4) were broadly in line with the rock physics and indicative of moderate to high CO_2 saturations (Chadwick et al. 2016).

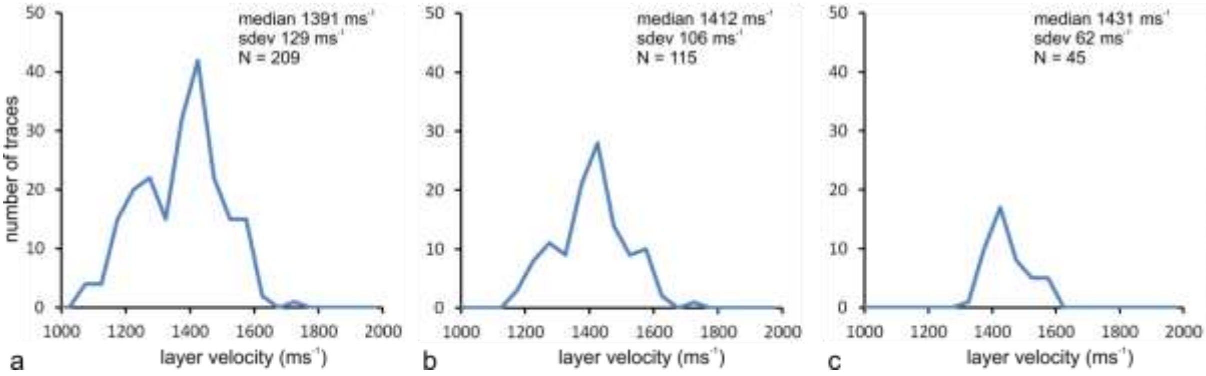

Figure 3.4 Calculated layer velocity distributions measured on multiple seismic traces for different ridge elevation (ΔT_E) thresholds a) $\Delta T_E > 2$ ms b) $\Delta T_E > 3$ ms c) $\Delta T_E > 4$ ms

Subsequently we developed a number of top layer topographic models, with a range of layer velocities, and computed synthetic seismic datasets to cover all likely topseal topography scenarios. From these we developed a methodology of identifying a more accurate CO_2-water contact level and also a means of correcting for interference induced time-shifts in the reflected wavelets.

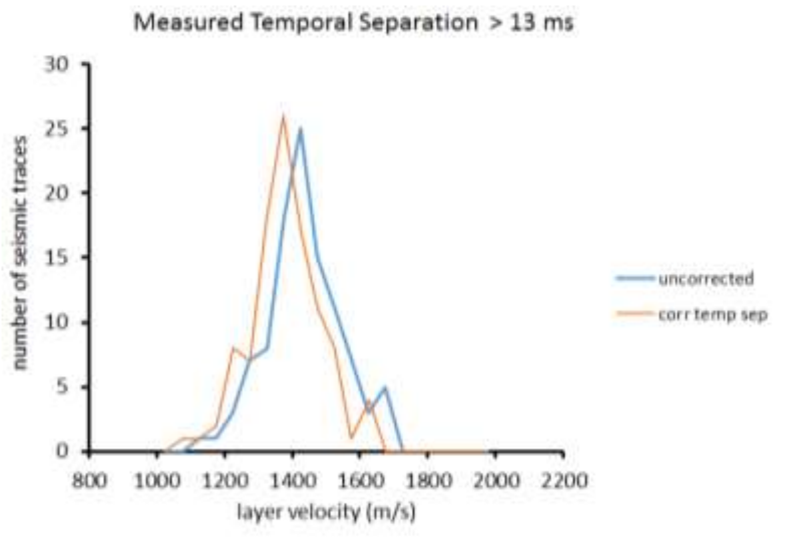

Figure 3.5 Layer velocities calculated for the topmost CO_2 layer at Sleipner in 2010 showing uncorrected velocity values and values corrected for top/base reflection interference effects.

Revised velocity estimates incorporating the synthetic model constraints (Figure 3.5) are rather lower than the earlier values, with a slightly smaller scatter.

Temporal layer thicknesses

In parallel with the above, a comparative study of multiple approaches to obtaining temporal thicknesses of the topmost CO_2 layer at Sleipner was carried out. These included direct measurement of the resolved layer from high resolution data (as above), frequency analysis using the smoothed pseudo Wigner-Ville distribution (SPWVD) spectral decomposition tool (Williams & Chadwick 2013), modified amplitude analysis, structural analysis of topseal relief and time-shifts both of the layer reflections (edge-pull-up) and of reflections beneath the layer (velocity push-down) (Figure 3.6).

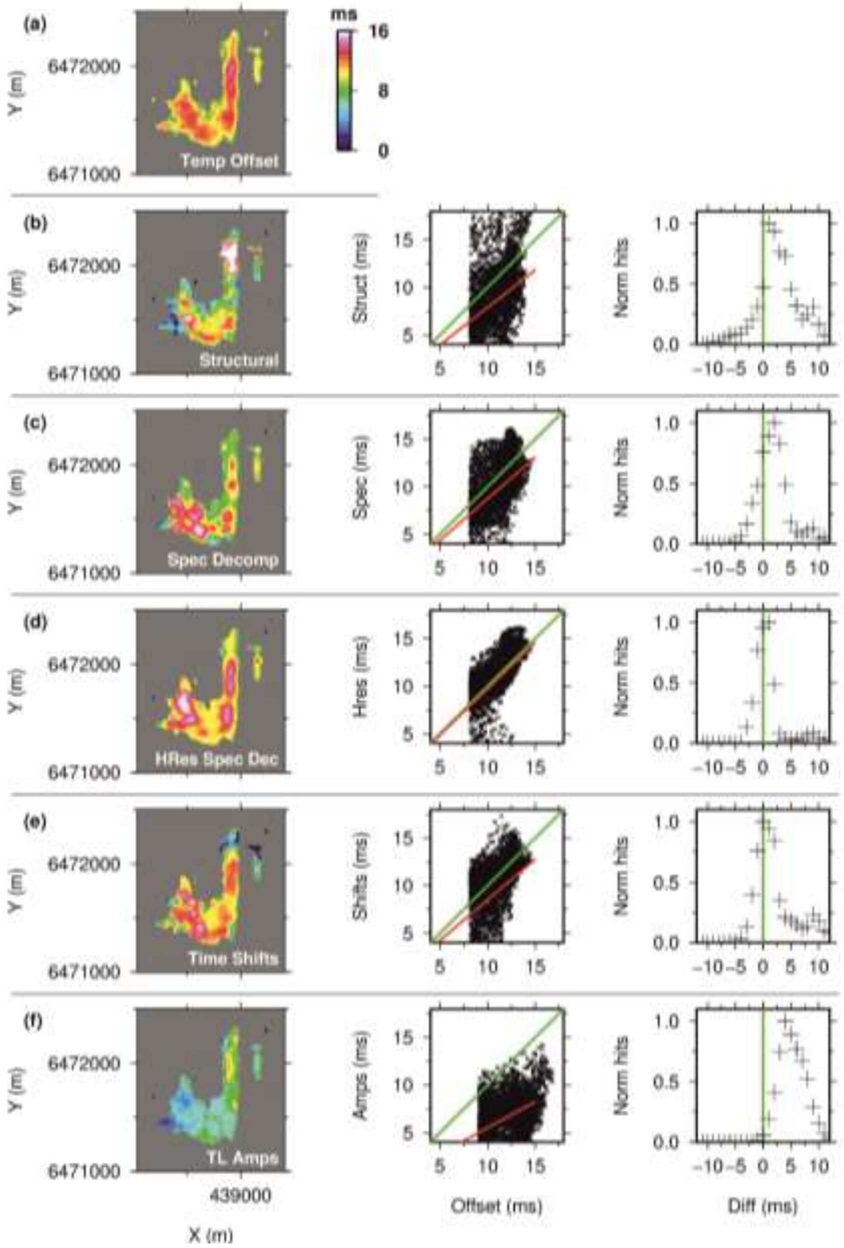

Figure 3.6 Left: Temporal spacings extracted from the central part of the layer shown in (a), where the directly measured temporal spacing exceeds 8 ms on the 2010IP data. Middle: Cross-

plots of temporal spacing derived from each analysis technique against corrected measured temporal spacing. Right: Normalised histograms of the difference between the spacing derived at each seismic trace using the particular technique and the corrected measured temporal spacing. The green lines indicate an idealised 1:1 correlation whilst the red line shows the actual linear best fit with an intercept through the origin.

Results indicate that, depending on layer thickness, different methods give the best estimates of temporal thickness and an optimal strategy for layer volume estimation could utilise a number of methods in combination. For example measured temporal spacings would be used in the central part of the layer, above the tuning thickness, spectral decomposition would be used down to the effective resolution limit and reflection amplitudes for the thinnest parts of the layer out to the layer edge. A quantification of the topmost layer at Sleipner, integrating a number of techniques, has been carried out (White et al. submitted).

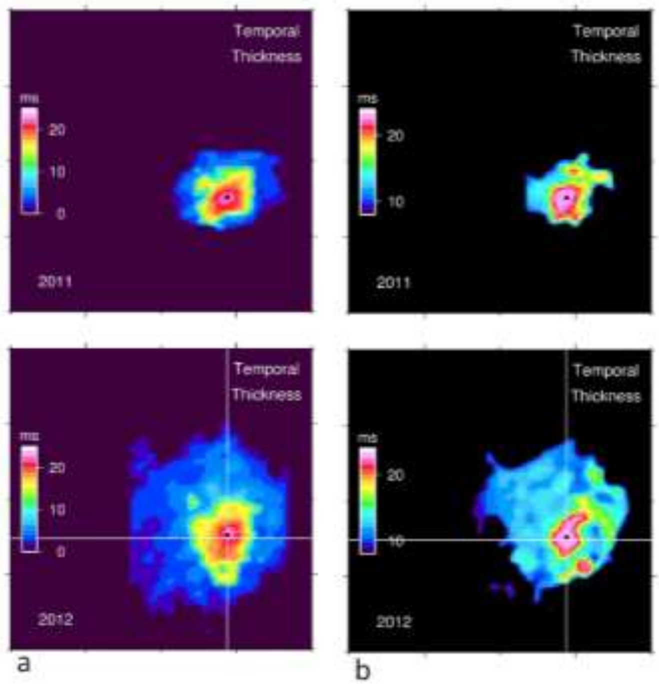

Figure 3.7 Temporal thicknesses (milliseconds) of the CO_2 plume in the Stø reservoir at Snøhvit in 2011 and 2012 a) from direct measurement and amplitude scaling b) from spectral decomposition.

A similar approach was taken to analyse the 2012 seismic dataset from Snøhvit which images second phase of CO_2 injection, into the Stø Formation (White et al. submitted). Here temporal layer spacings measured directly in the (thicker) central part of the plume, combined with temporal spacings derived from the SPWVD tuning frequencies and amplitude analysis, allows reliable mapping of temporal layer thickness across the plume extent (Figure 3.7).

3.1.2 Flow models

Fluid flow modelling work was carried out in conjunction with the seismic analysis. A number of numerical flow simulators were utilised, including TOUGH2, PFLOTRAN, Eclipse 100 and Eclipse 300, and analytical models of thin layer spreading were also developed using the axisymmetric gravity current formulation of Lyle et al. (2005). Numerical models included full 3-D and high resolution 2D axisymmetric geometry.

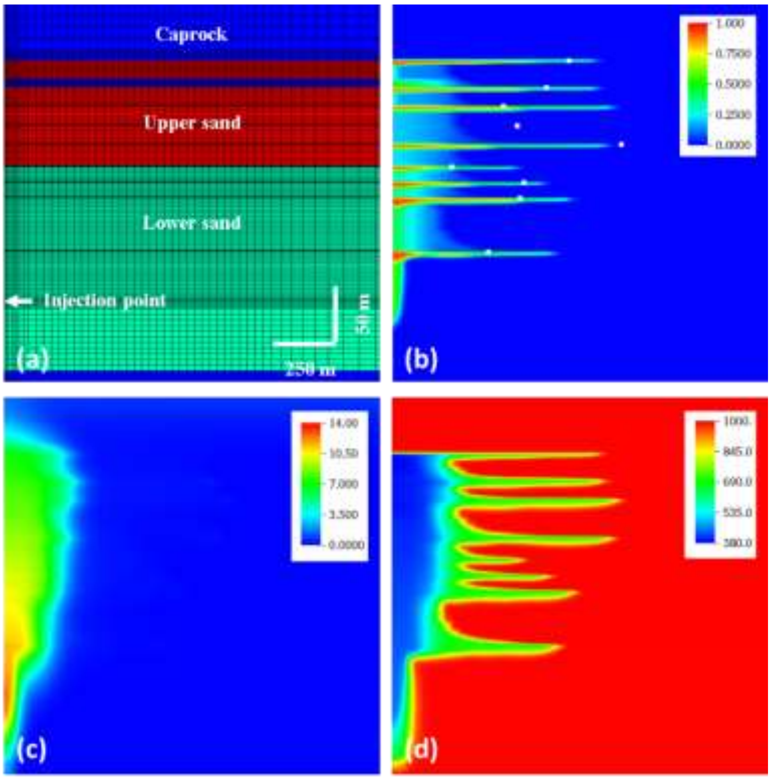

Figure 3.8 2D axisymmetric reservoir model showing the effect of injecting CO_2 at 48 °C into a cooler reservoir. The reservoir temperature at the injection point (labelled) is ~35 °C. (a) Simulation mesh, (b) CO_2 saturation in the reservoir, (c) thermal anomaly (°C), and (d) CO_2 density (kgm^{-3}). The simulation time-step corresponds to the 2006 seismic monitor survey. The radial equivalent extents of each seismically observed CO_2 layer in the plume are marked with a white square in (b).

The spread of the CO_2 plume at Sleipner has been a topic of much discussion in recent years, and a better understanding of this was a key research objective. Our focus was on the accuracy of the reservoir geological characterisation and on the thermal setting. Firstly, by properly integrating core measurements in the Utsira Sand with the geophysical log data, we obtained an improved assessment of reservoir permeability. Secondly, Statoil have estimated that the CO_2 is injected at about 13 °C above reservoir temperature, but this situation had not previously been modelled. Our simulation of the thermal effects of injecting 'warm' CO_2 at above the ambient reservoir temperature (Figure 3.8) suggests upward propagation of the thermal anomaly to the reservoir top with a significant effect on CO_2 mobility, at least in the axial part of the plume (Figure 3.8c, d).

By including higher reservoir permeability and higher CO_2 temperature we concluded (Williams & Chadwick 2017) that numerical simulations based on the assumption of Darcy flow can satisfactorily account for the observed rapid layer spreading (Figure 3.9). In fact the principle factor is the revised geological reservoir parameters, rather than the warmer CO_2.

In parallel with this work, we have carried out a very accurate flow simulation code comparison, comparing the relative performance of a number of numerical flow simulators on a range of carefully matched CO_2 injection scenarios and also comparing them with analytical models of a thin spreading CO_2 layer (Williams et al. 2018). A key conclusion is that the simulators all produced very similar results, with differences between the different codes less than interpretive uncertainty in the monitoring data.

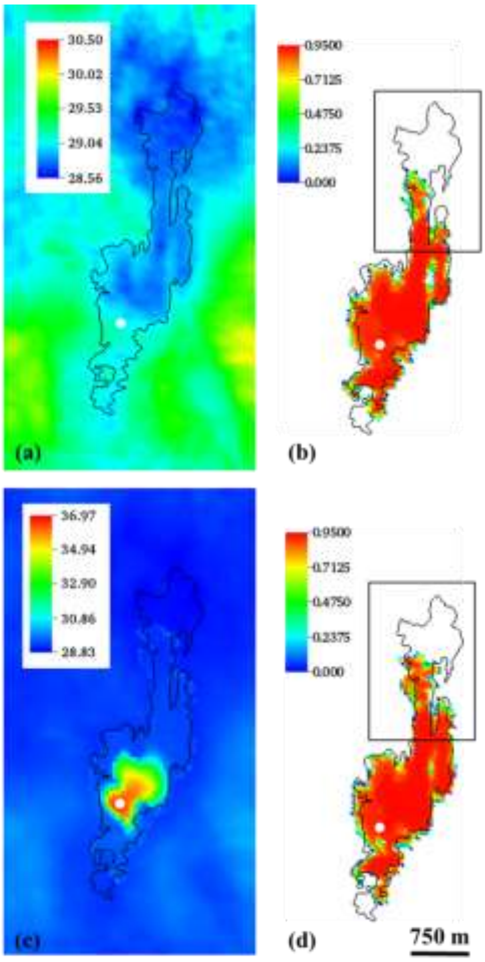

Figure 3.9 Effect of injecting warm CO_2 into the topmost sand body. (a) Ambient temperature distribution at the top of the reservoir. (b) CO_2 distribution at the time of the 2010 seismic survey, assuming the CO_2 enters the top sand body at the background reservoir temperature. (c) Thermal anomaly caused by CO_2 entering the top sand body at a temperature of 37 C. (d) Resulting CO_2 distribution at the time of the 2010 seismic monitor survey. Black polygon denotes extent of the CO_2 measured on the 2010 survey. White circle denotes feeder chimney through which the CO_2 enters the topmost sand from below. Temperature and thermal anomaly in °C, plume distribution shown as CO2 saturation.

3.1.3 Saturation - pressure discrimination by frequency analysis of thin and thick layers

Working on the Snøhvit time-lapse data, White et al. (2015) showed that for injection into the Tubåen reservoir, frequency analysis could be used to discriminate between fluid saturation changes associated with the CO_2 plume and more widespread pressure changes in the whole reservoir. Thus high frequency tuning occurs around the thin layers of CO_2 in the plume, contrasted with much lower frequency tuning associated with fluid pressure changes propagating across the full reservoir thickness.

Similar analysis of the more recent injection into the Stø Formation (White et al. in submission), shows no evidence of low frequency tuning away from the injection plume, which suggests a lack of significant pressure propagation into the reservoir. The seismic anomaly is more simple, and consistent with a cone-shaped plume formed by buoyancy-driven upward advection of CO_2, ponding and spreading radially beneath an impermeable topseal. Analytical modelling (Lyle et al. 2005) of radially-symmetric gravity currents shows that layer thickness varies with rate of injection, so the observed constancy is consistent with the roughly uniform rate of injection.

3.2 NOVEL METHODS FOR LAYER CHARACTERISATION (TASK 2.2)

This work package has addressed the seismic characterization of CO_2 saturation in thin layers. We have developed new theory for calculating frequency-dependent velocity and attenuation in rocks saturated by multiple fluids. The key advance is to describe the "squirt" and "patch" effects in a common theoretical framework. The new model reproduces existing work in suitable limits and demonstrates that patch effects can be produced by complex pore-scale fluid distributions, so that interpretation of data in terms of explicit patch sizes is problematic. The model has been calibrated against experimental data obtained in WP3, and provides a compelling explanation of velocity and attenuation as a function of CO_2 saturation. Combination of our rock physics models with a matching pursuit method allows application to layer characterization at Sleipner. Using only the frequency-independent theories the method produces results which can be compared to previous estimates using independent techniques. Repeating the analysis with the new modelling, we demonstrate the potential importance of including dispersion and attenuation for saturation estimation.

Estimation of CO_2 saturation in a thin layer is a generic and critical problem for CO_2 monitoring (e.g. Arts et al., 2004; Chadwick et al. 2004). Approaching this problem requires knowledge of the background velocity model for the reservoir and surrounding rocks, together with an understanding of the rock physics which link velocities and density to saturation. Finally, we need to be able to perform wavefield modelling which takes account of the amplitude versus angle response, travel-times through the saturated layers and the interference between top and bottom reflections.

The rock physics relevant to wave propagation through rocks saturated with multiple fluids is not fully understood. We expect multi-fluid saturation to give rise to strong dispersion and attenuation (e.g. Müller et al, 2010; Chapman et al., 2002). Such effects would have potentially important implications for estimation of fluid saturation within a thin layer.

Being able to address the issues of dispersion and attenuation in the context of practical monitoring of CCS relies on solution to a number of problems:

a) *Reliable modelling tools for the calculation of frequency-dependent velocity and attenuation*.
b) *Fast and efficient wavefield modelling for the effects of dispersion in complex velocity models*.
c) *Numerical simulation of the effect of dispersion on saturation estimation methods*.
d) *Demonstration of the techniques on suitable field datasets*

We have addressed each point within the DiSECCS research programme, and treat them in turn below.

3.2.1 Reliable modelling of frequency-dependent velocity and attenuation

The rock physics relevant to wave propagation through rocks saturated with multiple fluids is not fully understood. Modelling generally makes use of the patchy or uniform saturation theories, which are highly idealized and neglect potentially important effects. The difference in behaviour between the uniform and patch theories stems from a difference in physical assumptions- under the uniform model a single fluid pressure always obtains in each fluid and at each point in the pore space, while under the patch model there can be two such pressures, one for each fluid.

The patch effect itself can give rise to frequency-dependent velocity and attenuation, but such effects can often be understood well within the context of the “squirt-flow” theory. Combining the squirt and patch theories is a key research objective, which we have addressed by developing a new theory which combines the “squirt” and “patch” concepts.

The basis of the work is to extend previous analysis by assuming that induced pore-pressures are systematically different between the two saturating fluids. This can be due either to membrane effects or differences in fluid distributions. The difference between the fluid pressures is captured by a single new capillary pressure parameter, and with the addition of this relation we are able to re-derive the earlier squirt flow models based on Chapman et al. (2002), obtaining a new theory which contains both squirt and patch effects under a consistent parameterization.

The new theory reproduces key theoretical approaches, such as Gassmann-Wood and single fluid squirt flow theory in appropriate limits and predicts that the characteristic frequency where squirt flow effects are observed depends on relative permeability. A particularly interesting limit is the low frequency limit in which the behaviour is dependent only on the capillary pressure parameter. These results can be compared directly with the predictions of the so-called “Brie model”, which is widely used in fluid substitution problems related to CO_2 storage in Snøhvit (Grude et al., 2013), Sleipner (Carcione et al., 2006) and Nagaoka in Japan (Lumley, 2010).

Good agreement is seen between the theory and Brie’s model (Papageorgiou and Chapman, 2015), so that we have in effect given a theoretical derivation of what was an empirical model. This builds confidence in our approach, as well as allowing us to enhance existing interpretations based on the Brie model. A schematic representation of the various limits of the new theory is shown in Figure 3.10.

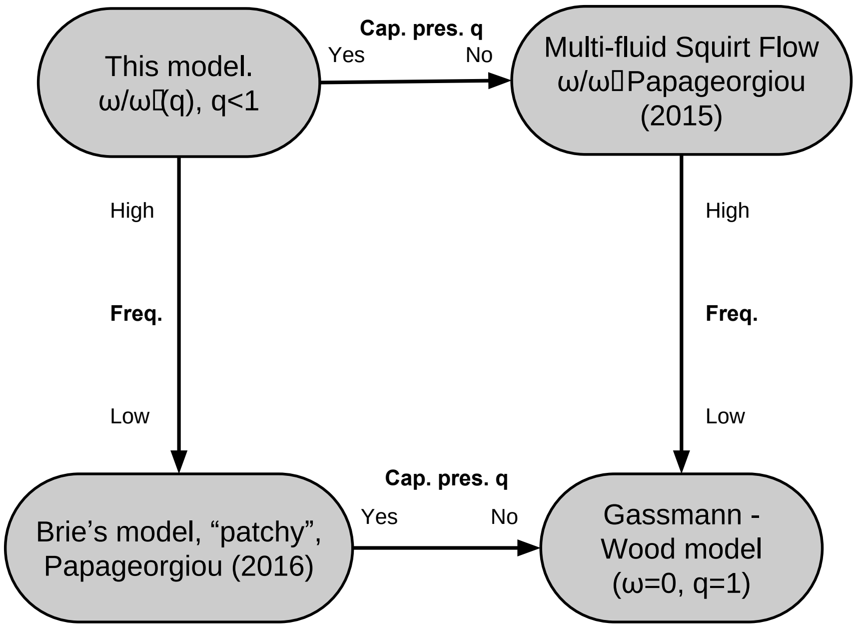

Figure 3.10 The partial-saturation squirt-flow model (upper left) developed here incorporates the effects of patchy saturation by letting the capillary pressure parameter be less than 1. It also incorporates the frequency-dependent effects of the squirt flow model of Chapman et al. (2002). Its limits depend on which of these parameters (frequency, capillary pressure parameter) is switched off.

We have also worked with WP3 to calibrate our new model against ultrasonic velocity and attenuation experimental data obtained at different partial saturation of supercritical CO_2 (Figures 3.11 and 3.12) The simultaneous fit of attenuation and ultrasonic velocity versus saturation means we constrained rock physics parameters determining the magnitude of squirt flow (crack density, characteristic frequency).

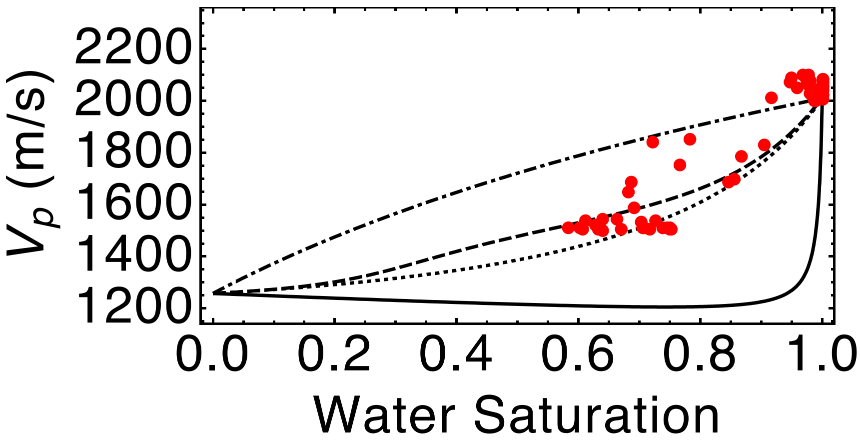

Figure 3.11 Seismic velocity (Vp) variation with supercritical CO_2-brine saturation and the fit of the squirt flow model for the ultrasonic velocity measurements of the Utsira Sand. The solid line is Gassmann's model with a Wood-averaged fluid, the dot-dashed line with a Voigt –averaged fluid. The dashed line is the best fit of our model to the data and the dotted line is its low frequency limit (data from WP3).

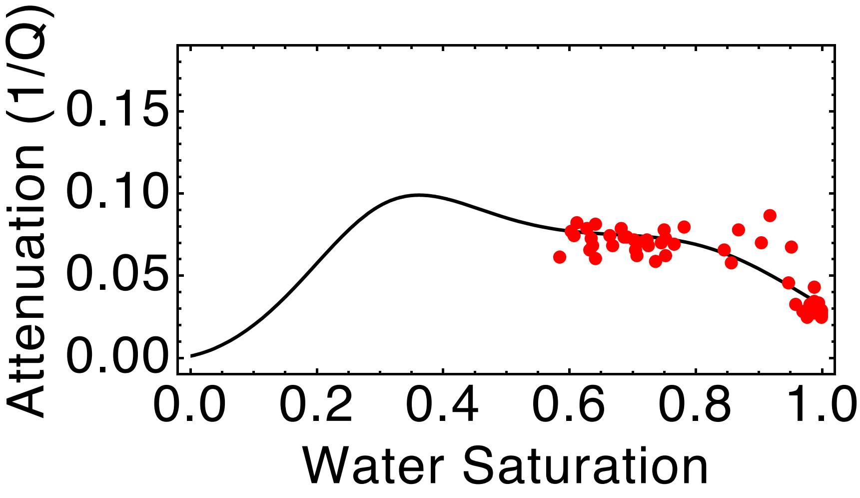

Figure 3.12 Attenuation variation with water saturation for the Utsira Sand. The fitted line is the attenuation corresponding to the squirt flow (dashed line) model shown in Figure 3.11 (data from WP3).

3.2.2 Convolutional based modelling incorporating the effects of frequency-dependent reflectivity

Realistic application of the models described above to the characterization of thin layers requires some form of seismic inversion. Most commonly employed seismic inversion is based on the convolutional model of a seismic trace. The convolutional model is computationally very efficient and has the key advantage that it simulates ideal data after processing. More sophisticated methods such as finite difference and reflectivity provide more rigorous solutions to the wave equation, but they model shot gathers and this output must itself be processed before it can be compared to seismic data. This requirement impedes the application of such methods to inversion of stacked data or pre-stack gathers.

Methods to incorporate frequency-dependent velocities and attenuations into finite difference and reflectivity methods are well established, but convolution-style modelling incorporating the effects of frequency-dependent reflectivity has been less well studied. To address this issue, we have developed an extended convolutional model which can compute synthetic seismograms in the time-angle domain on the basis of our developed rock physics models (see Jin et al., 2016). Unlike the conventional convolutional model, which accepts Vp, Vs and density logs as inputs, we also require porosity and fluid saturation to be specified, which opens the way to potentially inverting for saturation as a function of depth.

In the simplest case of a thin layer under normal incidence, the seismic response is the result of a complex interplay between thin-layer tuning, frequency-dependent reflectivity and phase effects on the wavelet resulting from the effect of attenuation on the reflection coefficient.

Application of the modelling to field data

Matching pursuit methods

Our approach to the analysis of the Sleipner dataset is based on combining matching pursuit methods and rock physics to detect thin layers and characterize saturation and thickness. Matching pursuit methods are a common means of decomposing seismic data into a sum of user-defined basis functions, specified in a so-called "dictionary". For our analysis, we specify a dictionary containing forward-modelled responses for various layer thicknesses, based on our rock physics model, so that the matching pursuit algorithm searches for these responses in the data. In this way, the algorithm both detects the presence of the thin layer, and finds the best fitting combination of thickness and saturation.

We applied this algorithm with the aim to determine the thickness of the layer of CO_2 visible in the Sleipner 2010 time-lapse data within inlines 1871 – 1877 and crosslines 1200 – 1220. We can construct our dictionary choosing only elastic rock physics models, or we can include the frequency-dependent rock physics models developed during DiSECCS for the reflectivity of the CO_2 -saturated sand layer.

<u>Elastic dictionary</u>

In this approach we build the dictionary using a wedge model consisting of a CO_2 -saturated sand of varying thickness encased between a shale caprock and a brine-saturated sand. Suitable values for the velocity and density were taken from Furre et al. (2015). The dictionary is built using elastic-only reflectivity on the shale-CO_2 and CO_2-brine interfaces and different fluid mixing laws are considered for the calculation of the velocities.

The different fluid averaging laws – Wood, Brie and Voigt – are substituted into Gassman's model and we then build the dictionary for each fluid mixing scenario based on the wedge model. By fixing the saturation, we invert for layer thickness. The method produces results comparable to those obtained using the overburden method introduced by Chadwick et al. (2006). In Figure 3.13 we show the result of this inversion together with published estimates of layer thickness in that location: one by Chadwick et al. (2006) and one by Williams & Chadwick (2013). The importance of our method lies in that it is blind so it provides a third, independent, way to distinguish CO_2 layer thickness.

<u>Frequency-dependent dictionary</u>

In this approach the dictionary is built on the assumption the reflectivity of the sand is dispersive which means that both the shale-CO_2 and CO_2-brine reflectivities are frequency dependent. Consequently, at each interface there are phase effects dependent on the attenuation of the layer encoded in the dictionary.

We calculated synthetic seismograms for a variety of layer thicknesses and saturations both with and without frequency-dependent reflectivity, for a Ricker wavelet with a central frequency of 35 Hz. Measuring the amplitude versus the time thickness for various saturations gave rise to the tuning curves shown in Figure 3.14. The curves for the elastic case are given on the left, and these are consistent with the work of Furre et al. (2015), but we note that the behaviour changes for the frequency-dependent case, due to the phase effects on the reflection coefficient.

This motivates us to compare inversions for saturation and thickness using both dispersive and non-dispersive models. We found that the phase effects have a modest impact on the inverted layer thicknesses (generally less than 2 m difference), but there is a more pronounced impact on the saturation estimation. Figure 3.15 shows the residuals of the elastic and frequency dependent inversion. The minimum for the elastic and dispersive dictionaries are different suggesting that it is important to consider dispersive effects for the estimation of saturation in a thin layer.

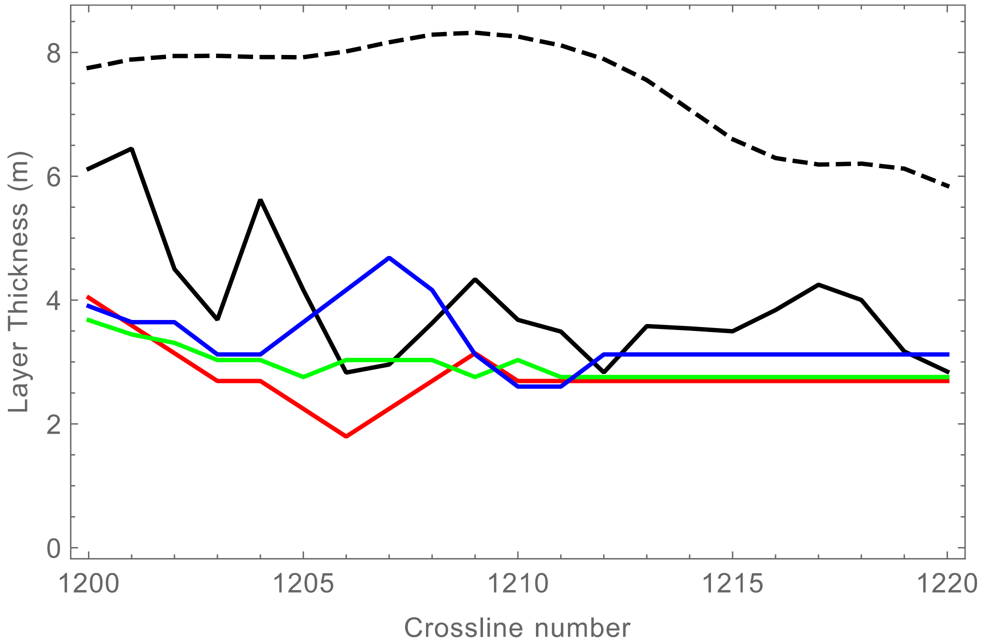

Figure 3.13: Estimates of layer thickness for inlines 1871 to 1877 using matching pursuit under different fluid substitution models: Wood (red), Brie (green) and Voigt (blue). The solid black line denotes the estimate of thickness using the overburden method of Chadwick et al. (2006) and the dashed black line shows the estimate using the spectral method of Williams and Chadwick (2013).

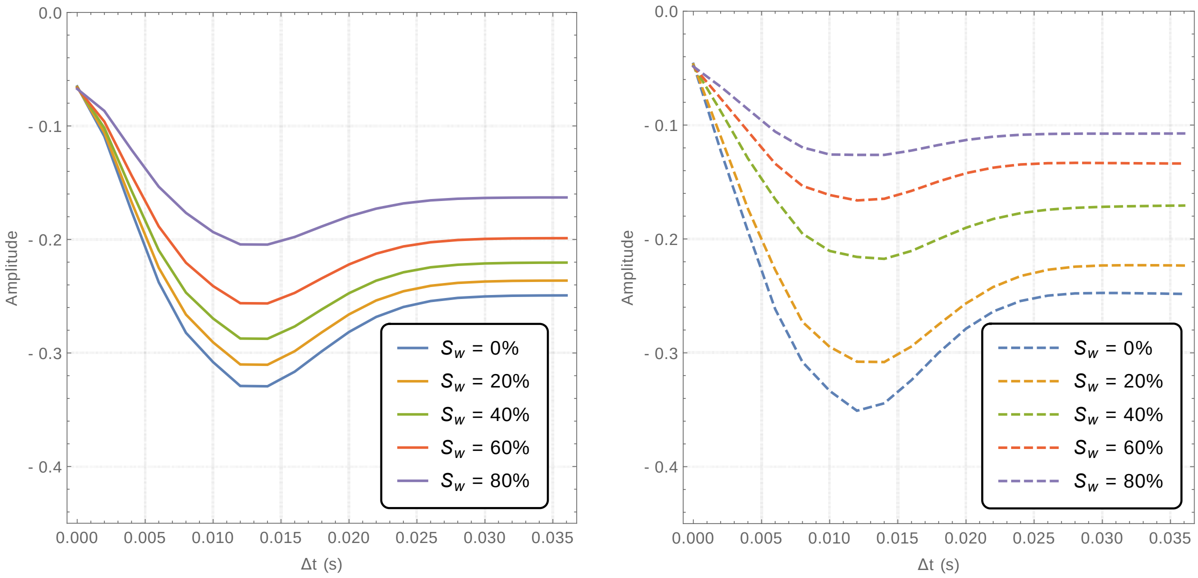

Figure 3.14: Amplitude tuning curves for a Ricker wavelet of central frequency 35 Hz. The elastic response on the left is derived using Gassmann's model with a Brie mixing law and on the right the dispersive rock physics theory has been used. The two methods give different tuning amplitudes and minima for different degrees of water saturation.

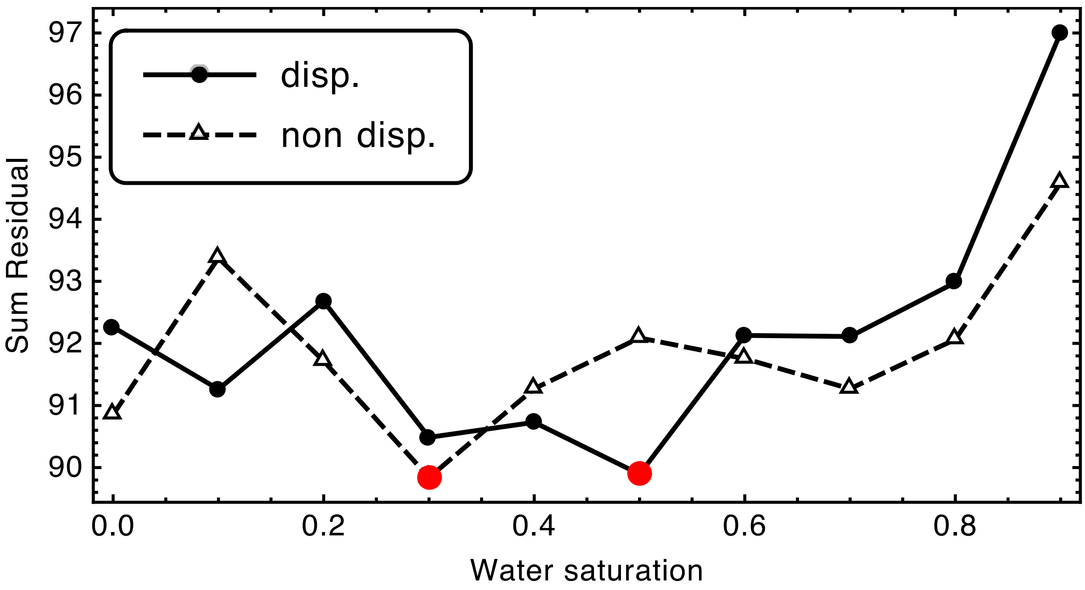

Figure 3.15 Sum of residuals of the matching pursuit inversion for the whole saturation range in 10% saturation steps. The residuals refer to the sum over the entire 7x21 cube of traces in the location of interest. The dispersive and elastic dictionaries have minima (red circles) at different saturations.

4 Work Package 3: Experimental rock physics

The original aim of WP3 was to take advantage of recent developments in the National Oceanography Centre (NOC) rock physics laboratory to investigate the effect of CO_2/brine saturation on the seismic response of synthetic rock samples with aligned fractures. The observations would be used to inform the development of theoretical rock physics models in WP2 linking seismic P- and S-wave velocity and attenuation to CO_2 saturation and the presence of fractures, their number density, size and orientation. The experiments were initially aimed at answering questions around the seismic detection of geotechnical effects in brittle formations prone to hydraulic fracture during CO_2 injection, such as the highly cemented reservoir sandstones at In Salah, and the intermediately cemented reservoir sandstones at Snøhvit. However, due to the failure to obtain monitoring data from In Salah and following developments in other work packages, our priorities shifted towards experiments on the very weakly cemented sands at Sleipner. This presented a number of new technical challenges as the ultrasonic rig was designed primarily for rock samples. However additional financial investment from NOC, allowed us to completely redesign our experimental rig for simultaneous monitoring of geophysical (ultrasonic, electrical resistivity), geomechanical (stress-strain) and fluid transport (relative permeability) properties under realistic pressures and temperatures simulating CO_2 injection. This has been a major achievement, producing the first comprehensive experimental datasets of this type (Falcon-Suarez et al, 2016).

A related NOC/University of Edinburgh collaboration sought to link fluid (air/water) saturation effects to rock physics models in fractured rocks, and those results are reported separately in the following publications: Amalokwu et al. (2016); Amalokwu et al. (2014); Amalokwu et al. (2015a); Amalokwu et al. (2015b).

The work developed here has focussed on the distinction between pore fluid distribution and geomechanical effects during CO_2-injection in Sleipner-like reservoirs. We have used synthetic sandstones as proxies of saline siliciclastic reservoirs and also real samples from the Utsira Sand at Sleipner to run a set of brine-CO_2 flow-through tests. The tests replicate shallow reservoir conditions (~900 m depth) and simulate different stages of CO_2-injection under hypothetical inflation/depletion scenarios.

The experiments were conducted with a new experimental rig for CO_2 injection simulations that was specially designed and assembled at NOC during the first and second years of the project (2013 - 2015). The rig was designed to relate geophysical signatures of reservoir sandstones to their hydro-mechanical, thermal and geochemical responses during the co-injection of up to two fluids (brine and CO_2), under realistic environmental and geological conditions.

4.1 EXPERIMENTAL METHODOLOGY (TASKS 3.1 AND 3.2)

4.1.1 Experimental rig

We have designed a new experimental rig for observing changes in geophysical, geomechanical and transport properties during flow tests of up to two fluid phases through a rock sample 5 cm in diameter, and 2.0 - 2.5 cm high, under realistic reservoir conditions (Figure 4.1).

The rig allows different configurations depending on the needs of the experiment. It is designed around a triaxial cell core holder for confining rock samples at pressures up to 69 MPa. The confining fluid (mineral oil) is delivered from a dual pumping controller (Teledyne ISCO model EX100D) that is configured in a non-coupled mode which allows the independent control of axial and radial confining pressures. Inside the vessel, a 6 mm wall, 190 mm high rubber sleeve isolates the core plug from the confining fluid. The rubber sleeve is perforated by 16 stainless steel electrodes for electrical resistivity tomography measurements. The wires from the electrodes are extracted from inside the pressure-vessel via feedthrough ports on the vessel-wall, and connected to an electrical resistivity tomography data acquisition system (North et al., 2013). The system uses a tetra-polar electrode configuration to minimize electrode polarization artefacts. A total of 208 individual tetra-polar measurements (using various permutations of current injection and potential difference sensing electrode pairs) are acquired during each acquisition run. These data are then inverted using software based upon the EIDORS MATLAB toolkit (Andy & William, 2006) for a uniform/homogeneous isotropic resistivity and heterogeneous isotropic resistivity distribution. Both inversion schemes employ a finite-element forward model of the sample and electrodes.

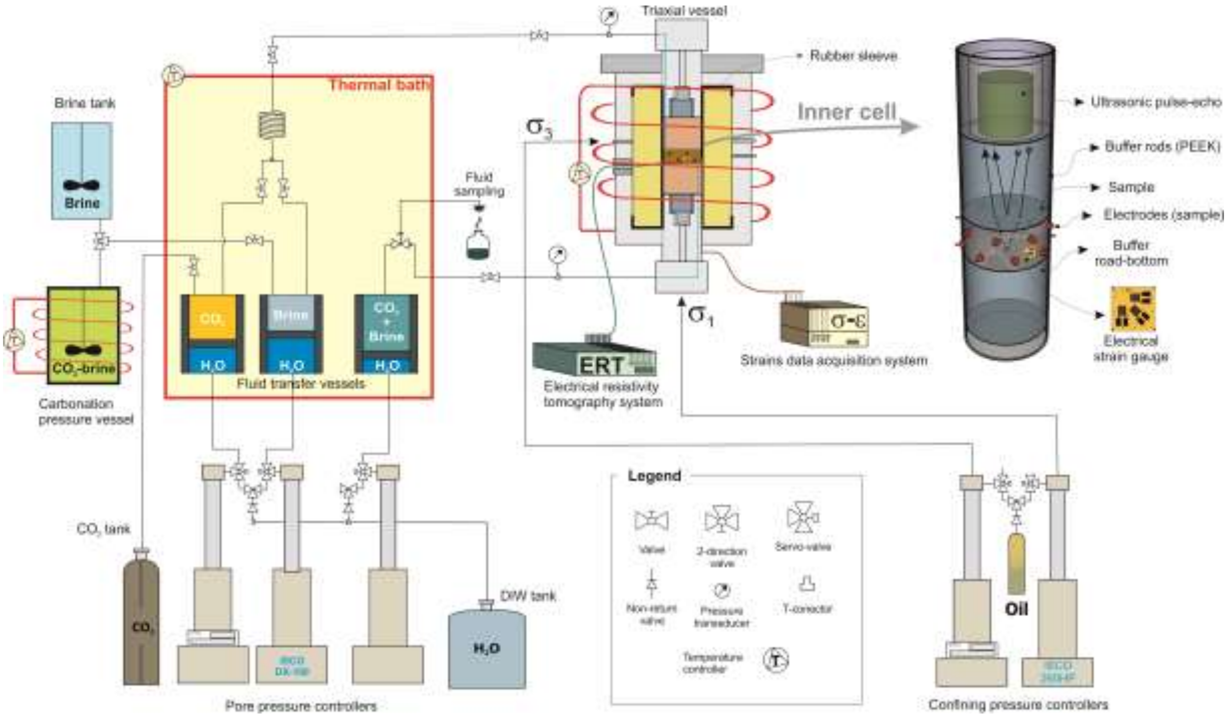

Figure 4.1. Schematic diagram of the experimental rig.

The sample is axially confined with two platens housing the ultrasonic pulse-echo sensors for measuring ultrasonic velocity and ultrasonic attenuation (Best et al., 2007). These are indirectly in contact with the sample but with the two buffer rods in between. As shown by the "inner cell" drawing (Figure 4.1), the core plug is isolated from the rest of the rig and the ultrasonic transducer by two PEEK buffer rods. The buffer rods have well-defined acoustic impedance and low energy loss, providing a reliable delay path to enable the identification of top/base sample reflections for calculating ultrasonic velocities (V_p and V_s) and attenuations (inverse quality factors Q_p^{-1} and Q_s^{-1}) using the pulse-echo technique (McCann & Sothcott, 1992). The technique provides useable frequencies between 300 - 1000 kHz with absolute accuracies of ± 0.3% for velocity, and ± 0.1 dB cm^{-1} for attenuation (for 1" diameter single mode transducers). For the brine-CO_2 flow-through tests (described below), we used dual P/S wave transducers which give accuracies of ± 0.3% for velocity and ± 0.2 dB cm^{-1} for attenuation (Best, 1992). The buffer rods have built-in pathways (inlet and outlet ports) to conduct the pore fluid through the sample. The surfaces of the rods in contact with the sample are specially designed with a circumferential fluid flow pathway to facilitate fluid spreading upstream and fluid collection downstream.

The axial platens and access to the inner triaxial vessel are configured to allow the bypass of leads from strain gauges epoxy-glued to the side-wall of the sample. The leads are connected to a 4-channel data acquisition conditioner (Vishay-Model D4), which accepts either full-, half-, or quarter-bridge configuration for 120-, 350-, and 1000-ohm bridges. The pore pressure is controlled by three high-pressure, high-accuracy, pumping controllers: a dual Teledyne ISCO model EX100D, configured in separate mode for delivering two independent fluids, and a single controller Teledyne ISCO model ED100 acting as back pressure downstream of the sample. The pore fluids are indirectly supplied via fluid transfer vessels (FTVs) with the aim of preventing potential damage to the controller from corrosive fluids such as brine or CO_2. Also, the FTVs allow heating of the fluids to target conditions by direct immersion in a tank made of PVC specially designed for temperatures up to 100 ºC. The three vessels are connected to the three pumping controllers: two for delivering brine and CO_2, and one for receiving the fluid, after passing through the sample, while setting the pore pressure constant. To further control the pore pressure, two piezo-resistive pressure transmitters (Keller model PA-33X) are located in the pipeline up- and downstream but very close to the sample, to accurately measure pressure drops and temperature changes during the test. An additional external carbonator-vessel is designed to prepare and store the CO_2-saturated brine, for refilling the FTVs. The carbonator contains magnetic stirrers excited by a magnetic motor located underneath, and can be pressurized up to 30 MPa and heated up to 80 ºC. The pipeline includes different ports both up- and down-stream of the sample for pore fluid sampling and geochemical analysis.

The triaxial vessel is also wrapped with an electrical rope heater connected to a PID (proportional/integral/derivative) controller (maximum temperature 150 ºC; accuracy ± 0.5 ºC) which sets the target temperature in the vessel according to the information received from an inner-vessel thermocouple. In addition, the load frame (containing the triaxial vessel and pipeline-pressure sensors) is enclosed in a commercial greenhouse cover system dotted with heat fans and automatic controllers to keep the temperature of the rig constant.

4.1.2 Samples

Experiments were carried out using synthetic sandstones and real samples of Utsira Sand, the storage reservoir at Sleipner. This section addresses the preparation and main physical properties of the samples used for the tests.

Synthetic sandstones

We prepared three synthetic sandstone specimens by mixing well-sorted coarse quartz-sand, kaolinite and silica cement at a specific ratio (Table 4.1), following the manufacturing process proposed by Tillotson et al. (2012). In all the cases, the mixture was then compressed in a 5 cm diameter stainless-steel mould, at the differential pressure conditions of a hypothetical 900 m depth CO_2 storage reservoir. Finally, the pressurized mixture was oven-dried for one week, according to the manufacturing procedure.

Table 4.1 Synthetic sample composition and properties. ø porosity; ρ_d density; k_{abs} permeability.

Sample	Q-sand	Kaolinite	Si-cement	ϕ	ρ_d	k_{abs}
	----------- (wt.%)	-----------			g cm^{-3}	mD
Synthetic-1	74	18	8	0.26	1.92	~1
Synthetic-2	86	11	3	0.45	1.47	~100
Synthetic-3	82	13	5	0.38	1.59	~50

After removal from the manufacturing mould, the resulting specimen was firstly flushed with de-ionised water to remove residual non-bounded particles from the porous medium. Then, ~2 cm length, 4.95 cm diameter samples were cut and ground in parallel within ± 0.01 mm. Porosity (ϕ) was determined by helium porosimetry, and absolute permeability (k_{abs}) to water (brine) was determined using the steady state method based on Darcy's law for the whole range of differential pressures simulated in the subsequent flow-through tests. The value of k_{abs} presented in Table 4.1 corresponds to those obtaining under starting-test conditions i.e. at maximum differential stress.

Utsira Sand samples
Samples from the Utsira Sand in the upper section (E641 - 1085-1085.25 m) of the well 15/9-A-23, Viking Graben, Central North Sea, were used to perform brine-CO_2 flow-through experiments. However, the available intact core material from this site was limited to trimmings of loose sand and a small piece of intact core (Figure 4.2).

Figure 4.2. Utsira Sand samples provided by the BGS and drawing of the core from well 15/9-A-23, Viking Graben, Central North Sea (Pearce et al., 2002).

The samples were contaminated with drilling fluid, especially the outer parts of the core, which could condition the geophysical properties of the sample. Therefore, trimmings were washed for several hours prior to taking measurements; the weak grain-packing of the intact core sample led us to conduct the washing in the triaxial vessel (before running the experiment) to preserve the original structure of the rock.

Table 4.2 Sample properties from the Utsira Sand

Sample	Description	Weight (g)
E641B2	Trimmings clean	195.5
E641A	Upper 5 cm. Waste	277.3
E641C	1085-1085.35	595.2
E641B3	Trimmings	244.7
E641A	Waste from samplings	248.3

4.1.3 Test configuration and methodology

Flow-through tests

We conducted five flooding tests using synthetic sandstones (three tests) and Utsira Sand samples (two tests; only one with CO_2-brine fluids). In all cases, the experiments were steady-state drainage tests where electrical resistivity was used to determine the saturation changes in the porous medium.

The flow-through tests were configured to simulate hypothetical inflation/depletion scenarios on shallow-saline-siliciclastic reservoirs such as those in the North Sea. Specifically, we applied Sleipner-like conditions as the initial conditions of our tests: lithostatic confining pressure (σ_c) of 16.5 MPa and 7 MPa of pore pressure (P_p); temperature between 32 and 35 ˚C depending on the test (to be above the CO_2 critical point of 31˚C and 7.39 MPa); sample (synthetic) saturated with degassed 35 g L^{-1} NaCl-brine (electrical resistivity ~0.19 Ω m).

Samples were saturated via imbibition under vacuum conditions. Once in the triaxial vessel the pore fluid was injected from the bottom end of the sample to remove any remaining air bubbles from the pore space, at a constant flow rate. To reach the target reservoir conditions of the starting point of the tests, the confining and pore fluid pressures were simultaneously increased whilst maintaining constant effective pressure ($P_{eff} = \sigma_c - P_p$). After not less than two days of free compaction and settlement (geomechanical stabilisation), the samples were subjected to brine-flow between 0.25 to 0.5 ml min^{-1}, while setting the pressure downstream to 7 MPa. Thereafter, an unload/loading sequence of effective pressures was reproduced by increasing the pore pressure downstream ~1 MPa stepwise from 7 MPa to 12 MPa and back to 7 MPa, while keeping the confining pressure constant at 16.5 MPa. For each step, a minimum of one pore volume (PV) was forced to circulate through the sample. Pore pressure up- and downstream and strains were continuously recorded, while at the end of each step, electrical resistivity and ultrasonic measurements were collected.

The brine-CO_2 co-injection stage started after the first (100% brine) flooding sequence. The new solution injected into the sample was a mixture of brine and CO_2 (with differential fractional flows) independently set by the corresponding pumping controller, but keeping the resulting total flow (Q) constant ($Q = Q_w + Q_{CO2}$). The delivered fluids met at a certain point in the pipeline, flowing together thereafter for no less than one hour along pipe of 1.6 mm internal diameter before reaching the sample, which ensured the resulting brine-CO_2 fluid was in equilibrium. In all the tests, this experimental procedure was repeated six times, varying 20% stepwise the fractional brine:CO_2 flow up to 100% CO_2, the final drainage stage. In two of the tests, an additional forced imbibition stage was simulated by flowing back 100% brine into the sample. Between two consecutive unload/loading sequences, the existing pore fluid was replaced by the new solution, which was forced to flow through the sample at the initial P_p of the sequence for no less than 4 PVs.

Electrical resistivity into degree of saturation

Archie's law (Archie, 1942) relates the degree of brine saturation (S_w) to the bulk electrical resistivity (ER_b) of a rock through the connectivity of the porous medium and the electrical resistivity of the pore fluid (ER_w):

$$ER_b = \frac{ER_w}{\varphi^m S_w^n} \cdot a \qquad (1)$$

where φ is the porosity, and a, m and n are empirical parameters for a particular rock, comprising the proportionality constant, cementation factor and the saturation exponent, respectively.

In our experiments, the initial stage is 100% brine saturation so that the initial bulk electrical resistivity (ER_0) is reduced to:

$$ER_0 = \frac{ER_w}{\varphi^m} \cdot a \qquad (2)$$

Later on, the brine-CO_2 co-injection implies partial saturations of both phases as $S_w = 1 - S_{CO2}$, which can be can be obtained by dividing equation (1) by equation (2) (Nakatsuka et al., 2010):

$$S_w = \left(\frac{ER_0}{ER_b}\right)^{1/n} \qquad (3)$$

Absolute and relative permeability

The absolute permeability to brine was calculated during the 100% brine flow stage of the experiments, for every P_{eff} step, using the steady state flow method based on Darcy´s law:

$$k = \frac{\mu LQ}{\Delta PA} \qquad (4)$$

where k is permeability, Q the volumetric flow rate, ΔP the pressure drop across the sample, A the cross sectional area, L the length, and μ the dynamic viscosity of the fluid.

Assuming a homogenous contribution of the whole cross sectional area to the flow through the entire core, the above expression can be modified for our two-phase brine-CO_2 system in which the relative permeability of each phase ($k_{r,i}$) is a function of the partial contributions to the total saturation:

$$k_{r,i}(S_i) = \frac{\mu_i L Q_i}{\Delta P A k_{abs}}, \quad (5)$$

where subscript *i* refers to each phase.

With the calculated relative permeabilities, we adjust the curves for each phase using the Brooks-Corey model (Brooks & Corey, 1964) for a brine-CO_2 two phase system ($k_{r,w}$ and $k_{r,CO2}$):

$$k_{r,w} = \left(S_w^*\right)^{N_w} \quad (6)$$

$$k_{r,CO_2} = k_{r,CO_2}\left(S_{wi}\right)\left(1 - S_w^*\right)^2\left(1 - \left(S_w^*\right)^{N_{CO_2}}\right) \quad (7)$$

$$S_w^* = \frac{S_w - S_{wr}}{1 - S_{wr}} \quad (8)$$

where N_w and N_{CO2} are the Corey fitting-components for brine and CO_2.

In our tests, the irreducible water saturation (S_{wr}) is also a fitting parameter.

Strains

Sample deformation was measured by 350 Ω m 90° bi-axial strain gauges. Our first approach was to epoxy-glue the gauges onto the side-wall of the rubber sleeve, within the triaxial vessel, and to calibrate the signal using an aluminium sample of well-known deformation properties and the information from the axial piston displacement. However, sleeve deformation masked the radial deformation of the sample, so we modified the design of our triaxial vessel to allow extracting the wires of strain gauges epoxy-glued directly onto the side-wall of the sample.

As a result, after the first test (Falcon-Suarez et al., 2016) axial (ε_{ax}) and radial (ε_r) strains were measured continuously during the whole test, allowing the monitoring of the volumetric deformation (ε_v) of the sample (i.e. relative changes of porosity) according to the following expression:

$$\varepsilon_v = \varepsilon_a + 2\varepsilon_r \quad (9)$$

4.2 RESULTS (TASKS 3.3 AND 3.4)

4.2.1 Synthetic sandstones

Figure 4.3 shows the results of the first test conducted on synthetic sandstone as presented in Falcon-Suarez et al. (2016). In this contribution, we presented our novel experimental approach for understanding the geophysical and hydrodynamic responses of reservoir sandstones under CO_2 injection. It was our first set of experimental data using the new setup for a CO_2/brine flooding test through synthetic sandstone, simulating a shallow, low permeability CO_2 storage reservoir. We measured simultaneously ultrasonic P- and S-wave velocities and attenuations, electrical resistivity (including tomography), axial strain and relative permeability for variable brine:CO_2 flow rates and differential stress conditions. Our results showed that it is possible to distinguish between geomechanical and pore-fluid effects on the measured elastic wave and electrical properties.

Similar data were obtained during the tests performed on synthetic samples 2 and 3, and the analysis and interpretation of results will be presented in coming contributions. For synthetic sample 2, the first test was repeated to study the effects of the injection on an anomalously high porosity medium. For synthetic sample 3, the experiment is particularly interesting because the porosity of the sample and the experimental conditions are similar to those estimated for Sleipner. Furthermore, we analyse the significance of geomechanical variations triggered by the injection of CO_2 in our rock sample during a brine-CO_2 flow-through test with respect to those associated to the natural recharge of the aquifer after ceasing the injection activities. The data suggest very little damage due to CO_2-aquifer interaction and potential brine-induced effects during the natural recharge of the aquifer after the cease of CCS activities (Falcon-Suarez et al. 2018).

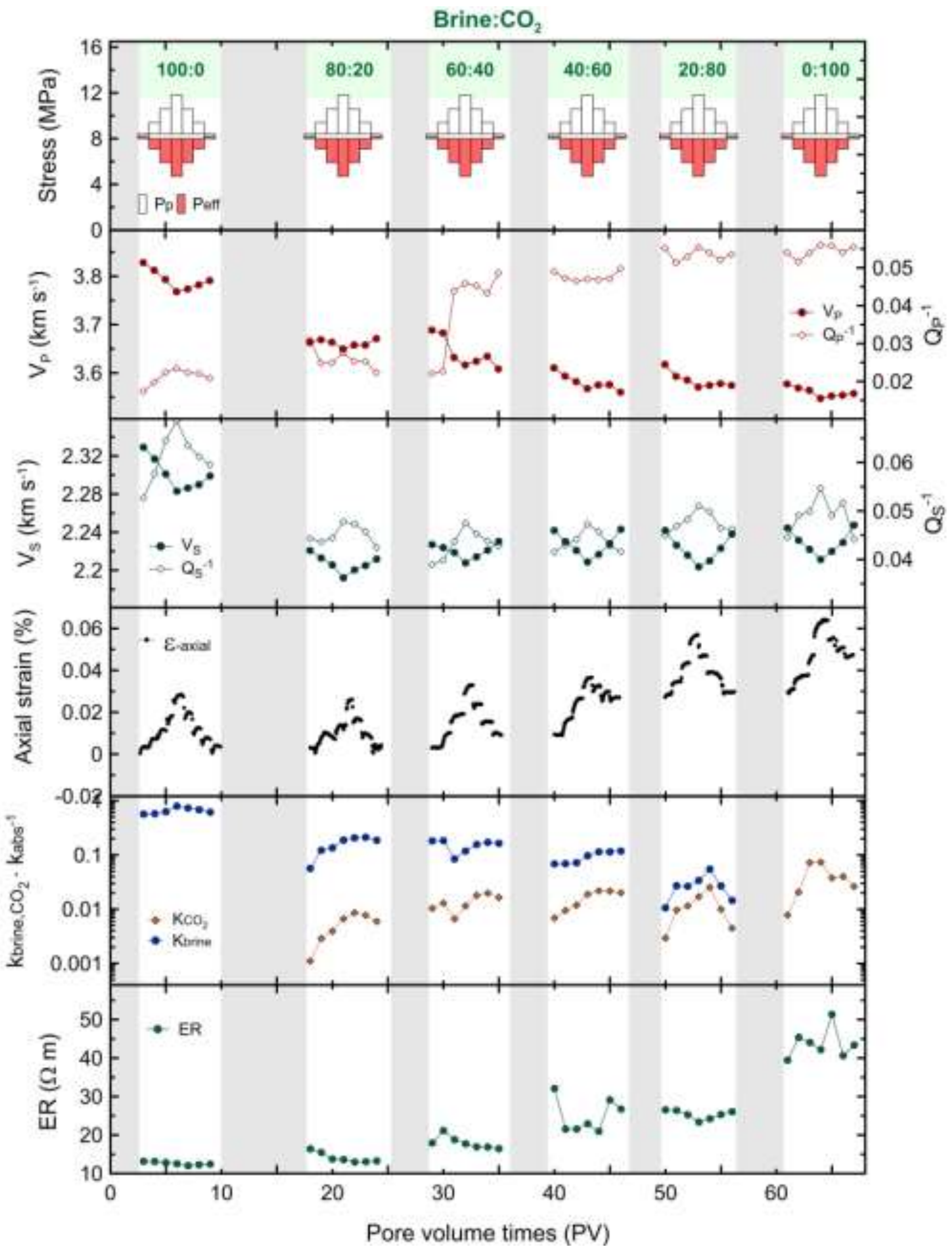

Figure 4.3 Brine-CO_2 flow-through test on Synthetic-1, 26% porosity synthetic sandstone (Falcon-Suarez et al., 2016). See text for units and properties measured.

4.2.2 Utsira Sand samples

The first sample, made from trimming fragments of loose sand, was subjected to the first unloading/loading 100% brine flow-through sequence applied on the rest of the tests. The results were presented in Falcon-Suarez et al. (2015). However, a number of issues arose when the brine-CO_2 co-injection stage started and the results are therefore limited to brine flow (Figure 4.4).

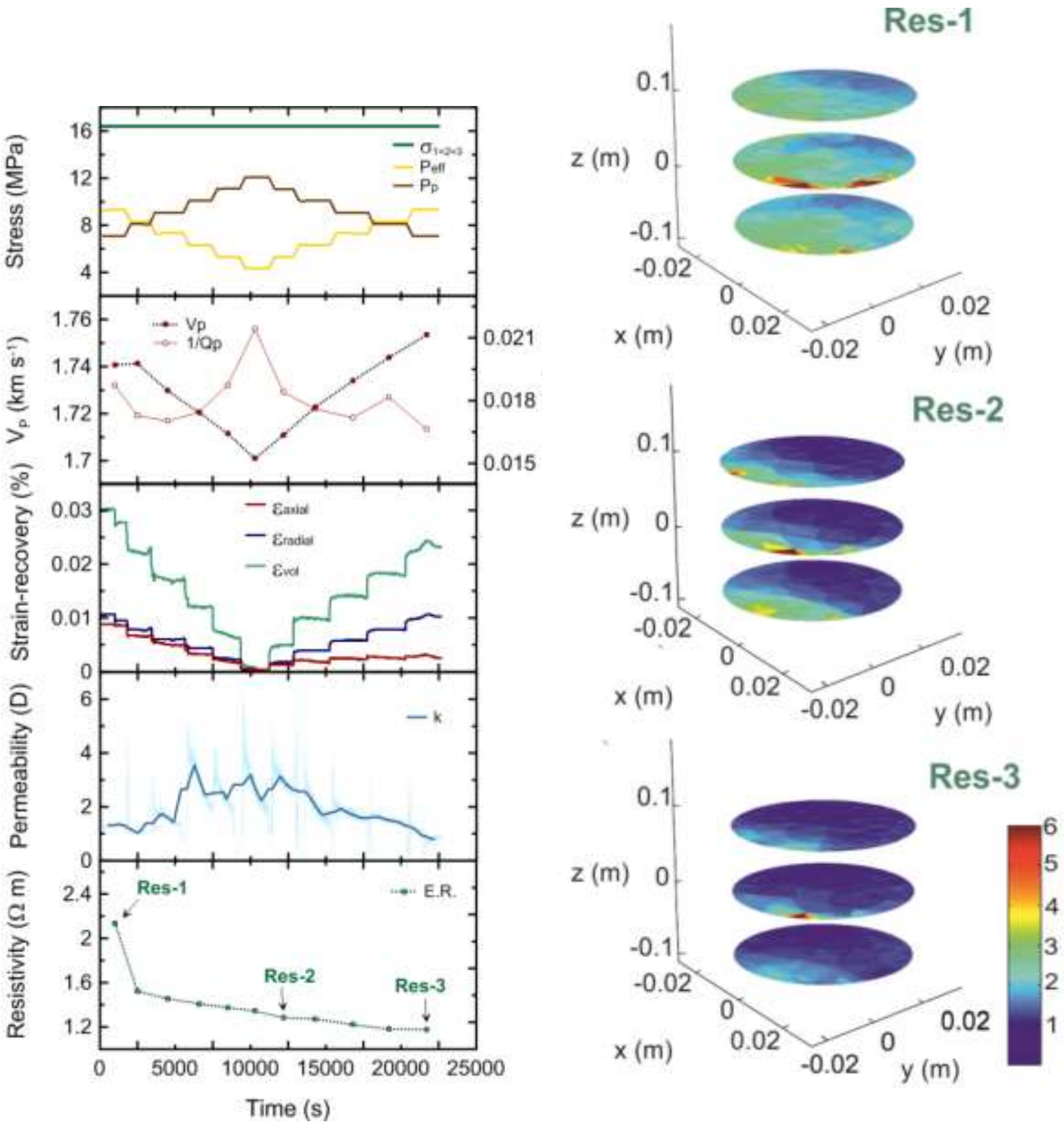

Figure 4.4. Geophysical monitoring and hydro-mechanical evolution of (loose) Utsira Sand during the initial brine flooding test, and three steps of 3D-ERT (Falcon-Suarez et al., 2015).

Our second experiment was carried out using an intact core sample from the Utsira Sand. In this case, the sample was particularly prepared for allowing brine-CO_2 co-injection while measuring deformation and geophysical signatures. However, such a careful sample preparation impeded relative permeability determinations. Furthermore, in this case, the ultrasonic wave velocities and attenuations were limited to P-waves. Analysis and interpretation of results will be presented in upcoming contributions

4.3 CONCLUSIONS

We have contributed new laboratory experimental capability and methods for realistic simulation of CO_2 reservoir injection, geomechanical and geophysical monitoring in reservoir rock samples. Moreover, we have produced the first comprehensive datasets of sand/sandstone responses to CO_2 injection that are worthy of further analysis and useful for generic geomechanical/seismic model development.

The new NOC experimental capacity has opened up new opportunities for further experimental runs aimed at reproducing the response of specific reservoir types. These could be addressed either by obtaining actual core samples, or by further development of our synthetic rock manufacturing methods. One issue is the wealth of data produced by the experimental runs to date. We have only just started to analyse these data in any great detail, and are now feeding the results across to Work Packages 1 and 2 and to follow-on modelling studies. In separate projects, we are developing acoustic frequency range measurements on sands and overburden sediments/rocks during CO_2/brine injection for informing well logging and high resolution seismic remote sensing for sub-sea CO_2 storage monitoring.

5 Work Package 4: Public Perceptions

This Work package is framed around the social licence to operate (SLO) concept, which goes beyond 'acceptance of' or 'support for' a particular technology, recognising complexities in the relationships between communities and technologies (Batel et al., 2013). Key to this is an understanding of the wider social context in which a technology is to be deployed (Ashworth et al., 2012; Bradbury et al., 2009). SLO can be broadly defined as informal permission given by the local community and broader society to industry to pursue technical work (Thomson & Boutilier 2011 quoted in (Dowd & James, 2014)). The SLO concept is yet to become widely established within the context of CCS; moreover, research in Australia suggests that, given the limited experience and awareness of CCS technology amongst the wider public, any SLO for CCS remains highly provisional and, hence, fragile (Dowd & James, 2014). In this context we argue that it is important to explore what factors might impact an emerging SLO, drawing lessons where possible from analogous technologies, in this case hydraulic fracturing for shale gas. We approach this research by considering what takes the SLO beyond a simple state of "public acceptance" of a technology.

The specific research objectives which we address are:

1. To explore the wider social context for CO_2 storage in the UK;
2. To assess potential social responses to subsurface injection and site monitoring approaches;
3. To identify significant factors in establishing a social licence in the context of CCS and in particular offshore CO_2 storage in the UK.

We address these objectives using a mixed method approach incorporating a media survey, stakeholder interviews, social network analysis (of both online and offline networks) and focus groups undertaken in two case study locations in northern England. The case studies were selected to map social responses in two areas which had respectively: i) recently experienced high profile planning applications for a new energy development (hydraulic fracturing 'fracking' for shale gas exploration), but no CCS proposals[1] (Lancashire) and ii) CCS development activity which was seeking to establish an industrial CCS cluster (supported by an industrial consortium with some initial government funding[2]), but where fracking was unlikely to be pursued in the near term (Teesside). Hydraulic fracturing for shale gas exploration was chosen as a potentially analogous technology from which lessons could be learnt for CO_2 storage because of comparable operational processes within the subsurface (drilling, injection and monitoring) and a link to fossil energy use (Herzog and Wolff, 2014) and the potential for common issues to be raised in this context, notably in the light of induced seismic events in the first case study area in 2011 (DECC, 2014; Pater & Baisch, 2011). We refer to the fracking analogue in order to explore what influence, if any, recent controversies might have on social responses to CO_2 storage and whether anything can be learnt that might inform the implementation of CO_2 storage. The research in WP4 is organised across two tasks: WP4.1 which provides the initial social scoping of the two analogue technologies (CCS and fracking) and WP4.2 which presents two focus groups in the case study

[1] http://www.lancashire.gov.uk/council/planning/major-planning-applications/shale-gas-developments-in-lancashire.aspx [accessed 1st july 2016]
http://www.teessidecollective.co.uk/ [accessed 1 August 2016]
[2] http://www.teessidecollective.co.uk/

regions exploring in further detail some of the specific issues identified during WP4.1, as they relate to CCS in general and CO_2 storage monitoring in particular.

5.1 CASE-STUDY ANALYSIS OF ANALOGUES (TASK 4.1)

5.1.1 Media survey

Print media data was collected for four case studies (Blackpool, Lancashire, Peterhead and Teesside) using the Factiva online database (Table 5.1). The data has been coded using Atlas.ti coding software, identifying key actors quoted in the articles and common issues shaping the various dialogues. This analysis was used to target recruitment for interviews and provide background information enabling us to scope the social context of the two study regions. An overview of the articles included in the analysis is shown in Figure 5.1.

Table 5.1. Media searches on fracking and CCS events

Location	Event	Dates	No articles	Search terms
Shale Gas Blackpool	Seismic events relating to Preese Hall well	01/01/2011-31/12/2011	247	Site name + Shale gas + fracking + Blackpool
Shale Gas Lancashire	Public Inquiry – into planning applications for shale gas exploration at 2 sites: Roseacre Wood and Preston New Road, Fylde	01/12/2014 - 16/03/2015	200	Site name + Shale gas + fracking + Lancashire
CCS Peterhead	Peterhead awarded FEED study funding	01/01/2014 - 16/03/2015	83	Peterhead + Carbon capture and storage +_ CCS
CCS Teesside	Tees Valley Collective launched	01/01/2013 - 16/03/2015	110	Teesside + carbon capture and storage + CCS

Themes that emerged in the reporting of shale gas included: environmental factors; water quality; earthquakes and induced seismicity; typically, hydraulic fracturing for shale gas was described as a “dirty” technology. Reporting of positive aspects of shale gas exploration related to the possibility of delivering cheaper energy, energy security and jobs. In contrast, CCS was reported in a more positive light, key aspects reported included: jobs; CO_2 reduction and climate change; CCS was described as a “clean” technology. The key negative feature related to the cost of CCS technology.

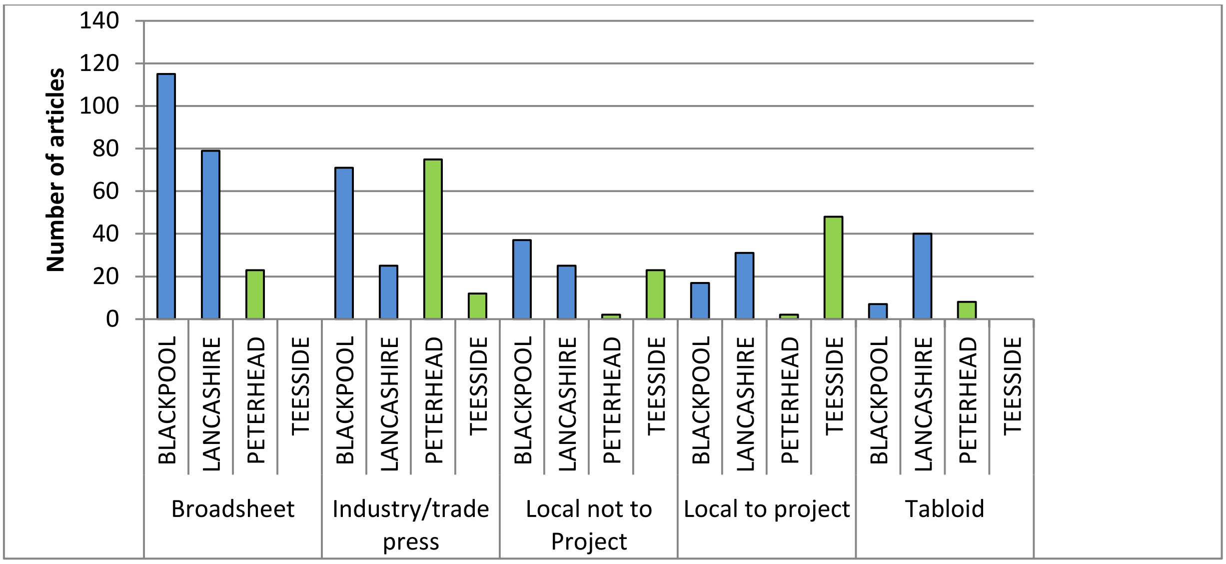

Figure 5.1. Print media reporting of shale gas(blue) and CCS (green).

5.1.2 Stakeholder interviews

Twelve semi-structured interviews with stakeholders were conducted with representatives of local, national and European Government, NGOs, industry, and academia from the two case study regions (see Table 5.2 for summary of interview representatives). Interviewees were asked similar questions about both CCS and fracking, covering awareness of the technology and its impact on the local areas, arguments in favour and against the technology, siting decisions, information sources and sharing, influence of campaigning groups and community engagement. Interviews took place between July and September 2015 and lasted between 40 and 90 minutes. Interviews were conducted with seven stakeholders located within the Teesside area, three in Lancashire and two from national organisations providing services to local authorities.

Table 5.2. Stakeholders interviewed in case study regions

	Teesside	Lancashire	National
Local Government (elected representative)	1	1	
National Government (MP)	1		
European Government (MEP)	1		
Industry	2		
NGO	2		
Quasi-NGO (local Government umbrella groups)			2
Academic		2	

The timing of recruitment in the Lancashire area coincided with the decision on an application from Cuadrilla to Lancashire County Council for licences to commence exploratory drilling for shale gas in the nearby town of Preston. This application was extremely controversial locally and although permission was denied due to noise and traffic concerns, the prospect of an appeal remained[3]. Following up with those who had declined to be interviewed revealed a deep reluctance to discuss the technology, although there were no formal embargoes on discussing the subject from any of the organisations contacted, and despite the independence of the research team and its primary focus on CCS technology. Although we returned to recruitment in the Lancashire area following completion of the Teesside interviews, widening the geographical scope within the county from the initial focus in the Blackpool area, difficulties in securing interviews remained, and is reflected in the small number of stakeholder interviews in this area. Three interviews were completed in relation to the Lancashire case study: a senior elected local government representative and two academics, both of whom have an in depth knowledge of the case study area and its recent history of shale gas development, one an energy research specialist, the other a legal and human rights expert.

CCS was viewed very positively by all of the stakeholders interviewed in the Teesside region, and potential economic benefits were identified as being particularly significant for the area in terms of maintaining the local chemical and process industry in the region, attracting investment and the associated local employment opportunities. Interviewees were asked about potential negative as well as the positive impacts of the technology – while some struggled to identify negatives, technology costs and who would bear them (NGO), possible public scepticism (MP) and concerns about possible leakage of stored CO_2 (MEP) were raised.

Interviews with the Lancashire and national stakeholders were more focused on fracking with more limited discussion of CCS, due to a self-declared greater awareness and understanding of the former in relation to the region. Tensions between political priorities, particularly at a national level, and the regulatory process were identified by several stakeholders with respect to fracking. However, the scepticism associated with fracking was not voiced in relation to CCS by any of the interviewees in this region; CCS was also viewed in a broadly positive light by these stakeholders, the only concern, raised by an academic, related to any possible local impacts or leakage risks. Stakeholders in both Lancashire and Teesside identified shortcomings in the current planning process, which was considered to lack transparency and tended to be combative, with poor dissemination as a factor that could erode trust in the governance of proposed technology projects. Both the regional and national stakeholders expressed a keen awareness of the long term impact on perceptions of a technology, such as fracking, once it becomes tarnished by high profile controversy. CCS was seen by respondents in both regions to be less controversial than fracking.

The interviews served two roles within the study: i) they provided further information on the social context and understanding around the development of the two technologies in the two case study regions, informing the focus group topic guides in Task 4.2; and ii) combined with analysis of twitter data, they enabled us to conduct a social network analysis (SNA) of stakeholder and community knowledge around CCS and shale gas for the Teesside area. The small sample of interviews in the Lancashire case study made the data unsuitable for completing an SNA in this region. The social network analysis (SNA) allows for the channels of CCS information to be

[3] Lancashire County Council, Shale gas developments in Lancashire, http://www.lancashire.gov.uk/council/planning/major-planning-applications/shale-gas-developments-in-lancashire.aspx; 2016

mapped as well as provide a deeper understanding of participants' understanding of CCS and in particular CO_2 storage.

5.1.3 Social Network Analysis

Empirical data collected from the interviews for the SNA required each participant to name their sources of information about CCS and where they shared CCS information. In addition, online data was procured from Twitter using the Tweepy API for a discrete period immediately after the interviews were completed (Oct – Nov 2015) using search terms #CCS and variants (e.g. #Ccs, #ccs). A database was created in neo4j and mondo.db open software, and cleaned to ensure that it only contained tweets that were #CCS linked to text that included "carbon" or "capture" or CO_2".

The flow of CCS information between the offline network of stakeholders, holding both formal and informal roles, was examined to understand where it was sourced from and where it was shared. Responses from the interviews were used to create affiliation and attribute matrices for all the entities identified through the interviews (i.e. individuals, websites, media etc) that included name, gender, location, and affiliation of both the ego (a specific person being interviewed) and alters (the other entities within the network). An ego's "Get" network was drawn from the ties between the interviewee and their source of information (Figure 5.2). A "Share" network was built up from the ties between an interviewee and the information recipient (Figure 5.3). The 'ego' networks for both "Get" and "Share" were manually stacked to identify any overlap between individuals' source and dissemination networks.

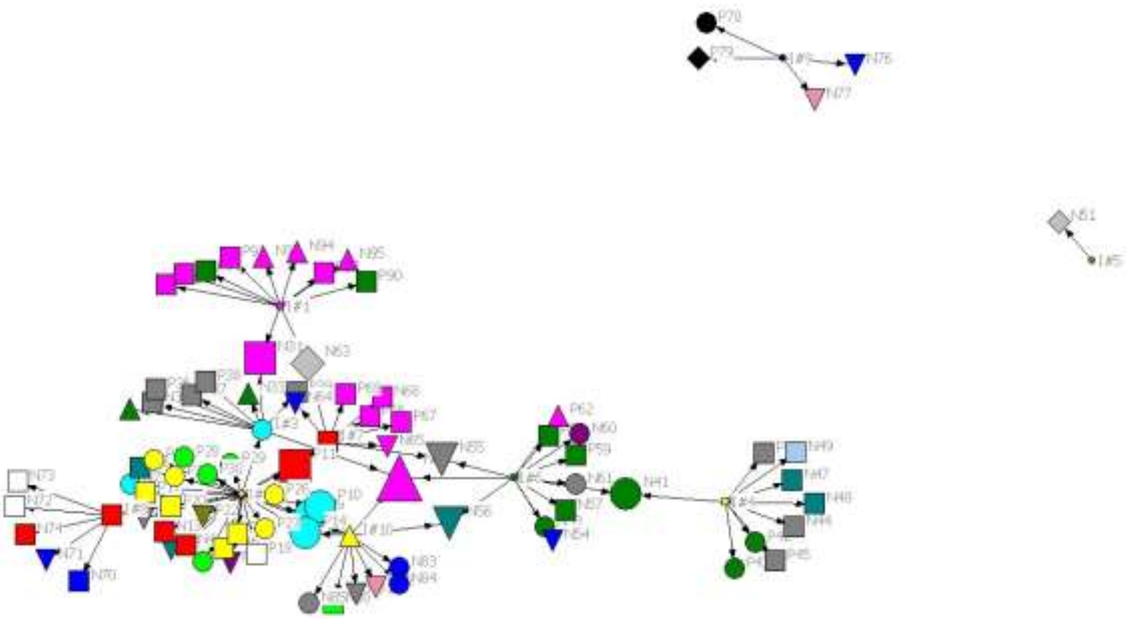

Figure 5.2. "Get" network for CCS, see Table 5.3 for explanation of symbols and colours.

Both the offline ("Get" and "Share" networks) and online (twitter #CCS) were visualized. The offline networks were visualised through SNA visualization tool NETDRAW and the output sociograms are related directly to the UCInet analysis with the layout of the figures being constrained by Euclidian distance; as such, the central nodes are located in the centre of the visualisation (Borgatti et al., 2002). The online data was visualised using ORA (Carley et al., 2012).

Analysis of the “Get” network for CCS (Figure 5.2.) highlights a number of important actors within this network. #2, a locally elected representative (yellow circle in the lower left quadrant) has many key connections, including a local council umbrella group (#7) and an academic (#3). Both academic information (magenta) and government information (taupe) are closely linked. Within the “Share” network, there is a dense cluster of local nodes (yellow), with far more online sources shared (diamonds).

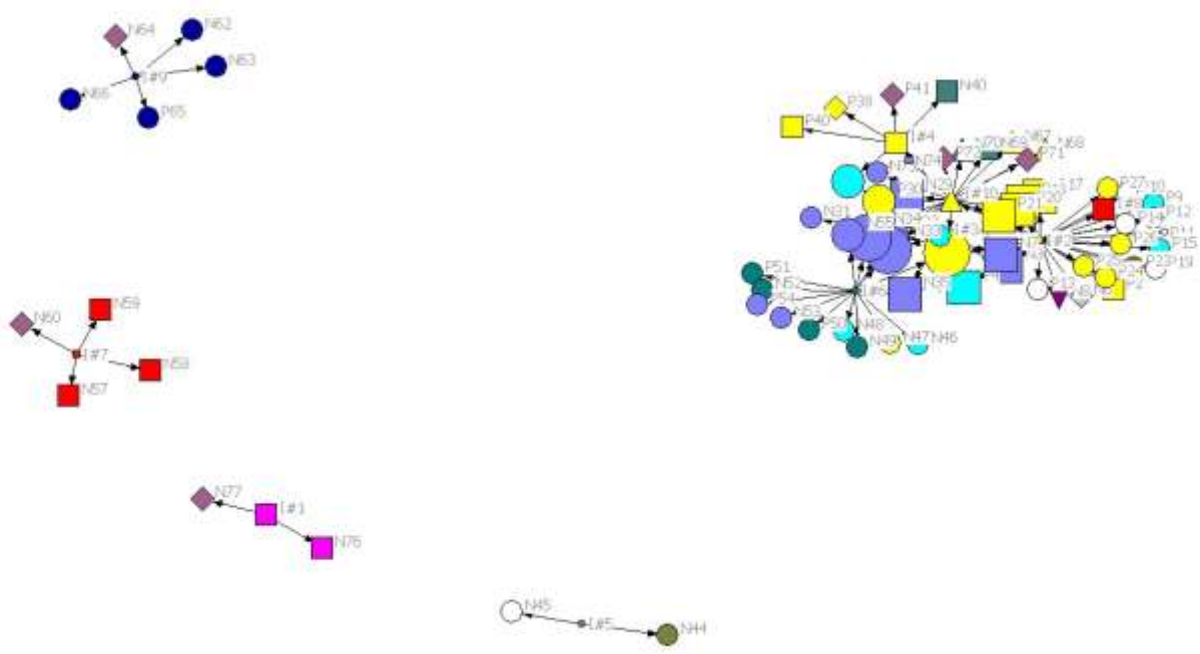

Figure 5.3. “Share” network for CCS, see Table 5.3 for explanation of symbols and colours

As illustrated in Table 5.3, the “Share” network is smaller than the “Get” network, with the 10 interviewees reporting 95 sources from which they sought information about CCS, and they shared CCS information with 77 others. Participants tended to get their information from national sources and share through local sources. Both academic and local council umbrella groups were at the centre of the “Get” network, while information was more widely distributed through media outlets.

Table 5.3. Visualization key and network summary

Location or scale of node	Symbol	“Get” nwork	“Share” nwork	Category of node	Colour
Local	○	27	42	Local government umbrella group	■ (red)
National	□	43	22	Elected Local Government	■ (yellow)
International	△	8	4	Government dissemination	■ (taupe)
Online	◇	3	8	Media	■ (light blue)
				Academic	■ (magenta)
Various	▽	14	1	Partnership organisation	■ (cyan)
		N=95	**N=77**		

For the online element of the SNA, a database of 68,256 tweets was initially created in neo4j and mondo.db open software. #CCS was found to be non-unique to CCS, for example referring to a music festival in Caracas and a school, so once the tweets had been cleaned to only include #CCS with relation to carbon capture and storage a total of 930 original distinct tweets were collected during the study period. 386 of these were retweeted at least once, resulting in a total retweet count of 1363. The most influential tweet during the selected period of October - November 2015 was from a media source, announcing the cancellation of the £1bn carbon capture and storage competition in the UK. This information source was retweeted 118 times. The second most retweeted tweet was from the BBC. In addition to media outlets, politicians, industry representatives and research institutions were in the top retweeted tweets. From the 386 retweeted tweets, only 12 were retweeted more than 10 times (3.08% of n386). In the context of big data, utilizing the Twitter API which in itself has limitations and biases (Morstatter et al., 2013), this dataset demonstrates that the #CCS network is currently small.

5.2 CITIZEN FOCUS GROUPS (TASK 4.2)

Two focus groups were held with members of the lay public in Blackpool and Teesside on 7th and 21st November 2015, respectively. A professional company was employed to recruit focus group participants resident in the specified areas (maximum of ten people per group), screening was performed to ensure no participants were: a) employed in the shale gas or CCS industry; b) a member of a campaigning group relating to shale gas or CCS; or c) had previously participated in Focus Groups conducted by the research team; each participant received a £40 high street voucher. In each group, the focus was on CCS, and specifically storage and monitoring; this framing was consistent with the broader DiSSECS project objectives and sensitive both to the challenges encountered during the stakeholder interviews in relation to shale gas and potential public reactions. Each group was structured according to a common topic guide, which was designed to explore some of the themes that emerged during the stakeholder interviews and the extent to which the views of the public participants were consistent with those of the professional stakeholders. The project PI, Andy Chadwick, presented information about CCS in general, and storage and monitoring in particular to the groups; Andy remained available for questions following the two short presentations but left the room for the subsequent discussions. Each group lasted for 2 hours and was recorded, transcribed, and imported into Atlas.ti for thematic coding, by a minimum of two individual coders in order to ensure accuracy and lessen bias.

Each group was structured around topics covering the following themes:

1. CCS: what it is, why we might need it
2. CO_2 storage: where it will be stored, how it will be monitored
3. Exploring energy in the local context

The Lancashire Focus Group discussions were strongly influenced by previous, unanimously negative, experiences of fracking, with participants seeking reassurance that CCS was a different technology. This group's initial responses to CCS focused on the possible impacts and risk associated with storage. In Teesside, the community was facing significant job losses due to the announcement of the closure of the steel works the preceding week and participants were focused on the benefits the technology might bring to the local economy. Further, Teesside participants echoed a sense of pride in the region's industrial legacy that was also expressed by stakeholders, typically viewing CCS as an incremental technology applied to existing industrial activities. Concerns regarding the subsurface also differed depending on whether the storage and monitoring of CO_2 was implemented onshore or offshore; in both groups a clear preference for offshore storage in the UK context was expressed. Both groups spontaneously raised the potential impact of natural earthquakes on the integrity of storage reservoirs, no-one raised concerns about the potential for CO_2 storage to induce seismicity.

A critical factor in how conditions for achieving a social licence to operate might change over time is how experiences with other technologies or projects influence perceptions. This was particularly evident in the Lancashire group, where recent applications for licences to explore for shale gas had been highly controversial. When fracking was raised by this group it was in the context of how the council handled and responded to the planning applications but participants also initially evaluated potential impacts of CO_2 storage with reference to experiences with fracking; both groups sought reassurance that CCS was different to fracking. Discussion in Teesside revealed a delicate balance whereby, despite living with and depending on large industrial installations, the underlying awareness of associated risks was ever present, even though there had been no major incidents in the area. Both focus groups articulated a greater level of trust in industry than local government to manage CO_2 storage, typically expressing confidence in their technical competence, supporting the views expressed by the professional stakeholders. However, the strong trust in industry expressed in the Teesside group contrasted with a more mixed view evidenced in the Lancashire group.

Both Focus Groups discussed the interplay between communities, government and industry. In Lancashire, referring to the recent shale gas controversy, participants felt that the council had not listened to communities initially, perceiving a lack of response to community opposition until protest reached a certain point at which it could no longer be ignored. Perceptions of “who pays for” and “who benefits from” these technologies was another recurring theme in discussions, with costs and benefits expressed in both financial terms as well as in terms of risks and wider impacts, and whether projects may lead to longer term investment in a region’s industrial economy. Participants in the Teesside group clearly recognised the trade-offs involved with hosting the heavy industries in their local area. Nevertheless, there remains a delicate balance between achieving a situation in which residents identify the potential for a project to provide a variety of mutual benefits to communities and industry and one which prompts scepticism towards compensation schemes and erode the social licence (as expressed specifically in the context of fracking in Lancashire). Furthermore, in Lancashire, there was a sentiment that the industry and government were not interested in the concerns of the local community and their views of the technology, rather that they focused on financial profit, with a perceived disconnection from environmental issues in particular. Discursive responses were further supported by a poll of participants’ views on the extent to which they agreed / disagreed with a series of statements relating to CCS (Figures 5.4 to 5.8).

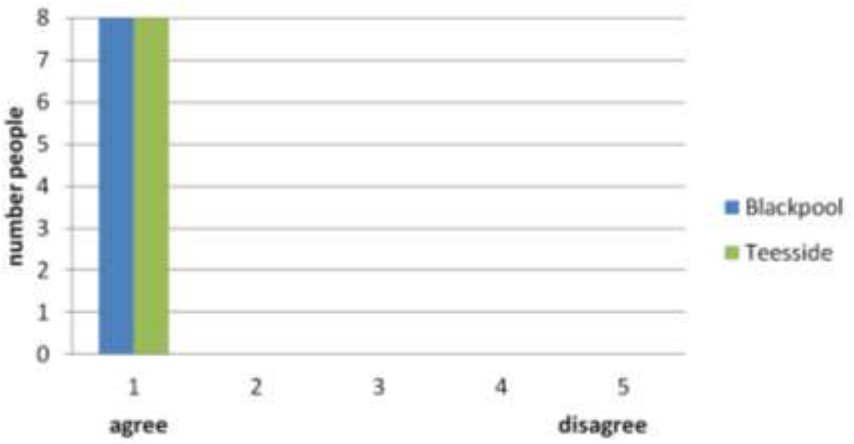

Figure 5.4. Focus groups poll result: Offshore storage of CO_2 below the seabed is a national not a local issue.

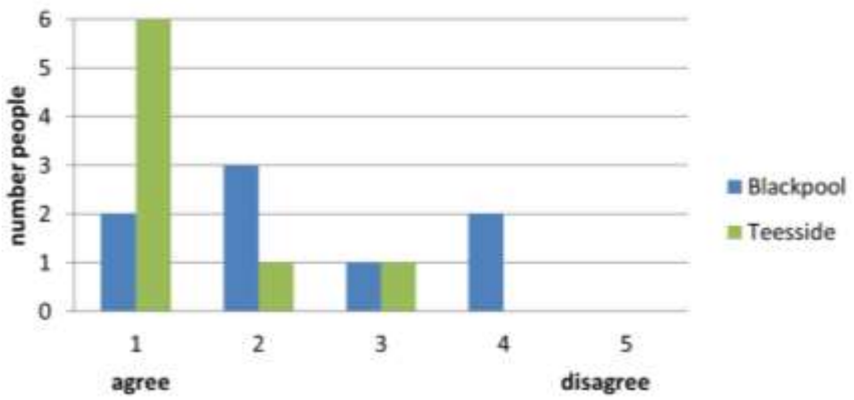

Figure 5.5. Focus group poll results: CCS is a good way to address climate change

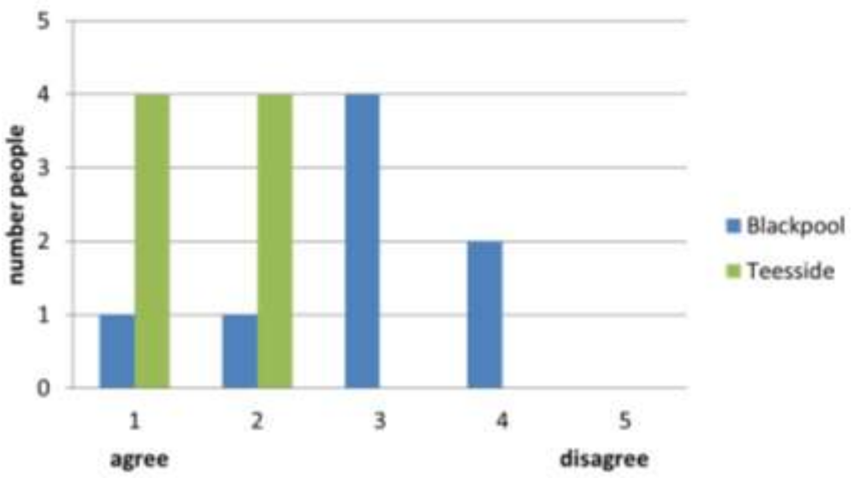

Figure 5.6. Focus group poll results: I trust industry to manage CO_2 storage

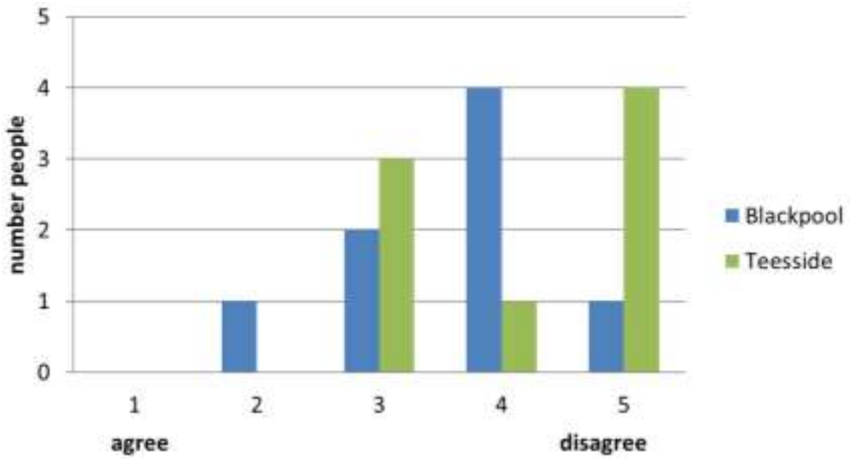

Figure 5.7. Focus group poll results: Regarding CO_2 storage, I trust Local Government to act in the interest of communities

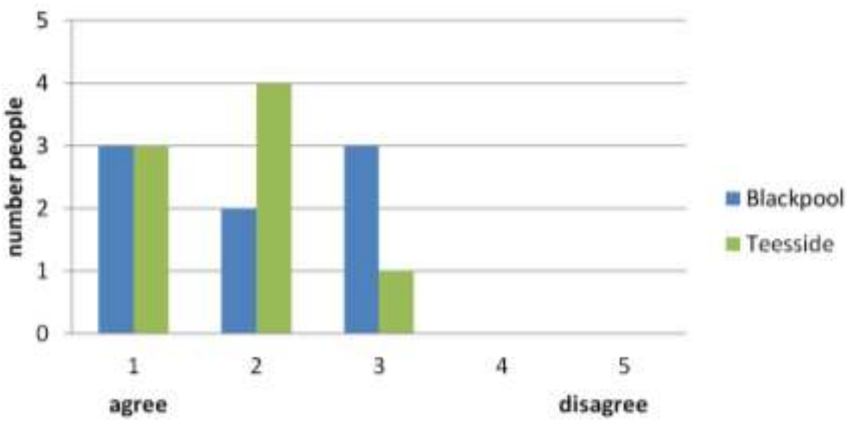

Figure 5.8. Focus group poll results: Scientists know what happens to CO_2 once it is stored.

5.3 WP4 CONCLUSIONS

5.3.1 Social Network Analysis

This work offers insights into the relationships that have emerged between CCS actors and the flows of information within the offline CCS network in Teesside. These findings are useful for actors both looking to enhance CCS focused communication and dissemination within this region, but also for them to consider how this social network could be strengthened in order to better support their fight to deploy CCS within the region and more widely.

Both the offline and online information networks from this case study demonstrated that CCS retains a niche audience. Findings from the offline case study highlighted that participants tended to get their information from national sources and share through local sources. Both academic and local council umbrella groups were at the centre of the "Get" network active in the offline network, while information was more widely distributed through media outlets. Elected representatives, local government umbrella groups and academics all provided a positive flow of information. The offline network was reasonably connected; however, the networks did not reach more broadly into the community, and remained more bound within industry, academia and local government. For implementation of a new technology such as CCS, where policy support and incentives are required from national government to support the work of local and regional government, a social network that is concentrated at the local and regional scale may not reach the seat of power. Although information and social capital exists within the network, is it being used effectively to reach those that matter and is the social capital that may be transferred within this network and beyond optimised? This niche knowledge network could result in a lack of policy pressure and lobbying power required to build a CCS coalition to push forward the technology.

In the online networks, it was national media outlets that held greater sway, however the social media (i.e. Twitter) analysis highlighted that CCS has yet to reach the general public, as even policy announcements and issues with local impacts, affecting jobs for example, don't "stick" in the Twitter imagination. Awareness of CCS amongst the general public remains low, and social media has yet to emerge as a vehicle for raising that awareness. Whilst public awareness does not necessarily translate into successful deployment and implementation, familiarity can serve to inform the context within which broader discussions and debate can take place.

Bringing together both the data on offline and online knowledge networks, this research suggests a need for those looking to deploy and further CCS to reach outside their existing networks into wider communities, and in the case of social media, consider how CCS can be made unique.

5.3.2 Qualitative analysis (Media, interviews and Focus Groups)

This work package presents a body of empirical research exploring the social context in which a social licence to operate CCS might emerge, drawing on experience in the UK related to exploratory hydraulic fracturing for shale gas. Fracking technology has received a significant level of press attention in the UK in recent years, having been linked to induced seismicity in the north west of England, and has been associated with a series of high profile public protests at proposed sites; a controversial ongoing planning application in the Lancashire region at the time of the research has influenced stakeholder and lay responses in the local area. In contrast, the smaller number of media articles in the print press relating to CCS, dominated by articles in local or specialist publications, supports previous research findings that CCS has not yet captured the wider public imagination (European Commission, 2011). While the arguments for and against shale gas technologies have been widely rehearsed in the press (see for example Jaspal and Nerlich, 2013), the representation of CCS in the media is far from established – in terms of both volume and content.

Previous research has identified the importance of economic arguments framed in terms of investment, employment and leadership opportunities and the possible benefits that CCS might bring alongside reductions in greenhouse gas emissions (see for example (Boyd & Paveglio, 2014; Nerlich & Jaspal, 2013). The importance of the relationship between the press and key stakeholders in influencing opinions on the technology within civil society has also been identified (Buhr & Hansson, 2011; Nerlich & Jaspal, 2013). Results from empirical research presented here reinforce the importance of economic arguments for establishing CCS in the UK, from the perspectives of both stakeholders and local communities. This is particularly evident in the context of the Teesside study region where the local economy is dominated by a cluster of process industries which provide significant levels of employment in an economically deprived area. Furthermore, the establishment of the Teesside Collective is an important factor in enabling the region to benefit from, and establish trust with, the industry cluster; it plays a central role in developing the cluster, provides a point of contact for regional, national and international stakeholders and is active in providing press communications about it.

Conditions for establishing an SLO go beyond merely establishing the economic benefits of the technology; trust and confidence in the ability and motivations of public and private sector institutions to implement and manage the technology are critical. In the context of the fracking debate, while identifying the economic and employment benefits as arguments in favour of shale gas exploration, local residents expressed scepticism about the potential for shale gas to deliver these benefits. Furthermore, residents in Teesside are acutely aware of the trade-off that local communities make in accepting the physical risks that may come with the benefits of living alongside particular industries. However, a high level of confidence in the industry's ability to manage CCS in Teesside was expressed by both stakeholders and lay participants alike, and a long history of pioneering industry in the Teesside region was repeatedly cited as grounds for trust in the companies involved. In contrast, in Lancashire, where companies involved in bringing fracking to the area have no such established reputation, the industry was viewed in the community with scepticism; focus group participants tended to express distrust in companies' ability to collect reliable monitoring data (to 'self-monitor') and deemed companies to be driven by short term profit. This distrust in industry was compounded by perceived dissonance between different scales of governance; on top of perceived differences in political and policy priorities at local and national levels, shortcomings in the planning process were also seen by some stakeholders to contribute to an erosion of trust in planning and regulatory processes. Thus, perceptions of trust in the competence and motivations of key institutions are critical and dependent on past experiences with different technologies and the track record of those institutions in managing technological and industrial processes.

Both the regional and national stakeholders expressed a keen awareness of the long term impact on perceptions of a technology, such as fracking, that has become tarnished by high profile controversy. Past experience of previous technologies may influence participants' opinions of other new technology; once trust is breached and SLO shifts, it can be difficult to rebuild, with the effects potentially spilling over to influence responses in the context of a different technology. The foundation for establishing a social licence for CCS appears to be in place but consolidating and maintaining support for CCS depends on the evolving social, industrial and political landscape.

6 Project outputs

The following outputs from DiSECCS have been recorded and entered on to the ResearchFish database.

6.1 PUBLISHED PAPERS / REPORTS/PROCEEDINGS

BGS. 2017a. DiSECCS – Final Summary Report. Work Packages 1 -4. British Geological Survey Report OR/17/002. 57pp.

BGS. 2017b. DiSECCS – Work Package 5 Seismic Analysis Toolbox. British Geological Survey Report OR/17/013. 35pp.

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Birnie, C., Chambers, K., Angus, D. & Stork, A. 2016. Analysis and modelling of pre-injection noise recorded on a permanent surface array at the Aquistore carbon storage site, *Geophysical Journal International*, 206(2), 1246-1260.

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6.3 PUBLIC LECTURES / OUTREACH

Gough C., Cunningham R., Mander, S. & Chadwick A. 2015. Focus Group on CCS at Thornton-in-Cleveleys, 7 December 2015.

Gough C., Cunningham R., Mander S. & Chadwick A. 2015. Focus Group on CCS at Teesside, 21 December 2015.

Gough, C. 2015. Panel member in Sense About Science: Capturing carbon: sensible solution or dangerous detour? Live Q & A 22 October 2015
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http://www.fph.org.uk/uploads/PHT%20Spring%202016_PHT%20Spring%202016.pdf

6.4 INFLUENCE ON POLICY/PRACTICE/TRAINING

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Chadwick R.A. 2015. Cost-effective offshore monitoring for CCS. UKCCS RC CPD Training Course. Cranfield University, 20-21 April 2015.

Tyndall Centre Manchester (Gough, C., Mander S.) 2016. Submission to the Energy and Climate Change Committee inquiry into the UK fifth carbon budget. 4 February 2016.

UKCCS Research Centre (Chadwick R.A.) 2016. Submission to the Energy and Climate Change Committee inquiry into the UK fifth carbon budget. 4 February 2016.

6.5 OUTPUTS IN PREPARATION / IN PRESS

The following outputs are still in preparation or are in press and will be entered into ResearchFish in due course.

Amalokwu, K., Papageorgiou, G., Chapman, M & Best, A. I. Modelling ultrasonic laboratory measurements of the saturation dependence of elastic modulus: new insights and implications for wave propagation mechanisms. (Submitted to IJGGC).

Falcon-Suarez, I., Lichtschlag, A., Robert, K., North, L. & Best, A. I.. Brine-CO_2 flow-through test to coupled geophysical-geomechanical interpretation of CO_2 storage in shallow North Sea-like reservoirs. (To be submitted to IJGGC).

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