SHARP Storage Final Report

An Accelerating CCS Technologies Round 3 Project

Project No. 327342

Acknowledgements

Contents

Executive Summary

The geomechanical response to CO_2 injection is one of the key uncertainties in assessing containment risk for proposed storage sites. The SHARP project introduces a geomechanical readiness level (GRL) to help evaluate the need for geomechanical data collection and modelling within a project. Key developments for the project include to: develop basin-scale geomechanical models that incorporate tectonic and deglaciation effects, and use newly developed constitutive models of rock/sediment deformation (WP1); improve knowledge of the present-day stress field in the North Sea from integrated earthquake catalogues and a comprehensive database of earthquake focal mechanisms (WP2); quantify rock strain and identify failure attributes suitable for monitoring and risk assessment using experimental data (WP3); develop more intelligent methods for in situ monitoring of rock strain and failure, and fluid pressure and movement (WP4); quantify containment risk using geomechanical models and observations from the field and laboratory (WP5); communicate technology development on containment risk to industry and regulators (WP6).

- SHARP project results include regional and site-specific data, models from case studies, updated workflows and methodologies and recommendations:

- Updated North Sea bulletin with the most homogeneous representation of North Sea seismicity available to date.

- Updated borehole stress database with new supplements to the World Stress Map 2016 database and improving in-situ stress characterization from seismic analysis.

- Evaluation of regional stress drivers including ridge push, burial and exhumation, glaciation and stress decoupling due to weak layers using comprehensive analysis of regional stress data and novel correlation methods based on mineralogy.

- New site-specific rock mechanical data on samples from Northern Lights Eos well, Aramis site, Lisa Structure, Bunter sandstone analogue and field case in India.

- Stress estimates for CO_2 storage using seismic anisotropy and shear wave splitting.

- Method development and demonstration for uncertainty quantification, failure probability, probabilistic seismic hazard assessment and quantitative risk assessment applying new data.

- Demonstration of pre-cursors for failure in velocity data at laboratory scale.

- Outlining and discussing the potential for fibre optic monitoring for detection of seismicity and subsurface pressure changes and deformation.

- Stable seismic event analysis, localisation, estimates of stress orientations and discrimination of natural and induced seismicity requires better offshore seismic resolution with near-source observations.

Selected case studies in the North Sea and India have been matured during the project period: the Northern Lights CO_2 storage project in the Horda Platform area (N); emerging storage prospects in the Greater Bunter Sandstone area, which encompass the Endurance site (UK);

the Lisa structure (DK). The North Sea projects have benefited from transferring knowledge from pioneering and more mature work in the Horda Platform area. Furthermore, new geomechanical data has been collected and evaluated for well-characterised offshore depleted oil and gas fields, like Aramis (NL) and Nini (DK), accelerating their transformation into viable and safe CO_2 storage sites. All the sites in the North Sea have benefited from the regional studies and matured their geomechanical readiness level (GRL) during the SHARP project period, whereas India has started initial screening for identification and characterization of potential storage sites.

Project identification

Project title: Stress history and reservoir pressure for improved quantification of CO_2 storage containment risks (SHARP Storage)

Project ID no.: 327342

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Project website: https://www.sharp-storage-act.eu/

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Role and contributions of project partners

The SHARP project is brought forward by a high-level, multidisciplinary, trans-national consortium of 16 partners from 5 countries. All partners have dedicated focus on maturing CO_2 storage for their respective countries and contributed to transnational value by collaboration within WPs. The project has had knowledge transfer focusing on a regional understanding of storage conditions in the North Sea area and kick-start CO_2 injection and storage development as a valuable climate mitigation action for India. SHARP project research areas and partners contributing with relevant expertise and data are given in Table 1.

Table 1: SHARP research areas and partners contributing with relevant expertise and dataset.

SHARP research areas	Partner contributing with relevant expertise/data
Site operation and development	Equinor, Shell, BP, INEOS, Wintershall Dea
Monitoring systems and experience	Equinor, U. Oxford, ASN, NORSAR
Risk assessment	Risktec, NGI, GEUS, Equinor, Shell
Geology	GEUS, BGS, NGI
Geomechanics	Rockfield, NGI, IIT Bombay, Equinor, Shell, INEOS, Wintershall Dea, NTNU, TU Delft, U. Oxford
Seismology	NORSAR, U. Oxford, TU Delft, GEUS, Equinor, BGS
Experimental labs and material properties	BGS, NGI, TU Delft, Shell, IIT Bombay, NTNU
Geotechnical Engineering	NGI, NTNU, IIT Bombay, Rockfield
Earthquake catalogues	NORSAR, U. Oxford, GEUS, TU Delft, BGS
Well data interpretation	Equinor, NGI
Geophysics	Equinor, ASN, NORSAR, U. Oxford
Reservoir engineering	TU Delft, Rockfield, Equinor, Shell, BP, INEOS, WintershallDea
Datasets and databases	
National earthquake catalogues	NORSAR, U. Oxford, GEUS, BGS, TU Delft
Offshore seismicity data (PMR)	Equinor
Horda area subsurface data	Equinor, NGI
Greater Bunter Sandstone data	BP, Rockfield, BGS
Nini field data	Wintershall Dea, INEOS
Lisa data	GEUS
Aramis subsurface data	Shell, TU Delft
Baghewala field	IIT Bombay, Oil India Limited

Activities and results

Overall, the project has focused on integrating new subsurface data from field observations, seismicity catalogues, and rock mechanical testing. New data on in-situ stress in the North Sea, probabilistic failure and seismic hazard models, and identification of precursors to failure has been brought forward in the SHARP project. The work has contributed to updated workflows for containment risk assessment by developing a geomechanical readiness level and methodologies supporting quantitative risk modelling. Monitoring methodologies has been focused on pore pressure changes and subsurface deformation utilizing geomechanical readiness mapping for several CO_2 storage sites and maturing the data handling and the use of fibre optics for detection of deformation.

WP1: Stress history

The focus of WP1 was to develop understanding of key processes that control in situ stress across the North Sea and constrain them through new workflows and site/regional scale geomechanical models. The models aimed to address questions about state of stress in both shallow sedimentary basin fill which hosts the storage targets and the deeper basement which is the source of much of the seismic activity, with a view to understanding the relationship better. The objectives were achieved through delivery of reports shown in Table 2.

Table 2: Overview of WP1 deliverables.

| Task ID	Task	Deliverable	Type	Contributing Project Partners
1.1	Data collation and evaluation of stress drivers	DV1.1a Glacial Contributions to In Situ Stress	Report	BGS, NGI, GEUS, Rockfield
		DV1.1b Stress Drivers and Outline of Proposed Numerical Modelling Campaign	Report	Rockfield, NGI, BP, GEUS
1.2	Assessment of lithological contributions to in situ stress and constitutive model development	DV1.2 Lithology Assessment and Constitutive Model	Report	NGI, Rockfield
1.3	Construction of geomechanical models	DV1.3 Accounting for Stress History and Lithology through Forward Geomechanical Modelling	Report	Rockfield

Task ID	Task	Deliverable	Type	Contributing Project Partners
1.4	Calibration & "sharpening" of model predictions	DV1.4a Calibration and Sharpened Modelling	Report	Rockfield
		DV1.4b Sharpened Modelling	Report	Rockfield, University of Oxford, NORSAR
		DV1.5 Stress Modelling Exports	Report/Data	Rockfield, University of Oxford, NORSAR

Early work package deliverables DV1.1a and DV1.1b developed an understanding of regional stress drivers, a term introduced to capture mechanisms perceived to be contributing to the paleo and/or present in situ stress conditions. These summaries are beneficial to all storage sites in the North Sea basin (and may apply to other basins too) with key mechanisms discussed that include ridge push, burial and exhumation/uplift, glaciation, and decoupling of stress due to the presence of weak layers e.g. evaporites.

The way in which stress develops in response to such drivers is known to exhibit sensitivity to the sediment composition (mineralogy) and this formed the foundation of subsequent investigations (DV1.2). A comprehensive analysis of regional stress data indicated by well shoe tests (LOP, XLOT, etc) was undertaken, including new measurements offered by operators, and the current understanding of stress for each storage site was provided to WP4, WP5. Novel log-based workflows for stress characterisation have been developed that integrate both stress history and mineralogy (DV 1.1b) and applied successfully in the Horda Platform area. The work is important as it illustrates how industry standard approaches can be modified and, usefully, integrate more readily available data – this is significant as in early stages of site development/characterisation where data may be limited.

Constitutive modelling based on sediment composition was also a focus of DV1.2 and applied existing data sets of synthetic and real samples summarised in the closely linked DV3.2. These characterisations were used in coupled forward geomechanical simulations as part of DV1.3. Simulations explicitly integrated stress drivers as loading scenarios and, with comparable inputs/assumptions, recovered similar stress profiles to the log-based workflows. These models formed a way of developing site-specific 1D geomechanical models (a key requirement reported in DV4.6) that incorporated burial, uplift and glaciation as necessary, and could address additional uncertainties such as the level of overpressure, thus offering further insights into key geomechanical risks (DV1.3).

Figure 1: Left, novel log-based stress characterization workflows applied to the Horda Platform area (DV1.2). Right, coupled forward geomechanical modelling of the same area assessed with the log-based workflows (DV1.3). Consistent stress interpretations are achieved by both methods.
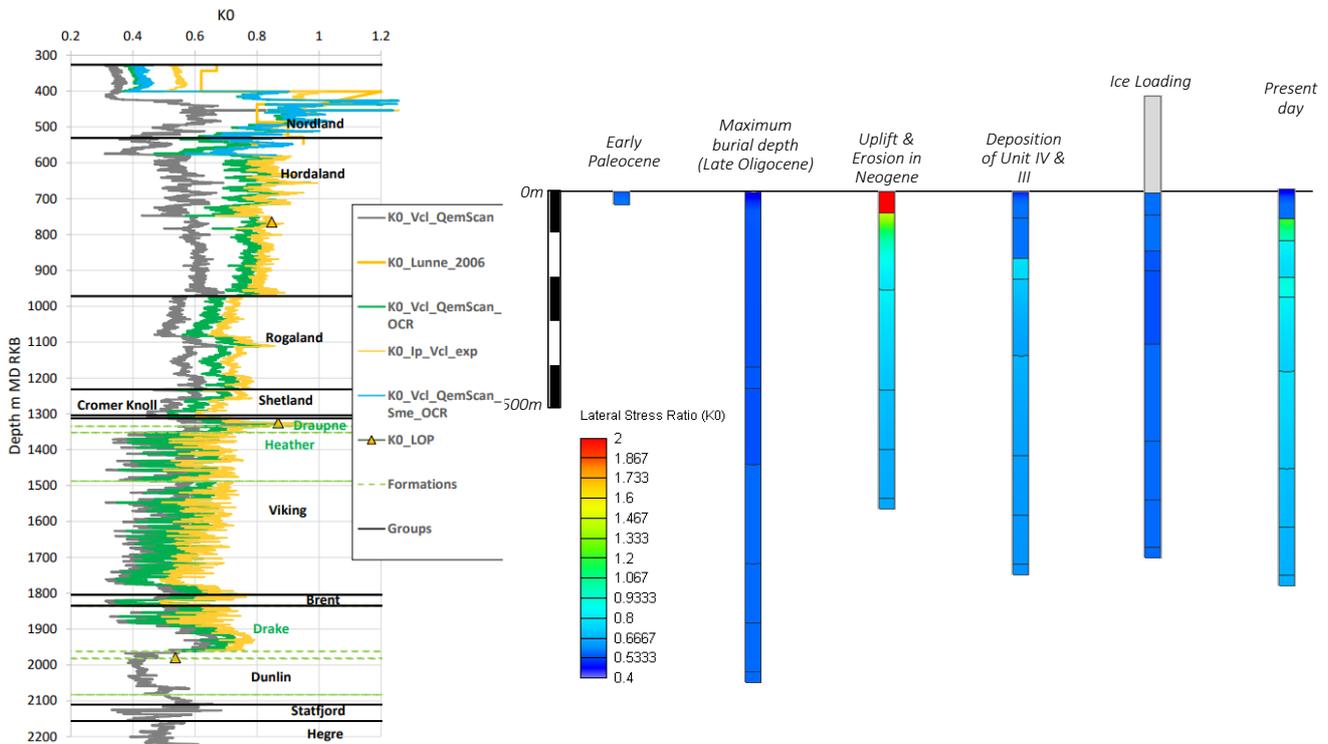
Additional geomechanical modelling became the focus of the remainder of the work package tasks. With some confidence established in the relative contributions of stress history a new 3D geomechanical model was developed for the Smeaheia storage site in the Horda Platform area (DV1.4a), using data and insights acquired through preparation of the preceding deliverables. Incorporating stress history through pre-stressing procedures was found to have important implications for overall fault stability at Smeaheia. Analysis of uncertainty in the horizontal stress anisotropy was also influential and so, in the context of sharpening model predictions, an attempt to better understand stress regime and stress anisotropy at regional scale was undertaken in DV1.4b. This work developed geomechanical models of the Northern North Sea with integration of constraints and observations from both WP2 and WP3. Models have investigated the influence of processes such as ridge push which would be a candidate to explain consistency in stress orientations in both deep and shallow sections across the North Sea.

WP2: Seismicity

The main objective of WP2 was to significantly improve the knowledge on the present-day stress field in the North Sea building on a new extensive database of earthquake locations and focal mechanisms. In combination with observations of stress drop, seismic anisotropy and borehole data, this task was ultimately providing mission-critical insights on caprock integrity

around the case study sites as well as valuable insights on actively slipping faults. The objectives were achieved through a set of six deliverables listed in Table 3.

Table 3: WP2 deliverables.

Task ID	Task	Deliverable	Type	Contributing partners
1	Integration of seismicity data and focal mechanism database	D2.1 Integrated earthquake locations and magnitudes plus focal mechanisms for the North Sea & construction of a velocity model	Database and report	TU Delft, NORSAR, GEUS, University of Oxford, BGS, Equinor, Shell, bp
		D2.4 Updated catalogue and focal-mechanism database	Database and report	TU Delft, NORSAR, GEUS, University of Oxford, BGS, Shell and bp
		D2.6 A hands-on guide for computing and exploring focal mechanisms in the North Sea for risk mitigation of large-scale CO_2 injections	Web report	TU Delft
2	Borehole stress observations	D2.2 Borehole stress observations	Report	GEUS, BGS, NGI, NORSAR, Shell
3	Crustal strength evaluation based on stress drop analysis	D2.5 Stress drop and crustal strength evaluation	Report	NORSAR
4	Measurements of seismic anisotropy	D2.3 Stress-induced seismic anisotropy: a promising tool to assess reservoir properties and caprock integrity	Report	University of Oxford, BGS

To compile the first version of the North Sea earthquake bulletin (D2.1), seismic event data was requested from all relevant data providers bordering the North Sea. The combined list of events was subsequently cleaned, and duplicate events were removed. An initial statistical analysis of the catalogue was derived, including a magnitude-frequency distribution and associated Gutenberg-Richter b-value. In addition, a focal mechanism catalogue was collected, and an overview and analysis of the available velocity models relevant for the North Sea area were presented.

The North Sea bulletin was updated during the project to be the first dataset of its kind - the most homogeneous representation of North Sea seismicity available to date (D2.4, Figure 1). The collected information is crucial for the understanding of the response of the reservoir and caprock to large-scale fluid injection. Two byproducts of the new bulletin are a catalogue

consisting of prime information and a catalogue extended to a larger region as base for the seismic hazard analysis performed in WP 5. Furthermore, analyses were performed on different magnitude scales. The usage of different formulas and input data makes direct comparisons between magnitudes difficult, especially for the local magnitudes. An analysis was also performed to relocate events within the North Sea bulletin, making use of the abundance of the new compilation of phase information. Our effort also included collecting waveforms for events that occurred later than 1990 and had magnitudes larger than M 3.5. Lastly, the focal mechanism collection was updated, and new moment tensors were calculated. The workflow for the probabilistic computation of moment tensors is detailed in deliverable D2.6.

Figure 2: Prime entries of the North Sea bulletin (forming the North Sea catalogue) as prepared in the SHARP Storage project. The red line delimits study area. Circle colours indicate year of occurrence of earthquakes, while circle sizes correspond to event magnitudes.
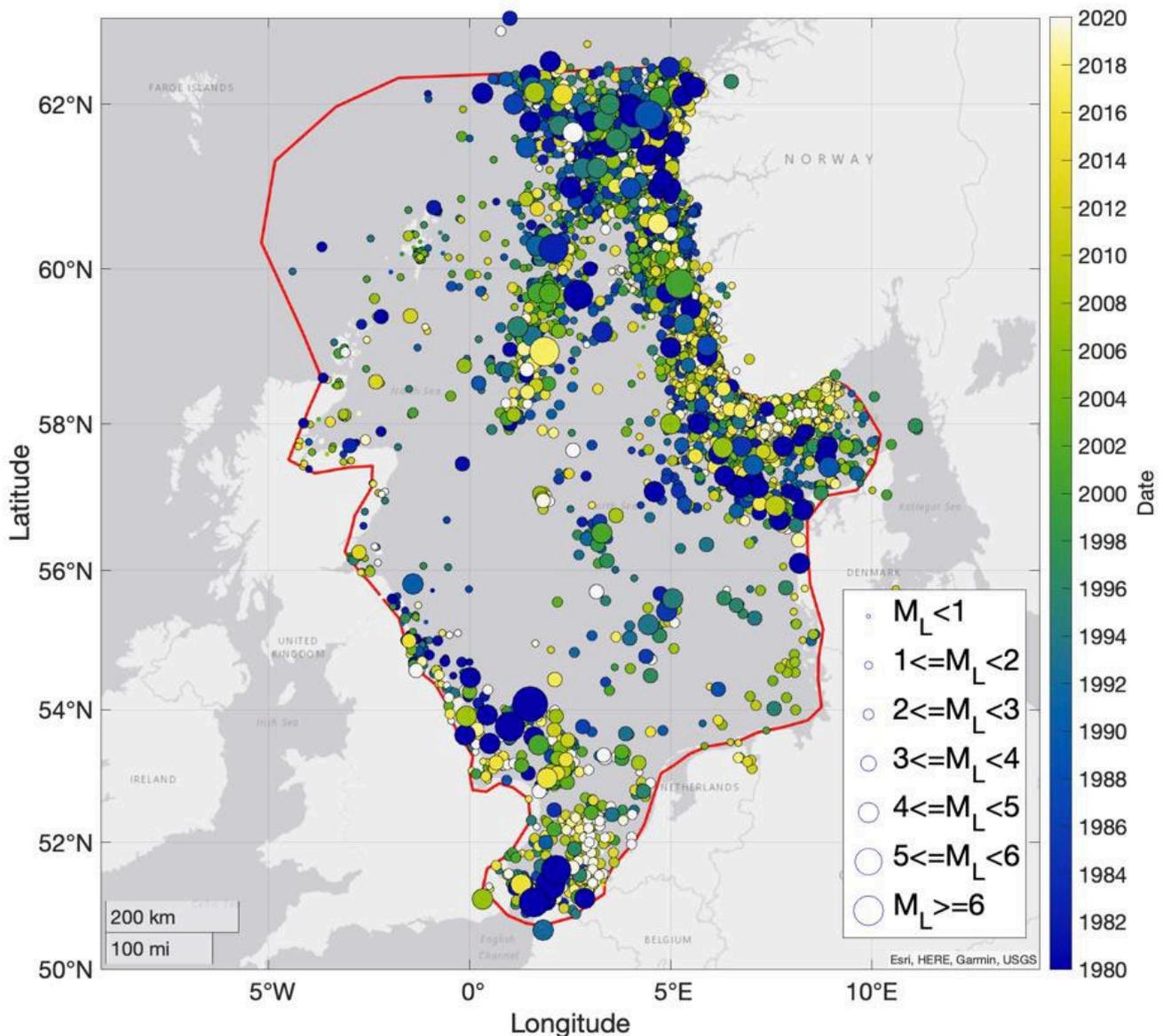
Further, a database of borehole stress observation was compiled with a focus on the SHARP study areas (D2.2). The compilation comprises the World Stress Map 2016 database supplemented with data and information derived from peer-reviewed publications that post-date the database release. In addition, non-published data and information from internal reports provided by various project partners were integrated and the database was analysed to provide a brief assessment of stress in the North Sea region based on borehole data.

In addition, we assessed the potential of seismic anisotropy to measure stress within the CO_2 storage complex, primarily the reservoir and overburden (D2.3). Using onshore passive seismic and stress data for the UK, we tested the potential for shear-wave splitting to be used to monitor the stress field in and above CO_2 storage sites. We focused on four regions: Northeast England, Northwest England, Southeast England and South Wales. Stress-induced anisotropy is observed in all regions and is particularly clear in Northwest England and Southeast England. We also showed, for the first time, that shear-wave splitting can be measured using seismicity recorded by offshore Permanent Reservoir Monitoring Systems (PRMs). Shear-wave splitting is measured at selected PRM stations at the Snorre field using data recorded from the 21st of March 2022 MW 5.1 Tampen Spur earthquakes and subsequent microseismic aftershocks (0.1 < ML < 2.6). These results prove that offshore sensors, such as PRM systems, are suitable for measuring shear-wave splitting for microseismic data even in relatively sparse deployments. This makes shear-wave splitting an important potential added value that should be considered when planning offshore passive seismic monitoring of CO_2 storage projects.

The estimation of stress drops for the Horda platform events using a spectral stacking approach turned out to be unreliable, since the spectral inversion for separating source contributions from site effects and path effects was unstable for the given event-receiver pair distribution (D2.5). A series of synthetic tests was conducted and showed that while it should be possible to apply the spectral stacking method to the given station geometry, a larger number of crossing ray paths with a larger available range of travel times is required. Thus, lowering the event detection threshold by installing denser networks closely distributed around the area of interest is a pre-requirement. Furthermore, our results also highlight the importance of a sufficient spectral bandwidth to reduce bias in moment magnitude estimations and corner frequencies. In addition, deliverable D2.5 integrates stress data from early deliverables for the Horda Platform, with the final aim of refining inputs for the local and basin-scale Numerical Geomechanical Smeaheia Model. The disparity in the volume of available data — specifically, the greater number of borehole measurements compared to focal mechanisms—introduced larger uncertainties regarding in-situ stress at depth. Although focal mechanisms offer valuable insights, the depth of events, for which focal mechanisms are computed, cannot always be reliably ascertained due to missing station coverage and large station-event distances. When interpreting the data, this aspect needs to be accounted for. Our integration revealed a generally consistent orientation of the principal maximum horizontal stress, aligning well with the values used in the Probabilistic Fault Stability Assessment. To improve data reliability and depth information, an increase in the number of seismic stations in proximity to events is recommended. In contrast, outside the Horda Platform, where a more extensive dataset is available, the updated focal mechanism catalogue indicates a predominantly reverse stress

regime with an E-W maximum horizontal stress azimuth. This finding is also consistent with the few newly computed focal mechanisms (D2.4).

Our main recommendation is to install offshore seismic stations, particularly stations close to potential sources, to increase the number of near-source observations and fill the azimuthal gaps in the station's coverage to enable a more precise event location, event depth estimates and source mechanism analysis as well as enhance magnitude estimates. CO_2 storage operators should be encouraged by regulators to share seismological data from storage monitoring networks with the seismological agencies, such that these data can be incorporated in their routine analysis workflows to enhance the knowledge on the North Sea background natural seismicity. The bulletin, as prepared in the SHARP Storage project, represents only a snapshot up to mid-2022. For future consistency, either the work steps need to be repeated, or the data processing itself needs to be harmonised between the seismological agencies of North Sea bordering countries.

Especially with a view on the start-up of CO_2 injection and storage, it is important to establish a more reliable event analysis specifically for lower magnitude events that may potentially be induced events during operations. Without a dedicated plan to install a larger number of stations within the North Sea, a stable event analysis and derivation of estimates of stress orientations remain only possible for the largest magnitude event, not to mention the impossibility of a discrimination of natural and induced seismicity.

WP2: Rock mechanics

The objective of WP3 is the characterization of the rheology and constitutive behaviour of rock material from North Sea caprock and reservoir rock in relation to stress history and operational stress changes and its sensitivity to a selection of observable monitoring attributes. This was done through six deliveries, as listed in Table 4.

Table 4: WP3 deliverables.

Task ID	Task	Deliverable	Type	Contributing partners
1	Characterize failure/creep in (ultra-) sonic measurements	D3.1 Rheology data overview for study sites	Report	TUDelft
		D3.5 Report on stress dependent rheology	Report	TUDelft
2	Stress and burial history impact on present day state	D3.2 Geomechanical parameters for stress history modelling	Report	NGI
		D3.6 Experiment derived permeability models	Report	BGS
3		D3.3 Calibrated constitutive model	Report	Rockfield

Task ID	Task	Deliverable	Type	Contributing partners
	Scale dependent model characterization and monitoring assessment	D3.4 Scale dependent attribute design and sensitive analysis for stress and deformation	Report	Shell
		D3.7 Report on field data assessment and sensitivity	Report	TUDelft

Through laboratory triaxial deformation experiments on coreplugs collected from different reservoir complexes in the North Sea, we have established their mechanical behaviours and tied them with timelapse ultrasonic attributes (D3.1 and D3.5). We established the petrophysical properties of reservoir rocks which influences the degree of velocity change and how those can be incorporated to develop a robust traffic light system to predict and, in some cases, forecast stress change in the reservoir during CO_2 injection. A crack development model is also proposed by benchmarking stress data with acoustic data during different stages of triaxial experiments, which might have wider applicability beyond CO_2 storage applications. Lastly, conducted some novel triaxial tests to emulate CO_2 injection in a critically stressed reservoir rock to see how the ultrasonic properties change in due course. We further compared the ultrasonic velocity change with acoustic emission measurements in some tests and found a very strong correlation between them. These insights will directly be useful for developing monitoring strategies for future CCS projects in the North Sea and beyond (D3.7).

Experimental data defining stress state and outlining burial history is presented in D3.2. A large dataset has been used to define stress ration (K0) and relate this to the clay content of the rocks. The trends are compared with published XLOT data form the North Sea and application for several CO_2 storage cases are demonstrated. We show that the glacial loading history effect on in-situ stress can be modelled reasonably well by laboratory experiments calibrated with field stress experiments, however overconsolidation needs to be addressed in more detail. D3.6 demonstrated that both porosity and permeability are stress dependent, and that accurate estimates of storage capacity in CO_2 reservoirs must account for the stress history, including the stress path experienced. The changes in porosity and permeability were generally small compared with the expected range of porosity and permeability expected in a reservoir because of natural variation of rocks.

DV3.3 focused on developing constitutive models for caprocks and storage formations across the North Sea. A constitutive modelling framework was presented that incorporated the required level of sophistication for capturing the constitutive response accurately. For caprocks a detailed assessment of the Intra Drake formation was undertaken and key aspects such as the strongly anisotropic elastic properties, and requirements for numerically back-analysing under undrained conditions. The ability of the constitutive models to successfully capture key stress paths, that exhibit sensitivity to sample orientation, provided confidence in their predictive capability. The models have been incorporated into wellbore-scale deformation analysis (WP1) to confirm in situ stress (DV1.4b).

Storage formations have also been characterised in DV3.3 using samples from across the North Sea, primarily focusing on sandstones from the Horda area (tested at NGI, TUDelft), Aramis field (tested at TUDelft), the Lisa Structure in Denmark (tested at TUDelft) and Bunter Sandstone analogue data supplied by BGS. A specific constitutive model has been applied that captures, in an upscaled/homogenised manner, pre-peak inelastic deformation (yielding) that is observed in most of the samples tested. In experiments the onset of yielding registers as increased acoustic emission activity and therefore provides a useful monitoring indicator, and so capturing this behaviour has implications for MMV. The characterisations have also been confirmed through numerical simulations of the triaxial tests themselves, with good correlation to volumetric straining, peak/yield stresses, and stress paths observed experimentally. The characterisations have been tentatively applied in THM simulations through collaboration with WP1 to highlight, at least conceptually, the links to monitoring workflows and strategies suggested by others (Grande et al., 2024). Cyclic testing on the Gassum formation has been attempted, but additional work is needed here to enhance the constitutive models.

WP4: Monitoring

The main objective of WP4 was to develop more intelligent methods for monitoring rock strain and fluid pressure. This was done through six deliveries, as listed in Table 5.

Table 5: Overview of deliveries to WP4.

Task ID	Task	Deliverable	Type
4.1	Determine initial 'round 1' rock failure risks for each case study site	D4.1 Round-1 site description and rock failure risk assessment for 5 sites	Report
4.2	Determine 'round 2' rock failure risks for each case study site	D4.2 Round-2 rock failure risks assessment for 3 to 5 sites	Report
4.3	Design improved monitoring scheme using 'right-time and right-place' detection	D4.3 Machine learning approaches for Microseismic detection	Report & algorithms
		D4.4 Optimal use of fibre optic monitoring scheme - North Sea case	Report
4.4	Integration of improved monitoring system with containment risk evaluation	D4.5 Strain detection and monitoring - India case	Report
		D4.6 Design improved monitoring scheme - multi-site	Report

The effect of improved stress configuration and detailed failure description on monitoring plans was demonstrated using an approach where the failure risk was determined before (Task 4.1: 'round 1' - D4.1) and after (Task 4.2: 'round 2' - D4.2) a detailed assessment of failure mechanisms and stress configuration for selected case studies. The case studies considered were as follows:

- Norway – Horda/Smeaheia region (mainly released datasets).

- UK Southern North Sea – Bunter storage play (mainly published data, White Rose dataset).

- Netherlands – Aramis site, Rotliegend pre-salt (relatively mature dataset).

- Denmark – Lisa Structure (few wells, more of a 'greenfield' site).

- India – Baghewala Oil Field (mature field with no CCS assessment)

Guided by studies in WP1, WP2, WP3, and work from Task 4.4 (D4.5), 'round 2' rock failure risks for each case study site were determined and changes in how uncertainties and risk factors have changed were tracked.

This work contributed to developing a system for "Geomechanical Readiness Level" (GRL); a scale intended to help storage operators evaluate the readiness of their potential injection site with respect to available data characterizing the stress conditions at the site. This was described in detail in Task 4.4 - D4.6. The GRL scale complements the more general 'Storage Readiness Levels' (SRL) proposed by (Akhurst, et al., 2021). The four GRLs defined were:

- GRL1 – Exploration and screening

- GRL2 – Technical appraisal and validation. GRL2 is sub-divided into two GRL categories, with the key distinction between GRL2a and GRL2b being the transition from regional studies to a more specific technical appraisal for the site in question.

- GRL3 – Towards permitting (demonstrating that the technical appraisal is sufficient to address the permitting requirements)

- GRL4 – Deployment (data maturation after the storage site is operational, including during site closure and post-closure periods)

The assessment is based on four geomechanical 'dimensions', with each dimension corresponding to a technical characterisation element required for comprehensive geomechanical assessment. The dimensions are: (a) in situ stress characterisation, (b) background seismicity data, (c) rock mechanical properties, and (d) rock failure assessments. Each of the storage sites were placed in their respective GRL level in 'round 1', and the maturation conducted during SHARP was used to place them in an updated GRL level in 'round 2'.

Task 4.3 focused on maturing different components of the monitoring toolbox, namely evaluating (a) machine learning (ML) approaches for automatic detection of earthquakes and (b) optimal use of fibre optics (FO) for monitoring.

Many ML models have been developed for earthquake detection and location. Each are trained on large datasets from specific regions and thus have ingrained biases for the features of the underlying training data. ML-based detection capability for a specific purpose can be improved by tuning the larger models using transfer learning, where the model is additionally trained on data from that specific network (with its own geometry, noise profile, event types, etc.).

In D4.3 we discussed how the performance of ML models can vary significantly. This is often considered to be due to features (network geometry, sensor type, station site conditions, event magnitudes, event distances, faulting style, etc) of the underlying data used to train the model. One clear drawback in the use of ML models, particularly for deep learning architectures, is their opacity with respect to feature extraction – it is often impossible to determine exactly what an ML model is identifying in the data. However, there are architectures which are less opaque, and can enable something approaching an understanding of the underlying features the ML algorithm is "seeing" in waveform data.

In general, the utilisation of FO sensing as a CO_2 storage monitoring solution is emerging fast and can include fibres both at surface and downhole. FO sensing can be used in several ways: (a) changes in temperature can be measured using distributed temperature sensing (DTS), (b) direct changes in rock strain can be recorded downhole using distributed strain sensing (DSS) and distributed acoustic sensing (DAS); (c) passive detection of microseismic events can be done using FO DAS cables, as well as (d) active seismic monitoring and seismic imaging. In D4.4 we illustrated with examples from published research and field trials from various regions worldwide, how combining these various monitoring technologies can create an enhanced monitoring scheme that provides a holistic understanding of subsurface dynamics in the Norwegian North Sea region.

In Task 4.4 – D4.6 we present a monitoring scheme applicable for CO_2 storage projects at different maturity levels and scales. Monitoring is a critical component of effective CO_2 storage and risk management, and evaluating the value of information (VOI) obtained from monitoring certain parameters is crucial for designing an optimal monitoring program. We present an overview of potential monitoring tools for detecting geomechanical pore pressure and stress changes and discuss their different applications.

Several factors influence how monitoring programmes may vary between onshore and offshore settings:

- The risk picture might be perceived differently, with the potential consequences of a leakage being more significant in densely populated onshore areas compared to offshore locations.
- The monitoring capabilities might also vary:
    o Onshore settings could offer easier access to infrastructure, but potentially with higher public focus on monitoring activities and their environmental impact.
    o Access to infrastructure is closely associated with cost, which might vary significantly between onshore and offshore.

      o   Other monitoring methods might be available onshore than offshore (e.g. satellite measurements).

- The public attention on the entire storage operation might be heightened onshore, making monitoring even more crucial for effectively communicating the safety of the storage site to the public.

Finally, we describe how an optimal monitoring programme needs to be tailored to the site(s) in question, selecting optimised monitoring tools depending on the relevant risks and geomechanical setting.

WP5: Risk quantification

The main objective of WP5 was to develop a new quantitative approach for assessing containment leakage risks associated with CCS. This was achieved by combining results from the other WPs into probabilistic workflows where uncertainties on input parameters as well as uncertainties inherent in the methodologies were considered. The work in WP5 combined theoretical investigations with data driven work. The methodologies were tested on selected case studies, and the applicability was discussed with stakeholders. The work progressed through seven deliverables, as listed in Table 6.

Table 6: Overview of deliverables in WP5.

Task ID	Task	Deliverable name	Type of deliverable
5.1	Probabilistic description of Stress-field related containment integrity	D5.1 Internal guideline for input uncertainties quantification	Report
		D5.4 Workflow for reliability assessment	Report
5.2	Seismic hazard and consequences of induced seismicity	D5.5 Development of GMPE and PSHA for the North Sea	Report
		D5.5b Natural seismicity input for risk modelling	Report
5.3	Quantitative modelling of CO_2 storage containment risks	D5.2 Initial methodology for quantified CO_2 containment risk assessment	Report
		D5.6 Containment risk quantification	Report

Task ID	Task	Deliverable name	Type of deliverable
5.4	Scientific guidance for quantifying risk	D5.3 Common understanding of risk between the scientific community and industry	Workshop and minutes
		D5.7 Interdisciplinary guidance towards quantitative containment risk	Workshop and report

A practical methodology for quantifying uncertainties in estimating geomechanical properties was developed in Task 5.1 (D5.1). A particular focus was on the uncertainties involved in regression when mechanical properties are derived from empirical correlations and spatially averaged properties. This was developed further into a probabilistic analysis of rock mechanical parameters to identify which uncertainties drive the risk for failure. Application of the methodology to the Horda Platform and Endurance case studies indicate that the primary driving uncertainties can be site specific, underlining that the probabilistic methodology for failure risk assessment described in D5.4 can be applied to other sites, where site specific results should be generated. Regional FE models (from WP1) combined with rock mechanical data (from WP3) can help identify locations with higher probability of failure.

The seismic hazard was analysed in Task 5.2 based on the harmonized earthquake catalogue developed in WP2. The main objective of this task was to develop a method for evaluating the risk for induced seismicity based on natural seismicity. To conduct a probabilistic seismic hazard analysis (PSHA) it is necessary to use realistic ground motion models (GMM). Standard GMMs exist for onshore sites, but the only available GMM for the North Sea before SHARP was more than 20 years old. Advanced waveform-based techniques were applied to produce new GMMs for the North Sea serving as input to PSHA. The resulting North Sea hazard maps are in line with values from national studies along the coasts and can be found in D5.5.

A new methodology to convert the results from PSHA to a shear stress hazard curve that can be used to estimate CO_2 containment risk was provided separately in D5.5b. The PSHA results applies only to the soil surface while the seismic risk assessment at depth is necessary to estimate containment risk related to CCS. The approach involves simplifying assumptions and the results are therefore expected to be approximate and contain a large amount of uncertainty. However,

The quantitative containment risk evaluation method in Task 5.3 is based on techniques used in the nuclear industry and adapted to CCS. To ensure applicability four half-day online workshop were held to develop a catalogue of generic release diagrams appropriate for CCS. Each generic release diagram was accompanied by an applicability matrix as described in D5.2. To assess the probability of failure, the release diagrams are populated with probabilistic

failure data from geomechanical modelling and earthquake data, and a Monte Carlo based event tree analysis is carried out. The methodology is described in D5.6.

Smaller sections of the Endurance and Horda Platform sites were selected as test cases for the risk quantification methodology. Four online workshops with relevant experts were carried out for each structure to map the applicable generic release diagrams onto the geological profiles. The event tree analysis provides overall quantification of risk and importance of initiation events and barriers, and it uses probabilistic failure data from geomechanical and seismic modelling.

Special efforts were made to ensure the applicability of the work in SHARP to all relevant fields within CCS. An interdisciplinary workshop on geological risks in CCS was held in Copenhagen in September 2022. The workshop brought together representatives from the scientific community, industry and government agencies from several countries. The workshop helped establish a common language and understanding of the challenges and important focus points among the participants. A summary of the workshop was made in D5.3.

Towards the end of SHARP, in September 2024, a public meeting on geological risks was held in Copenhagen to sum up the SHARP risking approach. At the meeting, results from geomechanics, seismicity, and laboratory work were presented, and how to deploy them in geological risking. An example of risking for the Endurance site was presented. Along with the risking, the meeting had presentations and extensive discussions on smart monitoring. The summary with guidelines is presented in D5.7.

WP6: Management and impact creation

Management and reporting

All WPs have had regular meetings and WP leads have gathered every 2-3 months for progress status and planning of events. The project has had the following consortium meetings with 20-40 in-person participants:

- Kick-off November 2021 – online
- Consortium meeting May 2022 – online
- Consortium meeting November 2022 – Oslo
- Consortium meeting June 2023 – Oxford
- Consortium meeting November 2023 – Delft
- Consortium meeting May 2024 – Bergen/Northern Lights visit
- Final meeting December 2024 – Online

A scientific advisory board of 4 members has been invited to all meetings and contributed with scientific input and feedback on work tasks. The steering committee for SHARP consisted of one representative of each partner. For selected consortium meetings in the early phase of SHARP, separate meetings with the steering committee were held focusing on setting up a

good system for the project. The project has been running without need for larger adjustments, and the steering committee meeting has been part of the consortium meeting.

Data management

A data management plan was created at the start of the project and has been updated during the SHARP project period. The plan addresses key public datasets utilized in the project, overview of new data and core material shared by the data owners during the project, internal sharing between work packages and a plan for archiving new data.

The archiving plan includes the International Seismological Centre for the updated earthquake catalogue, earthquake bulletin and focal mechanism. Updates to the North Sea waveform database will be hosted by NORSAR and updates to focal mechanism interpretation will be hosted by TUDelft. New data and correction in stress data has been reported to the World Stress Map database. Experimental data from TU Delft will be published in the TU Delft repository as part of the ongoing publishing process and BGS their laboratory test data.

Deliverables

All deliverables are listed in Table 7 with an active link to archive for publicly accessible reports using the Norwegian Brage system and will be transferred into Norwegian Nasjonal vitenarkiv (NVA). All public deliverables are available from the SHARP website https://www.sharp-storage-act.eu/publications--results/.

Table 7: List of deliverables and link to archive for publicly available reports.

WP no.	Deliverable no.	Deliverable name	Availability
1	D1.1a	Stress drivers and glacial contribution	Restricted
1	D1.1b	Inventory of data and designs for numerical modelling campaign	Public
1	D1.2	Assessment of lithological contribution to stress and constitutive model calibration	Public
1	D1.3	Geomechanical modelling results	Public
1	D1.4a	Calibration and Sharpened Modelling	Restricted
1	D1.4b	Sharpened Modelling	Restricted
1	D1.5	Updated modelling stress and material state data exports	Restricted
2	D2.1	Integrated earthquake locations and magnitudes plus focal mechanisms for the North Sea & construction of a velocity model	Public
2	D2.2	Borehole stress observations	Restricted

WP no.	Deliverable no.	Deliverable name	Availability
2	D2.3a	Stress-induced anisotropy, reservoir properties and caprock integrity assessment	Restricted draft, see D2.3b
2	D2.3b	Stress-induced anisotropy, reservoir properties and caprock integrity assessment – full report including interpretation and modelling	Public
2D	D2.4	Updated catalogue and focal-mechanism database	Public
2	D2.5	Stress drops and crustal strength evaluation	Public
2	D2.6	A hands-on guide for computing and exploring focal mechanisms in the North Sea for risk mitigation of large-scale CO_2 injections	Publication process in progress for a Web report hosted by TUDelft
3	D3.1	Rheology data overview for study sites	Public
3	D3.2	Geomechanical parameters for stress history modelling	Public
3	D3.3	Calibrated constitutive model	Restricted
3	D3.4	Scale dependent attribute design and sensitive analysis for stress and deformation	Restricted
3	D3.5	Report on stress dependent rheology	Public
3	D3.6	Experiment derived permeability models	Public
3	D3.7	Report on field data assessment and sensitivity	Public
4	D4.1	Round-1 site description and rock failure risk assessment for 3 to 5 sites	Public
4	D4.2	Round-2 rock failure risks assessment for 3 to 5 sites	Restricted
4	D4.3	Machine learning approaches for Microseismic detection	Public
4	D4.4	Optimal use of fibre-optic monitoring scheme - North Sea case	Public
4	D4.5	Strain detection and monitoring - India case	Public
4	D4.6	Design improved monitoring scheme - multi-site	Public
5	D5.1	Internal guideline for input uncertainties quantification	Public
5	D5.2	Initial methodology for quantified CO_2 containment risk assessment	Public
5	D5.3	Common understanding of risk between the scientific community and industry	Restricted
5	D5.4	Workflow for reliability assessment	Public

WP no.	Deliverable no.	Deliverable name	Availability
5	D5.5	Development of GMPE and PSHA for North Sea	Public
5	D5.5b	Natural seismicity input for risk modelling	Restricted, publication in progress
5	D5.6	Containment risk quantification	Public
5	D5.7	Interdisciplinary guidance towards quantitative containment risk	Public

Financial summary

Milestone ref.	Original GOL milestone claim date	Actual/revised milestone claim date (if different)	Original GOL total project budget	Actual achieved based on claims paid
MS1	31 Dec 2021	10 Jun 2022	£92,277.72	£26,733.15
MS2	31 Mar 2022	10 Jun 2022	£98,706.46	£74,192.85
MS3	30 Jun 2022	08 Aug 2022	£91,241.52	£113,548.47
MS4	30 Sep 2022	11 Oct 2022	£91,241.52	£101,738.75
MS5	31 Dec 2022	10 Feb 2023	£87,294.15	£80,605.13
MS6	31 Mar 2023	09 May 2023	£79,111.03	£95,261.89
MS7	30 Jun 2023	07 Aug 2023	£66,468.79	£95,720.29
MS8	30 Sep 2023	07 Nov 2023	£66,468.79	£75,378.01
MS9	31 Dec 2023	31 Jan 2024	£73,440.75	£75,185.19
MS10	31 Mar 2024	10 May 2024	£109,314.47	£58,996.18
MS11	30 Jun 2024	09 Aug 2024	£65,269.55	£61,950.73
MS12	30 Sep 2024	12 Nov 2024	£56,289.02	£66,690.10
MS13	31 Dec 2024	24 Mar 2025	-	£50,985.77
Total	-	-	£977,123.77	£976,956.49

Project impact

Project impact is reported first listing the broader impact of the project and then the direct impact of the project results.

Broader impact

Facilitation of CCS

The SHARP project has contributed with new data and maturation of regional and site-specific data for the North Sea highly relevant for understanding the containment risk during CO_2 injection. Several new CO_2 injection licenses has been awarded in Norway and in Denmark, and the UK has completed several CO_2 storage licensing rounds, and granted a CO_2 injection permit, during the project. The regional data from SHARP is expected to provide beneficial input in a development phase for these new license areas. The earthquake catalogue is already being used by several UK operators for their permit applications. With reference to Storage Readiness Level (SRL) (Akhurst et al., 2021) and Geomechanical Readiness Level (GRL) described during SHARP (D4.6), all the SHARP case studies have moved to a higher readiness level during the project period (Table 9). The Aurora (Northern Lights) is now ready to receive CO_2. For all sites, the SHARP research teams have contributed with data, discussions and methodologies to support the industrial operators work towards readiness.

Table 8: Initial and updated GRL (Geomechanical Readiness Level) score for the case studies in the SHARP project (D4.6).

GRL dimension	Baghewala	Lisa	Aramis	Bunter	Horda	Endurance	Aurora
In situ stress	1	1→2a	2a	2a	2b	2b→3	2b→3
Seismicity data	1	1→2a	2a	2a	2b	2b→3	2b→3
Rock properties	1→2a	1→2a	2a→2b	2a	2b	2b→3	2b→3
Rock failure assessments	1→2a	1→2a	1→2b	2a	2b	2b→3	2b→3
Overall GRL	1	1→2a	1→2a	2a	2b	2b→3	2b→3
Corresponding SRL range	1-3	1-3	3-5a	4-5a	5b-6	6-7	5b-8

Competitiveness of European companies

The SHARP team has engaged with the CO_2 injection operators, organized workshops and meetings for knowledge exchange and dissemination of new workflows and data. The involvement of 8 industrial partners in the consortium (5 operators and 3 service providers),

representing the needs of the end-users, has ensured industrial access to high-end primary data and experience, and on the other hand ensured validation of SHARP's results by prominent industries.

Public acceptance

The SHARP team has collaborated with the ACT 3 ENSURE project on organizing a workshop on public acceptance, hosted by Shell in the Netherlands. The workshop discussions highlighted high quality scientific input as one of the key requirements for ensuring public acceptance, and here SHARP is contributing with high quality data and robust academic work.

Direct impact

Updated seismicity catalogue

An updated North Sea bulletin forming the most homogeneous representation of North Sea seismicity available to date. The updated catalogue has provided the base for updated analysis on focal mechanism and probabilistic seismic hazard assessment (PSHA).

Strategies for monitoring

For regulators, SHARP analysis on informing the detection level for natural earthquakes provides many useful learnings for monitoring induced seismicity. For operators, SHARP findings on potential of seismological methods directly informs the development of project monitoring strategies.

Rheological data

New rheology data from North Sea (WP3) has been shared and helped mature the geomechanical readiness level for several sites in North Sea. It provides useful input to failure modelling, risk assessment and to understand seismic characteristics of a failure event.

Modelling

The geomechanical modelling framework has been updated based on new in-situ stress models for the Noth Sea and improved constitutive models using the new site-specific experimental data has been demonstrated.

Risk assessment

A quantitative risk assessment modelling method has been demonstrated within the SHARP project using two mature sites, the Endurance and Horda Platform as case studies. The methodology focuses on fault reactivation and fracturing, integrating probabilistic failure models and sensitivity analysis.

Commercialisation

The partners have agreed during the proposal phase that the expected outcome of SHARP is new knowledge on subsurface geological understanding and workflow/method development that are most suitable for open access publication and open-source codes. No work with potential for patents or IPR has been identified in the SHARP project.

Implementation

SET Implementation Actions

SHARP project has contributed to unlocking European storage capacity. The contribution is linked to Target 6 on at least 3 new CO_2 storage pilots in preparation or operating in different setting. SHARP has introduced a geomechanical readiness level (GRL) and demonstrated that new rock mechanical data and seismicity evaluation has matured storage readiness for several sites in the North Sea and India (Table 9).

Mission Innovation research priorities

The SHARP project addresses three of the Priority Research Directions in the Mission Innovation Report:

- PRD S-6 by improving fault stress state characterisation (WP1 and 2)
- PRD S-7 by linking geomechanics and seismicity (WP1,2 and 5)
- PRD S-4 by developing smart monitoring based on stress-strain data (WP3 and 4)

Industry engagement

The engagement from industry in SHARP work has been extensive. WP3 on rock mechanics has been led by Shell and WP4 on monitoring led by Equinor. The scientific work has focused on maturing the case studies in the North Sea and India. The industry has shared relevant samples for mechanical testing, stress data for modelling studies and contributed with input/discussion in meetings, writing of deliverables and QC of deliverables. In the SHARP project, case studies for storage maturation were included for all partner countries, covering a range of challenges and maturation levels. Storage maturation for the case studies is discussed using the geomechanical readiness level (GRL) as presented in Table 9 and further described below.

The Endurance and Greater Bunter Sandstone area in UK has benefited from new analogue experimental data measuring stress dependent porosity and permeability, a series of risk identification workshops part of developing the quantitative risk assessment methodology including detailed geomechanical modelling of the Endurance closure and risk of fracture of the overburden. The updated seismicity data and processing (particularly seismic hazard) also provides valuable knowledge for all the UK sites. This seismicity data, and the advanced monitoring schemes developed in the project, also will directly benefit many nascent projects with are undergoing the licensing and permitting process.

For the Dutch Aramis site, a total of >100 core samples have been collected and tested providing new rock failure data and identifying precursors to failure on lab scale. A database of

mechanical properties for the Rotliegend sandstones in the Aramis field has been established including the relationship with other properties such as porosity that can be linked to wireline log data. In addition, experimental work in which the acoustic wavefield is monitored during deformation suggests potential for a traffic light system based on changes in velocity and increasing micro seismicity, in which the different stages of deformation (elastic, inelastic, proximity to failure) can be identified.

The Lisa structure in Denmark is located near the most seismically active area in Denmark, hence the analysis of seismicity and the homogenized, comprehensive catalogues of earthquakes and focal mechanisms are of great importance to the maturation of the site. In addition, 13 core samples of the Upper Triassic – Lower Jurassic Gassum Formation, which is considered the most important sandstone formation for CO_2 storage in Denmark, has been tested providing rock failure data on a lab scale. A geomechanical model of the Nini West field, developed by the Danish industry partners in SHARP, were provided as input to the geomechanical modelling done in SHARP.

The Aurora, Smeaheia and Horda Platform area in Norway has benefited from detailed discussion of geomechanical data. New rock mechanical data from selected core samples from Eos well supplementing the Eos data published on CO_2 Datashare are closing some gaps addressing failure risk under low stress conditions. The geomechanical modelling using Eos image logs to support the regional stress models for the North Sea provided valuable input of the Equinor team and the updates on fault risk assessment on Smeaheia provided valuable discussions. The updated seismicity catalogue has value for both Horda Platform and the development of other licenses in the North Sea. Great progress on how we understand analysis of seismicity data has been achieved.

In India, an onshore case study from Baghewala field, Bikaner Nagaur Basin, India has been developed. The Baghewala field is primarily a two-way dipping, fault bounded anticline structure. The petroleum system is hosted within the Neoproterozoic Marwar Supergroup sedimentary system. The Jodhpur Formation reservoir sandstone has been envisaged as a potential storage unit, while the overlying Bilara formation, HEG and Nagaur formations act as caprock for effective containment. A numerical simulation study for representative Baghewala field architecture was conducted to envisage the changes in pore pressure at different injection rate of CO_2 injection. The geomechanical characterization from wireline borehole logs have also been performed. Based on this a site-specific monitoring scheme has been suggested (Singh et al., 2024).

Collaboration within the consortium

In SHARP each partner had several points of contact with the rest of the consortium, making a strong basis for knowledge and data sharing between the partners and countries in SHARP. All WPs had multiple partners and countries contributing. For details on the management structure, see subsection "WP6" in "Activities and results".

A significant added value of the transnational collaboration is the development of a homogenised earthquake catalogue for the North Sea made available for further analysis and development. Regional scale understanding of stress and geomechanics aids all countries/companies developing CCS in the North Sea. Further added value of the multi-country consortium is the sharing of experiences gained in mature case studies, such as the Horda Platform area in Norway, with less mature sites regions of the Greater Bunter Sandstone in UK, the Lisa site in Denmark, as wells as support for the initial steps towards applied CCUS technology in India.

The SHARP collaboration has resulted in new research ideas and new consortiums for further research have been established. Examples are the Q-Fibre consortium funded under the CET partnership in 2024, the SEALION initiative under development for Horizon Europe-CL3-2024-INFRA-01-01 call and the SAFE-C CET partnership initiative on developing a common North Sea bulletin through closer collaboration of the responsible seismic surveys coordinated by NORSAR.

Dissemination

SHARP Workshop events gathering researchers, industry, regulators and stakeholders:

- Two open dedicated risk seminars, one on risk identification and developing a common understanding among partners, regulators and stakeholders (September 2022 – Copenhagen) and one discussing the SHARP contribution on containment risk assessment and how to communicate risk (September 2024 – Copenhagen).
- One joint workshop on public acceptance together with ACT Ensure project (November 2023 – Amsterdam).

Open webinars sharing results from SHARP project:

- Online presentations on the topic of updates to the North Sea Stress field (January 2024).
- Online presentations on monitoring (November 2024).

An overview of all dissemination activities in conferences, outreach and meetings are provided in Table 10.

The high level of engagement from the industry partners in the SHARP projects proves that the work carried out has been of interest to the industry. This has materialized into several joint dissemination activities between industry and researchers within the project. The SHARP project has reached out to other industry actors, stakeholders and policy makers in conferences and national meetings. The feedback has been good and resulted in several invited lectures and seminars, and external industrial partners, researchers and stakeholders among the 190 attendees for the updates to the North Sea Stress webinar, and 125 attendees for the monitoring webinar. Interest in the updated seismic catalogue has been high both from CCS industry and stakeholders, as well as researchers and stakeholders related to other industries with interest in North Sea seismicity.

Table 9: Overview of dissemination activities within SHARP. Type of output is denoted by a series of codes: SPa – peer reviewed paper; PPa – popular science presentation; Pat – patent application; Po – poster; OPa – oral presentation and paper; PoPa – poster and paper; O – oral presentation; Web – webinar; WS – workshop; V – video; A – abstract; B – blog; I – interview; PR – press release; Oth – other.

Type	Authors	Title	Reference	Date	Partners	Other authors
A	Tine Larsen, Elin Skurtveit, Philip Ringrose, Kees K. Hindriks, Daniela Kühn, Dan Roberts, J. Michael Kendall, Marie Keiding, Auke Barnhoorn, Devendra N Singh, and the SHARP Team.	Stress history and reservoir pressure for improved quantification of CO2 storage containment risks (SHARP Storage)	Abstract submitted to The EGU General Assembly 2022	3-8th April 2022	NGI, Rockfield, NORSAR, Shell, Equinor, GEUS, Oxford, TUD, IITB, NTNU, BGS, Risktec, BP, INEOS, WintershallDea	

Type	Authors	Title	Reference	Date	Partners	Other authors
APoPa	Elin Skurtveit, Daniel Roberts, Daniela Kühn, Kees K. Hindriks, Philip Ringrose, Tine Larsen, Michael Kendall, Marie Keiding, Auke Barnhoorn, Devendra N. Singh, Jan K. Brenne, Rao M. Singh, John Williams, Steve Pearson, Tony Espie, Søren R. Poulsen, Andreas Szabados, Lars Grande	Improved quantification of CO2 storage containment risks - an overview of the SHARP Storage project	Abstract submitted to GHGT-16	23-27th October 2022	NGI, Rockfield, NORSAR, Shell, Equinor, GEUS, Oxford, TUD, IITB, NTNU, BGS, Risktec, BP, INEOS, WintershallDea	
A OPa	Lars Grande, Nazmul Haque Mondol, Elin Skurtveit and Nicholas Thompson	Stress estimation from clay content and mineralogy- EoS well in the Aurora CO2 storage site, offshore Norway	Abstract submitted to GHGT-16	23-27th October 2022	NGI, Equinor	UiO

Type	Authors	Title	Reference	Date	Partners	Other authors
Web	Auke Barnhoorn	Forecasting Failure and Seismicity: A laboratory Perspective: https://www.youtube.com/watch?v=4kd2EO-JE84	GeoEnergy Webinar	3 February 2022	TU Delft	
Web	Auke Barnhoorn	Acoustic detection of fault dynamics from a laboratory perspective. Monitoring fault activity prior to movement	Invited Lecture KNGMG-Noord, the Netherlands	1 February	TU Delft	
A	Lars Grande, Luke Griffith, Jung Chan Choi, Nazmul Haque Mondol	Dynamic versus static modulus in clays and mudstones in the North Sea	6th International workshop on Rock Physics	13-16 June	NGI	UiO
Oth	Hannah Rane	Student outreach: Earth Sciences introduction to CCS	Balliol College, Oxford: Outreach Frontier Science Programme	May 2022	University of Oxford	

Type	Authors	Title	Reference	Date	Partners	Other authors
PPa	D N SINGH	Geological Carbon Storage: An Introspection	13TH International Symposium on Environmental Geotechnology and Global Sustainable Development, Nanjing University, China	-9 Dec,2022	IIT Bombay	
PPa	Bahman Bohloli, Per Sparrevik, Elin Skurtveit	Fiberoptisk teknologi sikrer lagring av klimagasser under Nordsjøen: https://geoforskning.no/%ef%bf%bcfiberoptisk-teknologi-sikrer-lagring-av-klimagasser-under-nordsjoen/	Geoforskning.no: Formidlingskonkurransen 2022	30 May 2022	NGI	ACT2 SENSE project

Type	Authors	Title	Reference	Date	Partners	Other authors
O	Elin Skurtveit	Stress history and reservoir pressure for improved quantification of CO2 storage containment risks: https://static1.squarespace.com/static/574c47228259b5de6737fbfe/t/62c67db5c7639d6a697c83ba/1657175483741/SHARP+pitch_Skurtveit.pdf	US - Norway Collaboration on CCS/CCUS: http://www.us-norway-ccus.com/bilateral-meetings	June 29-30, 2022	NGI, All	

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Type	Authors	Title	Reference	Date	Partners	Other authors
Oth	Elin Skurtveit	Hvordan sikrer vi trygg fangst og lagring av CO2? https://www.ngi.no/Markedsomraader/Offshore-energi/Arrangementer/NGI-dag-paa-Arendalsuka-15.-august/NGI-paa-Arendalsuka-15.-august-Hvordan-sikrer-vi-trygg-fangst-og-lagring-av-CO2	Arendalsuka, Norway	August 15-19, 2022	NGI	Sintef, UiO, Gassnova, Bellona, Høyre, Venstre, FrP, AP
Po + A	Hannah Rane	Anisotropy and Shear-Wave Splitting as a Stress Indicator	BSM 2022 (British Seismology Meeting), Cambridge, UK (https://wserv4.esc.cam.ac.uk/bsm/) + PGRiP (Postgraduate Research in Progress), Cambridge, UK (https://pgrip2022.wordpress.com/)	12-09-2022 to 14-09-2022 + 14-09-2022 to 16-09-2022	British Geophysical Association (BGA)	British Geophysical Association, Güralp, Gaia Code, ISC, Smart Solo, KUM, Stryde, Nanometrics

Type	Authors	Title	Reference	Date	Partners	Other authors
Po + A	Peter Voss and "Partner list - all contacts"	The SHARP Storage project / https://www.helsinki.fi/assets/drupal/2022-10/JointNordicEPOS_53NSS_2022-abstracts_0.pdf	Joint Nordic EPOS and 53rd Nordic Seismology Seminar / https://www.helsinki.fi/en/conferences/joint-nordic-epos-and-53rd-nordic-seismology-seminar	25–27 October 2022	GEUS	
SPa	Tom Kettlety	Self-similarity of seismic moment release to volume change scaling for volcanoes: a comparison with injection-induced seismicity	Geophysical Research Letters, in press	2022	University of Oxford	
O	Mike Kendall	Seismicity and seismic hazards	Invited talk; SHARP risk workshop; Copenhagen	2022-09-28	University of Oxford	

Type	Authors	Title	Reference	Date	Partners	Other authors
PPa	Tom Kettlety	What is and what isn't slowing down geological CO2 storage? https://www.youtube.com/watch?v=SwQhd1y8Q5o	Invited talk, Oxford Net Zero seminar series	2022-10-31	University of Oxford	
ExA + O	Tom Kettlety	De-risking European CCS operations with the most complete earthquake catalogue for the North Sea	EAGE Annual 2023 extended abstract	2023-01-13	University of Oxford, TU Delft, NORSAR, KNMI, GEUS, BGS	

Type	Authors	Title	Reference	Date	Partners	Other authors
O	Daniela Kühn, Evgeniia Martuganova, Tom Kettlety, Johannes Schweitzer, Brian Baptie, Trine Dahl-Jensen, Hannah Rane, Annie Jerkins, Mark Fellgett, John Hopper and Cornelis Weemstra	Understanding North Sea seismicity for risk mitigation of large-scale CO2 injections	IUGG	July 2023	NORSAR, TU Delft, University of Oxford, BGS, GEUS	
AOPa	John Williams/Philip Ringrose et al	COMPARISON OF INITIAL STRESS STATE AND ROCK-FAILURE RISKS FOR FIVE PROSPECTIVE CO2 STORAGE SITES	TCCS-12, Trondheim	June 2023	BGS, Equinor, Shell, Oxford, ASN, NGI, GEUS, IITB, NORSAR	

Type	Authors	Title	Reference	Date	Partners	Other authors
WS	Atanu Mukhrjee, Age Stangelandan Elin Skurtveit, Roberts, Dan Phillips, Lars Grandee, Philip Ringrose, Susan Wienecke, Tine B Larsen, Auke Barnhoorn, Vivek Shrivastava, D P Chakraborty, Raju Goyal, Altaf Usmani, Vishali Surawar, Nimisha Vedanti, Pratim Sil, Abinash Bal	Stress history and reservoir pressure for improved quantification of CO2 storage containment risks:	SHARP DST IIT BOMBAY WORKSHOP	27,3.2023	All partners	DST, ACT
APo(Pa?)	Lars Grande, Carl Fredrik Forsberg, Nazmul Mndol, Elin Skurtveit, Rao Martand Singh, Nicholas Thompson	Impact of sediment composition, glacial loading and uplift on ground stresses in the Horda-Platform area	TCCS-12, Trondheim	June 2023	NGI, NTNU, Equinor	UiO

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Type	Authors	Title	Reference	Date	Partners	Other authors
APo(Pa?)	Luke Griffiths, Nicholas Thompson, Halvard Smith, Lars, Grande, Elin Skurtveit	Rock mechanical testing of core from Eos CCS validation well	TCCS-12, Trondheim	June 2023	NGI, Equinor	Norwegian CCS centre
Oth	Evgeniia Martuganova, Tom Kettlety, Daniela Kühn, Johannes Schweitzer, Brian Baptie, Trine Dahl-Jensen and Cornelis Weemstra	Understanding North Sea seismicity for risk mitigation of large-scale CO2 injection	NAC 2023, Utrecht	Mar-23	TU Delft, University of Oxford, BGS, GEUS	
A+Po	Evgeniia Martuganova, Menno Buisman and Auke Barnhoorn	Natural and artificial fractures response characterisation in large-size samples using distributed acoustic sensing technology.	EAGE Annual 2023 extended abstract	June 2023	TU Delft	

Type	Authors	Title	Reference	Date	Partners	Other authors
O	Evgeniia Martuganova, Tom Kettlety, Johannes Schweitzer, Annie Jerkins, Daniela Kühn, Peter Voss, Trine Dahl-Jensen, Brian Baptie and Cornelis Weemstra	The SHARP Storage project, WP2: New earthquake bulletin for the North Sea	Nordic Seismology Seminar	June 2023	TU Delft, University of Oxford, NORSAR, GEUS, BGS	
O	Dan Roberts, Dan Phillips, Lars Grande, Carl Fredrik Forsberg, Nazmul Mondol, Jung Chan Choi, Elin Skurtveit, Nicholas Thompson	Accounting for Stress History and Lithology in Geomechanical Models: Implications for Subsurface CO2 Storage Integrity on the Horda Platform	Abstracted to ARMA International Geomechanics Symposium, Al Khobar, Saudi Arabia	Oct-23	Rockfield, NGI, Equinor	UiO

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Type	Authors	Title	Reference	Date	Partners	Other authors
AO	Yu Feng, Lars Grande, Elin Skurtveit, Jung Chan Choi, and Nicolas Thompson	Reducing Uncertainty in Site-specific Stress Prediction for CO2 Storage in the North Sea, Norway	Symposium on energy Geotechnics, SEG23	Oct 3-5	NGI, Equinor	
O	Auke Barnhoorn	Rock Mechanics Presentation		14092023	TU Delft	Mijnraad (NL) Advisory Board to the Dutch Ministry
O	Auke Barnhoorn	Wireline Logging and Petrophysical/Mechanical Characterization in the Dutch Subsurface		7092023	TU Delft	Dutch Petrophysical Society

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O	Daniela Kühn, Evgeniia Martuganova, Tom Kettlety, Johannes Schweitzer, Annie Jerkins, Bettina Goertz-Allmann, Joseph Asplet, Trine Dahl-Jensen, Peter Voss, Brian Baptie, Mark Fellgett, Anna Dichiarante, John Hopper, Chen Huang, Nadège Langet and Cornelis Weemstra	Understanding North Sea (Europe) seismicity for risk mitigation of large-scale CO2 injections	AGU	December 2023	NORSAR, TU Delft, University of Oxford, GEUS, BGS	
O	Debanjan Chandra, Barbara Perez Salgado, Auke Barnhoorn	Wave velocities as a proxy to forecast deformation during cyclic loading-unloading in porous reservoir rocks	Euroconference on Rock Physics and Rock Mechanics	Oct-23	TU Delft	

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O, Web	Debanjan Chandra, Auke Barnhoorn	Applicability of wave velocities as a proxy to forecast deformation during cyclic loading-unloading in porous reservoir rocks	Accelerating safe CCS through targeted experimental campaigns" - a joint webinar by ACT RETURN, Cementegrity and SHARP	Sep-23	TU Delft	
O, Web	E. Skurtveit	Stress history and reservoir pressure for improved quantification of CO2 storage containment risks https://return-act.eu/act-webinar	Accelerating safe CCS through targeted experimental campaigns" - a joint webinar by ACT RETURN, Cementegrity and SHARP	Sep-23	All partners	
O, Po, WS	E. Skurtveit	SHARP status and impact	ACT knowledge sharing workshop, Paris	Oct.4-5 - 2023	All partners	

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PPa	E. Skurtveit & Thea Faleide	Frokostseminar CCS https://www.ngi.no/aktuelt/frokostseminar-co2-lagringer-trygt-og-avgjorende-for-a-na-klimamalene/	Oslo Forskningsdagene	22-Sep-23	NGI	NGI, Andreas Bjelland Eriksen, statssekretær Olje- og energidepartementet (AP), Asbjørn Torvanger, forsker ved Cicero
O	Daniela Kühn, Tom Kettlety, Evgeniia Martuganova, Annie Jerkins, Joseph Asplet, Bettina Goertz-Allmann, Johannes Schweitzer, Brian Baptie, Trine Dahl-Jensen, Peter Voss, Mark Fellgett, John Hopper, Chen Huang, Brian Carlton, Anna Maria Dichiarante, Nadège Langet and Elin Skurtveit	Understanding North Sea seismicity to gain stress field information and de-risk large-scale CO2 injections	British Seismological Meeting	25.-27.03.24	NORSAR, Oxford, TU Delft, BGS, GEUS, NGI	

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A + O	Evgeniia Martuganova, David F. Naranjo Hermandez, Daniela Kühn, Auke Barnhoorn	Assessing earthquake focal mechanisms in the North Sea for risk mitigation of large-scale CO2 injections	EGU General Assembly 2024	10-14th April 2024	TU Delft, NORSAR	
A	Joseph Asplet, Mark Fellgett, Tom Kettlety, Richard Luckett, Mike Kendall, Daniela Kühn	Seismic anisotropy as a measure of in-situ stress for safe CO2 storage	British Seismological Meeting	25/3/24 - 27/3/24	U Oxford, BGS, NORSAR	
A	Joseph Asplet, Mark Fellgett, Tom Kettlety, Richard Luckett, Mike Kendall, Daniela Kühn	Seismic anisotropy as a measure of in-situ stress for safe CO2 storage	EAGE	2024-06-10 to 2024-06-13	U Oxford, BGS, NORSAR	
A	Chen Huang, Brian Carlton, Tom Kettlety, Tine Larsen, J. Michael Kendall, Elin Skurtveit	Reevaluating seismic hazard and ground-motions for North Sea CO2 storage projects	EGU24		NORSAR, NGI, U Oxford	

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A	Chen Huang, Brian Carlton, Tom Kettlety, Tine Larsen, J. Michael Kendall, Elin Skurtveit	Preliminary Earthquake Ground Motion Database for the North Sea	EAGE	2024-06-10 to 2024-06-13	NORSAR, NGI, U Oxford	
A	Daniela Kühn, Evgeniia Martuganova, Tom Kettlety, Johannes Schweitzer, Annie Jerkins, Bettina Goertz-Allmann, Joseph Asplet, Trine Dahl-Jensen, Peter Voss, Brian Baptie, Mark Fellgett, Anna Maria Dichiarante, John Hopper, Chen Huang, Nadège Langet and Cornelis Weemstra	A better understanding of seismicity in the European North Sea for risk mitigation of large-scale CO2 injections	Annual meeting of the German Geophysical Society	11.-14.03.24	NORSAR, TU Delft, Oxford, GEUS, BGS	

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Oth	Jan Alexander Tubid Myhrvold Alf Eirik Valle Kopperud and	Consolidation and Stress History in Shallow Sediments in the Northern North Sea. https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/3095882	MSc thesis, NTNU	2023	NTNU, NGI	
Oth	Ramin Jalali	Consolidation and stress history in shallow sediments in the northern North Sea	MSc thesis, NTNU	2022	NTNU, NGI	
Oth	Pauline Kruiver, Daniela Kühn, Peter Voss, Florian Schmid	Environmental monitoring for North Sea CO2 storage site development	Session at ESC 2024	2024	NORSAR, GEUS	KNMI, K.U.M.

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A	Daniela Kühn, Anna Maria Dichiarante, Tom Kettlety, Evgeniia Martuganova, Joseph Asplet, Bettina Goertz-Allmann, Mark Fellgett, John Hopper, Annie Jerkins, Johannes Schweitzer, Jung Chan Choi, Peter Voss, Brian Baptie, Nadège Langet, Tine Larsen	Stress field information from seismicity to de-risk large-scale CO2 injections in the North Sea Horda platform region	39th General Assembly of the European Seismological Commission	2024	NORSAR, U Oxford, TU Delf, BGS, GEUS, NGI	
and Po	J. Damsgård, T.M. Hansen, P.H. Voss, H. R. Hansen, S. Steffansen, Egon Nørmark, M. Fyhn	Subsurface characterization using Distributed Acoustic Sensing (DAS) on an offshore fibre between Denmark and Norway	EGU24 / https://doi.org/10.5194/egusphere-egu24-414	2024	GEUS	Aarhus University, Department of Geoscience, Denmark and Energinet,

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A+ O	Chen Huang, Brian Carlton, Tom Kettlety, Tine Larsen, J. Michael Kendall, and Elin Skurtveit	Reevaluating seismic hazard and ground motions for North Sea CO2 storage projects, https://meetingorganizer.copernicus.org/EGU24/EGU24-14723.html	EGU	2024	NORSAR, NGI, University of Oxford, GEUS,	

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A+ Po	Tine B. Larsen, Elin Skurtveit, Steve Pearson, Tom Kettlety, Jung Chan Choi, Chen Huang, Brian Carlton, J. Michael Kendall, Michael Kupoluyi, Daniela Kühn, Daniel Roberts, Kees K. Hindriks, Anne-Kari Furre, Auke Barnhoorn, Devendra N. Singh, and the SHARP Team*	SHARP project – an integrated approach for assessing CO2 storage containment risks, https://meetingorganizer.copernicus.org/EGU24/EGU24-5579.html	EGU	2024	All partners	
A + O	Joseph Asplet, Mark Fellgett, Tom Kettlety, John Williams	Use of Shear-wave splitting to investigate stress field orientation (invited)	Geological Society of London special meeting "Tectonic Stress: from the lithosphere to the wellbore"	2024	U Oxford, BGS,	

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A + O TBC	Dan Roberts, Derek Speirs, Lars Grande, Elin Skurtveit, Jung Chan Choi, Luke Griffiths, Debanjan Chandra, Bård Bostrøm	Detailed Constitutive Modelling of North Sea Storage Formations and Caprocks: Implications for Effective Monitoring of CO2 Storage Sites	ARMA International Geomechanics Symposium - The Role of Geomechanics for Sustainability and Energy Efficiency	2024	Rockfield, NGI, TUDelft, Equinor	
A+Po+Pa	Grande, L., Skurtveit, E., Choi, J.C., Mondol, N.H, Thompson, N	Consolidation behaviours of clays, mudstones and shales - CO2 storage sites in Horda Platform, Offshore Norway (LINK)	58th US Rock Mechanics/Geom echanics Symposium held in Golden, Colorado, USA, 23-26 June 2024.	2024	NGI, Equinor	University of Oslo

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A+O	J.C. Choi and E. Skurtveit	Optimizing Resource Allocation in Fault Stability Assessment: Sobol Sensitivity Analysis for Smeaheia Area, Norway. https://www.earthdoc.org/content/papers/10.3997/2214-4609.2024101379	85th EAGE Annual Conference & Exhibition, Oslo 2024	2024	NGI	
A+O	K. Hindriks, S. Oates, T. Kettlety, E. Martuganova, D. Kuehn and V. Oye	Resilience to Potential CO2 Injection Induced Seismicity, Estimated from Historic Ground Motion Exposure, https://www.earthdoc.org/content/papers/10.3997/2214-4609.2024101584	85th EAGE Annual Conference & Exhibition, Oslo 2024	2024	Shell, U Oxford, TU Delft, NORSAR	

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A + Po	Evgeniia Martuganova, Auke Barnhoorn	Laboratory experiments as a tool to determine optimal measurement setups for monitoring carbon capture facilities.	Galileo conference: Fibre Optic Sensing in Geosciences	2024	TU Delft, NORSAR	
A+O	J. Asplet, T. Kettlety, M. Fellgett, R. Luckett, J. Kendall and D. Kühn	Seismic Anisotropy as a Measure of in-Situ Stress for Safe CO2 Storage, https://www.earthdoc.org/content/papers/10.3997/2214-4609.2024101469#abstract_content	85th EAGE Annual Conference & Exhibition, Oslo 2024	2024	University of Oxford, British Geological Survey, NORSAR	

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A+O	T. Kettlety, J. Asplet, T. Hudson and J.M. Kendall	Using Array Methods for Cost-Effective Onshore Passive Seismic Monitoring for Offshore CO2 Storage Projects, https://www.earthdoc.org/content/papers/10.3997/2214-4609.2024101519	85th EAGE Annual Conference & Exhibition, Oslo 2024	2024	University of Oxford	
SPa	Tom Kettlety, Evgeniia Martuganova, Daniela Kühn, Johannes Schweitzer, Cornelis Weemstra, Brian Baptie, Trine Dahl-Jensen, Annie Jerkins, Peter H. Voss, J. Michael Kendall and Elin Skurtveit	A Unified Earthquake Catalogue for the North Sea to Derisk European CCS Operations, https://www.earthdoc.org/content/journals/10.3997/1365-2397.fb2024036	First Break	2024	University of Oxford, TU Delft, NORSAR, BGS, GEUS, NGI,	GFZ, UiO, KNMI

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A+O	Brian Carlton, Pamela Pirie, Benjamin Bellwald	Development of site profiles to estimate amplification functions for the North Sea, https://www.jstage.jst.go.jp/article/jgssp/10/24/10_v10.OS-13-04/_article/-char/ja/	ICEGE-8	2024	NGI	
A+O	Brian Carlton, Olga-Joan Ktenidou	Estimates of high frequency attenuation (kappa) in the North Sea	World conference on Earthquake Engineering, WCEE-18	2024	NGI	National Observatory of Athens, Athens, Greece

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A+O	Johannes Schweitzer, Daniela Kühn, Evgeniia Martuganova, Tom Kettlety, Annie Jerkins, Bettina Goertz-Allmann, Joseph Asplet, Trine Dahl-Jensen, Peter Voss, Brian Baptie, Mark Fellgett, Anna Maria Dichiarante, John Hopper, Chen Huang, Nadège Langet, Cornelis Weemstra	For a Better Understanding of Seismicity in the European North Sea	15th General Assembly of the Asian Seismological Commission, Belek, Anatalya, Türkiye, 3 – 7 November 2024	2024	NORSAR, Delft University of Technology, University of Oxford, GEUS, BGS	
PPa	Elin Skurtveit, Auke Barnhoorn	https://geoforskning.no/key-advances-in-ccs-through-act/	Geoforskning . No	Dec-24	All partners	Anne pluymaker and Reinier Van Noorth, Cementegrity and Pierre Cerasi, Return project

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A + Po	Evgeniia Martuganova, David F. Naranjo Hermandez, Daniela Kühn, Auke Barnhoorn	Ensuring safe North Sea CO2 storage: the design of robust seismic networks to enable focal mechanism analyses for stress field orientation	The EGU General Assembly 2025	27th April - 2nd of May 2025	TU Delft, NORSAR	
A OPa	Anne-Kari Furre, Susann Wienecke, Philip Ringrose, Per Atle Olsen, Elin Skurtveit	Subsurface pressure and stress monitoring for CO2 storage: opportunities and limitations	TCCS-13, Trondheim, June 2025	Jun-25	Equinor, NTNU, ANS, NGI	
O+Pa	Ajendra Singh, Yogendra Singh, Devendra Narain Singh	Geomechanical Perspective for CO2 Sequestration Opportunity in Onshore Field, Bikaner Nagaur Basin, India	Fifth EAGE Global Energy Transition Conference & Exhibition (GET 2024)	Nov 4-7, 2024	IIT Bombay	

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SPa	S. Yogendra Narayanan, Devendra Narain Singh	Geological storage of CO2 in deep saline sandstone aquifers: A geomechanical perspective	Journal of Rock Mechanics and Geotechnical Engineering https://doi.org/10.1016/j.jrmge.2024.11.052	2025	IIT Bombay	

References

Akhurst, M., Kirk, K., Neele, P., Grimstad, A.-A., Bentham, M., & Bergmo, P. (2021). Storage Readiness Levels: communicating the maturity of site technical understanding, permitting and planning needed for storage operations using CO_2. International Journal of Greenhouse Gas Control, 103402. DOI: HTTPs://doi.org/10.1016/j.ijggc.2021.103402

Grande, L., Griffiths, L., Park, J., Skurtveit, E., & Thompson, N. (2024). Cooling-induced geomechanical response of North Sea reservoirs, and relevance for CO_2 storage monitoring. International Journal of Greenhouse Gas Control, 138, 10422

Singh, A., A Narayanan, Y. Singh, D.N. (2024) Geomechanical Perspective for CO_2 Sequestration Opportunity in Onshore Field, Bikaner Nagaur Basin, India. Fifth EAGE Global Energy Transition Conference & Exhibition (GET 2024) European Association of Geoscientists and Engineers. doi.org/10.3997/2214-4609.202421202.

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