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Improved quantification of CO_2 storage containment risks - an overview of the SHARP Storage project

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Abstract

Carbon Capture and Storage (CCS) is now maturing in Europe and worldwide with several Net Zero projects emerging. Hence, the need for safe and reliable CO_2 storage sites is accelerating and the accurate assessment of large-scale storage options at the gigatonne-per-year is critical. The SHARP project addresses the main priority areas required to improve current technologies to deliver CO_2 storage volumes at the scale needed to meet demands for large scale storage. Research needs identified in the industry has provided the base for this well-integrated project with the ambitions to reduce the uncertainty in the geomechanical response to CO_2 injection. Six case studies from sites in the North Sea and India will be matured during the projects. Ongoing work includes review of existing stress data, updating and integration of seismic catalogues and planning of new experimental data for improved constitutive models and rock failure attributes. Improved data analysis, compiling data from different sources, and new data generated in the project is expected to provide a base for updated failure risk assessment and more targeted monitoring. An initial assessment of rock failure risk in in progress and will be updated with a "Round 2" failure assessment incorporating new learnings and more mature data. The improved failure risk assessment includes the use of Bayesian statistical approach for quantification of uncertainties in geomechanical properties. Methods to quantify geological containment risk will be developed by reading across

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event tree techniques from other industries (e.g. nuclear). A set of generic release diagrams have been derived in a series of interdisciplinary workshops as a starting point for risk modelling.

Keywords: CO_2 storage; geomechanics; seismicity; monitoring; stress data; rock failure; microseismicity; risk assessment

1. Introduction

To meet the demands for new storage sites during the ongoing ramp-up and maturation of carbon capture and storage (CCS) projects in Europe, safe and reliable sites need to be identified and qualified. This requires a rigorous assessment of a wide range of reservoirs and top seals from various tectonic and structural settings for their suitability. Offshore sedimentary basins provide enormous potential with the real possibility of achieving the required storage capacity and injection rates [1]. However, the geomechanical response to CO_2 injection is one of the key uncertainties in assessing proposed storage sites.

The project "Stress history and reservoir pressure for improved quantification of CO_2 storage containment risks" (SHARP Storage) is a collaboration between 16 research institutions and commercial companies in Norway, UK, the Netherlands, Denmark, and India under the Accelerating CCS Technologies (ACT3) Programme. This interdisciplinary project focuses on understanding and reducing the uncertainties related to subsurface CO_2 storage containment risk. The main aim of the project is to mature the technology for quantification of subsurface deformation by developing and integrating models for subsurface stress, rock mechanical failure and seismicity. Quantifying risks associated with subsurface stress and strain response will improve the understanding of storage site behaviour, and progress storage site deployment readiness [2].

2. Approach

Key activities for the project are defined based on needs identified by industry, for demonstration and updated containment risk workflows for sites at different stages of development. The work focuses on: (1) developing basin-scale geomechanical models by incorporating tectonic and deglaciation effects, and use of newly developed constitutive models for rock as well as sediment deformation; (2) improving knowledge of the present-day stress field in the North Sea from integrated earthquake catalogues, focal mechanisms and boreholes stress indicators; (3) quantifying rock strain and identifying failure attributes suitable for monitoring and risk assessment using experimental data; (4) developing more intelligent methods for in situ monitoring of rock strain as part of the overall monitoring program; (5) quantifying containment risks using the developed geomechanical models and observations from field and laboratory studies.

The SHARP project is expected to accelerate the maturation of six sites from the North Sea region and India. The case study sites range from very mature projects such as the Northern Lights CO_2 storage project in the Horda area (Norway) to emerging storage prospects such as the Endurance site (UK) and the Lisa structure (DK). Furthermore, application of the methods to well-characterised offshore depleted oil and gas fields, such as Nini (DK) and Aramis (NL) will accelerate their transformation into viable and safe CO_2 storage sites. An onshore case study for CO_2 injection will be matured using lessons learned from the European projects in order to progress CO_2 injection and storage projects in India. Policy in India is focused on carbon emission reduction including development of carbon capture, utilization and storage (CCUS). In this paper, we outline the initial knowledge base for these case studies and explain our strategy for ‘sharpening’ the risk assessments.

3. Focus areas and results

3.1. WP1 Stress history

A precursor to any assessment of storage-related risks is a robust understanding of the in situ configuration of stresses. Stress characterization offers a variety of challenges, notably the fact that a number of processes may contribute that operate over different spatial and temporal scales. Within the North Sea, conventional stress analysis approaches have historically yielded contrasting interpretations of in situ stress regimes [3-5]; understanding the sources of such disparate interpretations is crucial for assessing CO_2 injection related risks. To address such open questions, the initial tasks are concerned with developing better understanding of the important stress mechanisms that have contributed to the present stress magnitude and orientations. These processes will vary across the storage sites but may include, for example, regional tectonics, halokinesis, and ridge push processes. An early assessment of the significance of such processes at each of the storage sites was developed. Specific emphasis was accorded to better understanding of the impact of geologically recent glaciotectonic processes. Initial assessments of glacial processes at both the Endurance structure and the Horda Platform area were developed, utilizing interpretation of shallow structure from high-resolution seismic data, and geotechnical data from shallow boreholes, respectively.

A second task concerns focused assessment of lithological contributions to stress and improved understanding of how composition affects the stress response during burial, exhumation, glacial loading and mineral transformation (diagenesis). This data incorporates an existing database of testing of various clay, silt-clay, and sandstone samples under uniaxial loading conditions [6, 7]. To date, 10 novel experimental characterisations have been developed and four of these are shown in (Fig. 1). The characterisations can be used for improving stress profiles during screening of potential storage sites. Additional characterisation work will be undertaken using new experimental data generated in the project.

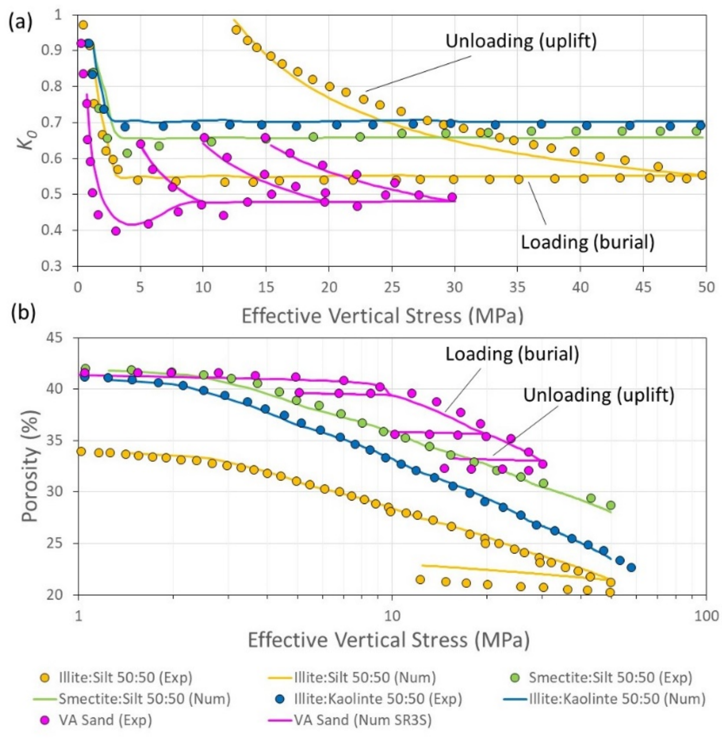

Fig. 1. Results of material characterisation workflows for select clay:clay, silt:clay and sandstone samples (a) Evolution of ratio of effective horizontal to effective vertical stress (K_0) during loading and unloading (b) Porosity changes during loading and unloading. Note a good agreement is observed between experimental data (points) and numerical back analysis (solid lines).

The data and outcomes arising from the first two tasks will form input to a third task that focuses on geomechanical modelling and integration of databases of in situ stress data. A range of models are anticipated that tackle stress characterisation at different scales. Uniaxial deposition and erosion models are anticipated at the Horda Platform area to complement work on the significance of mineralogy, with numerical modelling permitting consideration of diagenetic processes and investigation of stress trends in shallower and deeper strata. Assessment of both historic LOT (Leak-Off Test) data and newer XLOT (Extended Leak-Off Test) data provided by operating companies in the northern North Sea indicates regional and depth dependent variations in minimum horizontal stress magnitude and East-West and NW–SE orientation of maximum horizontal stress in various regions. XLOT data are a much preferred basis for minimum stress determination [8]. Coupled 2D regional-scale modelling is planned to illuminate the root causes of these variations in trends and attempt to quantify the relative significance of lithological variations, pore pressure, diagenesis, and coupling to deep, stiff basement units.

3D modelling is anticipated at (a) large-scale to understand the contributions of ridge-push as well as isostatic uplift and erosion stresses in the northern North Sea, and (b) at site-scale for the Endurance structure to investigate the response of salt structures to recent geological events. The outcomes of these models are expected to have relevance to all sites. Modelling results will be compared to observations from other work packages and inputs will be refined based on new understanding and interpretations.

3.2. WP2 Seismicity

Seismic hazard assessment is required to address and mitigate risks related to the geomechanical response to CO_2 injection. To improve the understanding of North Sea seismicity and stress fields, we will merge national catalogues to gain a holistic presentation (represented in Fig. 2). Existing seismicity catalogues for the North Sea are far from complete and in general only including larger magnitude events (> M3). Small earthquakes are typically recorded on fewer seismographs than larger ones, and it is therefore crucial to include all available data. As earthquakes smaller than M_L 3.0 are underreported to international agencies, data integration among neighbouring countries is an important part of the process. Specifically, we combined data from several data centres to form a database in IASPEI Seismic Format (ISF). The current version of the catalogue contains around 32,000 event recordings, extracted using a polygon bounding the North Sea area. The new integrated database consists of information from the Institute for Geosciences and Natural Resources (BGR, Germany), British Geological Survey (BGS), Geological Survey of Denmark and Greenland (GEUS), the International Seismological Centre (ISC), the Royal Dutch Meteorological Institute (KNMI), Norwegian National Seismic Network (NNSN), and Norwegian Seismic Array (NORSAR). It includes events recorded between 1382 and 2022. The newly created catalogue contains information on earthquake origins, interpreted phases and, in some cases, focal mechanisms within the region of interest. Future processing will involve removal of duplicates, magnitude harmonisation, and, eventually, re-computation of hypocentres for selected events. The resulting comprehensive database will serve as vital input for seismic hazard predictions during CCS operations.

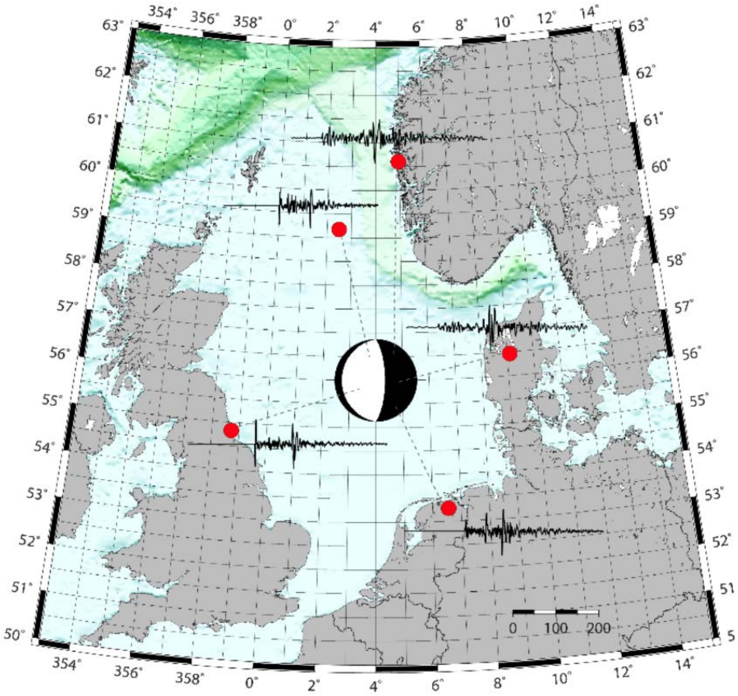

Fig. 2. Schematic of the planned earthquake data integration from combining national onshore, offshore, and temporal data for an improved earthquake catalogue and focal mechanism analysis.

A second task is focused on developing a catalogue of borehole stress observations from around the region. These primarily stem from evidence reported after the World Stress Map (WSM) database was published in 2016 [9], but data and information from the industry partners of the project is also incorporated. As much detailed information as possible is being integrated into the materials that will be provided to work package 1 for geomechanical modelling. This includes, for example, lists of individual stress indicators such as breakouts, their orientations, and depths of measurement. Publicly available input feeding into this task will be summarised into average azimuths and assigned appropriate quality assessments for incorporation into the WSM project. To date, over 100 new analyses have been identified, primarily in the UK and Dutch areas, and up to 20 new analyses are anticipated in the Norwegian and Danish areas in the coming months.

Finally, measurements of seismic anisotropy can be used as an independent method of measuring in situ stress orientation and magnitude. These are made from shear-wave splitting (SWS) measurements from raw waveform data, where a seismic wave splits into two orthogonal waves – a fast and a slow – when it passes through anisotropic material. Several effects cause seismic anisotropy, such as fractures, bedding, and mineral alignment. Fractures in particular produce anisotropy that is directly related to the in-situ stress state. From SWS measurements, one can infer the orientation of fractures, indicating the stress field orientation, and further modelling of the magnitude of anisotropy can be used to estimate the magnitude of the stresses.

The first dataset used in this study is the British Geological Survey's (BGS) catalogue of earthquakes in the UK since 2010. Shear-wave splitting is most clearly observed for near-vertical propagation of the shear-wave from approximately below the recording station. This naturally limits the number of earthquake observations for which this technique can be used. Candidate events have been identified from the catalogue and so far, consist of 607 events with magnitudes up to M_L 3.1. From these events, the stress measurements are compared to the pre-existing stress field database compiled by the BGS. Initial measurements of anisotropy indicate good agreement with the borehole-derived stress data. This clearly demonstrates the utility of SWS as an independent tool for measuring stress conditions at depth and motivates the processing of the remaining UK data. This study will result in an anisotropy-derived stress map for the UK and will expand to include events from all areas of interest to SHARP, including available offshore data.

3.3. WP3 Rock mechanics

Detailed characterization of the rheology and constitutive behavior of rock material from North Sea caprock and reservoir rock in relation to stress history and operational stress changes allows for defining sensitivity of observable monitoring attributes. Laboratory experiments allow for direct quantification of the actual deformation behavior of the reservoir and overburden rocks and estimates of burial and stress history. Translating the experimentally learned deformation behavior to field scale in situ conditions and changes requires appropriate upscaling and variational statistics as well as a proper design of relevant and quantifiable attributes that can be extracted from field scale monitoring campaigns. By combining existing databases, literature data and dedicated rock deformation experiments, we will characterize the North Sea rheology of selected reservoir and cap rocks with emphasis on case studies addressed by the SHARP proposal (Aramis, Horda area and Indian case study). Microseismic and sonic wave characterization of plasticity and creep within the range of expected site-specific stress conditions will be integrated into this characterization. The main aim is to design numerical constitutive behavior models for field scale applications to constrain the numerical assessment of historic and expected future deformation and flow conditions related to storage activities and development. In addition, measured acoustic and ultra-sonic responses from the deformation experiments under varying loading conditions, will be used to design relevant attributes to be extracted from on-site monitoring systems in support of quantifying deformation processed and altering stress conditions. New experimental work is currently in the planning phase together with a review and evaluation of potential for improved analysis on existing datasets.

3.4. WP4 Monitoring

The main objective of WP4 is to develop more intelligent methods for monitoring rock strain and fluid pressure (Fig 3). In the design of the overall research programme, we plan that WP4 will gain new insights from the laboratory and field analyses done in WP1, WP2 & WP3, and so be able to design improved monitoring systems that are targeted on the critical aspects of the rock system. These monitoring insights should then be integrated in an improved quantification of risks (in WP5). To set a current ‘state-of-the art’ reference, the first task in WP4 is to give a preliminary assessment of the state of stress at each study site and to make initial estimates for reservoir and caprock tensile and shear failure. The intention is to give an early assessment using available data to support the research, with a view to improving these assessments in future. We call this a ‘Round 1’ assessment. After we have developed novel ways to assess the many aspects of stress and strain in rock systems, we expect to develop updated and improved ‘Round 2’ assessments.

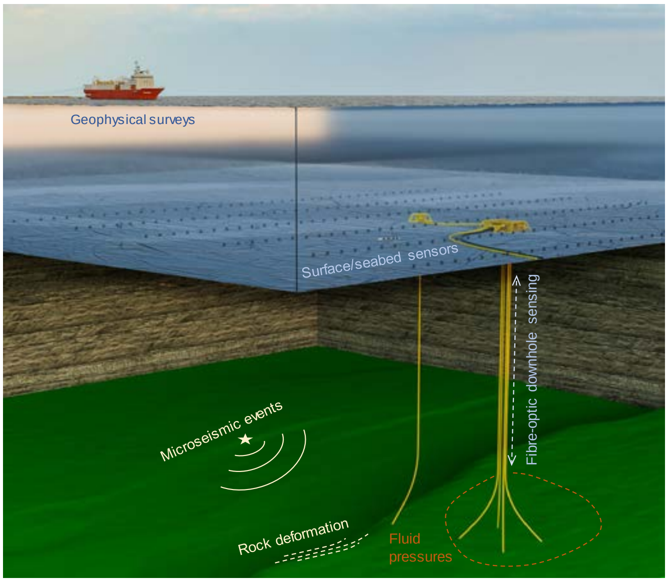

Fig. 3. Conceptual diagram illustrating the main options available for monitoring the state of stress, fluid pressures and rock deformation around a hypothetical offshore CO_2 injection site.

As part of the 'knowledge build' for this WP, we have focussed on an introduction to the scientific and technical basis regarding the following themes:

- *How to assess the state of stress around a site of interest.* This includes calculation of the state of stress from conventional well data, use of formation tests (such as XLOT) to estimate the lower bound for the minimum horizontal stress (S_{Hmin}) and geomechanical models to estimate an upper bound, S_{Hmax}. Reviews of regional natural seismicity data also provides valuable insights into stress field orientations, the strain mechanisms and possible depth dependencies of stress systems.
- *How to make initial estimates for reservoir and caprock tensile and shear failure.* This typically starts with a catalogue of available geomechanical laboratory test data for relevant rock units. Depending on the maturity of the site these data may be very limited and very regional, and insufficiently targeted on the detailed reservoir caprock units at the site. As a result, the initial rock failure estimates will likely be conservative and carry large uncertainties.
- *A summary of conventional site monitoring methods.* CO_2 storage site monitoring strategies have multiple objectives. For many sites, the focus has been primarily on plume monitoring, using either time-lapse seismic or downhole logging to monitor saturation changes. However, the importance of monitoring natural or induced seismicity, fluid pressure changes, and rock or surface deformation is becoming much clearer, especially if a risk-based approach to monitoring is adopted. The question then becomes how to use monitoring tools for multiple objectives. For example, seismic geophones can be used in active and passive mode, and the rapid developments in Fibre Optic (FP) sensing means that 4D seismic monitoring of saturation changes and microseismic listening can be done using the same detection array.

The case studies considered in the review of 'round 1' rock-failure risks assessments are:

- *The Norway Horda/Smeaheia region:* A relatively mature dataset, where published data [10] allows a good initial assessment of the state of stress, the nature of regional tectonic strain and the likely failure modes. However, the relatively good seismic monitoring coverage gets poorer with distance from the shoreline, leading to significant uncertainties in the stress state.
- *The UK Bunter storage play in the Southern North Sea (SNS):* Also, a relatively mature dataset, where published data allows good initial assessments of the state of stress and the likely failure modes. However, the target storage units have quite variable S_{Hmax} especially where they are affected by salt tectonics (halokinesis).

- *The Denmark Lisa structure case study:* An area in an early stage of maturation, with only a few regional wells, but with some good regional seismic monitoring data including focal mechanisms guiding the initial stress state assessment.
- *The Netherlands Aramis site:* The Aramis Area of Interest (AOI) is in a mature gas province with good background data. However, the area is at the cross-junction of four tectonic areas resulting in variable structural trends and overprinting of multiple faulting styles within a single area. The main target formation for storage is the (pre-salt) Rotliegend sandstone, which is the reservoir rock for most of the hydrocarbon fields in the Netherlands. The overlying Zechstein salt provides an excellent seal. The available seismic monitoring network is also good.
- *The India Rajasthan case study:* A region a with a good well database from oil and gas activities, but a more immature understanding of the state of stress and rock failure modes. The case study will mainly be used to develop concepts for early screening of green field CO_2 storage or CO_2 EOR prospects.

A comprehensive report on the initial assessments of rock-failure risks at all these sites is in progress (due to be completed in late October 2022). Fig. 4 show an example compiled dataset showing pressure measurements and Leak-off test (LOP) data from the UK Southern North Sea [11]. Datasets like these will be used to constrain the initial estimates for rock failure, with key uncertainties identified as a basis for a more targeted approach to site characterisation and monitoring. Improved analysis of in-situ stress measurements and pore pressure data [10] can be used to better understand stress versus depth trends in normal extensional basins and to identify potential high stress environments such as deeper strike-slip or reverse faulting regimes.

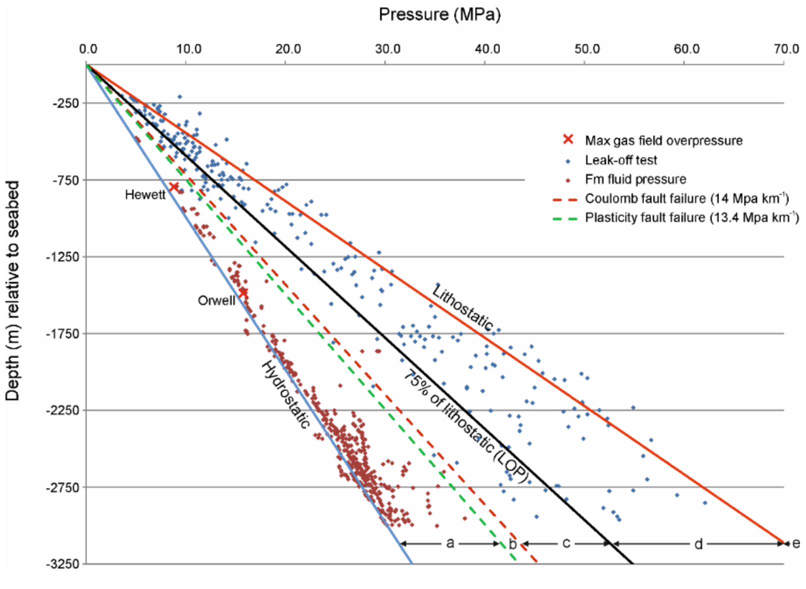

Fig. 4. Pressure measurements and LOP data from the UK Southern North Sea overwritten by hydrostatic pressure gradient, overburden (lithostatic) gradient and conservative fracture pressure gradient after Noy, Holloway, Chadwick, Williams, Hannis and Lahann [12], and fault reactivation gradients (Coulomb and Coulomb Plasticity) calculated by Williams, Holloway and Williams [11]. Pressure data shown courtesy of IHS, reproduced from Noy, Holloway, Chadwick, Williams, Hannis and Lahann [12]. Figure reproduced from Williams, Holloway and Williams [11]. BGS © UKRI (2022).

3.5. WP5 Methodologies for quantifying containment risks

Potential CO_2 storage sites are carefully selected based on extensive geological and geophysical investigations supplemented by geomechanical modelling. However, no matter how careful the analysis, some finite risk of leakage remains. Assessing the magnitude of this risk is a critical component of maturing a storage site, but the procedures are complex and not standardised.

In SHARP, practical methodologies are established to quantitatively determine the uncertainties related to geomechanical properties [13]. Special emphasis is placed on how to estimate uncertainties related to regression of mechanical parameters from laboratory cm scale to field km scale. Empirical relations often form the basis for estimating geomechanical parameters from point measurements of acoustic waves or petrophysical properties from well-logs or laboratory measurements. An empirical model is in itself associated with uncertainties as it does not represent a deep physical understanding of the processes. The model may be formed based on a limited number of measurements and may be skewed by natural variability in the physical properties. Observational errors also contribute to the total uncertainty.

Quantification methods to estimate reliable ranges for the physical properties are important, since the geomechanical stability assessments will be governed by weak points related to high and low estimates rather than average properties. Statistical uncertainties on parameters can be quantified by introducing a confidence and a prediction interval on the parameters, where the confidence interval contains the statistical and standard errors related to the mean values. The prediction interval covers data scatter and data variability around a mean and provides a likely range for the observations. A Bayesian statistical approach takes the uncertainty analysis one step further by applying probabilistic models to both observations and statistical parameters [e.g., 14]. In a Bayesian approach, prior information is included in the probability density function and the model is updated to a posterior distribution as new data become available. Applying multiple iterations moves the assessments from generic to more realistic. Bozorgzadeh, Grande, Choi and Skurtveit [13] demonstrates the variability in stress estimation for Drake cap rock in the Aurora field from available sources using data from the EOS well 31/5-7. The values vary considerably depending on the method used, included datasets, and the allowed degree of detail related to stress variation with depth or horizontal extension.

Quantifying geomechanical model uncertainties is an important step towards estimating uncertainties in the risk model. Stakeholders need to know how likely – or unlikely – the risk of leakage from a subsurface storage site is. Pearson and Kupoluyi [15] contains an extensive literature review on methods to quantify CCS geological containment risk. The most commonly used approach is based on quantified bowties and Layers of Protection Analysis [16]. However, event tree modelling, which is well established in the nuclear industry to assess containment risk, has not yet been fully developed for assessing CCS containment risk. In SHARP, risk modelling techniques from the nuclear safety industry will be adapted to CCS, and uncertainties in geological models and parameters will be included in the risk model.

As a precursor to setting up the event tree risk model, a catalogue of generic release diagrams (Fig.5) has been developed accounting for all realistic geology and release paths for CO_2 escaping from a subsurface reservoir. This work was performed through a series of four interdisciplinary workshops. Based on the generic release diagrams, Generic Event Tree Risk Modules will be developed using Reliability Workbench software. Release sequences will be modelled starting from an initiating event followed by the success and failure of subsequent barriers. The risk models will be populated with failure and uncertainty data from the other work packages, including both monitoring and mitigation strategies. As well as quantifying the overall risk of CO_2 leakage (and its uncertainty), risk modelling will also provide insights into the importance of specific leak mechanisms, monitoring strategies and mitigation measures.

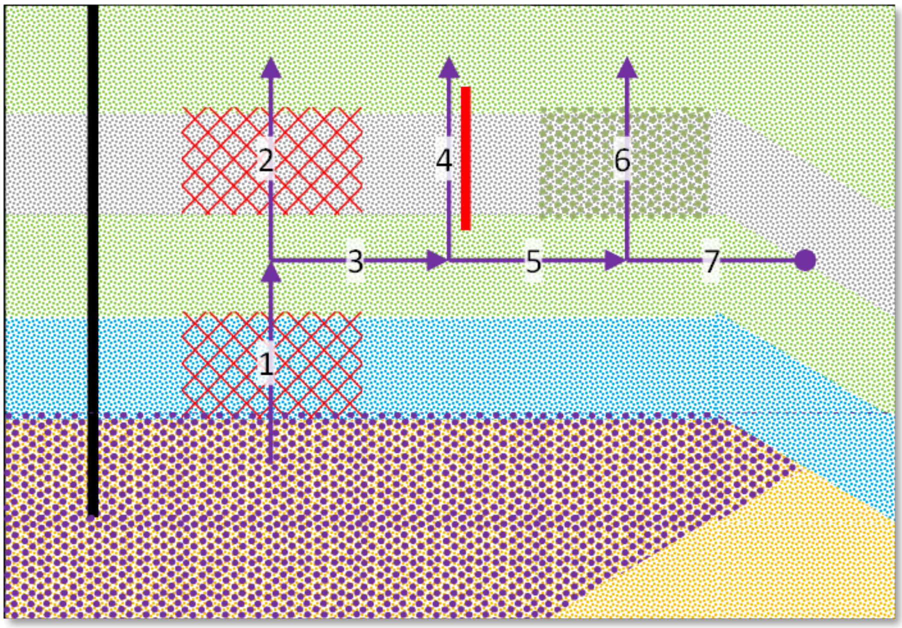

Fig. 5. Example of a generic release diagram to be used for risk modelling.

4. Summary and further work

Results of the project will be communicated to storage site operators and regulators to increase confidence in storage safety and seismicity risk assessment. The broad involvement of several international CO_2 storage operators in the consortium ensures that the SHARP project will deliver high impact to CCS development in Europe and beyond. The innovative approach will provide stakeholders (e.g. industry and regulators) with an improved framework for addressing and understanding containment failure and leakage risk. Using the project outcomes, site operators will be able to utilise the new approaches and findings to mitigate risks by optimising site development plans and sensing methods in a cost-efficient way.

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