A WORKFLOW FOR REGIONAL EXPLORATION OF CO_2 STORAGE SITES IN SALINE AQUIFERS

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Abstract

Regional screening for CO_2 storage sites within saline aquifers can benefit from play-based, risk segment mapping approaches developed by the exploration industry. Here, we outline a regional workflow focusing on containment and capacity for identification of storage sites that can be applied to any aquifer. A case study is presented of the northern Utsira Fm. aquifer (northern North Sea). A large-scale exploration dataset is utilised, including regional 3D, depth-migrated broadband seismic reflection data, full waveform inverted velocity data, and 141 exploration wells. A containment confidence (CC) matrix is presented as an approach to assess the seal and overburden, whereby matrix elements are mapped to constrain the most secure areas of the aquifer. Seal internal geometry, sandstone presence and sandstone connectivity are elements assessed, but other elements (e.g. faulting) could also be incorporated, if applicable. A full characterisation of the aquifer that considers 3D variability of reservoir properties is performed to inform capacity estimations. We incorporate regional porosity, intra-reservoir barriers and baffles and fill-to-spill analysis to identify prospective storage sites. Finally, minimum depth (700 m), minimum capacity (5 Mt CO_2) and positive CC cut-offs are applied. The optimal region for storage is in the northeast, where four prospects are identified, with a combined storage capacity of 53 Mt CO_2 (using 5% storage efficiency). Additional capacity could be achieved through use of the reservoir between adjacent prospects. These prospects can be put forward for detailed appraisal. Moreover, the mapping can form the basis of static and dynamic models, well plans and mitigation options. The workflow presented provides a systematic approach for regional CO_2 storage site screening that can be readily applied by geoscientists across the industry, with typical exploration-scale datasets.

Keywords: *Capacity, containment, and regional exploration*

1. Introduction

Carbon Capture and Storage (CCS) is now regarded as a 'necessity, not an option' to reach global greenhouse gas emissions targets [1]. Numerous studies have evaluated the storage potential of saline aquifers across a variety of basins, showing that many have gigaton storage capacities [e.g. 2-4]. As many of these aquifers lie in prolific hydrocarbon provinces, there are abundant hydrocarbon exploration and production data that can be re-purposed for evaluation of CO_2 storage targets. With regional-scale data and exploration-style approaches, detailed and pragmatic screening can be performed upon such aquifers to highlight the most advantageous regions for storage. Prospects can be identified and storage capacity estimates refined with a rigorous assessment of an aquifer's spatial variability [5]. Moreover, 'containment confidence' (the inverse of leakage risk) can be mapped for fuller constraint on security, through regional evaluation of the seal and overburden [6]. Parallel and systematic assessments of capacity and containment are essential inputs to models, to ensure realistic and well-constrained simulations for injectivity and migration predictions.

Here, we outline a regional workflow for CO_2 storage aquifer characterisation that addresses both the seal (containment) and the reservoir (capacity). The approach could be applied and adapted to any basin, but is showcased here with the northern Utsira Formation in the northern North Sea [5-6]. A 3D broadband seismic survey and 141 exploration wells are used to deliver a series of maps and ultimately, a portfolio of prospects.

2. Requirements for CO_2 Storage

Individual CO_2 storage sites require detailed assessment across various scales before they are deemed 'injection-ready'. Each site requires analysis of: 1) *containment*, ensuring CO_2 will remain in the reservoir through a sufficient seal; 2) *capacity,* outlining the volume of CO_2 that can be stored and in which area; and 3) *injectivity*, defining the extent, timescale and impact of fluid flow through well design and development planning.

In the same way that basin-scale exploration is the typical first step to identify hydrocarbon prospects, regional screening is required to identify potential CO_2 storage sites within an aquifer. The basic principles of play analysis and mapping for hydrocarbons (source, reservoir, seal) can be applied to CO_2 storage by adjusting the play elements (reservoir and seal equating to capacity and containment) and placing more emphasis on the overburden. Migration concepts are also transferable, as potential fluid pathways within and out of the aquifer must be constrained, including seal bypass systems, such as faults or connected sandstones. As such, the skills and risk-based approaches used in hydrocarbon exploration can be utilized for CO_2 storage site screening and form the basis of the containment and capacity workflow presented.

Injectivity is not assessed here, but upon identification of a suitable prospect, dedicated data collection for CO_2 storage from a well will provide information that includes, but is not limited to, seal integrity, sedimentology and pressure. Injectivity can then be rigorously assessed through dynamic modelling of the storage site and provide input to well planning.

2.1 Containment

The primary objective of a containment assessment is to evaluate the seal and overburden to establish whether CO_2 would remain in the reservoir. A secondary objective is to understand the potential migration route of CO_2 should it leave the reservoir. Core data are necessary to understand seal integrity, but legacy core data rarely cover seal rock intervals. As such, seal analysis in the screening phase is limited to seismic and other well data, which are suitable for assessment of: 1) seal distribution and thickness; 2) seal internal geometry; and 3) seal bypass systems. These form the basis of a regional assessment of containment confidence (CC) [6].

It is important to assess and map the presence of seal bypass systems, but also constrain their vertical connectivity through the overburden. This is achieved through subdivision of the stratigraphy above the aquifer into two units: 'Seal Interval' and 'Overburden Interval' (Fig. 1). The Seal Interval is the zone directly above the aquifer, defined as the minimum seal thickness required for CO_2 storage [6]. The absolute thickness will vary according to the aquifer. For example, the advised minimum seal thickness in the North Sea is 50 m [2], which is used here. A lesser thickness could be sufficient for containing CO_2, but prior to detailed data collection, a pragmatic approach is to take a conservative minimum.

The Overburden Interval comprises the stratigraphy from the top of the Seal Interval to either the seabed, a shallower potential CO_2 storage reservoir, or a theoretical maximum limit of migration. Accordingly, the Overburden Interval has variable thickness, and may be absent where there is only a Seal Interval separating two potential CO_2 storage reservoirs.

A regional CC assessment allows identification of the best and worst areas in terms of storage security and so should be one of the main considerations during exploration. It should be performed on the full aquifer, and not be limited to local storage sites. This is because CO_2 could migrate contrarily to predictions/models, and potential migration routes outside of the local injection area should be pre-emptively understood.

2.2 Capacity

Capacity is the assessment of how much CO_2 could theoretically be injected and is typically calculated based on available pore volume, either for the full aquifer [e.g. 2] or for all structural traps [e.g. 8], or through simulated injection until the pressure limit is reached [e.g. 9]. Although suitable for broad estimates, these approaches do not consider 3D variability of reservoir character, hence do not differentiate between high and low quality areas of the aquifer, which is addressed in the workflow presented here.

Our capacity workflow for the aquifer considers: 1) presence and extent of intra-aquifer mudstones; 2) porosity distribution; 3) identification of structural closures; and 4) storage capacity estimations. Upon integration with the CC assessment, a portfolio of ranked prospects across the aquifer are presented. Trapping potential outside of individual prospects is not considered, but could be included when considering storage in a network of traps through a fill-to-spill process.

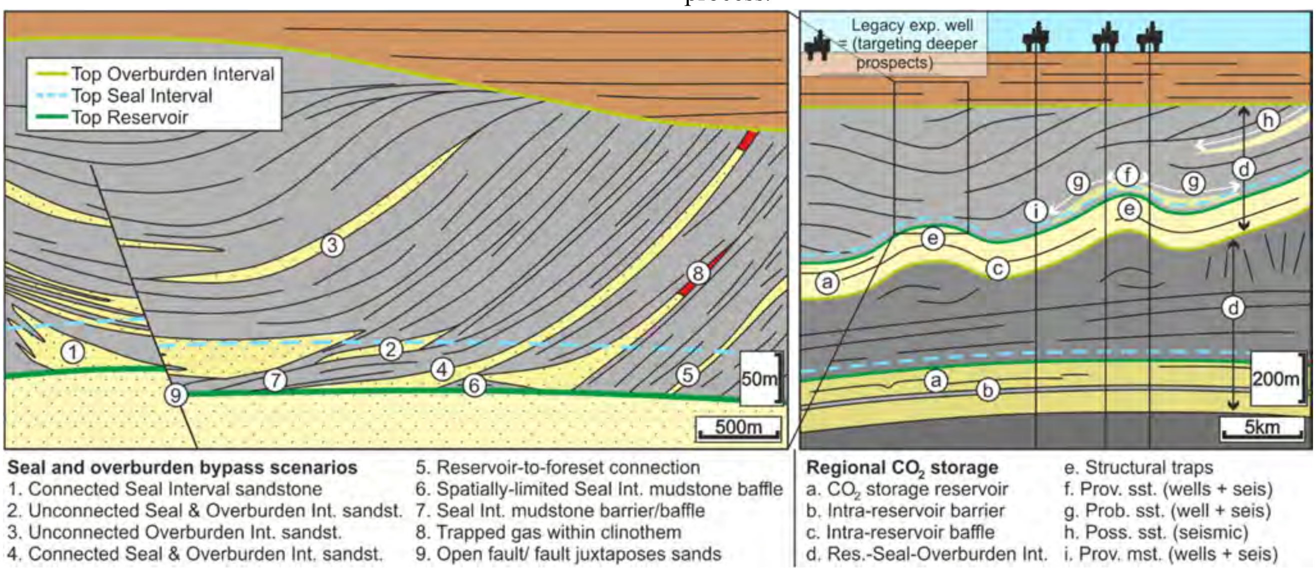

Figure 1| Schematic for regional exploration for CO_2 storage prospects - scenarios of seal bypass for the containment analysis (left) and definitions of intervals and sandstone presence (right). Prov. = proven; prob. = probable; poss. = possible; seis. = seismic.

3. Dataset and Data Preparation

The Neogene northern Utsira Formation was studied due to its large size, good reservoir properties and proximity to the current CO_2 storage license offshore Norway (Fig. 2). A 35,400 km^2 full 3D BroadSeis^{TM} seismic reflection survey acquired and provided by CGG was used for the analysis (Fig. 2). The original two-way time data were converted to depth by CGG, using advanced full-waveform inversion [10]. The FWI velocity cube has been re-purposed to evaluate porosity distribution (Section 4.2.1). The seismic data were coupled with 141 exploration wells (Fig. 2). Most of the wells are clustered around hydrocarbon provinces, which combined with the shallow depth of the studied interval (<1600 m TVD) means the distribution and quality of relevant well data are highly variable. A pre-interpreted lithology column was extracted from the TGS Facies Map Browser for each well, based on petrophysical logs and completion reports (Fig. 3). The interpretations are simplified for this study into ‘sandstone’, ‘mudstone’ and ‘other’ to focus on permeable versus impermeable lithologies and to allow simpler correlation between wells [6] (Fig. 3).

Prior to data analysis, a seismic stratigraphic framework was established. The reservoir limits, and seal and overburden stratigraphy were manually mapped with the seismic data, informed by well formation tops and previously published seismic sections for the reservoir [e.g. 11] and overlying stratigraphy [e.g. 12]. Intra-unit surfaces were mapped semi-automatically with Paleoscan^{TM} [5, 6, 13]. These were repeatedly checked for geological accuracy and were iteratively corrected. Seismic volume attributes were extracted onto mapped surfaces to assess geomorphological features.

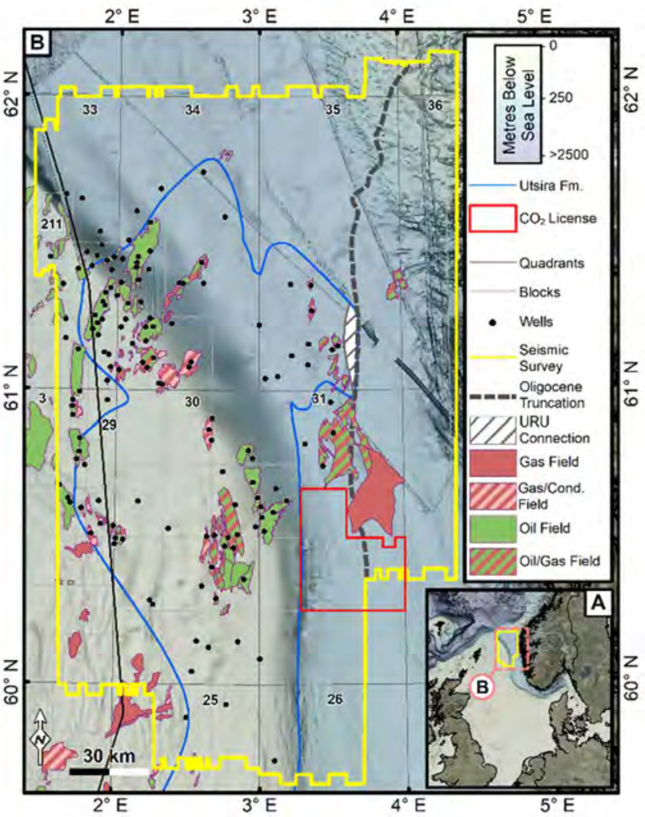

Figure 2| Dataset for the northern Utsira Fm., northern North Sea. Only studied exploration wells (141) are shown.

4. Containment and Capacity Workflows

The parallel workflows for containment and capacity analysis are presented in Figure 3. They can be performed simultaneously, however, the resultant containment confidence map is required as an input to the prospect identification stage and should be completed before storage capacity estimations.

4.1 Containment Confidence (CC) Assessment

Here, we outline the approach for the Containment Confidence (CC) assessment, applied to the Utsira Fm. To assess containment, seal geometric properties and seal bypass systems must be considered. To do this, we assess and map: 1) seal internal geometry; 2) Seal Interval sandstone presence; 3) Overburden Interval sandstone presence; and 4) sandstone connectivity. Each are scored according to a matrix (Table 1). Additional (or fewer) elements could also require analysis depending on the geology above a given aquifer. We also perform a regional shallow gas interpretation and cross-reference it with the identified overburden migration paths.

Within the matrix, a positive CC value is assigned if the component increases our confidence in containment, e.g. a full mudstone succession in the Seal Interval. A negative CC value is assigned if the component decreases our confidence in containment, e.g. sandstones in the Seal Interval. A CC value of 0 is assigned where there are either no data, or the component does not affect CC. Each element is scored relatively to the other elements, as they present variable contributions to containment. For example, a sandstone body within the Seal Interval (CC = -7) is considered to compromise containment more than a sandstone body in the Overburden Interval (CC = -1) (Table 1). Each of the four elements are regionally mapped to show the spatial distribution of CC according to that element (Fig. 4A-4D). The final step is to overlay and sum the individual element maps to give an overall CC evaluation (Fig. 4E). The final CC scores in the matrix are arbitrary numbers and dependent on the number of elements analysed in the matrix and the perceived containment contribution by the interpreter, but represent a relative, semi-quantitative approach to distinguish areas across the aquifer according to their CC.

4.1.1 Seal Internal Geometry

An assessment of seal internal geometry is only applicable to reservoirs that are overlain by non-parallel stratigraphy, such as the Utsira Fm., which is overlain by a clinoform succession. Dipping stratigraphy (e.g. clinoform foresets) in the Seal Interval juxtapose more sub-units against the reservoir than flat-lying stratigraphy. This increases the risk of a sub-unit with a high permeability zone (e.g. a sandy channel; Fig. 1) being in contact with the reservoir and so is assigned a negative CC score (CC = -3). A low negative CC score is assigned relative to the other elements (Table 1), as seal internal geometry is a minor contributor to containment. This is because it only increases the likelihood of seal bypass, rather than presenting evidence of a permeable route. Flat-lying/parallel-to-reservoir stratigraphy is assigned a neutral CC score of 0.

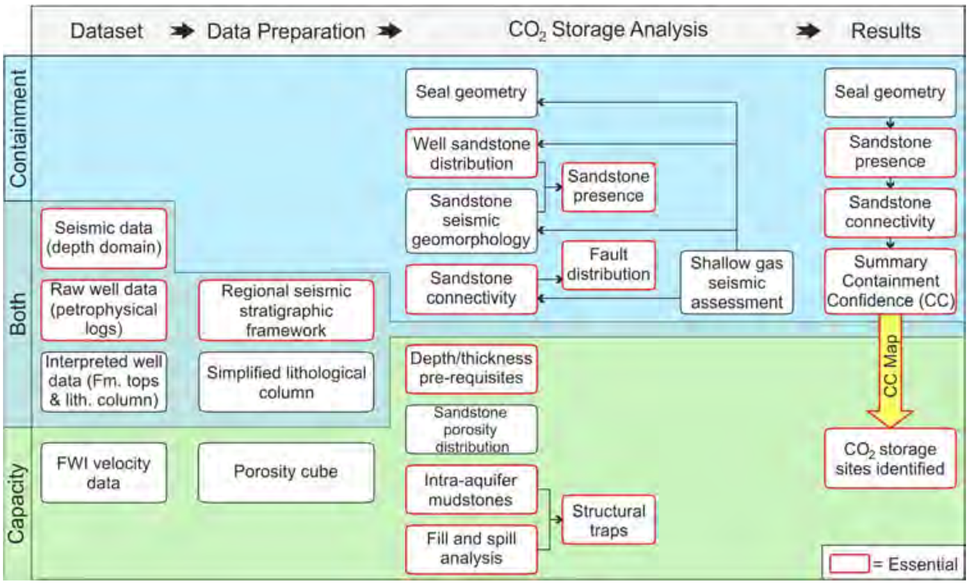

Figure 3| Workflow for containment and capacity assessment of an aquifer for CO_2 storage. The essential steps are highlighted (red perimeter). Fault presence is essential but as we encounter no major faults through the containment interval for the Utsira Fm., it is not considered here. The final output of the containment assessment (CC map) is used in the capacity assessment. The non-essential steps apply to the Utsira Fm. assessment but could also be applicable elsewhere.

The geometry of the Seal Interval is here assessed by creating a pseudo-surface at the top of the Seal Interval (50 m above the Utsira Fm. in our study). Seismic amplitudes at this surface were extracted, and in map-view, reveal the geometry of the intersection between the surface and the stratigraphy at that level. For example, alternating positive-negative amplitude bands are apparent where the surface intersects dipping stratigraphy. Broad areas of a single polarity occur where the surface intersects flat-lying or parallel-to-reservoir stratigraphy (Fig. 1 & 4A). For the Utsira Fm., dipping stratigraphy is recorded at the southeast and southwest margins. Flat-lying stratigraphy dominates in the northern and particularly north-eastern areas (Fig. 4A).

4.1.2 Sandstone Presence

Sandstone presence is essential to the CC assessment because it (and other permeable lithologies) can facilitate seal bypass. Mapping the presence of sandstone in the Seal Interval also acts to represent the absence of mudstone. Sandstones in the Overburden Interval could be migration routes if they are connected (Fig. 1). Sandstones bodies can be identified in well data and interpreted in the seismic data through correlations and identification of seismic geomorphologies that resemble sandstone features, e.g. submarine fans.

The CC score for sandstone presence depends upon two factors: 1) the stratigraphic position of the sandstones relative to the reservoir, and 2) the evidence for the sandstone. In terms of stratigraphic position, the CC assessment considers the Seal and Overburden Intervals separately, as sandstones that are proximal to the reservoir provide a greater risk to containment. For the evidence type (in the Seal Interval), the CC score is assigned according to whether the sandstones are 'proven', 'probable' or 'possible', based on the informing data (Fig. 1). 'Proven' sandstones are those that can be correlated between wells with the seismic, and so reduce containment confidence the most (CC = -7). 'Probable' sandstones are an extrapolation of 'proven' sandstones beyond well control using seismic (CC = -5). 'Possible' sandstones have no well penetrations but have a seismic response or geomorphological expression indicative of a 'proven' or 'probable' sandstone (CC = -3) [6]. Positive CC scoring areas are where mudstone has either been 'proven' (CC = +7) or is 'probable' (CC = +5), based on the same classification as sandstones. There is no specific seismic evidence of a mudstone in the studied interval, and therefore there is not a 'possible' mudstone CC score. Where there is no lithological evidence and the lithology is unknown, the CC score is considered unchanged (CC = 0). For the Overburden Interval, presence of sandstone alone (without connectivity) is not considered to greatly compromise CC. Therefore, a CC value of -1 is assigned for evidence of sandstones, and + 1 for evidence of mudstones.

Our dataset contains abundant well data, which allowed the areas of high sandstone content to be highlighted. We mapped sandstone bodies away from the wells with the seismic data, also utilising volume attributes, including sweetness, variance and spectral (frequency) decomposition [6]. Every high amplitude clinoform was mapped and assessed to identify potential sandy features. Several individual and amalgamated channels and lobes were identified on the Norwegian (east) and East Shetland Platform (ESP, west) sides of the basin, which could act as up-dip fluid migration pathways. In the Seal Interval, sandstones were primarily encountered in the west and southeast. Mudstones dominate in the northeast (Fig. 4B). In the Overburden Interval sandstones were encountered across most of the Utsira Fm. (Fig. 4C).

	Containment Confidence (CC) Score											
Element	-8	-7	-6	-5	-4	-3	-2	-1	0	+3	+5	+7
Seal Internal Geometry (SIG)						Dip			Flat			
Seal Interval Sandstones (SIS)		Prov.		Prob.		Poss.			Unknown		Mud Prob.	Mud Prov.
Overburden Interval Sandstones (OIS)								Pres.	Unknown	None		
Sandstone Connectivity (SC)	A-B-C			A-B			B-C		None			

Table 1| Containment Confidence (CC) matrix for the Utsira Formation. Prov. = proven; prob. = probable; poss. = possible.

4.1.3 Sandstone Connectivity

It is important to constrain the connectivity of the reservoir with overlying permeable routes that could allow CO_2 migration through the overburden. Connectivity is facilitated through amalgamation of sandstones or faults/fractures. Well data provide direct insight into connectivity at point locations. Away from the wells, seismic data can be used to map the thickness and amplitude of intervening mudstones; where thickness falls to zero (below seismic resolution) or amplitude response falls (reduced acoustic impedance contrast), connectivity between the sandstones is assumed.

In the CC matrix, connectivity is assessed between the reservoir (A), Seal Interval sandstones (B) and Overburden Interval sandstones (C) (Table 1). Where there is a full connection (A-B-C), CC is greatly reduced (CC = -8), as it implies a full potential migration path. Connectivity of A-B reduces CC (CC = -5), but not as substantially, because migration through the Overburden Interval is inhibited. Connectivity of B-C implies no connection to the reservoir but is still assigned a low negative CC score (CC = -3) as sandstones in the Seal Interval could be connected through sub-seismic migration routes. The CC score is only applied to the lowermost sandstone (e.g. in the Seal Interval), as this is the root of the connection. High connectivity was observed in the west around the ESP, where connected sandstones could be traced from the reservoir and up the clinoform foresets (Fig. 4D).

4.1.4 Shallow Gas Seismic Assessment

Shallow gas accumulates in sandstones and fractured mudstones, and can migrate through the stratigraphy using the same migration routes that injected CO_2 could follow, hence represent valuable observations to support the CC assessment. Strictly, shallow gas is not an element that contributes to containment, rather it highlights other elements, and as such, is not included in the matrix.

Shallow gas can be identified in seismic data, mostly due to its effect on seismic velocity and acoustic impedance. Typical diagnostic features include anomalously high, negative (in this dataset) amplitudes, seismic attenuation, chimneys and pockmarks. However, interpretation can be cryptic due to other phenomena producing gas-like responses, such as glacial tunnel valleys causing velocity disturbances [14] or amplitude anomalies from tuning [15]. Mostly, interpreted gas pockets are not verified as wells are placed to avoid them, however, gas encounters in wells can be used to identify gas-prone layers.

Here, we take a regional approach using only the seismic data; a more forensic approach could be applied to include the wells. We undertook a broad screening using a minimum amplitude (i.e. high negative) and variance extraction of the seismic data. We mapped anomalies above an amplitude threshold taken from a known, nearby gas accumulation (Peon discovery) [6]. Individual anomalies were assessed and cross-checked with mapped sandstones from the CC assessment. Interpreted gas-sands coincided with clinoform truncations and slope channels in the southeast, and within antiforms <200 m above the Utsira Fm. in the northwest, mostly coinciding with areas of high sandstone presence (Fig. 4D) [6].

4.1.5 Summary CC Map

Summation of each individual element map produces a regional summary CC map (Fig. 4E). This shows the best and worst regions of the aquifer for containment. The areas with the highest positive CC (best areas) are in the central and northern parts of the Utsira Fm, where there are flat-lying, mudstone-dominated stratigraphy in the Seal Interval (seal internal geometry: CC = 0; Seal Interval sandstone presence: CC = +5 or +7). Sandstones

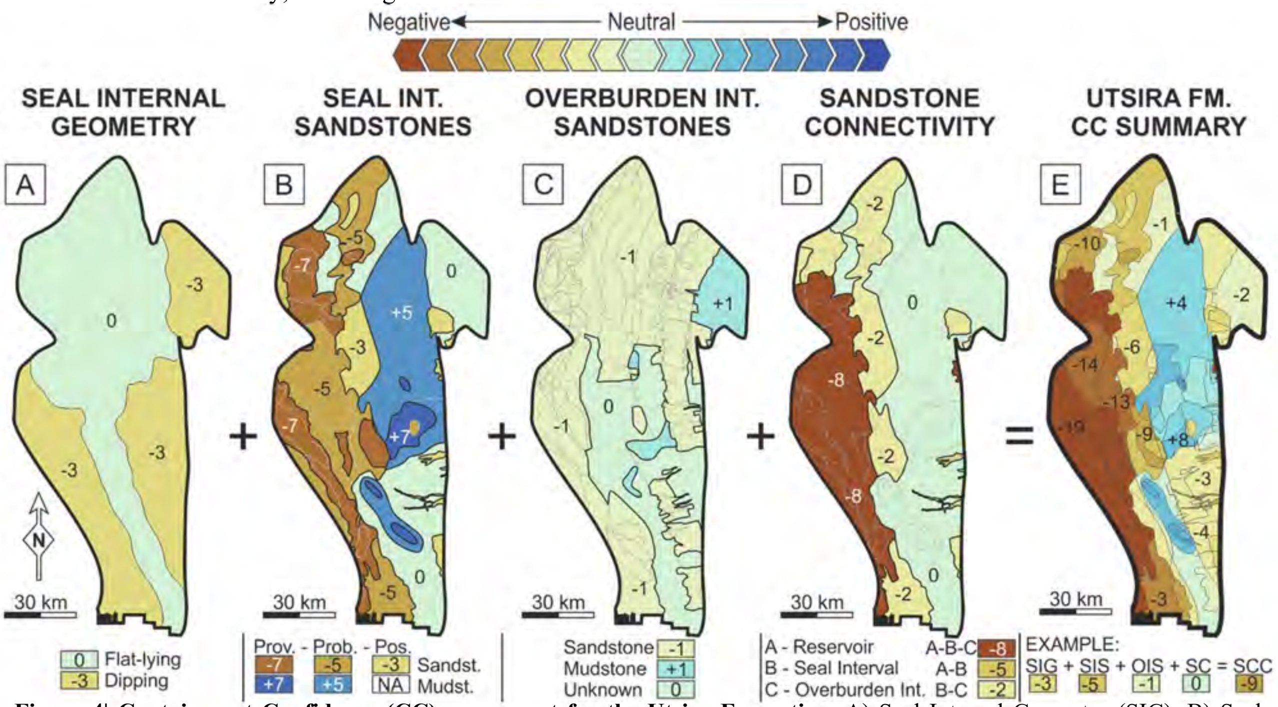

Figure 4| Containment Confidence (CC) assessment for the Utsira Formation. A) Seal Internal Geometry (SIG), B) Seal Interval Sandstones (SIS), C) Overburden Interval Sandstones (OIS), D) Sandstone Connectivity (SC), E) Utsira Fm. CC Summary (SCC). Scoring scheme is shown in Table 1. Int. = interval; sandst. = sandstone; mudst. = mudstone.

are present in the Overburden Interval, but they are unconnected (Overburden Interval sandstone presence: CC = -1; sandstone connectivity: CC = 0) [6].

The area with the highest negative CC (worst area), is the west of the Utsira Fm. There is a difference in seal internal geometry between the southwest (dipping stratigraphy, seal internal geometry CC = -3) and northwest (flat-lying stratigraphy, seal internal geometry CC = 0). Sandstones are present in the Seal Interval that are predominantly connected between the reservoir and Overburden Interval (Seal Interval sandstone presence: CC = -7 or -5; sandstone connectivity: CC = -8). The CC summary map is used to inform the identification of suitable prospects, but it could also be used for plume migration modelling and mitigation planning.

4.2 CO_2 Capacity Assessment

For the capacity assessment, 3D variability of the aquifer is considered. Here, we assessed the porosity distribution, and the presence and extent of intra-aquifer mudstones. Structural traps were identified at the interfaces to seal rocks/barriers, apex depths were considered and storage capacity was estimated for individual prospects. The results were combined with the CC analysis to identify suitable CO_2 storage prospects, which could go forward to more detailed appraisal.

4.2.1 Porosity Distribution

Porosity is a fundamental parameter in storage capacity calculations and represents reservoir quality. Petrophysical logs were used with the FWI velocity cube to create a 3D porosity volume of the Utsira Fm. sandstones (Fig. 5A). This approach allows for porosity estimations in areas with limited well data. First, density and sonic logs were converted into porosity and velocity logs, respectively [6]. The relationship between these two properties for sandstones in the reservoir was calculated for the studied wells that contained both logs (20 wells). The resultant linear function (Equation 1; R = -0.41), was applied to the velocity cube, converting it to porosity. A separate equation relating porosity to velocity is required for deeper stratigraphy below our studied interval.

Eq. 1: $Porosity = -0.00015251 \times velocity + 0.663317$

An average porosity of 35% was observed across the Utsira Fm., which is consistent with the average porosity at the Sleipner injection site in the southern Utsira Fm. [7]. Porosity decreases towards the northeast as the formation becomes deeper and further from the main sediment source in the southwest (ESP). Little vertical variability in porosity was observed within the Utsira Fm., but in a broader study of the full Utsira-Skade Aquifer, the underlying Skade Fm. showed a reduced average porosity compared to the Utsira Fm. (33%) [6].

4.2.2 Intra-Aquifer Mudstone Analysis

Intra-aquifer impermeable layers can act as baffles, temporarily disrupting the CO_2 plume during injection, or barriers, inhibiting further vertical migration and trapping the CO_2. On a regional scale, it is important to constrain their thickness and extent to establish which of the two are more likely. Regardless, mapped mudstones are also important inputs to geomodels.

Compilation of well data across the region provides a general overview of mudstone distribution. For the Utsira Fm., we measured the thickest intra-formation mudstone, along with the total net-to-gross of the interval in each well, and overlaid these onto a thickness map of the reservoir (Fig. 5B). This approach allowed quick screening to highlight mudstone-prone areas for more detailed mapping and assessment.

All the mudstones in the Utsira Fm. (in our study area) are <50 m (minimum seal thickness) and expected to only act as baffles to flow. There are few seismically-resolvable mudstones within the Utsira Fm, as most fall within a single wavelet. However, where mudstones could be mapped, channels were identified through sharp and marked reductions in amplitude. Channel erosion of the mudstone allows connection between underlying and overlying sandstones, thus resulting in a reduced acoustic impedance contrast [5]. As such, the mudstones are also not considered to be laterally-extensive. As part of a larger-scale study, considering the whole Utsira-Skade Aquifer, intra-aquifer mudstones were shown to be prevalent and in some areas, thick enough (>50 m) to contain CO_2 (top Skade Fm.) [5].

4.2.3 Fill-and-Spill Analysis

As the intra-reservoir mudstones were deemed to be baffles, only the top Utsira Fm. was considered suitable for long-term sealing of CO_2. Structural closures and potential CO_2 migration paths were mapped at this level. For this, we used a fill-and-spill simulation using Permedia^{TM}. We used 800 random source (injection) points to cover the full Utsira Fm. From each source point, fluid migrates up-dip beneath the sealing surface until it is trapped in a closure or reaches the boundary of the map (Fig. 5C). This method only considers structural gradients to determine fill-and-spill. It does not consider physical and chemical processes that act over different timescales, and their impact on fluid migration and trapping.

It is important to quality-check the simulation results, as velocity pulls-ups or onlaps onto underlying mounds (the latter of which are prevalent in our study area) can be erroneously plotted as closures. The authenticity of each individual closure was validated using seismic cross-sections.

The analysis revealed that most of the largest closures are in the centre of the Utsira Fm., and that migration paths mainly extend towards the southwest (Fig. 5C).

4.2.4 Storage Capacity Estimation

The effective storage capacity of each prospect was calculated using the following equation:

Eq. 2: $$Effective\ storage\ capacity = GRV \times Porosity \times N{:}G \times CO_2\ density \times SE$$

Gross Rock Volume (GRV, in MM Sm^3) includes the rock within the closure (structural trap) and immediately underlying reservoir, where other trapping mechanisms could act. Porosity was taken from the closure apex, which approximated to the average for the prospect. Sandstone net-to-gross (N:G) was taken from the closest or most appropriate well. A CO_2 density of 500 kg/Sm^3 (from 800 m depth) was used [2]. Storage efficiency (SE) is the fraction of the reservoir pore space that can be filled by CO_2 [8]. Locally, this fraction depends on several factors (including reservoir character, geometry and conditions) and varies from 3-40% [16]. We used a SE of 5%, from calculated values in the same formation at Sleipner (in 2013) [17], but higher values could be used if only considering the GRV within the structural trap [5].

4.2.5 CO_2 Storage Prospect Portfolio

Not all of the identified traps are suitable for storage and so some were discarded, i.e. those with: 1) an apex depth <700 m below sea level; 2) a negative CC score; and 3) <5 Mt CO_2 storage capacity (Fig. 5E). The depth limit was applied because CO_2 would leave the supercritical phase at shallow depths. The 800 m depth contour is also plotted on Fig. 5E, which could be used as a more conservative depth limit. A 5 Mt capacity cut-off was used to focus on the largest targets for injection. However, smaller structural traps could be utilized through a fill-and-spill approach during injection.

There are four prospects in the Utsira Fm. that are deemed suitable in terms of containment and capacity (Fig. 5E). The storage capacities of these are 32, 9, 7 and 5 Mt CO_2, but could be greater using a higher storage efficiency. These should be the targets for further detailed appraisal and could be used in isolation or as a network of traps.

The results are not directly comparable to existing full aquifer studies [e.g. 2, 9 and 10], because we provide site-specific storage capacities. Moreover, we only consider traps as prospects if their capacity is >5 Mt CO_2.

5. Discussion – Application of the Workflow

We advocate and present a play-based, risk segment mapping evaluation style for regional CO_2 storage site exploration. The objective of the workflow is to provide a screening method to identify potential storage sites in an aquifer, which would then require additional data collection and analysis for detailed appraisal.

Due to the inherent differences in geology and data availability/quality across basins worldwide, the workflows presented here are guidelines that can be tailored. For the CC assessment, through the use of a relative scoring system, elements can be added or removed and the relative scoring adjusted (although this limits comparison between aquifers). For the capacity assessment, additional elements (e.g. sedimentology, mineralogy, temperature) could be further added for aquifer delimitation and characterisation.

For the CC analysis of the Utsira Fm., we did not consider faulting or leakage from legacy wells, both of which could be important elements to include in the matrix. Faulting was not included as no large faults were observed [6]. The effect of legacy wells on leakage is debated [18] and their impact should be assessed on a local scale upon prospect identification. The number of well penetrations could be considered for comparisons and ranking of prospects [e.g. 6], however, there were no penetrations through the four identified prospects in the Utsira Fm. For the capacity analysis, alternative methods for porosity analysis could be adopted where FWI velocity data are unavailable. For example, using well logs or checkshots as point data for contouring.

Porosity (or sandstone quality) could also be considered as an element in the CC analysis, if there are sufficient data. For example, here, sandstones in the clinoforms of the seal and overburden of the Utsira Fm could be

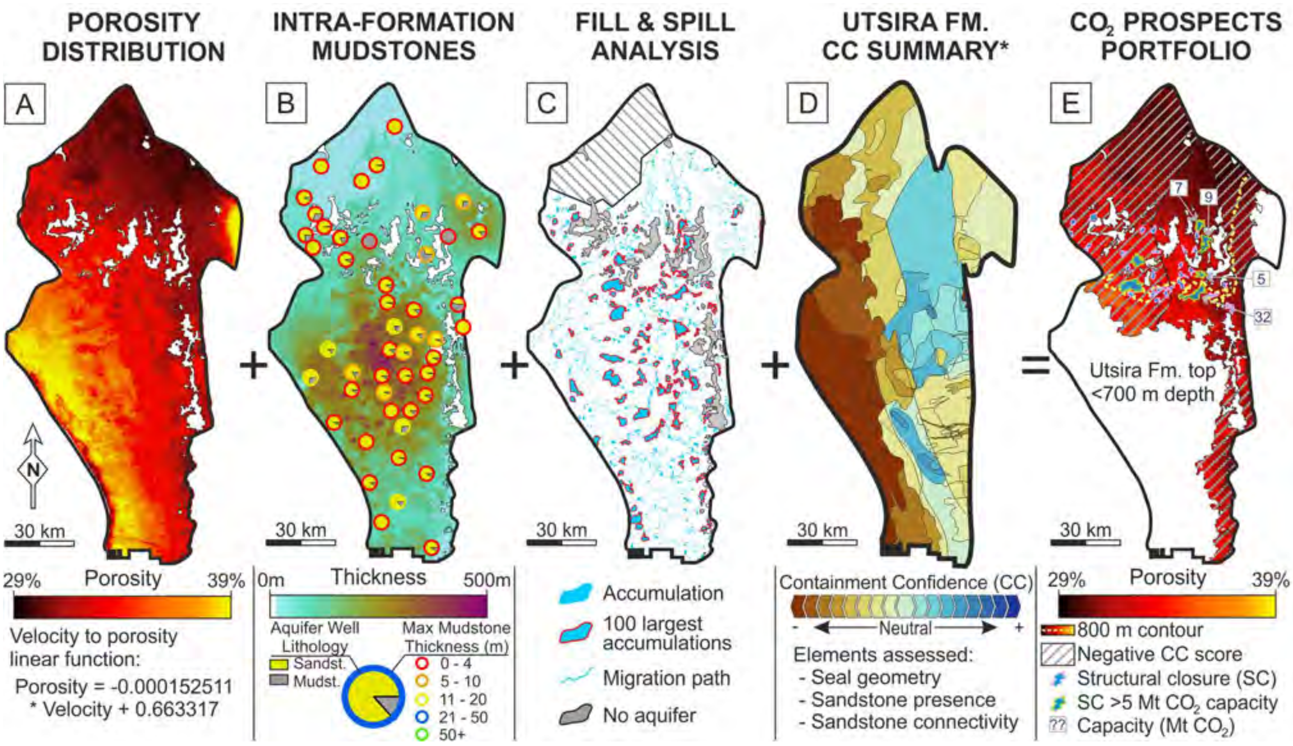

Figure 5| Capacity assessment for the Utsira Formation. A) Porosity distribution, B) Intra-formation mudstones (only displaying a subset of the studied wells), C) Fill-and-spill analysis, D) CC summary map (from Fig. 4), E) CO_2 prospect portfolio.

differentiated according to their different glacial (east-derived) and non-glacial (west-derived) origins [11, 12]. However, for screening, the presence of potential seal bypass systems is of primary importance [6].

A more detailed evaluation could be performed by introducing a second order into the elements. For example, for seal internal geometry in the CC analysis, the stratigraphy could be sub-divided into flat-lying, dipping 1-2° and dipping >2°, or for the capacity analysis, the intra-formation baffles could be split according to mudstone and siltstone lithologies.

6. Conclusion

Regional screening for CO_2 storage sites can benefit from play-based, risking exploration approaches. Here, we outline a widely-applicable workflow for regional screening of a CO_2 storage aquifer, using the northern Utsira Fm. as a case study. Containment and capacity are the primary factors that are assessed to identify suitable storage prospects. A containment confidence matrix is presented as an approach for seal and overburden assessment, which allows layer-based mapping of matrix elements to spatially-constrain the aquifer to the most secure areas. Seal internal geometry, sandstone presence and sandstone connectivity are the elements assessed, but faulting and well penetrations could also be incorporated, if applicable. The capacity assessment workflow aims to capture the 3D variability of the aquifer, which is typically not considered in storage capacity estimates. We incorporate regional porosity, intra-reservoir mudstones and fill-to-spill analysis to identify prospects. Finally, minimum depth (700 m), minimum capacity (5 Mt CO_2) and positive CC cut-offs are applied. For the Utsira Fm., the optimal region is in the northeast, where there are four prospects, with a combined storage capacity of 53 Mt CO_2. This workflow is based upon classic exploration approaches and can be applied with regional-scale legacy data. A portfolio of suitable CO_2 prospects can be identified and put forward for detailed appraisal. Moreover, output maps can also form the basis of static and dynamic models, well designs, and development, mitigation and monitoring plans.

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