Ranking and evaluation of CO_2 storage sites using an advanced workflow

Cyrille Reiser[1*], Noémie Pernin[1] and Nick Lee[1] describe a CCS workflow over a proof-of-concept area to assess CCS storage capacity and containment at a candidate saline aquifer site and highlight elements of the workflow to move towards automation.

Abstract

The world is in urgent need of carbon capture and storage (CCS) sites/facilities to achieve ambitious net carbon dioxide (CO2) emission reduction goals. After CO2 capture and transport, storage is the third step of the CO2 journey. Accessing and utilizing regional seismic information is a significant part of any workflow attempting to identify and characterize proposed subsurface CO2 storage sites. In this paper, we have developed and implemented a workflow over a proof-of-concept (PoC) area to assess CCS storage capacity and containment at a candidate saline aquifer site. Injectivity and monitoring/monitorability are assessed as part of an extended workflow. The integrated PoC CCS site assessment workflow allows validation of the various workflow elements and technologies, with the view to creating an efficient and scalable tool for regional site identification and characterization. The current project has been established using a PGS regional multi-client broadband seismic dataset in the North Sea which comprises an extensive cross-border regional dataset in the UK and Norway. The broadband nature of the seismic data allows significant and efficient site assessment, by providing detailed 3D characterization of the subsurface, away from areas with well control, and the parameterization of more accurate/reliable attributes for key storage attributes such as net-to-gross, porosity, and thickness. Finally, the integrated workflow and data integration allowed us to perform an efficient carbon storage site risk assessment as part of an overall site ranking process.

Introduction

Analysis by the Intergovernmental Panel on Climate Change (IPCC) points to the need for the development of carbon capture, utilization and storage to meet the 1.5 degree global warming ambition by 2050 (DNV report, 2021). A variety of carbon capture technologies are required to abate emissions from industrial sources, as well as deploy negative emissions technology to directly capture CO2 from the atmosphere post-2050. Large quantities of subsurface carbon storage will be required as part of the effort to meet the goals outlined by the IPCC. Recent analysis by Wood McKenzie suggests that while many projects are in development, the pace of project development is far short of what is required to meet the 1.5 degree target (Wood McKenzie, 2021). Its analysis points to less than 1 Gt of planned storage currently within the planning pipeline for 2030, with this needing to grow by eight times for the target to be met. Against this backdrop there is an urgent need to identify viable carbon storage sites that meet the cost and efficiency imperatives of this growing sector. PGS has a stated a strategic ambition to play a role in supporting the delivery of the energy transition alongside technical subsurface capabilities to deliver the necessary maturation of carbon storage sites. In practice, this means accessing and integrating a wide range of data, including regional high-quality broadband seismic and well information, and building efficient evaluation workflows that can identify and risk assess carbon storage sites.

As part of the technical development of a full subsurface evaluation workflow, an integrated geoscience workflow has been adapted from existing oil and gas evaluation methodologies as a proof-of-concept project to aid in the identification and maturation of carbon storage sites. The specific workflow is targeted at evaluating the capacity and containment characteristics of candidate sites. This project is part of a continuing effort to develop fit-for-purpose evaluation workflows extending from screening to simulation, to permit the full evaluation of a site from identification through to selection. Assessment of injectivity and the feasibility of monitoring CO2 plume migration are key elements of a fully integrated workflow, but these elements are not discussed in detail further in this article. The ambition of the workflow presented in this article is to create an efficient approach that is flexible and highly scalable, and able to be used on a range of data qualities, permitting regional evaluations of candidate storage complexes as well as more detailed characterization of site-specific containment and capacity risks.

Overall CCS project lifecycle workflow

Prior to CO2 injection at a specific site an integrated front-end project will be undertaken, following a similar path to a standard oil or gas field assessment (Figure 1). This would start with a screening phase intended to identify potentially feasible concepts, including identification of candidate subsurface site(s), their respective technical risks, their portfolio ranking, culminating with the selection of a site with required capacity characteristics.

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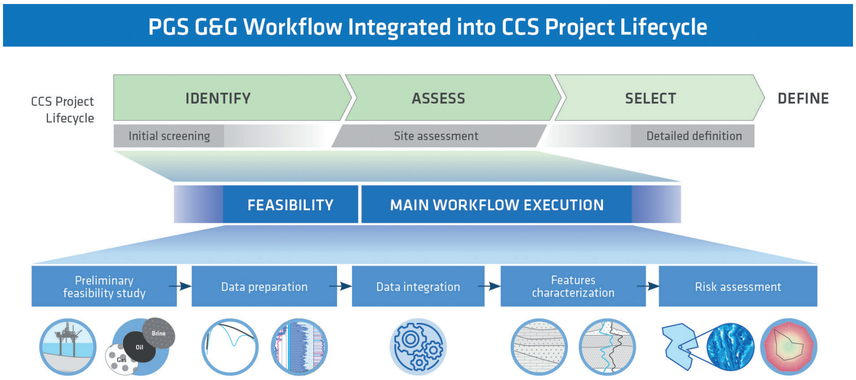

Figure 1 Carbon storage project lifecycle example. The figure represents a high-level view of the CCS project life cycle focusing on the early part of the project and encompassing elements such as petrophysics, rock physics, seismic data analysis-interpretation, and integration to the risk assessment matrix.

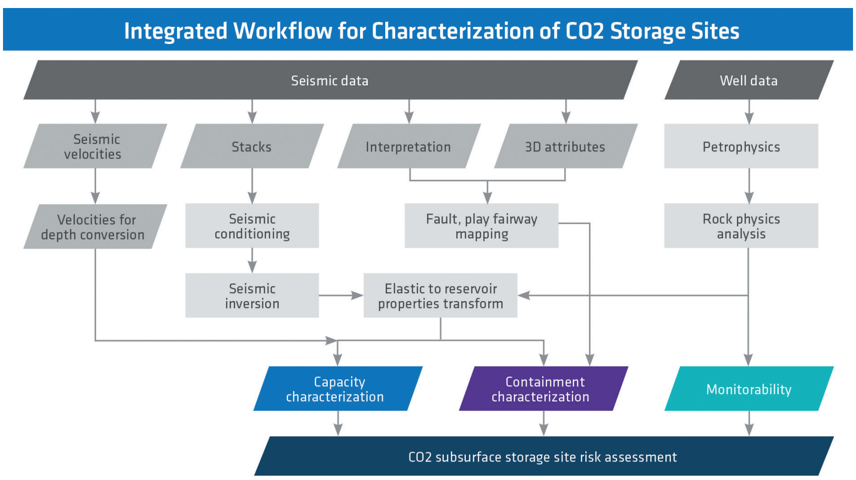

Figure 2 Overview of the integrated workflow for characterization of CO_2 subsurface storage sites.

Per the standard project workflow, the site would move into physical development and operational phases and finally closure. The focus of this article is a geoscience workflow that can be used during the early identification and assessment phases (Figure 1). It can be applied for storage complex evaluation and maturation of a site to early phase evaluation and provide a basis for more involved modelling and simulation work required for predicting CO_2 behaviour during injection.

Project CCS site assessment workflow overview

The workflow developed (Figure 2) for the characterization of a saline aquifer is very similar to what is performed in a conventional oil and gas seismic reservoir characterization or quantitative interpretation (QI) workflow including: petrophysics and rock physics analysis, seismic stack(s) optimization prior to seismic inversion for elastic property estimation, well-to-seismic calibration, transformation to reservoir properties, integration with a detailed seismic interpretation and conversion to the depth domain. A CO_2 storage site selection and characterization project must demonstrate compliance with three elements (coloured within the figure above). The characterization of capacity, monitoring and containment should be complemented by the injectivity for a full CO_2 subsurface storage risk assessment. One of the principal differences in the evaluation of potential CO_2 storage sites compared to oil and gas is the need to front-load more detailed analysis of the impact of geological reservoir heterogeneity on subsurface flow behaviour and integrate this insight into dynamic assessment when potentially less well data is available (where the site is a saline aquifer complex, for example). This is one of the key benefits of being able to implement reservoir characterization and QI workflows in the evaluation of carbon storage reservoir, seal and overburden properties away from areas of firm well control and is one of the primary benefits of high-quality broadband seismic data being available during the early stages of evaluation.

The integrated geoscience workflow was tested over a PoC area in the North Sea, where seismic data from a large unified, multi-client pre-stack depth migration broadband angle stack dataset was available. One of the first QC steps of the angle stacks showed reliable seismic signal from 2-4Hz to 32-64Hz, consistent spectral behaviour between stacks, high signal/noise ratio and good pre-stack time alignment. If needed, a dedicated Reservoir Oriented Processing (ResOP) sequence can be applied to prepare the input data for subsequent work. The optimization is performed to ensure the optimum pre-stack seismic quality at the storage reservoir and containment levels is achieved to estimate reliable elastic properties.

There are many ways of approaching site assessment using inversion with different algorithms and different inputs to the process. In this PoC area, a pre-stack relative inversion was performed generating 3D elastic attributes such as acoustic and shear impedances, and Vp/Vs ratios. Comparing the elastic attributes from wells and from derived seismic attributes only will give an indication of the quality of the products.

The output of the state-of-the art processing also delivered a high-quality, high-resolution well calibrated seismic velocity model for time-to-depth conversion. This conversion is an absolute prerequisite as geoscientists and engineers work in depth for estimating thickness of reservoirs, compute volumetrics or build reservoir models.

The wells went through a petrophysical and rock physics analysis to produce conditioned and high-quality interpreted logs. The well analysis has been performed in a regional and uniform manner ensuring consistency in terms of interpretation and workflows. These studies allow the correction and/or prediction of well logs and the derivation of reservoir property information such as total porosity (PhiT), clay content (Vclay) and water saturation (Sw).

Evaluation of reservoir properties is key to assessing the capacity and containment elements of a storage site. Once understood, it is possible to evaluate the link between reservoir properties (such as PhiT and Vclay) and elastic response (such as acoustic and shear impedances, Vp/Vs, Poisson's ratio) through rock physics analysis.

Ensuring a good match between wells and seismic data is necessary to get confidence in any elastic properties generated away from the wells and is a cornerstone of how the seismic method adds value to the site evaluation process, in areas where well data may be sparse. As the objective is to map the rock properties directly from seismic interpration, the integration of well-ties with elastic to reservoir property transformation is key.

Undertaking interpretation directly on reflectivity cubes or on 3D attributes brings additional valuable information when it comes to characterizing the capacity and containment of an area. Horizons can be used to produce a stratigraphic framework to map elastic attributes or reservoir properties cubes as described above. The production of incoherency cubes measures the dissimilarity between adjacent seismic traces and can be used as proxy to highlight areas of higher risk for seal integrity, due to faulting or fracturing. In complex geological contexts, a fault interpretation and analysis would be necessary to understand the true risk of reservoir compartmentalization and the potential leakage/breach risks within the storage complex. Structural interpretation can also be complemented by a 3D spectral decomposition analysis using blending of different seismic frequencies or blending different angle stacks at a specific frequency. This can reveal geomorphological features such as channels, crevasse splays and fans, identifying stratigraphic and sedimentological elements that refine the understanding of the storage unit and the overburden geology. In this way the rapid analysis of the 3D data can help to prioritize later, more detailed analysis, by identifying the most significant subsurface risk factors.

All the above analysis were used as input for establishing an automatic (as much as possible) site risk assessment. The cut offs from attributes were set to define the degree of risk associated to carbon storage components. Thereby, the comparison of different sites and the selection process can be made based on capacity and containment characteristics including integrity, lithological information, geometry evaluation, connectivity etc.

The significance of selecting the right data

A key element required for the site evaluation workflow is the assessment of the impact of data quality. The source of value to operating companies in CCS projects remains a matter of debate, but what cannot be debated is that costs should be a key driver in CCS project development, and screening workflows should not be exempt from this. Screening and evaluation workflows should take this into account as far as possible, being robust to the available data quality and the desire to use the available public data covering a large area (represented by a simple full stack seismic merged dataset, for example). It is, however, important to consider potential limitations on this approach:

- No pre-stack information could lead to inability to discriminate between a shale response and a porous reservoir seismic response
- Band-limited un-reprocessed conventional seismic datasets will be 'contaminated' with undesirable seismic responses such as side-lobes which would have an impact on the seismic interpretation and the overall geological understanding
- Processing that is not optimized for shallow or overburden imaging, but required for the assessment of containment, will affect the understanding of crucial containment intervals
- Poor seismic velocity resolution and accuracy will have an impact on the capacity assessment as the structure can be either seen or not and/or be smaller or bigger in reality.

All the above points will decrease the confidence in the site assessment risk when older vintage public datasets are used, but they remain valuable in developing evaluations to a certain level of fidelity (i.e. for a supra-regional overview/screening of a region). The value of high-quality data to realistically meet site evaluation objectives has been recognized by regulatory bodies. The North Sea Transition Authority's recent guidance (April, 2022) exemplifies this and details the relatively high level of technical assessment required to achieve a top-ranking application for a CO2 storage licence. The marking system clearly highlights the need to use the best available modern seismic dataset to collect as many marks as possible. As with any part of a front-end project, the decisions will be subject to risk-value trade-offs and the data quality question in the evaluation of CCS sites is no exception. There will certainly be a need to acquire high-quality site-specific seismic data at some point in the project lifecycle – as current North Sea projects are now demonstrating (e.g. Northern Endurance and Northern Lights).

Well log data is also crucial for successful completion of the workflow, but its availability for a CCS site assessment can also present a challenge when specific formation evaluation measurements could be missing in the overburden. To date, only one CO2 site-specific appraisal well has been drilled in the UKCS on the Endurance structure in Quad 42 where high-quality data required for detailed site characterization including in the overburden were obtained. Gathering as much well information as possible over a very large area (potentially larger than the site assessment) may be necessary to ensure sufficient log representation in the overburden, which could be used as a training model for well log prediction techniques (Ruiz R. et al, 2021). It should be acknowledged that, much as in the seismic case, an absence of suitable data to characterize a site might also drive a site developer to acquire additional well data at the site in certain circumstances.

Site assessment results

The results shown in the subsequent sections relate to a known shallow saline aquifer within the North Sea in the vicinity of infrastructure potentially relevant to CO_2 emitters (close to hydrocarbon production areas). The focus is on the capacity and the containment of the carbon storage site.

- **Capacity characterization and volume calculation**
  Figure 3 shows selected results of the characterization of an Oligocene shallow marine sandstone aquifer. The top-left map shows the integration of the seismic interpretation (results of an automatic seismic interpretation approach, Pauget et al., 2009) and spectral decomposition (blending of the near, mid and far stacks at 40Hz), which suggests presence of sand waves and points to potentially significant stratigraphic complexity relevant to CO_2 plume migration modelling during later stages of the site evaluation. This allows us to map the geological heterogeneity of the saline aquifer and obtain outputs that can be directly used in later workflow steps (i.e., as attributes to assist with the conditioning of reservoir properties during reservoir modelling). With calibrated seismic velocities and interpreted horizons, the estimation of the thickness of the reservoir (bottom-left map) can be accurately computed showing a thickness increase towards the bottom-left corner of the area of interest. The elastic attributes (acoustic impedance and Vp/Vs in depth section, centre panels in Figure 3) were computed from pre-stack seismic inversion integration with the wells and rock physics analysis (summarized in the top-right corner) allow the generation of not only calibrated elastic properties tying the wells, but also 3D reservoir property estimation such as porosity over the entire studied area (bottom-right map).

These properties (thickness, porosity, net-to-gross) can be directly utilized in the computation of the gross rock volume and pore volume required for the CO_2 storage capacity calculations.

- **Containment assessment**
  The second element addressed by this workflow is a site containment evaluation. The overlying containment interval comprises two geological components (Lloyd et al. 2021), the top seal (layer just above the storage reservoir) and the overburden (remaining section above). Figure 4 shows some results of the characterization of the containment intervals above the Oligocene saline aquifer. The high-resolution 3D interpretation, along with the regional geological interpretation (middle sections), display a conformable seal and overburden to the potential storage level. A suitable heuristic rule applied to seal evaluation is that the higher the shale content, the lower the containment risk, as opposed to the capacity where the target reservoir property was porosity, and here the relevant reservoir property degrading factor is volume of shale (top right cross-plot, Figure 4). Top seal and overburden conformity is also suggested by negligable difference in the dips of the seal compared to the container level, as shown in the bottom-left map. The seal faulting has also been assessed (top-left map, Figure 4), illustrating the increase of faulting towards the bottom-right corner of the map, where polygonal fault systems are developed. They might cause potential leakage, depending on fault properties and the relationship with other lithologies (for example

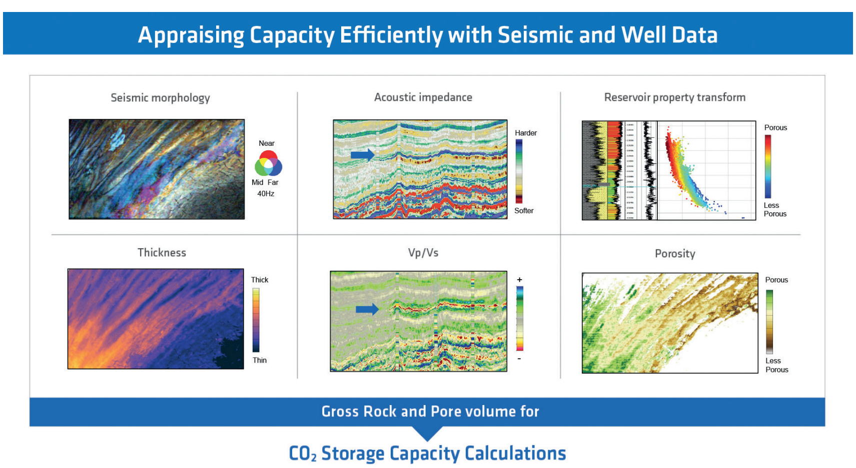

Figure 3 Overview of the main results of the storage site characterization that are contributing to the computation of gross rock and pore volume for subsequent CO_2 storage capacity calculations.

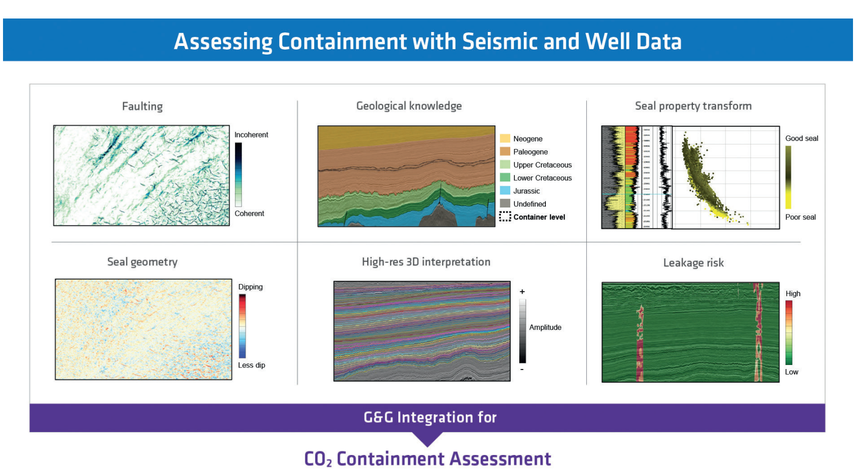

Figure 4 Overview of the main containment characterization results contributing to the overall CO_2 containment assessment.

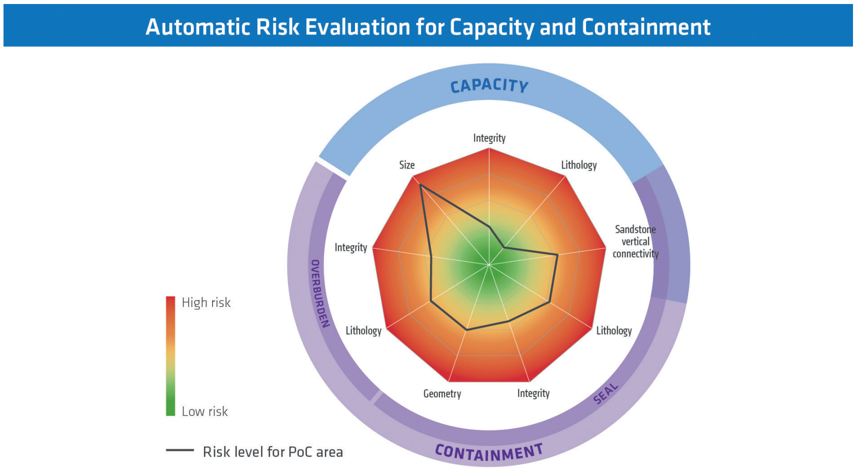

Figure 5 Semi-automatic risk assessment for the capacity and containment. The black polygon refers to the risk level associated with a site within the studied area for all the categories highlighted. Having an overall black line towards the centre of the spider diagram represents a lower risk for the site concerned. With this type of semi-automatic site risk assessment, various sites can be compared and ranked effectively.

such features can be exploited by injectites sandstones in deep-marine depositional settings, leading to seal bypass risks). However, faults were mainly observed in areas where the container is not present (compared with bottom-left map from Figure 3). Few faults are present towards the top of the map with some of them potentially prone to leakage risk. A more advanced fault interpretation and fault system analysis (permeable vs. sealed) should be considered in more complex overburden geometries to further assess the seal integrity of the area, particularly where there is a more complex association of sealing and localized non-sealing lithologies.

The use of the automatic seismic interpretation framework to map products (including the 3D lithology volume predicted from seismic elastic attributes) allows a rapid visualization of both the capacity and containment characteristics, showing both spatial and vertical variations. Appreciation of the link/relationship/connectivity between all these features is extremely valuable for the risk assessment.

- **Overall risk assessment**
  The CO2 subsurface storage site risk assessment integrates all derivative products generated during characterization of the capacity and the containment. Risking allows the comparison and ranking of potential storage sites in support of the site selection process. Some risks are directly associated with 3D volumes. For example, the integrity of the seal is linked to the density of faulting and some cut-offs were defined to automatically assign the risk level. Some other risks, such as connectivity of sands between the capacity and seal were based on Common Risk Segment (CRS) maps.

Figure 5 represents a spider diagram that scores features of a site related to its capacity at the top and related to its containment at the bottom and provides a visualization of risk elements. Low risk areas are highlighted in green whereas high risk areas are coloured in red. The risk assessment applied to the study area is illustrated by the black polygon. In this example, the main risk is associated with the volumetric capacity.

- **CO2 monitorability**
  Although monitorability is not directly part of the workflow discussed in this article, it is worth mentioning. The concept of monitorability is an important component of any site evaluation looking at the feasibility to monitor CO2 injection performance at a site throughout the project lifecycle. The plan to monitor a site is enclosed in the Measurement, Monitoring and Verification (MMV) plan. This is intended to ensure that a framework and technology is in place for the assessment of injected CO2, verifying that it behaves as expected and to detect any abnormal behaviour against forecast. MMV assessment spans the projects life cycle, pre-injection as a feasibility study, during and after post-injection, and following site closure. At the feasibility stage various components of the monitoring can be assessed (very similar as to what is performed in a hydrocarbon development workflow): seismic monitoring feasibility, reservoir/rock physics monitoring. A range of monitoring techniques (IEAGHG 2015) are available for CO2 geological storage offshore such as seismic, seabed gravity, controlled source electro-magnetic (CSEM), 4D Vertical Seismic Profiling, wellhead pressure, down-hole pressure and temperature, and passive seismic monitoring to named just a few. All these techniques have the aim of monitoring (measurement and control) the containment and the conformance to expectations as CO2 is injected and the plume migrates into and within the storage unit. Seismic data is widely used in hydrocarbon field monitoring and can also be very successfully applied to CO2 storage (Furre, et al. 2017, 2020). The monitoring approach, and techniques to be deployed for a particular site, should be risk-based and informed by the results of the containment risk assessment, for example, and informed by the workflow outlined here. Seismic data is recognized in the context of CO2 storage monitoring as a very flexible and cost-efficient technique for active monitoring, but the specific approach should be tailored to the specific needs of each project and consider a range of other non-technical factors (e.g. regulatory requirements). In fact, a risk-based approach, rather than deployment of a standard ‘monolithic’ workflow is vital to completing cost-effective site evaluation and monitoring in all aspects.

To consider the suitability of seismic methods, an interactive rock physics workflow enables the modelling of the seismic response through various CO2 saturation scenarios (Figure 6).

With this modelling, the sensitivity of the seismic response to saturation can be assessed and be an input to the seismic design, acquisition and imaging requirements. On the seismic or the survey design choices, seismic modelling can be performed with various acquisition configurations to optimize the seismic survey according to the above observation in relation to the variation of injected CO2. Additionally, the reservoir static and dynamic model can be used in conjunction with the rock physics model for the simulator-2-seismic workflow i.e., predicting the seismic response at a different time step of the CCS project life.

Thus, monitorability can be evaluated by a fluid substitution modelling process. It has been performed here on a well that encountered a thick, clean sand from a saline aquifer. Figure 6 reveals the impact of CO2 saturation on the acoustic impedance (AI) and Poisson's ratio (PR) elastic attributes (curves to the left) and on the synthetic Amplitude Versus Offset (AVO) modelling (panels to the right). Note the strong response at near offsets and on AI even for low CO2 saturation (10%). Increasing the CO2 saturation has little impact on AI; however, there is a better discrimination between the different saturation scenarios in PR or Vp/Vs domain. For this aquifer it appears that monitoring the CO2 saturation over time would require a pre-stack attribute, such as PR, to monitor the CO2 saturation change. It would therefore require the use of reliable AVO seismic data.

A new, efficient, scalable and flexible CCS workflow

The workflow discussed in this paper has been developed with a view to being flexible as far as possible with respect to the type of input data available, its quality and the overall objectives required during the early stages of a CCS site evaluation project.

The described data driven scheme creates a time-efficient workflow which is easily scalable. However, it does rely on availability and quality of the input data to achieve robust and usable results.

The a priori confidence in the evaluation of CO2 subsurface storage sites increases when:

- Good quality well data are available as calibration points, including across overburden units
- the rock physics favours a prediction of reservoir properties from elastic response
- High-quality 3D broadband pre-stack depth seismic data is available.

Some benefits of the broadband seismic data are: the data-driven seismic inversion approach, the stabilization of the automatic horizon interpretation due to the reduction of sides lobes (Ozdemir et al., 2009 and Reiser et al., 2012) and the improved reliability of the reservoir property estimation as the 'frequency gap' is very small and can be easily filled in with calibrated seismic velocities to obtain an absolute product. The access to AVO information, through pre-stack seismic, would bring value if the prediction of reservoir properties from elastic response requires Vp/Vs or PR. Finally, a 3D depth imaging workflow improves the reliability of the positioning of the seismic events in the depth domain, which will be useful for later integrated subsurface assessments or other project activities (e.g. well planning).

The workflow as described can also be integrated into a broader subsurface workflow, where derived seismic attributes can be used to constrain early-stage reservoir and simulation models, and insights from those attributes used to direct more focused work on specific areas of technical risk.

Ways of moving toward automation

The need to create cost-effective and time-efficient workflows for CCS has been noted, and this workflow has been developed with this need in mind. However, there are further improvements that can be implemented via faster analysis and delivery as represented in Figure 7. The improvement areas can focus on:

- **Seismic imaging**
  Recent developments in the simultaneous inversion for both estimation of the velocity and the seismic reflectivity (Yang Y., et al, 2021) could create the opportunity to generate an earth model shortly after acquisition. This would reduce the turnaround in the early stage of the CCS workflow and deliver valuable products such as a high-resolution velocity model.
- **Well log data**
  Ruiz et al. 2021, demonstrated the potential of using machine learning (ML) algorithms to accurately predict missing logs (such as Vs) and perform CPI analysis (including PhiT, SW and Vclay) from a limited amount of measured well logs,

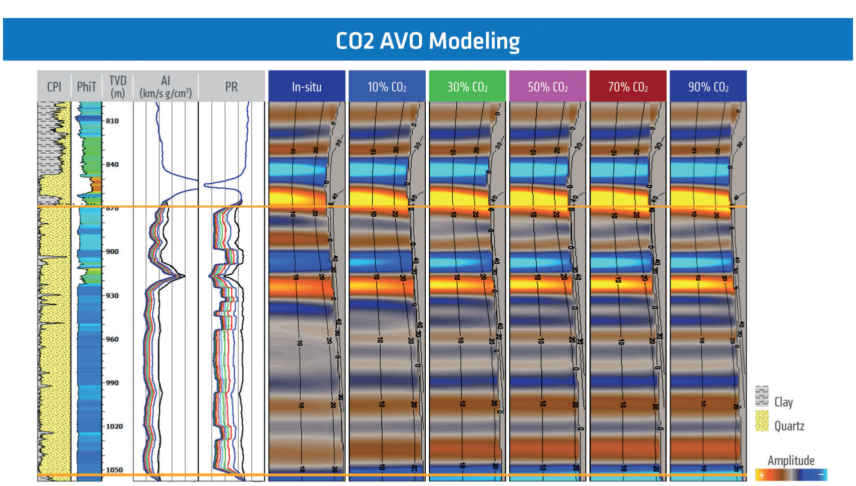

Figure 6 Example of ray tracing offset gathers synthetic modelling with scenarios of CO2 saturation ranging from 10 to 90% with an increment of 20%) (Ormsby broadband wavelet), *Oyetunji et al., 2022, unpublished results.* The different tracks in the above Figure are (from left to right): Computed Petrophysical Interpretation (or CPI), Total Porosity (PhiT), True Vertical Depth (TVD), Acoustic Impedance (AI), Poisson Ratio (PR) and the different seismic offset gathers for the different CO2 saturations from 10 to 90%.

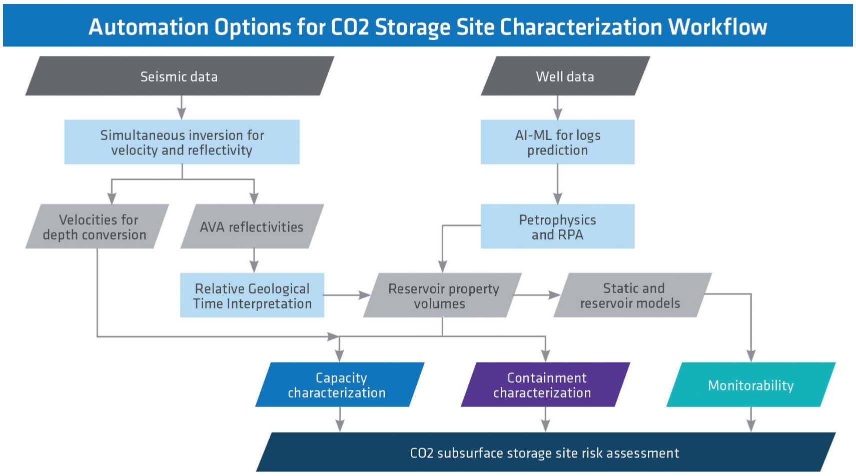

Figure 7 Same workflow as presented in Fig.2 with highlighted areas of possible automation (light-blue boxes) and/or significant speed-up tasks.

aided by an extensive petrophysical and rock physics training model from our multi-client library.

- **Seismic interpretation**
  An automatic horizon interpretation (Pauget, 2009) was performed to rapidly screen the capacity and containment levels based on the regional interpretation. The dense vertical/temporal interpretation (Figure 4, bottom centre section) enabled an efficient evaluation and screening of the seismic data and its derivatives/attributes while scrolling the 3D volumes. Horizons were used as a framework to guide the various amplitude extraction processes (Figures 3 and 4, left maps)

The workflow is mainly data driven (with limited input from the geoscientist for the well-to-seismic calibration) when it comes to assessing the capacity and containment from data QC, attribute derivation, rock physics and risk assessment. For the current project, the latter was performed automatically, based on equations and conditions using the relevant technical output of the PoC.

The interactive accessibility of rock physics modelling perturbation (Figure 6) and assessment over the modelled pre-stack domain enable rapid access to semi-automatic scenario modelling at the chosen well locations when examining impacts of CO_2 saturation.

Finally, the main advantage of this workflow is its applicability to other sites to develop a portfolio of storage options. The automatic risk assessment ranking between different sites can be performed and evaluated for the most desirable site going forward in a consistent manner.

Conclusions

The workflow describes the integration of high-quality broadband seismic data, well information, their derivative products, and several reservoir geoscience analysis tools to characterize key CCS site evaluation components: capacity, containment and monitorability. The interpretation stage on its own provides geological understanding: sediment distribution, faulting, layer geometry, and depositional environment relevant to the suitability and expected performance of a site. The petrophysical and rock physics analysis is the bridge linking elastic properties (AI and Vp/Vs) to reservoir properties (PhiT or Vclay). The well-to-seismic tie augments confidence in the reliability of the lithology prediction and reservoir property estimation away from the wells. Finally, the calibration of seismic velocities improves the depth transform for the structure of the storage reservoir and its thickness which is crucial for the capacity volumetrics. As the implemented workflow is mainly data-driven it can be easily extended over large areas for CCS site screening and characterization purposes. Ranking and evaluation of various CCS sites can be done using the presented risk evaluation matrix. Recent advancement in technology including machine learning and imaging techniques applied to seismic and well data gives insurance that in addition to being flexible and mostly automatic, the turnaround can be further improved as a step towards automation of the CCS site selection workflow. This could open up opportunities for the screening of large areas and the efficient site ranking prior to selection.

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