Integrated workflow for characterization of CO_2 subsurface storage sites

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Summary

The world is in urgent need of Carbon Capture Storage (CCS) sites/facilities to achieve ambitious net carbon dioxide (CO_2) emissions goals. One way to store CO_2 in significant quantities is to identify sufficiently large-scale subsurface CCS sites. There is an immediate need to identify viable CCS storage sites fast. To do this, accessing regional quality broadband seismic information would be a significant move in that direction.
An integrated G&G workflow has been developed and implemented over a proof-of-concept (PoC) area initially considering two aspects of the CCS storage: capacity and the containment. Other aspects of CCS, such as injectivity and monitoring, will be assessed at a later stage. The integrated reservoir geoscience CCS site assessment workflow allows local validation of the various technologies and workflows. This is opening the possibility this workflow to be apply regionally with the objectives being to evaluate the use of all data (seismic and wells) for an adequate capacity and containment assessment.

Introduction

The world is in urgent need of finding Carbon Capture storage (CCS) sites/facilities to achieve ambitious net carbon dioxide (CO_2) emissions goals. The subsurface storage of CO_2 which is required in significant quantities necessitates identification of sufficiently large-scale CCS sites. At present, there are less than 30 sites worldwide storing around 40 Mt of CO_2/year (GCCSI, 2020; Ringrose and Meckel, 2019), and the expectation is to have close to 300 Mt storage capacity per year by 2050 (European Commission, 2018). Thus, there is an immediate need to identify viable CCS storage sites fast. Efficient assessment of regional, high quality seismic information would be a significant step in that direction.
In this paper, we present a recent integrated G&G workflow over a proof-of-concept (PoC) area considering two aspects of the CCS storage: capacity and containment. The integrated reservoir geoscience CCS site assessment workflow allows validation of various technologies on a local scale, with the option and feasibility to be expanded regionally. The main objective of this study is to evaluate the use of all the data (seismic and wells) for CO_2 storage capacity and containment assessment.
The current PoC has been established using a PGS regional multi-client broadband dataset in the North Sea which comprises an extensive cross border regional dataset covering the UK and Norway. The broadband nature of the seismic data allows significant and efficient site assessment, by providing detailed descriptions and understanding of the subsurface, including more accurate/reliable pre-stack attributes for key storage parameters such as sediment net-to-gross, porosity and thickness. All of this is determined using primarily the seismic dataset, with secondary information from a few calibration wells. We will highlight the key elements of the workflow starting from the data itself, interpretation, rock physics, seismic inversion and more importantly the integration of all these aspects for mapping and characterization of the CO_2 container and containment.

Integrated Reservoir Geoscience Workflow

The area of interest (AOI) is located in the southern part of the Norwegian sector in the North Sea in a water depth around 60-70 meters. In the AOI, a field had produced oil until 2020 from the Upper Jurassic Ula Formation sandstone from a depth of around 4,000 meters. For this particular project, the stratigraphic interval of interest is the Oligocene saline aquifer whose sandstones were deposited in a shallow marine environment.

The workflow implemented (Figure 1) for the characterization of this saline aquifer includes steps very similar to what is performed in a conventional oil and gas seismic reservoir characterization or quantitative interpretation (QI) workflow including: pre-stack seismic optimization/conditioning prior to seismic inversion, petrophysics and rock physics analysis, seismic inversion for elastic properties estimation, transform to reservoir properties and integration with a detailed seismic interpretation. The main difference to an oil and gas exploration/development study is the emphasis on the containment (seal and overburden) rather than "just" on the reservoir aspect (capacity).

For the capacity and the containment characterization of the CCS site assessment, the main expectation of this study should be to map the sandstone porosity distribution, the shale distribution in the overburden and any indication related to integrity or sealing "efficiency". The effective CO_2 storage capacity is the product of the gross rock volume, the porosity, the net to gross, the density of the CO_2 and the storage efficiency for a saline aquifer typically between 2 to 8% (May *et al*., 2005) and being 5% average in this case.

Database and Assessment

The seismic data used for the project is part of a large unified multi-client pre-stack broadband dataset covering over 17,000 square kilometers in the North Sea Central Graben.

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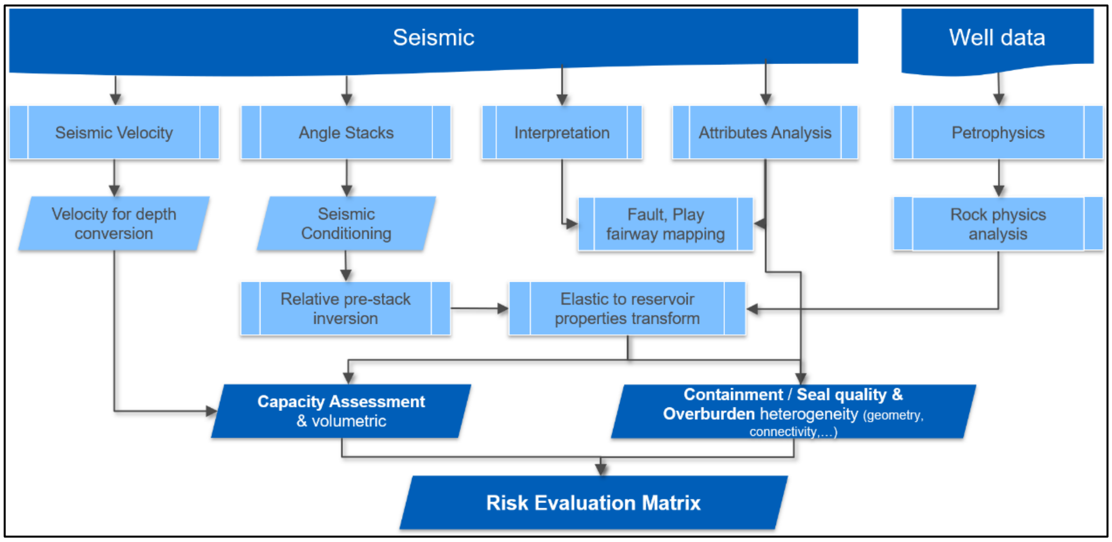

Figure 1: General overview of the seismic data analysis workflow implemented for the CCS container and containment analysis

This dataset went through an advanced depth imaging workflow using anisotropic velocity model building and Kirchhoff depth migration including compensation for earth absorption. The dataset has a very broadband seismic frequency bandwidth (close to 90Hz in the interval of interest) and an excellent signal to noise ratio over the entire seismic section depth range due to the multisensor deep tow streamer acquisition.

On the seismic data, detailed AVA (Amplitude Versus Angle) QCs were performed, followed by a final reservoir-oriented processing (ResOP) focusing on the Tertiary interval to optimize the data prior to seismic inversion. The main ResOP steps of this workflow included de-noise, spectral frequency balancing and post-stack alignment correction to ensure that the data is matching the wells. The seismic velocity used for the depth migration was further calibrated with well data to ensure a more accurate time to depth conversion making sure of a precise estimation of the container thickness, and representation of the overall geological structure.

As the objective is to map the rock properties such as porosity and volume of shale/sand, a link between the seismic and the well world needs to be established. Rock physics is the key and only element that links these two domains. Thus, a regionally consistent interactive rock physics modelling product (rockAVO) has been developed to build a homogeneous database of high quality interpreted and conditioned well data. Petrophysical analysis allowed 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). These reservoir properties are key to assess the efficiency of the container and containment elements of the CCS.

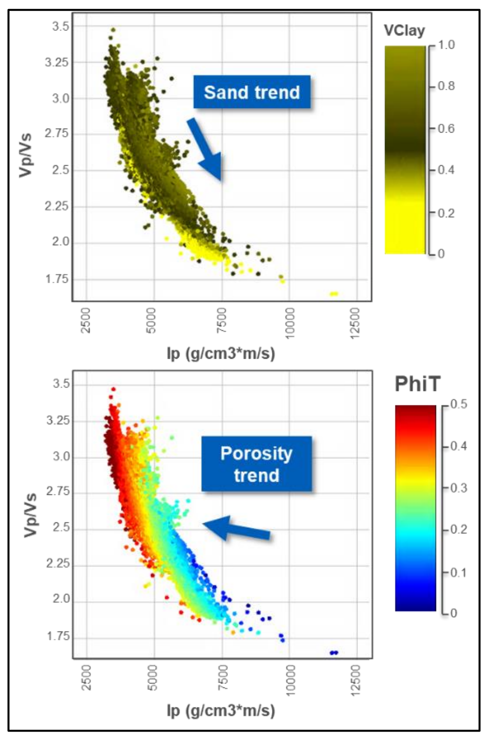

Figure 2: Rock property trends (sand content to the left and porosity (Total porosity PhiT) to the right) observed from well data within the elastic domain (acoustic impedance Ip vs. Vp/Vs) at the Oligocene saline aquifer level. A porous sand/container will exhibit a low acoustic impedance as well as a low Vp/Vs ratio (bottom left corner of the cross-plot)

The rock physics diagnostic allows the QC of any observable trends of reservoir properties within the elastic domain (Figure 2).

For this PoC, the chosen elastic domain is acoustic impedance (Ip) vs. Vp/Vs, and the targeted reservoir properties were: PhiT, Vclay and SW. As presented in Figure 2, a transform/relation can be found between the acoustic impedance, Vp/Vs and PhiT for example.

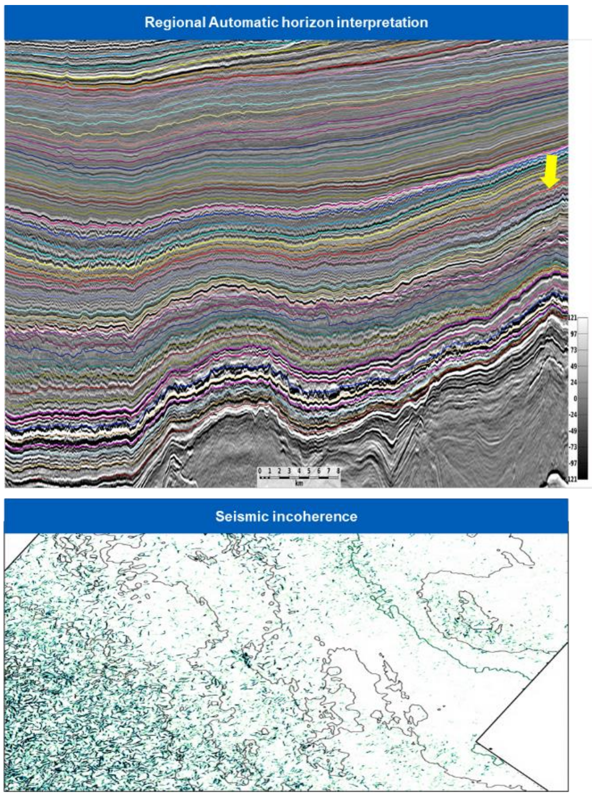

Figure 3: Representation of the automatic seismic interpretation building a Relative Geological Time (RGT) framework for the interpretation (top) and the mapping of specific seismic attributes such as the incoherency volume (bottom), showing zone of high discontinuity on the seismic reflection potentially indicating potential seal faulting issues

In parallel to the input seismic data QC and well study, an automatic regional horizon interpretation (Pauget, 2009) was performed to rapidly screen the containment. This interpretation was used as framework to guide the various amplitude extraction processes. The dense vertical interpretation grid (Figure 3, top) allows efficient evaluation of the seismic data and its derivatives/attributes while scrolling the overburden and seal characteristics in terms of: geometry of the sediment deposition (helping the seismic morphological interpretation), faulting and/or seismic discontinuity mapping (highlighting potential issues with containment).

One of the first attributes to be mapped on this horizon framework was an incoherency volume (the measure of the dissimilarity between adjacent seismic traces) computed from seismic amplitudes to identify areas of higher risk for seal integrity (Figure 3, bottom). This combined with a spectral decomposition result (both pre-stack AVA blend and frequency blend) using the above framework highlighted potential heterogeneities within the seal (Figure 4, left). From the CO2 container point of view, the spectral decomposition and its frequencies blend attributes revealed depositional environment geometries suggesting reservoir characteristics such as porosity or volume of clay from geological interpretation only. A top and base container interpretation has been performed for 3D structure analysis (trap shape, size estimation, etc.), thickness evaluation and detailed attribute mapping within the container level.

Fault interpretation and fault system analysis (permeable vs. sealed) could also be considered in more complex overburden geometries to further assess the seal integrity of the area.

Following this key step of geological understanding (container and containment), a pre-stack seismic inversion using the broadband data was performed to estimate the acoustic impedance (Ip), shear impedance (Is), and Vp/Vs using the conditioned angle stacks as input. Thanks to the broadband nature of the seismic data used, a data driven seismic inversion approach is possible (Ozdemir *et al*., 2009 and Reiser *et al*., 2012), which is commonly used in conventional hydrocarbon reservoir characterization. This data driven scheme makes it a time-efficient workflow easily scalable to large seismic volumes. Thus, with the rock physics analysis achieved and the seismic inversion performed, the derivation of the reservoir properties volumes through the established transform (coming from the rock physics analysis) is possible. The confidence in expanding this transform to 3D relies on a good correlation between the wells and the seismic data in the first place, hence a well to seismic tie effort was performed prior to the application of the transform away from the wells. Therefore, a good quality seismic is also needed in addition to a good quality well database and this is the case here. With the integration of all the above information, it is now possible to interpret directly on the rock property cubes by mapping the relevant vertical and lateral changes of lithologies and reservoir properties within the aquifer but also screening for any change in the overburden layer serving as a seal (Figure 4).

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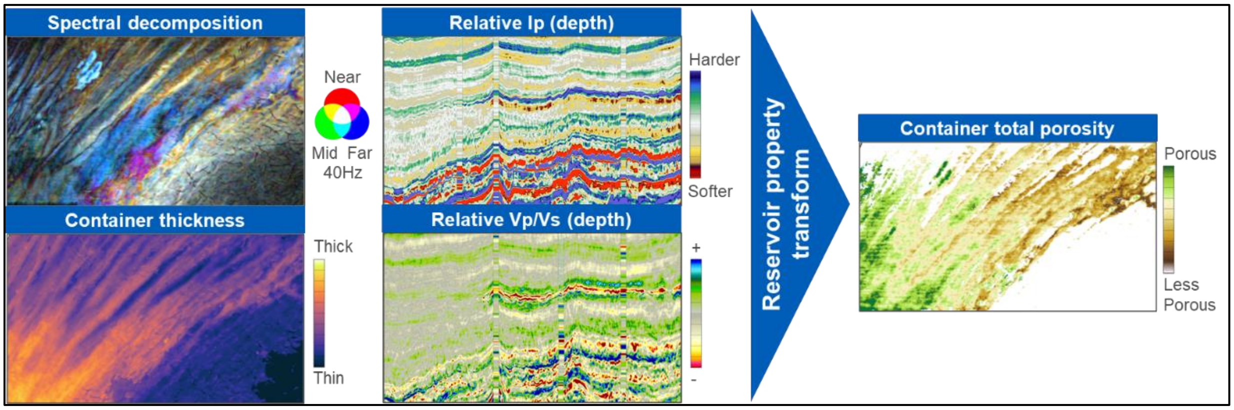
Figure 4: Brief illustration of some key results, left:3D seismic geomorphology interpretation (spectral decomposition of blended angle stacks at



40Hz frequency) and thickness of the container, middle: estimation of elastic attributes (Ip, Vp/Vs) from pre-stack broadband seismic inversion and reliable time-to-depth conversion are input to rock physics transform derived from well data only (arrow in the middle) leading to right: 3D volume of porosity within the container

Integration and risk evaluation

Following the technical assessment characterization for capacity and containment, a risk matrix was created for various components of the CCS such as: size of the capacity, integrity of the seal, lithology type, overburden integrity (Figure 5). The risk assessment applied to the PoC area is illustrated by the black polygon within the spider graph. For this specific area, the main risk for this site is the size of the container (too small potentially).

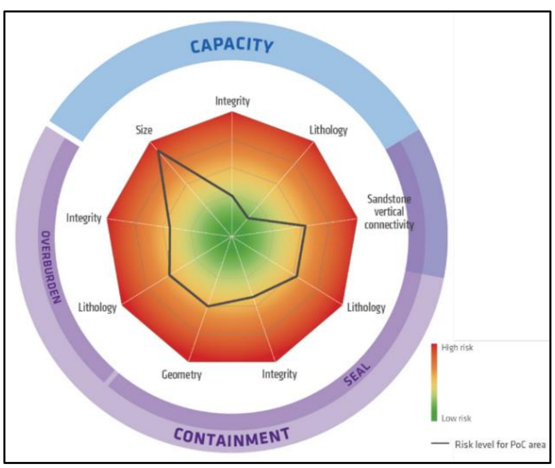


Figure 5: Risk evaluation matrix for the capacity and containment for this PoC located in the Norwegian sector in the North Sea. The plain line in the spider diagram represents the risk level for the various components of the assessment.

As the workflow is mainly data driven, this risk assessment has been performed automatically based on equations and conditions using the relevant technical output of the G&G analysis. The main advantage of this flow is therefore its applicability in other sites and effective deployment to larger areas.

Conclusions

The workflow described above, comprises the integration of high-quality broadband seismic data, well information, their derivative products, and several reservoir geoscience analysis tools to characterize two key CCS components: container and containment/seal. The interpretation stage on its own provides geological understanding: sediment distribution, faulting, layer onlapping, and depositional environment. The petrophysical and rock physics analysis is the bridge linking elastic properties (Ip and Vp/Vs) to reservoir properties (PhiT or Vclay) for both the overburden/seal level and container. The well to seismic tie augments confidence in the reliability of the reservoir properties estimation away from the wells. Finally, the calibration of seismic velocities improves the depth transform for the structure of the container or its thickness and is crucial for the capacity volumetrics. As the implemented workflow is mainly data driven it can be relatively 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 and open up the possibility to look for a site at scale.

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