Interactive rock physics for CCS and near field exploration, a UK Southern North Sea case study

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Summary

Screening, identifying, and characterizing a CCS site is of paramount importance as the sector faces considerable challenges in delivering sufficient capture and storage capacity to meet stated targets. With the urgency to develop more sites, there is a need to effectively evaluate the storage capacity and confirm future monitorability. This paper will demonstrate recent results in the Southern Gas Basin in the UKCS. We will show how an interactive rock physics analysis has been developed over a selection of key wells in the area and demonstrate its application in the evaluation of seismic sensitivity to CO2 injection. In saline aquifer storage sites, CO2 is injected in dense phase as a supercritical fluid. As a CO2 is not gas at subsurface conditions, it will interact differently with the rock frame and specific attention is required in the way the rock physics model is built and calibrated. The presented tool is designed to enable geoscientist to interactively assess any reservoir property perturbations and their subsequent effect on the seismic response and an early assessment of potential monitoring feasibility. This workflow is relevant as part of a suite of approaches suitable for monitoring, measurement, and verification (MMV) approaches to be evaluated

Interactive rock physics atlas for CCS and near field exploration, a UK Southern North Sea case study

Introduction

Carbon capture and storage (CCS) is recognized as a critical technology to reduce the impact of emissions CO2, to the atmosphere and is a necessary step towards moving to a net zero carbon energy system. Thus, there is an urgent need to find suitable sites for storage, to evaluate their expected “performance” of such a store and also make an early assessment on future monitorability.
In a CCS context, and prior to new acquisition, reprocessing or licensing of new data over a specific area for carbon storage, it is preferable to perform seismic modelling from the available well information as part of a feasibility study and / or part of Measurement-Monitoring-Verification plan (MMV). To do this, we have implemented a workflow allowing the seismic response to be modelled and other key reservoir parameters to be interactively assessed, based on injection of CO2 into the candidate storage unit. This platform allows geoscientists to perform at will any number of reservoir property model perturbation scenarios and observe the immediate effect on modelled synthetic seismic. The workflow has been developed in the United Kingdom Southern North Sea (UK-SNS) and tested on a deep saline aquifer target within the Triassic Bunter Formation sands (Bentham et al., 2014). Additionally, as this region is also of interest for near field hydrocarbon exploration in the prolific Permian (Zechstein and Rotliegende) stratigraphic interval (which may also be relevant for CCS purposes), the workflow was extended to cover this unit. This paper covers the methodology used and the main results focusing on the CCS Bunter sands interval.

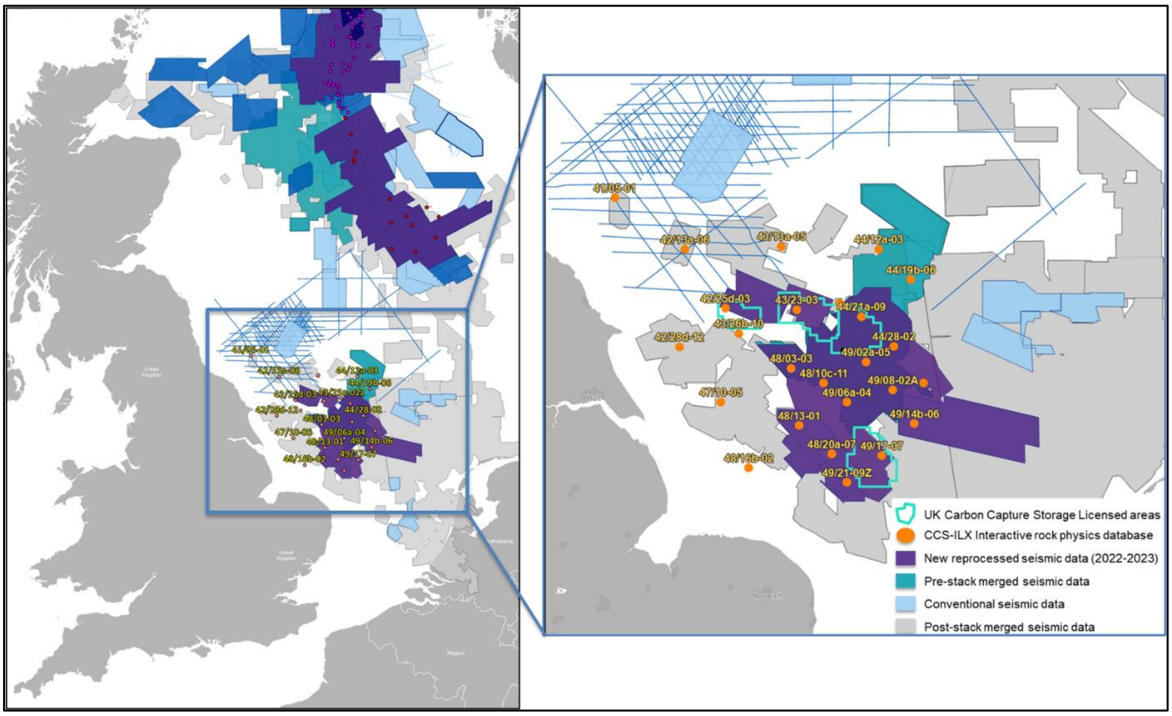

Figure 1 *Interactive rock physics well database distribution (25 wells) in relation to the UK Southern North Sea Carbon Capture Storage licensed area (cyan polygons highlighted, right figure) as well as multi-client seismic datasets, filled polygons with the on-going seismic reprocessing effort highlighted in dark purple.*

Method

The UK SNS area was chosen for this analysis, as the Bunter sandstone is thought to have significant potential to store CO2 (Chadwick, 2004) in this area. It has been extensively studied, with the storage potential evaluated by the British Geological Survey, and the first CCS project, Endurance, targeting Final Investment Decision (FID) in 2023. The Bunter sandstone overlies the deformed Zechstein evaporite seal, and commonly forms 4-way dip closed structures at Top Bunter level. At least 29 separate closures have been identified (Brook et al., 2003). To develop a proper understanding of the Bunter sandstone for CO2 storage, the rock properties, including porosity and volume of shale/sand and also variation of selected reservoir properties, such as saturation, need to be established alongside the seismic response.

Rock physics analysis provides the link between these two domains: the elastic, seismic domain and the reservoir rock property domain. Over the SNS area, a regionally consistent interactive rock physics modelling product/tool (rockAVO) has been developed to build a homogeneous database of high quality interpreted and conditioned well data (25, Figure 1). The various steps for the creation of this regional rock physics package are the following:

- **Data gathering and QC**: the focus area is over UK Quads 41 to 49. Screening of the entire exploration wells database was undertaken (close to 2,100 wells), and 25 wells have been selected, representing a reasonable spread of wells over the area (Figure 1). These wells represent the one with the optimum suite of logs available i.e., dipole sonic, enough record length for the main geophysical logs including the density and gamma-ray, and penetration of the Triassic Bunter Formation as well as the Permian-Zechstein reservoirs. For the well with short and / or missing elastic logs record, especially in the halite interval, a machine learning (ML) algorithm (Ruiz et al., 2021) was utilized. This advanced ML algorithm was trained using all the selected wells in the area as well as using an existing model from the Norwegian Sea. The combination of the two trained models was deemed to be the best way forward for estimating missing crucial log information prior to the petrophysical interpretation and rock physics analysis.
- **Petrophysical analysis or Geophysical Well Log Analysis (GWLA)**: a complete petrophysical interpretation has been performed over the Triassic interval as well as the other intervals (the Permian-Zechstein and Carboniferous intervals). This step allows 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 capacity of the candidate storage site and associated containment risks.
- **Rock Physics Diagnostics (RPD)**: this is the core of the workflow, which allows the QC of any observable trends of reservoir properties within the elastic domain. The process of rock physics diagnostics determines the best fit rock physics model to the existing "good" measured well log data. Various models exist such as: stiff and soft (or unconsolidated) sediment model. These models deterministically relate reservoir properties (i.e., minerals, fluids, porosity, and geometry) to elastic properties (i.e., Vp, Vs, and density) in a theoretical manner, which then need to be calibrated to the measured log data. The "best fit" model can then help to fill in the unknowns where the elastic data is of lesser quality or does not exist at all or simply to fine tune initial ML prediction. The rock physics model and parameterization at the level of the Bunter sands, where no density was available, relied on the experience of the rock physicist and ML from nearby wells with density data available in this interval. Otherwise, the contact cement model has been used to determine the change to Vp and density response for changes to volume of clay, porosity and cement. The coordination number for the model has been calculated from the final conditioned in-situ log response. A shear wave (Vs) model composed of a combination of the published Greenberg-Castagna equation (Greenberg et al., 1992), with a set of customized parameterizations of this relationship in different depth windows, and the Krief model (Krief et al., 1990) in anhydritic halitic, and dolomitic sections yielded the highest correlation with the acquired Vs data in the well perturbation modelling and synthetic seismic AVO modelling (following step).
- **Perturbation modelling**: based on the above, calibrated rock physics models to the measured log data, various reservoir parameters can be modified/perturbed at will by the user. The parameters in the reservoir interval, which can be perturbed, include: volume of clay, porosity, water/dense phase CO2/hydrocarbon saturation but also with the CCS in mind, the pressure aspect as well as the cementation through the halite cementation-precipitation, which makes the rock frame stiffer. Perturbation modelling also shows the effect of changing these properties on the elastic properties and modelled seismic response. Cleanest rocks (greater quartz content)

tend to exhibit higher acoustic impedance (Ip) and lower Vp /Vs ratio values than more clay rich lithology. Porosity changes also exhibit strong impact on the Ip. For the fluid substitution aspect of the model perturbation, and to calculate the acoustic properties of the dense phase CO2, we use the laboratory measured values for pseudocritical pressure and temperature in the Batzle-Wang (1992) equations as described by Xu, 2006. For deriving the acoustic properties of the fluid mixture (CO2 and brine in this case) there is the option to use either the standard homogenous or the patchy mixtures saturation (Mavko, et al., 2009). These represent the end-members of fluid compressibility, and the decision was made to not use Brie's fluid mixing equation, which would be somewhere in between the two end-members depending on the empirical constant used. This decision was made to simplify the workflow. These 4 steps are performed for all the wells in a sequential order with cross-validation and the reservoir rock physics model as fine-tuned to best fit to all the measured log as much as possible. The GWLA (supported by ML) 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 quality and capacity of both container and seal elements of the CCS which are evaluated at the same time as the Bunter sands and underlying potential hydrocarbon reservoirs. The RPD allows the QC of any observable trends of reservoir properties within the elastic domain. For this project, the chosen elastic domain is acoustic impedance (Ip) vs. Vp/Vs, and the targeted reservoir properties were: PhiT, Vclay and Sw.

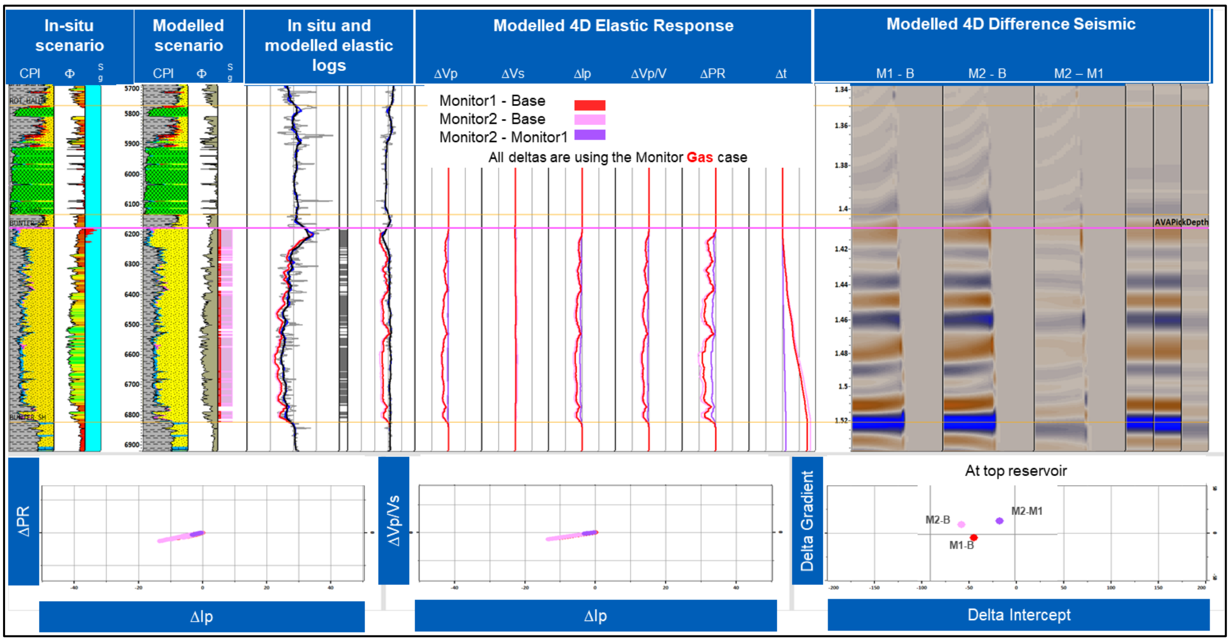

Figure 2 *Illustration of the result of one of the models for well 44/21a-9 (located in one of the UK CCS licensed area) and the 4D difference panels. The above shows a homogenous fluid substitution with a gas saturation for the M1 of 10% and 50% for M2 and gas density of 1.539 g/cm3 for M1 and M2 (CO2). Some seismic differences (right hand-side) can be observed alongside some differences in the cross-plots domain with the Delta Ip (acoustic impedance) versus Delta PR (Poisson Ratio), Delta Ip (acoustic impedance) versus Delta Vp/Vs and the Delta Intercept versus Delta Gradient for the 3 differences: Monitor 1 minus Base, Monitor 2 minus Base and Monitor 2 minus Monitor 1.*

This interactive rock physics modelling analysis/package for CCS and near field exploration, provides the user with the tool to interactively perturb, by changing parameters, to assess the measured seismic data response and to understand its AVO sensitivity to a significant number of rock, fluid and seismic property scenarios, variation. This can provide relevant insights to many questions including the below.
Is the seismic AVO response sensitive to different CO2 saturation levels and how this seismic difference can change between two CO2 saturation level?
How robust and sensitive would an AVO seismic response be in situations of varying fluid, porosity, pressure or mineralogy?

What would be the seismic response to cementation, precipitation of halite occurring due to CO2 injection? Cementation or halite impact in the Bunter sands is included into the modelling as this factor would produce some effects in the elastic-seismic responses and is necessary to assess.
Additionally, what is the effect on seismic frequency bandwidth for reservoir identification, resolution, detection? The seismic modelling can be adjusted in term of wavelet (ricker, Ormsby or extracted from measured seismic), bandwidth, and angle of incidence ranges.
What would be the time-lapse effect of model perturbation? The time-lapse element of the workflow allows the computation and the visualization of key 4D features: seismic differences between a base case (B), a time 1 (Monitor 1) and a time 2 (Monitor 2) with displayed differences M1 minus B, M2 minus M1, M2 minus B and their associated time-shift variation as well as cross-plot delta impedance versus Poisson ratio (at log and seismic scale) and delta Intercept vs. delta Gradient (Figure 2)

Conclusions

The implementation, development, and deployment of this workflow in a very active area for CO2 storage (UK-SNS) should allow geoscientists to evaluate, based on a calibrated rock physics model, the seismic, AVO seismic sensitivity to various injection scenarios and their effect on the rock frame. The work performed allows us to understand and predict the impact of CO2 injection on the rock frame through potential assessment of the cementation. An accurate estimation of the CO2 acoustic properties has been implemented allowing fluid substitution to be correctly performed with either a homogenous or patchy fluid distribution model into the matrix.
This is complemented by a dynamic visualization of the modelling through the display of various key 4D attributes, amongst them the time shift between different scenarios. Overall, this should enable more accurate assessment on the seismic sensitivity to CO2 changes in saturation-pressure which can be used as a possible or deciding factor to either acquire, reprocess and/or license new seismic data. More importantly, this should facilitate an assessment, calibrated on ground truth measurements through some of the existing wells, on how storing CO2 could impact the elastic and seismic properties of the Triassic Bunter sands, and therefore be an important tool in the MMV evaluation toolbox.

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