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4D Seismic Feasibility Study for Enhanced Oil Recovery (EOR) with CO₂ Injection in a Mature North Sea Field

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SUMMARY

A mature North Sea field with a long history of water flooding has been modelled to predict the potential for enhanced oil recovery (EOR) with CO₂ injection. This technique has the potential to further extend the life of the field by extracting more oil and to store the injected CO₂ in the reservoir. A feasibility study was conducted to assess whether 4D (time-lapse) seismic could be used as a monitoring tool during CO₂ injection. Different approaches were employed in this project; the initial examination using a 4D risk assessment table (Lumley et al., 1997) suggests that 4D seismic can be applied. For a more quantitative analysis, a petro-elastic model was designed to capture both the saturation and pressure signatures from the injected CO₂. 1D modelling using fluid substitution at well locations, and simulator to seismic modelling in conjunction with the compositional simulation model was performed to predict the three-dimensional 4D signatures within the simulation model grid. Based on this analysis a seismic impedance change of up to 9% is predicted which is above the limit that is typically considered for 4D applications. The discrimination between pressure and saturation signals is also discussed and the possibility to use 4D seismic to detect pressure changes was evaluated. This study makes suggestions regarding the seismic survey characteristics and appropriate timing to acquire the monitor surveys.

Introduction

After 30 years of production in a mature North Sea field (Field-X), where water flooding has been the major drive mechanism, CO₂ injection has been considered as an enhanced oil recovery and storage strategy. Senergy has performed a feasibility study, covering reservoir engineering and geophysical aspects of this project. The reservoir engineering side of the project covers the optimum scenario regarding the number of required wells (producers and injectors), well placement and completion intervals to maximise utilisation of injected gas and minimise inefficient recycling. The use of the existing wells was also investigated. The proposed development plan consists of a continuation of the current water flooding for 5 years, followed by CO₂ enhanced oil recovery. As part of the reservoir engineering studies, a compositional simulation model (Eclipse 300) was developed. This allows the reservoir performance under gas+CO₂ EOR for the next 30 years for different scenarios of well placements to be evaluated. The geophysical studies define the extent of the storage complex, identify the potential spill points from structural closures, characterise the subsequent migration of CO₂ and potential secondary/tertiary seals. A 4D seismic feasibility study was also completed. This 4D seismic feasibility study is the subject of this paper and included three stages: 1) preliminary 4D screening and petro-elastic modelling, 2) well-based modelling, and 3) 3D simulator to seismic modelling. The details of these studies are outlined in the following sections.

4D risk assessment (Lumley et al., 1997)

The 4D technical risk spreadsheet (Lumley et al., 1997) was examined for the field. Comparatively, based on the rock and fluid characteristics, Field-X falls (Score 16) into the range of a typical North Sea reservoir (score 15), with a good possibility for monitoring gas+CO₂ injection by the use of 4D seismic.

Property	Field-X	scores					
		5	4	3	2	1	0
Dry rock bulk modulus	~13 GPa	<3	3-5	5-10	10-20	20-30	30+
Fluid compressibility contrast	Up to 95% change	250+	150-200	100-150	50-100	25-50	0-25
Fluid saturation change	Water replaced by gas	50+	40-50	30-40	20-30	10-20	0-10
Porosity	~23 %	35+	25-35	15-25	10-15	5-10	0-5
Impedance change	Up to 9% change	12+	8-12	4-8	2-4	1-2	0

Preliminary 4D screening

Petro-elastic model (PEM) parameters were calibrated using an optimisation algorithm (Amini & Alvarez, 2014) based on well-log data from one well. Gassmann's (1951) fluid substitution model and MacBeth's (2004) model for stress-sensitivity was used to take pore-pressure effects into account. The magnitude of the impedance change due to gas+CO₂ injection is predicted to be up to 9% (Figure 1).

Well-based modelling

The pressure and saturation information were extracted from the compositional simulation model at the well location at different time steps. Using the calibrated PEM parameters, the elastic parameters were calculated at each time step and the 4D AVO seismic response was modelled. The 4D AVO analysis shows that to separate pressure and saturation responses based on angle stacks is challenging (Figure 2).

3D simulator to seismic modelling

Even though well-based 4D seismic modelling is useful in establishing the feasibility and evaluation of 4D AVO responses, they might be inadequate in understanding the lateral-sweep efficiency and the timing of the repeat surveys (Johnston, 2013). Additionally, the well data may not represent the variability of reservoir properties (wells are targeted to high net-to-gross areas) and hence bias the modelling results. Simulator to seismic modelling is a valuable tool in overcoming these challenges. Static and dynamic properties from the simulation model at the desired time-steps are extracted, and using the calibrated PEM parameters the elastic parameters were calculated at each time-step

(Figures 3-4). Simulator to seismic modelling was performed using a Senergy in-house software programme. It is observed that the saturation changes due to injection results in impedance changes above the threshold of what is considered a detectable 4D signal. This is due to the fact that most of the reservoir is water flooded after a long period of water injection, and the contrast between water and a gas+CO₂ mixture is large enough to generate an evident 4D signal. 3D modelling indicates that both pore pressure (pressure build-up) and saturation changes (mainly water being replaced by gas+CO₂) result in a decrease in impedance (softening). However, due to the choice of a relatively low stress sensitivity curve, the pressure signal due to CO₂ injection will be too small to be detected.

Conclusions

The 4D risk spreadsheet shows that Field-X is comparable to any typical North Sea field in terms of the rock and fluid characteristics needed to have a measurable 4D response. The results of the well-based modelling and simulator to seismic modelling show that 4D seismic can be used effectively to monitor the gas+CO₂ injection, even at low seismic resolution (dominant frequency 22 Hz). The expected magnitude of the 4D seismic response is estimated to be about 9%, which is above the threshold of what is considered a detectable 4D signal. Our modelling also indicates that the pressure signal will be too small to be detected, and it will be coupled with the effect of an increase in gas saturation. Our analysis can be used to plan future 4D seismic monitor surveys. The largest uncertainty in our study is related to the dry rock characterisation which could not be calibrated due to a lack of shear sonic data and laboratory measurements on core data; this will mainly affect our estimation of the pressure signal.

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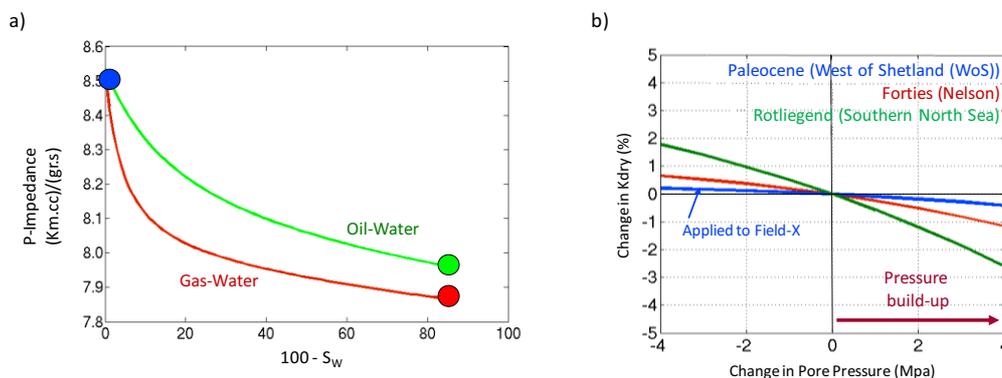


Figure 1. a) The curves represent a theoretical trend showing only the saturation effect (no pressure effect) for a rock with $\phi=23\%$, b) published rock stress sensitivity curves (MacBeth, 2004) for different samples of sandstones with a similar porosity as Field-X. In the absence of rock-stress sensitivity measurements, the curve with the lowest stress-sensitivity (West of Shetland) was selected. Since the reservoir in Field-X is deeper than the West of Shetland sample, the rock stress sensitivity is expected to be lower.

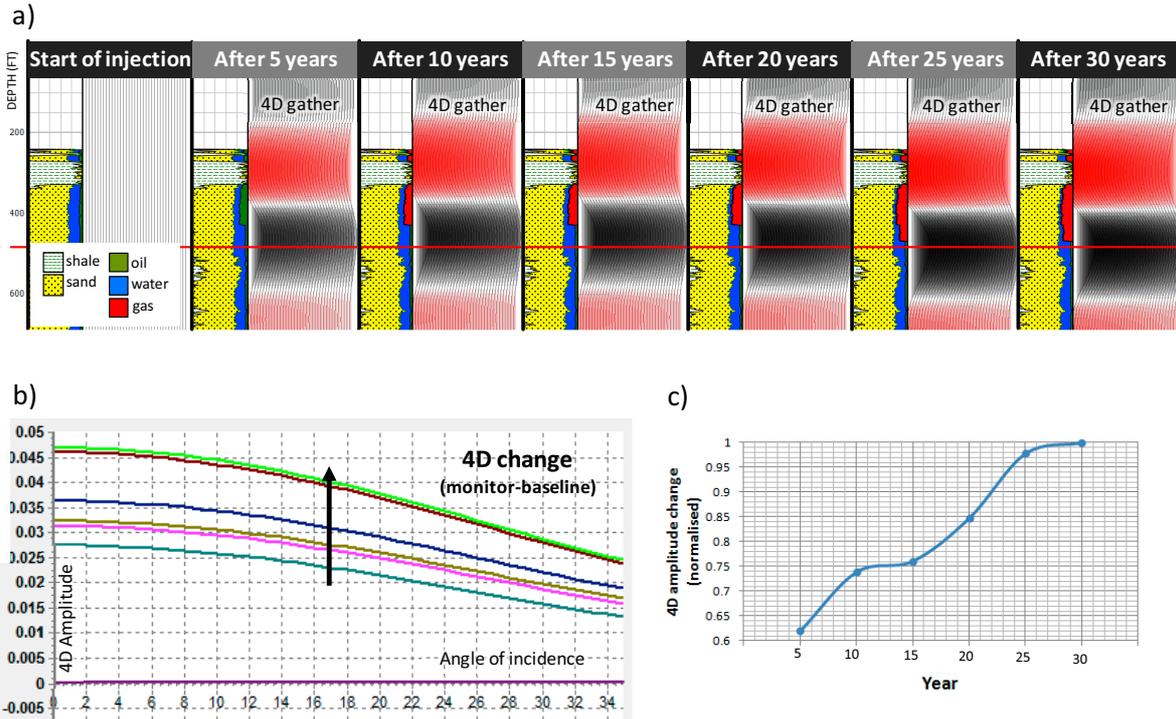


Figure 2. Pseudo-logs at well were extracted from the simulation model at 7 time steps over 30 years of gas+CO₂ injection. Calibrated petro-elastic model parameters were used to calculate V_P and density. A Greenberg-Castagna relationship was used to estimate V_S . Ricker wavelet (22 Hz) was used to calculate synthetic seismograms. **a)** the AVO gathers at 7 time steps; 4D signal is a function of both gas thickness and gas saturation. **b)** the AVO response at different time steps, **c)** extracted amplitude variations at the well location.

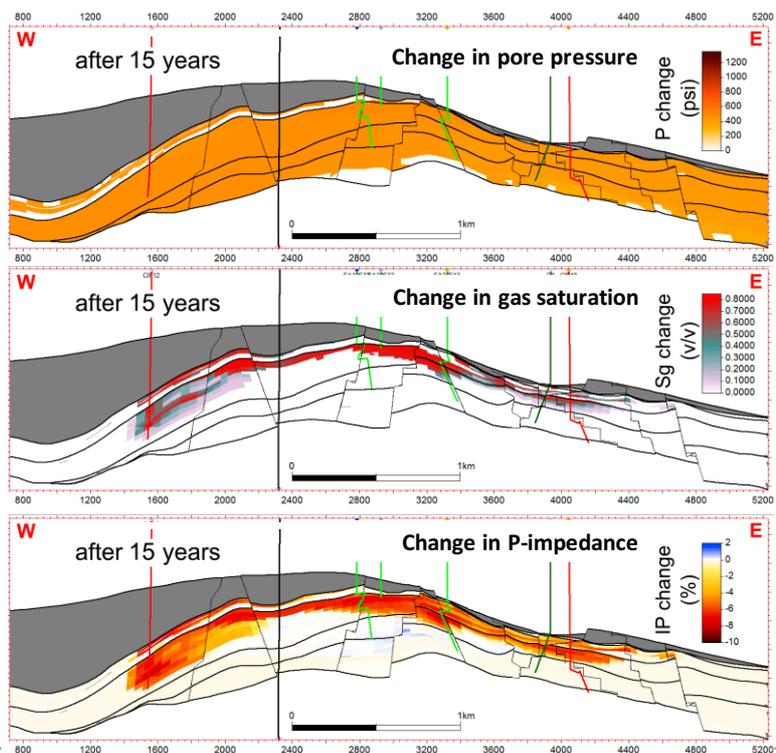


Figure 3. The vertical sections show the change in gas saturation and pore pressure (from the compositional simulation model) and the corresponding expected change in impedance after 15 years of gas+CO₂ injection (from simulator to seismic modelling).

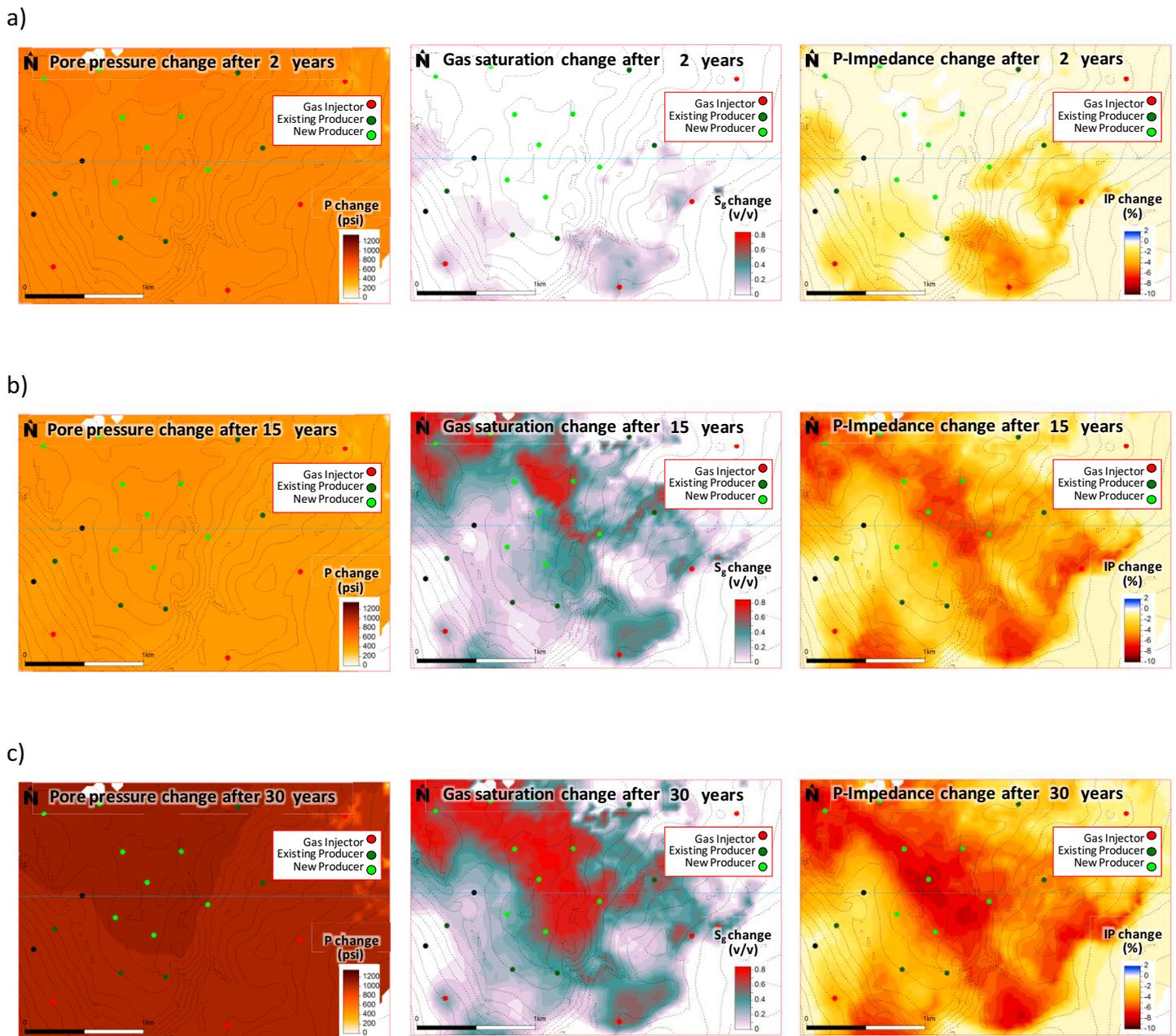


Figure 4. The maps show the change in gas saturation and pore pressure (from the compositional simulation model) and the corresponding expected change in impedance at different time steps (from simulator to seismic modelling).