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Feasibility of 4D Seismic Monitoring for CO_2 Injection in Open Versus Closed Depleted Gas Fields: Goldeneye and Hamilton Fields

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Abstract

Carbon capture and storage (CCS) technology represents a critical strategy for mitigating global climate change by limiting temperature increase in line with the Paris Agreement. This study investigates the feasibility of 4D seismic monitoring for CO_2 injection in depleted gas fields, focusing on the Goldeneye field as an open system and the Hamilton field as a closed system in the North Sea. Through flow simulation-to-seismic (Sim2Seis) modeling, the research compares the effectiveness of 4D seismic monitoring techniques in different geological storage configurations. The investigation found that CO_2 injection into open systems demonstrates more pronounced seismic signal. Fluid contact movement within these systems generates substantially stronger and more discernible seismic signal along the fluid contact compared to closed systems. These findings provide critical insights for developing more effective monitoring strategies for carbon sequestration projects in different geological settings.

Introduction

Carbon capture and storage (CCS) represents a key technology for achieving net-zero emissions targets and meeting Paris Agreement objectives. Successful implementation of CCS requires robust monitoring, measurement, and verification (MMV) protocols to ensure the safety and effectiveness of CO_2 storage operations. The European Commission (2009) CCS Directive mandates comprehensive monitoring plans that track CO_2 plume movement, assess trapping mechanisms, and validate subsurface storage models. The monitoring objectives can be divided into two main categories: (1) Containment monitoring: Ensuring injected CO_2 remains within the storage complex for long term storage and (2) Conformance monitoring: Ensuring storage complex is behaving in a predictable manner and is fully consistent with the subsurface model.

4D seismic monitoring has been a promising reservoir monitoring technique for hydrocarbon production and will remain so for CO_2 sequestration projects. This geophysical approach involves repeated 3D seismic surveys to image temporal changes in subsurface properties, providing insights into fluid migration and reservoir dynamics. However, the effectiveness of 4D seismic monitoring varies significantly depending on reservoir characteristics and injection conditions.

The primary research objectives encompass a comprehensive evaluation of 4D seismic monitoring feasibility in different geological storage configurations. The study aims to compare 4D seismic responses in open and closed reservoir systems, identify optimal monitoring strategies for CO_2 storage in depleted gas fields, and provide actionable insights for operators and regulators. By conducting an in-depth analysis of two distinct North Sea fields, the research seeks to enhance understanding of subsurface monitoring techniques critical to successful carbon sequestration efforts.

Methods

The study employs a comprehensive flow simulation-to-seismic (Sim2Seis) modeling approach to generate synthetic geophysical data through forward modeling of the dynamic subsurface model. This method integrates compositional reservoir flow simulation, petro-elastic modeling (PEM) and synthetic seismic data generation to provide a nuance understanding of CO_2 storage dynamics.

In this study, we employed calibrated petro-elastic modeling (PEM) to effectively integrate seismic and engineering domain insights. The research captured pressure-induced changes in elastic properties through rock physics modeling approach, combining Gassmann's equation with empirical pressure sensitivity relations as described by MacBeth (2004). Concurrently, we modelled the elastic properties of reservoir fluids during CO_2 injection using the hydrocarbon gas-CO_2 mixture correlation developed by Sutton and Hamman (2009).

The synthetic seismic modeling process encompassed four critical temporal stages: a baseline condition prior to CO_2 injection, and three subsequent monitoring points. These monitoring stages included an initial assessment one year after injection commenced, a midpoint evaluation of the planned injection period, and a final analysis at the conclusion of CO_2 injection. This allows us to observe the evolution of 4D signal over time and relate it to the fluid and pressure changes from the compositional reservoir flow simulation model.

Results

The research investigated 4D seismic monitoring capabilities in two contrasting depleted gas fields in the North Sea: Goldeneye field in the Central North Sea and Hamilton field in the East Irish Sea. The Goldeneye field, an open system within Captain sandstone, was modeled with CO_2 injection at 1 Mtpa for 20 years, while the Hamilton field, a closed system in Ormskirk sandstone, was simulated at 5 Mtpa of CO_2 injection for 25 years.

Sim2Seis modeling of the Goldeneye field revealed sophisticated fluid displacement dynamics in an open system. The analysis observed a progressive displacement of the original hydrocarbon-gas water contact, resulting in the formation of a new CO_2-hydrocarbon gas-water contact (Figure 1). A particularly significant finding was the generation of a 4D seismic signal at the fluid contact, which demonstrated a magnitude ten times stronger than the intra-reservoir signals, highlighting the potential of 4D seismic monitoring of CO_2 injection into a depleted gas field characterized by open system along the fluid contact.

The Hamilton field modeling presented a markedly different scenario characteristic of a closed system. CO_2 mixing with residual hydrocarbon gas produced weak 4D seismic signals (Figure 2). The counteracting physical property changes, increase in density but decrease in velocity as CO_2 mixes with the residual hydrocarbon gas, resulted in minimal impedance changes, rendering intra-reservoir signals challenging to interpret.

The comparative analysis highlighted fundamental differences in 4D seismic signal characteristics between CO_2 injection into open and closed depleted gas fields. The research conclusively demonstrated that CO_2

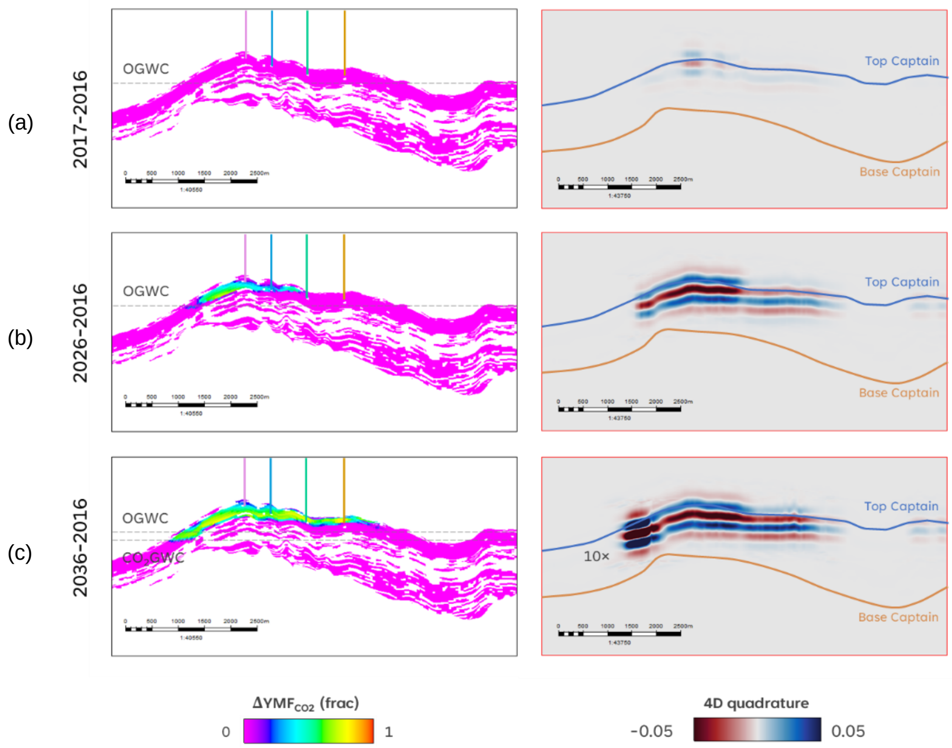

Figure 1 Evolution of vapor molar fraction of CO_2 (left) and corresponding 4D quadrature amplitude (full stack seismic) due to fluid saturation effects (right) during CO_2 injection in the Goldeneye field. From top to bottom: CO_2 injection durations of (a) 1, (b) 10, and (c) 20 years.

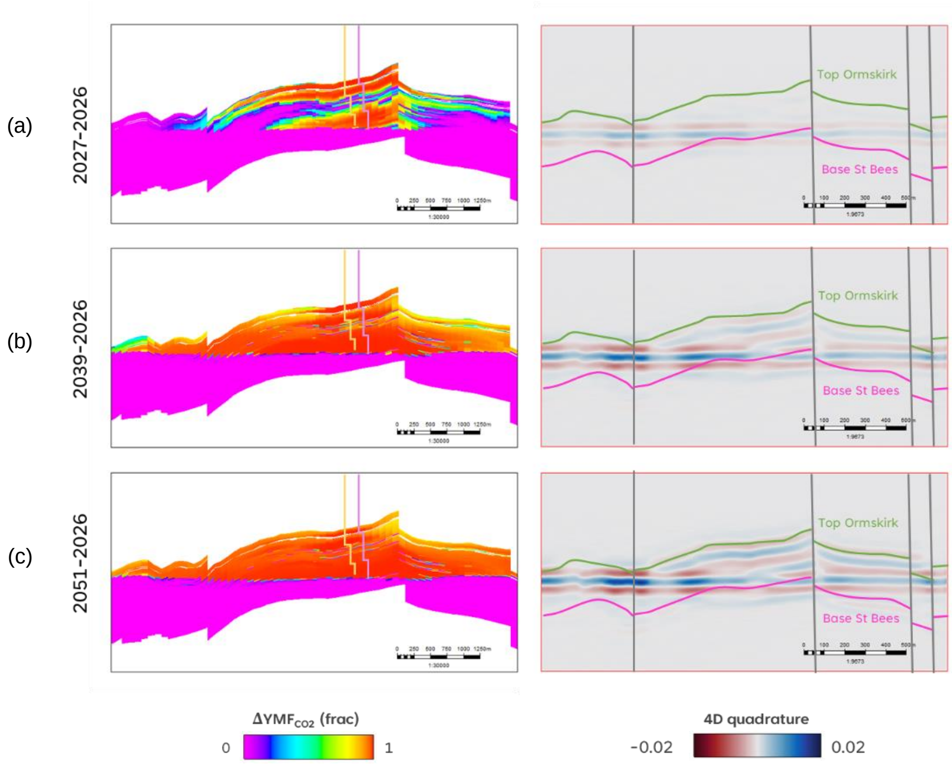

Figure 2 Evolution of vapor molar fraction of CO_2 (left) and corresponding 4D quadrature amplitude (full stack seismic) due to fluid saturation effects (right) during CO_2 injection in the Hamilton field. From top to bottom: CO_2 injection durations of (a) 1, (b) 13, and (c) 25 years.

and hydrocarbon gas mixing generates inherently weak signals in the reservoir interval but CO_2-hydrocarbon gas mixture displacing water into the aquifer will generate stronger seismic response. The response will be similar to CO_2 injection into saline aquifer.

Conclusions

This study demonstrates that 4D seismic monitoring effectiveness varies substantially between open and closed systems for CO_2 storage in depleted gas fields. Our analysis focused primarily on the strength of 4D saturation signals, which are fundamentally related to the compressibility contrast between fluid types. Although CO_2 increases the density of the gas mixture, the corresponding velocity decrease significantly cancels out these changes, resulting in minimal impedance variations.

For open depleted gas fields, 4D seismic can effectively support both containment and conformance monitoring by clearly imaging CO_2 migration pathways and tracking fluid contact changes. Notably, gas encroachment into the aquifer or water displacement presents a more favorable condition for generating observable 4D signals, with magnitudes up to ten times stronger than intra-reservoir signals. However, the complexity of these 4D signals necessitates comprehensive reservoir flow simulation studies to properly characterize the underlying fluid flow physics.

In contrast, closed depleted gas fields present more challenging monitoring conditions, with 4D seismic primarily suitable for containment monitoring due to weak signal generation and complex fluid interactions. The complexity of the signals for the closed system has not been fully demonstrated, and the 4D pressure signals are not evident in our modeling as the pressure build-up remains below 10 MPa in both open and closed systems. Given these limitations, alternative monitoring methods such as time lapse gravity and seafloor deformation should be evaluated for conformance monitoring.

For optimal MMV plans, 4D seismic surveys should prioritize fluid contact zones, particularly in open systems where signal strength is greatest, with particular attention to analyzing accumulated time-shifts at the base of the reservoir, especially for CO_2 injection into depleted gas fields. By establishing a comprehensive framework for evaluating 4D seismic monitoring potential and exploring alternative technologies, this research enhances the safety and reliability of carbon capture and storage projects.

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