7.9 USING MARINE CSEM FOR RESERVOIR MONITORING BASED ON PETROPHYSICAL MODELING

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ABSTRACT

The Marine Controlled-Source Electromagnetic (CSEM) method is a technique used to measure electromagnetic fields transmitted by an active source either at the seafloor or just a few tens of meters above it. This method allows us to image the electrical resistivity beneath the seafloor, making it valuable for identifying resistivity anomalies, particularly those related to high saturations of petroleum. Since its introduction in 1981 by Cox, the marine CSEM method has been gaining popularity in petroleum exploration. However, the applications of electromagnetic research have started to expand beyond petroleum exploration into an active production monitoring tool, which is the focus of our study. To achieve this, we created realistic geoelectric models by utilizing dynamic reservoir properties obtained through reservoir simulation of the Wisting field in the Norwegian part of the Barents Sea. The geologically consistent rock physics models developed in our study can also allow us to transform the simulation results into resistivity maps. Using a Finite Difference Time Domain (FDTD) forward modeling workflow, we demonstrate that the resistivity map for each time-step can be used as an input model to generate synthetic EM data. This synthetic EM data is then studied and analyzed to understand production-induced changes in the reservoir during different production phases. This helps us develop a technically feasible reservoir monitoring workflow suitable for time-lapse CSEM. Our findings indicate that the CSEM responses vary during different production phases, making the method effective for production monitoring purposes. Additionally, our study enables the testing of other time-lapse workflows with realistic complexities, allowing us to evaluate the potential of this technology for field application. We investigate resolution limitations and repeatability requirements to gain valuable insights for future implementations of the technique.

KEYWORDS: 4D, controlled-source electromagnetic method, reservoir monitoring

INTRODUCTION

The controlled-source electromagnetic (CSEM) method is a reliable technique for hydrocarbon exploration, complementing seismic studies due to its sensitivity to resistive and conductive anomalies like oil reservoirs and water. Researchers are increasingly exploring its potential for time-lapse production monitoring, especially in realistic reservoir models at various production phases.

Our research focuses on enabling time-lapse 3D CSEM for reservoir monitoring by using geologically consistent rock-physics models. These models convert dynamic reservoir properties of the Wisting field in the Norwegian part of the Barents Sea into resistivity models for different time steps. These resistivity models are used as inputs in a Finite Difference Time Domain (FDTD) workflow (Werthmüller et al., 2021) to generate synthetic EM data for studying time-lapse production effects.

The Wisting discovery was made in 2013 at well 7324/8-1, located on the Wisting Central prospect (Figure 1). The reservoir, part of the Realgrunnen Subgroup (Fruholmen, Nordmela, and Stø Formations), was penetrated at a depth of 662 meters with a water depth of 400 meters. Wisting has notable electric properties, with a background resistivity of up to 20 Ωm (Granli et al., 2017), making it favorable for CSEM applications. The primary objective of drilling well 7324/8-1 was to explore hydrocarbons in the Jurassic Realgrunnen Subgroup, and it proved successful as a discovery well (NPD, 2022).

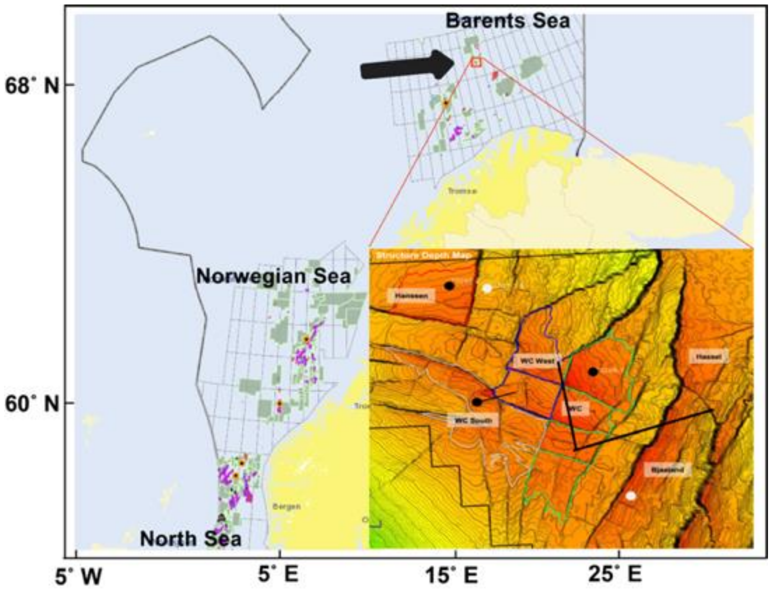

Figure1 The Wisting field is situated in the Barents Sea, marked by a red rectangle on the map.

In this research, we've compiled a comprehensive dataset, including production simulation models, well-logs, and 3D CSEM inversion results. Our main goal is to use this data within a rock physics framework to create realistic resistivity models representing various oil production phases. These models will be used to assess the potential of time-lapse CSEM for reservoir monitoring, considering survey parameters and feasibility. The study consists of two main parts. The first part involves constructing and calibrating the reservoir model to match observed data, establishing a reliable foundation. The second part explores the viability of time-lapse CSEM using the realistic resistivity models. We analyze synthetic EM data to gain insights into CSEM's potential for monitoring production changes over time. Note that repeatability requirements are not addressed here but remain a crucial aspect for future research.

METHODS AND PETROPHYSICAL MODELS

CSEM data is crucial for imaging subsurface resistivity structures, especially for time-lapse reservoir monitoring in fields like Wisting. Key factors influencing resistivity include the saturation exponent "n" and rock wettability, with complex effects in clay-containing

reservoirs. Wisting's possible oil-wet nature, as suggested by Alvarez et al. (2018), allows for adjustments to "n" to yield higher resistivities. Our study explores the non-linearity of "n" in oil-wet formations, dependent on water saturation. Oil-wet formations exhibit higher "n" due to isolated non-conductive water globules in larger pores. Wettability effects are pronounced as

brine saturation decreases. A connate water saturation threshold (10%) was established using capillary pressure curves and FWL depth maps, enhancing resistivity modeling accuracy. Gas-bearing zones require special "n" considerations; a gas saturation threshold of 70% effectively distinguishes them from oil-wet rocks. Our non-linear saturation exponent model assigns "n" based on these thresholds. We set saturation exponent values depending on a 10% connate water saturation threshold and a 70% gas saturation threshold. We used a rock physics model to convert water saturation simulations into resistivity maps for time-lapse CSEM studies in Wisting. Figure 2 illustrates this application.

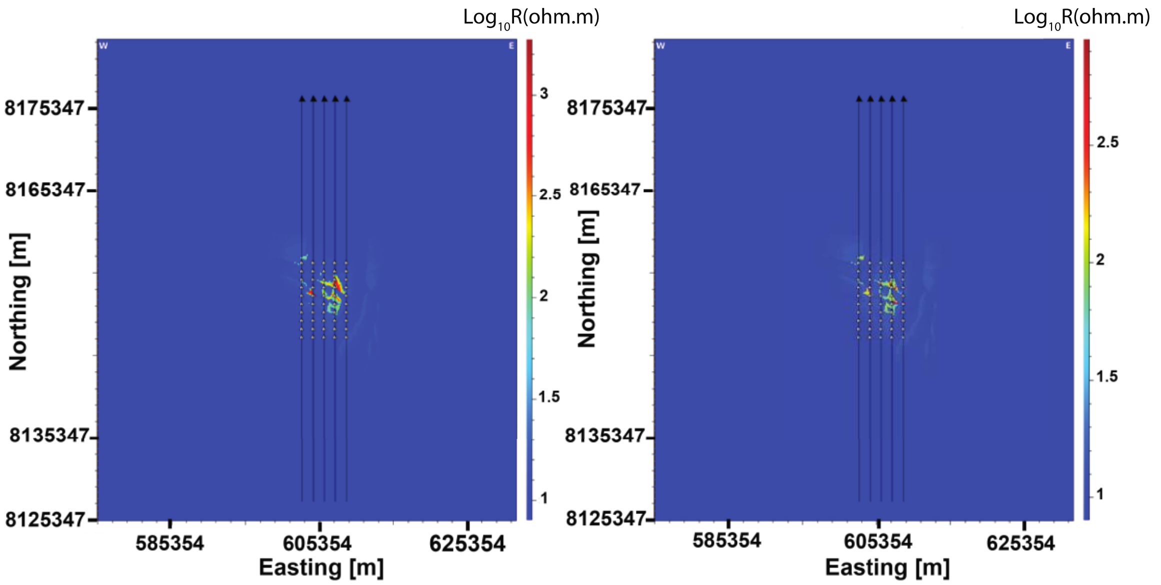

Figure2 The provided 2D resistivity maps howcase the subsurface conditions at two different time steps. The left for the year 2027, the right for the year 2057. The white rectangles are receivers and the black vertical lines going through them are owlines.

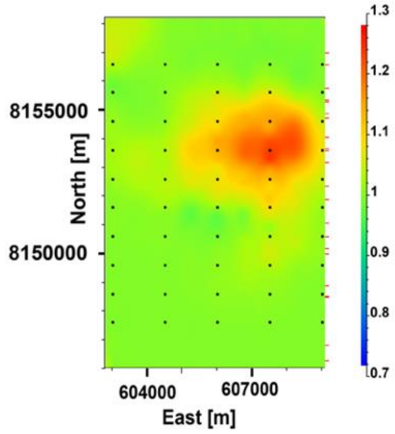

Figure3 The provided 2D maps display the Normalized Magnitude (NM) of the Ex field component for two distinct time steps. The plot represents the Ex fields of the year 2057 normalized by the Ex fields of the year 2027

4D CSEM RESPONSES

The simulation, conducted with a source-receiver offset of 2667 meters and a 5.0 Hz frequency, focuses on two critical time points: production onset in 2027 and 30 years into production in 2057. Figure 3 displays Ex-field normalized magnitude (NM) maps for these time steps. NM values of 1 (light green) signify no change in subsurface reservoir fluid content, while values greater or smaller than 1 indicate changes.

Figure 3 clearly reveals production-induced changes, seen as red positive anomalies, matching the resistivity maps in Figure 2. These anomalies align with the predicted production activity location. In hydrocarbon fields, decreasing petroleum volumes due to water injection result in lower resistivity values over time. Towards the field's end, the target resistor depletes, leaving a final resistivity response without it. Figure 3 emphasizes this with the positive anomaly, showing the 2027 response exceeds the 2057 pseudo-background response. The relatively high frequency in Figure 3 indicates higher resolution. This is also related to the combination of higher background resistivity and shallow burial depth. These results in Figure 3 offer valuable insights into subsurface reservoir changes during 30 years of production, showcasing CSEM's potential as an effective monitoring tool for tracking production-induced alterations.

CONCLUSIONS

In this study, we demonstrated the process of converting dynamic reservoir simulations at different time steps into resistivity spatial distributions using a detailed, realistic, and geologically consistent rock-physics model. These resistivity maps served as inputs in a FDTM forward modeling workflow to generate synthetic CSEM data. By studying and analyzing the CSEM data using various approaches, we aimed to develop a practical workflow for time-lapse CSEM studies. The results of the study revealed the capability of CSEM data to effectively detect and capture production-induced changes in the fluid content of a hydrocarbon reservoir during production. The presented workflow demonstrated the feasibility of using time-lapse CSEM as a monitoring tool in reservoir management. Future research will focus on investigating the repeatability requirements and limitations of time-lapse marine CSEM, and optimize and refine the workflow for practical applications in the oil and gas industry. Understanding the repeatability of the method is essential to ensure the reliability and consistency of the data obtained in multiple monitoring surveys over time.

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