Introduction

The Marulk field is a gas condensate accumulation located in the Norwegian Sea on the Dønna Terrace, which forms a large down faulted block on the western margin of the Trøndelag Platform, situated between the Nordland Ridge and the Vøring Basin. The field was discovered in 1992 and hydrocarbons were encountered in late cretaceous formations by two exploration wells. The field is in production since 2012 under license 122 through two development wells with a direct tie-in to the existing Norne floating production storage and offloading (FPSO) unit. Marulk field is operated by Vår Energi with its partners Equinor, INEOS and DNO Norge AS.

The main reservoir is Lysing Fm. (Upper Turonian-Lower Coniacian) and consists of a confined turbidite system; sandstone lobes onlap the crest of a tilted block. The secondary reservoir Lange Fm. (Uppermost Albian–Lower Turonian) consists of heterogeneous turbiditic sands alternating shale and is penetrated by three exploration wells. Lange Fm. is separated into several reservoir units. The Lange 4 (LA4) reservoir unit was discovered in 1992 by exploration well 6507/2-2, being a 30 m thick heterogenous reservoir unit with 2-4 m thick sand layers and alternating shales. The sands are laterally and vertically graded into the deep-water clays and were deposited in a relatively unconfined basin. A high uncertainty is related to the sand distribution as the geometry and dimension of the sand bodies are not proven. The volumes from LA4 reservoir were included as potential upsides in the plan for the development and operation (PDO) of Marulk by adding reserves to the current remaining reserves. The purpose of drilling an additional production well was to target and exploit the LA4 reservoir unit and to utilize the spare capacities in the existing facilities, maximizing the value generation from the field. The project contributes to the company’s production as well as reserves replacement targets. The reservoir was decided to be targeted by one single horizontal gas production well (Marulk Lange) and following a strict geosteering strategy aimed to optimize the reservoir exposure and acquire key log data for a comprehensive reservoir evaluation and well completion purposes. Despite the reservoir complexity and some drilling constraints, landing of the well was planned through ultra-deep electromagnetic look ahead capabilities avoiding additional cost for a pilot hole that would have added approx. 50 MNOK to the project.

The planning of the well posed several critical challenges. The first being crossing of the highly depleted Lysing Fm., having +/-10 m of uncertainty on the top-of-reservoir and little margins in well anti-collision. Accidental drilling into the depleted sand would have led to severe mud losses and put the entire wellbore at risk. The next critical task was to master the landing just 3 m inside the LA4 reservoir, while having +/-30 m of uncertainty (Figure 1). Inappropriate landing would have compromised the well placement into the reservoir. The third issue was optimizing the well placement inside the heterogeneous LA4 reservoir itself, mitigating uncertainties related to sand distribution and structural setting while honouring limited steering capabilities constrained to reduce risks running a complex completion.

![Figure 1](image-url)  
*Figure 1* Three scenarios landing in LA4 reservoir under uncertainty of +/-30m at top reservoir and the three corresponding planned well trajectories; base case reservoir (red) with base case well trajectory (red dotted), the extreme deep case reservoir (blue) with the planned deep well trajectory (blue dotted) and the extreme shallow reservoir (yellow) with the planned shallow trajectory (yellow dotted). The discovery exploration well is used as the offset well (black).
Solution and methodologies

The solution and methodologies for mitigating the high risks were an optimal mix of detailed well planning, interactive and multidisciplinary workflow and the use of breakthrough technologies. Innovative and predictive logging-while-drilling (LWD) acquisition, alternative mud system and a fit-for-purpose completion were chosen to accomplish the well design, maximize operating efficiency and minimize risks and HSE exposure. The presented case study is an example of how Ultra-Deep EM directional technologies have been used to significantly reduce both drilling risks and cost in a highly uncertain and complex reservoir with limited steering capabilities. The Ultra-Deep EM technology, used for a safe geostopping above the depleted Lysing Fm., was optimized for a look-ahead sensitivity. The measurements and the stochastic inversions were optimized to solve for resistivity contrast features ahead of bit in real time (Seydoux, J. et al., 2019). To maximize look-ahead capability, the Bottom Hole Assembly was run without Rotary Steering System to have as short transmitter offset to bit as possible. In addition, the well inclination was optimized (<~45 deg) for this purpose.

The Ultra-Deep EM technology was also used for accurate landing inside LA4 reservoir. For this application the tool was run with three receivers on the Bottom Hole Assembly in order to optimize the depth of investigation, detecting the LA4 reservoir top at a sufficient distance with the aim to set the casing shoe 3m inside the reservoir. The technology was giving a real-time mapping of the reservoir to be used in a combination with a real-time 3D visualization of the seismic data and reservoir model to optimize the landing.

Finally, to fulfill the main objective of the well; geosteering into target and crossing as many sand bodies as possible optimizing the sand exposure in the complex reservoir environment and keeping the limited steering margins (deviation and DLS), the Ultra-Deep EM resistivity tool was assembled using two receivers with a medium spacing transmitter to receivers option (Xu, Y. et al., 2018). The Ultra-Deep EM reservoir mapping tool was run in the first global application of geosteering operations using a sourceless “green bottom-hole-assembly (BHA)” in oil-based mud (OBM). A comprehensive real-time dataset including radioisotope-free bulk density, neutron porosity, sigma and elemental capture spectroscopy measurements was enabled by a pulsed-neutron-generator (PNG) unique in the LWD arena. A novel high-definition dual physics resistivity and ultra-sonic borehole imager was utilized to get better control of the structure and allowing detailed geological interpretation (Maeso, C.J. et al., 2018). The LWD technology provided a complete reservoir and geological description of the heterogeneous turbidite sandstones in the Lange Fm.

Results

The use of Ultra-Deep E.M directional tool successfully allowed for a safe geostopping 7 m TVD above the depleted Lysing Formation (Figure 2). The stochastic inversions solved for a resistivity contrasts with a distance to bed detection of about 10 m TVD ahead of bit with an uncertainty of 3 m.

Figure 2: Curtain section to the left showing the results of the Ultra-Deep EM directional Look-Ahead inversion from the conductive overburden to the resistive depleted Lysing Fm. Figure in the middle showing the different inversions resistivity distribution with the P50 in pink. Figure to the right showing the P40H resistivity readings (blue) with the modelled Rh (pink) and Rv (pink dotted).
After that, a successfully landing of the well 3 m inside LA4 reservoir with a planned well inclination of 85 degree was performed using the Ultra-Deep EM tool. First confident identification of top LA4 reservoir was ~25 m TVD below the bit (Figure 3).

Figure 3 Curtain sections showing the results of Ultra-Deep Resistivity Look Around inversion used for landing in the resistive LA4 reservoir from the conductive overburden (upper curtain section; Deep Resistivity HD Deterministic Inversion, lower curtain section; HD stochastic inversion).

And finally, optimizing the sand exposure within the LA4 reservoir keeping the drilling constrains was successfully performed by using the resistivity map delivered by Ultra-Deep EM inversion together with high resolution resistivity bore hole images. The inversions were continuously tracking the top of reservoir, characterized by a resistive package contrasting the conductive overburden (Figure 4). The inversion also mapped several resistive layers within the reservoir (Figure 4). The high resolution image logs gave valuable geological information such as minor faults, dips, small scale injectites and sand-shale bedding, used to help steer the well.

The well was TD as per plan meeting the geosteering success criteria, penetrating most of the reservoir unit avoided drilling out of reservoir.
Figure 4 Curtain sections showing the results of Ultra-Deep Resistivity measurements used to geosteer inside the LA4 reservoir. The top figure shows the resistivity image, the horizontal logs displays density/porosity (upper), resistivity (middle), gamma ray and near bit gamma ray (bottom track). The bottom figure shows the Curtain Section model with the original Petrel model in the background: the upper inversion display shows Ultra-Deep Resistivity HD Deterministic Inversion and the lower inversion display the MC3 stochastic inversion. The real-time trajectory is displayed in black.

Conclusion

The case studied is a great example of how use of advanced technologies in combination with a strong interaction between professionals both in the planning and execution phase, resulted in maximizing well project while minimizing costs and operational risks exposure. By use of Ultra-Deep EM directional tool a successfully global well placement operation was possible even in a highly uncertain environment and without drilling a pilot hole. As the first time on the Norwegian Continental Shelf, a Logging While Drilling sourceless Bottom Hole Assembly encompassing petrophysical logs, high resolution resistivity bore hole images and pressure measurement in one go was run successfully in oil-based mud environment. A high-resolution sand count interpretation from dual physics borehole imaging tool confirmed the maximum net reservoir potential. The data acquisition improved the understanding of the complexity of the Lange reservoir which is valuable input for potential further development of the Lange Formation.

The well was successfully drilled and completed with up-time close to 90%, the reservoir success criteria were met and the well is currently producing at the predicted rate.

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References

