Introduction

Installing an array of seafloor receivers over a producing oil reservoir enables a multitude of additional monitoring technologies apart from 4D time lapse imaging. A particular strength of cabled installations is their ability to capture reservoir processes in real time for immediate decision support (Goertz & Wüstefeld, 2018). Permanent installations have for example been successfully utilized to monitor subtle near-surface overburden changes (Bussat et al., 2016), or for monitoring injection-induced microseismicity (Bussat et al., 2018; Dando et al., 2018). Veire et al (2018) have shown an application of microseismic monitoring during drilling of an appraisal well using a temporarily deployed ocean bottom cable. One of the seismic signals that are captured by such arrays is the seismoacoustic noise emanating from an active drill bit, which in turn can be utilized to locate the drill bit for geosteering purposes (Houbiers et al., 2020). Especially for long lateral wells, the accuracy of the well deviation obtained from passive seismic drill-bit location is typically higher than what can be obtained by downhole logging methods. This, because the drill-bit location error obtained from passive seismic is independent of measured depth along the horizontal well path, whereas is accumulates along the wellbore with downhole logging methods. Apart from locating the drill bit itself with the help of direct seismic arrivals, we can also analyse seismic-while-drilling (SWD) signals for reflections of the drill-bit signals from formation boundaries and other obstacles below or around the drill bit. Poletto et al. (2019) have shown an offshore example where SWD provides information comparable to a walkaway VSP without the need to stop drilling for lowering a borehole receiver array.

In this paper, we built upon the drill-bit location results presented by Houbiers et al. (2020) and present that the same data also contains seismic reflection information that can be utilized to obtain a check shot, walk-away, or walk-over VSP dataset without any additional acquisition. We present first an overview of the Grane field and PRM array in which this test was carried out, and then describe the method utilized to process the passive SWD data to a reverse VSP (RVSP) dataset. We discuss the data quality obtainable in this offshore setting and the final VSP corridor from which reflections below the drill bit can be identified, interpreted, and located relative to the most recent drill-bit location.

The Grane field and PRM array

The Grane field is located in the central North Sea in about 128 m deep waters and produces heavy oil from the Heimdal formation at about 1800 m depth. The field is developed by drilling long horizontal production wells with up to 7 km measured depth (MD), oftentimes with several splay-offs. In 2013, a permanent reservoir monitoring (PRM) array of seismic seafloor cables was installed over the reservoir to optimize production by way of 4D time-lapse imaging (Thompson et al., 2015). The array
is one of the largest PRM arrays to date with 3458 seismic stations arranged with 50 m inline and 300 m crossline spacing, covering an area of about 50 km² (Figure 1). The array is trenched about 1 m into the seafloor and each station consists of a pressure sensor (hydrophone) and three orthogonal particle velocity sensors (3C geophone). The PRM array is mainly used for 4D time-lapse imaging of the reservoir with regular monitor surveys every half year. More than 10 repeat surveys have been acquired to date over the field, revealing production- and injection-related 4D seismic signatures with unprecedented detail (Elde et al., 2019). Capitalizing on this level of detail with field development decisions requires not only accurate planning of infield wells based on 4D results, but also precise drilling of long lateral wells and side-tracks. There is hence a strong business case to utilize the existing PRM array also in the time periods between active seismic time-lapse surveys to passively record the seismic signals emanating from microseismic events and drilling or workover activities in the field. The field operator has established a real-time data streaming workflow doing just that on a continuous basis (Bussat et al., 2018, Houbiers et al., 2020). To test whether it is feasible to extract reflection information below the drill bit from such data, we analysed a 30-hour time period during drilling of one well using a ca. 2 by 2 km subset of the PRM array with 654 nodes (Figure 1).

Extracting Drill-bit signals from passive PRM data

![Figure 2 Example common drill-bit source gather after denoising and correlation with focused pilot.](image)

![Figure 3 Common-receiver gather for node 60257 at a distance of ca. 1 km from the wellhead, assembled to common drilling time and plotted together with the rate of penetration (ROP) of the drill bit. Coherent signal is mainly observed during drilling.](image)

In order to prepare the raw, rotated passive recordings for SWD processing, we remove water-borne noise from the dataset to the first order by means of a PZ summation, i.e., summing the pressure and
the vertical component to only keep the upgoing P wavefield. Additional denoising may be necessary during certain time intervals. This includes removal of further distant ship traffic noise, or noise from neighbouring platforms which we address with an adaptive subspace filter (Liu, 1999). Since the drill-bit signal is a continuously emanating wave train, it needs to be correlated with a pilot trace, i.e., a good representation of the source signature, in order to extract the medium response. In the Grane case, we had no downhole or top-drive accelerometer available, and therefore estimated a source signature from the recorded data itself through focusing and stacking, as described in Poletto & Miranda (2004). The large aperture provided by the PRM array is a clear advantage, allowing us to separate the drill-bit signal from rig noise with high confidence, leading to little correlation bias (Poletto et al., 2019). The result of the correlation on 2 min long records is shown in Figure 2. Each trace represents a node from the subset of the PRM array depicted in red in Figure 1. We observe a clear first arrival with arrivals up to the 2nd order multiple can be observed with high signal-to-noise ratio. If we rearrange the data of one node only according to drilling time (Figure 3), we can clearly observe how the travel time increases as the drill bit deepens, and how the signal diminishes when the rate of penetration (ROP) drops to zero. These pauses arise from adding drill pipe and need to be discarded in processing. Regularization ensures even sampling of the drill bit source in depth. The choice of depth sampling is a trade-off between signal-to-noise ratio (short spacing means fewer drill-bit records to be stacked) and sharpness of the signal (long spacing implies the drill bit can no longer be treated as point source).

VSP check shot processing

The regularized VSP receiver gathers cover a depth range from 1000 to 1400 m TVD and can now be treated with a typical VSP processing flow consisting of deconvolution, up/down wavefield separation, cosine correction, assembly of a corridor in two-way-time (TWT), and stack. Figure 4 shows the VSP gather aligned on the first breaks before (left) and after (right) VSP processing. Before processing, the aligned total wavefield shows water-layer multiples (black arrows), and some indication of reflected P-wave energy (blue arrow) and downgoing shear (red arrow). After deconvolution and two passes of wavefield separation, the primary upgoing P wavefield is clearly visible (right, green arrows). Further enhancement of the data in the corridor domain and a corridor stack yield VSP data suitable for interpretation and can...
be used to quantify the relative distance of the current drill-bit location from target reflectors. A comparison with a crossline section of the 3D surface seismic in Figure 5 reveals good correspondence with the SWD reflection results.

Conclusions

We have extracted reflected arrivals with high signal-to-noise ratio from passive seismic recordings of drill-bit noise with a seafloor PRM array. We can identify reflections from below the target reservoir at ca. 1800 m TVD in the corridor from ca. 1200 m drilling depth onwards, and hence manage to see reflections from up to 400 m distance below the drill bit. The borehole was drilled using a PDC bit with penetration rates of 20-45 m/h, which implies correlation lengths of 2 to 4 minutes per RVSP trace. We obtain these results without the use of a downhole pilot for correlation but rely on a large PRM receiver array for focusing drill-bit signal and removing noise. While robust, our current time-domain approach is geared towards horizontal layering. Lateral structural variations and highly deviated wells require ultimately a depth-domain approach which is work in progress. Nevertheless, the method can produce check-shot VSP information in real-time while drilling without the need to stop and pull the drill string for wireline deployment.

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