NOVEL ACQUISITION DESIGN TO IMPROVE ILLUMINATION FOR VELOCITY ESTIMATION AND IMAGING, NORTH SEA CASE STUDY

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Summary

In this paper, we will demonstrate how a novel marine multi-azimuth acquisition solution enabled better illumination below and within complex velocity structures like sand injectites, chalk and basement in the Viking Graben area, North Sea. We will show how this led to a successful velocity model estimation based on Full Waveform Inversion.

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Introduction

Successful seismic exploration requires sufficient sampling and illumination of the subsurface to enable reliable velocity estimation, imaging and inversions for rock properties. The acquisition design needs to be adapted to the geological complexities based on the existing knowledge of the area.

We present a case study from the Viking Graben in the North Sea where the acquisition design was tailored to accommodate a series of known imaging challenges from previous projects. In this region, several velocity anomalies (sand injectites) create an unbalanced image response. The large velocity contrast creates local shadow zones and their irregular shape and high impedance contrast generate a complex scattered wave field, where limited energy transmits through these structures. The presence of a rugose high impedance chalk layer creates strong migration swings that can completely mask the target sands. The water depth is around 100 meters, which requires near offset recordings for shallow imaging with primaries. In addition, the long offsets are desired to stabilize the velocity estimations with Full Waveform Inversion (FWI), where the high velocity chalk and basement refractions can be utilized. A new multi-azimuth acquisition design was developed for velocity model building and imaging. We illustrate the benefits.

Imaging challenges and acquisition solution

The study area was conducted in the southern Viking Graben, a part of the North Sea Jurassic rift system which hosts a number of plays that have been successful throughout decades of exploration. Recently, new exploration concepts have opened new plays such as Paleogene injectites, Upper Jurassic sands, Zechstein carbonates, and the fractured/weathered basement.

The complex geology in this area introduces significant challenges for imaging and model building (Figure 1a). A large set of cemented sand injectites (yellow arrows) can create an unbalanced and blurred image response. The high velocity contrast of these bodies influence the illumination of the structure below. Their highly irregular shape and strong impedance contrast creates a complex scattered wave field, where limited energy transmits through these structures. The illumination and migration response will depend on the acquisition direction, where the acquisition with the shortest path through these anomalies will be less distorted, providing the best image and hence easier to utilize for velocity estimation. The rugose high impedance chalk layer (annotated in blue) requires a well sampled wave field as input to migration to avoid strong migration swings on the output. The acquisition solution (Figure 1b) was a multi-azimuth design to enhance the illumination below the cemented sand injectites combined with wide-towed sources to improve the crossline sampling, reducing the migration swings. The wide-towed sources where deployed closer to the streamers in order to improve the near offset sampling for shallow imaging with primaries. Two of the twelve cables where longer to facilitate an improved sampling of the chalk and basement refraction for FWI, which will sample the lateral velocity variations within a structure where the pre-critical energy is limited to a narrow angle range. Two new acquisitions where acquired on top of an existing acquisition with conventional design. Further details about the acquisition parameters and the full processing sequence can be found in Widmaier et al. (2020) and Oukili et al. (2020).

Methodology

The FWI implementation uses an inverse scattering imaging condition (ISIC) to separate the velocity kernel from the migration isochrones (Ramos-Martinez et al., 2016), enabling accurate low-wavenumber model building, simultaneously using transmitted and reflected energy. To include reflections in FWI, hard boundaries can be introduced in either the velocity or the density model. This may be difficult, when an accurate density model is not available, or the velocity model is immature or inaccurate. The FWI method uses an alternative approach based on vector reflectivity in the wave-equation to initiate reflections during forward modeling. (Yang et al., 2020).

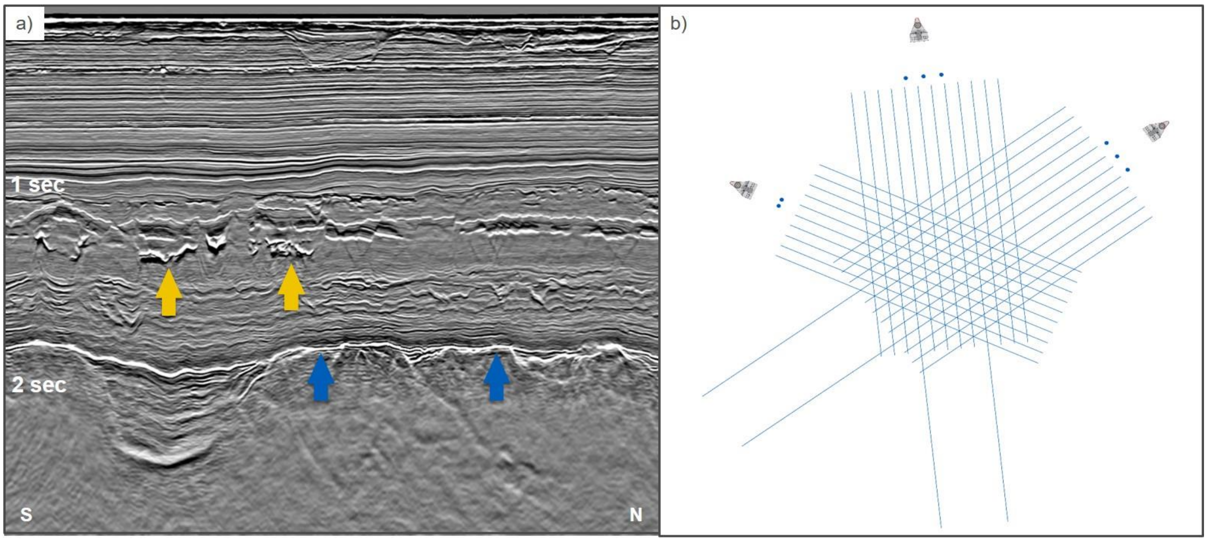

Figure 1. *(a) Seismic section in the time domain, and the acquisition design (b) to facilitate multi-azimuth illumination below the cemented sand injectites (yellow arrow) and better sampling to reduce the migration swings from the high impedance chalk reflector (blue arrow). The two long cables for the two new acquisitions targeted the chalk/basement refractions.*

Velocity estimation with FWI

The velocity model estimation relied mainly on Full Waveform Inversion (FWI) and only residual corrections with reflection tomography were required to optimize the model for imaging purposes. A smooth version of the existing vintage model provided an appropriate initial model for the inversion.

The inversion was done in cascaded frequency bands, up to a maximum of 15 Hz; gradually growing the data selection and increasing the wavenumber content initially by transmission energy, and then the entire wavefield. All the azimuths were utilized in the inversion process to best illuminate and update the model through and below the complex injectites. Figure 2 shows a 9 Hz sensitivity kernel for two different shooting directions with the two new acquisitions, containing a mix of back-scattered and refracted energy. The background model perturbations are relatively similar for both directions. The multi-azimuth inversion utilized all the data and stabilized the inversion process.

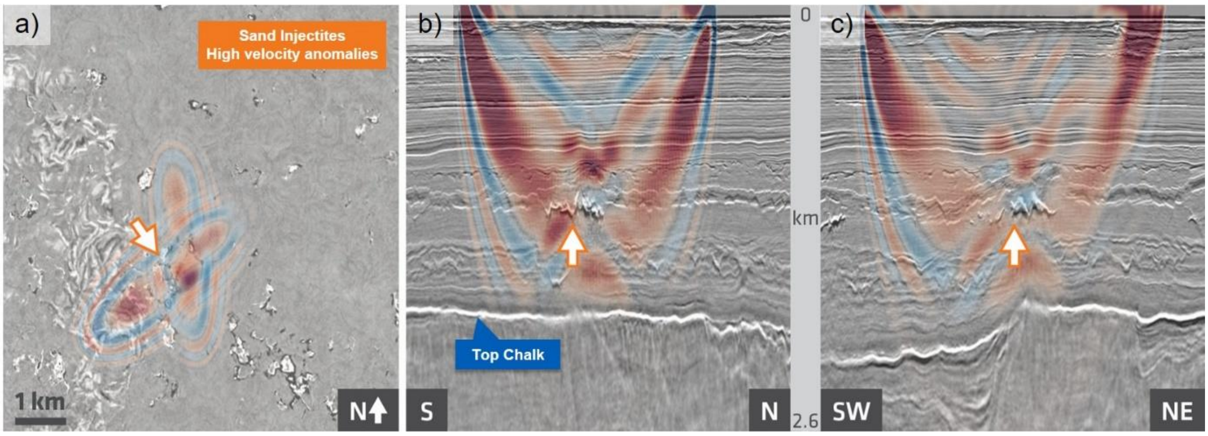

Figure 2. *9 Hz sensitivity kernel for two different acquisition directions. Depth slice through the cemented sand injectites (a), and seismic sections following the two sail line directions (b) and (c). The orange arrows point at the sand injectite and shows the shape of the anomaly in the two directions and how the Top Chalk reflector (annotated in blue) below is poorly illuminated.*

Figure 3 shows a comparison between the vintage and the new final velocity model. Figure 3a and 3b show depth slices at 1170 and 1300 m depth in addition to a seismic line through the middle of the area. Figure 3d, 3e and 3f shows the corresponding results from the new processing project. The orange arrows point at the cemented sand injectites that are usually associated with high velocities. In the vintage model, these structures where captured and scaled in the model based on their amplitude contrast and a coherency attribute (Korsmo et al., 2017). In the new processing, all wave modes and kernels were used in the FWI process, enabling a data-driven process that provided a better definition and estimation of these structures. The blue arrows point at low velocity zones, believed to be associated with a mud diapir. This anomaly has been captured in the new processing, which is important for the overall structural image but could also indicate an overpressured area . The new FWI process captured all the key geological structures and served as an excellent background trend for depth imaging.

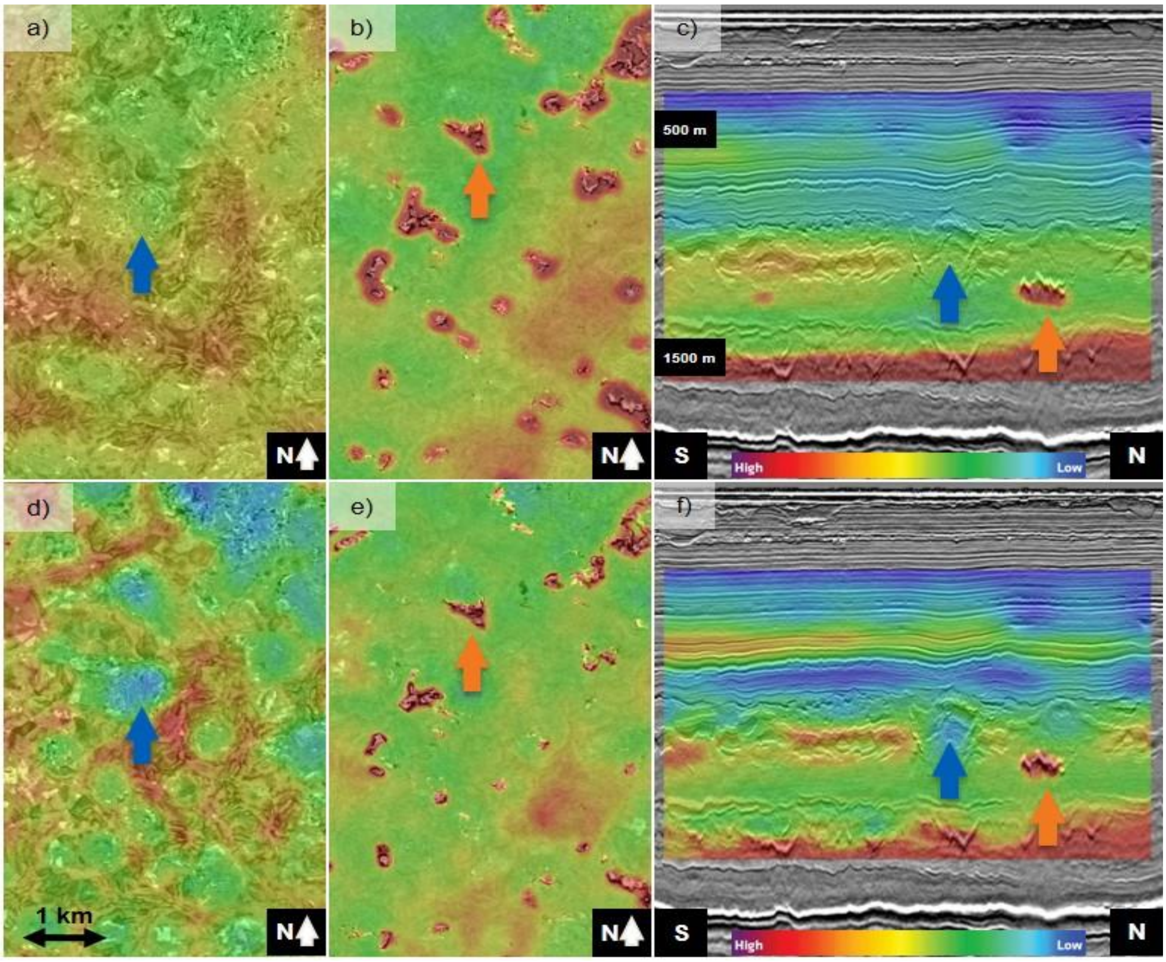

Figure 4. *Depth slice of the vintage model overlaid on the image at 1170 (a) and 1300 meters (b) together with a seismic section (c). The corresponding results from the new processing shown in d, e and f. The blue arrow points to the mud diapir and the orange arrow points to the cemented sand injecties, both anomalies where better resolved with the new acquisition and processing.*

The chalk and basement reflectors are associated with high velocity contrasts and therefore generate strong refracted events. This has a significant impact on the useful angle range for reflection tomography and imaging. Post-critical energy at Top Chalk can start as low as 25 degrees angle-of-incidence (AOI) and limit the ability to use move-out discrimination in reflection tomography. With this in mind, the two new acquisitions where configured with two extra-long cables, to sample the chalk and basement refractions for FWI purposes. Figure 4a shows a shot point at 6 Hz for one of the streamers with the extra-long cable and the corresponding sensitivity kernel at 10 km offset in Figure 4b. The remaining cables in the new acquisitions where limited to 6 km offset as shown in Figure 1b. As can be seen in Figure 4a, the refracted events from the chalk/basement are well samples between 6 and 10 km offset (yellow arrow). The kernel display shows the diving wave contributions from the long cables into the chalk and basement structure. Figure 4c shows the accumulated velocity difference at 8 Hz and illustrates how the shallow sediments, the chalk layer and the basement structure have been updated with FWI.

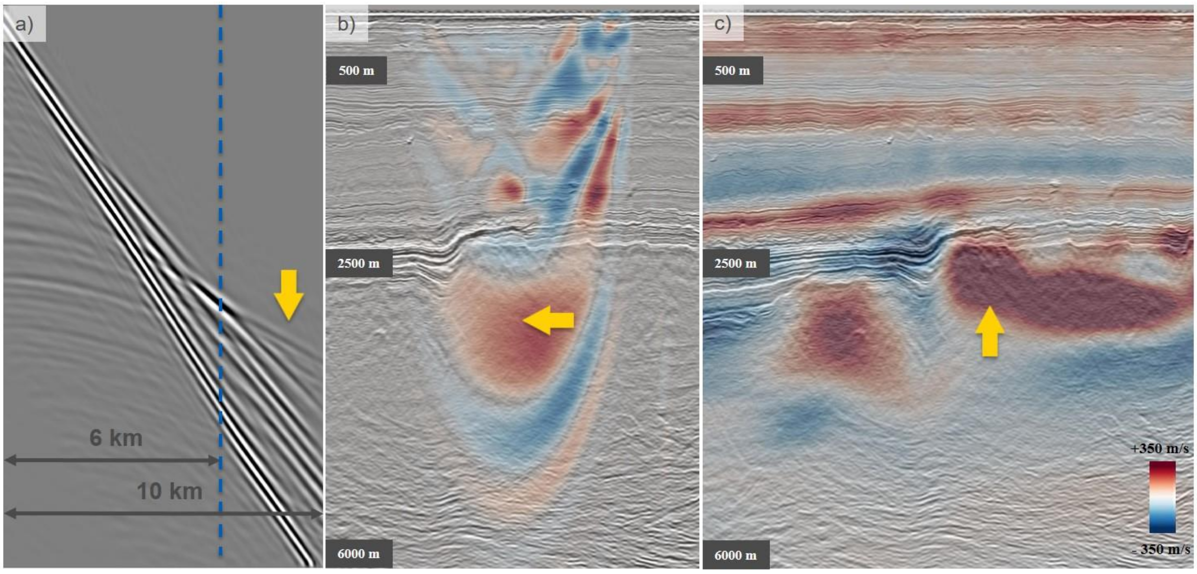

Figure 4. *Observed shot point at 6 Hz with extra-long cable (a), the corresponding sensitivity kernel at 10 km offset (b) and the accumulated velocity difference achieved at 8 Hz (c). The chalk and basement refractions are well sampled between 6 and 10 km offset and provides stable and deep updates (yellow arrows).*

Conclusions

In this paper, we have described how the acquisition design was adapted to mitigate the well-known imaging challenges of the study area. The multi-azimuth approach enabled improved illumination through and below the complex high velocity anomalies in the overburden, stabilized the FWI process, and improved the structural image. The two extra-long cables sampled the chalk and basement refractions and enabled reliable updates in this high velocity zone.

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