Multi-azimuth multisensor quantitative interpretation: a South Viking graben case study, Norway

Cyrille Reiser[1*] and Eric Mueller[1] look at the reservoir characterization of a recently acquired and processed multi-azimuth multisensor survey in the prolific South Viking Graben, offshore Norway.

Abstract

The quest for any geoscientist trying to build an accurate reservoir model, or to estimate petroleum resources, has always been to extract reliable, high-quality reservoir properties from seismic data in an efficient manner. This article looks at the reservoir characterization of a recently acquired and processed multi-azimuth multisensor survey in the prolific South Viking Graben, offshore Norway, an area that has delivered numerous significant successes in multiple plays over the past decade. We focus our analysis on the quantitative interpretation of the various stratigraphic intervals ranging from the Tertiary to the Permian reservoir levels by integrating the seismic data with a significant number of wells within and around the area of interest. A proprietary, interactive, regional rock physics modelling tool was used to analyse the available well log information and rapidly assess the expected elastic properties variation and the prestack seismic responses for a range of changes in local reservoir conditions. The case study presented here highlights how newly acquired broadband seismic data, integrated with regional well information, successfully addresses some known regional and near-field exploration challenges. The project is continuing, however, very promising results have already been achieved for the evaluation of reservoir and trapping styles for existing fields and discoveries and also regarding the mapping of new opportunities for future near-field exploration activity.

Introduction

A variety of marine seismic acquisition techniques have been developed with the objective of obtaining the best description

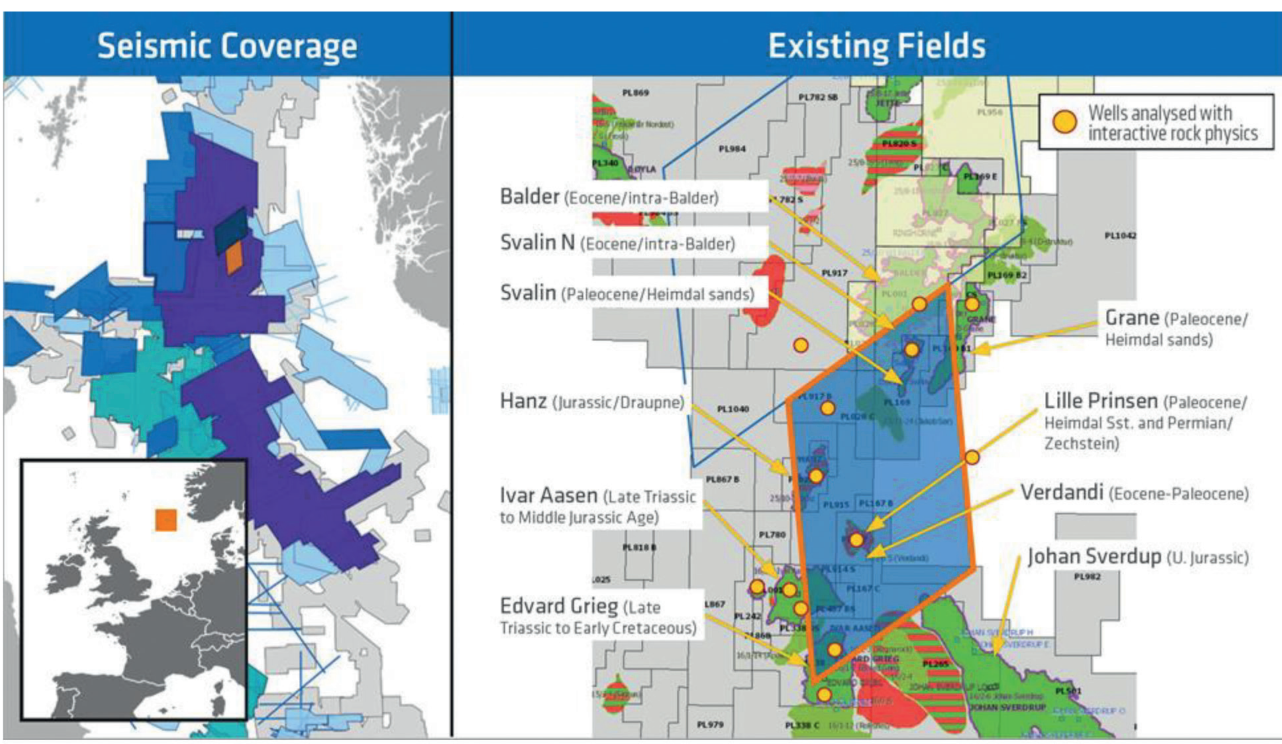

Figure 1 Left: Location of the 2019 multi-azimuth multisensor survey (orange polygon) and its surrounding multi-client products in the UK and Norwegian North Sea. Right: Study area covers approximately 545 km^2 over various fields of different stratigraphic age, as well as some recent discoveries (Verdandi and Lille Prinsen are highlighted in the middle of the survey). Various wells analysed along with the seismic data using a proprietary interactive rock physics modelling tool are also shown (orange dots).

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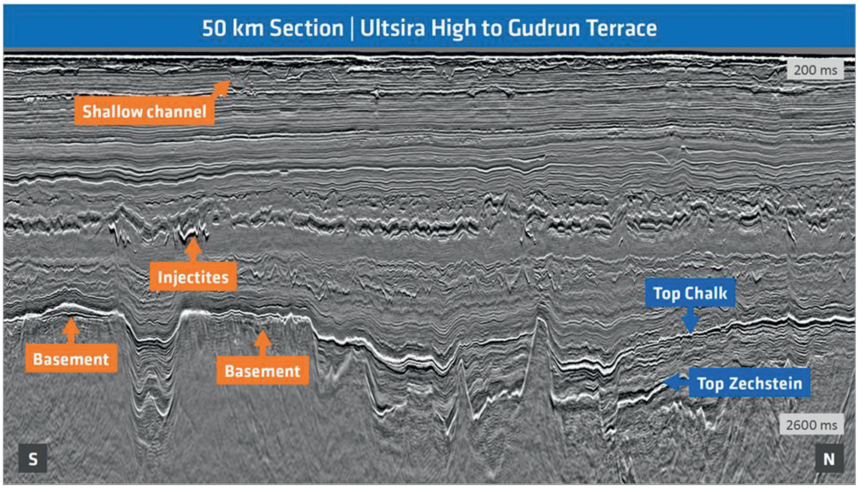

Figure 2 Seismic section showing the main geological challenges present in the survey area: shallow channels, the presence of high velocity sand injectites or so-called V-brights, the rugose chalk interval, and the deeper imaging of the Zechstein and basement.

and understanding of specific reservoir targets, as well as aiding the detailed imaging of the overburden and the geology that is proximal and distal to the reservoir zones of interest. These acquisition techniques range from the familiar 3D narrow-azimuth towed streamer seismic to multi, wide or full-azimuth towed-streamer acquisition, as well as seismic recording using ocean bottom nodes or cables. Different acquisition geometries can be combined to form the optimum source and streamer templates (Widmaier et al., 2019 and 2020; O'Dowd et al., 2020) determined by the sampling and resolution requirements of the use of the seismic data, such as frontier exploration, near-field exploration, and/or appraisal and development. For example, while narrow-azimuth seismic acquisition is adequate in benign structural settings, it provides limited illumination of complex geological features such as injectites and fluvial channels, and limits the reliability of full reservoir characterization in terms of azimuthal anisotropy estimation.

The area of interest for this study is situated in the South Viking Graben, offshore Norway (Figure 1). Major producing fields located in this area comprise several stratigraphic intervals and from north to south:

- Eocene Balder sands
- Paleocene Heimdal sands (Grane, Svalin)
- Upper Jurassic – Draupne (Hanz)
- Late Triassic to Mid. Jurassic (Ivar Aasen),
- Late Triassic to Early Cretaceous sandstone (Edvard Grieg),
- Upper Jurassic intra-Draupne sandstone (Johan Sverdrup).

More recent discoveries include Lille Prinsen, drilled in 2018, which encountered various hydrocarbon intervals in the Eocene (Grid sand), Paleocene (Heimdal sand) and Permian (Zechstein Group).

Although the North Sea is a mature basin, it still holds significant hydrocarbon potential. Some of the challenges associated with the optimization of near-field exploration or infrastructure-led exploration (ILX) are highlighted in Figure 2 on a seismic section from the survey area:

- Shallow subsurface channels, shallow gas,
- Tertiary low-velocity anomalies and high-velocity sand injectites (so-called V-brights),
- Paleogene polygonal faults,
- Late Cretaceous high-impedance rugose chalk interval, and
- Signal attenuation in the basement.

All these complex geological features distort, obscure, attenuate, dim, and/or scatter the seismic signal, and thus prevent the accurate and reliable characterization of the Tertiary to Paleozoic reservoir levels.

To overcome these diverse and complex challenges, an innovative multi-azimuth (MAZ) multisensor acquisition solution was designed. MAZ acquisition was first implemented more than 10 years ago. Examples include the Nile Delta (Keggin et al., 2007), which was used to overcome local challenges such as imaging below the Messinian salt of Miocene age, and applications to quantitative seismic interpretation (Marten et al., 2008).

In this case study, the MAZ survey included two new, deep-tow azimuths (acquired in 2019) over legacy seismic data (acquired and processed in 2011). The new acquisition used a 12 × 6 km × 85 m, high-density, multisensor streamer spread, including two 10 km-long streamer tails for improved deep velocity model building with Full Waveform Inversion (FWI). The two new broadband azimuths were acquired at 60 degrees relative angle, to provide optimal azimuthal coverage to complement the legacy survey.

To ensure sufficient near-offset seismic data, a wide-tow triple-source design with 225 m separation between outer source arrays was included in the design, allowing reliable near-offset coverage in the 50-125 m offset range necessary for high-resolution imaging of the very shallow section. More information about the acquisition design can be found in O'Dowd et al. (2020). The multisensor seismic streamers were towed at between 25 and 28 m depth, for improved signal-to-noise ratio and enhanced low frequency recording. By combining one legacy and two new acquisition directions, the survey provided rich azimuth/offset information and illumination both below and above the various intervals of interest, overcoming the various aforementioned geological challenges.

Regarding data processing and imaging, the MAZ dataset went through a modern prestack depth migration sequence with the main processing steps summarized below (Oukili et al., 2020):

- Sail-line processing including denoising, wavefield separation for the up-going wavefield separation, deghosting and designature,

- Comprehensive demultiple sequence addressing the short and long period multiples, integrating 3D SRME (Surface Related Multiple Elimination) and SWIM (Separated Wavefield Imaging),
- Full Waveform Inversion based on refraction information up to 12 Hz; from 0 to 10 km using the two long streamer tails, and reflection FWI up to 15 Hz for 0 to 6 km offset,
- As the azimuth distribution and offset diversity is rich with this dataset, up to 2 km offset and 40 degrees of incidence angle down to the chalk interval, six azimuthal sectors were generated, with three azimuths corresponding to the vessel acquisition direction and three additional azimuths in between. All six datasets were regularized and migrated as one five-dimensional volume, which was used in a quantitative interpretation project that focused on the shallower section of the survey.

Understanding the link between the elastic properties extracted from seismic data and the reservoir properties delivered from well data is key to evaluating and risk-ranking prospects. A regional interactive rock physics modelling tool (PGS rockAVO) was used to better understand the elastic property responses that were due to changes in reservoir properties (e.g. VClay, Porosity) and fluid saturation over the intervals of interest.

The rockAVO interactive tool has been specifically developed to facilitate the integration of well-log data and rock physics models to help further derisking and to make it easier for exploration or asset teams to identify play analogues for prospect screening and analysis. The key benefits are:

- Consistent high quality conditioned, interpreted and modelled well data immediately available for use in licensing round work,
- Integration of seismic and well data during and after the processing and imaging sequence,
- Ability to perform and visualize the effects of model perturbations of reservoir properties on the seismic data, and
- Rapid screening for analogues and scenario testing of lithology, fluids, and porosity in real-time.

The detailed rock physics modelling used in this case study consisted of the following steps: data gathering, well-log data interpretation, conditioning, modelling using the geophysical well-log analysis, rock-physics diagnostics and rock-physics modelling. Various fluid and lithology scenarios were modelled, and their respective seismic response was computed for direct comparison with the measured seismic AVA (Amplitude versus Angle) behaviour. By perturbing the reservoir properties in the model and rapidly generating synthetic AVA gathers, it was possible to test the sensitivity to any fluid saturation changes at stratigraphic intervals of interest.

Based on the interactive rock physics modelling analysis, the following AVA responses would be predicted for the main reservoir types in the survey area: Class II/IIp AVO for the Tertiary Heimdal sands with hydrocarbons (well Lille Prinsen, 16/1-29S), and Class I/II both for the Upper Jurassic Draupne sands (Hanz, 25/10-8) and the Permian Zechstein carbonate over the Lille Prinsen side-track (16/1-29ST2). For the Heimdal

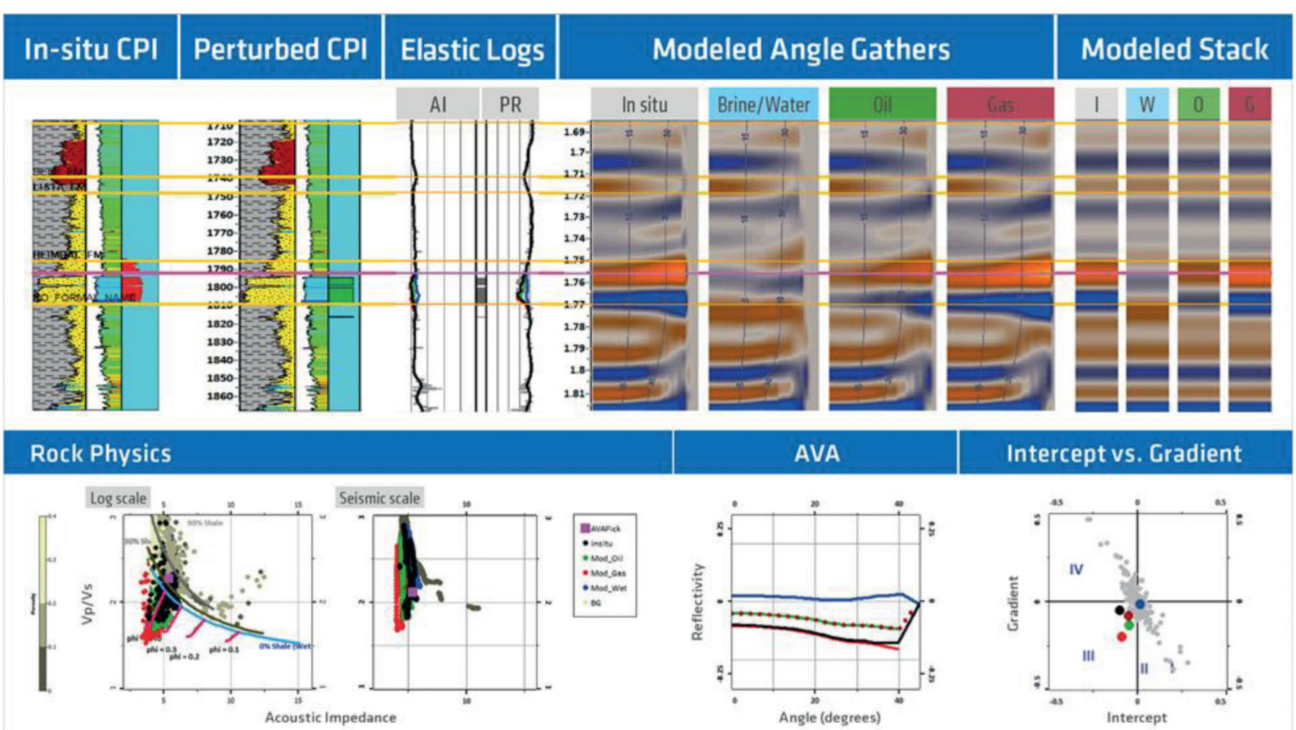

Figure 3 Montage view of the Paleocene Heimdal sands at the Lille Prinsen well (16/1-29S). The prestack seismic angle gather modelled response using a broadband wavelet (0-4-70-80Hz Ormsby parameters) corresponding to the MAZ seismic bandwidth and with different fluid-fill scenarios (brine/water, oil and gas). Seismic panels from left to right: in-situ (I), brine (W), oil (O), gas (G) and the respective angle stack responses. The cross-plots at the bottom of the image correspond to the rock physics template at log and seismic scale. The pink dot on the cross-plots indicates the AVA response at top of the reservoir interval, in this case 1792 m. Additionally, at this depth, the AVA curve expected for different fluid responses (in-situ brine, oil and gas) in the AVA Intercept-Gradient domain is shown. The display panel indicates that the Lille Prinsen well exhibits a Class IIp/III behaviour, depending on the fluid content.

sands in particular, the expected elastic property characteristics are very weak acoustic impedance and strong Vp/Vs response. This reservoir is more or less invisible on the near-angle stack, but visible on the far and ultra-far angle stack; requiring accurate prestack processing and conditioning to preserve the Class II/IIp response in the presence of hydrocarbons. Prospect definition is, therefore, extremely challenging without a detailed prior AVO understanding and careful prestack processing to ensure a potential polarity flip over the measured offset range is preserved in the recorded seismic data. The AVA responses were later confirmed by the well-to-seismic tie.

Analysis and main results

Seismic interpretation was conducted over the whole survey area using the well-calibrated MAZ broadband seismic. Specific focus was given to the Tertiary section, as well as some deeper events such as the Upper Jurassic interval.

For the deep lower-middle Jurassic interval, a meandering fluvial channel system can be observed more clearly on the MAZ full-stack data than on the legacy data (Figure 4), even after legacy data reprocessing. Significant facies details are revealed, such as the various meanders, oxbow lakes, and associated crevasse splays. On the legacy dataset, the individual channel meander loops are masked and very difficult to interpret, making it challenging to achieve an overall understanding of the sedimentary facies. On the MAZ dataset, the channel system and the RMS responses related to point bars, chutes, and crevasse-splay deposits can be seen with much more clarity.

In parallel with the seismic interpretation, a Reservoir Oriented Processing (ResOP) exercise was performed using all six azimuths and over four angle stacks, with focus on the main reservoir intervals. The ResOP sequence included processing steps such as spectral harmonization, denoise, low-frequency enhancement, multi-angle-azimuth time misalignment correction, and estimation of the isotropic/anisotropic Gradient and Intercept (Rüger, 1998). One of the main outcomes of the targeted seismic data conditioning was a distinctive broadband wavelet (3/4 to 80 Hz bandwidth in the Eocene/Paleocene interval) with very low side-lobe energy. The corresponding seismic wavelet is characterized by very high peak-to-trough ratio, low ratio between the side-lobe and the zero-crossing, and as a result, a high bandwidth index according to Araman et al. (2014).

The final image quality of the MAZ dataset enabled good-to-excellent well-to-seismic ties for all azimuths and their associated angle stacks. The statistics are very encouraging, with an average cross-correlation of 80-85% for all azimuths/angles across 10 wells. The AVO classes observed at the various reservoir levels from the well (e.g. Figure 3) were confirmed on the MAZ dataset.

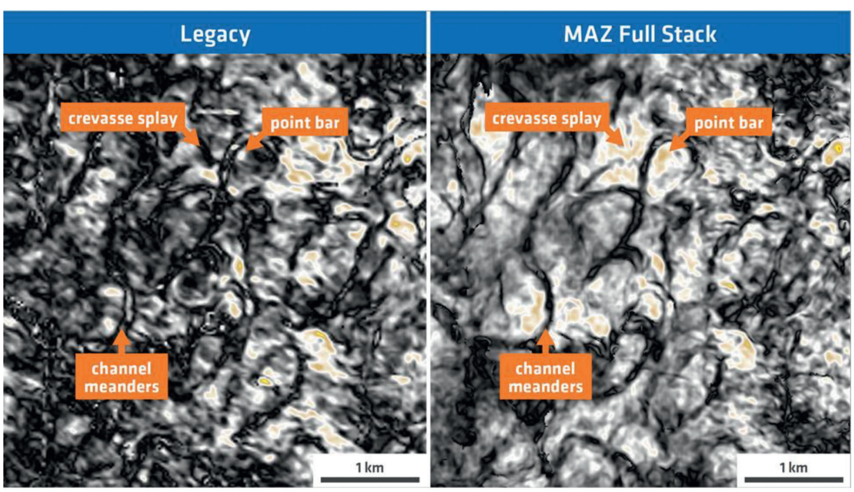

Figure 4 RMS amplitude extraction on a late-middle Jurassic horizon using the legacy (left) and the MAZ (right) datasets. The differences in image quality of a Jurassic meandering fluvial system are clearly observed. A significant improvement in resolution and signal-to-noise ratio of the MAZ dataset allows a more detailed understanding of the fluvial system depositional facies.

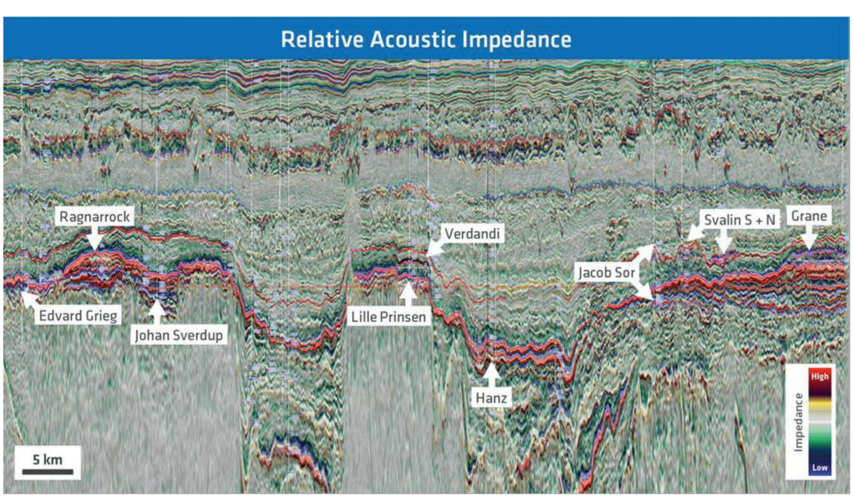

Figure 5 Regional full stack relative acoustic impedance display following a random line across the main fields. Recent discoveries and their respective stratigraphic ages are labelled. The section also delineates many features which degrade historical subsurface imaging such as injectites and irregular, high impedance chalk.

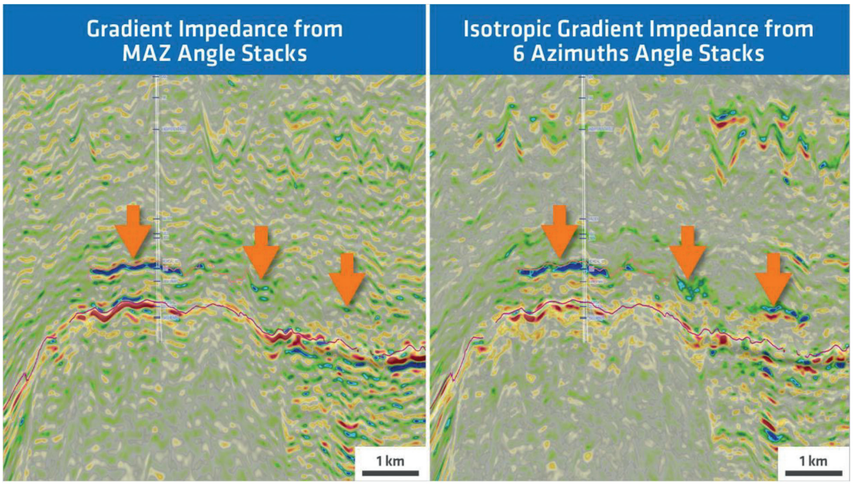

Figure 6 Relative Gradient Impedance inverted from the summed MAZ angle stacks (left); and the relative Isotropic Gradient Impedance (Rüger, 1998) inverted from six azimuths and their conditioned angle stacks. Clear improvements (marked with blue arrows) can be observed at the Heimdal sands level. Low impedance features flanking the main structure on the right are far more visible, indicating additional downdip hydrocarbon potential.

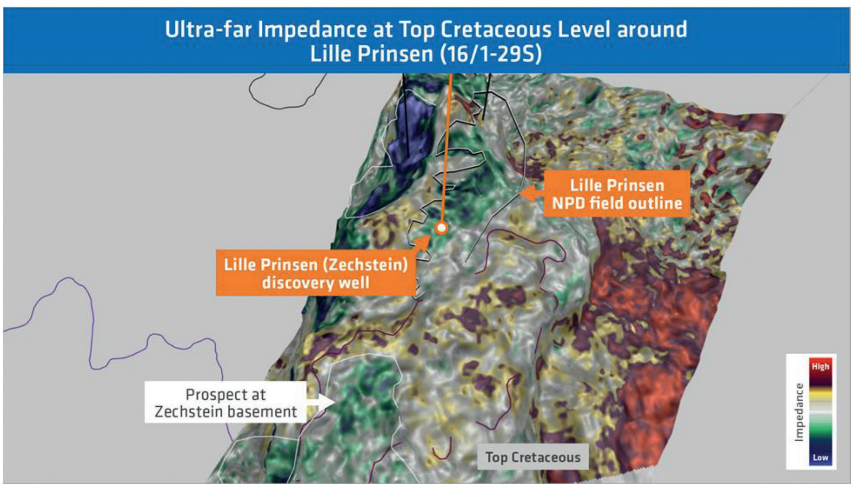

Figure 7 Ultra-far relative impedance map extraction is highly correlated to Vp/Vs at the top Cretaceous over a 16ms window. Blue anomalies match well with the Norwegian Petroleum Directorate (NPD) outline for the Lille Prinsen discovery at this level. A visible anomaly further north-west was tested successfully by a recent appraisal well. Additional opportunities exist to the south of Lille Prinsen, as well as down-flank.

As mentioned in the introduction, several fields are present in this area, comprising reservoirs from the Tertiary Balder down to the Jurassic, with additional new opportunities in the Permian evidenced by the recent Lille Prinsen discovery. These fields can be clearly seen on the relative acoustic impedance section (Figure 5). Many of the features delineated in this section were degraded in the historical subsurface imaging, as discussed earlier. Thanks to the broadband nature of the multi-azimuth multi-sensor dataset achieved in this case study, the target geological features were fully imaged and inverted with unprecedented detail and quality.

A relative prestack inversion was subsequently performed using all four angle stacks for each of the six azimuths, which demonstrated that that low Gradient Impedance and Vp/Vs anomalies estimated using the Isotropic AVA attributes (Rüger, 1998) match and precisely delineate the Heimdal hydrocarbon interval at Lille Prinsen/Verdandi (wells 16/1-29S and 16/1-6S) by comparison to the equivalent attributes inverted from the (summed) MAZ angle stacks (blue arrows on Figure 6). A substantially more stable Gradient Impedance estimation was achieved from the ellipse fitting using all six azimuths, providing clean, stable, and continuous Gradient and inversion results; especially at the Heimdal sand level. Additional hydrocarbon potential is indicated (second arrow on the righthand side of the Figure 6), which was not clear on the MAZ Gradient Impedance.

This multi-azimuth quantitative interpretation also provided interesting results for the deeper reservoir levels. Several additional wells have been drilled following the Lille Prinsen discovery, to examine the potential in the deeper stratigraphic intervals such as the Jurassic sandstone and the Permian. Based on our elastic-attributes extraction on the pre-Cretaceous interval (Figure 7), clear indications of hydrocarbons are visible at the Upper Jurassic and Zechstein levels. These anomalies are of reasonable size and could constitute interesting near-field exploration targets.

Conclusions

This paper has demonstrated how an innovative acquisition solution, using multi-azimuth broadband seismic with wide-tow triple-source shooting, has overcome the main exploration challenges in the prolific southern Viking Graben. Further, improved understanding and characterization of the various reservoir intervals have provided evidence of additional nearby hydrocarbon potential. The integrated approach of acquisition, imaging and reservoir characterization utilized on this project has delivered encouraging results in a very cost-efficient and effective manner. The resulting datasets allowed us to accurately map the existing fields and known discoveries in the area, as well as highlight new leads and opportunities suitable for near-field exploration. More work will be presented in due course.

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