Introduction

West African Exploration and Production (WAEP) have two objectives in this area. The first objective is to restart production of the Kalaekule oil field, which ceased in 2002 following a decline in production and a sudden increase in water cut. The second is to develop new fields in two shallow-water blocks located in the Niger River delta in southeastern Nigeria. To accelerate the exploration and development phases and reduce their uncertainties, WAEP contracted for a solution design and modelling (SDM) study to recommend the future strategy for seismic data acquisition and application of bespoke processing algorithms for this area.

The SDM workflow analyses the legacy seismic data to understand the imaging challenges (e.g., shallow gas, poor water-bottom imaging, fault shadows, and others). This knowledge guides parameterization for reprocessing and is combined with forward modelling to define the data acquisition strategy — one that was designed to meet the exploration objectives in a cost-effective manner. The modelling also helps identify the limits of a given acquisition strategy and guides the applicability of complementary processing options.

Legacy data review and parameter design

A crucial part of designing a new seismic survey is reviewing legacy seismic data from the area. During this step, we aim to gain an understanding of the limitations in these data sets and how data quality could be improved by a new acquisition combined with modern processing and whether reprocessing the original data alone is of value. In the case of the Kalaekule oil field, the legacy data included several vintages, as well as different acquisition techniques, resulting in a greater understanding of how the subsurface affects the seismic measurement. A thorough analysis was undertaken that included analysing the legacy data sets, both prestack and poststack, from a frequency bandwidth and signal-to-noise ratio point of view. As part of the review, the legacy processing sequences were evaluated to help identify any limitations introduced during processing that would constrain our understanding and to determine if a different seismic processing approach or imaging techniques could bring an uplift to the data quality. The outcome of the review was the requirement for improvements in near-offset coverage (illustrated by the poor imaging of the near surface in shallow-water areas), increased maximum offset (highlighted in the review of common midpoint gathers and comparison of stacks from legacy surveys), and finer spatial sampling (determined through modelling).

Building on the results of the legacy data review, forward modelling and theoretical resolution estimation were used to determine the core parameters of a new seismic strategy: the sampling and offset requirements.

The theoretical resolution was estimated using a combination of 1D modelling (using well velocities) and target modelling (using a velocity model together with an interpreted target surface), with both drawing on the knowledge gained during the legacy data analysis. In the 1D modelling, we looked at the vertical resolution, based on the tuning thickness (Kallweit and Woods, 1982), fault resolution (Chapman and Meneily, 1990), and lateral resolution (Lindsey, 1990). The target modelling extended our understanding by providing an areal view of the resolution and gave insight into the lateral variation of the resolution.

In determining the required bin size, we considered the lateral resolution together with the imaging requirements, considering the dip and frequency at target. In this study, it was found that a small bin size was required to meet these criteria. This, in turn, determined the spatial sampling requirements for the shots and receivers.

Acoustic modelling was used to generate synthetic gathers. These were used to determine the required offset range of the new acquisition (Figure 1). In determining the maximum offset, we considered what would be useful in processing for both imaging and velocity model building at all target levels. These gathers were also used in generating footprint stacks, demonstrating the need for a narrow spread to image the seafloor.
The output from the theoretical analysis and modelling are a set of core acquisition parameters for new acquisition. These are used in the subsequent parts of the study.

Figure 1 Example of acoustic modelling to estimate the useful offset range for new acquisition. The left panel shows the gather without moveout, the centre panel shows the gather with moveout, the top right panel shows the impact of stretch muting of 120% and the bottom right panel shows a stretch mute of 140%. Each of the moveout-corrected gathers shows the amplitude variation with offset angles. With a 120% stretch factor, the maximum offset at 3.5 s is 4600 m; this increases to 6000 m with a stretch factor of 140%. Potentially, the maximum useable offset is 7125 m, but this has a stretch factor of around 160%.

Illumination analysis

The illumination analysis was used to evaluate the proposed acquisition geometry, investigate the impact of the shallow gas bodies, and evaluate the potential uplift from imaging with multiples.

In evaluating the proposed acquisition geometry, we compared it with the illumination from the legacy geometry and considered the shooting direction. This is achieved by producing illumination maps (Drottning et al., 2009).

For this analysis, a 3D earth model was built using interpreted horizons and well data. The analysis showed that the deep target was better illuminated by the longer offsets of the proposed acquisition parameters. The acquired offsets would be limited by muting during processing; to simulate this, the hit-count maps were produced after applying an angle mute and these also showed an uplift in illumination compared to the legacy geometry (Figure 2). Due to the three-dimensional nature of the target, the offset-azimuth analysis performed did not identify a preferred shooting direction.
One of the challenges identified within the proposed survey area was the presence of shallow gas bodies. To investigate the impact of these bodies, we build a simple layer-cake 3D model. Into this model, we inserted an interpreted shallow gas body from one of the legacy surveys. Ray tracing, using the proposed geometry, was performed to demonstrate the impact the shallow gas has on the illumination. The raypaths for selected shots are shown in Figure 3.

The analysis used the worst-case scenario of 100% attenuation within the gas body. This was chosen to show the extent over which the gas would have an influence on the seismic image. It is probable and correct to assume that, in reality, given the correct velocity field within the gas body (aided by processes such as full-waveform inversion (FWI) model building), that an image may be recoverable within this area identified by this modelling. The longer streamer length of the proposed geometry will undershoot the observed gas body and with the velocity model building by means of FWI.

Seafloor imaging had been identified as a key challenge for new acquisition. This was taken into account during the parameter design, but it still constitutes a challenge. One potential processing technique that could be used to further improve the seafloor imaging and the near surface is imaging with multiples.
To understand the potential improvement this could bring, we designed a ray-tracing experiment. Figure 4 compares the seafloor illumination with the primary reflections to that from the first water-bottom multiple. In addition to the proposed geometry, we also considered a wider, more efficient, spread. This showed that, by imaging with the water bottom multiple, a wider spread could be used, but with an increased footprint in the data.

Reprocessing strategy

While the primary survey design objective is to define the optimum acquisition parameters to overcome the seismic imaging challenges associated with the geological complexity, it also allows us to understand the limitations of the existing seismic data and tailor a reprocessing strategy based on it. This avoids lost time caused by trying to obtain results beyond the limitations of the recorded data. A reprocessing project with the existing data sets should be carried out to improve the Kalaekule oil field imaging prior to potential new acquisition. From the SDM study, velocity model building with emphasis on using diving FWI rather than reflection tomography was identified to overcome the lack of near-surface illumination. Imaging with multiples is recommended to obtain a water-bottom image that would be used for the demultiple workflow, which is not possible with primary reflections due to a lack of very short offsets. An illumination study using the existing 3D velocity and positioning data would give interpreters greater confidence as it helps identify areas of poor illumination; in these areas, the data present would have a higher uncertainty due to noise. The illumination study would be improved by a new velocity model derived from reprocessing using the advanced model building techniques described above, e.g., FWI.

Conclusion

Using a workflow of data analysis and forward modelling, we designed a seismic acquisition strategy to mitigate the identified imaging challenges found in the shallow-water areas, offshore Nigeria. This is achieved using narrow-azimuth towed-streamer acquisition with improvements including better near-offset coverage and recording longer offsets.

Recent developments in processing technology were reviewed and are expected to provide significant uplift. These include imaging with multiples to improve the water-bottom image in the shallow area and FWI to improve the accuracy and resolution of the overburden velocity model to aid imaging beneath shallow gas and around faults and illuminate deeper sequences.

References


