Simulating large-scale streamer and OBN acquisition over subsalt targets – an example of successful remote collaboration between survey design and survey evaluation

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Abstract

In this article we look at how ray-based wavefront modelling can be used to evaluate competing acquisition techniques with significantly different illumination properties and associated acquisition cost. We compare subsurface illumination of complex sub salt reservoirs typical of those found in the Gulf of Mexico for a variety of towed-streamer and full azimuth long offset ocean bottom node surveys. Single, dual and triple azimuth towed-streamer surveys are considered.

This project was accomplished using a new connector between ACTeQ's survey design and optimization software and NORSAR's 3D modelling software. This project is an excellent example of competitors collaborating to better achieve a customer's needs.

The project was also accomplished in a fully remote environment, and none of the authors were in the same city at any time during the project. Remote collaboration is becoming an increasingly effective low-carbon approach to complex challenges.

Introduction

The Gulf of Mexico is a prolific oil and gas production area. Much of the area is covered by high quality multi-client towed-streamer acquisition that is more than adequate for exploration. However, the presence of complex salt bodies means that narrow azimuth towed-streamer data often provides poor illumination in some areas. For field development time lapse monitoring and identification of near field opportunities, additional data must often be acquired. In this exercise, we considered three options to achieve better illumination of a cluster of Mesozoic sub-salt plays typical of the Mississippi Canyon area.

- Option 1: Combine existing multi-client data (acquired approximately east-west) with a new north-south acquisition, using a longer streamer.
- Option 2: Combine three acquisitions (acquired at 0/180, 60/240 and 120/300), using a longer streamer
- Option 3: Acquire a new long offset, full-azimuth ocean bottom node survey

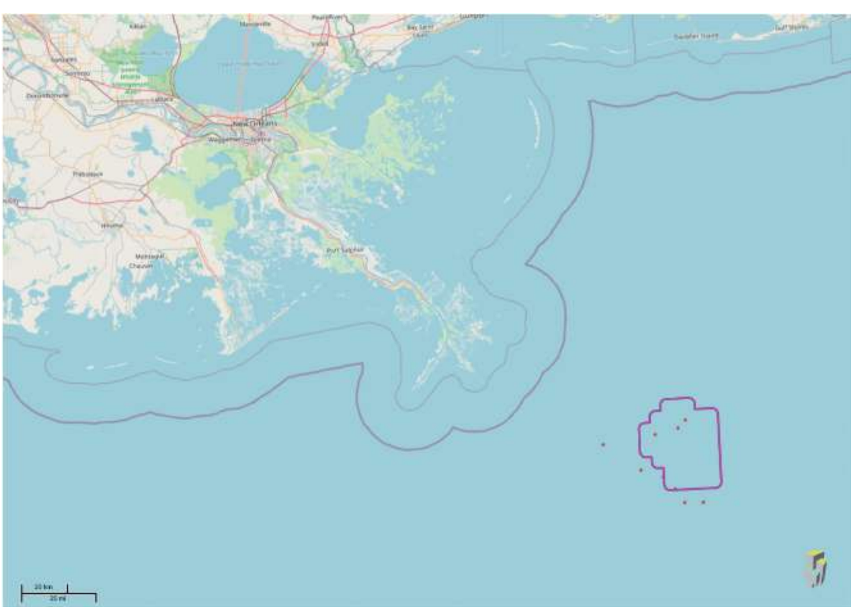

Figure 1 Map showing approximate location of survey.

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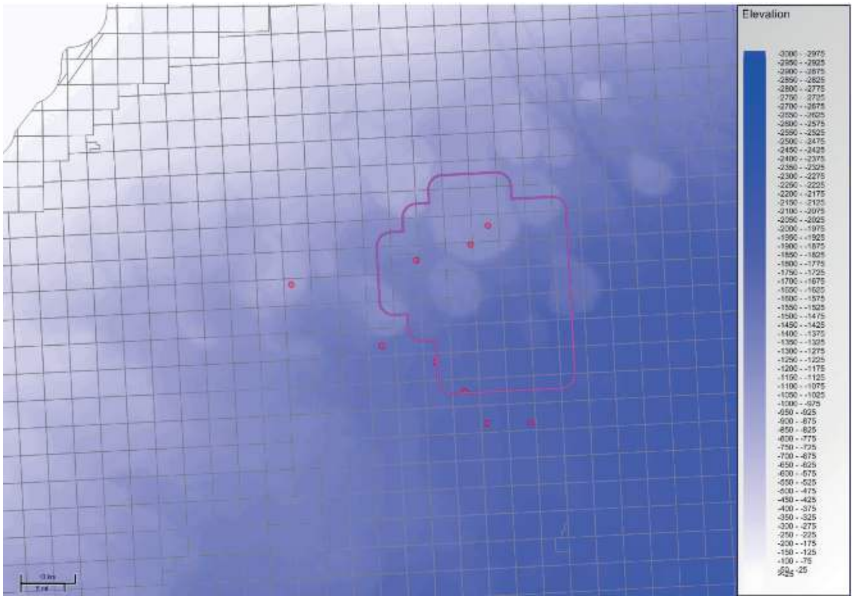

Figure 2 Bathymetry (Courtesy of GEBCO).

Finally, we consider one of the perennial concerns of modellers. If the model is perfect, there is no point in acquiring new data. Therefore, all models are imperfect, and all decisions derived from them need careful evaluation and error control. Our survey design exercise examined the sensitivity of the design to address the inherent concerns when modelling. As George Box famously said, ‘All models are wrong, but some are useful’.

The survey area

Our project is located about 350 km south east of New Orleans, in the Mississippi Canyon area of the Gulf of Mexico, as indicated by the purple boundary in Figure 1 and Figure 2 (covering roughly 1400 km^2). The survey area is adjacent to the continental shelf margin and water depths vary from 300 m at the north western edge of the survey to just over 1800 m at the southern boundary, as shown in Figure 2. The survey boundary used for this modelling exercise is irregular based on federal block boundaries and our a priori estimate of the required migration aperture. Several obstructions are present in the survey area.

Survey geometry

All the survey geometries described in Table 1 were generated in ACTeQ’s survey design and optimization software. To make the modelling exercise as realistic as possible, a hydrodynamic streamer model was used to describe the streamer position as the survey vessel moved around the obstructions in the survey area, as shown in Figure 3. A streamer feather was also applied based on ocean and tidal current predictions supplied by SeisIntel and incorporated into the survey design.

For the OBN survey, the shot lines were also deviated around the obstructions, though a smaller turn radius was used to reflect the increased maneuverability of the source vessel not towing streamers. Receivers were excluded from a 100m-wide area around the pipelines for safety reasons … and to ensure low receiver noise.

Once the survey geometry was constructed, a newly established link between the survey design and modelling tools was used for transferring all five surveys ready for modelling, without any need of writing and reading SPS or P1/90 survey files.

Survey ID	1	2	3	4	5
Status	Acquired (Multiclient)	Proposed	Proposed	Proposed	Proposed
Type of acquisition	Towed Streamer	Towed Streamer	Towed Streamer	Towed Streamer	Ocean Bottom Node
Shooting direction	90/270	0/180	60/240	120/300	90/270
Receivers	8 streamers 100m spacing 6000m 12,5 stations	12 streamers 100m spacing 10,000m 12,5 stations	12 streamers 100m spacing 10,000m 12,5 stations	12 streamers 100m spacing 10,000m 12,5 stations	32 lines live 480m x 480m
Sources	2 x 50m	3 x 33.3m	3 x 33.3m	3 x 33.3m	3 x 50 m
Maximum continuous offset	6000m	10,000m	10,000m	10,000m	10,000m
Azimuth	Narrow	Narrow	Narrow	Narrow	Full

Table 1 Survey geometries.

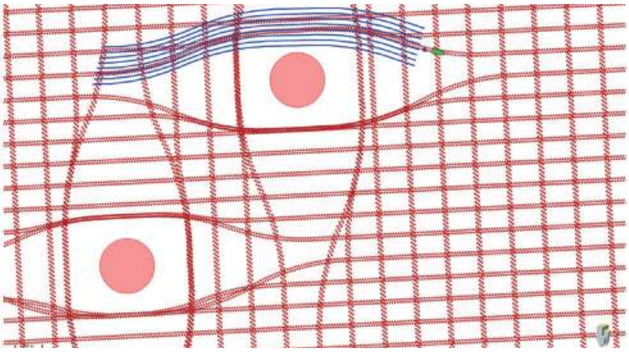

Figure 3 Detail of hazard avoidance for orthogonal towed-streamer surveys.

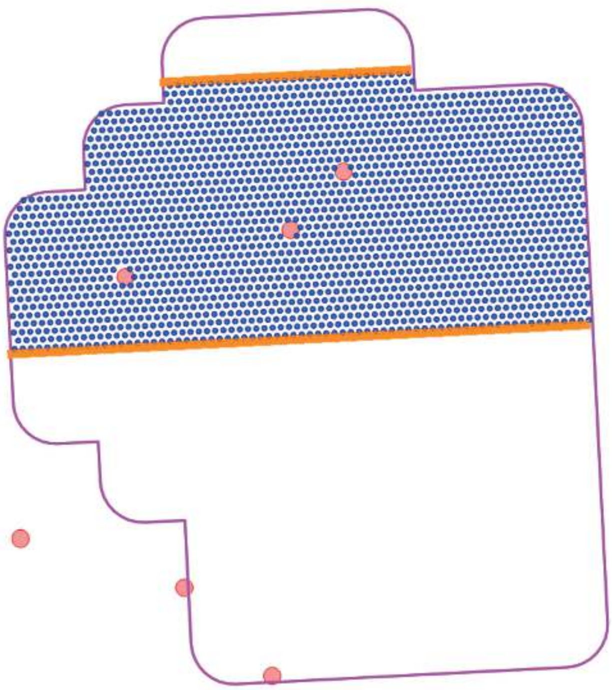

Figure 4 Detail of H-pattern roll used for OBN survey. Shot lines are shown in orange. Receivers in blue.

Model construction

The model (Figure 5) is a synthetic set-up of salt structures typical of the Mississippi Canyon area. Real bathymetry has been used but in conjunction with synthetic salt bodies. On a real project, the salt bodies would be interpreted from the best available seismic data and well logs. The goal was to simulate a situation as commonly observed in the Gulf of Mexico or other areas, with a focus on salt diapirs peaking through the target interface, developing canopies at shallow subsurface depth. As the focus was on the effect of salt on target illumination, the velocity model outside the salt was chosen to be a constant gradient, with a constant starting P-wave velocity clamped to the seabed. For this specific exercise, only kinematic modelling was deemed necessary. Thus S-wave velocity was represented by a constant V_P/V_S ratio and density was kept constant, as neither of them affect P-wave ray paths. Q-values (for attenuation) and Thomsen parameters (for anisotropy) were not included as a model dominated by salt (that otherwise is kept simple) was considered to fully fit the purpose of the study.

Ray-based wavefront modelling

Ray tracing in this study is applied in terms of wavefront construction [Vinje et al, 1993], which is considered more efficient and more stable than the classic two-point modelling approach. Rather than tracing single rays between a starting point (the source) and an ending point (the receiver), wavefront construction mimics true wave propagation in the sense that entire wavefronts are propagated time-step by time-step creating a 'moving surface' that passes through a sub-surface model (Figure 6). This concept is applicable to both isotropic and anisotropic property fields and can handle all parts of the wavefield, including primaries, multiples, phase conversions and multi-pathing events. Most of all, the approach allows for adaptively controlling ray density in all parts of the model (as new rays can be added on the fly and wherever needed). As rays are generated dynamically and reflection points are known, wavefront propagation is ideally

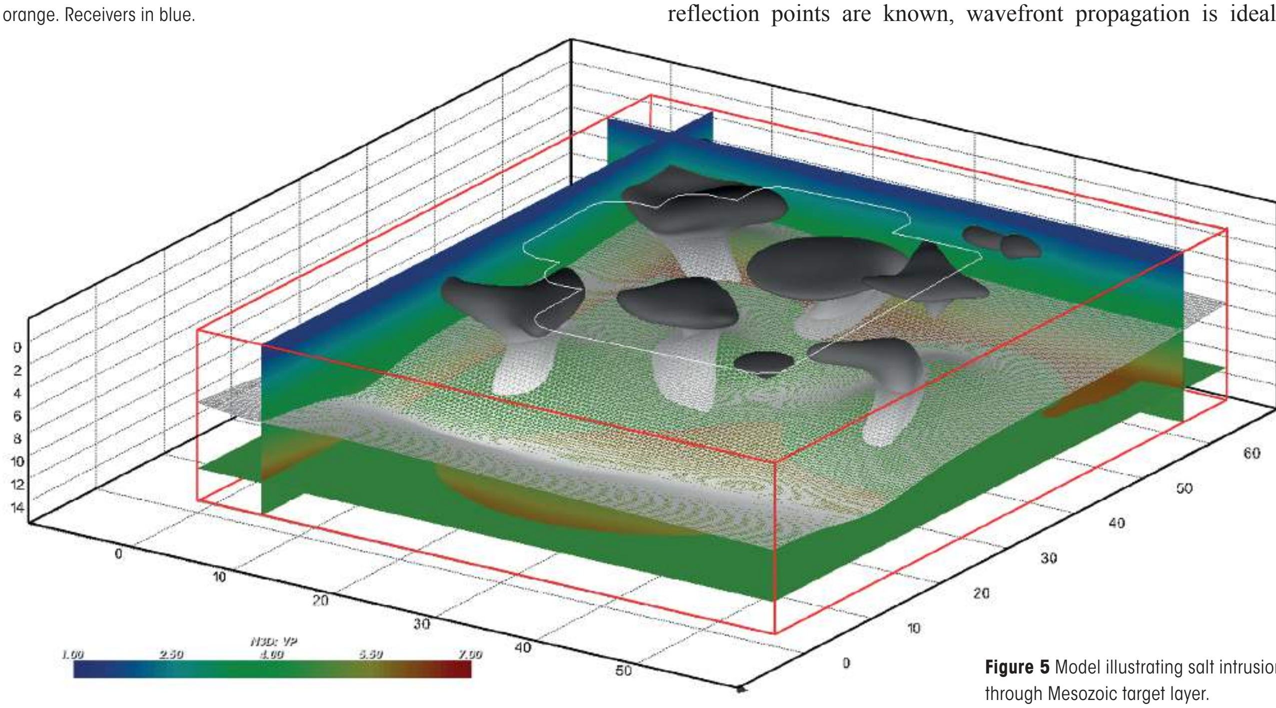

Figure 5 Model illustrating salt intrusions through Mesozoic target layer.

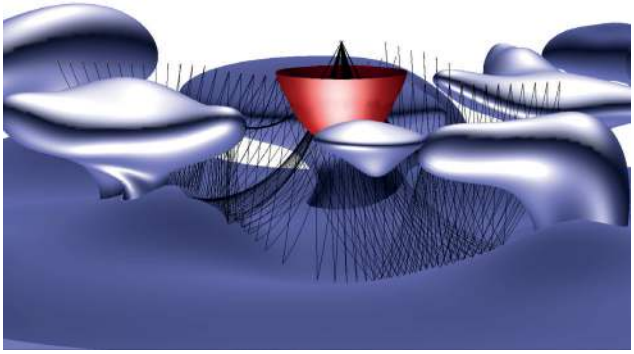

Figure 6 Model (purple) and wavefront (red) with rays (black).

suited for generating illumination maps. All attributes that are stored along the rays can be filtered, sub-selected, and sorted into mapping cells that are regularly distributed along reflection or transmission targets (target domain) or at shot or receiver levels (survey domain). Through ray modelling, detailed survey design will be supported and improved by learning about the best contributing shot and receiver locations, required survey azimuth and survey offset, required listening time and migration aperture, the expected relationship between offset and incident angle, the expected amplitude distribution after migration, and a wide range of other parameters that can be extracted from modelled seismic reflection (or transmission) data. Ray-based modelling can even be used for simulating point-spread functions [e.g., Lecomte, 2008], e.g., for estimating both lateral and vertical resolution at target level, or the calculation of Green's functions [see, e.g., Aki and Richards, 1980] that allow for the generation of pre-stack gathers and migrated sections by means of Kirchhoff modelling and target migration [e.g., Gjøystdal et al., 2007; Zühlsdorff et al, 2018]. However, ray tracing in this study was mainly used for generating hit density maps, to compare the expected target response of different survey types in terms of relative fold and illumination

Illumination results for different surveys

To reduce computational effort, all surveys were 'decimated', i.e., only a fraction of the shots was modelled and hit counts were scaled by a respective correction factor. This is a common short-cut that does not degrade any mapping result when used within reasonable limits; it rather exploits the benefits of a smooth macro model that is not supposed to vary much on a meter scale. More care is required when selecting maximum colour scale clipping values, especially when comparing different survey types. Using too large clipping values would create an overall low-fold impression that may be equally misleading as using too small clipping values for creating a false high-fold impression (making map generation a potentially subjective task). Typically, a reasonable calibration value is the survey's nominal fold, as then higher fold

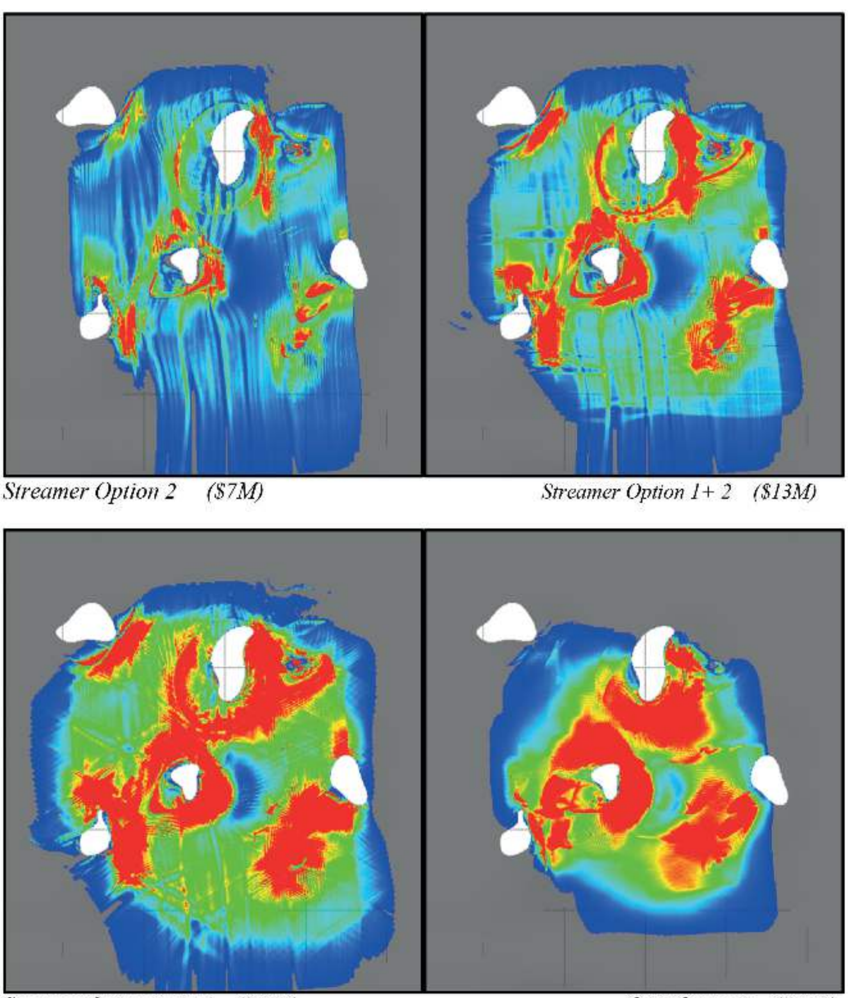

Figure 7 Illumination intensity plots and cost estimates for 4 acquisition options. Red colours indicate 150% of nominal OBN fold or higher, blue colours indicate low fold. White holes indicate where the target is replaced by salt.

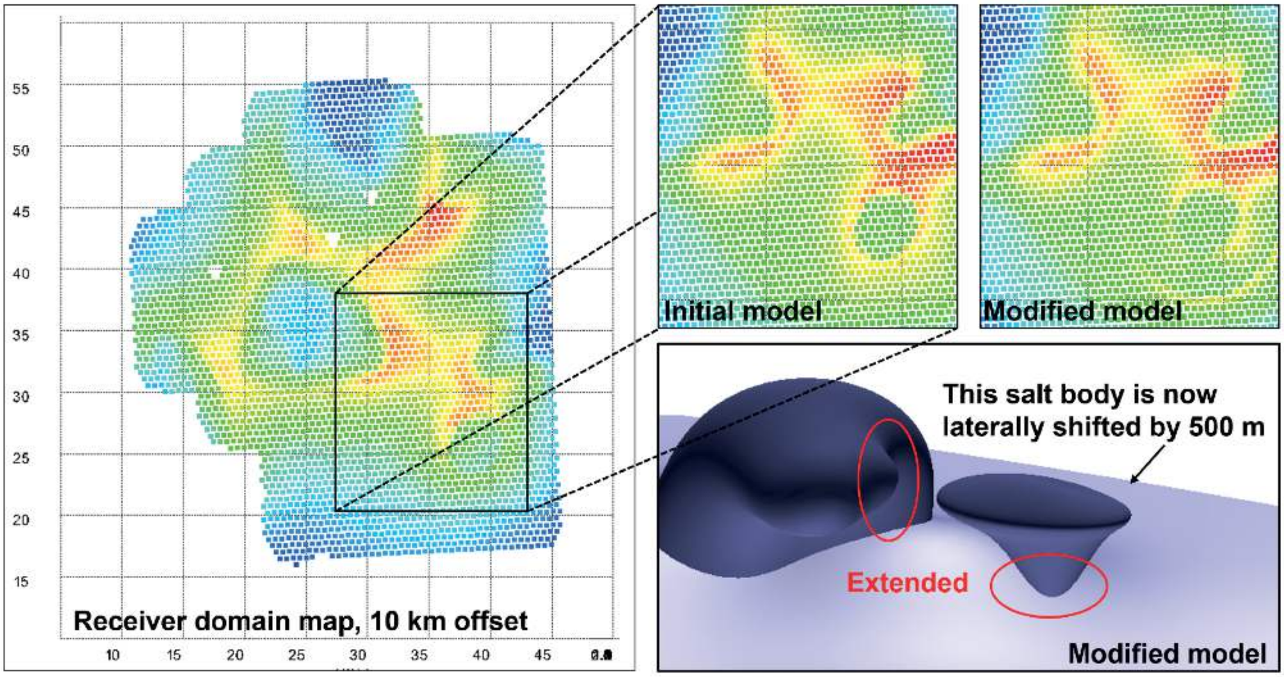

Figure 8 Survey domain map for the initial and the modified model. Red colours indicate receivers that contribute most to target illumination. For model adjustment, salt volume was locally extended, and one salt body was laterally shifted by 500 m.

values would just indicate sufficiently illuminated areas, whereas lower fold values are distributed along a reasonable stretch of the colour scale, making any distinction between low fold, very low fold, and no fold areas much easier. In the given case, 150% of the nominal OBN fold was used as a colour clip for all maps in Figure 7, as OBN has the largest nominal fold of the surveys to be compared, and as there is a significant amount of multi-pathing in the data (i.e., the average number of events for each shot and receiver pair is about 1.5 due to additional ray paths through the salt domes).

The first observation is rather obvious: the general fold level increases as more narrow-azimuth surveys are combined, going from narrow azimuth (single survey) to dual azimuth (two surveys) to multi azimuth (three surveys). The full azimuth (OBN) has the highest fold level. It is to be noted that, in this exercise, 12.5 m streamer groups are compared to 50 m OBN shot spacing. Many modern OBN surveys would probably use 25 m shot spacing, which would make the fold difference between the OBN set-up and the streamer survey combinations more pronounced. However, it would also make it more difficult to find a common colour scale clipping that would give a fair impression of all maps, so the given comparison seemed to be more illustrative.

The second observation is less obvious but more important: there is a low-fold zone just east of the central survey area that is almost circular for the narrow azimuth survey and becomes half-moon shaped for the multi-azimuth survey (but is still there). Only OBN would be able to generate almost nominal fold inside this area. Generally, OBN also provides better fold close to the salt diapirs and underneath the canopies, i.e., in areas that may be interesting from a prospecting point of view. In spite of higher cost, OBN may be considered to better fit the purpose in some target areas.

The maps in Figure 7 also show some residual footprint of the respective streamer surveys, even when combining two or three of them. This in principle is a natural and true effect, even though it may be more pronounced in this case by using a synthetic model in which salt shapes may be overly smooth. For rather regularly feathered cables in combination with 100 m by 100 m cells, hit counts may be more systematically distributed than for more irregular models (as based on seismic interpretations and migration velocity fields). This also explains the rather sharp salt imprints as observed for the lower fold surveys. However, this has no impact on map interpretation or the purpose of this study, because it is a recognizable and explainable effect.

Note that in order to allow 'apples to apples' comparison, the approximate cost estimates shown in Figure 7 are based on the time to acquire each survey as a stand-alone survey. In reality the multi-client data, survey 1, could be procured at a significantly lower price. The acquisition time estimates, include 10% downtime on all surveys and 20% infill on the single azimuth streamer survey. Vessel day rates and mobilization costs have been estimated. Note that as a result of the irregular survey boundary, the streamer surveys acquired at 60, 90 and 120 degrees are less operationally efficient than the survey acquired in a N-S orientation.

Target domain mapping and model sensitivity

Survey domain maps indicate the contribution of each shot or receiver to target illumination. Accordingly, receiver domain maps as shown in Figure 8 can be used in the survey design tool for updating and improving the next iteration of the survey design, guided by the model-based evaluation of the previous design.

Receiver domain maps can be combined with areal filters, e.g., taking only reflection points from a selected target area of interest into account. In this study, however, they were used for testing the sensitivity to moderate model variations. It may be tempting to reduce survey cost by eliminating low contributing receivers (or shots), but it needs to be considered that subsurface models are never perfect. One advantage of ray-based modelling is that models can be easily modified. In this case, one of the salt bodies was laterally shifted by 500 m, and its root was extended. Also, the flank of the adjacent salt body was extended (Figure 8). These changes are supposed to reflect some moderate degree of model inaccuracy. Still there is no significant change in receiver domain maps observed. It could therefore be concluded that the designed survey is robust against model inaccuracies on a 500 m scale, providing additional confidence in the final set-up.

A note on co-opetition

As our industry struggles against the headwinds of carbon neutrality and ever smaller profit margins and higher risks, it is tempting for competitors to race to the bottom. The authors of this article have chosen a different path. Although both companies offer survey design and modelling services, when our customers approached us and asked us to make it easier for our software products to work together, we quickly agreed a technical and commercial way forward. The authors believe that this type of co-opetition will be essential to the future success and stability of our industry.

A note on remote working

ACTeQ is an unusual organization in that since it was founded in 2016 it has never had an office location. All ACTeQ employees work from home and have always done so. For this project the ACTeQ team was located in California, Texas and Colorado in the USA. When COVID hit in 2020 the rest of the world was forced into remote working too. The NORSAR team for this project was based in Norway and Germany. In spite of the complexities of a new and complex business relationship and a new and complex technical integration, this project was accomplished in a few weeks without anyone setting foot in an aeroplane. Remote work is effective, and it is here to stay.

Summary and conclusions

Not every survey design needs 3D modelling, but in the presence of complex subsurface geology rules of thumb, simple equations and 1D modelling are inadequate to determine the aperture and offsets requirements for a 3D survey. When survey design choices have multi-million dollar implications 3D modelling at a cost that is <1% of survey acquisition and processing cost is a sound investment.

In this case modelling confirms that a full azimuth OBN survey will produce the best image, but multi-azimuth towed streamer may be sufficient in most areas at significantly lower cost. It should be noted that this conclusion is specific to the model used. The results could be different in different geologic settings.

It should also be noted that small changes in the model can have a material impact on the expected contributions to the final image from individual sources and receivers. The sensitivity of the illumination should be tested for different survey designs and different models.

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