Final report

1. Project details

Project title	Development and Demonstration of Advanced Inversion Technology for Optimized Reservoir Characterization – DAITORC
File no.	64018-0591 DAITORC
Name of the funding scheme	EUDP 2018-II
Project managing company / institution	GEUS
CVR number (central business register)	55145016
Project partners	Qeye
Submission date	13-03-2022

2. Summary

Within the discipline of seismic reservoir characterization, there is a continuous ambition to improve the accuracy and detail of seismic data analysis, whether it is for site evaluation for geological CO2 storage, geothermal resources, or hydrocarbon exploration. In addition, proper tools for assessing the uncertainties associated with seismic reservoir characterization is crucial to reduce geological risks and better resolve and predict various subsurface conditions. In this regard, Qeye developed a new quantitative interpretation tool called *Direct Probabilistic Inversion* (DPI) by integrating seismic AVO data with well data and geological prior information.

To develop, test and demonstrate new DPI functionalities, the DPI tool was applied to four different case studies in the Danish Central Graben representing various geophysical data foundations, geological settings, and lithological properties. Each case study has its geological challenges and unknowns that were interrogated using the DPI tool, for example outlining pinch-out of reservoir formations, resolving thin layers at sub-seismic resolution, and better delineation of reservoir quality distribution across fields. The different case study sites range from frontier exploration settings with limited subsurface data to developed hydrocarbon fields with denser data coverage. For each case study a standard deterministic AVO inversion for the elastic acoustic impedance and Vp/Vs properties were performed and compared with the improved DPI technology. The results demonstrate how the DPI tool can be used to extract more geological information from seismic AVO data than conventional interpretation techniques in a probabilistic manner, thereby reducing geological risks.

The technological developments through this project have improved DPI's ability to handle large amounts of data and better assess the inversion uncertainties. After completing the DAITORC project the DPI performance has reached new levels, and Qeye can now offer some of the best probabilistic inversion tools on the market. Qeye has already experienced increased interest and demand from existing and new customers for the DPI

tool, which is hereby better documented as a well-tested and established quantitative tool through the DAITORC project for describing reservoirs and seal properties. Furthermore, Qeye has improved competence and ability in offering DPI solutions to companies focusing on applications within green energy, CCS and hydrocarbon exploration, both national and international. In collaboration with GEUS, Qeye can now offer services to a broader range of customers ranging from a single seismic inversion cube to a more complete geological 3D model with descriptions of reservoir and seal properties as an integrated Qeye/GEUS product.

Summary (dansk):

Den eksisterende software til inversion af seismiske AVO data er baseret på en deterministisk metode. Den deterministiske metode finder kun ét muligt resultat af akustisk impedans, Vp/Vs og densitet. Disse elastiske egenskaber bruges efterfølgende i en klassifikation til at identificere mulige kulbrinte-bærende reservoirer. Metodens primære begrænsning er at den kun finder én mulig løsning og der dermed ikke er mulighed for afsøge flere mulige scenarier i én arbejdsgang.

Qeye's "*Direct Probabilistic Inversion*" (DPI) teknologi har mulighed for at afsøge flere mulige geologiske scenarier og kan dermed mere effektivt og præcist give brugeren et usikkerhedsspænd af mulige geologiske scenarier. Derudover kan DPI algoritmen fødes med geologisk viden og dermed muliggøre en mere præcis prædiktion af undergrunden. Målet med dette projekt har været at videreudvikle DPI således at der kan opnås en bedre reservoirkarakterisering end hidtidige metoder har kunnet præstere. Denne metode giver mulighed for en mere præcis beskrivelse af både reservoirer og segl, og dermed mulighed for en optimeret udnyttelse af undergrunden ifbm. lagring af CO_2, varmelagring/køling, geotermisk varme og kulbrinte efterforskning.

I dette DAITORC-projekt er DPI-softwaren blevet videreudviklet til at kunne håndterer store mængder data ved både at optimere selve algoritmen samt at gøre den klar til også at kunne blive kørt i Google cloud (Google's cloud løsning for beregningstunge databehandling). Dertil er DPI funktionalitet blevet testet og dokumentere i en bred vifte af realistiske, specifikke geologiske scenarier. DPI algoritme er er blevet testet på data fra den danske del af Centralgraven hvor seismiske 3D data og boringer og den fornødne datadensitet og kvalitet er tilstede for en fyldestgørende test af den nye programmelpakke. Viften af geologiske scenarier inkluderer variation i:

- Reservoir lithologi type (sand, kalk, organisk skifer),
- Reservoiregenskaber (lagdeling, porøsitet, dybde, tryk/temperaturforhold (HP/HT), opsprækning)
- Fældetype (strukturel, stratigrafisk)
- Forseglingsegenskaber (ler, organisk indhold, tæthed, tykkelse, lagdeling)

I alt fire specifikke områder i den Danske Nordsø blev i samarbejde med GEUS identificeret til at kunne belyse de ovenstående scenarier – Nete, Hejre, og Tippo.

For hvert scenarie er der blevet kørt en standard deterministisk inversion og inversion med den forbedrede DPI inversionteknologi. I alle scenarier er der blevet opbygget en geologisk 3D model på basis af relevante boringsdata, samt kvantificerede egenskaber ekstraheret fra DPI inversionsresultaterne. Heraf har det været muligt at kvantificere den opnåede kvalitetsforbedring, herunder reduktionen af usikkerhed.

Resultat og slutprodukt

Den forbedrede DPI version har (når baggrundsdata var tilstrækkelige) vist sig at kunne håndterer både de store mængder data samt givet en signifikant bedre inversionsresultat samt en bedre forståelse af usikkerheder. Efter gennemførelsen af projektet er DPI nu udviklet til et stadie der gør Qeye ledende inden for probabilistisk inversion. Qeye mærker nu markant øget efterspørgsel fra både eksisterende kunder og nye kunde. DPI anses nu for at være et gennemtestet værktøj til kvantitativ beskrivelse af reservoirer og forseglinger.

Qeye vil kunne bruge DPI i deres udbud af serviceydelser til selskaber indenfor både grøn energi, CCS og kulbrinteefterforskning, såvel nationalt som internationalt. Serviceydelsen kan, i samarbejde med GEUS, strække sig helt fra levering af en enkelt seismisk inversionskube, til en geologisk 3D modelpakke med beregnet reservoiregenskaber, som et integreret Qeye/GEUS produkt.

3. Project objectives

The objectives of the DAITORC project were to:

- Develop, test, and demonstrate applications of the DPI software based on a range of realistic and specific geological settings in the Danish Central Graben.
- Build geological 3D static models based on available well data for a reference and comparison to the DPI results.
- Perform a conventional seismic AVO inversion for comparison with the DPI tool and investigate potential pros and cons with various methods.
- Add a new functionality to the DPI software to predict continuous reservoir parameters, such as porosity, lithology, and fluid saturation, to give a more quantitative and accurate description of both reservoirs and seals, thus constraining geological risks associated with CO_2 storage, heat storage and/or cooling, geothermal heating, hydrogen storage, and hydrocarbon exploration.
- Develop the DPI product from a TRL 3-7 level towards a TRL 8/9 level.

In more general terms, the DAITORC project aims at improving seismic inversion from the more conventional method by considering a 1-step rather than 2-step inversion (**Fejl! Henvisningskilde ikke fundet.**) for a simpler approach, create stronger relations to geological prior information, and implement uncertainty from data and geological constraints in a more consistent manner. This provides a more robust and user friendly tool for subsurface characterization and to reduce risks associated with optimizing site locations and reservoir management for geological CO_2 or hydrogen storage and geo-energy utilization.

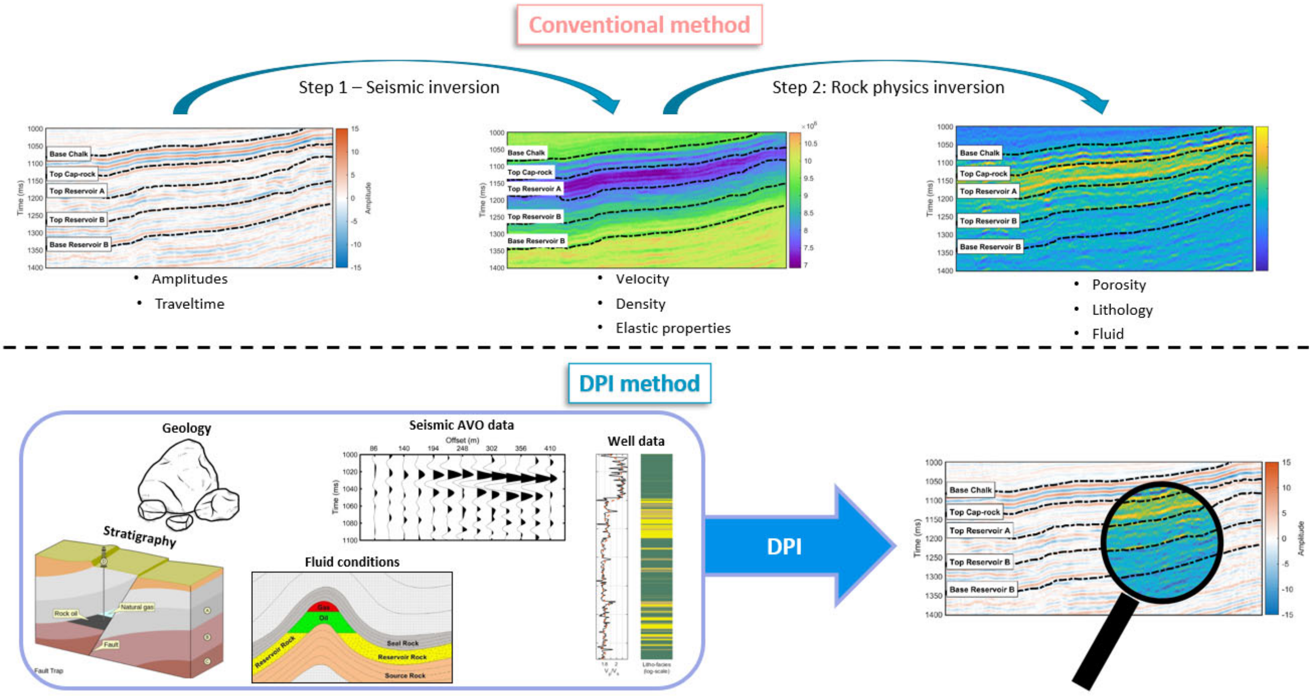

Figure 1: Schematic illustration of seismic inversion by the conventional method (upper) and the DPI method (lower).

4. Project implementation

The DAITORC work plan comprise a total of two work packages:

WP1 (Project Coordination):

- Coordinate and manage the overall project and establish a good communication channel between GEUS and Qeye.
- Plan and arrange quarterly workshops and meetings between GEUS and Qeye.
- Prepare and submit annual status and financial progress reports to EUDP

WP2 (Development, Test and Demonstration): This work package focuses on the technical aspects related to the iterative approach of developing, testing and demonstrating the DPI tool. An overview of the project flow is given in the attached final Gantt chart.

Some of the key project progress steps were:

2019

- A joint kick-off and annual meeting were held 10 April 2019 with all project members from GEUS and Qeye.
- GEUS performed initial screening of case study candidates to be selected for subsequent development and testing of the DPI tool and building static 3D models. Four case studies were defined (**Fejl! Henvisningskilde ikke fundet.**):
    - "Nete": The Nete prospect is located on the northern flank of the Pollernes Ridge and is a potential stratigraphic trap within the Upper Cretaceous to Earliest Paleocene Chalk

  Group where high-porous reservoir facies (Tor and Ekofisk formations) are wedged between a base seal (low-porous Hod Formation) and upper seal (Paleocene clays). The DPI tool is used to test if the pinch-out of the reservoir can be better delineated spatially.
  - “Hejre”: The Hejre Field is located in the northernmost part of the Danish Central Graben, where hydrocarbons have been discovered in 2001 within the Upper Jurassic Heno Formation, comprised of alternating shoreface sands and offshore clays. Because the reservoir is deeply buried (5000 – 5400 m TVD), seismic resolution is low (~80 m) and characterizing the reservoir is a challenge (reservoir thickness up to 50 m). The DPI tool potentially can reveal sub-seismic features and is therefore tested in this setting.
  - “Siah”: The Siah case study is located in the former Upper Jurassic turbidite sandstone Siah prospect, which, after drilling, showed no occurrence of reservoir. Instead, several organic-rich shales have been observed within the Upper Jurassic Farsund Formation, which from well logs show clear decrease in density and velocity. The DPI tool is therefore tested to see if these organic-rich shales can be predicted from seismic data.
  - “Tippo”: The Tippo case study is located along the flanks of the Svend diapir in the northern part of the Danish Central Graben, and comprises hydrocarbons observed within diatomite-rich clays of the uppermost Lark Formation. The diatomite-rich layers have very different acoustic properties compared to the surrounding clays due to their mineralogy (SiO_2) and high porosity. The DPI tool is therefore used to predict the occurrence of these layers within the uppermost Lark formation. However, there are large challenges with not having shear velocity data, and very poor seismic data quality due to salt tectonics.

  All case studies are related to exploration or field development of hydrocarbons because of the availability of seismic AVO and well data, but are equality applicable for other purposes such as geological CO_2 storage, heat storage and geothermal.

- Qeye investigated and procured relevant hardware and cloud-based solutions to run the DPI tool on the large geophysical datasets covering the different case studies.

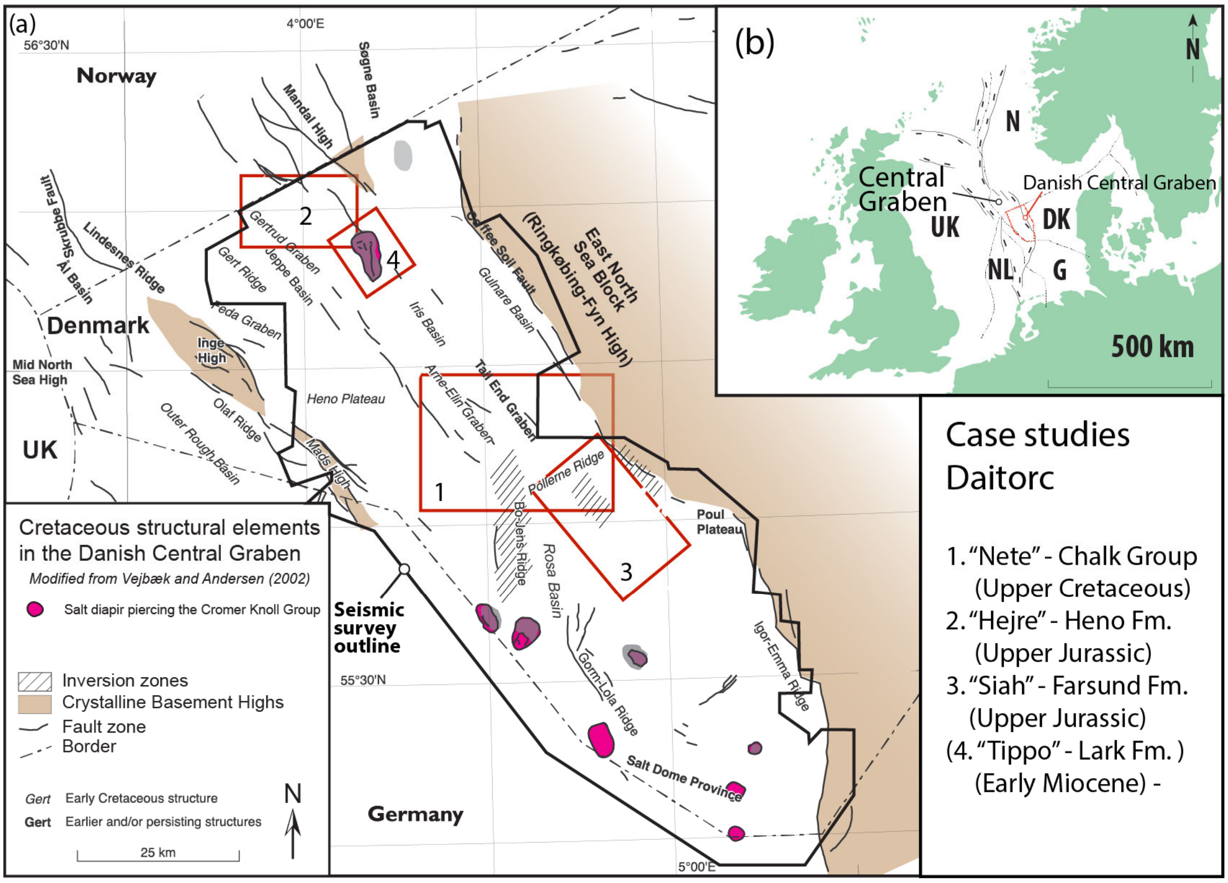

Figure 2: Map of the Danish Central Graben with the location of the different case studies. (a) Map with structure elements during the Cretaceous. (b) Location of the study area within NW Europe.

2020

- Qeye worked on improving the algorithm used in the DPI tool run time for large datasets.
- The Covid-19 situation made it more impractical to work on some of the WP2 tasks that ultimately got delayed by 3-4 months.
- It was found that the well log data base available for the areas of interest was too sparse and further limited by log quality in key formations and a general lack of shear data to support inversion for continuous variables. Furthermore, Qeye found that developing the DPI tool to handle continuous variables required more time and computational power than originally anticipated. Hence, it was concluded that developing this DPI feature under the DAITORC project was infeasible.
- The first steps towards building static/geological 3D models were derived by GEUS using the Petrel software from Schlumberger.

2021/2022

- Due to organizational changes at GEUS, a new project leader was assigned to the DAITORC project in June, as well as a reservoir modeller.
- An updated work plan was submitted with the proposal for extending the DAITORC project with 3 months until 31.03.2022 because of Covid-19 and changes in project management.
- From October 2021 to March 2022, GEUS and Qeye arranged monthly status meetings to finalize the project deliverables.

The main risks associated with the implementation of the DAITORC project were:

- Identification of suitable and realistic case studies containing sufficient seismic and well data for developing, testing and demonstration of the DPI tool in a robust manner.
- Improvements on computational power and time requirements for predicting the continuous variables using the DPI tool.
- Availability of well data in the specific case studies for building a robust static 3D model for comparison.

The project implementation developed according to the milestones as agreed upon prior to project start until encountering some practical challenges following the Covid-19 and lockdown situation from March 2020. Furthermore, the organizational changes at GEUS led to a change in project management also had its implications for the project progress and was handled by formulating a new Gantt diagram during June-July 2021, including a 3-month project extension proposal. Despite these unforeseen challenges the project team collaborated nicely together and obtained some very interesting and satisfying results in the end.

5. Project results

The original objectives of the DAITORC project were successfully obtained, with the only exception of adding the new functionality to the DPI software for predicting continuous reservoir parameters (see section 3). Developing and building this feature into the DPI tool demanded more time than originally anticipated and was deemed infeasible under the DAITORC project. Focus has instead been on:

- Improving run time for the DPI algorithm
- Develop Qeye's IT infrastructure such that it can handle large seismic datasets
- Develop a cloud version of the DPI tool such that it can run on the "*Google cloud*" platform to enable computation of the large data sets.
- Demonstrate DPI on some various case studies representing different input data foundations and geological problems to be interrogated with the DPI tool

5.1 R&D work on the DPI tool

Many significant improvements of the runtime were developed and implemented to handle data amounts relevant for large commercial projects/exploration setting of DAITORC.

PCA dimensionality reduction technique was implemented in the evaluation of the many local likelihoods used in DPI which significantly reduced the runtime. This is very important when upscaling the seismic to get more accurate spatial statistics necessary to capture thin beds or other challenging geological scenarios.

The code was also restructured to efficiently use massive parallel computational platforms like Google Cloud and integrate it into a large-scale queuing system (SLURM). Jobs are now run routinely on 300 hosts.

Qeye also developed "online" algorithms for estimating large covariance matrices used as input to DPI. Online algorithms have a small memory footprint and can continuously collect more and more statistics over time to improve the estimation of the covariance matrix as more data becomes available/desire to improve statistics not needing to start from scratch.

Several additions to the existing algorithms in the DPI platform were developed. The addition of handling non-stationary statistics which in this context is the handling different elastic depth trends for each facies by allowing the mean to vary from sample to sample. A very relevant example is that depth trends of the sands can be very different from the encasing shale due to complicated processes making the contrast strong for some sands and render the sands invisible for deeper sands. The straightforward implementation of allowing different statistics in all seismic grid points is computationally not feasible. However, this can be alleviated significantly by assuming that only the mean changes with depth and some clever integration of the interpolation of the trends into the evaluation of the likelihood functions which allows for some precomputations in the inversion step.

To be able to realistically sample petrophysical variables, standard multivariate techniques do not capture the complexity of the real data. Preferably the statistical method should be able to capture the mean, the second order statistics, that is inter-variable correlations, sample to sample correlations and the marginal distributions (think histogram). Using Copula theory, a method was developed for these properties and generates multivariate correlated data of petrophysical variables obeying the (marginal) statistics of the wells which are far from Gaussian (histograms) and the inter-variable correlations and correlation between spatial coordinates (using any covariance function).

To improve the inversion results and reduce uncertainty there is a push to continuously improve the seismic forward modelling. The standard linear AVO model assumes small contrasts and small angles and is derived from the non-linear reflectivity model of Zoeppritz. The non-linearity is a complicating fact in the DPI workflow. When linear the approximating second order statistics (rock physics models are not Gaussian) can be analytically calculated. But integrating the non-linear reflectivity model directly into the estimation of the second order statistics and estimate the second order statistics directly in the seismic domain it is feasible to use DPI on non-linear models. The runtime of the actual inversion is not affected but sampling and estimating the covariance matrices are more expensive because of the before mentioned forward modeling step to the seismic domain and Zoeppritz is much more demanding than the linear AVO equation. But this step is straightforward to parallelize.

5.2 Case studies

The DPI tool was executed on the four case studies “Nete”, “Hejre”, “Siah” and “Tippo”, in each specific case interrogating the associated geological challenges or unknowns. Furthermore, static 3D models and conventional AVO seismic inversion was performed on the same datasets for comparison with the DPI results. In the following, a short summary of the results for the given case studies are presented. We show some more technical details from the Nete case study as an example of the general workflow that has been applied to all case studies.

5.2.1 Nete

Nete is a hydrocarbon prospect with the Ekofisk and Tor Formations as reservoir targets within the Upper Cretaceous and earliest Paleocene chalk successions, located 10 km northwest from the Siah-NE-1X well, and approximately 5 km east from the Nora-1 well (**Fejl! Henvisningskilde ikke fundet.**). It represents a wedge of potential high-porosity reservoir chalk between a lower low-porous Hod Formation and upper Paleocene clay. The reservoir facies onlap the northern flank of the Pollernes Ridge inversion structure, thereby resulting in a pinch-out in southern direction. The main geological challenge that was investigated with the DPI tool is related to distinguishing the reservoir formation from the overburden and underburden formations as well as better resolving the reservoir pinch-out.

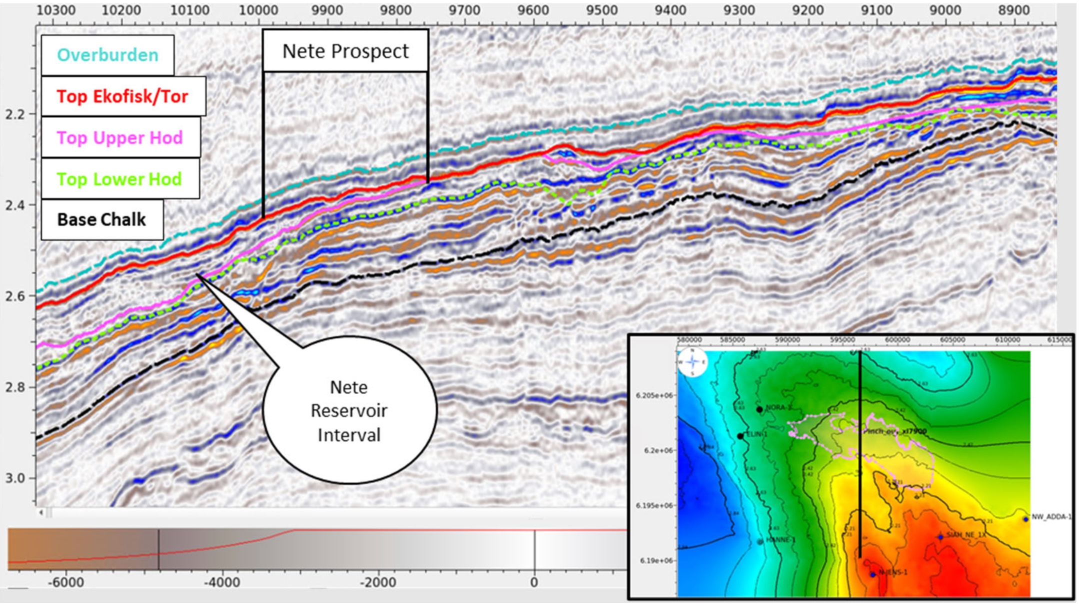

Figure 3: A seismic section through the Nete prospect outlined in pink in mapview overlaying the Top Chalk horizon.

Static reservoir model

The static reservoir model of the Nete prospect was constructed by first performing 3D seismic interpretation of the main chalk events, to map out the large-scale architecture of the Chalk Group (Table 1). The top and base of the Chalk Group form the top and base of the static model, while the Top Lower Hod forms the basal surface upon Upper Hod, Tor and Ekofisk formations are onlapping upon. The top Upper Hod marker forms the base of the porous reservoir chalk intervals, or top of the low-porous sealing unit. The layering architecture is set such that it follows the seismic geometries (e.g., conformable, erosional, onlapping) and can be recognized in Figure 4. Four wells (Hanne-1, Elin-1, Nora-1, Siah-NE-1X) were included in the static model to provide initial porosity distributions in three defined zones (Tor/Ekofisk, Hod, Hidra), and used to define the vertical variability of porosity (how rapidly the porosity change). Then a simplified porosity-depth dependency was implemented to account for increasing burial compaction with increasing depth, which is a simplification since differences in overpressure could offset this trend, but it was decided for the current study to be an adequate approximation. The trend surface was constructed using the minimum and maximum burial difference of the three zones, and the maximum decrease in porosity (as a result of increasing burial depth) was calculated from the porosity-depth curves. For the Ekofisk-Tor this difference was 12%, Hod and Hidra 13% between top of the static model and the deepest level of each zone.

Table 1: Nete seismic interpretation parameters

Name seismic marker	**Architecture element**	**Horizon type**
Top Chalk Group / Top Ekofisk Fm.	Top Reservoir	Erosional
Top Upper Hod	Base Reservoir	Conformable
Top Lower Hod	Base onlapping surface	Conformable
Base Chalk Group / Base Hidra Fm.	Base lower seal	Base

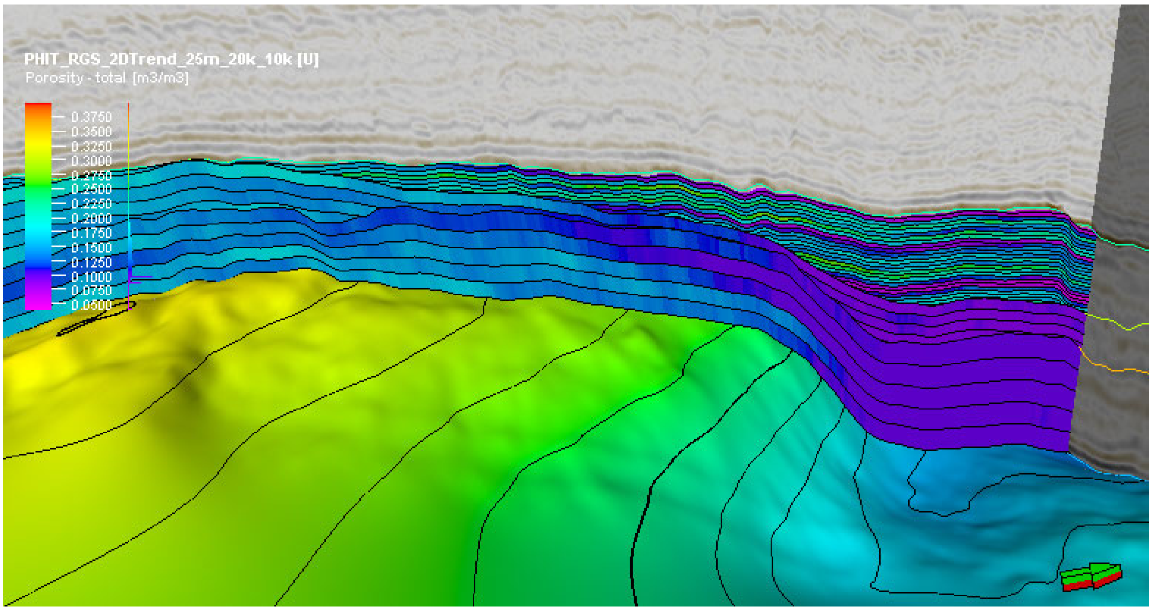

Figure 4: Porosity distributions from the static 3D model of the Nete case study.

Inversion results – Deterministic AVO inversion and Direct Probabilistic Inversion

Two different seismic inversion approaches were performed – deterministic AVO inversion (the traditional approach) and the improved direct probabilistic inversion (DPI) approach. Both inversion methods are developed by Qeye. An overview of the workflow is given in the below table.

<table>
<tr><th colspan="2">Preparation phase</th></tr>
<tr><td colspan="2">• Conditioning of input seismic CDP gathers
• Angle stacking
• Preparation of well database
• Seismic well ties
• Wavelet estimation</td></tr>
<tr><td colspan="2">Inversion phase</td></tr>
<tr><td>Deterministic AVO inversion
Output:
Acoustic impedances and Vp/Vs ratio</td><td>Direct probabilistic inversion (DPI)
Output:
Probabilities of each facies: Shale, High porosity chalk with oil, High porosity chalk with brine, Medium porosity chalk with oil, Medium porosity chalk with brine, Low porosity chalk</td></tr>
<tr><td colspan="2">Comparison phase</td></tr>
</table>

The main challenge in the workflow for Nete was related to lack of nearby shear sonic log data to generate rock physics likelihood models (RPMs), which had to be derived from only one well, NW-ADDA-1X located far from the Nete prospect and buried 150 ms TWT shallower on the seismic. However, the availability of three wells (SIAH-NE-1X, NORA-1 and ELIN-1), albeit without shear sonic log data allowed for a robust quality control of the DPI results against the available petrophysical log data (water saturation, volume of clay and porosity).

Two DPI approaches were tested for the Nete prospect. The first being a zonal setup using well markers to define each litho-fluid class. The second being a more classic approach defining each litho-fluid class based on petrophysical properties (water saturation, porosity and volume of clay) in the wells. The most stable and competent results were produced using the approach based on rock physics trends and relationships. A definition of litho-fluid classes (LFCs) in the elastic domain (AI vs. Vp/Vs) were formulated to more reasonable LFC classifications that yield a better match to petrophysical well log observations and the 3D static model. A set of LFCs were defined within some of the major zones:

- Shaly overburden (ShOvb)
- Ekofisk-Tor (Zone of interest: Zi)
- Upper Hod (UHod)
- Lower Hod (LHod)
- Shaly underburden (ShUb)

The various LFC definitions that were implemented into the inversion is shown by the coloured scheme in Figure 5. The defined LFCs include variations in porosity (high, medium and low), whether the chalks are clean or marly (tight and shaly chalks) and whether the pore-volume is mainly brine or hydrocarbon saturated. For the low porosity scenario, only a brine saturation scenario was considered. This leaves us with 10 distinct LFCs, represented by each circle in Figure 5. Each circle is then subdivided in accordance with which zones the LFCs are mainly relevant for. For example, the Upper Hod zone is expected to be brine saturated chalks. Hence, the prior probability for oil is set close to zero. Using such geological prior information to constrain the number of LFCs will reduce the non-uniqueness of the inverse problem and boost computational efficiency.

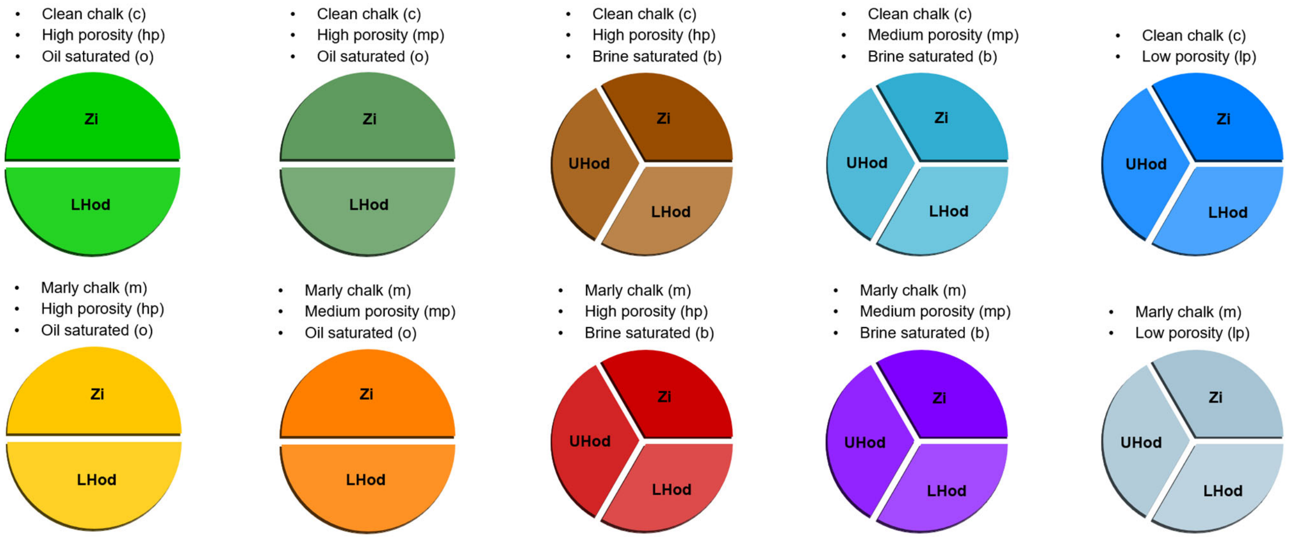

Figure 5: Definition of Litho-Fluid Classes (LFCs) for the Nete case study. The presented LFCs focus on the three main zones within the target interval: Ekofisk-Tor (Zone of interest: Zi), Upper Hod (UHod) and Lower Hod (LHod).

Fejl! Henvisningskilde ikke fundet. shows the normalized thickness overview of each LFC, giving some initial hints as to which of the predefined LFCs that are dominating the dataset as observed in the NW-ADDA-1X well. The marly chalks seem to dominate the thinner sequences, whereas the cleaner chalks are typically between 5 to 8 samples thick.

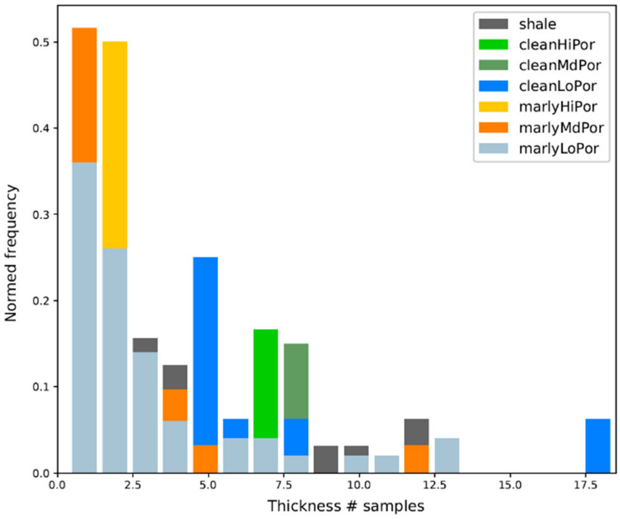

Figure 6: Thickness of the various LFCs observed in the Nete case study from the NW-ADDA-1X well. The shale facies represents the overburden and underburden.

Figure 7a shows resampled AI vs. Vp/Vs data from the NW-ADDA-1X well within the target interval and Figure 7b shows the corresponding RPMs as dashed ellipses (Gaussian distributions). Notice that the insitu data in the target interval does not represent all the LFCs that we want to investigate. For example, because the NW-ADDA-1X is a dry well, a fluid substitution was performed to model different oil saturated scenarios in different porosity (high, medium, low) and lithology (clean, marly) settings as well. In addition, some of the RPMs that were underrepresented by data were edited to give them more meaningful elastic properties. Notice the overlap of the various RPMs. Sufficient separation between the RPMs is crucial for the inversion to be able to distinguish seismically between the corresponding LFCs as it is linked to the seismic expression (i.e. amplitudes). Therefore, the more overlap we observe between two different RPMs in Figure 7b, the more difficult it is for the inversion to discriminate seismically between them.

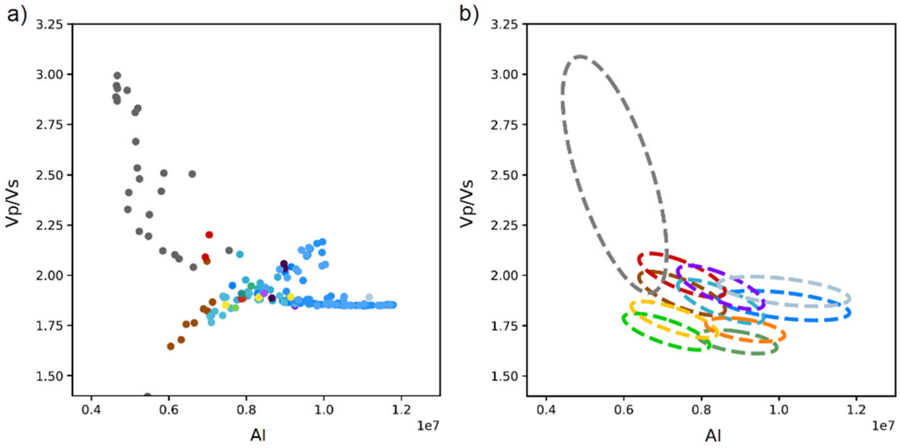

Figure 7: Acoustic impedance (AI) versus Vp/Vs: (a) data from the NW-ADDA-1X that contains shear sonic measurements, (b) the corresponding rock physics model likelihoods defined from the data and fluid substitution modeling.

The standard deviation of the Gaussian distributions defining the RPMs are approached by matching the observed and modelled (or realized) reflectivities. Figure 8 shows the estimated reflectivity distributions for the AI and Vp/Vs to the left from the NW-ADDA-1X data in the top row and the corresponding cross-plot to the right. The middle and lower rows represent Gaussian simulated data for the various LFCs using a variance factor of 0.3 and 0.5, respectively. In this way, AI and Vp/Vs data are realized based on the statistical information from the limited NW-ADDA-1X well data.

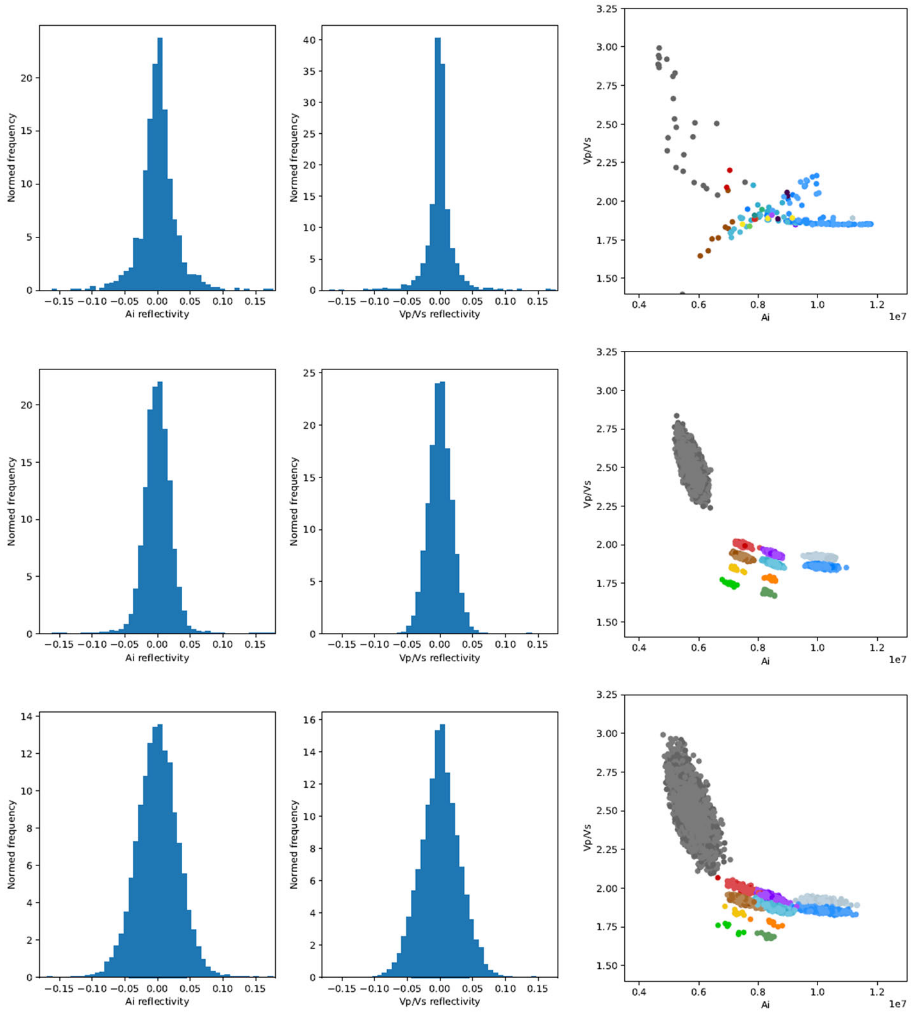

Figure 8: Realizations of AI and Vp/Vs for the rock physics likehood models in the Nete case study.

The vertical ordering (or combination) of the LFCs follow the rules below as part of the prior model:

- Thickness distributions are estimated to be exponential
- Facies vertical ordering follows a first order Markov process
- The ordering statistics vary between all intervals
- Fluid gravitational ordering is assumed
- Older sequences are always located below younger sequences
- The elastic properties within each facies can modelled with a Gaussian
- The correlations of elastic properties within a given facies is modelled with an exponential correlation model

Figure 9 shows the corresponding Markov model transition probability matrix, where all the combinations of LFCs within the various zones (Ekofisk-Tor, Upper Hod and Lower Hod) are quantified in accordance to the list of rules given above. The corresponding prior probability models are shown for the Siah-NE-1X, Nora-1 and Elin-1 wells in Figure 10. Notice smooth prior probability boundary transitions due to uncertainties applied to the horizon surfaces.

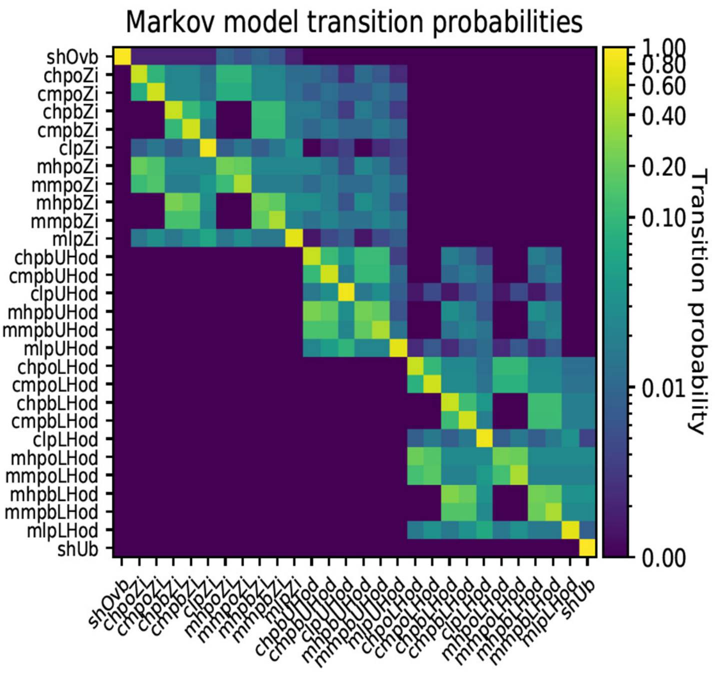

Figure 9: Markov model transition probability matrix defined for the Nete case study. shOvb and shUb: shale overburden and shale underburden, respectively.

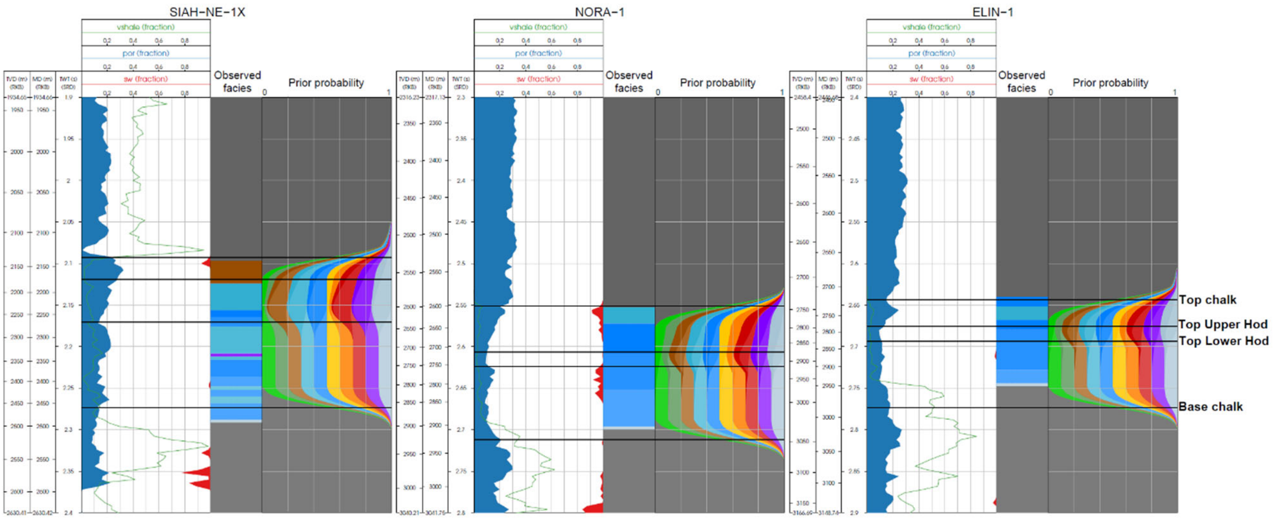

Figure 10: Prior probability field setup for the Siah-NE-1X, Nora-1 and Elin-1 wells. From left-to-right: shale volume (vclay), porosity (por) and water saturation logs, observed (or reference) facies profile and the posterior probabilities as a function of time/depth. The four seismic surfaces are plotted: Top Chalk, Top Upper Hod, Top Lower Hod and Base Chalk.

Moving over to the seismic data, Figure 11 shows the input seismic data, Figure 12 and Figure 13 shows the deterministic AVO inversion results and Figure 14 shows the DPI inversion results. The DPI results showed that the facies inverted for are geologically consistent and in line with GEUS expectations. The DPI inversion thereby reduced geological uncertainties associated with the Nete chalk prospect. The high porosity brine features seen to the outermost left of the section (Figure 14) were difficult to interpret both on the seismic (Figure 11) and using the traditional deterministic AVO inversion approach (Figure 12 and Figure 13).

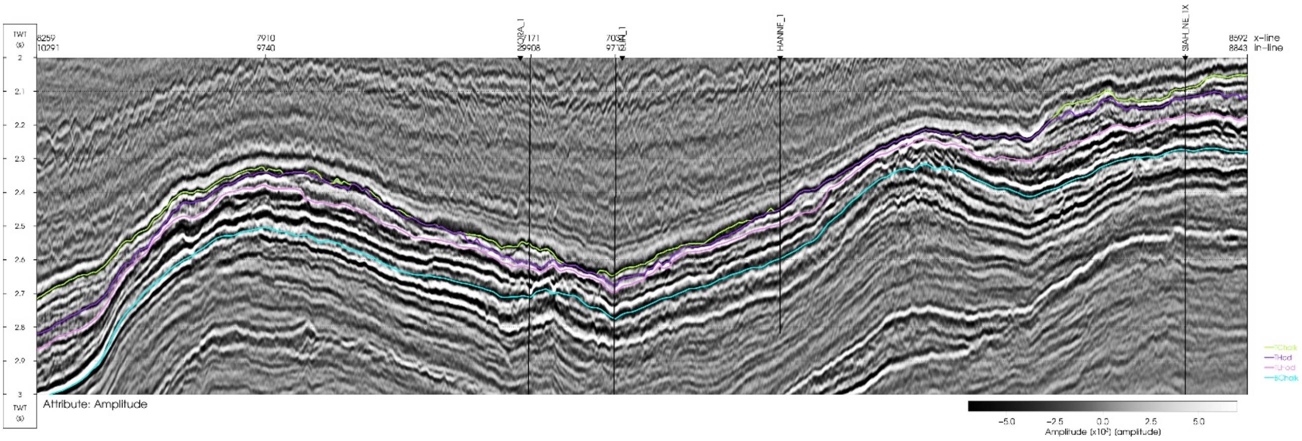

Figure 11: 10°-15° angle-stack seismic data from a composite seismic line through the Nete area. Well trajectories intersected by the composite line are plotted. The four seismic surfaces used are plotted.

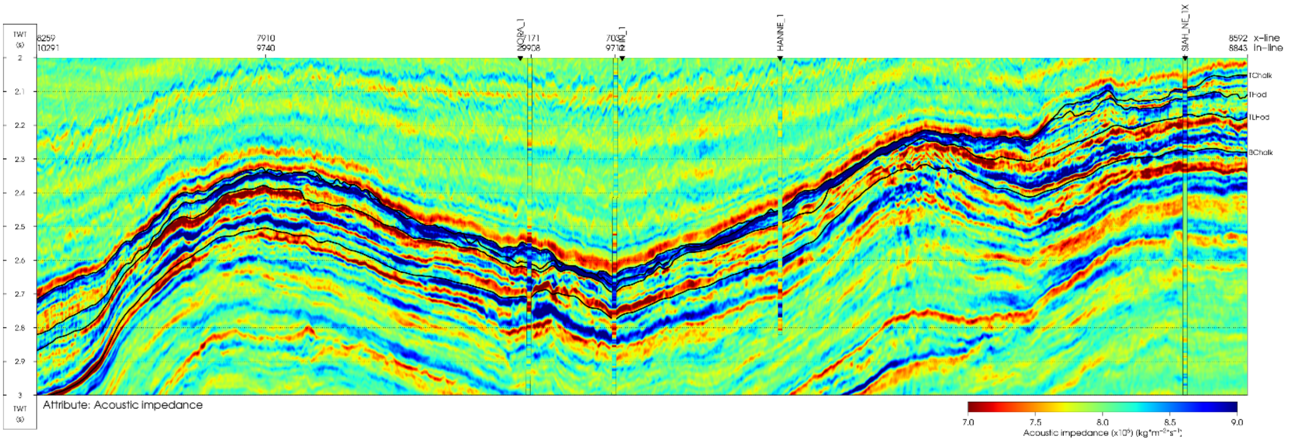

Figure 12: Deterministic inversion result – acoustic impedance from a composite seismic line through the Nete area. Well trajectories intersected by the composite line are plotted with Vp/Vs log data were available. The four seismic surfaces used are plotted in black.

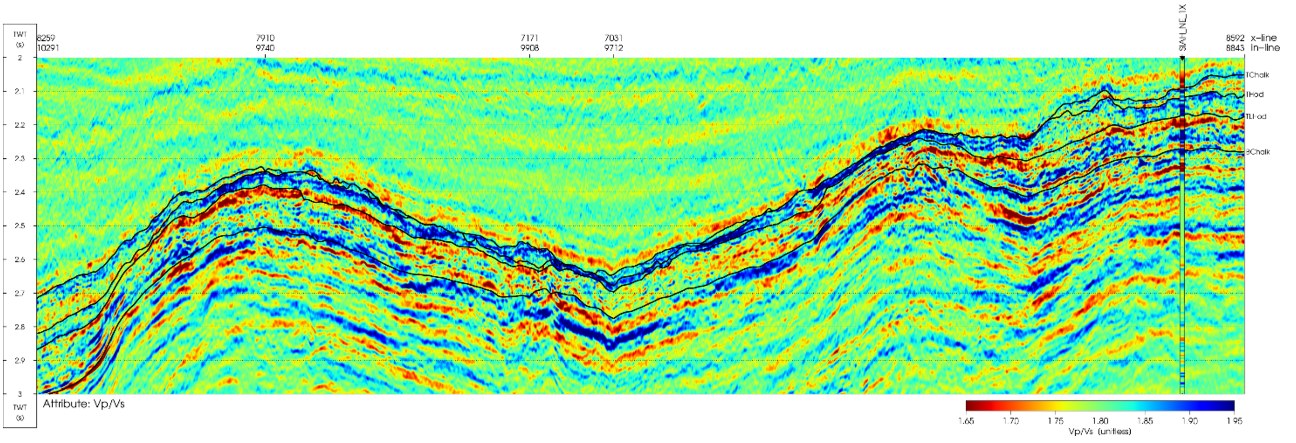

Figure 13: Deterministic inversion result – Vp/Vs ratio from a composite seismic line through the Nete area. Well trajectories intersected by the composite line are plotted with Vp/Vs log data were available. The four seismic surfaces used are plotted in black.

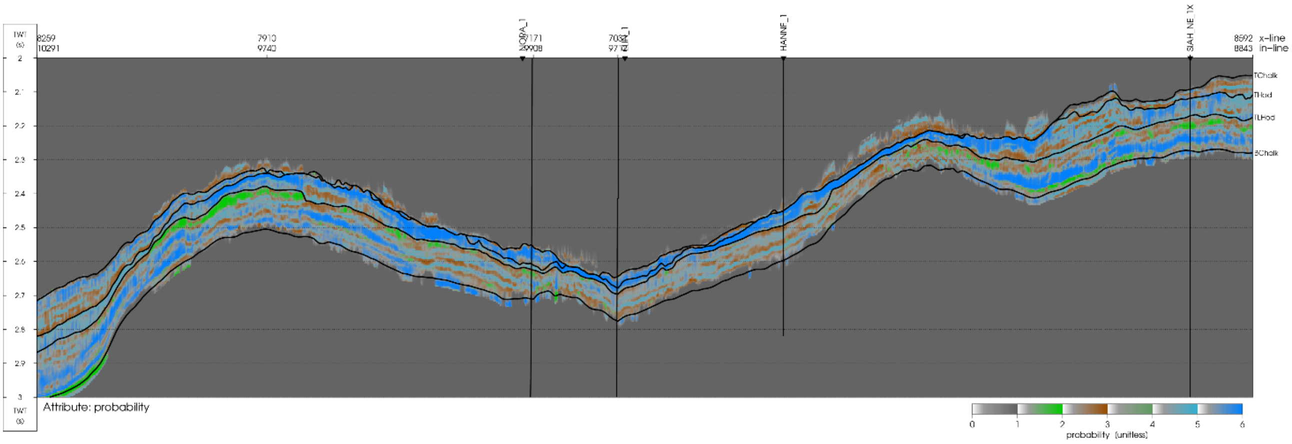

Figure 14: Direct probabilistic inversion result along a composite line through the Nete area. The individual colors represent the most likely geological facies inverted for. Color scale represents the 6 facies inverted for and is from left to right – 1: Shale, 2: High porosity chalk with oil, 3: High porosity chalk with brine, 4: Medium porosity chalk with oil, 5: Medium porosity chalk with brine, 6: Low porosity chalk. Well trajectories intersected by the composite line are displayed as black lines. The four seismic surfaces used are plotted in black.

Comparison of traditional reservoir modelling workflow and DPI output

The interesting element of the Nete case study is the prediction of potential high porous reservoir chalks that are onlapping the inversion structure and therewith also the pinch-out position, which affects the prediction of total oil potential. The traditional reservoir modelling workflow uses internal chalk surfaces and geostatistical extrapolation of porosity data to obtain the porosity distribution and pinch-out position (Figure 15a). The DPI results show the probability of high porosity chalks, which looks fairly similar to the distribution obtained from the traditional reservoir modelling workflow – albeit without actual porosity estimates (Figure 15b). However, it also shows the locations of the pinch-out of high porosity reservoir facies, being similar to the traditional workflow but completely data-driven, which can be used to refine the static reservoir model to better reflect the actual seismic data.

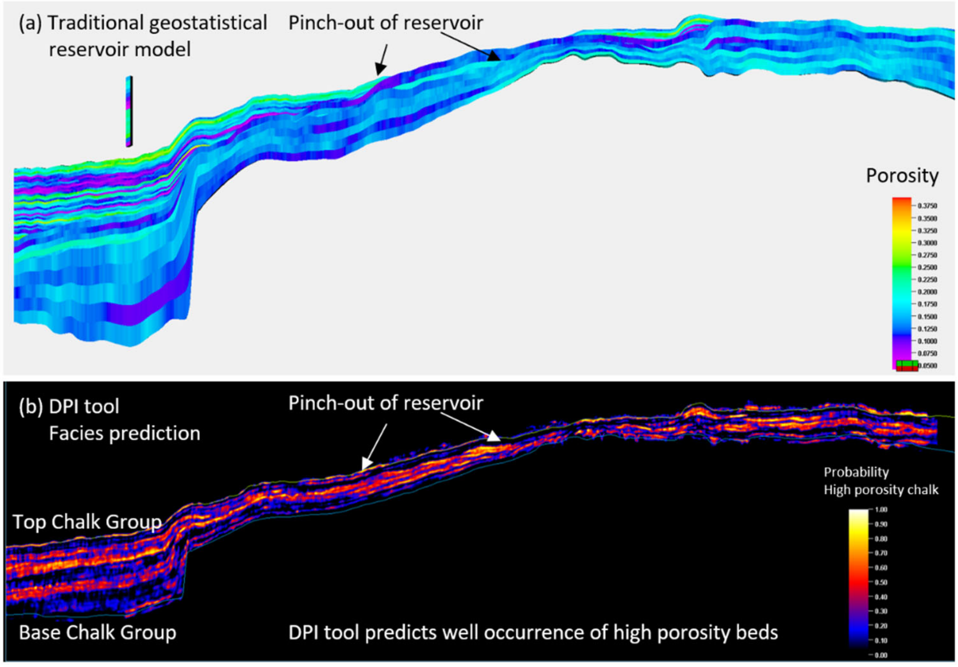

Figure 15: Comparison of (a) traditional geostatistical reservoir modelling method, extrapolating data from well logs and (b) prediction of high porosity chalk facies from the DPI tool.

5.2.2 Hejre

The Hejre case study is located in the northernmost part of the Danish Central Graben and covers the Hejre Field where hydrocarbons occur within the Upper Jurassic Heno Formation. The succession in this area is characterised by a lower boundary with a hiatus and contact to Rotliegend volcanics and in some places some Triassic sediments. The hiatus is followed by a transgressive Lower Gert Member sand ending with an offshore flooding deposit of clay- and siltstones. The overlying Gert Mb upper sand is interpreted as a regressive shoreface sandstone deposited during a period of relative sealevel fall, and is capped by a thinner transgressive shoreface sand. This is followed by a unit of offshore claystones belonging to the Lola Fm. In the uppermost Heno Fm the claystones are interrupted by the sandy Ravn Mb being only a few meters thick, consisting of relatively clean sandstones. The Heno Fm is overlain by a thick package of offshore claystones of the Farsund Formation. Given the large depth of the reservoir (5100 – 5500 m TVD), seismic resolution is very poor compared to the thickness of the main reservoir units (80 m vs. 5 – 20 m). However, the DPI tool can increase the vertical resolution due to added geological prior information, and therefore the hope is that it is able to resolve sub-seismic architectural elements.

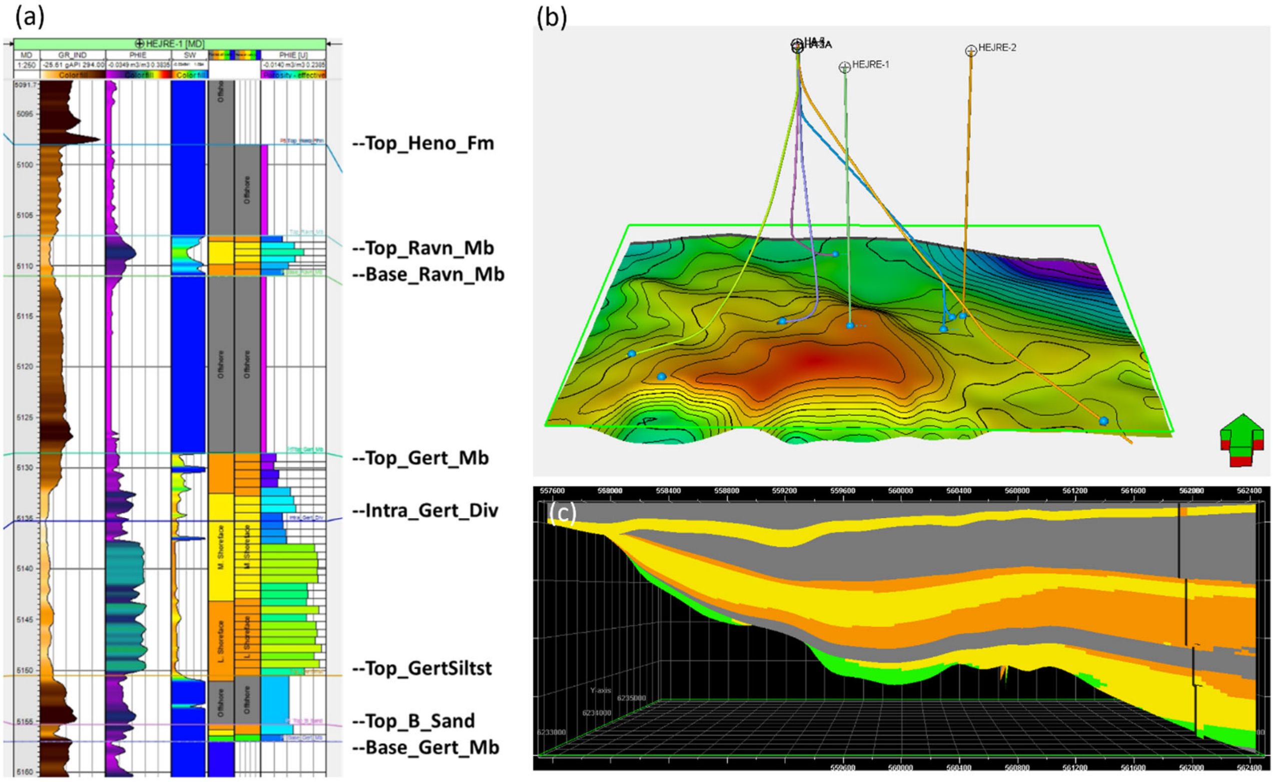

Figure 16: (a) Well section through Hejre-1 with gamma-ray, effective porosity, water saturation, facies logs (offshore clay, lower shoreface, middle shoreface, and transgressive sandstones), and upscaled porosity. (b) Depth-converted Top Heno Formation horizon from seismic and adjusted to production wells. (c) Reservoir grid section flattened on Top Heno Formation.

Static reservoir model

The modelling procedure for the Hejre area is largely following the same principles as used in the original work by DONG in their analysis of the reservoir potential. The architecture of the static model is constructed using a combination of 3D seismic mapping of the Top Heno Formation on a depth-converted seismic volume and defined well tops in all 7 wells in a 5 x 3 km area. This was necessary since the Heno Formation is complex in the area due to the low seismic resolution, wedge-shaped architecture leading to variable seismic character, and occurrence of faults that significantly offset the succession. Facies interpretation was largely based on available core descriptions and in combination with log interpretation and were upscaled using the “most of” method (Figure 16a). Based on the intra-Heno Fm. well tops and associated dominant facies, 7 zones were specified that would be modelled differently. Vertical cell height is variable to reflect the different zones (e.g. a clay zone with 1 layer 5 – 15 m thick, while the sandstone units have more layers resulting in 0.4 m average thickness). The facies have been modelled using Truncated Gaussian with Trends since the succession can be interpreted as alternations of transgressive/regressive movements of the shoreline and facies belts. A shoreline orientation has to be set, as well as vertical facies aggradation angles, both of which are inspired by work of DONG energy. Regional studies of facies show that a N-S oriented shoreline is most likely, and relative shallow angles to reflect large movement of the shoreline over the study area. Lastly, in the southwestern corner, production well HA-3 shows the absence of the Gert and Ravn members, and therefore are modelled to have zero thickness.

Inversion results – Deterministic AVO inversion and Direct Probabilistic Inversion

Two different seismic inversion approaches were performed – deterministic AVO inversion (the traditional approach) and the improved direct probabilistic inversion (DPI) approach. Both inversion methods are developed by Qeye. An overview of the workflow is given in the below table.

<table>
<tr><td colspan="2">Preparation phase</td></tr>
<tr><td colspan="2">• Conditioning of input seismic CDP gathers
• Angle stacking
• Preparation of well database
• Seismic well ties
• Wavelet estimation</td></tr>
<tr><td colspan="2">Inversion phase</td></tr>
<tr><td>Deterministic AVO inversion
Output:
Acoustic impedances and Vp/Vs ratio</td><td>Direct probabilistic inversion (DPI)
Output:
Probabilities of each facies: Shale, Offshore, Lower shoreface, Middle shoreface, Transgressive, Rotliegend</td></tr>
<tr><td colspan="2">Comparison phase</td></tr>
</table>

The main challenge in the workflow for Hejre was related to limitations in seismic data quality and resolution. The field is located between 5100 and 5400 metres vertical depth and data from this interval is naturally affected by attenuation of the signal during transmission through the overlying rocks. The seismic frequencies available over the target interval are within the range 10-45Hz (dominant frequency approx. 25Hz) compared to the overlying chalk interval where the dominant frequency is approximately 35Hz. Figure 17 shows the seismic data along the composite line and the low frequency nature of the seismic as well as gently dipping noise cross-cutting reflectors in the right of the section. Well log data from the two vertical exploration wells (Hejre-1 and Hejre-2) and the six production wells (HA-1, HA-1A, HA-2, HA-3, HA-3A, HA-4 and HA-5) had patchy vertical coverage, however, it was possible to obtain a log suite covering the target interval from the following wells, Hejre-1, HA-4, and HA-5. These wells were used in the rock physics modelling phase and also allowed for sufficient quality control of the DPI results.

- Litho-fluid classes (LFCs) were defined using the well log data in the elastic domain (AI vs. Vp/Vs). Six facies were estimated (Shale, Offshore, Lower shoreface, Middle shoreface, Transgressive, Rotliegend) using independently estimated and optimized probability density functions.
- The three sand facies (Lower shoreface, Middle shoreface, Transgressive) were ambitiously defined separately during the DPI initiation phase, though it was observed that the elastic properties of these

facies were similar due to the petrophysical properties (e.g., volume of clay and porosity) also being similar. Therefore, after the inversion it was decided to group these facies to a single sand facies allowing for easier interpretation and modelling of the sand distribution (Figure 21).

- The seismic data quality also added to the uncertainty of the interpreted seismic surfaces. Therefore, the DPI result was allowed extra freedom to model within a range of approximately 60 ms above and below the input surfaces. This can be observed in Figure 20.

Figure 17 shows the input seismic data, Figure 18 and Figure 19 shows the deterministic AVO inversion results and Figure 20 and Figure 21 shows the DPI inversion results. The DPI results showed that the facies inverted for are geologically consistent and in line with GEUS expectations. The sand bodies predicted by the DPI (Figure 21) were difficult to interpret both on the seismic (Figure 17) and using the traditional deterministic AVO inversion approach (Figure 18 and Figure 19). The DPI results thereby reduced geological uncertainties associated with the distribution of the sand bodies of the Hejre Field.

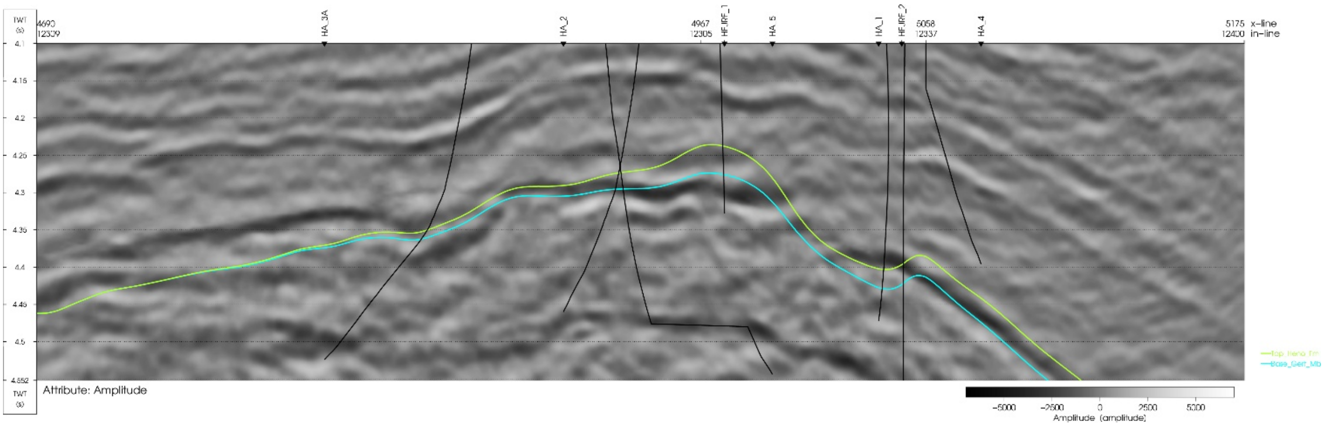

Figure 17: 10°-15° angle-stack seismic data from a composite seismic line through the Hejre area. Well trajectories intersected by the composite line are plotted. The two seismic surfaces used are plotted.

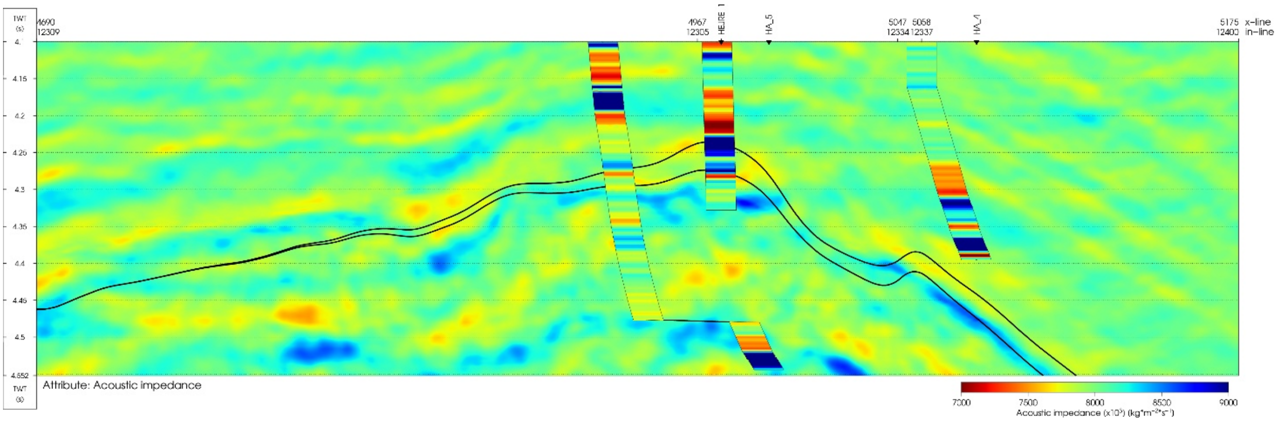

Figure 18: Deterministic inversion result – acoustic impedance from a composite seismic line through the Hejre area. Well trajectories intersected by the composite line are plotted with acoustic impedance log data were available. The two seismic surfaces used are plotted in black.

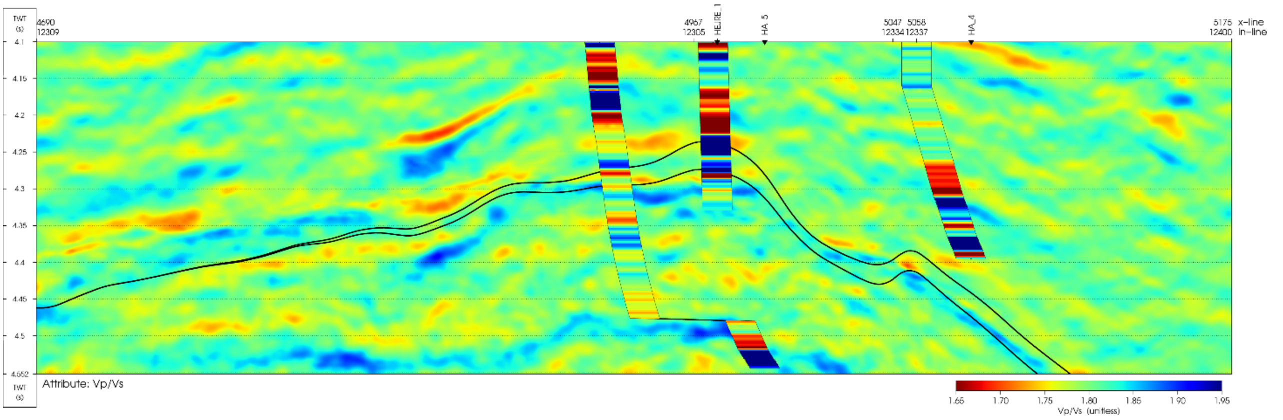

Figure 19: Deterministic inversion result –Vp/Vs ratio from a composite seismic line through the Hejre area. Well trajectories intersected by the composite line are plotted with Vp/Vs log data were available. The two seismic surfaces used are plotted in black.

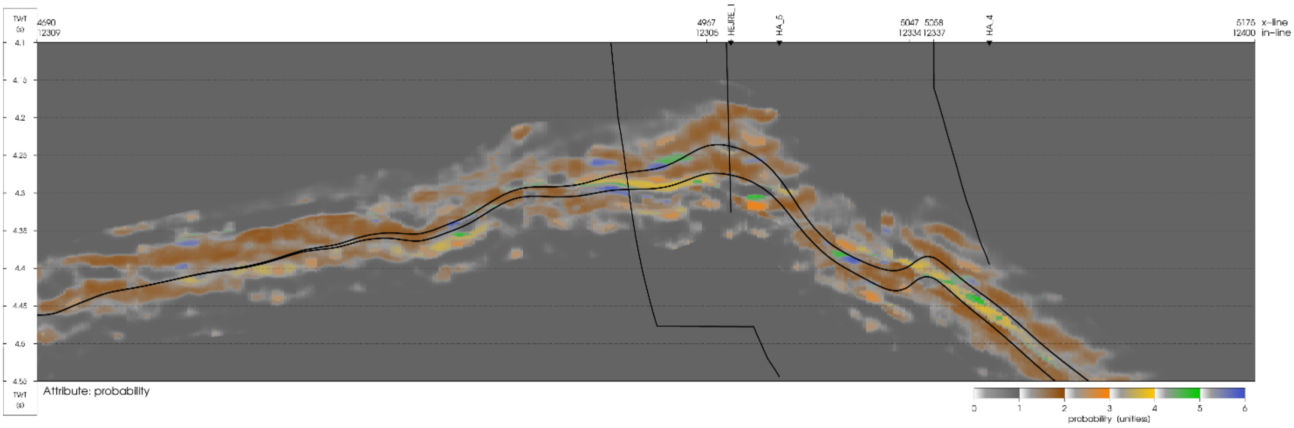

Figure 20: Direct probabilistic inversion result along a composite line through the Hejre area. The individual colors represent the most likely geological facies inverted for. Color scale represents the 6 facies inverted for and is from left to right – 1: Shale, 2: Offshore, 3: Lower shoreface, 4: Middle shoreface, 5 Transgressive, 6 Rotliegend. Well trajectories intersected by the composite line are displayed as black vertical lines. The two seismic surfaces used are plotted in black.

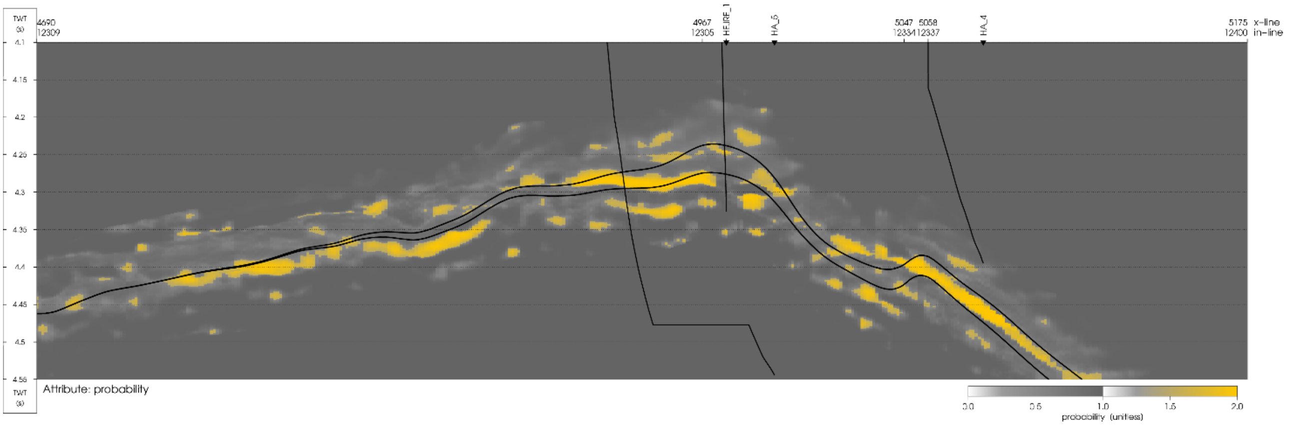

Figure 21: Direct probabilistic inversion result along a composite line through the Hejre area grouped by sand (lower shoreface, middle shoreface, transgressive) facies and non-sand (i.e. shale, offshore, rotliegend) facies. The individual colors represent the most likely geological facies inverted for. Color scale represents the 2 grouped facies inverted for and is from left to right – 1: Non-sand, 2: Sand. Well trajectories intersected by the composite line are displayed as black lines. The two seismic surfaces used are plotted in black.

Comparison of traditional reservoir modelling workflow and DPI output

The architecture of the reservoir and overlying sealing units in the traditional workflow is largely based on thickness variations observed in the two exploration wells and six development wells, since the reservoir units are below vertical seismic resolution (Figure 22b). Therefore, both the top and base of the static model is largely driven by the Top Heno seismic marker adjusted to match internal thickness variations observed in wells, whereas the facies model is driven by conceptual models tied to core descriptions. The Most Probable Facies attribute of the DPI output shows a data-driven likelihood of facies, which shows sandy units thinning from the east to the west – conform well log data in Hejre-2 (Figure 22c). However, it also shows that the sandy deposits are possibly less continuous and could have locally been eroded, as seen immediately west of Hejre-2. The output of the DPI tool can thus be used to adjust the top and base of the Hejre reservoir model to be more closely resembling the seismic reflections, as well as the internal layering and facies distributions. This can be done directly, by taking the most probable facies attribute as a facies model (after depth-conversion) or using the individual facies probabilities as input to sequential indicator simulation algorithms for example. Considering the vertical resolution of the seismic data to be in the order of 80 m at this depth, it is remarkable that the DPI workflow predicts the occurrence of sub-seismic reservoir zones – which is in line with the theory behind the tool (to be able to obtain sub-seismic information).

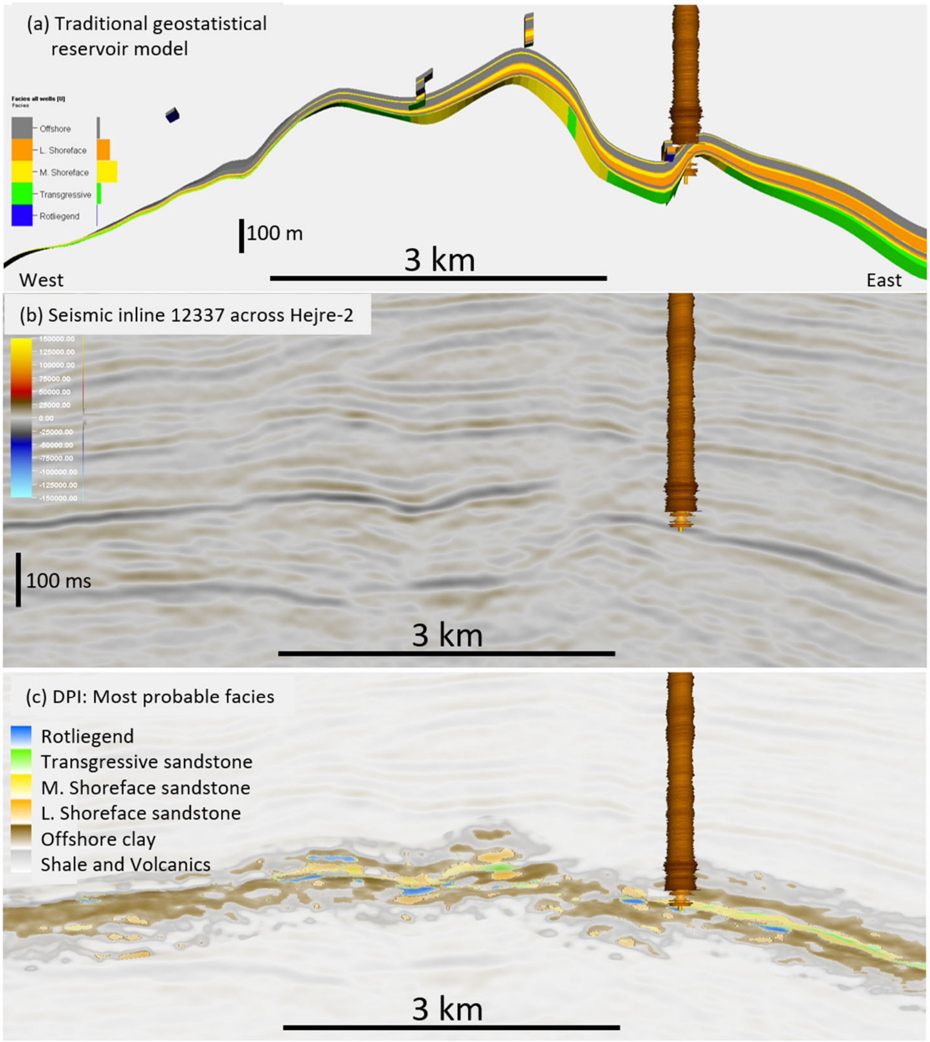

Figure 22: Comparison of an W-E section through Hejre-2, with the (a) traditional geostatistical reservoir model; (b) seismic section showing the difficulty picking top reservoir; (c) Most probable facies attribute from the DPI output indicating likelihood of defined facies.

5.2.3 Siah

The Siah case study focuses on the prediction of organic-rich shales within the Farsund Formation, with thicknesses between 5 – 80 m (the thickest being the Bo Member, e.g., Ineson et al. 2003) which show lower density and velocity values compared to non-organic rich shales. In addition, thin (0.5 – 2 m) limestone stringers can also be observed with much higher density and velocity than surrounding shales and organic-rich shales. Therefore, given that these features have specific acoustic impedance patterns it is expected that the DPI tool might be able to detect them.

Static reservoir model

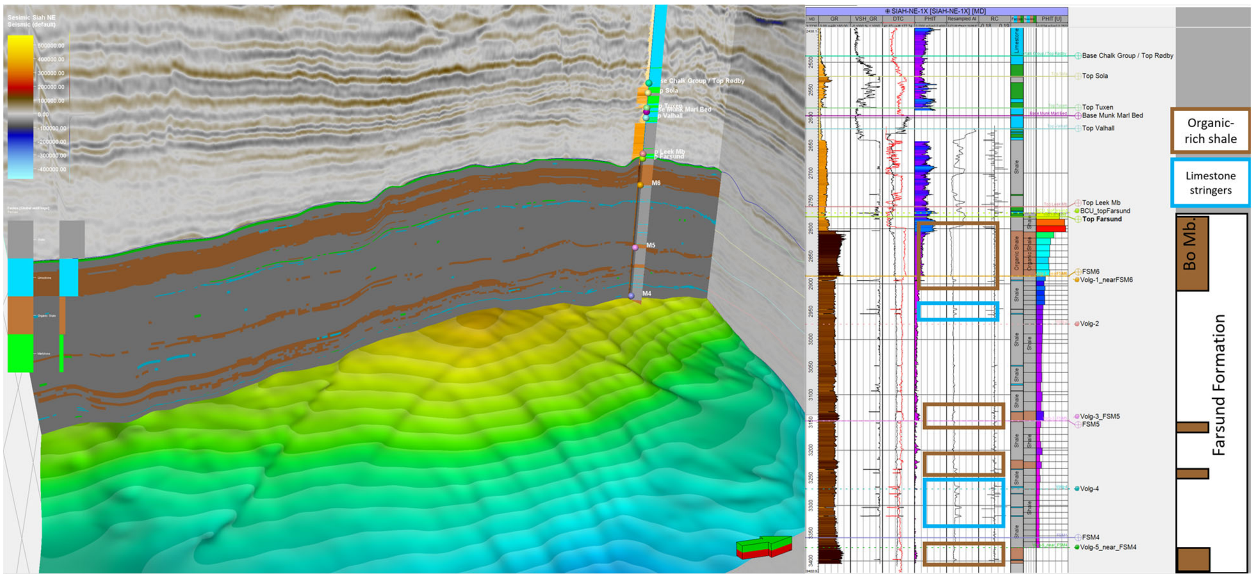

Figure 23: Left: A N-S oriented section through the facies model over the Siah structure (grey: shale, brown: organic-rich shale, blue: limestone stringers, green: marlstones. Shown 3D seismic horizon is FSM4 (base model) and the Siah-NE-1X well with facies log and tops. Right: Well section through Siah-NE-1X, first column gamma-ray, second shale volume, third sonic (red) and density (black), fourth porosity, fifth acoustic impedance, sixth reflection coefficient, seventh facies log.

The static model of the Siah case study was constructed by first interpreting the main seismic horizons from the 3D seismic dataset to obtain the large-scale architecture, whereby Base Cretaceous Unconformity (BCU) forms the top of the model, and the FSM4 marker the base (600 m thickness), with two intra-Farsund Fm. seismic markers (FSM5 and FSM6) (Figure 23a). Seismic sections also reveal that the internal layering of the Farsund Formation is largely conformable which is reflected in the layering architecture of the model. Based on log pattern and lithology descriptions in the final well report of Siah-NE-1X, four facies were interpreted: 1) shale; 2) organic-rich shale; 3) thin limestone stringers; 4) marlstones (Figure 23b). In total 150 layers were constructed, with an average thickness of 4 meters, which should be sufficient to capture the organic-rich beds (20 – 80 m thick), but to also include the thinner limestone stringers we introduced a bias weight of 2 in the upscaling algorithm. Since limited wells penetrate this succession, and we only had 1 well in the study area (Siah-NE-1X), we used geological principles to populate the facies in the reservoir grid. Since a marine depositional environment is inferred during which the shales and organic-rich shales were deposited (Ineson et al. 2003), it is expected that the facies occur over large areas (e.g., kilometres to tens of kilometres). We therefore introduced relatively large major and minor variogram values (20 km x 20 km) for these two facies and took the vertical variogram values from the well (80 m for clay, 40 m for organic-rich shale, 0.5 m for limestone stringers, 10 m for marlstones). For the limestone stringers slightly smaller major and minor direction values were chosen in agreement with our understanding of these limestones to be methane-derived authigenic carbonate (e.g., Judd and Hovland, 2007). Vertical proportion curves provided the vertical probability of a facies to occur. A section through the resulting grid can be seen in Figure 23a.

Inversion results – Deterministic AVO inversion and Direct Probabilistic Inversion

Two different seismic inversion approaches were performed – deterministic AVO inversion (the traditional approach) and the improved direct probabilistic inversion (DPI) approach. Both inversion methods are developed by Qeye. An overview of the workflow is given in the below table.

<table>
<tr><td colspan="2">Preparation phase</td></tr>
<tr><td colspan="2">• Conditioning of input seismic CDP gathers
• Angle stacking
• Preparation of well database
• Seismic well ties
• Wavelet estimation</td></tr>
<tr><td colspan="2">Inversion phase</td></tr>
<tr><td>Deterministic AVO inversion
Output:
Acoustic impedances and Vp/Vs ratio</td><td>Direct probabilistic inversion (DPI)
Output:
Probabilities of each facies: Shale, Marlstone, Limestone, Organic shale</td></tr>
<tr><td colspan="2">Comparison phase</td></tr>
</table>

The main challenge in the workflow for the Siah case study was the lack of shear sonic well log data to generate rock physics likelihood models in the organic shale bearing interval, Farsund. Two approaches were tested, the first assuming an acoustic only response using parameters estimated from the well log data, the second using the acoustic parameters (i.e., acoustic impedance) from the well and elastic parameters (i.e., Vp/Vs) based on empirical data. The method assuming both an acoustic and elastic response produced the most stable and correct result when compared with the well, Siah-NE-1X.

In the Farsund Formation, three litho-facies classes were defined, shale, organic shale and limestone. Although the limestone stringers are very thin, they possess a significant acoustic contrast relative to the surrounding lithofacies and have thicknesses significantly below seismic resolution. Yet, these limestone stringers give rise to a measurable seismic response, and hence it is important to model the vertical structure/configuration at a relatively finer scale. For this reason, it was decided to work on a scale with a seismic sample rate of 0.0005 s TWT for the Monte Carlo Markov Chain modeling. This sample interval was considered as a trade-off between accuracy and computational burden.

Figure xx shows the input seismic data, Figures xx & xx shows the deterministic AVO inversion results and Figure xx shows the DPI inversion results. The DPI results showed that the facies inverted for are geologically consistent and in line with GEUS expectations. The DPI inversion thereby reduced geological uncertainties associated with the distribution of the organic shales. The organic shale predicted in the DPI (Figure xx) were extremely difficult to identify on the seismic (Figure xx) and using the traditional deterministic AVO inversion approach (Figure xx+xx).

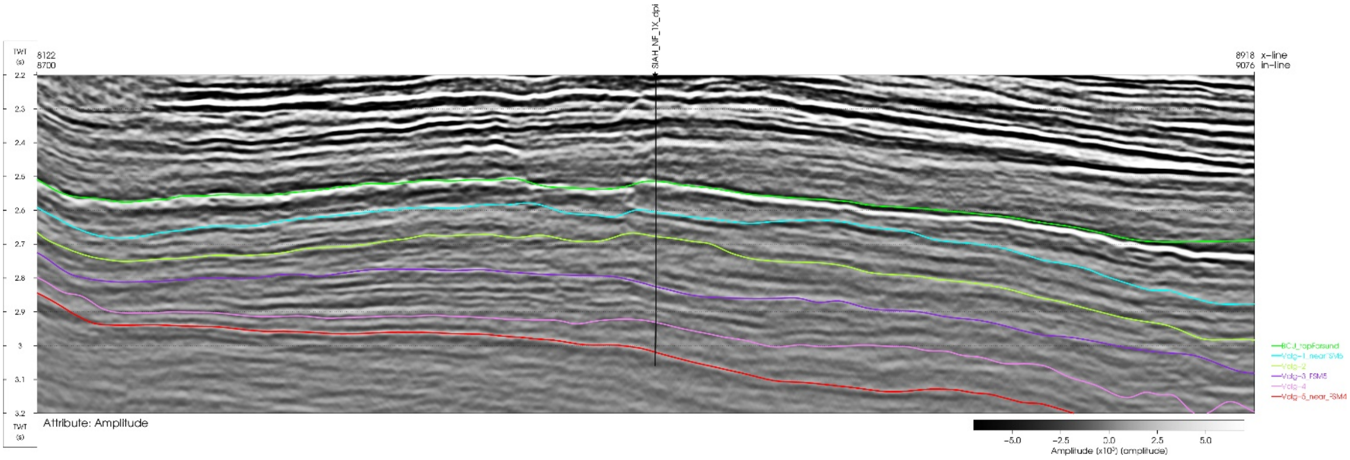

Figure 24: 10°-15° angle-stack seismic data from a composite seismic line through the Siah area. The well trajectory intersected by the composite line is plotted. The six seismic surfaces used are plotted.

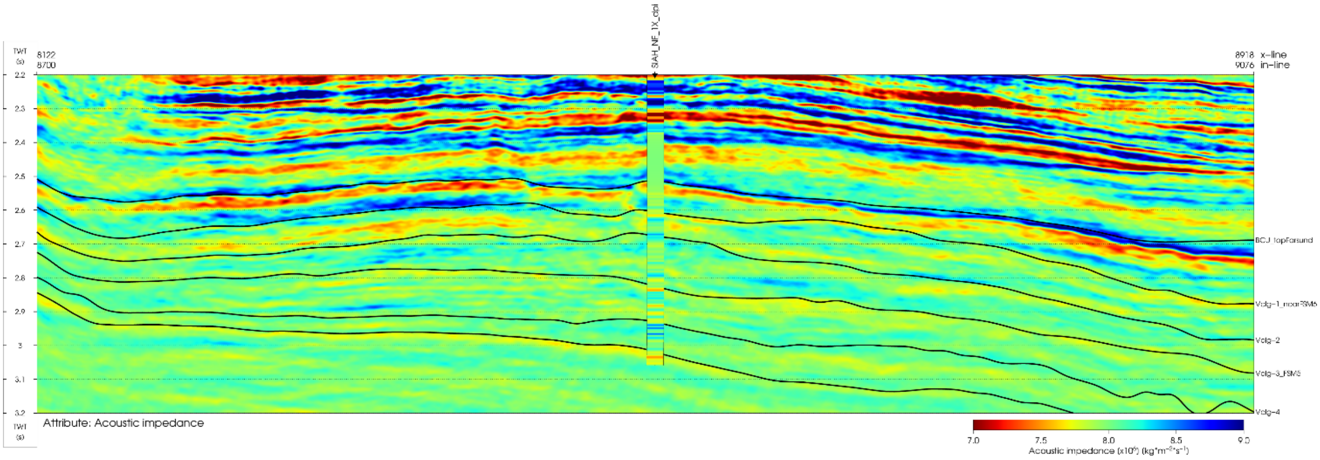

Figure 25: Deterministic inversion result – acoustic impedance from a composite seismic line through the Siah area. The well trajectory intersected by the composite line is plotted with Vp/Vs log data. The six seismic surfaces used are plotted in black.

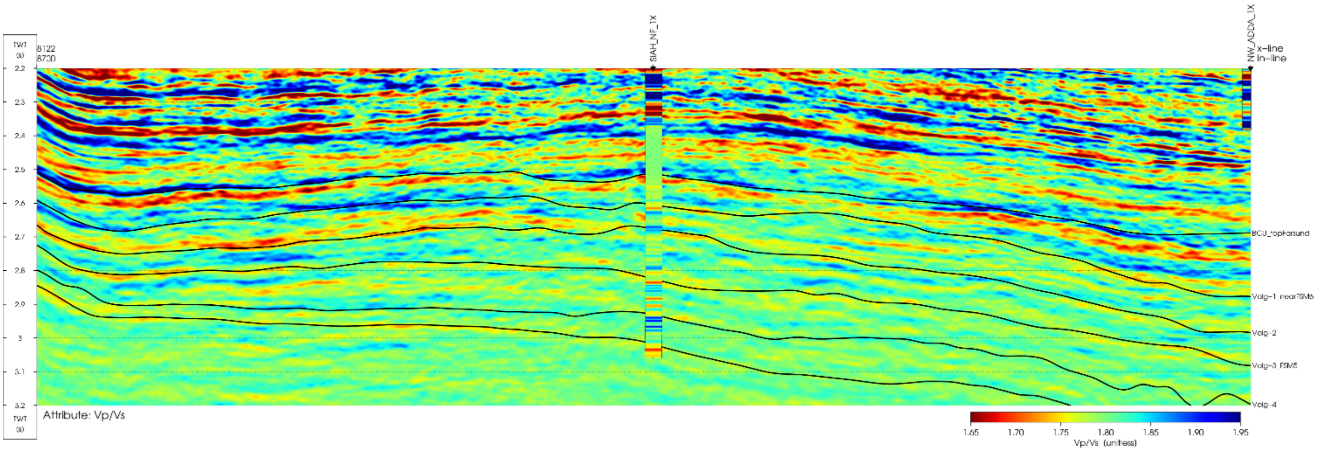

Figure 26: Deterministic inversion result – Vp/Vs ratio from a composite seismic line through the Siah area. The well trajectory intersected by the composite line is plotted with Vp/Vs log data. The six seismic surfaces used are plotted in black.

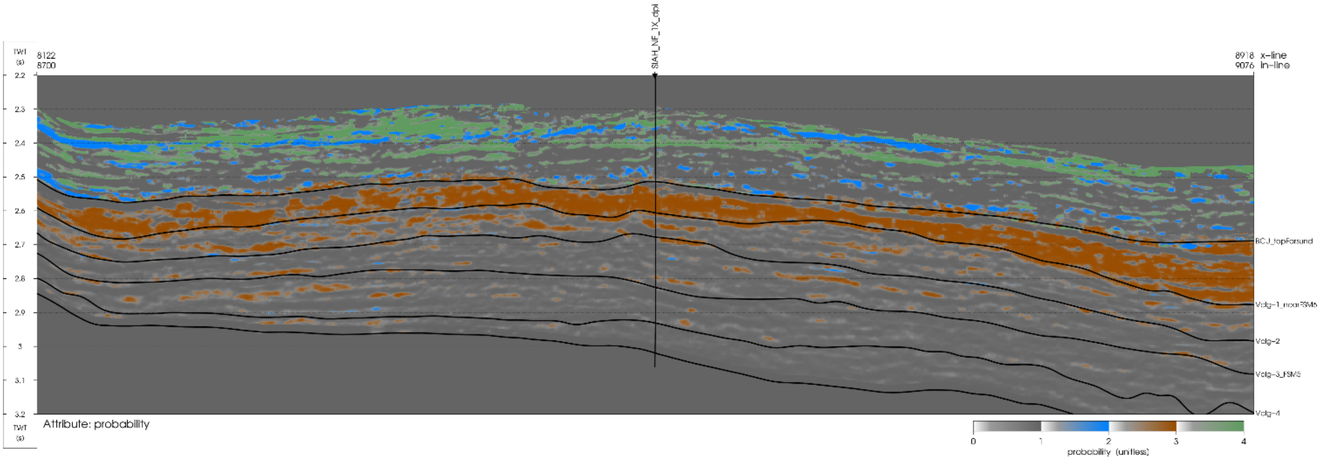

Figure 27: Direct probabilistic inversion result along a composite line through the Siah area. The individual colors represent the most likely geological facies inverted for. Color scale represents the 4 facies inverted for and is from left to right – 1: Shale, 2: Limestone, 3: Organic shale, 4: Marlstone. The well trajectory intersected by the composite line is displayed as a black line. The six seismic surfaces used are plotted in black.

Comparison of traditional reservoir modelling workflow and DPI output

The architecture of the Farsund Formation in the traditional reservoir modelling workflow is largely based on extrapolation of the facies from the Siah-NE-1X well and the geological concept that the facies are widespread (Figure 28a). The DPI results show a similar prediction of the organic-rich Bo Member to be present over large parts of the study area (Figure 28b). Some organic-rich shale beds are also observed within the deeper parts of the Farsund Formation but are less continuous according to the inversion workflow compared to what is modelled using geostatistical methods. This may be because the layers are too thin to be observed by the inversion (from well log data between 1 to 5 m) compared to the vertical seismic resolution of over 50 m. However, it could also indicate a real signal, such that the layers are less continuous and more locally preserved. This would therefore change the geological concept a bit for the deeper levels. It is interesting that also limestone beds within the Farsund Formation are predicted from the DPI results, indicating that these limestone stringers, even though thin (0.5 – 3 m), have a significantly different acoustic signal compared to the other facies so that they are identified. Not included in the reservoir model, but the Lower Cretaceous sediments show the occurrence of significant marlstones and limestones within the levels of the Tuxen and Sola Formations, but not the Valhall Formation. This is conforming our geological understanding of these formations (Ineson, 1997) and shows that in such mixed carbonate-siliciclastic system the DPI tool performs well.

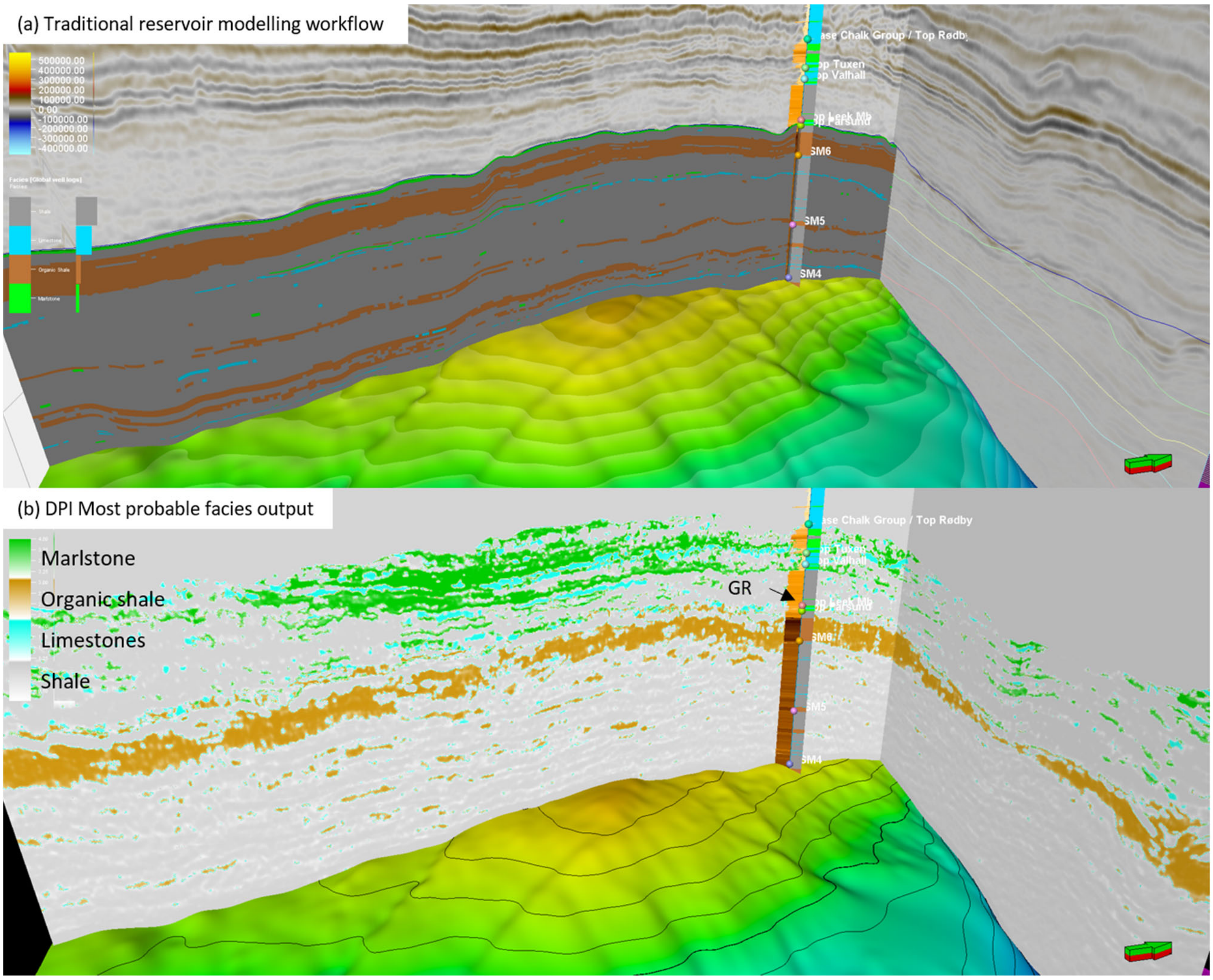

Figure 28: N-S oriented crossline 8470 through well Siah-NE-1X showing (a) the reservoir model for the Farsund Formation. (b) Most probable facies attribute from the DPI tool, showing the distribution of the four different lithologies. Note that also the Lower Cretaceous sequence is included in this inversion. Prediction of the organic-rich shales is very good.

5.2.4 Tippo

The Tippo case study experienced some unforeseen challenges that impeded the deployment of the DPI tool on this case study. First of all, the 3D seismic data quality was highly degraded by gas leakage phenomena, resulting in difficult mapping of the reservoir zones, and no reliable amplitude data could be obtained. Secondly, there was no shear wave log data available in the diatomite reservoir zones and no rock physics models available for this type of lithology. From this assessment it became clear that the Tippo case study did not have the required input data for the DPI inversion, and therefore could not contribute with any valuable information. This case study therefore demonstrates that prior to running DPI, the specific seismic and well log data requires a health check to assess the feasibility and inversion uplift potential. For the Tippo case, the input data content and quality was deemed insufficient for running DPI.

5.3 Application of DPI results into reservoir modelling workflow

There are different applications of the results obtained from the DPI tool that are useful in the reservoir modelling/characterization workflow (Figure 29). For each defined facies, the DPI tool takes in a prior probability 3D model and transform it to a posterior probability 3D volume that can aid reservoir characterization in multiple ways. First, high-probability anomalies for specific facies (for example of high porous chalks or sandstones) can guide the interpretation of boundary/interfaces of various reservoir zones, for example, by adjusting the reservoir top or base horizon to better match the high-probability anomalies from the DPI results and thus the structural framework. This can be particularly useful in areas where it is challenging to accurately map specific reservoir targets with conventional seismic interpretation techniques, for example due to limited seismic resolution in the data. Secondly, populating the reservoir zones with depositional facies, the 3D probability volumes of each facies can be inserted as a 3D probability constraint in geostatistical methods (sequential indicator simulation or Truncated Gaussian simulation). Another possibility is to extract 2D probability maps for each facies in specific zones and insert those as 2D constraints in the same geostatistical methods. An alternative avenue is to use the Most Probable Facies 3D volume, which is constructed from selecting the facies exhibiting the highest posterior probability at each point within the 3D volume (Figure 29). This volume contains discrete facies definitions that can directly be used to constrain the static reservoir model. These workflows thus allow better delineation and definition of reservoir zones and geometry, and improved construction of 3D facies models through seismic constraints obtained from the DPI tool.

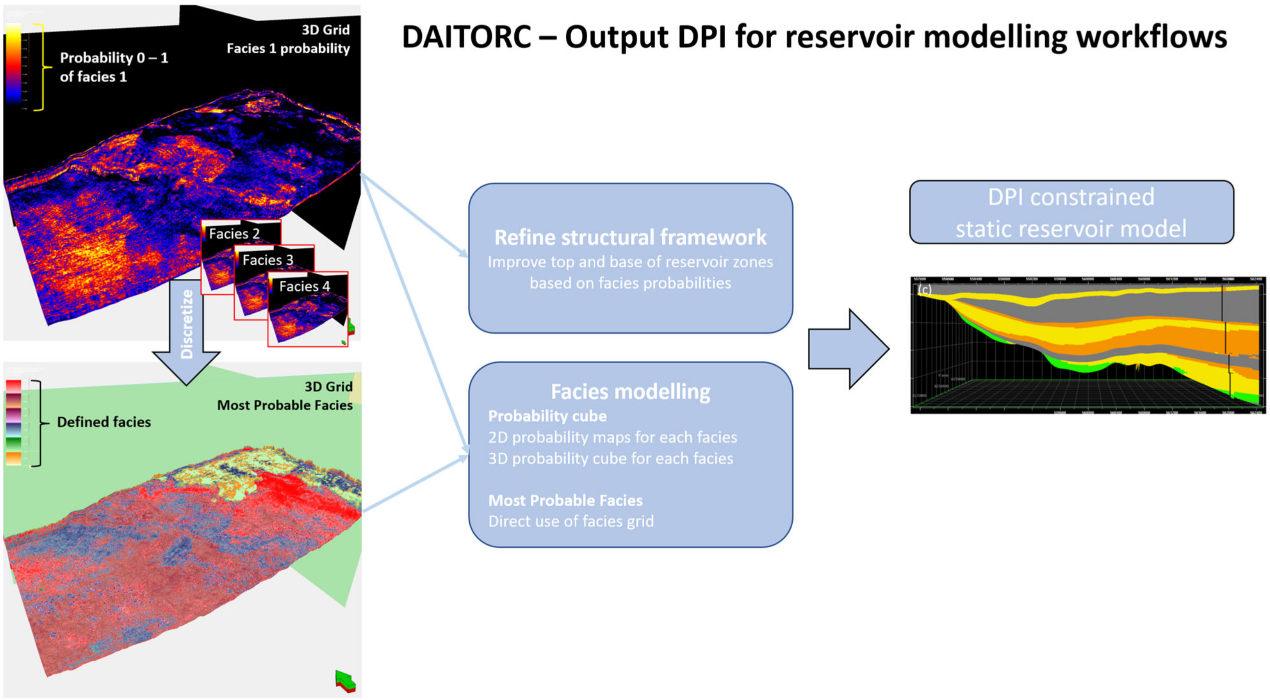

Figure 29: Output of the DPI tool for reservoir modelling/characterization purposes.

The case studies above demonstrate the potential of the DPI tool for extracting more reservoir information from seismic data. The results show that the DPI tool yield more robust predictions when sufficient well log data and high signal-to-noise seismic data are available, which is more common close to existing fields. Because many international oil and gas companies aim at a green transition, less of future hydrocarbon exploration will likely occur in frontier areas but rather within licenses close to existing fields and infrastructures. The presented case studies are all related to hydrocarbon exploration or field appraisal or development that have yield a broad data coverage in the Danish Central Graben. However, as more data will be acquired for future geological CO2, hydrogen and heat storage and exploiting geothermal resources, the DPI tool will in principle be just as valuable for these purposes as well. Hence, Qeye will aim the marketing of the DPI product towards current and future relevant customers.

6. Utilisation of project results

The DPI results yield additional information about the subsurface that cannot always be obtained from more traditional seismic interpretation and reservoir modelling workflows. The results from the case studies in the North Sea demonstrates this very clearly in different geological settings and with various data foundations. The results give some implications for how it can be used to derisk different subsurface prospects, whether it is for CO_2 or hydrogen storage or geoenergy resources. Most of the geophysical data are associated with hydrocarbon exploration, but the DPI setup is flexible for other areas of application and geological challenges as well.

The DPI tool has now been improved to a level that makes is commercially ready to handle large seismic datasets. The DPI tool is already now at the end of the DAITORC project resulting in growth in the client demand for the DPI tool. Qeye's revenue from the DPI tool was at the start of the project about 10% of Qeye total revenue. At the end of the DAITORC project was the revenue from the DPI tool about 60% of Qeye total revenue. Qeye's worldwide revenue has grown from about 14M DKK to now 20M DKK and the growth is mainly coming from projects that involves the DPI tool. Numbers of employees has grown both in Denmark and for the Qeye daughter companies in Australia and Canada. Total head count in Qeye today is 27 (11 in Denmark, 9 in Canada, 4 in Australia plus 3 consultants). For comparison, Qeye had worldwide about 12 people employed at the start of the DAITORC project. Qeye expect continued growth the coming years due to the improved DPI tool and due to expanding Qeye business more into the renewables sector (CCS, geothermal and windmill foundation surveying).

The Qeye competitors listed by size are:

- **Geosoftware (www.geosoftware.tech)**
- **SCHLUMBERGER (www.slb.com)**
- **Paradigm (www.pdgm.com/solutions/reservoir-characterization/)**
- **ION (www.iongeo.com/products_services/reservoir_services/)**
- IKON SCIENCE (www.ikonscience.com)
- Sharp Reflections (www.sharpreflections.com)
- DELFT INVERSION (www.delft-inversion.net)

The competitors listed in bold are offering a broad range of services and only a small fraction of their services competes directly with Qeye. Qeye's size is about the same as Sharp Reflections.

Most of the competitors to Qeye have inversion solutions that competes more with Qeye's deterministic inversion solutions. It is only Sharp reflections who are offering an inversion tool (PCube+) that directly competes against the Qeye DPI tool. Qeye believes that Sharp reflections PCube+ has some limitations (number of facies inverted for and amount of data that can be handled) which DPI does not have. Whereas PCube+ is sold by Sharp Reflections as a software module, Qeye is only selling their DPI tool as a service to their clients. Qeye's business model is that clients provide their data to Qeye and then Qeye perform the seismic inversion from which the final inversion results are delivered to the client. This business model is unique compared to all the Qeye competitors who also are selling software and hence has less focus on their service business. This approach positions Qeye uniquely in the competition landscape. This approach can however be a sales barrier to Qeye as some clients do wish to perform inversion projects themselves. Qeye is – to overcome this sales barrier - discussing with clients (for example ExxonMobil) if they could be interested in Qeye setting up service centers in house the client offices.

Qeye has five offices in, Copenhagen, Calgary, Perth, Houston and Kuala Lumpur. The Houston and Kuala Lumpur offices are manned when needed for specific projects. The plan is over time also to man these two offices. The number of Qeye offices is a relatively low number compared to the larger competitors who also have much higher headcount. Hence, Qeye has less impact in geographical areas where Qeye is not present.

Africa, The Middle East and South America are the areas where Qeye has less activity compared to its competitors. Qeye plans over time to engage with either local agents or to establish office in these areas and hence expand Qeye's business in those areas.

The DAITORC project did with success test out the DPI tools capability of characterizing oil and gas reservoirs in the Danish North Sea. GEUS and Qeye do believe that the improved DPI tool also will enable GEUS to make better assessments of potential geological structures for CO_2 and hydrogen storage and enable an improved understanding of geothermal reservoirs.

Windfarm developers are using ultra high resolution seismic (UHRS) to perform near surface (just below sea bottom) geological mapping to build ground models and geotechnical models for the planning of the foundation design for the offshore windmills. Qeye has during the last couple of years been developing their deterministic inversion tool to help the geological mapping process for offshore windmill farms. The DPI tool could potentially also be suitable for this purpose. The DAITORC project improved the DPI tool capability to handle large dataset. Datasets from UHRS seismic use in the offshore windmill farm industry is considerably large. Hence it is believed that there likely is a substantial market growth opportunity for the DPI tool within offshore windmill farm surveying.

The DPI tool has been presented by Qeye to relevant customers at various conferences:

- EAGE 2019
- SEAPEX SEC 2019
- SEG 2019
- EAGE Seismic inversion 2020
- Seismic2020 online
- Devex 2020 online
- EAGE 2020 online
- SEG 2020 online
- Geoconvention 2020
- EAGE/AAPG Digital subsurface for Asia Pacific conference 2020
- Geoconvention 2021
- SEG 2021
- EAGE 2021
- GeoExpro magazine March 2022

Qeye has also presented the DPI tool at two client webinars in 2021. In addition, the DPI tool has been presented on road shows to a selection of key clients.

A manuscript draft is under preparation for submission to a peer-reviewed journal that is based on some of the results from the case studies presented in this report.

7. Project conclusion and perspective

New developments to the Direct Probabilistic Inversion (DPI) tool were performed through the DAITORC project. Four different case studies in the Danish Central Graben representing various geophysical data foundations, geological settings and lithological properties were considered for demonstrating the DPI tool. Each case study had its geological challenges and unknowns that were interrogated using the DPI tool, for example outlining pinch-out of reservoir formations, resolving thin layers at sub-seismic resolution, and better delineation of reservoir architecture. The different case study sites range from frontier exploration settings with limited subsurface data to developed hydrocarbon fields with denser data coverage. The results demonstrate how the

DPI tool can be used to extract more geological information from seismic data than conventional interpretation techniques in a probabilistic manner, thereby reducing geological risks.

The next steps for developing the DPI tool further will be to invent some innovative algorithms that can boost computational efficiency for handling continuous variables. Furthermore, the DPI tool can be adapted to also handle time-lapse seismic data (also called 4D seismic) to surveillance dynamic reservoir changes, such as injected CO_2 saturations or produced geothermal and hydrocarbon resources. This will meet the increasing demand for better monitoring of reservoir changes associated with establishing full-scale CO_2 storage and geothermal production, as well as maximizing recovery rates from already producing hydrocarbon fields. Another route for further developing of the DPI tool is to make the DPI tool ready to be used for the offshore windmill farm surveying/planning. As more geophysical data becomes available from green projects, such as the new seismic data acquired in February 2022 over the Stenlille gas storage aquifer for CO_2 storage derisking, the DPI tool can be adapted to address the subsurface challenges and unknowns present in a study area.

8. Appendices

The following appendices are attached to this report:

- Appendix A: Final GANTT chart
- Appendix B: Geological facies model for the Hejre area