Best Practice for Quantitative Seismic Interpretation Methods in Danish Geothermal Reservoirs

GEOTHERM WP2

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GEOTHERM - Geothermal energy from sedimentary reservoirs - Removing obstacles for large scale utilization (engelsk)

GEOTHERM - Geotermisk energi fra sedimentære reservoirs - Fjernelse af hindringer for stor skala udnyttelse (dansk)

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Questions regarding this report can be addressed to Esben Dalgaard (ebd@qeye-labs.com)

Qeye Labs
Lersø Parkalle 107
DK-2100 Copenhagen Ø
Denmark
Phone: +45 7220 7009
Email: info@qeye-labs.com

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Chapter 1

Preface

In the oil and gas industry seismic amplitude versus offset (AVO) inversion has for several years been an effective technology used for quantitative seismic interpretation (QSI) in order to de-risk prospects. In the project GEOTHERM the applicability of AVO inversion in geothermal projects is investigated. From the seismic it is possible to invert for different elastic properties such as acoustic impedance (AI), Vp/Vs, and density. For sedimentary rocks, AI typically correlates well to porosity, whereas Vp/Vs combined with AI typically acts as a good lithology discriminator. Applying seismic AVO inversion for de-risking geothermal plays will therefore add value, as we in this case also are aiming at identifying the different lithologies together with a porosity estimate in the geothermal target zone.

This report is a product of a collaboration between GEUS, Aarhus University and Qeye as a part of the GEOTHERM research project supported by Innovation Fund Denmark (IFD) under grant number 6154-00011B. As a part of a larger study, the work presented here is focusing on gaining experience in utilizing seismic AVO inversion in a geothermal context. Based on a specific field case it is demonstrated how 2D seismic AVO inversion together with well log analysis can aid the QSI of a geothermal play in the northern Zealand of Denmark (Chapter 5). In this report our experience is collected and a best practice is established in order to apply seismic inversion for QSI in geothermal projects. A general summary in Danish is given in Chapter 2.

Chapter 2

Resume (Dansk)

Baggrund

Den danske undergrund indeholder en meget stor geotermisk energiressource, der kan udnyttes til f.eks. boligopvarmning via fjernvarmesystemer og til procesvarme i industri. Imidlertid har stor skala udnyttelse af ressourcen hidtil været hæmmet af flere forhold. En af de vigtigste barrierer har været den geologiske usikkerhed, der er forbundet med efterforskning af ressourcen, idet det er vanskeligt præcist at forudsige hvor i undergrunden et geotermisk reservoir findes med tilstrækkelig god kvalitet inden en kostbar boring udføres. I GEOTHERM projektet, støttet af Innovationsfonden, er det derfor undersøgt om metoder udviklet indenfor olie-gas industrien med fordel kan overføres og anvendes indenfor geotermisk efterforskning.

Data

I Danmark er der gennem årene indsamlet mange data fra seismiske undersøgelser og data fra dybe borehuller, primært med fokus på at lede efter olie og gas i undergrunden. De sidste års stigende interesse for udnyttelsen af det store geotermiske potentiale har medvirket til at disse data gennem diverse forskningsprojekter er blevet brugt til at kortlægge udbredelsen og dybden til de relevante formationer med geotermiske reservoirer. Ligeledes har tolkningen af de seismiske data medvirket til kortlægningen af større forkastninger og brudzoner i undergrunden, som kan bryde reservoirernes kontinuitet. Desuden har de seismiske data i kombination med borehulsdata øget vores viden om reservoirernes interne opbygning f.eks. lagenes litologiske sammensætning og kontinuitet.

I dag har vi derfor en god regional forståelse af den danske undergrund, og hvor de velegnede geotermiske reservoirer kan forventes at findes. Den stigende interesse har imidlertid også bevirket, at der i dag er et større ønske om at udnytte de seismiske data til at vurdere de kortlagte reservoirers interne egenskaber, dvs. lagenes litologiske sammensætning, kontinuitet og porøsitet, så det så vidt muligt sikres, at geotermiske boringer placeres optimalt. Udover at bruges til kortlægningen af undergrunden kan de seismiske data således også bruges til at estimere egenskaber i reservoiret som porøsitet og ler/sand fordeling hvis de integreres med borehulsdata.

Denne rapport tager udgangspunkt i en kvantitativ seismisk tilgang, hvor numeriske metoder fra olieindustrien er overført og brugt i geotermisk regi til at vurdere reservoirets interne egenskaber. De numeriske metoder er i forbindelse med et studie på moderne 2D seismiske linjer brugt til at analysere betydningen af den seismiske datakvalitet og hvordan metodens enkeltelementer indvirker på sikkerheden af det endelige resultat.

For at opnå en numeriske karakterisering af reservoiret beskrives det workflow, der har været benyttet, samt hvordan samspillet og integrationen mellem seismiske data og borehulsdata udnyttes optimalt, så man kan opnå den bedst mulige karakterisering og beskrivelse af reservoirerne til prædiktion af porøsitet og sand/ler fordeling inden en boring udføres.

Rapporten er tænkt som en guide til reservoirkarakterisering, men har også til formål at sikre, at man i forbindelse med planlægningen af kommende indsamlinger af seismiske data i nye geotermi licenser opnår den bedst mulige seismiske datakvalitet og dermed sikrer det bedst mulige grundlag for at vurdere og de-riske kommende geotermiske projekter.

Ved brug af kendte succesfulde tekniker fra olie- og gasindustrien tilpasset den geotermiske industri er det undersøgt hvilke data typer, der er nødvendige og hvilke, der er gode at indsamle og bevare i forhold til at opnå den bedst mulige reservoirkarakterisering ved brug af seismisk (AVO) inversion. Arbejdet har taget udgangspunkt i den danske undergrund og danske datasæt, men metoderne beskrevet her vil også kunne anvendes udenfor Danmark.

Data typer

Seismiske data sammen med borehulsdata bruges til at kortlægge undergrundens strukturelle opbygning og til at kortlægge dybden til reservoirerne. De seismiske data bruges til at danne et seismisk billede af undergrunden. Data bliver skabt fra jordoverfladen ved at en trykbølge sendes afsted fra en vibrator, eksplosion eller anden bølgekilde. Denne bølge forplanter sig i jorden og bevæger sig igennem forskellige geologiske formationer i undergrunden. De forskellige formationer har forskellige fysiske egenskaber bl.a. densitet og evne til at forplante trykbølger, og disse forskelle danner kontraster, der reflekterer den udsendte trykbølge. Disse refleksioner kan måles på jordoverfladen via såkaldte geofoner, og kan hermed bruges til at danne et billede af de forskellige geologiske formationers udbredelse og tykkelse.

For at lave en seismisk inversion, dvs. hvor man omdanner seismiske (refleksions) data til en kvantitativ beskrivelse af et reservoirs egenskaber skal man bruge migreret seismisk pre-stack data. Seismiske data i kombination med borehulslogs, borekerner og en geologiske model af undergrunden danner basis for etablering af en kvantitativ analyse og beskrivelse af det geotermiske reservoir.

En optimal integration mellem seismiske data og borehulsdata er vigtig. Borehulsdata (petrofysiske data) er de data, der opsamles i et borehul bl.a. når det gennemborer et geotermiske reservoir. Elastiske borehulsdata såsom densitet og lydbølgehastigheder er meget vigtige data, da det giver information om den relation, der er mellem de målte seismiske data og undergrunden. Sammen med de elastiske borehulsdata er de petrofysiske data, såsom især porøsitet vigtige, da de giver mulighed for at evaluere den seismiske inversion og hvorvidt det er muligt at prædiktere undergrundens porøsitet, ler/sand fordeling etc. Både de elastiske og de petrofysiske logs bruges til at opstille en 'rock physics' model, som bruges til at relatere den seismiske inversion til undergrundens petrofysiske egenskaber. En 'rock physics' model også kaldet en bjergartsfysisk model bruges til at vurdere kvaliteten af eksisterende borehulsdata for at verificere om de seismiske egenskaber er følsomme over for forskellige ler/sand fordelinger baseret på de regionale borehulsdata. Ud fra denne analyse kalibrerer man en række lithologi/facies-afhængige bjergartsfysiske modeller som bruges til kvantitativt at beskrive de seismiske inversionsdata med hensyn til ler/sand fordeling og reservoiregenskaber. Figur 2.1 viser et potentielt getermisk sandstens reservoir i Nordsjælland baseret på seismisk kvantitativ analyse.

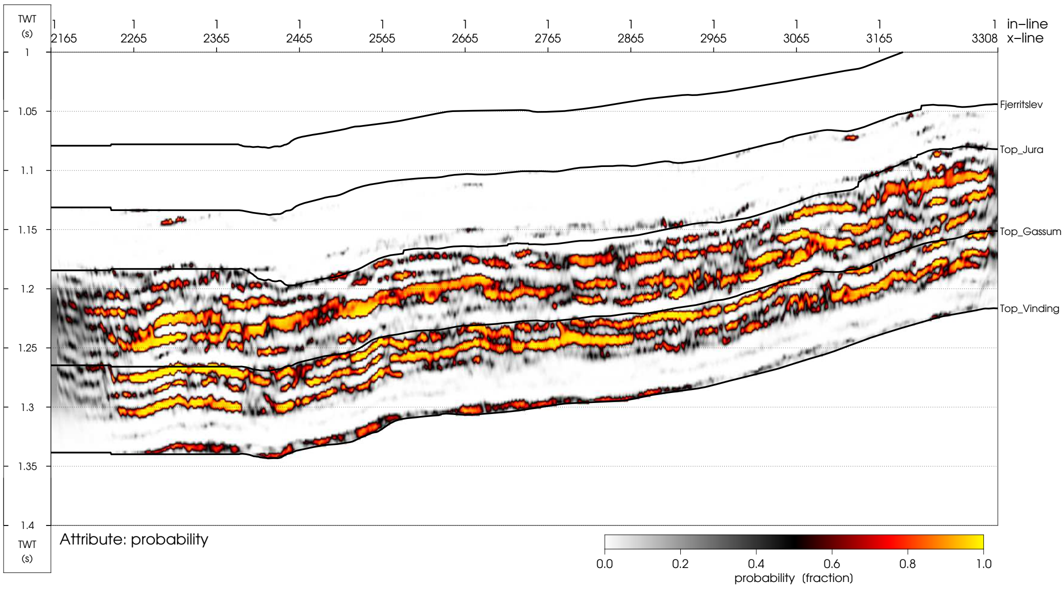

Figure 2.1: *Sandsynlighed for sandstensreservoirer baseret på seismisk reservoirkarakterisering.*

Analyse og test af metode

For at udføre en seismisk inversion er det nødvendigt at have gode seismiske data. Men for at kunne lave den bedst mulige seismiske inversion er det nødvendigt at integrere så mange af de data, der er tilgængelige. En inversion baseret alene på seismiske data vil altid kunne give en generel beskrivelse af undergrundens beskaffenhed, men vil være behæftet med stor usikkerhed. Alle typer af supplerende seismiske data både pre- eller post-stack data etc., men også elastiske data og petrofysiske logs, borekerner etc. har betydning for, hvor stor sikkerhed der kan tillægges den seismiske inversion. Des mere brønddata der er opsamlet, des bedre kan resultatet af inversionen evalueres, og jo bedre og mere præcis vil relationen mellem de indsamlede seismiske data og undergrunden være.

Reservoirkarakterisering er en dynamisk proces, hvor resultaterne og deres troværdighed øges efterhånden, som flere data typer integreres og nye data indsamlet i nye boringer indgår. Hvor sikker og præcis den endelige karakterisering af et reservoir er afhænger bl.a. af de forskellige trin og tolkninger, de anvendte data har gennemgået. Den samlede unøjagtighed er summen af enkelte unøjagtigheder, dvs. usikkerhed i forbindelse med den primære dataindsamling, afstanden til boringer med borehulsdata, usikkerhed på de modeller der beskriver en relation mellem data og undergrunden etc.

Selvom det således ikke muligt at komme med et eksakt estimat for den samlede unøjagtighed, er det muligt at evaluere kvaliteten og validiteten af den endelige reservoirkarakterisering, især hvis de seismiske data og borehuls logdata ligger tæt på hinanden.

For at efterprøve metodens brugbarhed, er der gennemført et studie i området omkring Hillerød-Farum (se Kapitel 5 for detaljer). I studiet er det undersøgt hvordan man kommer fra moderne 2D seismiske linjer til en prædiktion af porøsitet og sand/ler fordeling i undergrunden via seismisk (AVO) inversion og borehulsanalyse. Resultaterne fra studiet demonstrerer, hvordan man med (AVO) inversion integreret med borehuls loganalyse i form af en bjergartsfysisk model kan lave en pålidelig reservoirkarakterisering og derved bidrage til at reducere risikoen i forbindelse med et geotermisk projekt. Studiet viser, hvordan det er muligt at tolke både forskellige litologier og sammenhængende sandstenslag med høj porøsitet langs 2D seismiske linjer. Dette har yderligere styrket prognosen for en tilstedeværelse af et godt geotermisk reservoir i Hillerød området.

Anbefalinger til Indsamling af nye data

Forud for indsamling af nye seismiske linjer skal opbygningen og kompleksiteten af områdets undergrund vurderes og beskrives så omfanget af den seismiske dataindsamling kan klarlægges. Den indledende undersøgelse skal således vurdere tætheden og kvaliteten af eksisterende seismiske data og borehulsdata, da dette oftest har indflydelse på udlægningen af de nye seismiske linjer. Ligeledes skal undersøgelsen vurdere undergrundens beskaffenhed og kompleksitet, da dette ligeledes kan vanskeliggøre indsamlingen af de nye seismiske linjer. Erfaringsmæssigt vides det at geologiske forhold som f.eks. tilstedeværelsen af forkastninger, dybde til, tykkelse og litologisk sammensætning af reservoiret har afgørende betydning for det geotermiske potentiale og dermed muligheden for geotermisk produktion.

Ofte vil udlægningen af nye seismiske linjer følge veje eller lignende strækninger for at sikre minimal ulempe for lokalmiljøet. De nye linjer vil normalt udlægges, så mindst én af linjerne har forbindelse til eksisterende boringer, evt. via eksisterende seismiske linjer. På denne måde kan data fra boringer overføres til de nye seismiske linjer og dermed styrke tolkningen forud for den seismiske reservoirkarakterisering. Den benyttede metode kan således medvirke til at styrke vurderingen af det geotermiske potentiale både til gavn for beslutningstagere og operatører i området.

Eksemplet fra Hillerød-Farum området har vist at en optimal brug af metoden understreger vigtigheden af en solid forståelse af undergrundens strukturelle opbygning og de geologiske lags sammensætning, kombineret med tilgængeligheden af optimale og processerede seismiske data og borehulsdata.

Som vist i studiet kan man nå langt med de nyeste seismiske data og borehulsdata af god kvalitet, men for at opnå den størst mulige nøjagtighed/sikkerhed på den kvantitative reservoirkarakterisering, er det vigtigt, at alle de rigtige data er til rådighed så usikkerheden minimeres. Datatyper som pre-stack data, densitets- (Vp/Vs)- og hastighedsdata, samt porøsitetsdata fra borehullet er alle meget vigtige for et godt resultat og bør altid indtænkes i forbindelse med en ny indsamling af data. På denne måde opnår man også en optimal relation mellem den seismiske inversion og de bjergartsfysiske modeller.

Chapter 3

Introduction

The following chapter gives a short technical introduction to the disciplines that typically are involved in quantitative seismic interpretation (QSI). The steps described are used in the example in chapter 5, where a QSI is performed based on the seismic AVO inversion and lithology classification.

3.1 Seismic AVO inversion

Historically, seismic data was used to generate images of the geological structure in the subsurface. Modern QSI extracts additional, high value information from the (usually pre-stack) seismic data.

The variation of the seismic amplitude with incident angle (AVO) at a geological interface contains information on the elastic rock properties in the layers. These elastic properties are affected by the petrophysical properties, such as porosity and mineralogy, hence the petrophysical properties can be related directly to and derived from the seismic elastic properties.

The key steps in all QSI workflows use the AVO information to convert the seismic data from amplitude at an interface to elastic and petrophysical properties in a layer. The process is controlled and calibrated by any available well log data and by traditional structural interpretations from the stacked data.

Seismic inversion algorithms are typically globally optimized and full bandwidth. It inverts all input seismic stacks simultaneously for the best fitting earth model. It uses the simulated annealing algorithm, which belongs to the class of global optimization schemes capable of locating the global minimum of a given function (e.g., minimisation of the error function describing the misfit between modeled and observed data).

The prediction of subsurface lithology and fluid content can be performed using two approaches:

- The first approach is a Bayesian lithology classification scheme, which provides the probabilities of selected lithologies from their elastic response.

- The second approach uses the derived rock physics models to directly invert for petrophysical properties such as porosity and volume of clay.

This enables the transformation of seismic data into a domain that is very useful in de-risking and modelling of reservoir flow properties.

3.2 Lithology classification

Lithology classification is an approach to do an interpretation of the seismic AVO inversion. In the lithology classification the elastic properties are coupled to lithologies, for example clay and sand, through lithology probability distributions. Uncertainties from the seismic inversion can be taken into account when deriving the probability distributions.

The Bayesian lithology classification is based on non-Gaussian probability density functions estimated using a Gaussian kernel-density estimation technique.

The facies classification workflow includes the following:

- cross plotting of relevant inversion outputs (e.g., Vp/Vs vs. acoustic impedance)
- classification of selected lithology classes
- calculation of lithology probability distributions
- calculation of lithology probability cubes

3.3 Rock physics modelling

To bridge the gap between seismic data obtained by remote sensing at surface and petrophysical data obtained by direct measurements in a wellbore, we implement the use of rock physics models.

Rock physics provides the relationship between rock properties such as porosity, mineral fractions and water saturation to elastic properties that drive the seismic response such as P- and S-wave velocity and density. Rock physics analysis therefore enables rock properties that were previously only available by means of drilling to be estimated from remotely sensed data.

To ensure a reliable rock physics relationship is derived, various quality control and modelling steps can be performed to obtain a calibrated rock physics model to a specific reservoir. These include geophysical cross-plot evaluation, rock physics analysis and modelling, shear wave velocity estimation and advanced fluid substitution.

The rock physics model uses a nonlinear regression based model that obeys the physical bounds (Voigt, Reuss, Hashin-Shtrikman) and honors single- (Gassmann equation) and multi-mineral fluid substitution theories. It connects the elastic moduli of the rock with porosity, mineral fractions, mineral moduli and effective fluid moduli. Furthermore, any variable that potentially influences the rock matrix can be used as a regression variable (e.g., effective pressure/stress). The model is adaptable to any specific rock type. The model framework is flexible since it allows for calibration to log data, capturing local trends of the field as well as enforcing theoretical models for pressure sensitivity. Since the model honors the classical physical bounds, it has good interpolation and extrapolation properties outside data support. This is very important for rock physics inversion and, in particular, in cases with weak data support.

3.4 Uncertainty

Deterministic seismic inversion is a very good tool to identify reservoir intervals and lithologies, making use of the differences in their elastic properties from its surroundings. Mathematically, the deterministic inversion represents a minimum of a cost function in some parameter space, however, evaluating the properties of the earth from seismic data is inherently non-unique. There are uncertainties accumulating from all stages in geophysical applications: from the raw measurements itself (well log measurement and the seismic), through the models and methods that connect the data to the sub surface properties, to the decision-making based on the final results.

Even though we do not get a number that summaries all uncertainties from data acquisition to the final decision making, it is possible to evaluate the validity and quality of the QSI by taking geological understanding into account and comparing the different data types. Uncertainties from seismic itself can be taken into account by defining varying signal to noise rations going into the seismic inversion. The uncertainties of the seismic modeling can be addressed in the interpretation of the seismic inversion for example in the lithology classification or the rock physics inversion.

Other more advanced inversion methods are available where the uncertainties on the seismic modeling are quantified. This could for example be with a probabilistic inversion approach.

Well log data are very important in order to evaluate the quality of the QSI. Also, a good understanding of the geology and structural settings are important to evaluate the validity of the results.

Chapter 4

Workflow and best practice

4.1 General workflow

Figure 4.1 shows a flow chart of the general workflow. The single most important input for the seismic AVO inversion is the seismic itself. For an AVO inversion the seismic gathers need to be migrated and pre-stack or stacked into angle/offset bands. All other types of data are nice to have and if not available assumptions can be made to obtain an inversion resulting in a more general quantitative seismic interpretation (QSI).

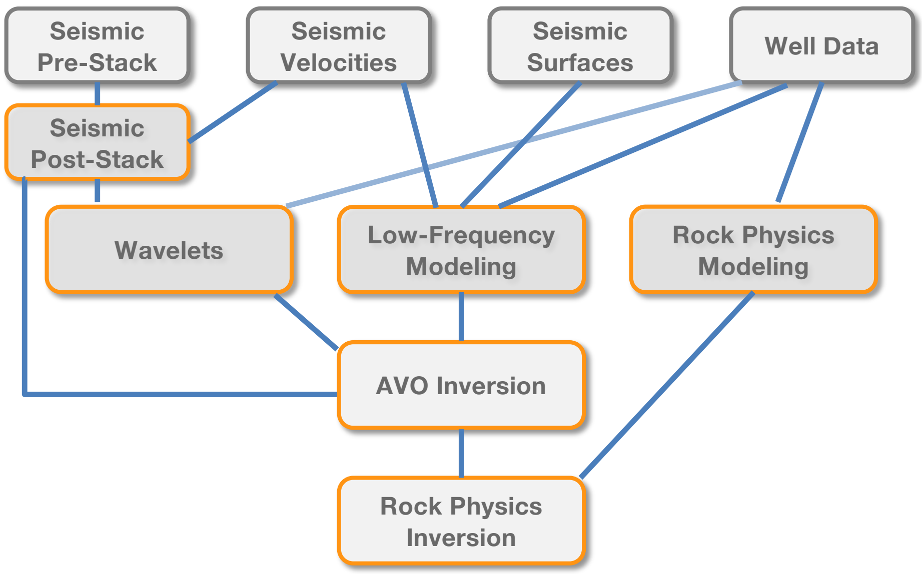

Figure 4.1: *Flow chart for the general workflow. First row lists the input data. The steps towards the rock physics inversion through the AVO inversion are marked with orange outlines.*

Seismic pre-stack gathers
2D/3D migrated pre-stack (or stacked into angle/offset bands) data is needed. Obtaining

angle of incidence up to 40°-50° is optimal, but due to geology and survey setup there will be limits to the angle of incidence.

Well data

Well log data with elastic and petrophysical properties covering the target can be used for wavelet estimation, low frequency modelling and rock physics modelling. Also, well log data are very important for evaluating the quality of the inversion and QSI results. If well log data are not available a seismic driven wavelet can be estimated resulting in a more general seismic inversion. The rock physics modelling can be obtained from well logs further away as long as they cover a similar geology. The more well log data one have the more precise a rock physics model can be obtained. If some well log properties are not measured, empirical relations can be applied to establish a full log suite.
Below is a list of logs used in an geothermal QSI project:

Sonic (p-wave) log is used for calculating acoustic impedance and Vp/Vs. If not present it can be predicted from the density log through empirical relations.

Density log is used for calculating acoustic impedance. If not present it can be predicted from the sonic log through empirical relations.

Shear (s-wave) log is used for calculating Vp/Vs. If not present it can be predicted from the p-wave log through empirical relations.

Porosity log is used for rock physics modeling and evaluating the result

Volume of clay is used for rock physic modeling and evaluating the result.

Seismic velocities

Seismic velocities are a product of the seismic processing. Velocities are used for calculating the angle-bands in the subsurface. Velocities can be very useful for a more unbiased and data-driven low-frequency model. If the seismic velocities are not available a velocity can be assumed for the angle-band calculation.

Seismic surfaces

The seismic horizons are used to help guiding the low-frequency model and also to help locating the seismic zone of interest.

Wavelets

Wavelets are the link between the seismic and the subsurface elastic properties. Different methods for estimating wavelets exists. The more well log data that are available within the seismic area the more specific a link can be established.

Rock physics modelling

A rock physics model is the link between the subsurface elastic and petrophysical properties. With this model we can convert the seismic inversion results such as acoustic impedance and Vp/Vs into parameters like porosity and volume of clay in the seismic cube.

Low-frequency modeling

As seismic data in nature are lacking information in the low-frequency range the low-frequency model can give us this information. With the low-frequency model we can go from a relative to an absolute inversion result.

AVO inversion
The inversion is a global seismic simultaneous AVO inversion algorithm, which inverts partial stacks directly for acoustic impedance, Vp/Vs and density.Other types of seismic inversions are possible for example a probabilistic inversion or if azimuthal seismic data are available an AVAZ inversion.

Rock physics inversion
The rock physics inversion or lithology classification is an interpretation of the seismic inversion result. The outcome can be a discrimination of different lithologies and porosity estimates.

4.2 Best practice

To make a seismic AVO inversion one only need to obtain pre-stack migrated seismic data, more data are nice to have and needed to obtain a more reliable and more specific inversion.

An inversion with little or no more information than the seismic itself can be very useful in the exploration stage of a project. After the well is drilled the inversion can be revisited to obtain a more specific QSI as input for de-risking production wells or for input to the reservoir modelling.

The best possible QSI project will therefore consist of more phases:

Initial phase
Seismic in a sparse grid is obtained over a bigger area and used for input to a general QSI. The aim is to locate areas with good reservoir properties and thereby good spots for placing exploration wells and further investigation.

New well log data obtained
Every time new well log data are available, the same seismic from the initial phase can be revisited for a more specific QSI. The aim is to get results for a better de-risking of injection and production wells and obtain input for the reservoir modelling.

New seismic obtained
The inversion can be revisited if new seismic is obtained. The new seismic can be obtained in a smaller area covering the geothermal target in a finer grid and longer offset to improve the AVO. The aim is to obtain data for a more precise result over the geothermal target. This result can again be used for input to the reservoir modelling and de-risking wells.

Borehole data provide very detailed information of the local subsurface geology. Normally wells are located along seismic lines. From the well tie points the geological information can be extrapolated along the seismic lines. Acoustic boundaries, e.g. top or base of potential geothermal reservoir units, are mapped using the reflections in the seismic data.

For optimizing the evaluation of the internal reservoir quality, QSI is used. To obtain a successful evaluation of reservoir quality high quality seismic and well data is very important. An important step in QSI is seismic AVO inversion. Input for seismic AVO inversion is seismic pre-stack migrated CDP gather data and borehole data. Acoustic logging (i.e. Vp & Vs velocities and density logs) is important for a successfully estimation of the reservoir properties. For an optimal result it is important that the log data covers the expected reservoir unit, together with a sufficient interval above and below the expected reservoir unit.

Evaluation of existing data
Generally, existing data will be sufficient for interpretation and mapping of the depth to potential reservoir units. However, for detailed mapping of e.g. possible faults and for QSI to reduce uncertainties existing data are in general insufficient. Consequently, new data will in most cases be necessary for a full evaluation of reservoir quality.

Survey planning of new seismic data
The following steps is recommended to be included in the initial survey planning stage, during the testing stage before running the new survey and in the subsequent seismic processing:

- Proper survey planning in order to ensure good tie to existing data, tie to existing wells, necessary survey lay out to ensure proper mapping of possible faulting in the area and with line lay out as close as possible to possible well locations of a future geothermal power plant
- Appropriate equipment to be used for seismic survey setup in general and especially for vibrator equipment for source signal generation
- Testing of influence of shotpoint distance towards seismic signal to noise ratio of final data
- Testing of number of vibrators to be used, number of sweeps and sweep length for optimum result
- Testing of frequency bandwidth and type of source sweep (linear, logarithmic or other)
- Ray tracing to ensure angel of incidence for far offsets up to 40℃-50℃ (keep attention to limitations to angel of incidence at reservoir level from high velocity formations above reservoir units)
- Pre-stack migrated gathers (time and/or depth) are included among deliverables in addition to standard stack data deliverables
- Stacking and migration velocities among deliverables
- Final source and receiver static corrections among deliverables

Collection of new well data
It is strongly recommended that acoustic wells logs are included in the well log program i.e.:

- Vp velocity logs through and in appropriate zone below/above reservoir units
- Vs velocity logs through and in appropriate zone below/above reservoir units
- Density logs through and in appropriate zone below/above reservoir units

All these recommendations are necessary in order to establish the optimal input data for QSI and to minimize the uncertainties related to characterization of the geothermal reservoir.

Table 4.1 includes a list of what is needed to obtain the best possible QSI based on seismic AVO inversion.

Seismic data	
Migrated pre-stack seismic data	☐
Obtain angle of incidence of at least 30°	☐
Seismic velocities	☐
Structural knowledge included in survey planning	☐
Seismic interpretations of geological surfaces	☐
Data from well logs	
P-wave velocity	☐
S-wave velocity	☐
Density	☐
Porosity	☐
Volume of clay	☐
Logged in as long interval as possible	☐
Logged at least over the target interval and its transitions	☐
Formation tops	☐
Deviation survey	☐
Checkshots	☐
Involved technical disciplines in the well and seismic planning	
Geophysicist	☐
Geologist	☐
Reservoir engineer	☐
Drilling engineer	☐
Seismic survey planner	☐

Table 4.1: *Best practice checklist for an optimal geothermal QSI, see section 4.1 for a description of the various data.*

Chapter 5

Example: Quantitative Seismic Interpretation in the Hillerød-Farum area

5.1 Background

A field case is demonstrated to show how 2D seismic AVO inversion together with well log analysis can aid in quantitative seismic interpretation (QSI) of a geothermal play in the Hillerød-Farum area (Figure 5.1). From the seismic inversion it is possible to make interpretations of the different lithologies and estimating porosities via links established at the well logs.

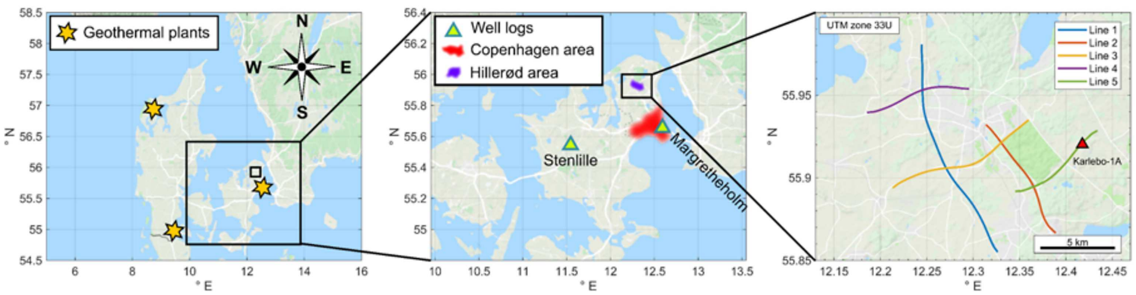

Figure 5.1: *Location map of the study area in the Northeast of Zealand, Denmark showing seismic and well log data used in this study. Wells at Margretheholm and Stenlille are located approximately 30 and 60km away from the prospect area, respectively. Courtesy to Google Maps.*

The target is located within the Lower Jurassic reservoir unit (LJRU) and the Gassum Formation (Figure 5.2) at a depth of around 2 km below surface. The Gassum Formation has proven very good reservoir quality at several locations and act as a geothermal reservoir for two other geothermal plants in Denmark. The temperature in the Gassum Formation is in this case expected to reach levels around 50-55℃.

The Karlebo-1A well (Figure 5.1) was used for establishing the link between the earth properties and the seismic by a wavelet and a background model. This well is the closest and it is located

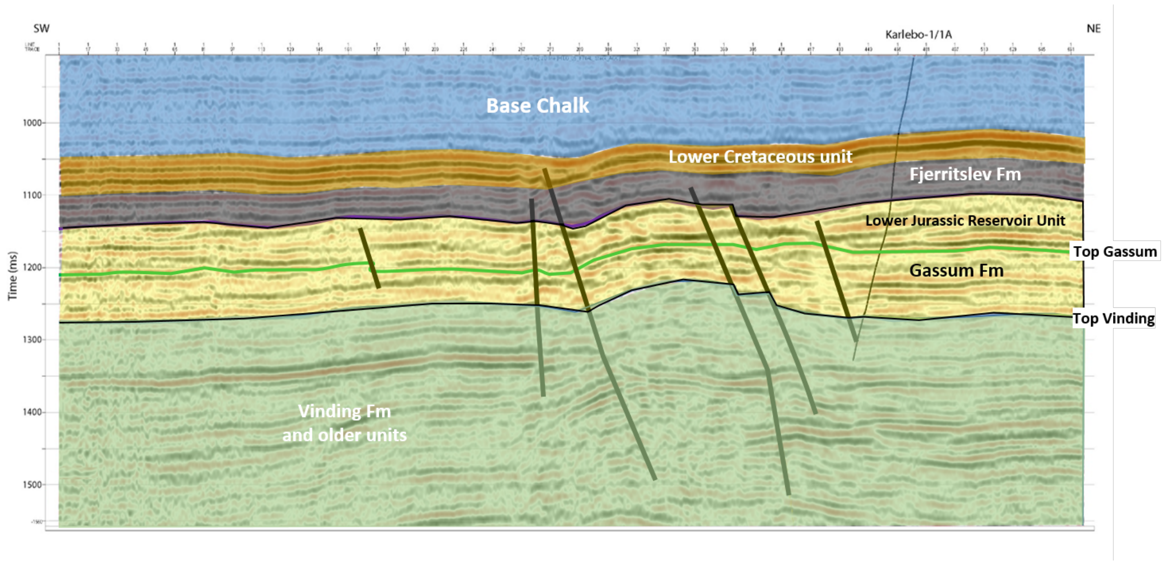

Figure 5.2: *A geological interpretation in Two-Way-Time (TWT) of the main geological formations based on the seismic line number 5, about 7 km in length. The Karlebo-1A well path Northeast of a significant NW-SE orientated fault-system is projected into the seismic section.*

around 77 meters to the nearest point on line number 5. Karlebo-1A has a limited amount of measured logs and therefore the well at Margretheholm was used to support Karlebo-1A in order to obtain a sufficient amount of well logs.

5.2 Well logs

A key challenge for this specific project was linked to the limited amount of logs in the Karlebo-1A well. Therefore, the available logs, including gamma ray, sonic and a porosity, was used to derive additional density, shear sonic and shale volume logs. Margretheholm-1A, which contains a complete set of logs, was used to calibrate empirical relations to be used at Karlebo-1A. Margretheholm-1A represents a good reservoir analogue to the Karlebo-1A well as it penetrates the same formations in the same geological setting and is located 30 km southeast. As a porosity log is available in the Karlebo-1A well, this was considered to represent the most appropriate reservoir property to evaluate the seismic inversion results within. Therefore, the seismic inversion was used to predict lithologies and porosities via links established at the well logs from Karlebo-1A (Figure 5.3 and 5.4) and Margretheholm-1A.

5.3 Inversion setup

The seismic inversion scheme used in this setting is a global seismic simultaneous AVO inversion algorithm, which inverts partial stacks directly for acoustic impedance, Vp/Vs and density. Input to the simultaneous AVO inversion is a wavelet for each partial stack and a low-frequency model for each property to be inverted for.

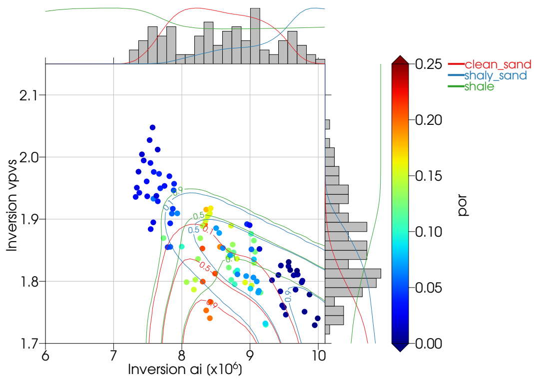

Figure 5.3: *AI vs Vp/Vs cross-plots color-coded with porosity from Karlebo-1A overlain with PDFs for clean sand, shaly sand and shale data points from the seismic inversion.*

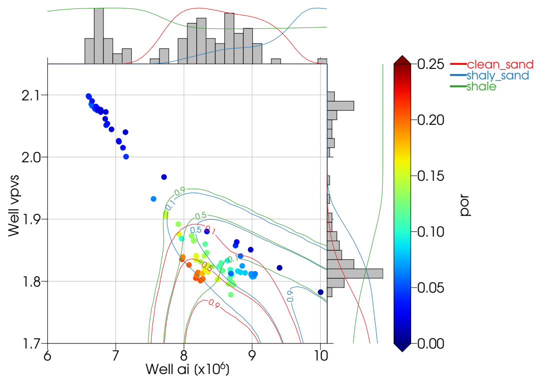

Figure 5.4: *AI vs Vp/Vs cross-plots color-coded with porosity from Karlebo-1A overlain with PDFs for clean sand, shaly sand and shale data points from the Karlebo-1A well.*

As elastic well log data in this case was limited, the wavelets used for the seismic inversion are statistical wavelets based on the seismic data only. The spectral amplitude content is derived directly from the seismic data. The phase and the scaling of the wavelet is estimated based on seismic inversion tests. As the seismic data in nature is lacking information from the low frequencies, this is consequently extracted from the well logs. The background model is based on the Karlebo-1A well log data. The log information was extrapolated along the horizons using a radial basis interpolation method.

5.4 Lithology classification and porosity estimation

A classification of three facies: 1) clean sandstone, 2) shaly sandstone and 3) shale, are performed based on non-Gaussian probability density functions (PDFs) estimated using a Gaussian kernel-density estimation. These PDFs (Figure 5.3 and 5.4) are subject to interpretation and honor the well log observations from Karlebo-1A and Margretheholm-1A and the geological model of the area. The PDFs were applied to the inversion results. Figure 5.5 shows how the seismic lithology classification is matching the Karlebo- 1A well, where a pure shale package in the Fjerritslev Formation is classified, and thin sand packages within the Lower Jurassic reservoir unit and the Gassum Formation are classified as well.

The AI vs. Vp/Vs cross-plots from Karlebo-1A in Figure 5.3 and 5.4 show a strong correlation between AI and porosity ϕ. A simple linear relation $\phi = a_F * AI + b_F$ is estimated for each facies F, and applied to calculate a facies-dependent porosity. The total porosity is obtained by weighting the facies-dependent porosities with the probability of the given facies.

In Figure 5.5 the seismically estimated porosity shows a good match to the corresponding porosity log from Karlebo-1A. Figure 5.7 shows the porosity estimates along line 1, which are consistent with the Karlebo-1A and Margretheholm-1A trends. For example, the porosity predictions approach 20-25% within the Lower Jurassic reservoir unit and the Gassum Formation, whereas 2-4% is the case for the Fjerritslev Formation.

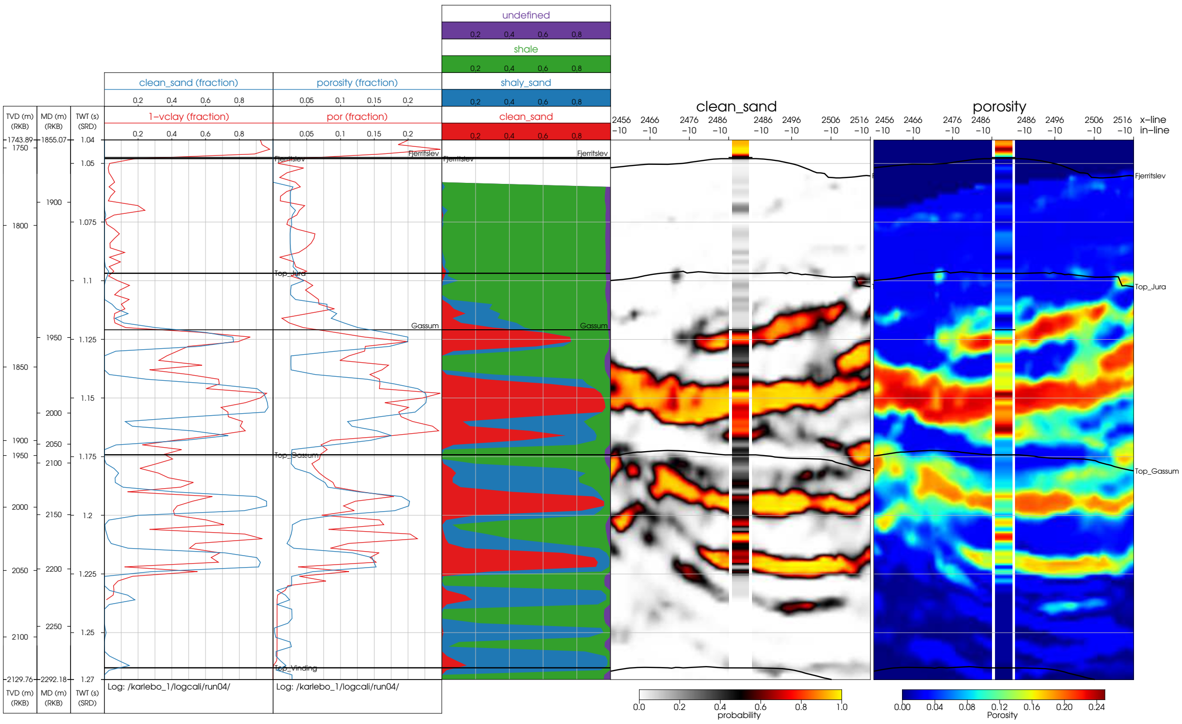

Figure 5.5: *Lithology and porosity results predicted from the seismic inversion and projected on Karlebo-1A. First panel is showing seismic predicted probability of a clean sand (blue curve) and volume of clay from well log reversed (red curve). Second panel is showing seismic predicted total porosity (blue curve) and porosity from the well log (red curve). Third panel are showing the probability of the different lithologies based on the seismic inversion. Fourth panel is showing seismic predicted clean sand at a mini-section crossing the well log. The Fifth panel is showing the seismic predicted porosity at a mini-section crossing the well log.*

5.5 Conclusions

It was demonstrated how 2D seismic AVO inversion together with well log analysis can aid geothermal QSI and thereby help de-risking geothermal plays. From the seismic inversion it was possible to interpret different lithologies and estimate porosities via links established at well logs. With the specific results it is possible to plan future target zones for geothermal energy plants in the area of Hillerød in Northern Zealand, Denmark. Several connected high porosity sands were predicted, and with an expected temperature of around 50-55℃ in the target zone this strengthens the prognosis for a potential good geothermal reservoir.

Despite lack of elastic logs from the Karlebo-1A well, it was possible to evaluate the inversion results. An evaluation was performed in the elastic domain between predicted elastic properties in the well and the elastic inversion results. As the porosity log was available in the Karlebo-1A well, the main evaluation of the seismic product was performed in the porosity domain by establishing transforms between facies specific porosities and the seismic inversion results.

With this specific field case it is demonstrated how seismic AVO inversion can be used for geothermal QSI in order to obtain a better understanding of potential geothermal plays for de-risking new wells and for reservoir modelling.

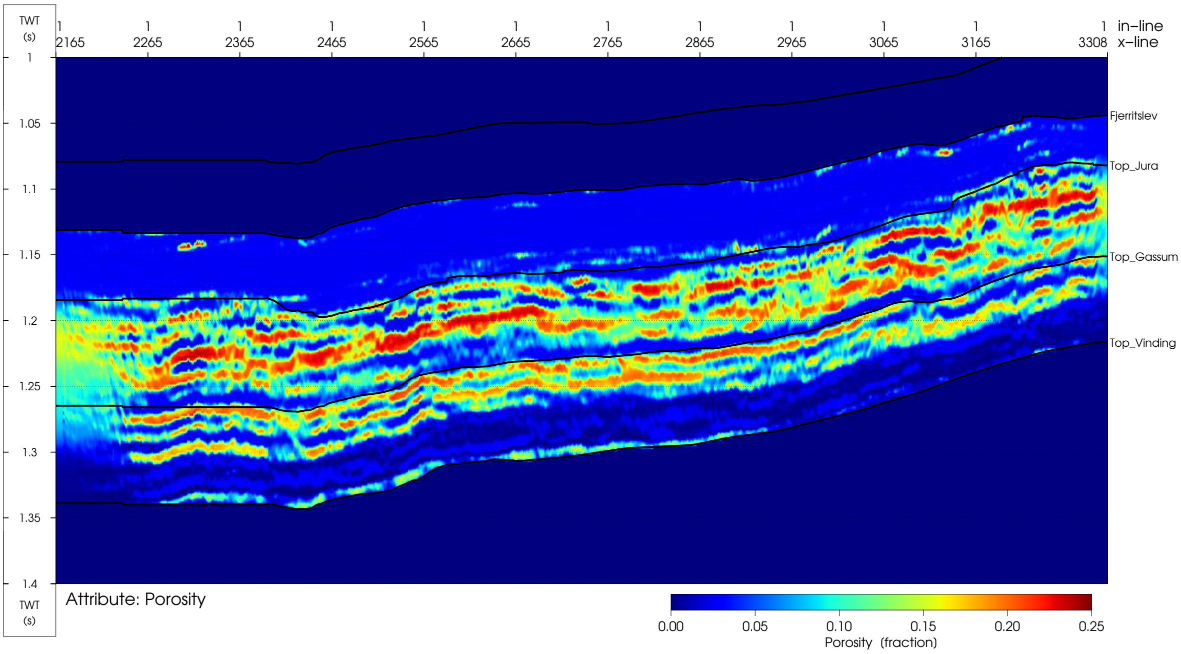

Figure 5.6: *Total porosity estimated from the inversion and the lithology classification at line number 1.*

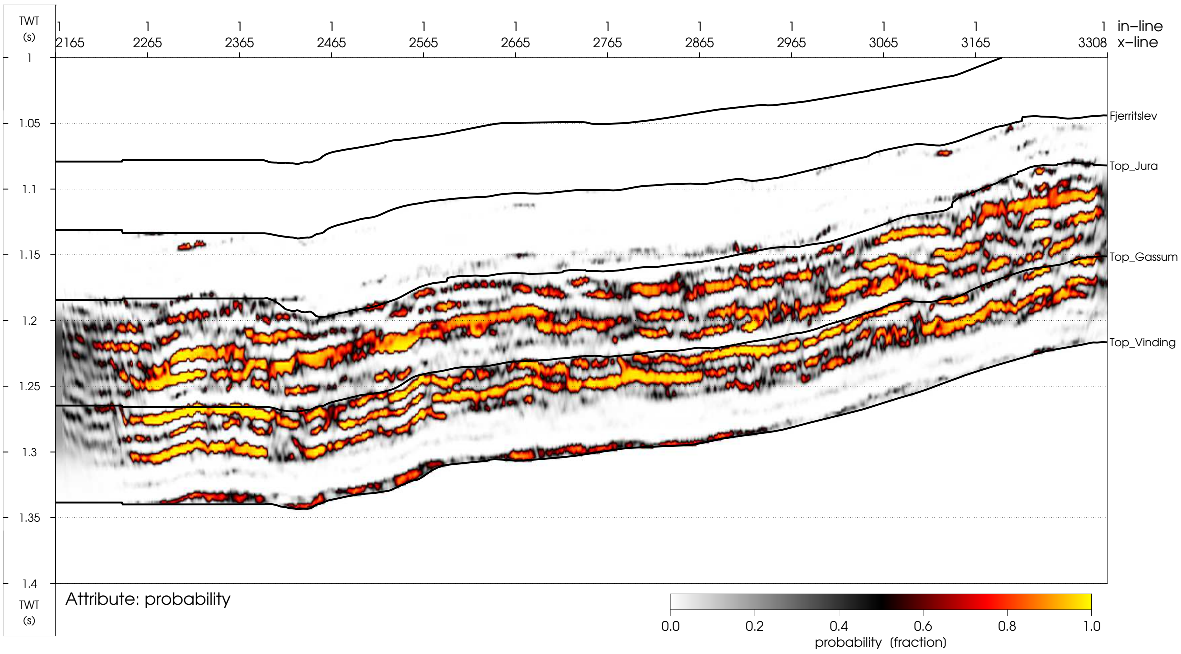

Figure 5.7: *Sand probability estimated from the seismic inversion at line number 1.*