Wave-Equation Based 4D Joint Inversion of PP and PS Seismic Data

Geology and field history

The Edvard Grieg field was discovered in 2007 by Lundin Energy Norway’s very first exploration well drilled, 16/1-8 on the Utsira High (see Figure 1). Several appraisal wells followed, and the plan for production, development and operation (PDO) was sanctioned in 2012. The total expected recoverable reserves from the field has steadily increased from PDO sanction at around 180mmboe up to today’s ~350mmboe. The reservoir zone sits in a half graben at approximately 1800-2000m depth. It consists of an upper aeolian sand dune high permeability zone underlain and mixed with shales and conglomerates. Understanding the areal distribution of the conglomerates and the high porosity sandstones is a critical component in the reservoir development of the field. Some parts of the field also consist of thin cretaceous sands draped on top of weathered fractured basement with varying porosity. The ability to distinguish lithology and fluid parameters in a reservoir setting consisting primarily of three very different facies has been the main driver behind adopting more complex and data driven inversion methods. As of today, three rounds of full field 4D OBC data have been acquired in 2016, 2018 and 2020. The field is currently pressure supported by four water injectors and the key driver behind the 4D seismic is to monitor the injected water movement and oil draining from the reservoir.

Simultaneous wave-equation based joint AVO inversion of 4D time-lapse PP and PS data

WEB-AVO inversion is different from conventional linear AVO inversion because it iteratively solves the full elastic wave-equation. In this way, the approximation of primary reflections only is overcome and interbed multiples, multiple mode conversions and transmission effects are properly accounted for, as long as they are generated over the inversion interval (e.g. Gisolf et al., 2017). The WEB-AVO technique is particularly suitable to handle time-lapse seismic data, because the non-linearity caused by reflectivity changes together with travel-time changes is automatically handled by the wave-equation. Various applications to field data have been reported such as Barajas-Olalde et al., (2019) and Dhelie et al., (2020). This previous inversion work was based on the availability of seismic PP data only for base and monitor surveys. In this paper we report on the first application of joint WEB-AVO inversion of 4D PP and PS seismic data for time-lapse reservoir monitoring. The inversion scheme minimizes the mismatch between the input seismic and the predicted synthetics for all datasets simultaneously (PPbase, PPmonitor, PSbase, PSmonitor), while solving for common subsurface models in terms of the compressibility and shear compliance and their corresponding time-lapse changes. This allows us to apply a sparseness constraint on the time-lapse property changes, effectively mitigating the impact of different noise realisations in the base and monitor surveys. The elastic wave-equation is defined in time and depth, where the seismic data is the elastic wavefield (P and S) in time, in the data domain, while the elastic subsurface parameters are defined in the depth domain.

Data input and inversion workflow

For the current study, four seismic datasets were used, acquired over the Edvard Grieg field in 2016 and 2018. The deployment of an OBC system allowed measurements of the PP and PS converted seismic data for both vintages. The baseline and monitor datasets were similarly processed and imaged.
by using a Kirchhoff depth migration. In this way, migrated pre-stack offset gathers were made available that are commonly used as input for AVO inversion projects. A Low Frequency Model (LFM) was built by inverse distance weighting interpolation of logs between five wells. Seismic horizons were used to guide this process. A single well was used to extract seismic wavelets for the PP and the PS datasets. While the ray-parameter dependent wavelets reflect the different bandwidth of the PP and PS data, the same wavelets were used for the base and monitor surveys.

**Synthetic example**

A well-known challenge of seismic time-lapse studies is the limited availability of 4D well log measurements. This complicates an independent calibration (wavelet estimation) of the baseline and the monitor surveys, but also the verification of the technology in a controlled environment. Here we decided to build a realistic synthetic model by merging available well logs with the elastic properties from the Petro Elastic Models (PEMs), which were available for the times of the data acquisition. The merging was required as the reservoir simulations is performed over a limited interval only which would be too short for a meaningful modelling and inversion of synthetic gathers. Therefore, an overburden model was created from measured well logs and then combined with time-lapse representations of the reservoir states before and after production/injection. Synthetic PP and PS data were generated by Kennett modelling. This technique also provides the full elastic response of a stack of layers but is implemented very differently from the integral representation of the wave equation that is used in the inversion.

![Figure 2](image-url)  
*Figure 2 Results of synthetic study for demonstration of the technique. The inversion successfully allows identification and separation of injected related pressure effects (red) and production related fluid effects (green).*

In Figure 2, the outcome of the synthetic modelling and inversion study is summarised. The PP and PS input data (a and b) compare very well with the predicted synthetics (c and d). The same statement holds for the corresponding time-lapse signals (e, f, g and h). In all sub-plots the green rectangle refers to a production related change of water replacing oil and the red rectangle highlights a pressure related change. In i, j, k and l the absolute properties and the corresponding time-lapse changes are shown. The true properties (turquoise) are matched nicely by the inverted properties (blue) given the seismic bandwidth. The low frequency model, obtained by applying a 5Hz low-pass filter to the true logs, is
shown in grey. It should also be mentioned that 3% random noise was added to the input data. While random noise is less of a problem with field seismic, it is good practice for synthetic examples to prove the robustness and stability of the inversion engine. The example also highlights the fact that the shear compliance is truly insensitive to fluid changes. At the same time, compressibility is mainly affected by fluid changes with only minor pressure induced changes.

Field data example

Prior to inversion, the seismic data was pre-conditioned using structurally oriented filtering, some mild Radon filtering and static corrections to flatten the gathers. In Figure 3, full stacks of the seismic data and the corresponding time-lapse signals are shown. From the baseline stacks, a) and c), the difference in bandwidth between PP and PS data becomes apparent. The peak frequency for PP seismic is around 30 Hz but only around 12 Hz for the PS data. This will naturally be reflected in the estimated wavelets that are used as input to the inversion. Along a selected arbitrary line, we observe clear time-lapse amplitudes on the PP data as a result of oil production between 2016 and 2018. The ringy character in the center of the line is intriguing as the 4D signal is much longer than what would be expected from the known interval of the reservoir sand. For PS, the time-lapse signal is noisier, and it is difficult to identify clear changes based on the visible differences.

Figure 3 Full stacks generated from the input pre-stack data. The top row (a and b) shows the baseline PP and PS data while the bottom row (c and d) are the corresponding time-lapse signals.

In Figure 4 the corresponding inversion results are shown along an arbitrary line but also for some horizon maps covering two reservoir intervals. The 4D compressibility changes (a, c and d) clearly reveal hardening (blue) of the reservoir sands where the oil is replaced by brine. At the same time the shear compliance (b, e, f) increases around the injector wells which is consistent with the expected pressure increase in those areas. What is also interesting to realize is that the rather long time-lapse signal that was observed on the PP data (Figure 3c) translates to a very well-defined elastic property change in the depth domain. This is a consequence of WEB-AVO intrinsically updating the travel times to be consistent with the latest inverted subsurface model. The inversion technology automatically detects potential pull-ups/pull-downs between the baseline and monitor surveys by connecting the time (seismic) and depth (property) domains. This can be interpreted as automatic time warping and it is a nice illustration of the non-linear character of WEB-AVO inversion.
**Figure 4** Inversion results for time-lapse compressibility and shear compliance. Absolute results are shown along an arbitrary line as well as simple averages over two reservoir intervals.

**Conclusions**

Wave-equation based joint 4D inversion of PP and PS seismic data has been introduced and demonstrated. The technique was first verified on a realistic synthetic dataset before being applied to a 4D OBC field dataset acquired over the Edvard Grieg field in the North Sea. The inversion results allow a successful separation of production and injection related property changes. The addition of PS data to the inversion improves the recovery of 4D pressure changes that drive changes in the shear compliance, while saturation changes are consistent with previous projects where only PP data was used. By accounting for pull-ups/pull-downs in the seismic time domain, due to time-lapse velocity changes in the depth domain, the inversion has correctly collapsed an extended 4D time signal to a single local property change in depth in the subsurface model from inversion.

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**References**

