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Geomodel Update Using 4-D Petrophysical Seismic Inversion on the Troll West Field

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SUMMARY

This paper presents results from the R&D collaboration between CGGVeritas and Statoil on 4-D Petrophysical Seismic Inversion (PetroSI-4D) on the Troll field. The proposed 4-D petrophysical inversion workflow inverts simultaneously multiple angle stacks from several time-lapse seismic surveys in order to estimate the time evolution of the hydrocarbon saturation and update the geometrical and petrophysical properties of an input geomodel. Inversion results can be used directly for well planning.

The 4-D seismic data on the Troll field are used to monitor production effects such as the thinning of the oil column, while the main production challenge is the optimisation of in-fill drilling locations. The main objective of our study is to improve the existing fine-scale geo-model and coarser scale flow model that host more than 10 years of production information. As permeability is not directly accessible from seismic measurements, the targets are porosity estimation in the oil leg for sand quality prediction and saturation changes.
Introduction

This paper presents results from the R&D collaboration between CGGVeritas and Statoil on 4-D Petrophysical Seismic Inversion (PetroSI-4D) on the Troll field. It builds on previous 3-D petrophysical pilot studies, using individual seismic surveys from the same field (Wijngaarden et al., 2007). The proposed 4-D petrophysical inversion workflow inverts simultaneously multiple angle stacks from several time-lapse seismic surveys in order to estimate the time evolution of the hydrocarbon saturation and update the geometrical and petrophysical properties of an input geomodel. Inversion results can be used directly for well planning.

The Troll field is one of the biggest gas field of the Norwegian North Sea. It consists of a shallow offshore sandstone reservoir of good porosity and permeability. In the Eastern part, the gas is produced by pressure depletion while in the Western part, a thin oil leg is produced first to minimise the volume of non-recoverable oil. To date, more than 130 multi-lateral horizontal drains have been drilled. Oil production in Troll West yields expansion of the gas cap pushing downward the GOC but also inducing oil column vertical movements, observed when drilling new wells.

The reservoir has been characterised using a fine-scale geological model where two categories of sands quality, namely Clean-sands and Micaceous-sands, alternate in the Sognefjord formation following a prograding sequence. These sands correspond to different sorting and lead to different permeability distributions while the porosity distribution is almost overlapping. The large contrast in permeability gives a non-uniform drainage, which is monitored by using time-lapse seismic measurements. The Troll West field has 5 repeated surveys, from the base, acquired in 1991 before the start of production, to the latest one acquired in 2007.

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Petrophysical inversion methodology

Unlike traditional seismic inversion that provides elastic properties in TWT from seismic data, the petrophysical inversion objective is to reconcile an existing fine scaled geo-cellular model defined in depth with the measured pre-stack seismic data defined in the time domain. The model framework is a 3-D stratigraphic grid, constructed from an existing geo-model or flow simulation model.

The PetroSI workflow (Bornard et al., 2005, Coléou et al., 2005) is illustrated in Figure 1. We start from a laterally coarse scale model; i.e., the lateral grid block size of the input geo-model is typically coarser than the seismic bin. This model is down-scaled horizontally at the seismic bin to produce the initial fine scale model for inversion (upper left). The inversion model grid is infilled with initial values for static petrophysical properties and dynamic properties, such as pressure and hydrocarbon saturation, calculated at the different survey times and obtained by re-sampling the corresponding attributes from the geological and flow simulation models.

The inversion algorithm is an iterative process where the initial model in depth is updated by perturbing the thickness of the layers and the values of the volume-dependent petrophysical properties until all data and constraints are honoured. Seismic forward modelling for each vintage includes the computation of the elastic response (lower left) in each cell of the geo-model through the Petro-Elastic Model (PEM) from stored values of porosity, rock type, pressure and saturations. Once a time-depth reference has been established - usually at a major seismic horizon - the geo-model is defined simultaneously in depth and at the various TWT of the seismic vintages. Consistency is maintained...
with the PEM-derived compressional velocities throughout the inversion process, which can also incorporate depth-specific constraints. Angle-dependent 3D synthetics (lower left) are then computed through Zoeppritz equation and 1D convolution at each trace location for comparison with observed seismic data until convergence.

After convergence, the updated petrophysical properties which honour the seismic measurements for each inverted vintage are available for updating the coarser scale models (upper right in Figure 1). This multi-vintage workflow can be applied independently on different seismic vintages or include several vintages simultaneously. Geometry and properties have been updated but up-scaling from seismic bin to geo-model or flow model scale is straightforward as the layering is explicit in all models and shared throughout the process. Sharing the layered geometry enables consistent and reversible exchanges without loss of information.

**Figure 1: 4D petrophysical inversion workflow**

**Inversion parameterisation**

We consider both static and dynamic properties in the joint inversion. In the case of Troll, the compaction simulation model has not predicted any significant geo-mechanical effects due to pressure change since production started; i.e., less than 0.5% in pore volume reduction in the reservoir. Compaction is therefore considered negligible. Consequently, porosity, depth and layer thickness at each trace location and for each cell of the model are assumed to represent static variables that do not vary across vintages during the inversion process.

Dynamic properties such as saturation and pressure are expected to vary in time due to production. In our inversion process, saturation variations are handled using a moving fluid contacts model which is independent of the layering of the geo-model. At each trace location, the saturation model is set so that each fluid leg is defined by its upper and lower contact position in depth and by average saturation values. Starting from an initial fluid contact and saturation model defined from the flow simulator, the contact vertical positions and average saturations in each fluid leg are updated trace-by-trace at the different acquisition times. The saturations are coupled through time and proposed changes on vintage N can be transferred to vintage N+1 or N-1 depending on its sign. This enables saturation increase or decrease at a given location for a given time interval. An interesting fact is that the sparse parameterisation of the saturation field implies that the number of unknowns increases less rapidly than the number of observations when the number of vintages increases. The high reservoir permeability makes this model realistic for the Troll West field.

During the simultaneous inversion of all pre-stack seismic vintages, this sparse parameterisation provides a suitable framework for the joint inversion of static variables such as cell thickness and porosity and dynamic variables such as contact positions, residual saturations and gas out of solution saturations for each vintage. It enables tracking of the contact position through time, giving access to production-induced oil-column thickness changes and vertical displacement. It also accounts for the
gas out of solution progressively appearing through time in the oil leg and in a residual oil zone below the OWC that has a strong influence on the 4-D seismic signal (Wijngaarden et al., 2007).

PEM calibration

The Petro-Elastic Model (PEM) is the cornerstone of the inversion process as it is used to make the link between the geological model expressed in the depth domain and the seismic measurement in TWT. In the case of Troll, the PEM is based on the rock physics template obtained after comprehensive studies by Hydro (Avseth et al., 2005). The petro-elastic model provides the necessary relationships between the elastic properties Vp, Vs, ρ and the petrophysical properties such as Φ and fluid saturations throughout the inversion process. The production effect in the model is guided by the sand quality, the porosity as well as by the saturation and pressure changes. The pressure-dependent PEM is shared across vintages and provide the vintage-dependent elastic response necessary for seismic forward modelling.

Geomodel update with multi-vintage porosity results

On the Troll West field, the seismic bin is 12.5mx18.5m. A fine-scale geological model exists over the 160m thick Sognefjord reservoir formation, with average horizontal cell dimensions of 75mx75m. The model is divided in 314 layers grouped in 32 zones describing the C-sand and M-sand succession. Petrophysical properties in the geo-model were derived by well-based interpolation. The flow model is an up-scaled version of the geological model, with a coarser horizontal resolution, around 150mx150m but its geometry is not completely consistent with the geological model. Information transfer between the inversion model grid and the flow model is therefore a challenging task.

The seismic inversion model has the same layering of the geological model. Data transfer between the two models is a reversible process based on horizontal data up/downscaling according to the layering.

The porosity inversion results have been judged satisfactory both in mono and multi-vintage modes (Norenes Haaland et al., 2008). Porosity inversion results (Figure 2 C) have been transferred back into the geological model after horizontal upscaling (Figure 2 D). The updated model provides a more detailed image of porosity variations between the wells.

Multi-vintage inversion results: tracking of the oil leg vertical movement

The decoupling between the rock and fluid properties provides the absolute depth of the fluid contact position and the saturation values with the fluid leg for each vintage. This information can be upscaled and exported in the flow model. Inversion results show downwards movement of the GOC position around horizontal well locations, as expected from gas cap expansion. The relative fluctuation of the GOC from one vintage to another quantifies this expansion and gives an insight of the drainage area along a given drain.
More information is obtained by looking at relative variations of the OWC with respect to the initial contact position. The OWC has been found shallower or deeper in some areas, translating vertical movement of the Oil column. These results are consistent with the observations obtained when drilling new horizontal drains that are located just above the OWC position at the time of drilling.

**Figure 3:** A- Relative GOC vertical movement between 2005 and 2007 showing the main gas cap extension along the most productive wells. B-Vertical variation of the OWC with respect to initial OWC position before production. The contact is pushed down with time.

**Update of the time-depth conversion in the geomodel.**

The inversion provides an update not only of the petrophysical properties and the contact positions but also of the absolute position of the reservoir in depth. The initially flat OWC is providing a time depth reference position at each location that is used to improve the depth conversion of the top reservoir. On Troll West, it translates into a significant reduction of the mismatch with well markers.

**Conclusions**

The parameterisation of the 4D petrophysical inversion is directly using Porosity, Contacts position and Saturations in a layered model in depth compatible with reservoir zonation. This facilitates integration of seismic monitoring information into the geological- and flow model. On Troll West, the validation of the inversion results, their incorporation into the geological modelling and use of the oil thickness maps for planning infill wells are ongoing.

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**References**


