4D Petrophysical seismic inversion on the Troll West field

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Abstract

Inversions of seismic surveys often give quite low-resolution results that are difficult to compare with well data and geological models. We are therefore developing a multi-vintage seismic inversion based on a Petro-Elastic Model (PEM), called PetroSI-4D. This involves input from the geological model and good control on the petrophysical correlation between porosity and PEM-based seismic velocities. All vintages and input angle stacks are combined to jointly invert for layer thickness, rock properties and saturations. Perturbations of selected properties of the geological model are introduced using a simulated annealing algorithm to optimise the degree of match between the synthetic and the real angle stacks. There are no restrictions on number of input angles or number of monitor surveys, but new monitor surveys require new input to 4-D PEM. The base inversion result is delivered in porosity cubes instead of ordinary acoustic impedance and Vp/Vs results. The 4-D inversion result is planned to deliver saturation cubes instead of cubes of acoustic impedance or Vp/Vs changes. These parameters should be easier to compare and use in update of geological and reservoir models to validate the results.

The Troll West Field shows that the Petrophysical seismic inversion with rock physics PEM connected to the inversion, gives good results and comparison with the porosity input model is shown. The purpose of 4-D petrophysical inversion is to make use of all available seismic data simultaneously, multi-vintage and pre-stack, to constrain the evolution of the saturation field.

Introduction

Since 1998, 4-D seismic has been developed and used on the Troll Field with great success. But inversion has never given the best answers on the Troll field since the seismic amplitude data have already a really high resolution. Numerous attempts have been done to invert these data and finally we can report improvements in these results.

The Troll Field is an offshore field outside the west coast of Norway, an offshore sandstone reservoir characterised in an existing fine-scale geological model, with well-understood geological setting and good quality seismic data. Permeability is the main petrophysical variable that controls the oil production behaviour in the western part. In the geological model and for well planning purposes the sands in the Sognefjord formation are divided into two categories, namely Clean-sands and Micaceous-sands corresponding to different sorting and leading to different porosity distributions. The large contrast in permeability gives a non-uniform drainage, which is monitored by time-lapse seismic.

This paper presents results from the R&D collaboration on 4-D Petrophysical Seismic Inversion (PetroSI-4D) on the Troll field. It is based on previous pilot studies of 3-D Petrophysical Seismic Inversion (PetroSI), (Wijngaarden et al., 2007 [1]), on the base data to apply this new methodology (Bornard et al., 2005 [2]), (Coléou et al., 2005 [3]). The purpose of 4-D petrophysical inversion is to make use of all available seismic data simultaneously, multi-vintage and pre-stack, to constrain the evolution of the saturation field. The 4-D seismic on the Troll field is used to understand and explain the production effects from the gas out of solution after start of production. The 4-D data used in this study is base from 1991 and second monitor survey from 2003. The Troll West field has 5 repeated surveys, the latest one from 2007.

Petrophysical Seismic Inversion : Methodology

Petrophysical Seismic Inversion is applied on a geo-cellular model filled with rock properties in depth. The objective is to make it consistent with observed pre-stack seismic observations. The PetroSI workflow is illustrated in Figure 1. We start from an initial fine-scale geomodel defined from a 3-D stratigraphic grid in depth (left). Seismic forward modelling includes the computation of the elastic response (middle) in each cell of the geomodel through the Petro-Elastic Model (PEM) from stored values of porosity, rock type and saturations.

Angle-dependent reflectivity series are then calculated from the elastic properties through the Zoeppritz equation at each trace location. The resulting reflection coefficient series are converted from depth to time using the compressional velocities stored in the stratigraphic grid. Angle-dependent 3-D synthetics (right) are finally generated by wavelet convolution and compared to the observed seismic. Perturbations of selected properties of the geomodel are introduced using a simulated annealing algorithm to optimise the degree of match between the synthetic and the real angle stacks. After convergence, the final geomodel honours the observed seismic amplitudes, is consistent with the user-specified PEM and integrates inversion-based velocities that ensure coherence between the depth and time domains.

This single-vintage workflow has been applied independently to different seismic vintages before being modified to include several vintages simultaneously.

PEM Calibration

This step is critical. It reconciles different static measurements (cores, logs and seismic) obtained at different scales and different domains (depth and TWT). The PEM is based on the Rock Physics Template obtained after comprehensive studies by StatoilHydro (Avseth et al., 2005 [4]). The use of the petro-elastic model establishes the necessary link between VP, VS, ρ and ϕ. In addition, for 4-D purposes, the pressure dependency has to be considered. Velocity measurements from 38 core plugs have been used to establish the velocity–pressure relations for wet (water) condition. The measurements have been normalized to the value at 30 MPa and fitted to a second-degree polynomial as shown in Figure 2. Since the start-up of production, the pressure depletion in the Troll reservoir is relatively small, about 10 bars up to the 2003-survey. The corresponding changes in velocities according to the core measurements are approximately 0.5-1 %. Also, due to pressure release, for the oil leg, a transition from the liquid oil phase to gas phase will appear, since this is a saturated fluid system in equilibrium.

Results from pilot studies

The PetroSI result for the 1991 data is shown in Figure 3, together with the input model and the petro-elastic relations linking velocity and porosity, comparing linear trends with Hashin Strikman model for water bearing sands. The initial primary target is the porosity distribution in the gas zone above the contact.

The inversion has clearly changed the input model considerably, but in a geologically reasonable way. One of the main challenges on the Troll West field is to remove the imprint of the flat spot on the porosity model. This shows that with no gas out of solution as input model, the imprint of the flatspot is less significant, referring to (Wijngaarden et al., 2007 [1]). Still there is a mismatch between the model and the inversion and more analysis on the input PEM model can improve the results.

The correlation between a typical well and the inverted data is shown in Figure 4. The main problem with comparing horizontal well log data with inverted seismic, is the fact that it is not possible to do a vertical upscaling, as one normally will do with well log data. Plotted in red is the uncertainty, in terms of spatial standard deviation of the inversion result around the well branch. Not shown is the standard deviation above 1600 m MD where the well is near vertical. In this part, the dispersion perpendicular to the wellbore is minimal, implying greater variations in the vertical plane than in the horizontal. Given the uncertainty, the trend of the inverted porosity matches the measured one very well.

4-D petrophysical inversion objectives

On the Troll West field, the objective is to track vertical movements of GOC and OWC after production and to define the remaining Oil column thickness. The standard interpretation of 4-D seismic data is made using a map of the RMS stacked 4-D amplitude difference. This process has the advantage of providing a good interpretability through a lot of data reduction. Interpretation is assisted by massive forward modelling (Gjerding and Ona, 2007 [5]). However, ambiguity remains regarding vertical displacement of the Oil column and thickness resolution.
The purpose of 4-D petrophysical inversion is to make use of all available seismic data simultaneously, multi-vintage and pre-stack, to constrain the evolution of the saturation field in a joint inversion scheme. Avoiding data reduction prevents loss of information but requires a much larger modelling effort.

4-D petrophysical inversion parameterisation

The Sognefjord sands are poorly consolidated but Pressure changes are currently small, in the order of 2MPa since start-up of production (*Figure 2*). Compaction simulation models predict less than 0.5% in pore volume reduction in the reservoir. The compaction effect is therefore considered negligible and the Porosity will be kept constant for all vintages, as well as the thickness of the cells in the layered model. The saturations are changing and the flow simulator model provides initial positions for the contacts at the different seismic acquisition times. The good permeability and cleanliness of the sands induce very small transition zones and enable a sparse parameterisation of the saturation field based on contact surfaces. Such a parameterisation enables contact position tracking through time, giving access to production-induced Oil-column thickness change 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 have a strong influence in the 4-D seismic signal (Wijngaarden et al., 2007 [1]).

During the simultaneous inversion of all pre-stack seismic vintages, we jointly invert for production-independent variables such as cell thickness and porosity and for production-dependent variables such as contact positions, residual saturations and Gas out of solution saturations for each vintage. The workflow (Figure 1) is updated to operate with a single geomodel with a single porosity field and as many saturation fields as there are vintages. The Pressure-dependent PEM is shared through all vintages and provides the vintage-dependent elastic response necessary for the seismic forward modelling. The use of a single depth axis for all vintages and of petrophysical variables entails very strong coupling during the inversion, both in terms of Two-Way-Time and elastic behaviour. TWT shifts as well as amplitude differences are accounted for in the inversion process therefore seismic 4-D processing should not include TWT cross-equalisation. The results are directly expressed in contact vertical location at every trace. 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 inversion results should become more and more robust as more seismic is acquired.

Conclusions

To better understand how a hydrocarbon reservoir is being drained and to optimise future production scheme, quantitative 4-D interpretation is required. Beyond simple 4-D difference analysis or elastic inversion in the TWT domain, joint petrophysical multi-vintage seismic inversion is an important step in that direction. The manipulation of a geomodel in depth and the parameterisation in petrophysical variables (e.g. porosity and saturations) provide results immediately exploitable for production enhancement without further need for interpretation.
Such an inversion is only possible if forward modelling is satisfactory and therefore requires a good petro-elastic model, the link between rock properties and seismic data that is at the core of seismic calibration.

The verification process to validate the use of the inversion results and to incorporate the results into the geological modelling is an ongoing step in the integration of seismic data directly used in a model update.

Acknowledgments

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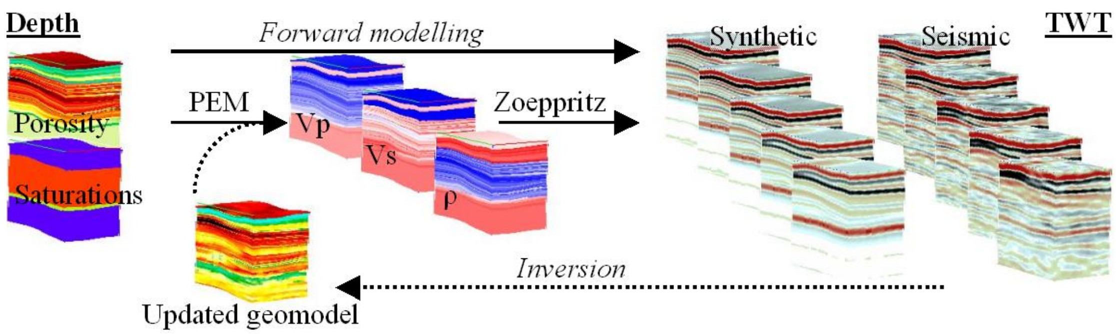

Figure 1: Petrophysical Seismic Inversion workflow

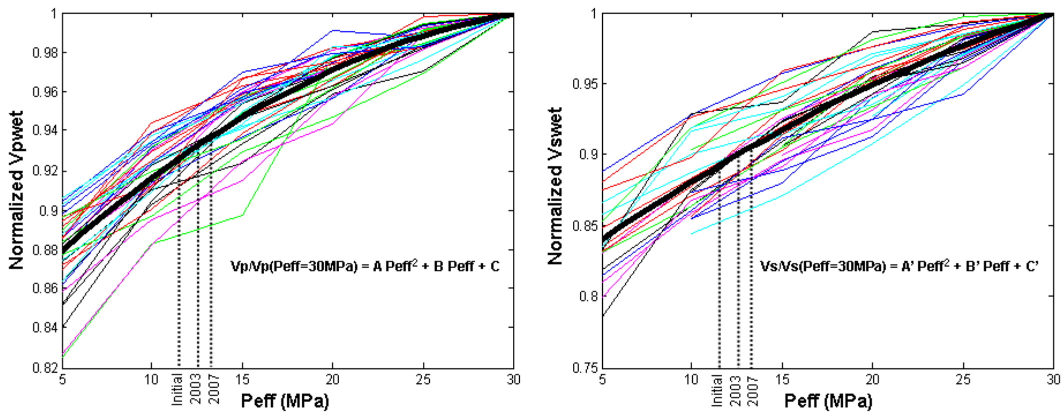

Figure 2: Normalized P- and S-velocity as a function of effective pressure. The data are from ultrasonic core measurements on water saturated plugs.

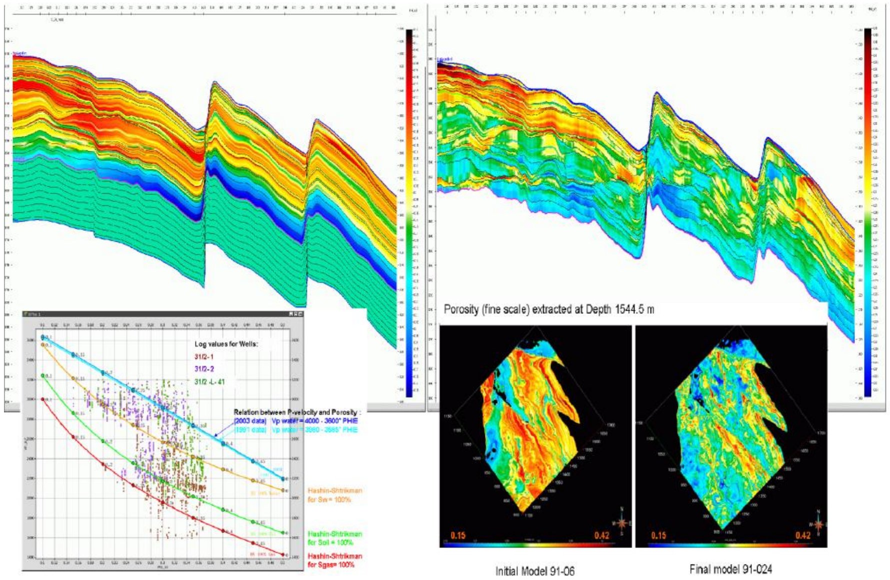

Figure 3: The input porosity and the final result of the inversion (top), the petro-elastic relation (bottom left) and maps extracted at the GOC for the input porosity and the final result of the inversion (bottom right).

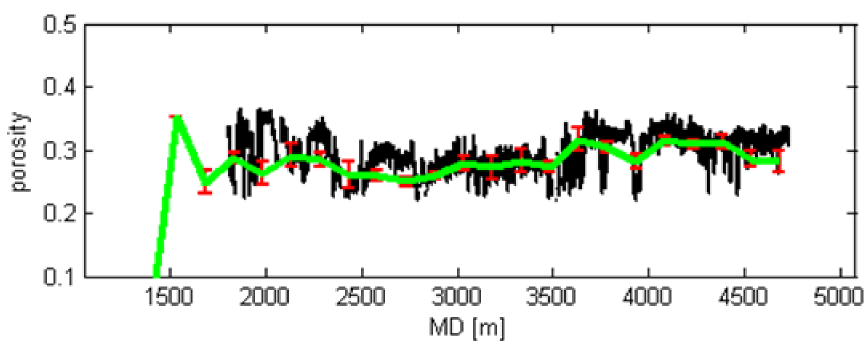

Figure 4: Measured well log porosity (from a horizontal branch in the oil leg) in black and the estimated result in green .Red is the uncertainty, as spatial standard deviation around the horizontal branch.