WS05

Probabilistic inversion into lithology and fluid classes in the North Sea – Comparison of one- and two-step approach

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Summary

Lithology and fluid prediction from seismic data is traditionally done in two steps; first an inversion of the seismic data to elastic parameters, and subsequently a prediction of lithology and fluid based on a rock physics model linking the elastic parameters to individual lithology and fluid combinations. Recently, a number of inversion algorithms have been developed that, based on Bayesian statistical methodology, estimate the probability of lithology and fluid directly from seismic data.

In this paper we compare the performance of two state-of-the-art Bayesian inversion algorithms on a real data set from the Volund field in the North Sea. The first algorithm follows the traditional two-step approach and cannot take into account the stratigraphic ordering of lithology and fluid. The second algorithm, referred to as one-step, evaluates possible lithology and fluid combinations within a vertical window around each inversion point enabling correct stratigraphic ordering.

We find that the one-step inversion resolves more details and honours the data more strongly than the two-step approach. The latter is more prone to return the prior model if information in the seismic data is not sufficiently strong. Both models detect hydrocarbon filled sand injectites that are typical for the field.

Introduction

Lithology and fluid prediction from seismic data is traditionally done in two steps; first an inversion of the seismic data to elastic parameters, and subsequently a prediction of lithology and fluid based on a rock physics model linking the inverted elastic parameters to individual lithology and fluid combinations (e.g. Buland et al., 2008; Grana and Rossa, 2010). Recently, a number of inversion algorithms (e.g. Kemper and Gunning, 2014; Kolbjørnsen et al., 2016) have been developed that, based on Bayesian statistical methodology, estimate the probability of lithology and fluid directly from the seismic data.

In this paper we consider two state-of-the-art Bayesian inversion algorithms that invert seismic data to lithology and fluid. One algorithm uses a two-step approach, the other a one-step approach. Our objective is to compare their performance on a real data set from the Volund field in the North Sea. We discuss their strengths and weaknesses and the inverted results are compared to well logs and known characteristics of the reservoir.

The Volund field consists of good reservoir sandstones that have been injected into surrounding shale, forming a characteristic sand injection complex (Schwab et al., 2015). The field has a deeper central part surrounded by shallower and steeply dipping sand dykes (i.e. injectites) that are challenging to map. The complex structure makes the field a good candidate for testing the performance of the two inversion algorithms.

The inversion algorithms

Both inversion algorithms utilize high quality pre-stacked seismic data and estimate the probability of lithology and fluid from the variation in amplitude versus offset (AVO) using a linearized weak contrast approximation of the Zoeppritz equation (Buland and Omre, 2003). The first algorithm (Buland et al., 2008) follows the traditional two-step approach, in a Bayesian framework reporting probabilities of lithology and fluid given a probabilistic prior model and the seismic data. The algorithm uses a point-wise approximation and cannot take into account the stratigraphic ordering of lithology and fluid in the vicinity of the inversion point.

The second algorithm, referred to as one-step inversion (Kolbjørnsen et al., 2016), evaluates possible lithology and fluid combinations within a vertical window (i.e. neighborhood) around each inversion point. By excluding illegal combinations (e.g. brine sand above hydrocarbon sand) the correct ordering of stratigraphy and pore fluid is ensured, and by keeping the window small the number of legal combinations and hence the computational complexity is manageable.

The Volund field

The Volund field, a tertiary deep-marine reservoir, is located in the central Viking Graben of the North Sea. It consists of injected sand dykes and sills in the surrounding shale of the Balder formation (Schwab et al., 2015). The sand is believed to originate from the deeper Hermod Sandstone formation. The sand has good reservoir properties with average porosity of about 32% and Darcy range permeability.

The seismic response of the Volund sand is “soft” meaning that the reflection at the interface between the sand and the overlying (and harder) shale causes a negative trough. For hydrocarbon filled sand the minimum of the trough decreases versus offset and is classified as a typical Class III AVO (Rutherford and Williams, 1989) with negative intercept and gradient. The AVO response is enhanced by a gas cap that is identified on top of some of the steeply-dipping oil filled sand dykes. The steeply-dipping dykes and the possibility of subseismic sand intrusions makes the field complicated to image.

The prior model

From petrophysical analysis of wells 25/9-5 and 25/9-6 at Volund we identify a set of possible lithology and fluid classes (LFCs) that are relevant for explaining the seismic reflection amplitudes. Each LFC is modelled by Gaussian distributions of P-wave velocity (Vp), S-wave velocity (Vs) velocity and density (Rho). Their mean, standard deviations, and covariance are estimated from acoustic and density logs in depth intervals defined by the petrophysical interpretation and well tops. Outliers and noise in the logged data are removed. Unfortunately, Vs was not measured in the wells and we rely on the Vp to Vs transformation that is provided in the well log data. This may lead to erroneous classification of hydrocarbons as will be shown below.

In the seismic data the top Balder surface is most often recognized as a “soft” reflection due the overlying stiffer rock of tuffeous shale followed by an interval of softer shale. The injected sand dykes sometimes penetrating the top Balder are also characterized as “soft” reflectors, but with a different AVO response (i.e. gradient). To distinguish between sand dykes and shale along the Balder surface we have in the subsequent inversions modelled a Tuff class and a Soft Balder class, representing the harder and tuffeous shale above and the softer shale just below the top Balder surface. In the well logs the tuffeous shale is identified in short depth intervals with higher acoustic impedance (AI) than surrounding shale. The identified LFCs and their elastic distributions in Vp/Vs versus AI are plotted to the left in Figure 1.

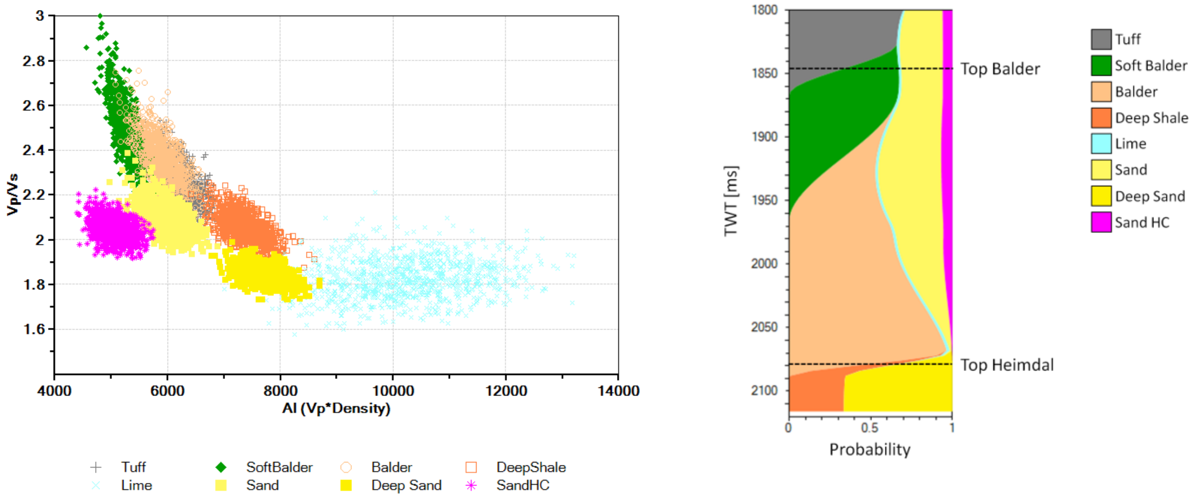

Figure 1 *Gaussian distributions of the elastic properties of the LFCs (left) and the prior probability model (right) versus depth (time) in a single trace, i.e. the prior model.*

A 3D prior model with prior probabilities of the LFCs versus depth (i.e. two-way travel time) is established based on geologic knowledge of the area and the rock volume fractions obtained from the petrophysical interpretation in wells 25/9-5 and 25/9-6. Also included is the depth uncertainty of surfaces and probabilities for transition between different LFCs within a layer. The resulting prior probability model is shown to the right in Figure 1 (in a single trace).

To model the intrusion of sand into overlaying and surrounding shale there is a fairly constant probability for encountering brine or hydrocarbon filled sand (Sand and SandHC in Figure 1) from the top of the inversion interval (1800 ms) and halfway into the Balder formation. The probability then decreases with depth. Below top Heimdal we expect a different sand (Deep Sand) and shale (Deep Shale) with higher AI in accordance with the well logs. Observed limestone stringers in Balder are made possible by means of a low prior probability for limestone (Lime). The one-step inversion algorithm can utilize prior information on layer thicknesses. This information is not utilized by the two-step approach.

Results

The left pane of Figure 2 shows maps of maximum hydrocarbon probability in the inversion area for the one- and two-step inversions. The outline of the Volund field and complex structures due to the steep dipping sand dykes surrounding the central part (well 24/9-6) is clearly visible. The one-step inversion is able to map further details and reaches high hydrocarbon probabilities in larger areas than the two-step result. Some noise and false hydrocarbon detection is visible outside the outline of the field. This is believed to be caused by incorrect Vp/Vs of the hydrocarbon filled sand, relative to the surrounding shale because of synthetic Vs data. We have also noticed that false hydrocarbon detection can occur as a result of erroneous time shifts between angle stacks causing false AVO responses.

The right pane of Figure 2 shows a comparison between well log data for well 24/9-6 and results from the inversions. The hydrocarbon layer in the well is detected by both inversions, but the full layer thickness is better reproduced by the one-step inversion. The latter also detects the limestone stringer between 1970 and 1980 ms, even though the thickness of this stringer is below the seismic tuning resolution.

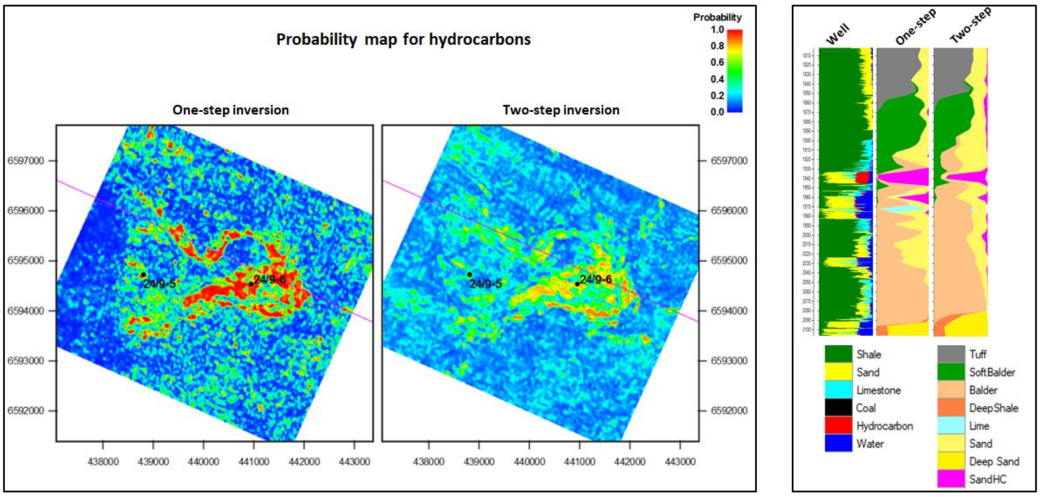

Figure 2 *Left pane: Probability map for hydrocarbons, one-step inversion (left) and two-step inversion (right).The magenta line correspond to the location of the cross section through the inversion interval in Figure 3. Right pane: LFCs from well log (left), one-step inversion (middle), and two-step inversion (right).*

The most probable LFC at each point in the cube is obtained from the posterior probability cubes for every LFC. Figure 3 shows a cross section through the most probable LFC cube along the magenta line of Figure 2 (left pane). The injected sand dyke to the right is more pronounced and penetrates the green Soft Balder layer in the one-step result, while in the two-step result the dyke seems disconnected. Also notice the thin limestone stringer (Lime) and brine filled sand layers (Sand) below the central part of the field. The brine filled sand layers are not detected by the two-step inversion.

The accumulated thickness of sand being brine or hydrocarbon filled, between top Heimdal and top Balder is illustrated in Figure 4. The one-step inversion (left) is clearly more prone than the two-step inversion (middle) to obtain results that differ significantly from the prior model (right). Also, the one-step inversion indicates less sand in the western than in the eastern part of the inverted area. This trend is not seen in the results of the two-step inversion, where the accumulated sand thickness to a larger degree follows the prior model.

Conclusions

We have compared the results of a one-step neighbourhood inversion with the results of a two-step point-wise inversion to lithology fluid classes in the Volund field in the North Sea. We find that the one-step inversion resolves more details and honours the data more strongly than the two-step approach. The latter is more prone to return the prior model if information in the seismic data is not sufficiently strong. Both models detect injectites that penetrate through top Balder, and both detect thin limestone stringers. The hydrocarbon layer thickness seen in well 24-9/6 is slightly better represented in the one-step than in the two-step approach.

We would like to express our thanks to Aker BP for providing the data and to the Volund license partners for permission to publish the results.

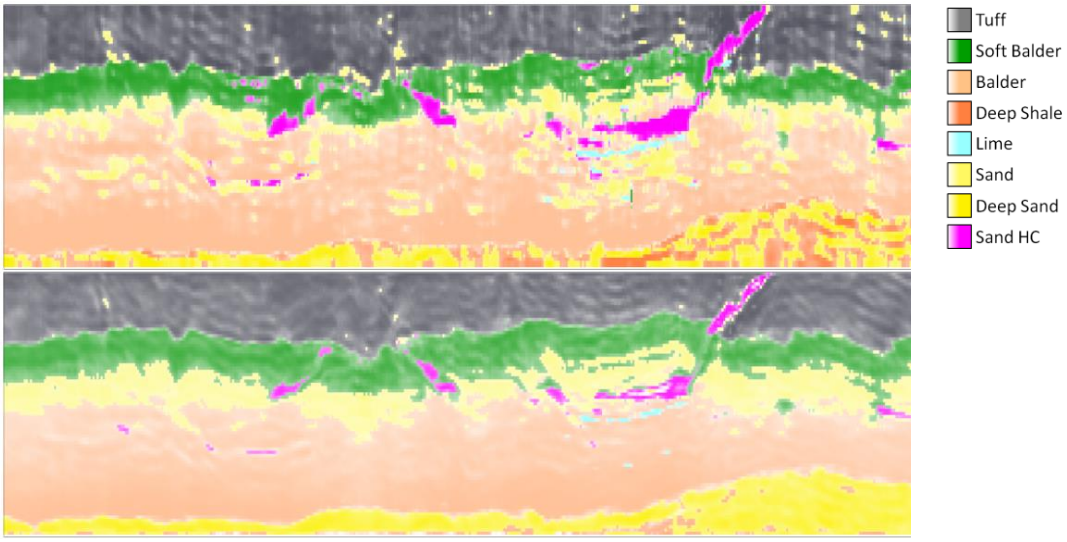

Figure 3 *Cross section along the inline direction (see Figure 2) of most probable LFC of one-step inversion (top) and two-step inversion (bottom). Intense colors are more certain.*

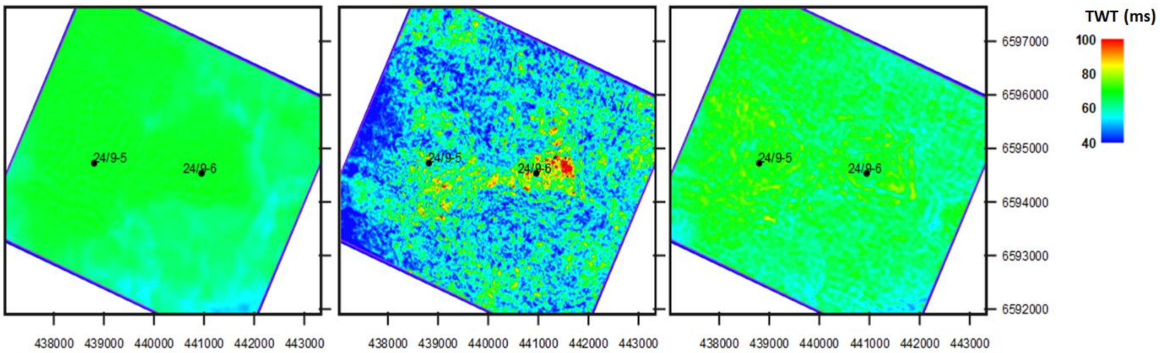

Figure 4 *Accumulated thickness of brine sand and HC sand (Sand and Sand HC) in ms (TWT) between top Balder and top Heimdal. Prior model (left), one-step inversion (middle), and two-step inversion (right). Color scale adjusted to showing the details of the one-step inversion.*

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