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Practical Multi-Parameter FWI at the South Arne Field

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Summary

The South Arne field, in the Danish North Sea, presents a velocity-model building challenge with a large gas cloud obscuring underlying chalk reservoirs in a structural anticline. In the near surface, lateral and vertical velocity (Vp) variations are significant, with a thin, shallow layer of strong anisotropy occupying an otherwise isotropic overburden. Because of the near-surface complexity, and strong attenuation in the gas cloud, the velocity model was built using multi-parameter FWI to solve for Vp, Q, and epsilon. Using surface seismic data, 3-parameter FWI is a challenging problem, and, for practical reasons, this was done with two passes of 2-parameter joint FWI: first Vp/epsilon, then Vp/Q. The inversions were run with combined OBN and towed-streamer input data, using a shot weighting strategy to balance the contributions to the FWI gradient and cost function. Results in the near surface are consistent with nearby borehole data, and produce good depth tie of imaged reflectors to lithological well tops without explicit depth calibration. The gas zone has low-Q, low-Vp pockets which, after migration, produce a seismic image with significant structural changes to chalk reservoirs below the gas when compared with an image produced from a model built mainly with reflection tomography.

Introduction

The South Arne field (Schiøtt et al., 2008) presents a difficult case for velocity-model building, with a large gas cloud obscuring underlying chalk reservoirs in a structural anticline (Figure 1). Above the gas cloud is a complex near-surface with lateral velocity (Vp) variations around 10 % and stacked vertical velocity inversions. Additionally, a thin layer of strong anisotropy occupies a near-surface interval in an overburden that is otherwise close to isotropic.

Attempts to build a velocity model in 2016 mainly used reflection tomography to construct a large central zone of low-velocity gas and a coincident zone of low attenuation quality factor (Q). The model was re-visited in 2018 with a focus on Full Waveform Inversion (FWI), seeking to improve the gas-zone architecture and achieve greater accuracy in the positioning of the top chalk reflectors.

This paper describes the methodology and results of a 3-parameter (Vp, epsilon, Q) FWI model build at South Arne. It is well known that multi-parameter FWI is a challenging problem with surface seismic data. There has been some progress with implementation of 2-parameter joint FWI for Vp and Q (Malinowski et al., 2011; Stopin et al., 2016; Xiao et al., 2018), and Vp and epsilon (Plessix and Cao, 2011; Cheng et al., 2014). For pragmatic reasons, therefore, rather than use a complete 3-parameter inversion the three model parameters at South Arne are updated with two passes of 2-parameter joint FWI: first Vp/epsilon, then Vp/Q.

The main dataset used for velocity-model building is an Ocean Bottom Node (OBN) array covering approximately 40 km^2 with full-azimuth offset > 6 km. In addition, narrow-azimuth towed streamer data with approximately 200 km^2 coverage exists over the area, providing 4.7 km maximum in-line offset. To extend the useful part of the model update outside the area of the OBN array, FWI was run with combined OBN and towed-streamer input data using a shot weighting strategy to balance their contributions to the gradient and cost function.

Method

The velocity model was initialised using guided-wave inversion (Hou et al., 2018) to define the shallowest layers. Below this a one-dimensional velocity profile was built using sonic logs from Well-2 (Figure 1), located immediately to one side of the gas cloud. The sonic logs from Well-1 (which penetrates the gas cloud) and Well-3 (on the flank of the anticline) were not used, and thus represent blind test data. The model was then updated with long-wavelength reflection tomography.

The initial anisotropy model assumed tilted transverse isotropy below 700 m, with an isotropic overburden above. In the near surface, and in contrast to the 2016 model, a one-dimensional layer of

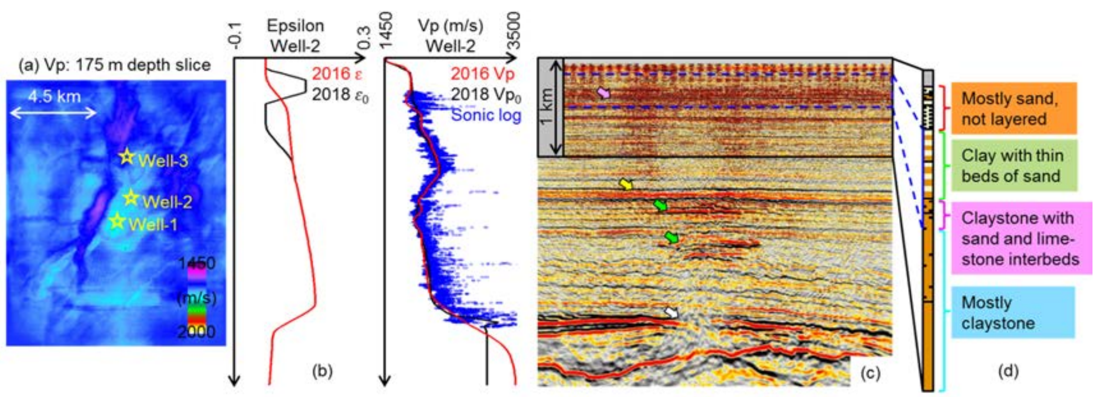

Figure 1 *(a) Location of wells relative to near-surface channel feature. (b) 2016 final tomographic model (red) with 2018 initial FWI model (black) and sonic log from Well-2 (blue). (c) The near surface (pink arrow) presents the velocity-model building crux, with gas cloud (green) below Top Lark (yellow) representing the imaging crux for underlying chalk reflectors (white). (d) A shallow layer of strong anisotropy (blue) is consistent with nearby borehole data.*

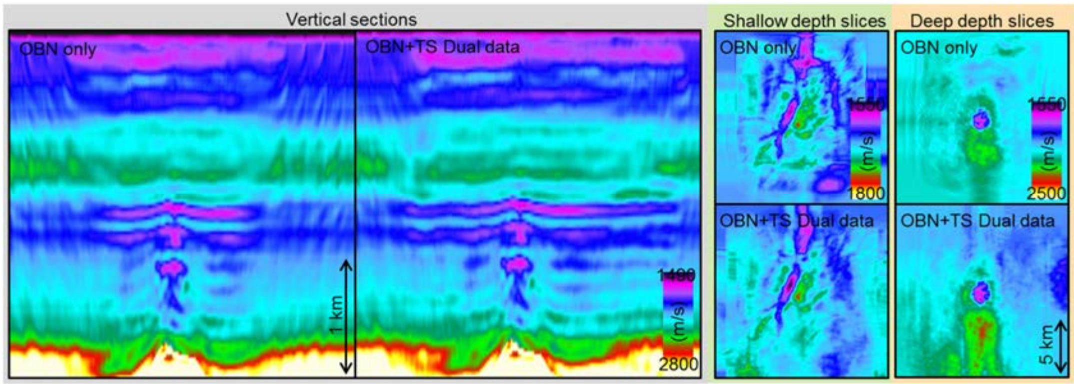

Figure 2 *Vp-only FWI tests using OBN input data, versus dual-data (OBN+towed streamer) input with the OBN weighted prior to contributing to the global gradient and cost function. Shallow (175 m) and deep (2350 m) depth slices both show the benefit of dual-data input.*

anisotropy (epsilon 12 %, delta 4.8 %) was inserted between 130 m and 480 m (Figure 1). This near-surface layer was incorporated to resolve cycle skipping of diving waves emerging around 2.5 km offset. However, the magnitude of epsilon in this shallow layer was approximate. In particular, epsilon was expected to change in a large near-surface channel feature visible in the initial Vp model produced with guided-wave inversion. This channel feature is expected to contain sediment with different properties (and different anisotropy) to the surrounding rocks.

The FWI part of the model update took place in three stages: (1) Vp/epsilon joint FWI with focus on the near surface; (2) Vp/Q joint FWI with focus on the deeper gas cloud; (3) final Vp FWI with focus on the full depth range, including chalk horizons below the gas. The FWI was run with both the OBN and Towed Streamer (TS) datasets combined (Figure 2). To achieve parity in the contributions of these datasets to the FWI gradient and cost function, the OBN residuals were weighted prior to back propagation. The dot product of residuals from each shot was then normalised by the same weight prior to contributing to the least-squares cost function.

The first attempts at Vp/epsilon joint FWI used diving waves only, but model perturbations showed the same change being introduced to the two parameters (Figure 3), suggesting strong coupling. A better separation of the Vp and epsilon perturbations was achieved by introducing reflections to the FWI in a manner inspired by Mothi and Kumar (2014) and Allemand et al. (2017). This increased the range of useable angles in the data in order to exploit the differences in Vp and epsilon radiation

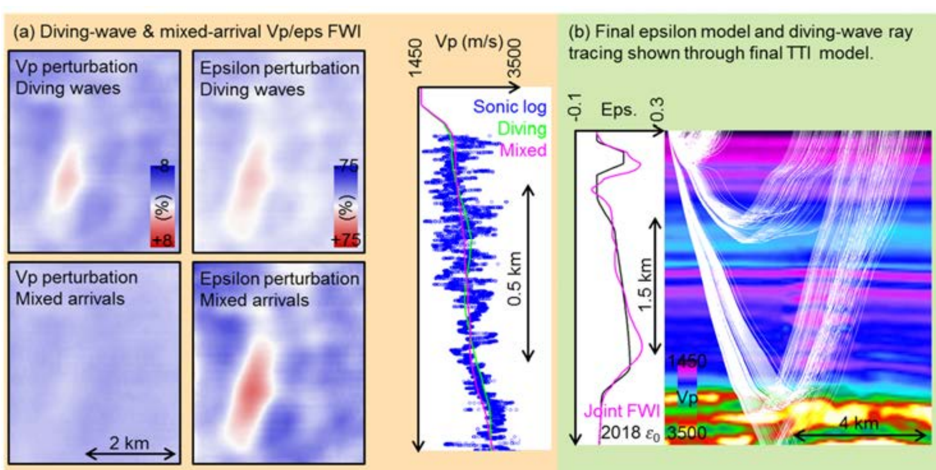

Figure 3 *(a) Depth slices, at 250 m, through perturbations from Vp/epsilon joint FWI at 4.5 Hz using diving-waves only (top row) and mixed-arrivals (bottom row). The sonic log with velocity profiles is from Well-1. (b) The final epsilon model (pink) generates a shallow waveguide trapping near-offset energy in the uppermost 500 m.*

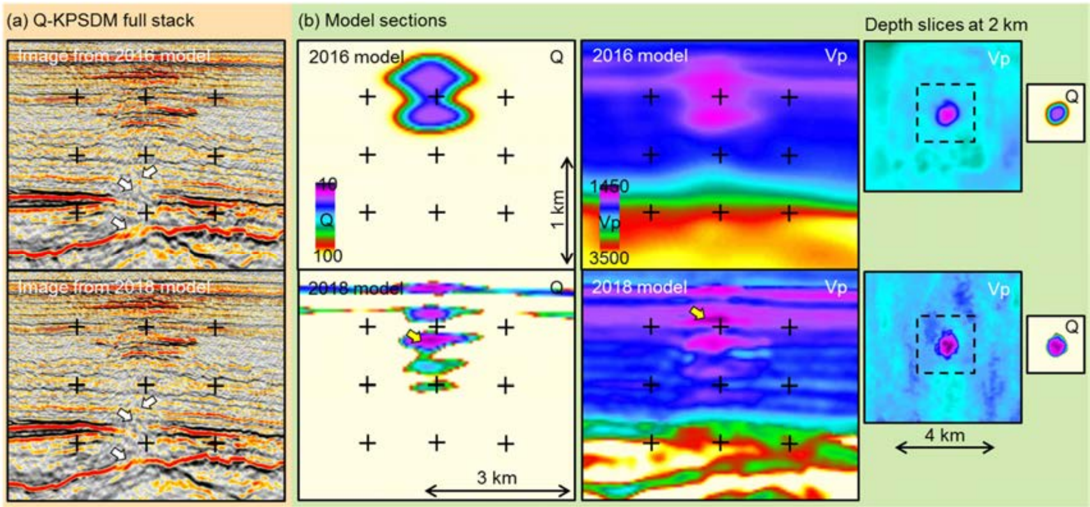

Figure 4 *Final velocity model comparison from 2016 tomographic workflow (top row) and 2018 multi-parameter FWI workflow (bottom row). Yellow arrows mark locations of minimum Q and minimum velocity in the 2018 model. White arrows highlight significant changes to imaged structure below the gas cloud. Depth slices show detail of low-Vp low-Q gas pockets.*

patterns. The model perturbations then showed lateral variation of epsilon in the near-surface channel feature without the same variation in the Vp perturbation (Figure 3). This feature was already present in the initial Vp model, so a smaller Vp response was expected. After Vp/epsilon joint FWI was run from 4.5 Hz to 6.5 Hz, pre-stack Kirchhoff depth migration positioned reflectors at the Top Lark horizon within 5 m of the corresponding lithological tops picked from well data, indicating that the joint inversion had correctly recovered the average overburden velocity.

The Vp/Q joint FWI then began with the updated epsilon model and constant Q=100. Again, both reflections and refractions were used. As the FWI progressed from 4.5 Hz to 9 Hz, it was evident that the Q parameter converged first, and that Vp and Q were sufficiently de-coupled at 9 Hz for the Vp to update without degrading the Q model. The joint inversion produced locally low Q values in small pockets within the gas cloud, with the most attenuating pockets located in a different part of the gas cloud to the lowest velocity (Figure 4). Using the updated epsilon, Q, and Vp models, a final pass of 9 Hz Vp-only FWI, honouring the other model parameters, was used to add detail to the velocity model.

Results

Migrations using the updated velocity model have several interesting features. First, the strongly anisotropic near-surface layer (peak epsilon values around 23 %) is consistent with lithological interpretation from a nearby geotechnical borehole, and has lateral variation related to a large near-surface channel. The agreement between imaged Top Lark reflector depth and the lithological top, without explicit depth calibration, indicates that the average near-surface velocity is correctly recovered from the Vp/epsilon joint FWI. After Vp/Q joint FWI, the gas cloud has local pockets with Q < 20 and Vp values 18 % slower than the surroundings. These pockets significantly affect the structural shape around top chalk after depth migration (Figure 5), reducing pull-down below the gas. These changes may alter the reservoir volume calculations and motivate a re-build of the reservoir model. The correlation of Vp with blind sonic logs in Well-1 and Well-3 is reasonable, although small differences persist. These may relate to the use of reflections, which are sensitive to density changes that may be incorrectly captured by the FWI.

Conclusions

The South Arne area presented several difficulties for velocity-model building, requiring three model parameters to be estimated by FWI: Vp, epsilon, and Q. Inversion of both OBN and towed streamer

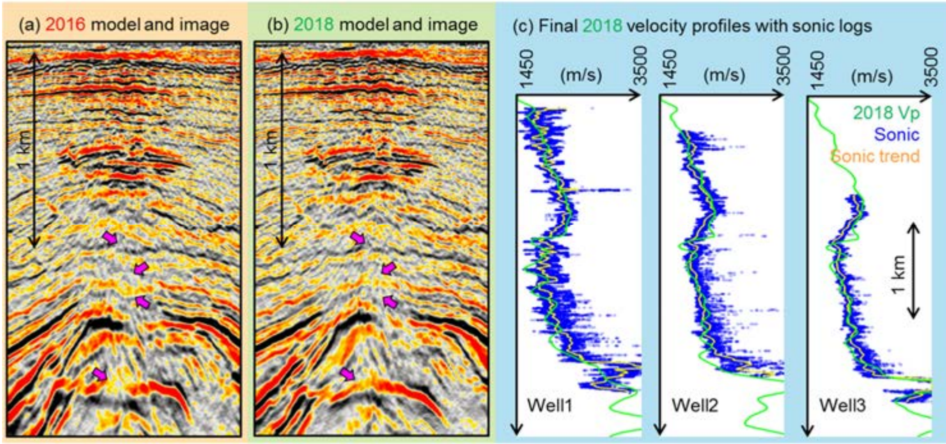

Figure 5 *OBN data after pre-stack Q-Kirchhoff migration show significant sub-gas structural improvement in the 2018 model. Pink arrows mark the structural changes of interest.*

data, using two passes of 2-parameter FWI, was able to naturally extend the model update outside the area of the OBN array and produce a model compatible with both datasets. The interpretation of chalk reservoirs below the South Arne gas cloud is improved as a result of the multi-parameter FWI, with structural changes that may affect reservoir volume calculations. The impact of parameter cross-talk between Vp and epsilon was mitigated by incorporating reflections as well as refractions to the FWI. Cross-talk between Vp and Q was mitigated by extending the bandwidth to 9 Hz, at which point the perturbations of these parameters were no longer strongly correlated for the final iterations of FWI.

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