C012 Integrating 4D seismic, geomechanics and reservoir simulation in the Valhall oil field.

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Summary
Time-lapse seismic monitoring of compacting reservoirs measures changes that occur both inside and outside of the reservoir interval. Inside the reservoir, changes in saturation, porosity, velocity, and layer thickness alter the reflection coefficients and intra-reservoir travel times that result in both amplitude and travel time changes. Outside of the reservoir, the compaction creates long-wavelength changes in the stress and strain fields that perturb the seismic velocity and produce additional changes in the seismic travel time and amplitudes from the rocks above and below the reservoir. Understanding these changes in the amplitudes and timeshifts leads to an improved understanding of the reservoir behavior and provides additional tools to better manage our fields.

In order to account for changes that occur simultaneously inside and outside the reservoir we employ an integrated workflow that combines the results of reservoir simulation and geomechanical modeling to produce time-lapse synthetic seismic that is then compared with the actual time-lapse results. Discrepancies indicate areas where we need to focus our attention and update the underlying models. We apply this workflow to the massively compacting Valhall chalk field located offshore Norway.

Time-lapse observations from Valhall
The Valhall field has produced over 500 MMSTB from the high porosity (40+) Tor and Hod chalk formations (Barkved et al, 2003). The initially overpressured chalk reservoirs compact substantially when produced leading to seafloor subsidence in excess of 5m (Patillo et al, 1998). Several seismic surveys have been acquired over this field including a 1992 streamer survey, 1997 OBC survey, 2002 repeat streamer data, and the permanent OBC surveys that began regular acquisition in 2003.

In previous work, the various vintages of Valhall seismic data have shown large 4D effects (e.g. Hall et al 2003, Lewis et al 2003, Barkved et al 2003, Barkved et al 2004, and Kommedal et al 2004). Amplitude changes due to chalk hardening and thinning are found to occur near the top/base chalk reflection events and there are large timeshifts occurring in the overburden indicating a slowdown of the velocities in the rocks overlaying the compacting reservoir.

Figure 1A shows a vertical section around the flank of the Valhall field showing timeshifts calculated using a moving gate cross-correlation window between the 1992 and 2002 streamer seismic data. (In this and subsequent figures, model predictions that are described below are displayed alongside the actual results in the B-side of these figures.) The top reservoir event occurs near 2600 ms and is shown in this figure. The timeshifts are such that the monitor survey reflection times arrive later than those of the baseline, indicating a slowdown in the overburden rocks above the compacting reservoir.

Overburden time delays reported by Guilbot and Smith (2002), Hatchell et al (2003), and Stammeijer et al (2004) for other fields are similar to those observed at Valhall. It is believed that the slowdown in the overburden is related to the stress and strain relaxation as the overburden expands slightly in response to the reservoir compaction.

Figure 2A shows the 1992-2002 shifted difference seismic that is generated after removing the cross-correlation timeshifts from the 2002 data and subtracting these from the 1992 data. Note that the timescale in this figure is zoomed in from that shown in Figure 1. The shifted difference seismic shows well-resolved changes at the top and base reservoir that result from the chalk hardening and thinning. There is little or no change in the shifted difference seismic outside of the reservoir interval.

The timeshift extracted at the top reservoir horizon is shown in Figure 3A and the RMS amplitude measured in a +/- 40 ms gate around top reservoir is shown in Figure 4A. The missing zone in the center of these maps is where the influence of the gas cloud above the Valhall reservoir is large making the data in this area less reliable.

Qualitatively the timeshift and amplitude maps convey similar information since both tend to be largest in the vicinity of producing wells. Quantitatively there are large differences between these measurements. The amplitude and timeshift responses are independent measurements made at very different frequency scales and they offer complementary information that can be used to understand the production in the field.

The timeshift map is most sensitive to the overburden stretching (and therefore the net compaction of the underlying reservoir) and is a robust measurement that can be made using large time windows. In regions close to the edge of the gas cloud, the seismic amplitudes are attenuated with the result that interpretation of the 4D amplitude changes becomes difficult. The timeshifts in these attenuated zones still appear reliable, indicating that the timeshift measurement is less susceptible to the effects of the gas cloud. The amplitude changes are also quite sensitive to the overall reservoir thickness because of tuning related effects that do not impact the large-wavelength timeshift measurement.

Forward model synthetics

The synthetic seismic is generated from a reservoir simulation model that was developed for the Valhall field. At each output time-step the pressure, pore-volume, and saturation values are calculated within the reservoir simulation. The changes in pore-volume from the simulator are used to calculate the change in reservoir thickness using the assumption of uniaxial compaction.

Inside the reservoir interval a layered model is built directly from the gridblocks of the reservoir simulation. As the pore volume changes, layer thicknesses are appropriately updated and as the porosity decreases from the compaction, the compressional and shear-wave velocities are updated based on a porosity-velocity relationship derived from well log data.

Outside of the reservoir we build a geomechanical model to calculate the changes in stress and strain fields by applying the thickness change predicted by the reservoir simulation to an elastic overburden model based on the mechanical properties described by Kristiansen (1998, 2004). Implicit in this technique is a one-way coupling between the reservoir displacements and the resulting geomechanical model. An improved model would be based on full coupling between the reservoir simulation and the geomechanical model (see, for example, Minkoff et al 2004) and this coupling will be investigated in future work.

The timeshifts that accumulate in the overburden are a combination of the changes due to displacements and velocity changes. For simplicity, we will concern ourselves with vertical raypaths. For a single thin layer of thickness, z, the change in relative seismic travel time is (Landro and Stammeijer 2004):

$$\Delta t/t = \Delta z/z - \Delta v/v, \qquad (1)$$

Where t represents the two-way travel time and v is the velocity of the layer.

The biggest uncertainty in the above relationship is how to relate the changes in the velocity to the changes in the stress and strain tensor as predicted by the geomechanical model. By comparison to measurements on reservoir rocks, measurements on non-reservoir rocks tend to be infrequent.

In the general case, the change in seismic velocity will be anisotropic (see for example Sarkar et. al. 2004; Wang, 2002), and it is of great interest to measure this anisotropy from the in-situ seismic data. If we test out some hypothetical velocity relationships such as relating velocity to the change in total vertical stress, Szz, or the net change in total pressure -(Szz + Syy + Sxx)/3, or the vertical strain Ezz, we find that each of these produces qualitatively-similar responses in the overburden. If we relate the change in velocity to vertical strain then Eq. (1) becomes very simple.

For example, if we set $\Delta v/v = -R^* Ezz$ (adopting the sign convention that positive strains are extensional and tend to decrease velocity), and noting that $Ezz = \Delta z/z$ we can then write the relative change in the seismic travel time as being proportional to the vertical strain,

$$\Delta t/t = (1+R)^*Ezz. \qquad (2)$$

The dimensionless parameter R in the above equation represents the ratio of timeshifts that result from changes in velocity to timeshifts resulting from changes in displacement. We determine R by matching observed timeshift magnitudes and find it to be approximately 5.0.

Equation 2 is a simple result. If we integrate the timeshifts predicted by the above equation from the seafloor to the top of the reservoir then we find that the predicted two-way time change is proportional to the stretching of the overburden.

Discussion

Comparisons between the real and synthetic seismic are shown in Figs. 1-4 A and B. In Fig.1, we see that the geomechanical model predicts the behavior of the timeshifts in the overburden. The timeshifts are largest close to the reservoir and decrease in a predictable manner above the reservoir. There is also a good match between the real and predicted difference-seismic shown in Fig. 2. The synthetic models accurately predict both changes in amplitude and timeshifts.

The reservoir simulation model does a good job of capturing most of changes that are observed on the 1992-2002 4D survey. Examination of figures 3 and 4 show that there is some room to improve the models. For example, in the Southern part of the field both the amplitude and timeshift changes are underestimated near some of the producing wells potentially indicating that greater compaction is occurring there. The converse is true in the North of the field where the timeshift predictions are larger than those observed indicating that the reservoir compaction in this area is less than that in the model.

This integrated modeling approach is a useful tool for understanding the production of the Valhall field. The same approach will be essential for analyzing the permanent OBC data.

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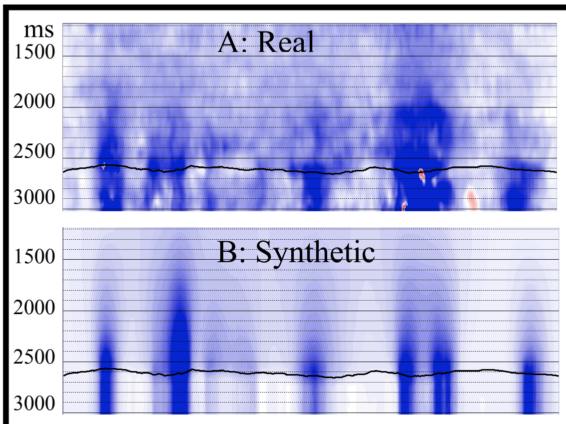

Figure 1: Cross-correlation timeshifts calculated from the real (A) and synthetic seismic data (B). Color scale to 10ms.

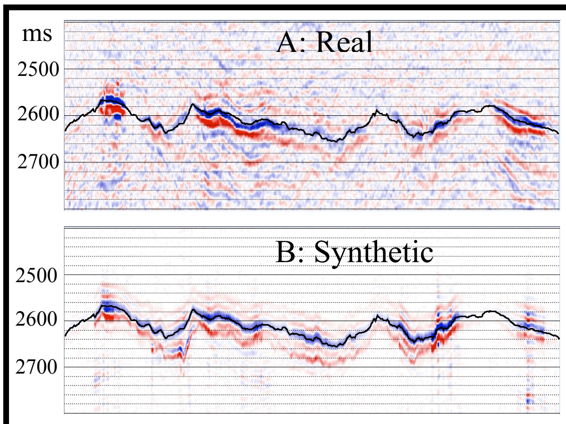

Figure 2: Difference seismic calculated from the real (A) and synthetic seismic data (B).

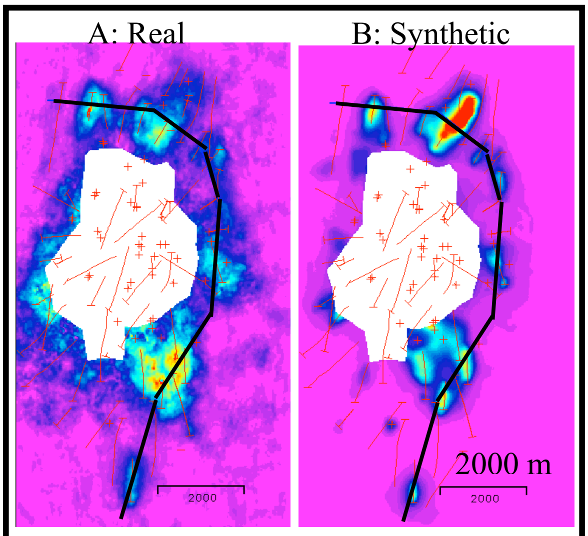

Figure 3: Top reservoir timeshifts calculated from the real (A) and synthetic seismic data (B). Timeshift color scale runs from 0 to 20 ms. The seismic traverse shown in Figs 1 and 2 is indicated by the irregular line.

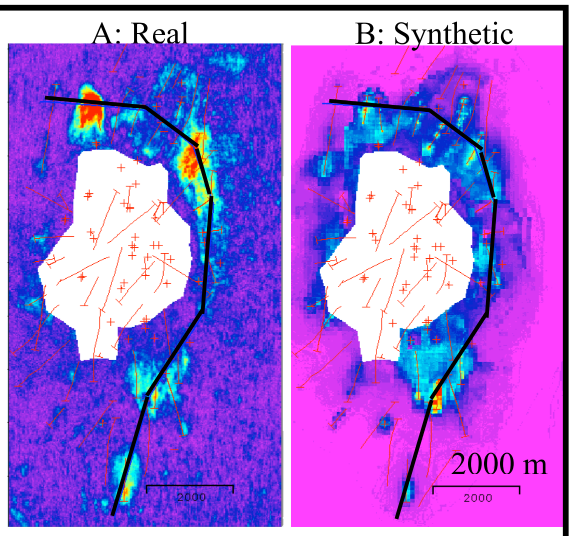

Figure 4: RMS amplitude measured at the top reservoir event from the real (A) and synthetic (B) shifted difference seismic.