Well Performance Analysis using 4D Seismic

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Introduction

Well integrity and reservoir seal integrity are critical parameters for a hazard-free and cost effective production from a hydrocarbon reservoir or injection of CO2 into a geologic formation. Still given the natural variability of geo-mechanic properties in the subsurface and limited measurements to constrain these, seal breaches and out-of-target injection around an injector well can occur. In such an adverse situation it is very important to get an overview over the affected area in the overburden, in order to know what kind of corrective measures in the production strategy have to be taken and/or in order to adapt the remaining drilling program for the field to avoid possible over-pressured zones.

In this paper we show an example where an injector well generated an over-pressured region in the overburden. Higher pore pressure in the overburden results in decreased seismic velocities and hence time-lapse seismic could be used as a potential tool to image the affected region.
We demonstrate that by estimating the apparent displacement of the seismic events and inverting these to relative changes in the velocity, we were able to image the over-pressured zone in the overburden. In particular, velocity changes less than Δv/v~1% could be detected. Such a high sensitivity can only be reached with very good repeatability of the time-lapse seismic acquisition and an efficient estimation scheme that provides good displacement estimates with adequate resolution. Hence, we look in this paper also at the relation between the signal to noise ratio, the seismic bandwidth and the uncertainty of the estimated displacements. It should be noted that all conclusions drawn on the case study are the authors opinion and do not reflect any viewpoint of the license team.

Method and Theory

It took some years since we first introduced our non-rigid matching (NRM) scheme [Nickel 1999], which in the mean time was extended from 1D to a full 3D, before its application [Nickel 2001], [Sønneland 2002] (or that of comparable approaches) got more widely accepted. Lately however, there has been renewed interest in schemes that are able to estimate the displacement or shift of observed in sets of seismic time-lapse volumes, since there has been an increased focus on geo-mechanic modeling of the stress and strain field around a reservoir [Fuck 2009], [Hatchell 2005], [Haukås 2009]. The displacement observed on the time-lapse data could obviously be used to constrain the geo-mechanic model. Yet, at least for reservoirs that do not show extreme compaction as e.g. chalk fields, modeling exercises do predict that the observed displacements will be rather small. Consequently, in order to assess whether the observations are reliable enough to be used quantitatively in an inversion scheme rather than qualitatively describing the present geo-mechanic effects, it is important to have a good understanding of the uncertainty in the observed displacement. Hence, we address this issue in the following.

Given two signals (e.g. seismic traces) that are time-shifted in between each other and subjected to additive noise. Then the variance of the estimated shift between the two signals is bounded by the following inequality [Carter 1987]:

$$\sigma^2_{\Delta T} \geq \frac{1}{T_W \int (2\pi f)^2 \frac{G_{12}(f)}{1-G_{12}(f)} df} \qquad (1)$$

with

$$G_{12}(f) = \left| \frac{\Phi_{12}(f)}{\sqrt{\Phi_{11}(f)\Phi_{22}(f)}} \right|^2$$

and

$$\Phi_{ij}(f) = F\{\varphi_{ij}(\Delta T)\}$$

the cross power spectrum of the signals $s_i(t)$ and $s_j(t)$. In the case of $s_i(t)$ and $s_j(t)$ being seismic signals, modeled as convolution of a band-limited wavelet $w_l(t)$ with the reflectivity series $r_l(t)$, l=i,j, the above formula can be rewritten as:

$$\sigma^2_{\Delta T} \geq \frac{3}{2\pi} \frac{\frac{1}{\rho^2}\left(1+\frac{1}{SNR_1}\right)\left(1+\frac{1}{SNR_2}\right)-1}{T_W\left(f_u^3 - f_l^3\right)} \qquad (2)$$

where T_w is the length of the window over which the time shift is (or can be assumed to be) constant, f_l and f_u, the lower and upper cut off frequencies of the wavelets, SNR, the average signal to noise ratio of the two observed signals over the signal band, and ρ, the correlation coefficient between the wavelets of the two signals (i.e. $\rho=1$ if towing depth, acquisition parameters such as sea state and water temperature and the processing is the same). From equation (2) we see that if the time shift is varying along the signal, the observation window over which we can assume a constant shift has to be reduced, leading to larger uncertainty in the time shift estimate. Furthermore, we see that depending on the frequency spectrum of noise, smoothing i.e. reducing fu, does not necessarily improve the reliability of the time shift estimate though the average SNR may increase.

In the numerical experiments we conducted, we managed to confirm the bound given by equation (2). Though this equation is derived for the 1D case, it gives qualitative insight for the 3D case as well. Yet to study our special 3D non rigid matching algorithm, which is not based on conventional correlation analysis using fixed windows and assuming const displacement over these, we performed the following numerical analysis. We took the observed baseline seismic of our real case example (which will be shown below) applied a realistic 3D shift to create a time lapse volume, added to both of these cubes colored Gaussian noise and then re-estimated the 3D shift using our NRM algorithm. The process was iterated for several realizations of the noise enabling us to assess the statistics of the estimation process. In Figure 1 we show the change of the average displacement error and its standard deviation in dependence of the signal to noise ratio. We observe that the estimator has a bias less than half a sample for noisy data and less than a tenth of a sample at medium and high signal to noise ratios. Furthermore, we recognize the inverse behavior of the standard deviation with the signal to noise ratio as predicted already from equation (2). We also see that the vertical shift is estimated more reliably than the inline shift, with the crossline shift being the least constraint. This is in accordance with our intuition. Finally, we see that with a good signal to noise ratio we can achieve displacement estimates with accuracies significantly below a sample. Having demonstrated the reliability of our method, we next show a real case example where the method was used to analyze the pressure induced by an out-of-target injection.

Real Case Example

The above mentioned 3D non-rigid matching scheme was applied on time-lapse seismic data over a field where the operator experienced problems with one injector well, which did not give the expected pressure support towards the producers. In Figure 2 the estimated relative change in the seismic velocity which is derived from the 3D displacement estimate is shown superimposed on the seismic section of the reservoir. A decrease in seismic velocity is colored in shades of blue indicating a pressure increase in areas around the injectors where only water is present as pore fluid. Whereas the pressure increase is restricted by the reservoir cap rock interface (H3 in Figure 2) around the injector well on the left, it is clearly seen that increased pressure is migrating into the overburden around the injector on the right. Even the horizon H1 in the overburden, which acts as a main barrier for the pressure (from a second time-lapse survey we saw that the velocity anomaly was spreading horizontally below this interface), is breached at one location (see arrow). The relative change in velocity in the faint areas is below 1%. Yet, these values are still reliable since the time-lapse data set showed very high repeatability. The signal to noise ratio estimated as the average signal energy of the baseline survey divided by the

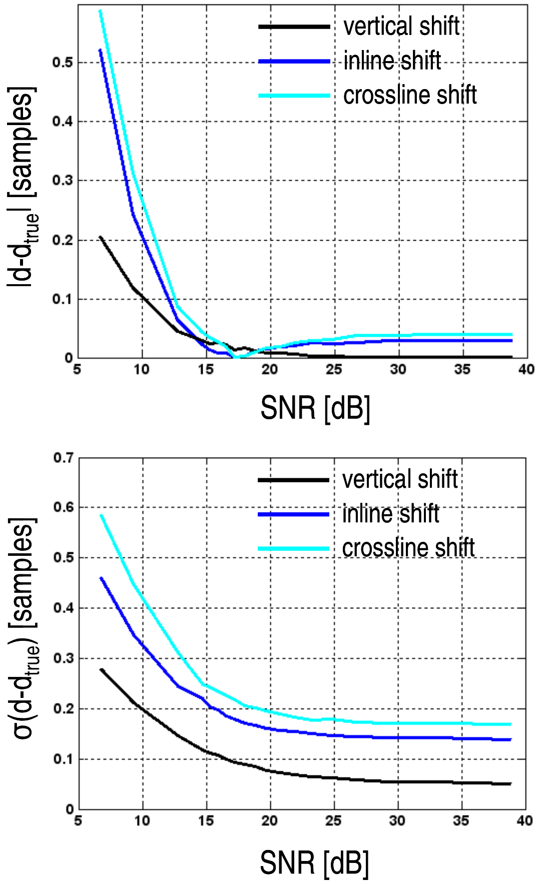

Figure 1: Dependency of the average error of the estimated 3D displacement versus the signal to noise ratio (upper) and dependency of the standard deviation of the 3D displacement error versus signal to noise ratio (lower). The signal to noise ratio characterizes the noise which is superimposed on the seismic input volumes used for displacement estimation.

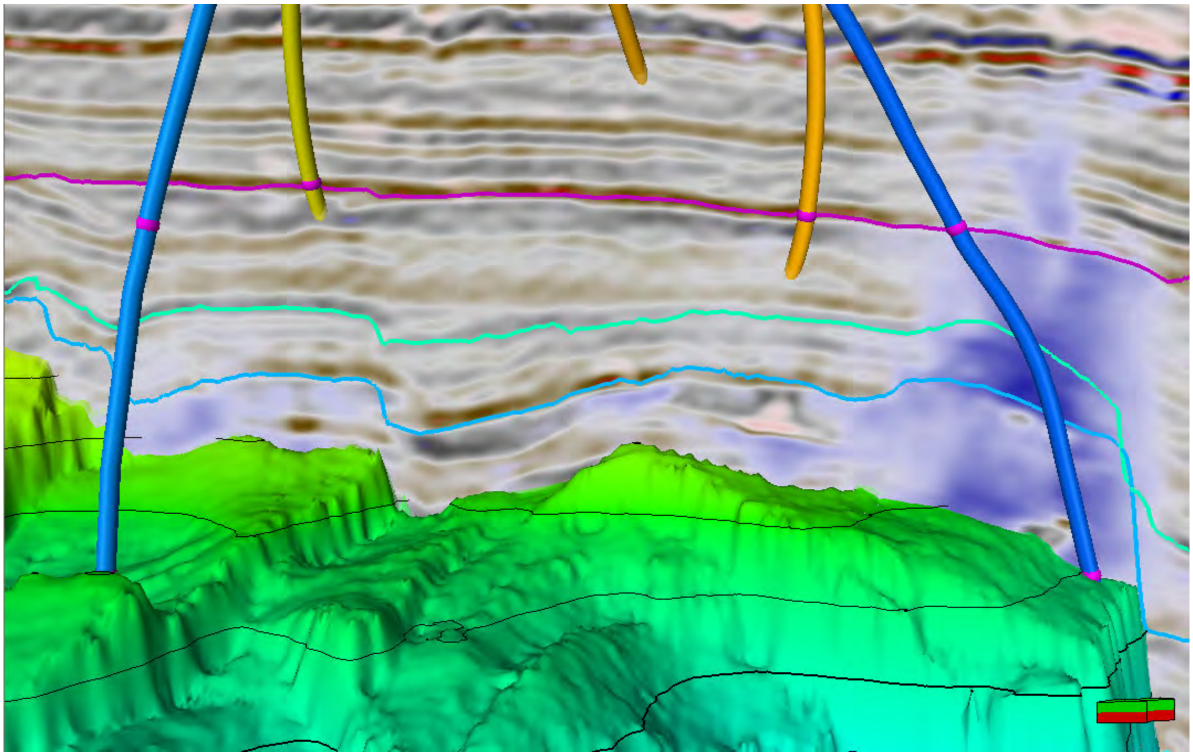

Figure 2: Seismic section at reservoir level with superposition of the estimated velocity change in scales of blue. The base reservoir horizon is shown as surface whereas other key horizons are visible on the seismic section as overlays. Injector well trajectories are blue and producers yellowish. Decreased seismic velocities (see color scale upper left) can be observed around the injector to the left spreading from the reservoir through the cyan cap rock horizon. The shallower purple horizon (H1) acts partly as barrier since the velocity cloud seems to spread below it. Yet it is also visible that the velocity decrease spreads even further up.

signal energy of the seismic difference (in areas not exhibiting production related 4D effects) was as high as SNR~20dB. Another example of the robustness of our attribute is given in Figure 3. Here, we plot the relative velocity change along a new well trajectory that was drilled after the out-of-target injection had occurred. When drilling into the formation bound by the horizon H1 an unexpected overpressure was experienced. Finally, the relative velocity change derived from the estimated displacement proved to be more robust than the amplitude difference signal as can be verified in Figure 4. We do clearly see a residual where the seismic amplitude signal is affected by the decreased velocities. Yet the border where this residual drowns into the noise floor is not as apparent and quantifiable as in Figure 2.

Conclusions

We have demonstrated that given high repeatability, as can be achieved e.g. with a permanent cable layout or a steerable streamers, subtle changes in velocities due to changes in the formation pressure rather than saturation changes become detectable. These may be used as input to geo-mechanic modeling or as an important indicators for increased pore pressure. Obviously, monitoring of pressure increases within a reservoir or saline formation is also a highly relevant tool for the case of CO2 storage.

Acknowledgments

We would like to thank StatoilHydro and the license partners ENI Norge and Petoro for providing the dataset.

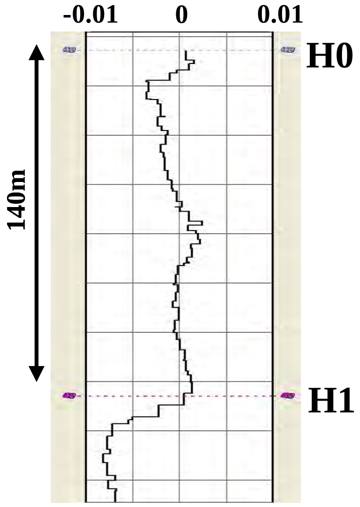

Figure 3: Relative velocity change (horizontal axis) along a new well trajectory. While the attribute response is close to zero in the overburden, it significantly decreases to Δv/v<-0.5% when entering the formation bounded by the marker of H1 indicating a higher than initial pressure.

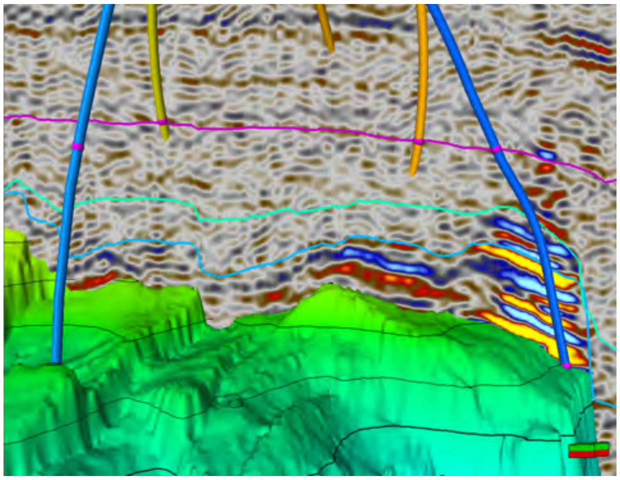

Figure 4: Seismic section of the time-lapse difference. An increased residual as a result from the decreased seismic velocity is visible as in Figure 2. Yet the extent of this anomaly is less clear and the sensitivity is inferior compared to the displacement related attribute. (The seismic color scale is amplified by a factor of 10 compared to Figure 2.)

EDITED REFERENCES

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