Integration of time-lapse seismic analysis with reservoir simulation

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Summary

Integration of dynamic and static models can provide a useful description for reservoir models. This procedure can also provide many economic benefits for reservoir management. This paper presents some of common approaches to reservoir characterization by the integration of production (engineering) and time-lapse seismic data. The different case studies reviewed in this paper show how the complete integration procedure can solve different issues in the creation of reservoir models. Minimizing the difference between the synthetic seismogram derived from a reservoir simulation and the real time-lapse seismic data is a challenging step in the integration process, but one that is well worth doing. The rock physics model is the most significant step in the tieing of the seismic and simulation data, and can be done using various approaches. In our paper, we show several of these techniques and discuss their relative merits.

Introduction

In recent years, the acquisition, processing and interpretation of 4D (time-lapse) seismic data has improved dramatically in the oil industry, and there is no doubt that the application of this technique can produce valuable information about the elastic properties and dynamic fluid properties of the reservoir. The 4D time-lapse seismic technique involves using repeated seismic surveys to image the same part of the earth's subsurface. Time-lapse seismic data can help to monitor the changes of production and Enhanced Oil Recovery (EOR) processes. The reason for this is that during reservoir production using EOR processes such as thermal recovery, the pressure and the fluid properties of the reservoir are changed and hence elastic properties such as velocity and density will also change. With correct processing, time-lapse seismic data thus have the ability to explain the variation caused by production and EOR processes in the reservoir. This has been successfully shown by many researchers, for example Lines et al. (1989) and Lumley (2001).

There is therefore a great need in the oil industry to find the optimal way in which to use time-lapse seismic data for reservoir characterization. This is due to the fact that additional information provided by time-lapse data, in addition to derived geological and reservoir information described above, can efficiently reduce the uncertainty in the final reservoir models and thus have a positive effect on the economics of reservoir development.

The way that time-lapse seismic studies are analyzed has an important effect on the results. In general, time-lapse seismic studies can be integrated both qualitatively and quantitatively with reservoir engineering studies. In qualitative analysis the normal approach is to visually interpret the time-lapse seismic results to track the anomalies. In this type of qualitative study, there is no need to perform flow simulation and the significant issue is to track the anomalies very quickly. However, in quantitative studies, there is an attempt to combine time-lapse seismic studies in a quantitative loop with reservoir simulation results.

Methodology and Discussion

The main challenge is to show how time-lapse seismic analyses may be incorporated into the reservoir characterization technique. Integration of time-lapse seismic data in the history-matching process can reduce the uncertainty found in using reservoir simulation on its own. The type of time-lapse seismic data measurement used for the property estimation has varied. Some researchers have used indirect measurements such as seismic wave velocities, or saturation and pressure changes (Landa and Horne 1997). In other works, seismic elastic parameters are used as observation data. Huang et al (1997) used time-lapse amplitude differences as input data. Dadashpour et al (2009) and Landrø (2001) used zero offset amplitude and AVO gradient differences.

The flowchart below shows the process of quantitative 4D seismic interpretation. The 4D seismic synthetic derived from the reservoir simulation and the simulator results can be taken through forward rock physics modeling to predict either acoustic impedance or seismic amplitude, and can then be compared to the time-lapse seismic results. The main advantage of the quantitative integration of the time-lapse seismic data and the reservoir simulation is to use it to improve the reservoir simulation models, and to make them more representative of the true earth, which leads to better reservoir performance prediction (Edris, 2009).

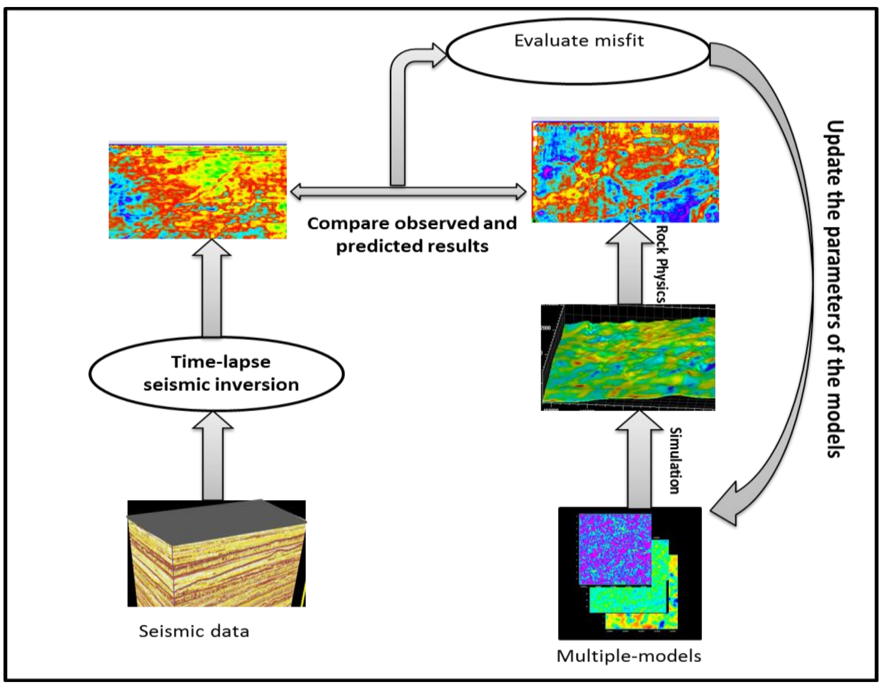

Figure 1. 4D Quantitative history matching process

As just discussed. Rock physics models are used to convert the output of the reservoir simulation to the equivalent synthetic seismic data. This is a forward seismic modeling process. The saturation/pressure changes obtained from the simulation results are converted into compressional and shear impedances at each cell. There are a number of relationships published in the literature which link the elastic properties of rocks with pressure, fluid saturation. Gassmann's equation (1951) and the Hertz Mindlin (1949) model can be used for estimating seismic parameter changes caused by fluid saturation and reservoir pressure changes, respectively. By using the Gassmann equation, the saturated bulk modulus for each lithofacies can be derived. The Gassmann equation is given by

$$K_{sat} = K_{dry} + \frac{\alpha^2}{\frac{\phi}{K_{fl}} + \frac{1-\alpha}{K_m}} \quad \text{Eq.1}$$

where

$$\alpha = 1 - \frac{K_{dry}}{K_m} \quad \text{Eq.2}$$

where ϕ is the porosity, K_m is the bulk modulus of the mineral. Here, K_{fl} is the fluid modulus and is given by the saturation weighted harmonic average of the individual phase bulk moduli:

$$\frac{1}{K_{fl}} = \frac{S_w}{K_w} + \frac{S_o}{K_o} + \frac{S_g}{K_g} \quad \text{Eq.3}$$

where S_w, S_o and S_g are the water, oil and gas saturations respectively, and K_w, K_o and K_g are the water, oil and gas moduli respectively, obtained by using the equations from Batzle and Wang (1992) and lab data for the field. K_{dry} is the bulk modulus of dry rock and the value for it is usually derived from lab data. Stephen et al. (2006) developed a technique for deriving dry bulk modulus experimentally from lab measurements. They use dry bulk modulus at standard temperature and pressure (K_{inf}), the excess compliance (E_k) and stress sensitivity (P_k) to estimate dry bulk modulus as

$$K_{dry} = \frac{K_{\inf}}{1 + E_k \exp(-P_{eff} / P_k)} \quad \text{Eq.4}$$

where P_{eff} is effective pressure. The impedance for a column of cells in the simulation model is then calculated as:

$$I = \sqrt{\langle \rho \rangle \langle \frac{1}{M} \rangle^{-1}} \quad \text{Eq.5}$$

In the equation above, ρ is the bulk density and M is P-wave moduli. The brackets < > indicate a vertical volume weighted average over the reservoir interval (Stephen et al, 2006). Figure 3 illustrates the estimated acoustic impedance which is obtained by this technique.

On the other hand, pressure and saturation can be estimated directly from time-lapse seismic data. The approach of Dadashpour et al. (2008) is based on a modified version of Hertz- Mindlin model to estimate the critical bulk and shear moduli (Eq. 6 and Eq. 7). In these equations, K_{HM} and μ_{HM} are critical bulk and shear modulus, respectively. P_{eff} , P_{ext} and P_i are effective pressure, hydrostatic pressure and initial pressure, respectively and n represents the coordination number.

$$K_{HM} = K_{ma} \sqrt[n]{P_{eff} / (P_{ext} - P_i)} \quad \text{Eq. 6}$$

$$\mu_{HM} = \mu_{ma} \sqrt[n]{P_{eff} / (P_{ext} - P_i)} \quad \text{Eq. 7}$$

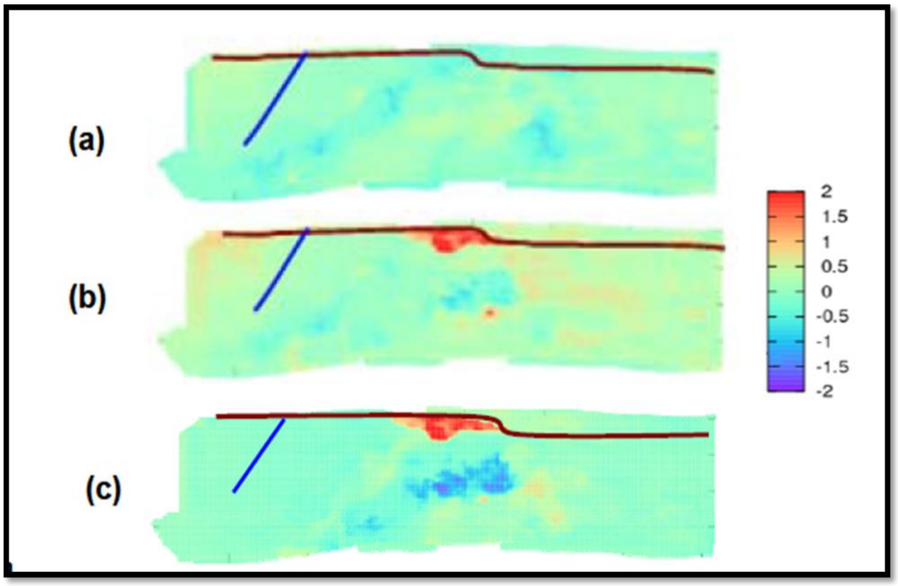

Figure 2. Estimated acoustic impedances profiles by seismic history matching for the same profile in (a) base survey, (b) monitor 1 survey, and (c) monitor 2 survey (Edris et al, 2008)

In another technique, Landrø (2001) showed that the amplitude versus offset (AVO) method and near and far offset stacks from successive seismic surveys can be used for direct estimation of saturation and pressure. By assuming the Vp/Vs ratio is equal to 2 and using empirical relationships derived from the field, he estimated the saturation (ΔS) and pressure (ΔP) changes by Eq. 8 and Eq. 9 respectively to get:

$$\Delta S \approx 8(\Delta R + \Delta G) \quad \text{Eq. 8}$$

$$\Delta P \approx 23\Delta R - 35\Delta G \quad \text{Eq. 9}$$

where ΔR and ΔG are the intercept and gradient changes. As shown in Figure 3, modified from Landrø (2001) the estimated pressure and saturation changes fit very well with the observations.

Scale Conversion

As stated in the previous section, the elastic properties can be computed from the results of flow simulation. There is a scaling problem when comparing the output of seismic results and the flow simulation. Figure 4 shows the need for upscaling and downscaling to be able to compare the results of these two datasets.

Evaluation of the Misfit

The misfit function can be defined as the difference between the results of the simulation and the time-lapse seismic. The goal in this stage is to minimize the misfit function. The quantitative loop leads to an inverse problem. As shown in Figure 1, minimizing the misfit function is an iterative process which continues until we have a small error. The next stage involves updating the reservoir model parameters is minimizing the misfit function. This continues until the misfit is at some acceptable level.

Conclusion

Time-lapse seismic data can help to reduce the uncertainty in reservoir characterization studies. Extracting important parameters such as pressure and water saturation from time-lapse seismic data and integrating these results with the reservoir simulation output is the main topic in this paper. The steps mentioned in the previous sections must be done accurately because a small error can cause a large uncertainty in the final results.

Acknowledgements

Authors would like to thank CHORUS Sponsors for their support.

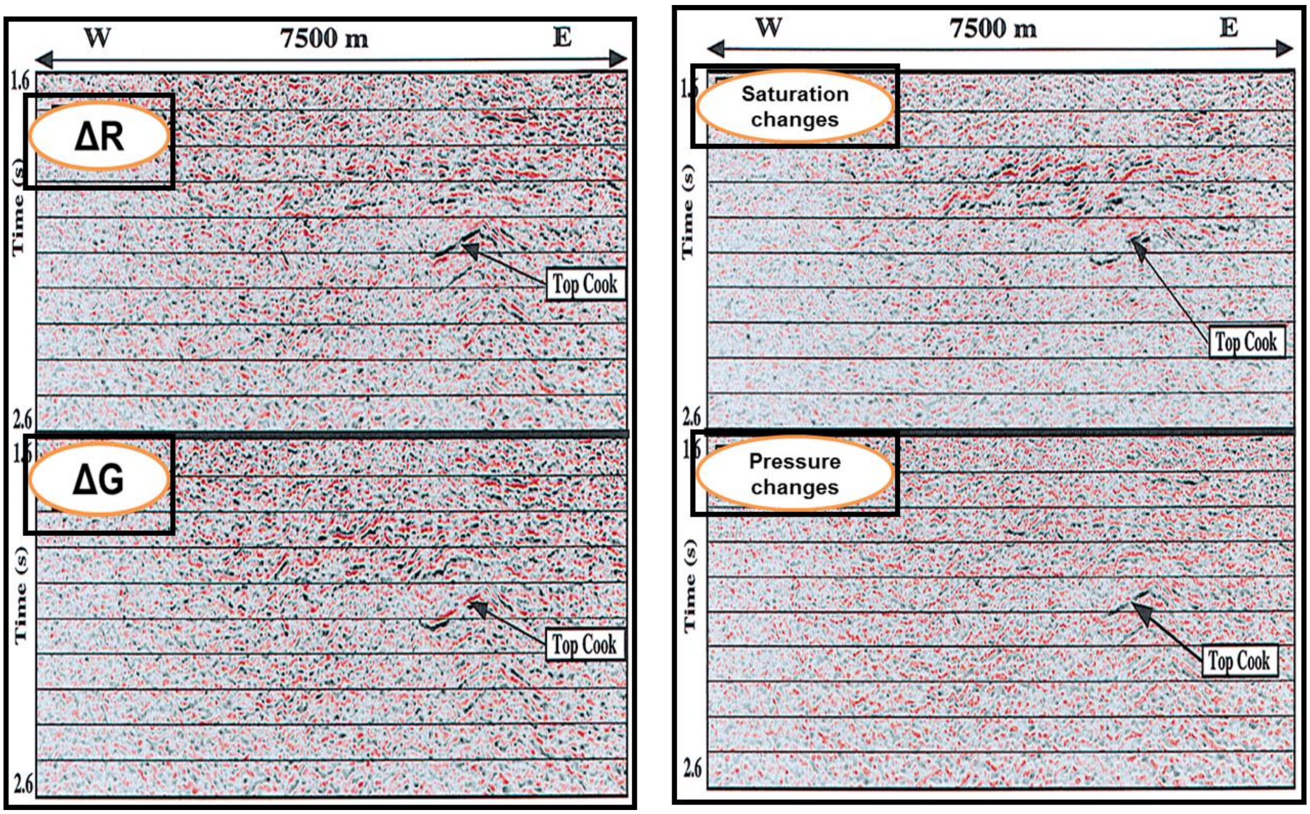

Figure 3. Left: Intercept(R) and Gradient (G) changes and Right Estimated saturation and pressure changes for the same seismic profile, Modified from Landrø (2001)

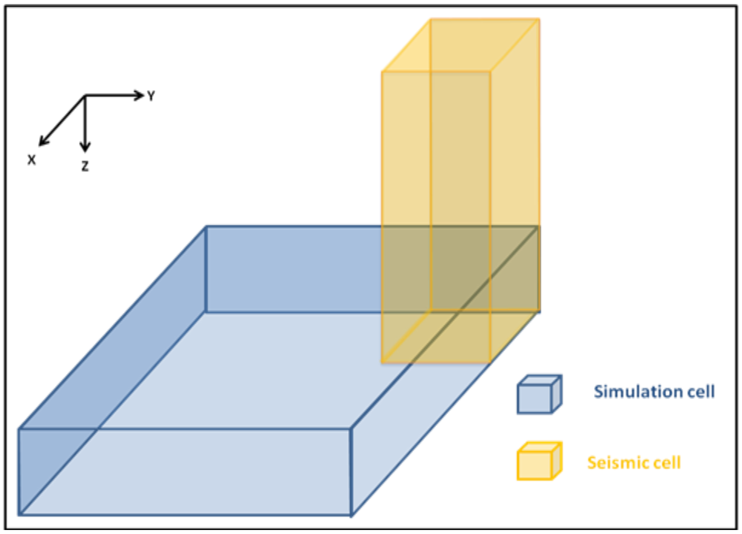

Figure 4. Different scales in seismic and simulation cell

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