Integrating reservoir flow simulation with time-lapse seismic inversion in a heavy oil case study

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Summary

The need to integrate the available resources is vital to enhance the recovery of hydrocarbon production in economical ways . Time-lapse seismic data has the potential to record the elastic changes in the reservoir during hydrocarbon production. Furthermore, reservoir simulation can provide important information on the saturation and pressure of the reservoir. Time-lapse seismic data has the ability to validate reservoir simulation results. In this paper, we will show time-lapse seismic inversion results, reservoir simulation results, and the process of simulation to seismic (Sim2Seis) approach. We will show how Sim2Seis results support the time-lapse seismic analysis in a heavy oil case study.

Introduction

Time-lapse seismic data provides important information about the reservoir during hydrocarbon production and recovery processes. One type of analysis of time-lapse data involves deriving time-shift changes between the horizons at the top and base of the reservoir between repeated surveys and mapping these time-shift changes. Since changes in the reservoir due will often affect the seismic velocity (for example, in a steam flood), the extent of the measured time shift anomalies should correlate with the area of the affected reservoir. A second method is to map the amplitude changes in the reservoir during hydrocarbon production of the reservoir. Again, these changes in amplitude should correlate with changes in the elastic properties of the reservoir during production. Both of these approches provide qualitative information about the changes in the elastic properties of the reservoir during the specific time of hydrocarbon production. However, these approaches are not adequate when we look for quantitative changes to optimize the recovery process of the reservoir. To this purpose, time-lapse seismic inversion can be performed to detemine quantitative elastic property changes, such as acoustic impedance and shear impedance changes.

Reservoir flow simulation enables engineers to predict reservoir behavior by simulating production data changes over a specific time interval for a given input model. This prediction includes the production rate as well as pressure and saturation changes in the reservoir. The hydrocarbon behavior in the reservoir is described by a phase diagram which relates the reservoir fluid state to the pressure and temperature. Depending on the reservoir conditions, different types of flow simulations can be applied. For the reservoir studied here, we applied the black oil reservoir model in the ECLIPSE software.

The simulation to seismic (Sim2Seis) process is an important step in the quantitative comparison of reservoir simulation and the time-lapse seismic inversion results. The Gassmann fluid substitutional model (Gassmann, 1951) and MacBeth sandstone stress sensitivity relationships (Macbeth 2004) were used as fundamental models in our sim2seis approach.

Methodology

Time-lapse seismic inversion

The algorithm which we used for pre-stack inversion is the simultaneous seismic inversion technique (Hampson et al, 2005). In simultaneous inversion, pre-stack seismic data are inverted to produce P-impedance, S-impedance, and density volumes simultaneously. Simultaneous seismic inversion solves the Fatti et al. (1984) equation which is a modification of the Aki-Richards equation (Aki and Richards, 1981) and is written:

$$R_{PP}(\theta) \approx a\, R_P + b\ \ R_S + c\, R_D, \qquad (1)$$

where R_P, R_S, R_D are the P-, S- and Density reflectivities, respectively. The scale values a, b, and c are:

$$a = \frac{1}{2} sec^2\theta\ , \qquad (2)$$

$$b = -4\left(\frac{V_S}{V_P}\right)^2 sin^2(\theta)\ \text{, and} \qquad (3)$$

$$c = \frac{1}{2} - 2\left(\frac{V_S}{V_P}\right)^2 sin^2(\theta)\ . \qquad (4)$$

R_P, R_S, R_D can be related back to the seismic data by:

$$S_{PP}(\theta) = aW(\theta)DL_P + bW(\theta)DL_S + cW(\theta)DL_D \qquad (5)$$

where W(θ) is the wavelet matrix which is dependent on θ (angle of incidence), D is the derivative matrix, and L is the log of the impedance values.

Reservoir flow Simulation

The basic two equations for a multiphase flow medium are mass conservation and Darcy‘s Law. By considering the presence of three phases, the conservation of mass can be expressed as:

$$S_w + S_o + S_g = 1 \qquad (6)$$

where S_w,S_o,and S_g are saturation percentages (expressed in decimal value) of the water, oil, and gas phases, respectively. If we assume there is no mass transfer between phases, mass is conserved within each phase, leading to the following partial differential equation:

$$\frac{\partial(\emptyset\rho_\alpha S_\alpha)}{\partial t} = -\nabla.(\rho_\alpha U_\alpha) + q_\alpha \qquad (7)$$

Each phase (α) has its own density (ρ_α) , mass flow rate (q_α), and Darcy’s velocity (U_α), where ∅ is the porosity of the porous medium.

In this case study, the ECLIPSE black oil model simulator was used. The black oil model simulator is a set of partial differential equations that estimates derivatives in both space and time by applying the finite difference method (Trangenstein and Bell, 1989). The ECLIPSE black oil model is fully implicit and considers three phases and components of water, oil, and gas through a porous medium. Building different geological models, including porosity, permeability, and saturation models are the inputs of the black-oil model simulator. All of these geological models were derived by using geostatistical methods such as sequential Gaussian simulation method.

Sim2Seis process

The Sim2Seis process converts the simulation results to seismic attribute results. By applying the Gassmann equation, we derived the saturated bulk modulus changes due to the pressure and saturation changes. The Gassmann equation is given by:

$$K_{sat} = K_{dry} + \frac{\left(1 - \frac{K_{dry}}{K_m}\right)^2}{\frac{\emptyset}{K_{fl}} + \frac{1-\emptyset}{K_m} - \frac{K_{dry}}{K_m^2}} \tag{8}$$

where $\emptyset$ is the porosity, K_{dry} is the bulk modulus of the dry porous frame of the rock, K_{fl} is the bulk modulus of the fluid and K_m is the bulk modulus of the mineral.

To model the variation of dry bulk modulus with pressure, the MacBeth (2004) relationships were used to convert pressure and saturation changes to seismic attribute volumes. MacBeth introduced several semi-empirical relationships to parameterize the overall behavior of the bulk modulus and shear modulus. The bulk modulus and shear modulus can be derived as below (MacBeth, 2004):

$$K(P) = \frac{K_\infty}{1 + K_\infty Z_N(P)} \tag{9}$$

and

$$\mu(P) = \frac{\mu_\infty}{1 + \mu_\infty (4Z_N(P) + 6Z_T(P))/15} \tag{10}$$

where P is confining pressure, and K_∞ and μ_∞ are the background high pressure bulk modulus and shear modulus, respectively. Z_N and Z_T are total normal and tangential compliances is given to the rock mass, respectively. These relationships are valid for both the consolidated and unconsolidated sandstones.

Results and Discussions

As mentioned earlier, pre-stack time-lapse seismic inversion was used to produces acoustic impedance, shear impedance, and density volumes in both base and monitor seismic surveys. Figure 1 shows normalized RMS (NRMS) maps of the acoustic Impedance and shear impedance in the reservoir zones.

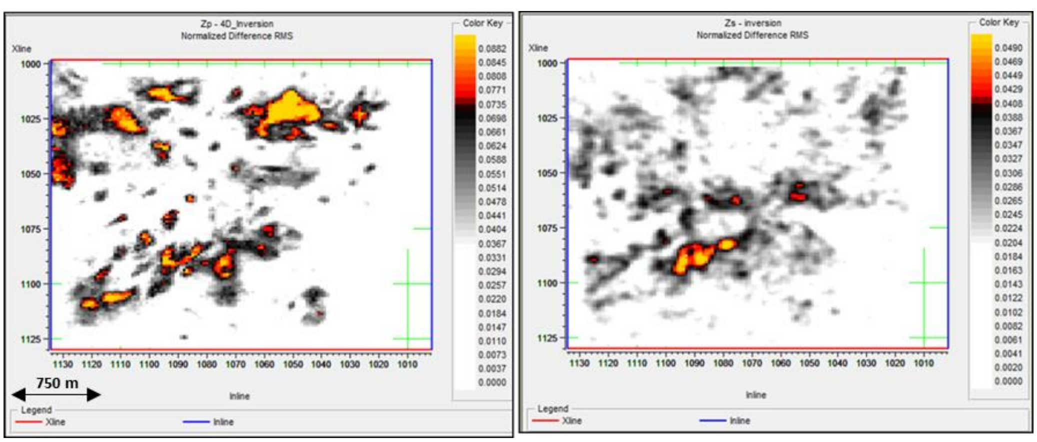

Figure 1. NRMS maps of acoustic impedance (left), and shear impedance (right) in the reservoir zone; average NRMS values for acoustic impedance and shear impedance in anomalous zones are 8% and 5%, respectively.

The Sim2Seis process was applied after extracting different saturation and pressure changes in different time steps including the base and monitor seismic acquisitions times. A Matlab program was written to derive bulk and shear modulus from the reservoir flow simulation results by considering the procedure explained earlier. Figure 2 shows the result of acoustic impedance map taken from Sim2Seis process at the monitor seismic survey time.

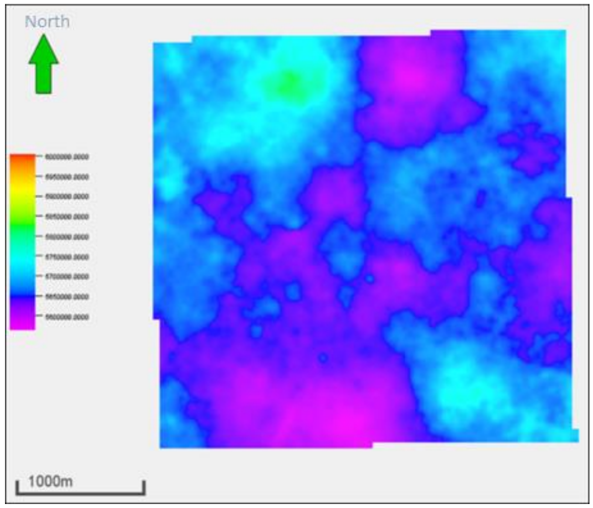

Figure 2. Acoustic impedance map taken from Sim2Seis process at the monitor seismic survey time.

We reached a good agreement between the results when comparing the Sim2Seis results with the time-lapse seismic inversion outputs. Although the history matching result was very good, we needed to update the geological models in the zones with low agreement between the time-lapse seismic and Sim2Seis results to reduce the observed differences. In the areas which have high agreement in results, important zones for hydrocarbon production were identified. The location of infill wells was possible by analyzing all these results.

Conclusions

The Sim2seis process was applied to reservoir simulation results to convert pressure and saturation results to acoustic impedance and shear impedance. MacBeth's (2004) method was used to derive the dry bulk modulus changes which were the result of pressure change. This could be done because unconsolidated sands have a higher stress sensitivity to dry bulk modulus and thus understanding the behavior of the bulk modulus helped us to derive the correct elastic parameters. These elastic parameters were then correlated with the time-lapse seismic results. The results of applying the Sim2Seis process on the reservoir simulation results correlated well with the time-lapse seismic results and showed us that the results of the reservoir simulation applied in this case study are reliable.

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