Integration of reservoir simulation with time-lapse seismic modeling

Ying Zou, Laurence R. Bentley and Laurence R. Lines, University of Calgary, Calgary

2004 CSEG National Convention

Abstract

Time-lapse seismic modeling was conducted for the Pikes Peak heavy oil field using the results from a reservoir simulation model. Cyclical steam stimulation (CSS) started in 1981 and continues to the present. A flow simulation model was constructed for the region around a seismic profile that was conducted in 1991 and repeated in 2000. The simulator was run from the start of production in 1981 through 2000. The porosity, saturation, pressure and temperature were extracted from the reservoir zone from the flow simulator for the early-production condition in 1991 and almost 10 years later in 2000. The seismic response of the reservoir was computed using a fluid substitution procedure and seismic forward modeling. Comparing the results of 1991 and 2000 indicated that the gas saturation changes caused the largest change in the simulated seismic response. Seismic difference sections showed that thick zones of gas saturation caused more time delay in reflection by lower velocity within the reservoir zone. Thin zones of gas caused reflection amplitude differences, but not much time delay differences. Temperature and pressure were also correlated with seismic changes, but not as quantitively as the gas saturation. The simulated seismic response difference section was compared to the measured seismic response difference section, and the two difference sections are very close in characteristics although the reservoir simulation model could be adjusted in future to make the match even better.

Introduction

Knowledge of the spatial variation of reservoir parameters such as porosity, pore-fluid content, permeability, pressure, and temperature are critical in order to accurately evaluating the total volume of recoverable hydrocarbon reserves in place and to predict fluid flow in the reservoir. Reservoir simulation is often used to help understand the changes in reservoir conditions with the stages of production. Reservoir simulation is based on models that are created from well information, seismic data and geologic maps. The results around wells are controlled by engineering data, but the results between or beyond wells cannot be verified by engineering data. Seismic surveys can be used to interpolate or extrapolate reservoir information between or beyond wells. Through rock physics equations, seismic properties such as velocity and density can be estimated from the output of reservoir simulation for seismic modeling. Synthetic seismic sections can be created and compared with the sections of field seismic surveys. By analyzing the differences between the synthetic seismic section based on the reservoir simulation and the real seismic sections, we can update the reservoir model and locate the remaining oil and trace steam fronts. There is a recognized need to combine the skills of geoscientists and engineers to build optimized reservoir models that incorporate all available engineering, geological and geophysical data. There are some early research works that construct seismic models using reservoir simulation output (Lumley, 1995) for primary depletion. There are also some published seismic modeling works and simplified reservoir simulation works on steam based recovery reservoirs (Jenkins et al, 1997, Eastwood et al, 1994, Biondi et al, 1998). These is only one published example which deals with Cyclic Steam Stimulation (CSS)(Eastwood et al, 1994) but the reservoir simulation was not carried to seismic modeling stage.

This work focuses on the conversion of reservoir simulations to synthetic seismic sections for the Pikes Peak heavy oil field and it is a part of an ongoing combined study of seismic survey analysis, reservoir simulation and seismic modeling. With PVT data, permeability, porosity and production history data from Husky, we undertook history matching for the partial reservoir that encompasses 140 meters on either side of two time-lapse seismic lines in the Pikes Peak heavy oil field. We have previously designed a procedure (Zou and Bentley, 2003) to calculate velocity and density from the temperature, pressures and saturation distributions resulted from reservoir simulations based on several empirical relations (Batzle and Wang, 1992). For two producing stages at 1991 and 2000, synthetic seismic sections were created. The simulated reservoir changes after 10 years of production cause significant changes in the synthetic seismic difference section which is the 2000 synthetic seismic section minus the 1991 synthetic seismic section. This synthetic difference section was compared with processed seismic survey difference section and a discussion will be given for the matching results.

Geology, Geophysical and engineering background

Pikes Peak Field is located 40 km east of the Alberta-Saskatchewan border. The producing reservoir is in the Lower Cretaceous Waseca Formation. It is about 500 meters below the surface. The reservoir's porosity is around 0.32~0.36 with 80% heavy oil saturation. The Waseca production zone has been divided into a homogeneous, well-sorted, predominantly quartz lower unit, and a sand-shale interbeded upper unit (Sheppard et al, 1998, Miller and Given, 1989). Steam drive technology has been applied to enhance recovery by reducing the effective viscosity of the oil. A successful Cyclic Steam Stimulation (CSS) started at Pikes Peak in 1981. In the eastern part of the reservoir, CSS has been in operation from 1983 until the present. Husky Oil acquired a set of 2D swath lines in the north-south direction in 1991. To investigate time-lapse effects, the University of Calgary and Husky acquired a repeat line on the eastern side of the field in 2000. Table 1 contains the basic reservoir properties and Figure 1 shows typical logs from well 1A15-6 (X6i in Figure 2).

Table 1. Pikes Peak Waseca Channel homogeneous unit reservoir properties

Depth	500 m
Initial temperature	18 ^{o}C
Initial pressure	3350 KPa
Net pay (including lower interbed)	5.7 – 27.5 m
Air permeability	4500-10,000 md
Porosity	0.32 – 0.36
Water saturation	0.08 – 0.22
Oil density	985kg/m^3
Dead oil viscosity	25,000 mPa.s
Oil formation volume factor	1.025 m^3/m^3
Initial GOR	14.5 m^3/m^3
Oil Saturation	0.80 – 0.90

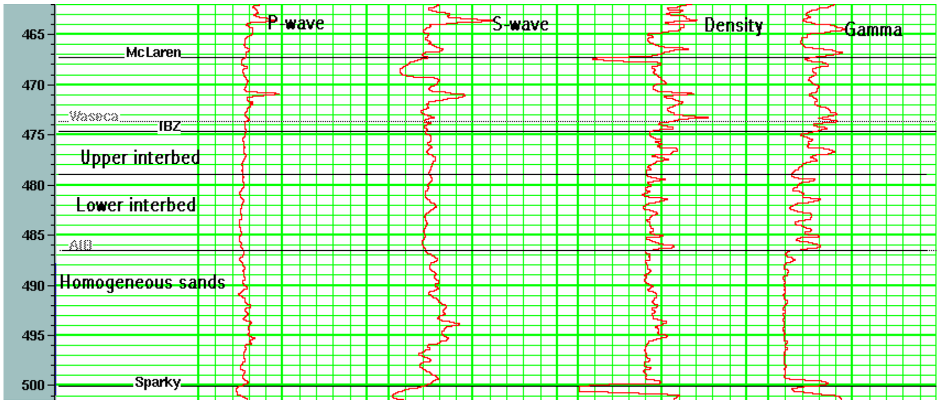

FIG. 1. P-wave, S-wave, density, and gamma logs from well 1A15.

Reservoir simulation

The reservoir model for the present reservoir simulation was built by Husky Oil. The reservoir grid geometry, well locations, and time-lapse seismic line location are shown in Figure 2. The seismic lines are in the middle of the reservoir in north-south direction. The 1991 and 2000 surveys are separated by 5 m. The grid dimension is 20 X 20m horizontally. There are three vertical layers with varying thickness. To date we have considered the three layers as having individually uniform but distinctive properties that correspond to two upper shale and sand interbeded layers and lower homogenous sand layers.

CSS started in the southern part of the reservoir in 1983 at well 1D2-6. Average steam injection duration was 10 to 30 days followed by 5 to 10 months of soak and production. The reservoir simulation is based on the injection and production history from Jan. 1981 to Aug. 2003. Temperature increase represents steam progress. The temperature front moves about 5 m to 8 m per year. It spreads faster in the north-south direction than in the east-west direction. Pressure spreads much quick than temperature. The resulted distributions of pressure, temperature and gas saturation on the 2D profile where seismic line located will be shown with the resulted synthetic seismic difference section in the Discussion and Conclusions.

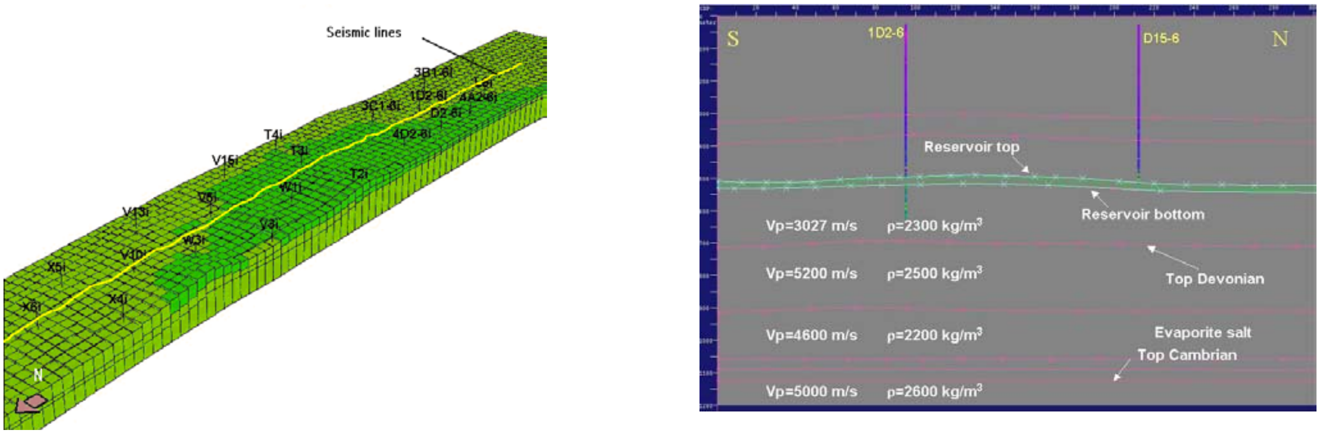

FIG. 2. Reservoir model geometry and time-lapse seismic line location (yellow line) on the left, seismic model on the right.

Synthetic seismic section

Since the time-lapse seismic surveys were in Feb. 1991 and March 2000, we did seismic modeling for these two time steps. Using the procedure described in previous seismic modeling work (Zou et al, 2003), we constructed velocity and density model using well logs for regions above the reservoir and calculated the velocity and density within the reservoir using reservoir simulation. Since there is no well that reached the Devonian, we borrowed average values for the deeper formation from well logs 8 km away from the seismic line. The seismic modeling was performed using point sources and shot gathers for better simulation results. The source is 60 Hz zero-phase Ricker wavelet. NMO stack and post stack migration were carried out after shot gather generation. Usually the reservoir simulation mesh is different than the seismic grid, and an interpolation is applied to reservoir simulation output to make the seismic model compatible with the seismic survey.

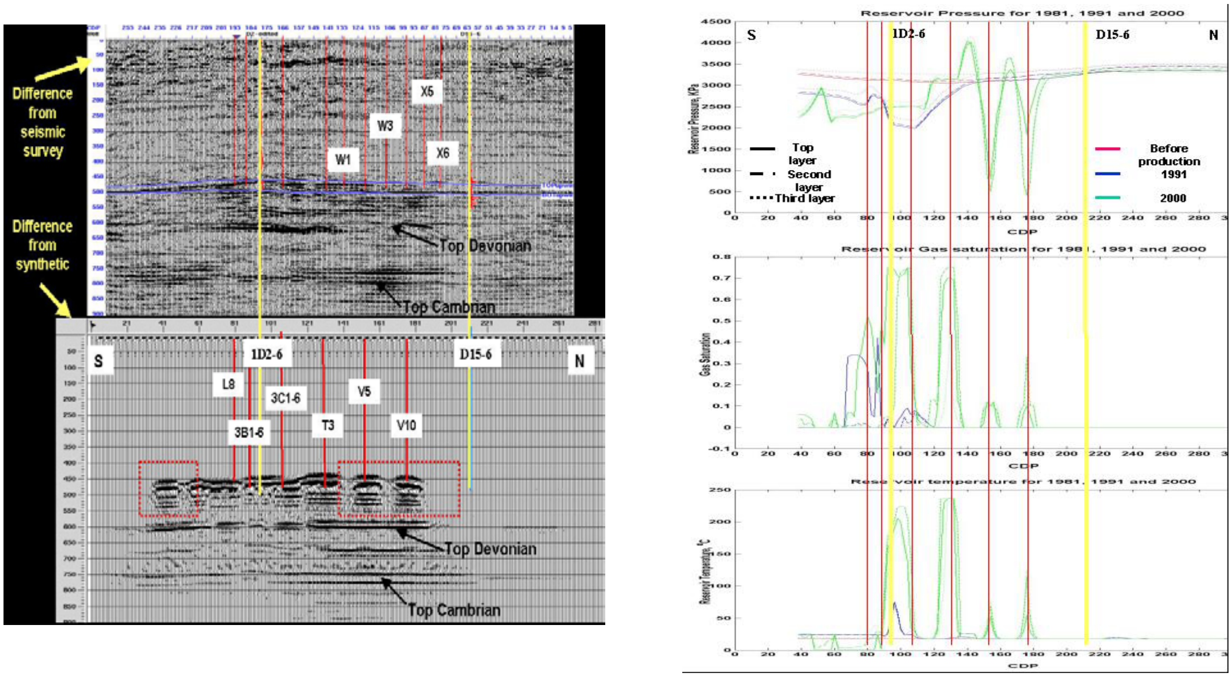

FIG. 3. Left is the synthetic seismic difference section (bottom) comparing to the seismic survey difference section (top). Right is the reservoir pressure (top), gas saturation (middle) and temperature (bottom) on the seismic profile from reservoir simulation.

Discussion and conclusions

Figure 3 left is the synthetic difference section (bottom) between the 2000 and 1991 synthetic seismic sections and seismic survey difference section (top). The overall matching between seismic survey difference section and synthetic seismic section is very good. The seismic difference banding effects are in both synthetic difference and seismic survey difference sections around CSS wells. The large difference energy between well V5 and V10 around Cambrian top appears on both difference sections. We believe that the broken energy on seismic survey difference section around Devonian Top is due to seismic survey or processing error. The simulated reservoir pressure, gas saturation and temperature distributions are plotted in Figure 3 right for three reservoir layers at 1981, 1991 and 2000 time steps. Gas saturation in 1981 is zero. The gas saturation here is for a gas phase and is constituted of different components such as water vapor and methane. The marked wells are those within 60 m around seismic lines.

According to the history data, well 1D2-6 and 3B1-6 have been in CSS operation since 1983, well L8 was in CSS operation started in 1983 and end in 1997. L8 and 1D2-6 were shut in from 1988 to 1992, therefore in 1991 the reservoir in this part was heated up some but not in high temperature. Wells 3C1-6, T3, V5 and V10 are in CSS since 1992, 1995, 1996 and 1997 respectively. The large seismic difference energy appears around the area with these active wells since they were not active in 1991. The W wells started CSS in late 1999, therefore have no impact on the seismic change. We can see that the temperature change between 1991 and 2000 on the left side of well 1D2-6 is not much (the small decrease is numerical error). We also found that gas saturation corresponding to pressure decrease even with low temperature (CDP 40 to 80), and the difference energy is visible around 600 ms and 750 ms at CDP locations100 to 200 but is restricted to the top of the reservoir at other CDP locations (CDP 40 to 80).

Comparing the saturation, temperature, and pressure results from the reservoir simulation (Figure 3, right), we derived the following conclusions: 1) The areas with a gas saturation difference between two compared time steps have seismic differences, because the presence of gas reduces the bulk modulus and bulk density of the saturated rock (Domenico, 1974). 2) Thicker gas zones correspond with larger traveltime delays in the seismic section. The thin gas zones only induce large reflectivity, and do not have enough time delay to have strong seismic difference in the deeper regions below the reservoir zone (CDP 40 to 80 on synthetic seismic difference section). 3) High temperature regions also correlate with areas having seismic energy differences but the correlation is not as strong as the correlation with the gas saturation differences. 4) Pressure spreads very quickly and its value depends on whether the location is in the injection or production stage. The pressure dependence of the seismic data is due to its influences on gas saturation.

Future work

The pressure induced changes may be significant because the sands are unconsolidated and are at moderate confining stresses. We will consider dry bulk moduli change with effective pressure in future work. Although the matching between the synthetic seismic difference and seismic survey difference is very good, there are two areas (dashed red box in Figure 3 bottom) for which the mismatch is large. The next step is to upgrade the reservoir model for the two mismatch areas, and rerun reservoir simulation.

Acknowledgements

We want to thank CREWES sponsors for their constant support. A special thank to Husky for contribute their data to us. We really appreciate the input from Larry Mewhort and Don Anderson at Husky. We also want to thank Dennis Coombe and Peter Ho at CMG for their help on reservoir simulation.

References

Batzle, M. and Wang, Z., 1992, Seismic properties of pore fluids, Geophysics, **57**, No. 11, 1396-1408.

Biondi, B., Mavko, G., Mukerji,T., Rickett, J., Lumley, D., Deutsch, C., Gundeso, R. and Thiele, M., 1998, Reservoir Monitoring: A Multidisciplinary feasibility study, The Leading Edge, **17**, No. 10, 1404-1414.

Domenico, S. N., 1974, Effect of water saturation on seismic reflectivity of sand reservoirs encased in shale, Geophysics, **39**, No. 6, 759-770.

Eastwood, J., Lebel, P, Dilay, A., and Blakeslee, S., 1994, Seismic monitoring of steam-based recovery of bitumen, The Leading Edge, **13**, No. 4, 242-251.

Jenkins, S., D., Waite, M., W., and Bee, M., F., 1997, Time-lapse monitoring of the Duri steamflood: A pilot and case study, The Leading Edge, **16**, No. 9, 1267-1273.

Lumley, D. E., 1995, Seismic Time-lapse monitoring of subsurface fluid flow, Ph.D. thesis, Stanford Exploration Project, Stanford University.

Miller, K. A. and Given, R. M., 1989, Evaluation and application of Pikes Peak cyclic steam injection pressure data, JCPT, **28**, No. 1, 26-32.

Sheppard, G.L., Wong F.Y., and Love D., 1998, Husky's success at the Pikes Peak thermal project, UNITAR Conference, Beijing, China.

Zou, Y. and Bentley, L. R., 2003, Time–lapse well log analysis, fluid substitution, and AVO, The Leading Edge, **22**, No. 6, 550-554

Zou, Y., Bentley, L. R. and Lines, L. R., 2003, Seismic modeling for a heavy oil reservoir time-lapse study, SEG Convention, Dallas