Time-lapse seismic modelling for Pikes Peak field

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ABSTRACT

Predicting changes in seismic response within thermally produced reservoirs provides an important tool for time-lapse seismic survey interpretation. As a step towards linking thermal reservoir simulators to synthetic seismogram generation, we have studied the effects of substitution of thermal fluids in a synthetic reservoir that is based on the Pikes Peak field. We used the Gassmann equation and the fluid property relations of Batzel and Wang to predict the effects of fluid substitution. Fluid substitution was used to investigate the changes in seismic response at the Pikes Peak field. The predicted velocity decrease due to the steam injection process is 17 percent and is similar to the lab test results. The synthetic seismic time-lapse analysis gives similar results to the time-lapse analysis for the real seismic survey. The difference section shows a significant difference within the reservoir zone that had experienced thermal fluid substitution. Large differences under the changed reservoir zone are due to the time delay caused by fluid substitution and the changes are similar to the response on the real seismic time-lapse difference section. Non-cancelled energy appearing outside of the effected reservoir zones is also observed on the real seismic time-lapse difference. We suspect that these changes are processing artifacts. The behaviour of the synthetic P-wave traveltime change has similarities to the traveltime changes from the time-lapse seismic surveys, and the major differences may be due to early production that was not accounted for in the modelled results. An overall increase in traveltime within the Waseca formation in the synthetic seismograms may be due to processing artifacts and needs further investigation.

Introduction

The time-lapse seismic reservoir monitoring has potential to improve reservoir management because it may allow us to image dynamic reservoir processes such as fluid movement, pressure change and heat flow in a true volumetric sense. Many factors affect time-lapse seismic responses, such as the contrast of compressibility between fluids, changing temperature, and changing effective pressure. There is a recognized need to combine the skills of geophysicists and engineers to build quantitative reservoir models that incorporate all available reservoir data. A combination of time-lapse seismic survey analysis, reservoir simulation and seismic modelling provides a comprehensive approach to understanding the time-varying connection between changes in seismic and reservoir properties for a given producing reservoir. This study focuses on seismic modelling for Pikes Peak field and it is a part of an ongoing combined study of seismic survey analysis, reservoir simulation and seismic modelling. The modelling process also can be used for feasibility and risk analysis to determine if there are sufficient changes in magnitude and sufficient resolution in the time-

lapse seismic response to reasonably image changes in saturation or pressure (Lumley, 1998).
The Pikes Peak heavy oil field is located 40 km east of Lloydminster, Saskatchewan. Husky Energy Ltd. has operated this field since 1981. Husky acquired a 2D seismic swath survey in 1991 which forms a grid of 29 north-south lines spaced every 100 metres. In year 2000 the University of Calgary AOSTRA (Alberta Oil Sands Technology Research Authority) group and Husky acquired a repeat line on the eastern side of the field (*Fig. 1*). A reservoir characterization analysis using this time-lapse seismic survey has been done recently by CREWES researchers(Watson et al., 2002). The seismic reflectivity difference section, acoustic impedance difference section, interval P-wave travel-times for the monitor and base survey were examined in their research.

In this study we created a synthetic seismic model using pre-production logs from two wells, D15-6 and D2-6 (*Fig. 1*) that were logged in 1978 and 1981. A fluid substitution is performed around 6 wells to simulate the reservoir state after production of these wells in year 2000 and a modified model is generated corresponding to the reservoir after steam drive production. The resulting synthetic seismic difference and P-wave traveltime analysis are compared to the time-lapse seismic analysis for the real seismic survey. The match between the synthetics and the real seismic results indicates that the welllog based synthetic model plus a practical fluid substitution method can be an effective way to model the seismic responses due to production.

Theory And Methodology

Gassmann's equation and Batzle and Wang's relationships (Batzle and Wang, 1992) are used to calculate fluid and saturated rock bulk modulus and densities. The detailed theory and methodology is presented in Zou and Bentley (2001).

Geology And Rock Physics Of Pikes Peak

The Pikes Peak field is located on an east-west structural high within an incised valley fill complex. Dissolution of Middle Devonian salt beds caused a northeast dip in the normally southwest dipping strata. The Pikes Peak field is situated on part of the resulting antiform (Sheppard, Wong and Love, 1998). Oil is trapped within sands deposited in a north-south oriented channel system at a depth of approximately 500 m (Van Hulten, 1984). The channel system in the Pikes Peak area is the lower Cretaceous-aged Waseca formation. The Waseca formation is characterized by a homogeneous, well sorted and predominantly quartz lower unit, and a sand/shale inter-bedded upper unit. Production is predominantly from the lower homogenous unit with some production contribution from the inter-bedded zone.

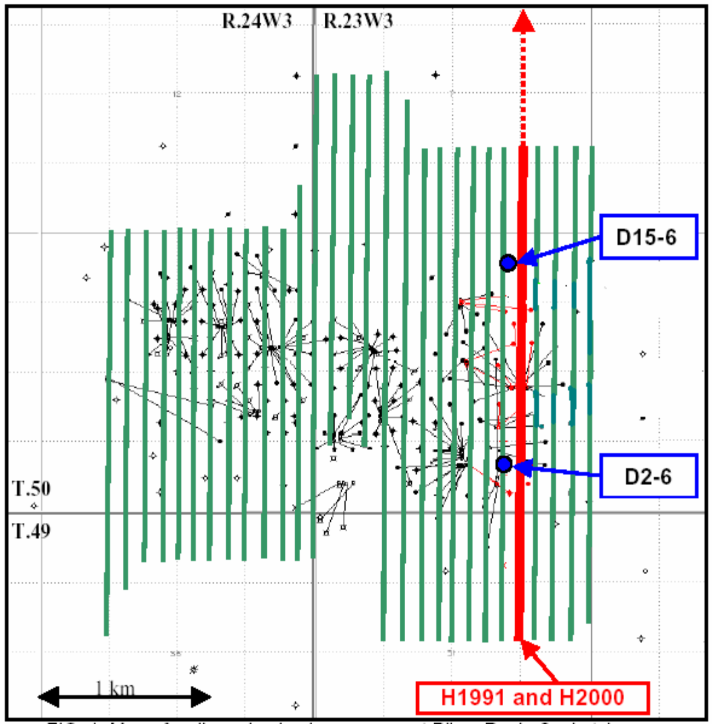

Fig. 1. Map of swath-based survey (green thin lines), repeat multi-component seismic survey (red thick line) and two well locations (after Watson et al, 2002).

A set of lab tests was done on cores from the Pikes Peak field to examine the influence of temperature and pressure on bulk modulus and shear modulus. The test results have been analyzed by other researchers(Downton and Lines, 2000). Their analysis shows that, to first order, the dry shear and bulk modulus are not a function of temperature and pressure. Due to the high porosity of the samples (37% to 38.5%) the values of the shear and bulk modulus are very low. Within the reservoir, the homogeneous formation's average porosity is 32%. Consequently, we do not use the laboratory determined moduli for the earth model. Instead, we use log data from well 1A15-6 (logged in 2000) which is located less than 50 m from the time-lapse seismic line. We use the Vs log and the density log to compute the average shear modulus of the Waseca formation which is 4.9 GPa. Since 1A15-6 was logged after production commenced we use the average shear modulus of 4.9 GPa and the Vp and density logs from 1D2-6 (logged 1981) to calculate the average Waseca formation dry frame bulk modulus of 2.9 Gpa. We use the first order approximation from lab tests that the dry frame bulk modulus and shear modulus are not a function of temperature and pressure. Using the previously discussed methodology (Zou and Bentley, 2001) and the reservoir properties, we can do fluid substitution calculations. Some of the reservoir properties we used are listed in *Table 1*.

Table 1. Initial reservoir properties

φ (%)	Swi (%)	Soi (%)	P (Kpa)	T (°C)	°API
32	22	78	3350	18	12

Synthetic Base Section And Time-Lapse Section

The Promax software is used to do the modelling. *Fig. 2* shows an earth model in depth. Density and p-wave velocity logs from wells D15-6 and 1D2-6 were median filtered and then stretched to tie with the 1991 time-migrated base seismic section. The stretched logs were then tied into the depth-migrated section. Within Promax, the structures are picked and the well logs were interpolated along the structures. The interpolated logs form the earth model velocity and density matrices. The number of CDPs is 282 which is the same as the number within the base survey. The CDP interval is 10 m. The depth of the model is 1480 M. The horizontal grid dimension is 10 m (one CDP interval) and the vertical grid dimension is 4 m. A wavelet with central frequency of 60 HZ is used for synthetic seismogram generation.

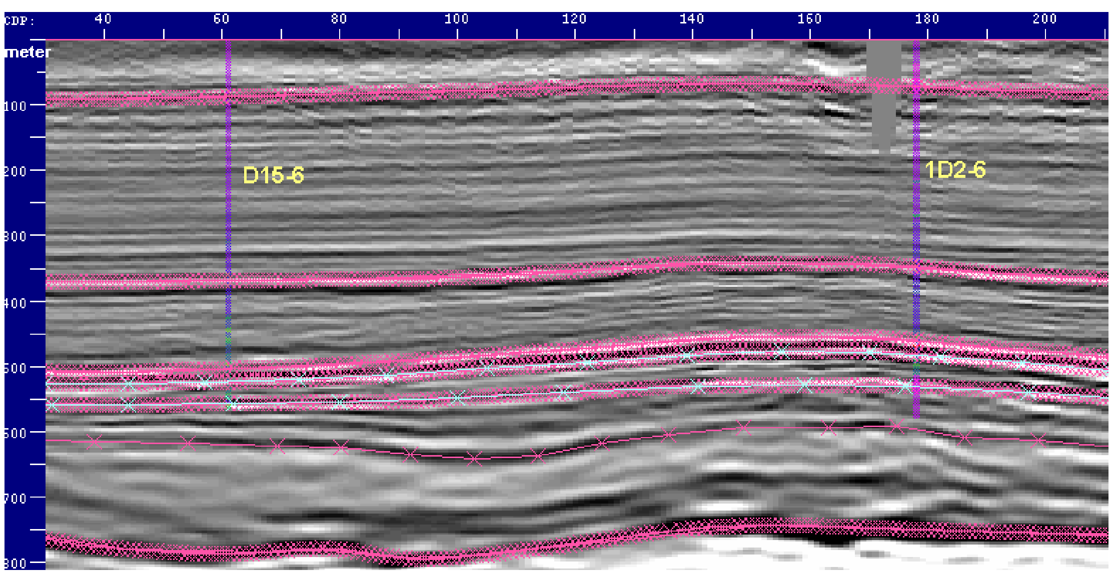

Fig. 2. Depth section of the earth model with the reservoir outlined in blue (please see the CD of this report for colour figures)

The synthetic velocity model is shown in *Fig. 3*. A zero-offset synthetic seismic section was created based on the velocity and density model. We performed a finite difference migration on the zero offset seismic section. The migrated section is shown in *Fig. 4*. This section is used as the simulated pre-production base seismic survey.

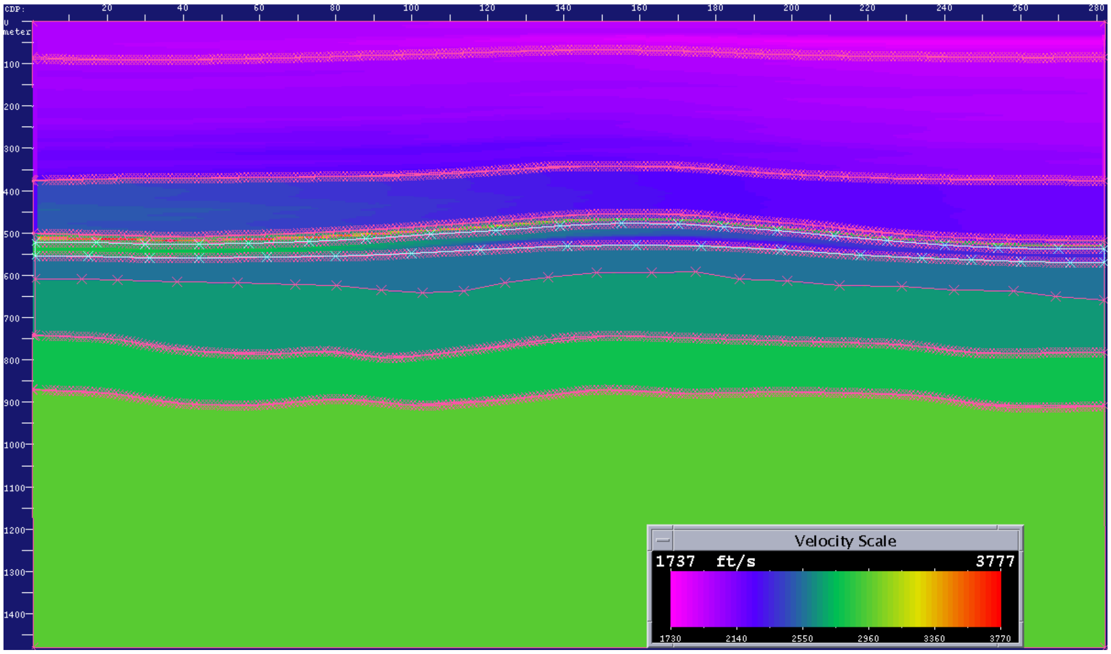

Fig. 3. Velocity model before production with reservoir outlined in blue (the horizontal axis is CDP and the vertical axis is depth in metres)

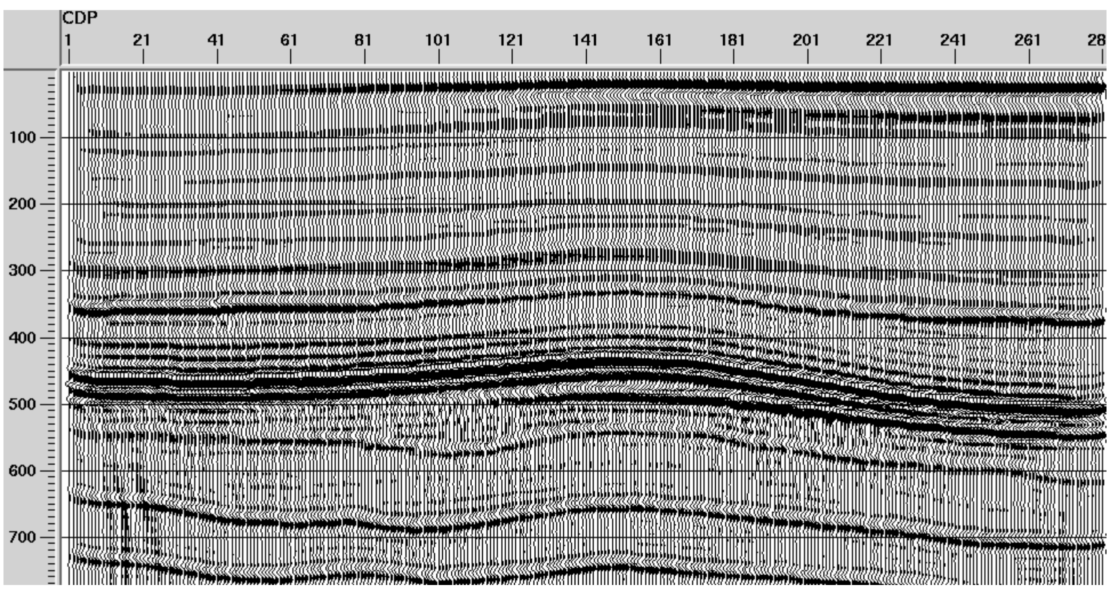

Fig. 4. Pre-production migrated synthetic seismic section (the depth is in time)

Six wells underwent either cyclic steam or steam drive production close to the time-lapse seismic line before the 2000 seismic survey was acquired. They are 1D10-6 (production from 1997), 2B9-6 (production from 1997), 3B8-6 (production from 1995), 3C1-6 (production from 1984), 1D2-6 (production from 1983) and 3B1-6 (production from 1982). To simulate the impact of production, we need to recalculate the velocity and density in steam zone surrounding the wells. The estimated steam zones are from Watson et al (2002). The actual temperature and pressure in 2000 within the reservoir will vary for the individual steam zones and will be subject of future reservoir simulation efforts. Given the limited information about the reservoir properties for these wells, we use an estimated temperature and pressure from relative information obtained from published papers. We use logs from 1D2-6 to calculate velocity and density changes and applied these changes to all steam zones. The velocity and density changes on the margins of each steam zone are smoothed to background to avoid sharp discontinuities in reservoir properties. The approximated reservoir conditions after production and the velocity and density changes are listed in *Table 2*. According to lab test results Vp decreased 21% (Downton and Lines, 2000) which is larger than our calculation 17% from well logs, but we consider our values reasonable given that the porosity of the cores is higher than the reservoir porosity. The new velocity profile is shown in Figure 5.

Table 2. Reservoir properties after production

T (^{o}C)	P (KPa)	Sw (%)	Sor (%)	Sg (%)	ΔVp (%)	$\Delta\rho$ (%)
210	1950	48	42	10	-17	-4

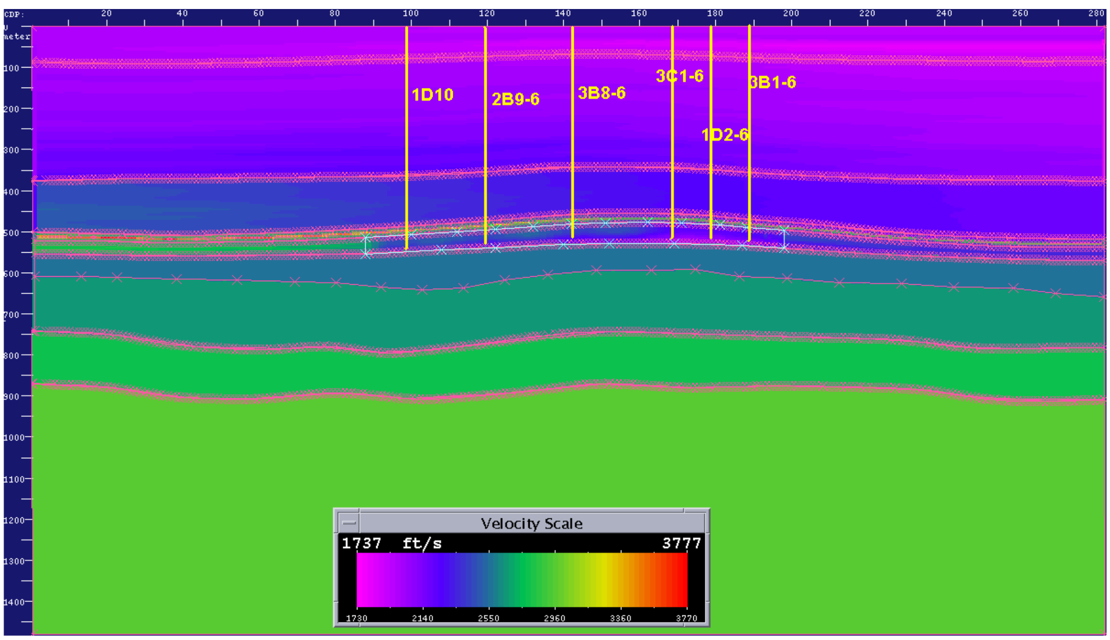

Fig. 5. Velocity model after production with changed reservoir within the blue line (the horizontal axis is CDP and the vertical axis is depth in metres)

A new synthetic seismic section was created and then migrated using the same procedure as for the base synthetic section. *Fig. 6* is the final time-lapse synthetic seismic section and *Fig. 7* is the difference between the base synthetic seismic section and the time-lapse seismic synthetic section.

The difference section shows a strong change starting at the top of the Waseca. The strong changes below the Sparky are due to the time delay caused by velocity changes within the reservoir. Non-cancelled energy is visible on the two sides of the steamed portion of the reservoir. This part of the reservoir was not changed and these differences appear to be due to the processing procedure; however, we do not have a good explanation at this point. Similar energy can be seen on the difference section of the time-lapse analysis for 1991 and 2000 seismic surveys (*Fig. 8*).

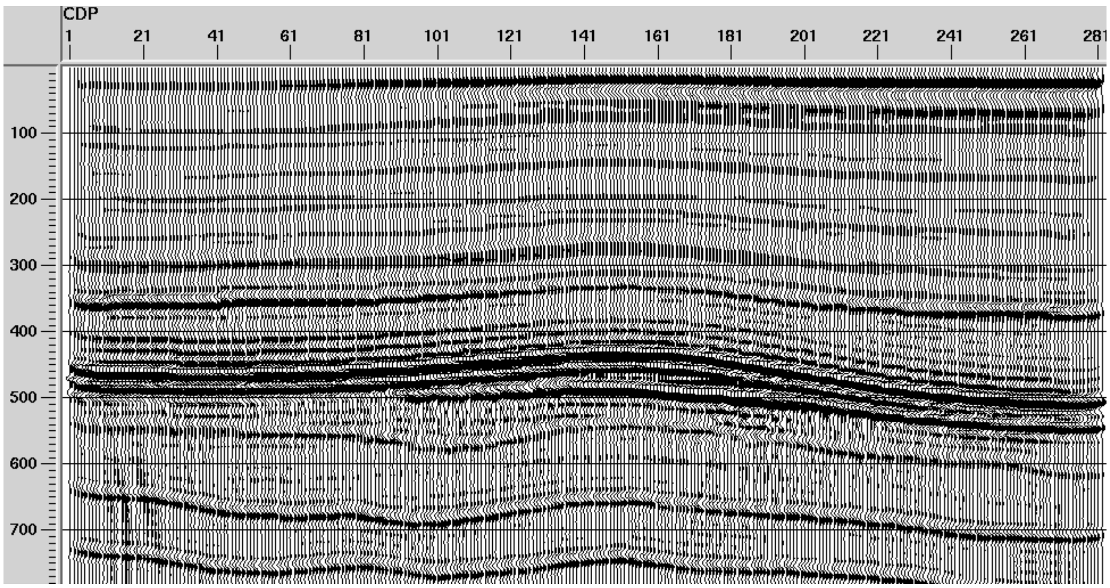

Fig. 6. Post-production migrated synthetic seismic section. Vertical axis is time (ms)

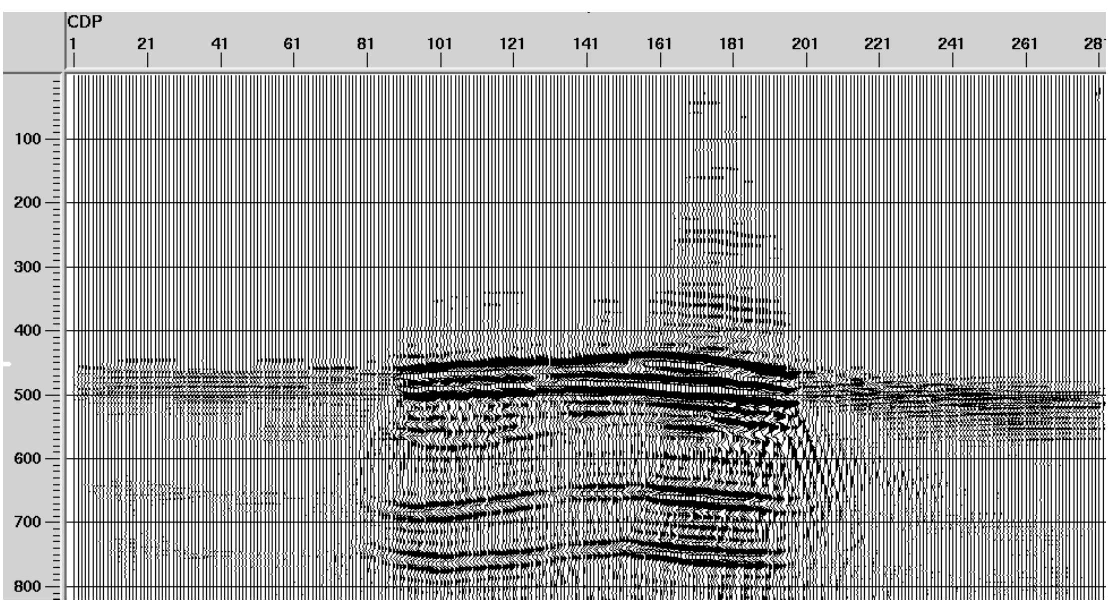

Fig. 7. The difference between the base synthetic and the time-lapse synthetic.

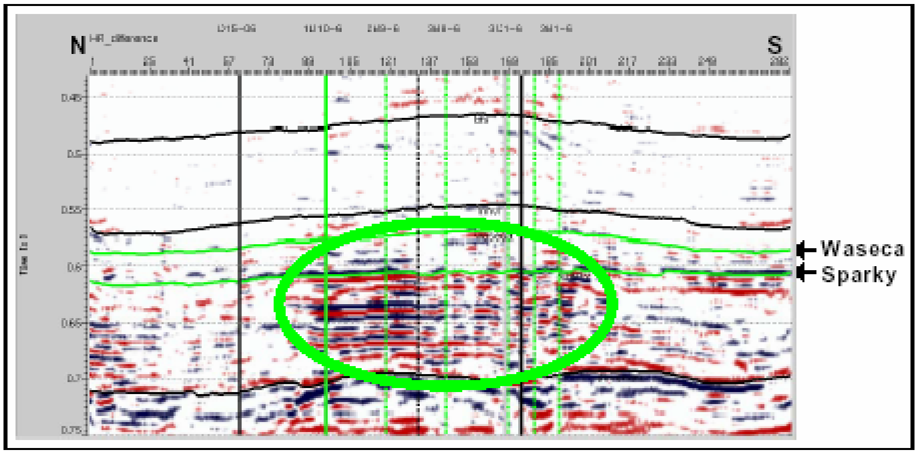

Fig. 8. The difference plot for 1991 and 2000 seismic survey (Watson et al., 2002)

The events from the top and the bottom of the Waseca formation are shown in blue in *Fig. 9* for the pre-production synthetic seismogram. We picked the traveltime for each trace. We also picked the traveltime between the top and bottom of the Waseca for each of the traces from the post-production synthetic seismograms. The ratio of post-production to pre-production for each trace is shown in *Fig. 10A*. The isochron ratios are generally larger than one, with large ratios within the steamed zone. At this point, we cannot explain the general increase in the isochrons, but we suspect it is a processing artifact and is related to the difference energy that is out of the steam zone in *Fig. 7*. Watson et al. (2002) also presented isochron ratios for the time-lapse surveys and those are shown in *Fig. 10B*. Their results show about a 10% increase in travel time within the zone adjacent to wells 1D10-6 and 2B9-6 which is consistent with the modelling results in *Fig. 10A*. The survey results show a slight decrease in travel time in the zone of 3C1-6, 1D2-6 and 3B1-6; the synthetic results show a 5 % increase. Those wells had been under production since the early 1980's which is several years before the 1991 base survey was conducted, and the effects of earlier production may be included in the base survey. However, the effects are not included in the base synthetic survey, and that difference may explain the difference in the traveltime ratio. Issues such as these will be explored with thermal flow simulation in the future.

Conclusions

Fluid substitution was used to investigate the changes in seismic response at the Pikes Peak field. The predicted velocity decrease due to the steam injection process is 17 percent and is similar to the lab test results. The synthetic seismic time-lapse analysis gives similar results to the time-lapse analysis for the real seismic survey. The difference section shows a significant difference within the reservoir zone that had experienced thermal fluid substitution. The large differences under the changed reservoir zone is due to the time delay caused by fluid substitution and is similar to the response on the real seismic time-lapse difference. Non-cancelled energy appearing outside of the effected reservoir zones also is observed on the real seismic time-lapse difference. We suspect that these changes are processing artifacts. The behaviour of the synthetic P wave travel time change has similarities to the travel time changes from the time-lapse seismic surveys, and the major differences may be due to early production that was not accounted for in the modelled results. The overall increase in traveltime in the synthetic differences may also be due to processing artifacts and needs further investigation.

The next step in the project is to use a thermal simulator and real production information to model the details of the Pikes Peak production and reservoir evolution. The simulator results will be linked to the synthetic seismogram procedure to give a more detailed and realistic prediction of changes in the synthetic seismograms. These results will then be compared with the time-lapse seismic survey results.

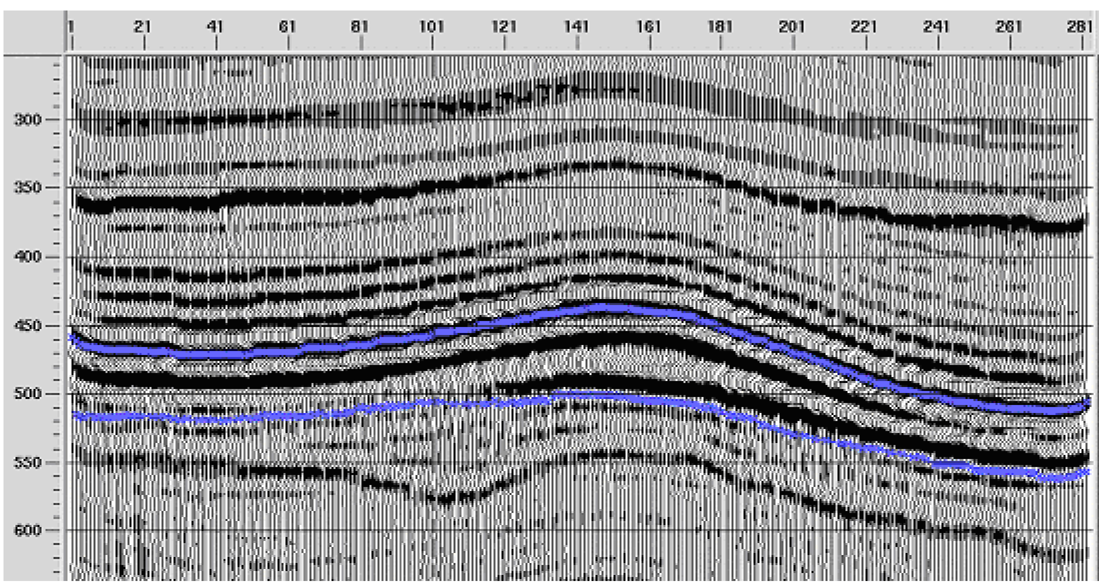

Fig. 9. Waseca top and bottom picks (blue) from pre-production synthetic seismogram. Vertical axis is time (ms).

Acknowledgments

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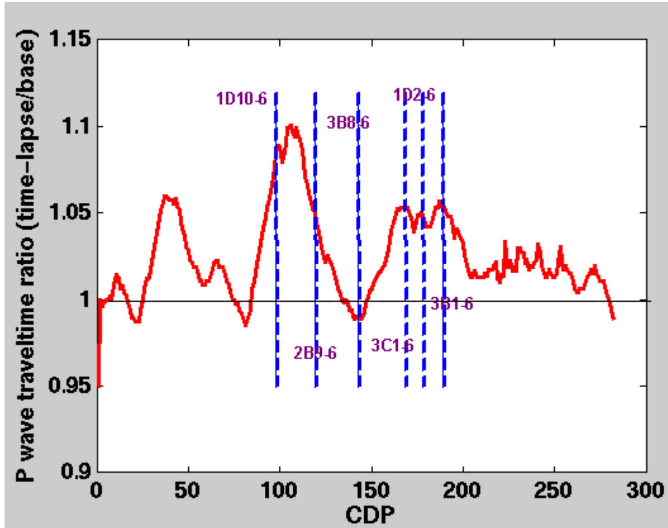

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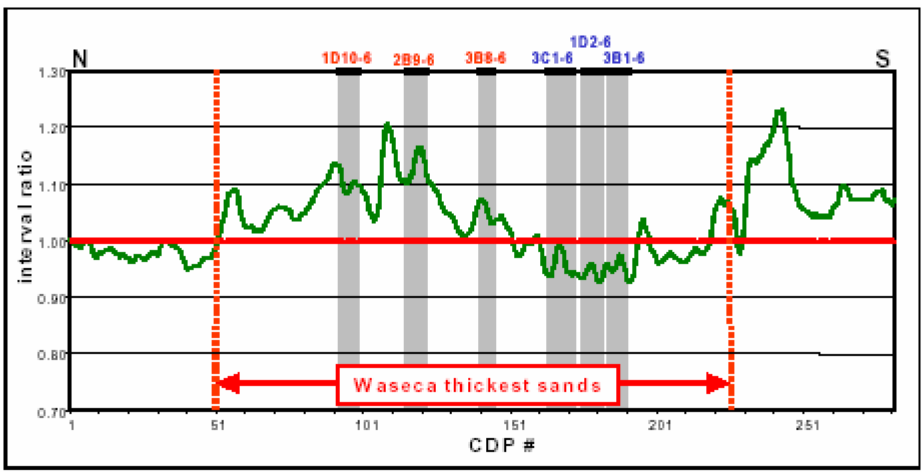

B (after Watson et al., 2002)

Fig. 10. The ratio of Waseca interval traveltimes for P-wave. A is for the synthetic seismiogram and B is for the real time-lapse seismic survey