Time-Lapse EEI Inversion, a key monitoring tool in unconventional reservoirs

Naimeh Riazi, Brian Russell** and Larry Lines****

**Department of Geoscience, University of Calgary, Calgary, Alberta*

***Geosoftware, Calgary, Alberta*

**** A tribute to prof. Larry Lines*

Summary

The application of time-lapse (4D) seismology in the monitoring and development of different oilfields has proven to be valuable in reservoir characterization. Time-lapse seismology utilizes successive seismic surveys acquired during the production of a reservoir in order to monitor production related changes by measuring the difference in elastic properties of subsurface. To monitor the reservoir related changes, rather than seismic processing and acquisition changes, a calibration process should be implemented to optimize and improve the repeatability of non-reservoir zones and consequently enhance the production-related anomalies in the reservoir. We can use two different approaches in our analysis, one based on seismic horizon changes and the other based on seismic volume changes. In time-lapse seismic horizon interpretation, we measure the time-shift and amplitude differences along the seismic horizons both in the base and monitor surveys. In volume interpretation, we use seismic inversion, which incorporates time and amplitude changes in the reservoir, to derive impedance volumes and thus infer both pressure and fluid saturation changes. Here, we apply extended elastic impedance (EEI) inversion to time-lapse data acquired over a cold production heavy oilfield. We show which chi angles correlate best with our petrophysical attributes of interest. Furthermore, we illustrate how time-lapse EEI inversion results can help to optimize the positions of new infill wells and can improve reservoir development in heavy oilfields.

EEI method

Connolly (2009) proposed the elastic impedance technique to generalize the acoustic impedance term for any angle of incidence in the partial angle-stacks.

$$EI = V_P^{(1+tan^2(\theta))} V_S^{(-8Ksin^2(\theta))} \rho^{(1-Ksin^2(\theta))} \qquad (1)$$

where $K = \left(\frac{V_S}{V_P}\right)^2$ and normally can be considered as the average of the ratio, $(V_S / V_P)^2$ for an interval. Elastic impedance is a generalized form of acoustic impedance which can be derived for different angles of incidence. Acoustic impedance is equal to elastic impedance at normal incidence. To account for the fact that EI does not scale correctly at different angles of incidence, Whitcombe (2002) modified and normalized Connolly 's elastic impedance equation by using the reference velocity and density constants (V_{P_0}, V_{S_0}, and ρ_0) averaged over a target interval to normalize the elastic values in the equation and thus introduce non-dimensionality into the Connolly equation:

$$EI(\theta) = V_{P_0}\rho_0 \left[\left(\frac{V_P}{V_{P_0}}\right)^{(1+tan^2(\theta))} \left(\frac{V_S}{V_{S_0}}\right)^{(-8Ksin^2(\theta))} \left(\frac{\rho}{\rho_0}\right)^{(1-Ksin^2(\theta))} \right] \qquad (2)$$

Whitcombe et al (2002) proposed replacing $\sin^2 \theta$) with tan (χ) in the second term of the Shuey equation to create a new transform in which the A and B intercept terms could be rotated by the angle χ. The reflectivity was also multiplied by cos (χ), and a scaled reflectivity R_S expressed as:

$$R = A + B\tan\chi = \frac{(A\cos(\chi) + B\sin(\chi))}{Cos(\chi)} \tag{3}$$

$$R_S = R\cos(\chi) = A\cos(\chi) + B\sin(\chi) \tag{4}$$

Then, the elastic impedance equation replaced with the extended elastic impedance, or EEI, equation, which is written as:

$$EEI(\chi) = V_{P_0}\rho_0\left[\left(\frac{V_P}{V_{P_0}}\right)^p\left(\frac{V_S}{V_{S_0}}\right)^q\left(\frac{\rho}{\rho_0}\right)^r\right] \tag{5}$$

where

$$p = \cos(\chi) + \sin(\chi) \tag{6}$$

$$q = -8\mathrm{K}\sin\chi \tag{7}$$

$$r = \cos(\chi) - 4K\sin(\chi) \tag{8}$$

The chi angle range is from -90 to +90. The chi angle can be chosen in a way that correlates with elastic properties such as bulk modulus, Lamé constants, shale volume, water saturation, and porosity. In EEI inversion, equation 4 is used to create the starting model, and equation 5 is used to create the seismic volume to be inverted.

Workflow

Elastic impedance (EI) inversion has been applied to the reservoir zone. As mentioned in previous section, this technique is based on the three-term Aki-Richards approximation and is function of angle of incidence. One of the difficulties in analyzing the elastic impedance inversion process is the restricted range of angle of incidence and rapid changes of elastic impedance at different angles of incidence. Here, we applied elastic impedance inversion to time-lapse seismic data in order to monitor the changes caused by hydrocarbon production and fluid changes in the target zone. To process the elastic impedance inversion, we first divided the total angle gather data into two sub-angle gathers. In the studied area, two angle gathers were made for both base and monitor surveys. The near angle gather range is 0-15 degrees and the far-angle gather is 15-30 degrees. Elastic impedance logs, from the wells which have dipole sonic logs, were made corresponding to the average angle of incident in each angle-gather. The angle gather is then converted to angle-stacks and, by using the interpreted horizons and extracted elastic impedance logs from available wells, a low frequency elastic impedance model was built separately for the partial angle stacks. Near and far angle-stacks were independently inverted to give elastic impedance cubes for near and far stacks. This procedure was repeated for the monitor survey to give the time-lapse seismic inversion.

We applied the elastic impedance inversion to pre-stack time-lapse seismic data on the studied heavy field. We used the total range of angle gathers in EEI process. First of all, A and B, the first two terms in the Aki-Richards equation should be derived by AVO intercept/gradient analysis both in base and monitor surveys on angle gathers in each survey. In the next step, the best chi angle (χ) was determined in the reservoir zone. For this process, we used two methods. In the first method, cross-correlation of EEI values from well data was compared with different petrophysical and elastic parameters such as P-wave velocity, S-wave velocity, acoustic impedance, shear impedance, bulk modulus (κ), shear modulus (μ), and the Lamé attributes.

Selected Results

Figure 1 shows an inverted seismic section of EEI (χ =45) in the base and monitor seismic surveys. The evident decrease is observed in the reservoir zone from base survey to monitor survey due to production.

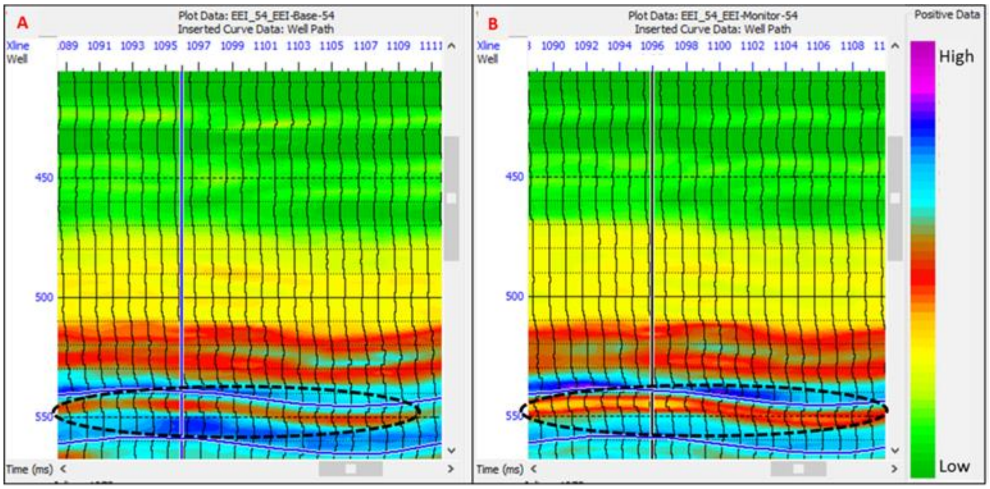

Figure 1. A seismic section of EEI (χ=45) in A) base survey B) monitor survey. The area inside the ellipse is located at the reservoir zone, illustrate the changes during the production and recovery process.

Figure 2 illustrates the NRMS maps of time-lapse EEI $(\chi = 45)$ and $(\chi = 27)$. As is evident in the figure, EEI $(\chi = 45)$ shows higher change (15%) in the production zone However, EEI $(\chi = 27)$ shows the small production changes (3%) in the vicinity of the wells which their heavy oil production. In Figure 3, we compare the difference in the cumulative oil production with the results of the EEI inversions. In this figure, bubble size corresponds to the volume of cumulative oil production in the wells.

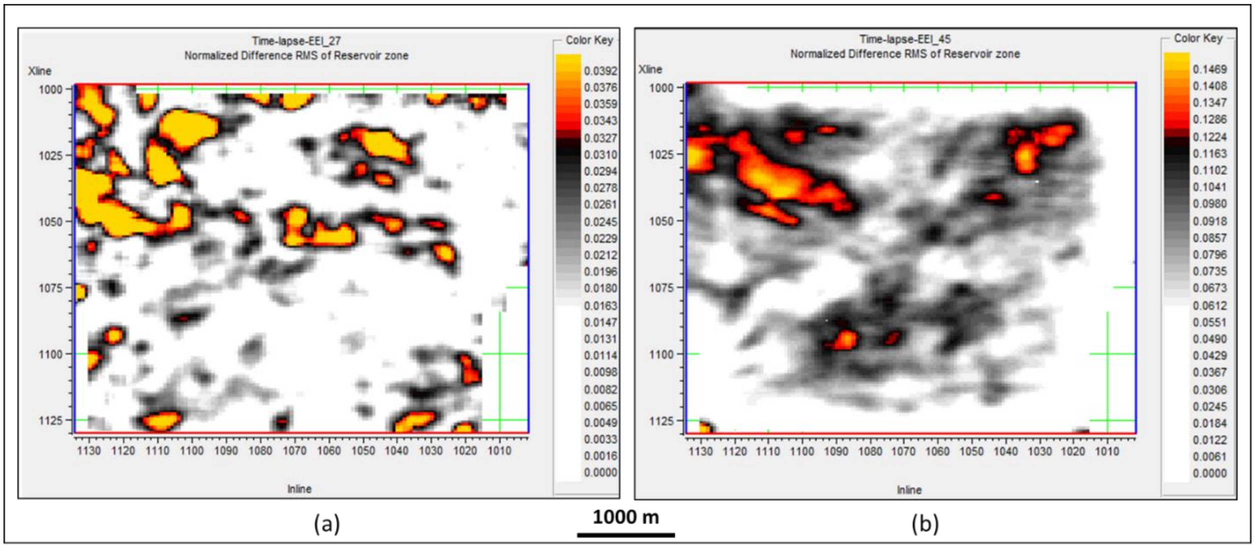

Figure 2. NRMS map of time-lapse EEI inversion between the top and base of the reservoir for χ =27 (left) and χ =45 (right).

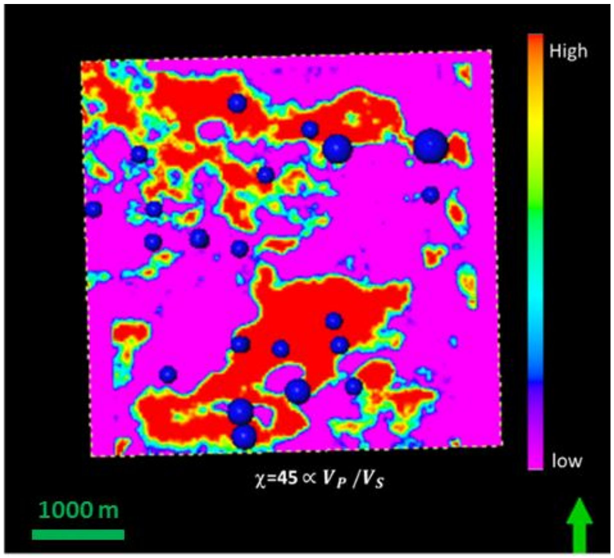

Figure 3. Comparison of EEI (χ =45) difference inversion with accumulative oil volume difference in the production time. Bubble size correlates with the volume of cumulative oil production between base and monitor surveys.

Conclusions

Time-lapse seismic analysis is a powerful technique for understanding fluid changes during the production of a reservoir. In this study, we applied extended elastic impedance inversion techniques to time-lapse seismic data acquired over a heavy oil field which was produced by the cold heavy oil production with sands (CHOPS) method. By comparing the results of the time-lapse EEI (χ=45) inversion, we could observe that the areas which have higher production-related changes coincide with the areas of low EEI in the monitor survey. The high anomaly in the time-lapse analysis could possibly provide useful information for future drilling.

Acknowledgements

This abstract is based on our paper published on Journal of Seismic Exploration, cited as below: Riazi, N., Lines, L., & Russell, B. (2015). Monitoring Heavy Oil Recovery by Time-Lapse EEI Inversion. Journal of Seismic Exploration, 24(4), 343-364.

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