GeoConvention
Calgary • Canada • March 7-11 2016
OPTIMIZING RESOURCES

The importance of seismic attributes in reservoir characterization and inter-well connectivity studies of tight oil reservoirs

Naimeh Riazi* and Christopher R. Clarkson*
*Department of Geoscience, University of Calgary

Summary

The application of seismic data for understanding reservoir complexity has been implemented for several years. In this study, applications of seismic attributes for evaluating the Viewfield Bakken tight oil reservoir in Saskatchewan are demonstrated. Operators are now implementing waterflood pilots that utilize multi-fractured horizontal wells as injectors and producers. Seismic studies reveal some of the controls of stratigraphy and structure on hydraulic fracturing that are not possible using other methods, and can be important for not only assessing lateral changes in reservoir quality, dictating flood sweep efficiency, but also connectivity between hydraulic fracture stages for injector-producer pairs. For example, seismic attributes displayed as azimuth maps illustrate lineaments which can be interpreted as fractures/faults in the reservoir. These lineaments are analogous to features previously observed in the U.S. Bakken reservoirs, but with variations in orientation. Stratigraphic features of the Viewfield Bakken were also analyzed by studying acoustic impedance changes in the reservoir. The combination of these techniques (azimuth and acoustic impedance mapping) are demonstrated to be critical for understanding inter-well connectivity of multi-fractured horizontal wells producing from tight oil reservoirs.

Introduction

Tights oil reservoirs include clastics/carbonates which have low permeability (<0.1 md) and require hydraulic fracturing to produce commercially (Clarkson and Pederson, 2011). Currently horizontal wells that are completed in multiple hydraulic fracturing stages (multi-fractured horizontal wells or MFHWs) are used to product tight oil reservoirs commercially, including the Viewfield Bakken tight oil reservoir studied in this work. Historically, MFHWs have been used only for primary depletion of tight oil reservoirs, but recently operators have extended their use to enhanced oil recovery operations (MFHWs as both injectors and producers), including waterflooding. A challenge for EOR operations using MFHWs is determining inter-well/fracture stage connectivity, which dictates sweep efficiency. Although several techniques exist to aid in determining fracture stage and well connectivity between injector-producers (tracers, well-test methods etc.), we argue that seismic attribute analysis can provide additional important information.

Use of seismic attributes for reservoir characterization has been commonplace for many years. Seismic data provides important structural and stratigraphic information in three dimensions. Seismic attributes are useful tools for detecting fractures or faults and geological lineaments which are below the seismic resolution (sub-seismic, normally less than 15 meters).

Amplitude, phase, and frequency are the main characteristics of seismic traces. Extracting instantaneous and local values of these parameters is useful for revealing subsurface features. In addition to these basic attributes, weighted averaging of instantaneous seismic attributes is beneficial. This technique is most useful for reducing spikes and noise variations (Barnes, 2000).

Among the various seismic attributes, curvature attributes are most useful for detecting structural features. Curvature attributes include both dip and azimuth attributes. They can be classified as either horizon-based or volume-based. Horizon-based curvature is sensitive to the interpreter‘s ability to pick seismic horizons as well as the quality of the seismic data (Chopra and Marfurt, 2008). Volume-based curvature computation is now more popular. In addition to fault and fracture detection by curvature analysis, stratigraphic features can also be recognized through curvature volumetric attributes. This is due to the fact that most of the seismic stratigraphy depends on the morphology of the seismic texture (Chopra and Marfurt, 2008).

Higher fracture density can cause heterogeneity in the reservoir zone. In this study, we applied different seismic attributes for evaluating inter-well connectivity between injector-producer pairs in a Viewfield Bakken waterflood pilot area.

Theory and Methods

The seismic attributes play an important role in deriving critical information from the seismic data because they can increase seismic resolution. Application of azimuth attributes has been successfully demonstrated by many papers (Hesthammer and Fossen, 1997, Sigismondi and Soldo, 2003, Marfurt, 2006). In this section, the different categories of seismic attributes are reviewed, including seismic curvature attributes, amplitude-weighted attributes, and seismic inversion attributes.

- **Curvature attributes**

  Curvature is the amount of bending of a curve at a particular point, i. e. the amount of curve deviation from a straight line at this point (Roberts, 2001). Thomas (1972) showed that curvature can be quantified using the second derivative of the curve. Structural features such as faults, fractures, and folds often change the dip and azimuth of the seismic reflection. There are different types of curvature attributes - curvature can be measured in different directions. Mean, maximum, minimum, most positive, most negative, angle of maximum dip, and the azimuthal value of the direction of the maximum dip were used in this case study.

  Different seismic attributes can be extracted by performing different mathematical transformations on the seismic data. The Hilbert transform is one of the basic transformations where a complex time-series can be viewed as the imaginary part of a complex series. Amplitude envelope (A_t), instantaneous phase ($\emptyset_t$), and instantaneous frequency (ω_t) can be extracted by equations below:

$$A_t = \sqrt{({S_t}^2 + +{h_t}^2)} \tag{1}$$

$$\emptyset_t = \arctan(h_t/S_t) \tag{2}$$

$$\omega_t = \frac{d\emptyset_t}{dt} \tag{3}$$

  There are also amplitude-weighted attributes which cause a decrease in the noise content of seismic data. Amplitude-weighted phase ($A_t\phi_t$) and amplitude weighted frequency ($A_t\omega_t$) are among two most popular attributes in this group.

- **Seismic inversion**

  Acoustic impedance is one of the most helpful attributes for detecting lithology and stratigraphic changes in the reservoir. Acoustic impedance, which is the product of density and velocity, can detect rock and fluid changes in the reservoir. Here, we extracted the acoustic impedance volume by model-based inversion. In model-based inversion, the low frequency information is extracted from high cut acoustic impedance logs in wells. Therefore the combination of this low-frequency information with seismic frequency can provide the full frequency band. The model-based technique (Russell and Hampson, 1991) involves building the low frequency model as a starting guess for the seismic data. The model is then perturbed so that the output seismic synthetic traces match the seismic data in the least-squares sense. A comparison between real traces and synthetic seismic traces is made in the next step. The goal is to update the model in an iterative way to minimize the difference between the seismic and synthetic traces by generalized linear inversion algorithm as shown below:

$$J = weight_1(S - W * R) + weight_2(M - H * R) \quad (4)$$

$$weight_1 + weight_2 = 1 \quad (5)$$

  where M is the initial model and H is the integration operator which convolves with the final reflectivity (R) to produce the final impedance seismic volume.

Results and Discussion

In this section, the results of different attributes are shown and quantitatively compared with connectivity analysis. As mentioned earlier, an azimuth map can provide valuable information about changes in the dip direction of seismic reflections. **Figure 1** shows an azimuth map in the reservoir which illustrates azimuth angles in the direction of maximum dip. It is clear that anomalous trends are observed in NW-SE and NE-SW directions. The results are consistent with other Bakken reservoirs in the United States such as the Elm Coulee Field (Sonennberg, 2009).

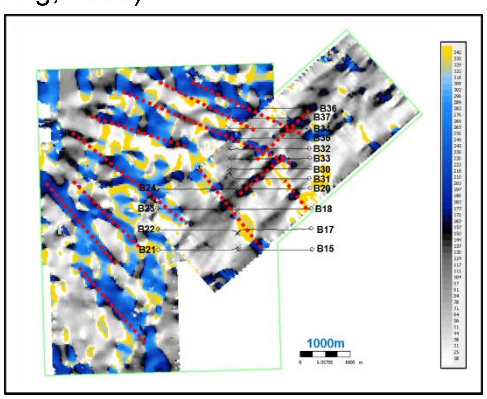

Figure 1. Azimuth dip of maximum dip in the reservoir; possible fracture/faults are shown with red dashed lines.

Model-based inversion was also performed in the case study. The product of model-based inversion is a 3D acoustic impedance seismic volume. **Figure 2** illustrates the average acoustic impedance in the studied area.

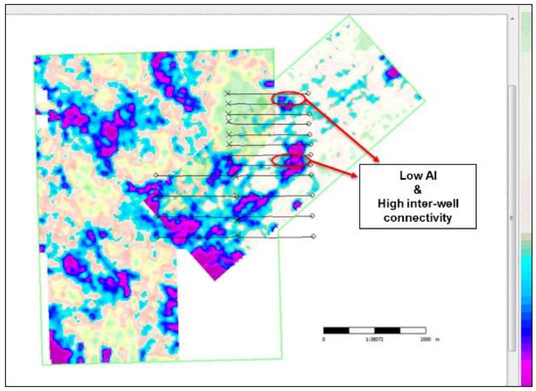

Figure 2. Average acoustic impedance of the reservoir in the study area.

To compare seismic attributes with connectivity analysis, one section of the target area was divided into different zones. Each zone includes an injector and a producer. The average values of different attributes in each zone were derived and compared quantitatively with inter-well connectivity, which in turn was derived using the methods described by Mirzayev et al, 2015. The results (**Figure 3**) show a good relationship between the acoustic impedance and connectivity. As acoustic impedance decreases, the inter-well connectivity increases. Also, higher inter-well connectivity is mostly observed in the areas where the lower values of acoustic impedance are observed.

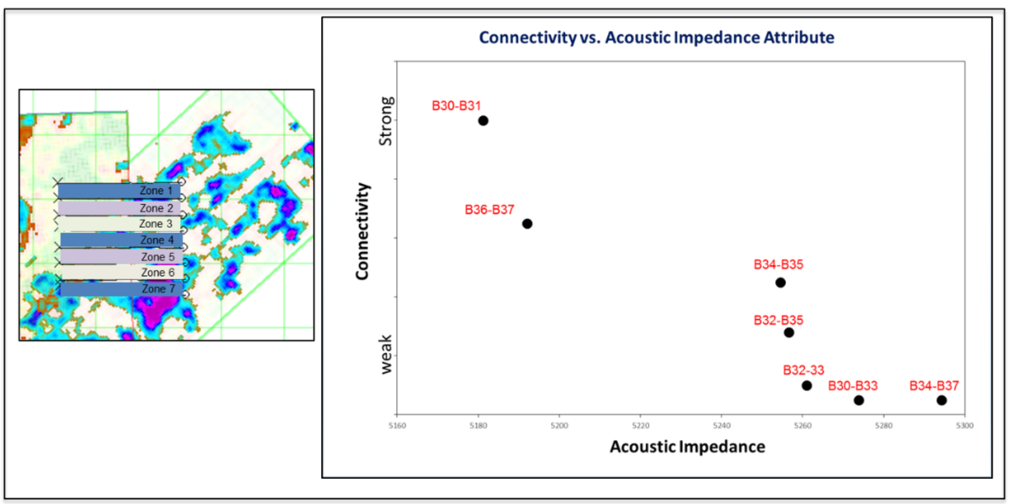

Figure 3. Comparison of average acoustic impedance in different zones (shown in left figure) with the inter-well connectivity in each zone.

We also tested the relationship between the acoustic impedance and porosity in one of the wells in the studied area which has dipole sonic logs. A crossplot of acoustic impedance versus porosity is shown in **Figure 4**. It is clear that acoustic impedance decreases with increasing porosity in the reservoir. Therefore, low acoustic impedance (**Figure 3**) can also be an indicator of high porosity zones in the reservoir which can affect the inter-well connectivity.

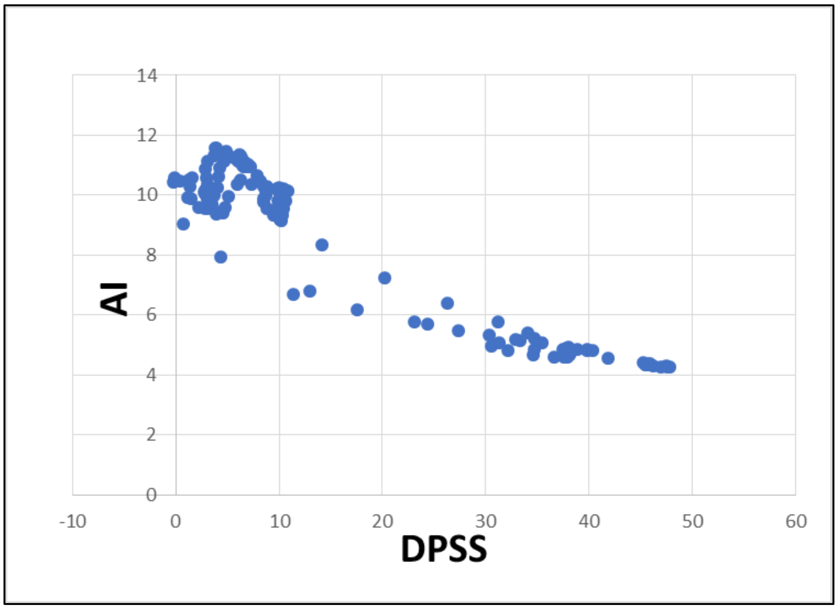

Figure 4. Crossplot of acoustic impedance (AI) vs. density porosity in one of the wells in studied area.

The amplitude weighted by frequency was also investigated. The results show that the decrease in amplitude weighted by frequency can be correlated with strong inter-well connectivity. However, the correlation coefficient is not very good. Filtering the seismic data can increase the signal to noise ratio in the seismic data. In this study, amplitude of the filtered seismic data shows a good correlation with the connectivity analysis. Further, it was also observed that the connectivity can be changed by structural features such as sub-seismic fault/fractures and lineation. Both of these approaches help engineers to interpret the higher production in the wells to lower structural and stratigraphic barriers.

Conclusions

In this paper, seismic attribute analysis was applied to the Viewfield Bakken tight oil reservoir to investigate reservoir complexity and possible correlations between seismic attributes and reservoir connectivity. Seismic attribute analysis can help geoscientists gain important information regarding the structural and stratigraphic features in the reservoir. Three main groups of the post-stack seismic attributes were used; curvature attributes, amplitude-related attributes, and seismic inversion. With curvature attributes, the azimuth of maximum dip showed some sub-seismic fault/fracture or lineation trends which can cause barriers to fluid connectivity in the reservoir. Further, they may show some lithology changes which increases the reservoir heterogeneity and makes the fluid connectivity weaker. Acoustic impedance is one of the attributes successfully used in this study, which is extracted by model-based inversion. Low values of acoustic impedance correlate well with strong inter-well connectivity. Well log analysis demonstrates a correlation between acoustic impedance and porosity. Quantitative analysis was performed to compare different attributes with connectivity analysis - a good correlation between acoustic impedance and connectivity analysis was demonstrated. Filtering seismic data also proved fruitful in this study – this is because the bandpass filter removes noise variation of the seismic data providing more reliable data for analysis.

Acknowledgments

We would like to thank Tight Oil Consortium (TOC) sponsors for financial support of this project.

References

Barnes, A. E. (2000). Weighted average seismic attributes. Geophysics, 65(1), 275-285.
Chopra, S., & Marfurt, K. J. (2008). Emerging and future trends in seismic attributes. The Leading Edge, 27(3), 298-318.

Clarkson, C. R., & Pedersen, P. K. (2011) Production analysis of Western Canadian unconventional light oil plays. In Canadian Unconventional Resources Conference. Society of Petroleum Engineers, SPE 149005.

Hesthammer, J., & Fossen, H. (1997) Seismic attribute analysis in structural interpretation of the Gullfaks Field, northern North Sea. Petroleum Geoscience, 3(1), 13-26.

Marfurt, K. J. (2006). Robust estimates of 3D reflector dip and azimuth, Geophysics, 71(4), P29-P40.
Roberts, A. (2001) Curvature attributes and their application to 3d interpreted horizons. First Break, Volume 19.2 pp. 85-100.

Mirzayev, M., Riazi, N., Cronkwright, D., Jensen, J. L., & Pedersen, P. K. (2015) Determining Well-to-Well Connectivity in Tight Reservoirs. In SPE/CSUR Unconventional Resources Conference. Society of Petroleum Engineers.

Russell, B.H., and Hampson, D.P. (1991) A comparison of post-stack seismic inversion methods, Annual Meeting, Abstracts, SEG, p. 876-878.

Sigismondi, M. E., & Soldo, J. C. (2003). Curvature attributes and seismic interpretation: Case studies from Argentina basins. The Leading Edge, 22(11), 1122-1126.
Thomas, G.B. (1972) Calculus and analytical geometry. Fourth edition. Addison-Wesley Publishing Company.

Sonnenberg, S. A., & Pramudito, A. (2009). Petroleum geology of the giant Elm Coulee field, Williston Basin. AAPG bulletin, 93(9), 1127-1153.