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# Rock physics and time-lapse seismic analysis of thermal heavy oil production

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## Summary

Time-lapse (4D) seismic monitoring of thermal heavy oil production represents a simple and cost-effective method of characterizing changes in reservoir conditions due to steam injection. Typically, seismic amplitude data is used to map the spatial extent of reservoir changes, however the physical cause of the changes cannot be determined from amplitude data alone. Using simultaneous 4D AVO inversion, we can directly invert partial stacks from multiple vintages for changes in elastic properties due to production. In conjunction with rock physics analysis, 4D AVO inversion has the ability to quantify changes in reservoir conditions, bridging the gap between seismic amplitudes, elastic properties and reservoir parameters.

This study outlines the workflow implemented to quantify changes in reservoir conditions due to steam injection and production of an Athatbasca Oil Sands bitumen reservoir. A holistic approach to interpretation was implemented, encompassing unconsolidated rock physics analysis, 4D low-frequency modeling, 4D AVO inversion and rock physics driven probabilistic lithology classification to separate the inverted elastic changes into steam or gas and mobile oil. Ultimately, the identification of various production related effects lead to improved reservoir optimization opportunities, allowing for an increase in bitumen production.

## Introduction

4D seismic monitoring of thermal heavy oil production is becoming increasingly important in the current economic environment as companies seek to improve margins by increasing operational efficiencies. This technology has the potential to offer insights into the effectiveness of a development plan by detecting residual oil saturation and steam chamber development, anomalous pressures and monitoring of cap-rock integrity and other environmental concerns. Conventional 4D seismic analysis compares amplitudes between surveys to map the spatial extent of areas affected by steaming and production, but to maximize the value of 4D seismic, a transition from qualitative to quantitative interpretation is required. Using 4D AVO inversion in conjunction with rock physics analysis, we are able to quantify changes in elastic properties and separate these changes into their underlying petro-physical cause.

## Theory and/or Method

*Rock physics modeling*

A 4D rock physics model was created to investigate the elastic response of the reservoir during thermal heavy oil production. This model forms the basis for the interpretation of changes in elastic properties estimated through 4D AVO inversion. The rock physics model used for this study is a non-linear regression based model that obeys physical bound theory and honours single and multi-mineral fluid substitution theory. The model connects the elastic moduli of the rock with porosity, mineralogy and fluid content.

Since bitumen has a finite shear modulus, we consider the bitumen as a third mineral phase in addition to sand and clay. A re-normalization of the in-situ volume of shale, porosity and water saturation was performed to yield a three mineral mix of bitumen, sand and shale, where the re-normalized porosity is completely water saturated. Subsequently, Bachrach's (2008) method was used to predict the volume fraction of non-slip sand contacts thereby correcting for the anomalously high Vp/Vs values observed in the wells logs. The resulting effective sand parameters were used to derive a calibrated in-situ rock physics model. Finally, to investigate the rock physics response due to changes in pressure, temperature and fluid, we applied experimentally derived relationships based on the work done by Kato et al. (2008) to obtain a 4D rock physics model that can differentiate between bitumen, heated oil, water and steam. This model will serve as the basis for interpretation of our 4D AVO inversion results. Figure 1 shows the 4D rock physics model in Vp/Vs vs Acoustic Impedance (AI) space.

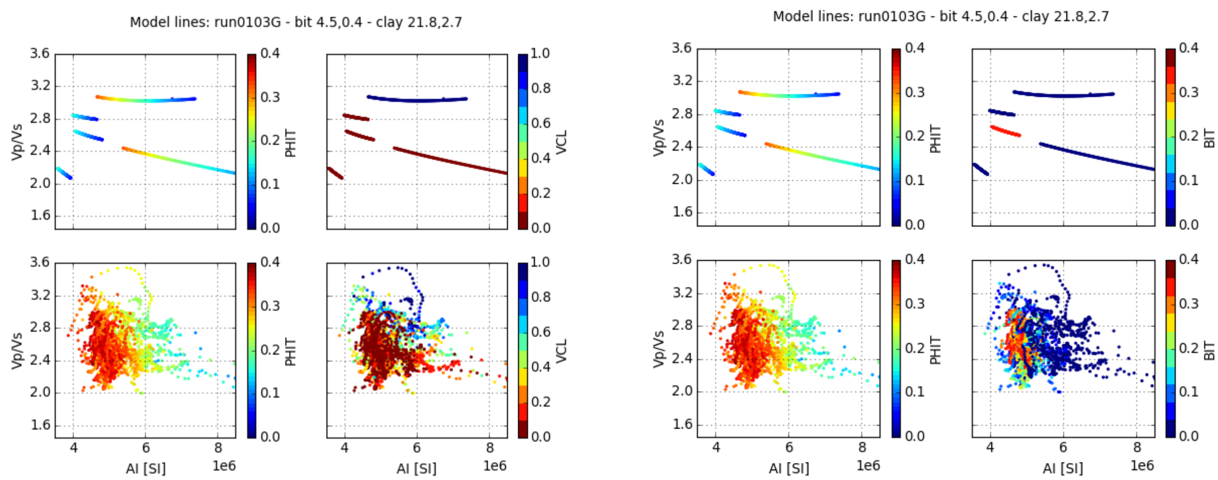


***Figure 1*** *4D rock physics model with sand, clay, bitumen, steam and heated oil trend lines and observed data color coded by porosity and volume of clay (left) and porosity and volume of bitumen (right). Fluid substitution points are shown as shorter trend lines.*

*Seismic pre-conditioning*

To ensure accurate and consistent results in the 4D AVO inversion, it is necessary to apply a preconditioning workflow designed to reduce noise and match the data between vintages while preserving the 4D changes related to steam injection and production. Without this essential step, 4D anomalies due to differences in acquisition, processing and travel times are incorrectly identified as physical changes in the subsurface. Depending on the level of repeatability between vintages, an optimized pre-conditioning workflow must be tailored specifically to the project. In this case, the pre-conditioning steps included, 1) low-pass filtering, 2) exponential gain correction, 3) spectral matching and 4) 3D seismic warping. The 3D seismic warping is applied in time as well as the in-line and x-line directions to compensate for the differences in positioning of reflection events due to changes in velocity. The seismic warping is performed by first estimating a smoothly varying dynamic displacement field in time and the in-line and x-line directions to maximize the cross-correlation of events between the seismic data volumes. Displacements are computed in an iterative fashion to ensure maximum similarity between sub-stacks going into the warping. Subsequently, the cumulative displacement field is applied to correct for any travel time and/or imaging differences between vintages. The time and in-line and cross-line shifts between baseline and monitor vintages are computed on the full-stacks to limit bias. Figure 2 shows the difference of the baseline and monitor full-stacks before (a) and after (b) data pre-conditioning.

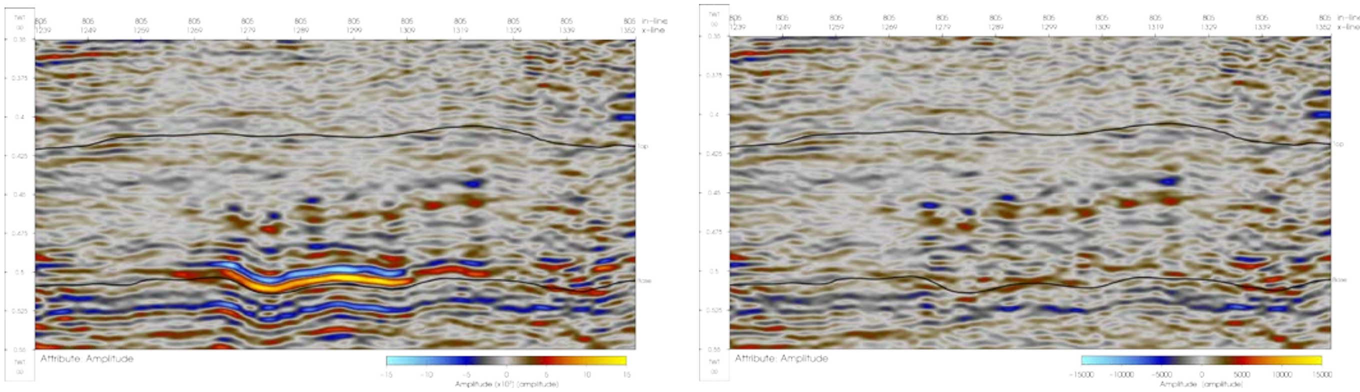


***Figure 2** In-line cross-sections of full-stack seismic amplitude difference across all well bores before pre-conditioning (left) and after pre-conditioning (right).*

*4D low-frequency modeling*

Understanding the frequency limitations of 4D inversion results is an essential step for proper interpretation. In particular, the missing low-frequencies inherent to seismic data are a significant impedement to achieving optimum results. In a 3D AVO inversion, the missing low-frequency components of our elastic properties are typically derived from low-pass filtered well logs extrapolated across the seismic volume using horizons. In a 4D sense, we do not have access to any such well data. As such, low-frequency models must by derived from other sources.

Gray et al. (2016) and Zhang et al. (2016) among others have demonstrated how we can use differentiated 4D time-shifts of PP and PS data from seismic warping to obtain velocity changes, which, under the assumption of a non-compacting reservoir, can be used to obtain 4D low-frequency models for both AI and Vp/Vs. Unfortunately, as is the case for this study, PS data is often not available. In this study, we used a probabilistic facies classification on relative (i.e. flat starting model) inversion results to derive a 4D Vp/Vs low-frequency model using only PP data. From rock phyiscs modeling, we observe that the expected time-lapse changes for both AI and shear impedance (SI) to be decreases from baseline to monitor. It follows that any observed increases in our relative inversion results are a direct consequence of the band-limited nature of our signal. These increases are therefore side lobe energy and are non-physical. We make use of this knowledge by applying a simple probablistic event classification in SI vs. AI space to separate our relative 4D inversion into steam (decrease in AI and Vp/Vs) and oil (decrease in AI and increase in Vp/Vs). These probability volumes are then used in conjunction with our differentiated PP time-shifts to create a 4D Vp/Vs low-frequency model. Section plots of the 4D AI and Vp/Vs low-frequency models are shown in Figure 3.

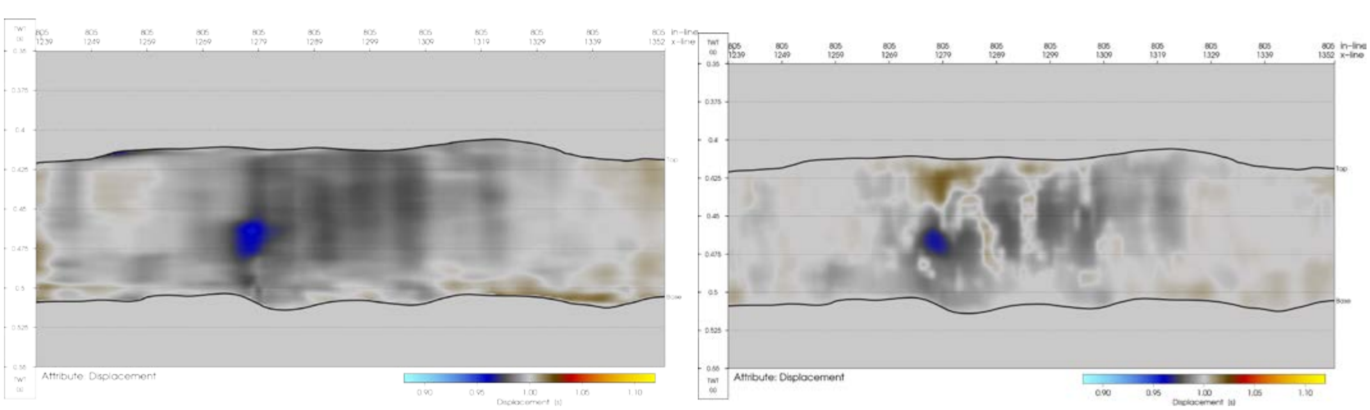

***Figure 3*** *4D low-frequency models for acoustic impedance (left) and Vp/Vs (right).*

## Results and Conclusions

Pre-conditioned angle-stacks for both vintages were inverted simultaneously for changes in acoustic impedance, Vp/Vs ratio and density. Figure 4 shows a section view of the results for the change in AI and Vp/Vs for a line across all eight horizontal wells in the survey area. All eight wells are clearly defined in both the AI and Vp/Vs results with a characteristic decrease in both AI and Vp/Vs corresponding to the steam response predicted by our rock physics modeling. The varying values observed for these decreases could be related to steaming efficiency and could be used to inform an improved development plan. Additionally, indications of heated oil are seen in areas both above and below the steam chambers as evidenced by a characteristic decrease in AI coupled with an increase in Vp/Vs. The presence of heated oil bounding steam chambers is consistent with the theoretical SAGD models wherein bitumen is conductively heated and mobilized in areas surrounding steam chambers. The detection of these anomalies in such an immature dataset (monitor survey was acquired approximately six months into steaming) reinforces the ability of time-lapse surface seismic to effectively monitor reservoir changes throughout a projects' life cycle.

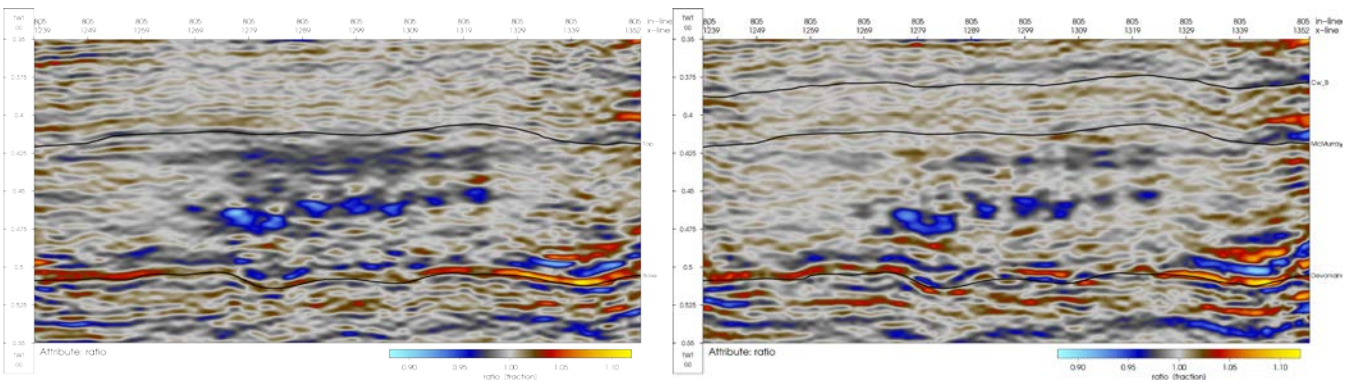


***Figure 4*** *4D inversion results for dAI (left) and dVp/Vs (right) expressed as monitor divided by baseline.*

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