Time-lapse AVO inversion and rock physics analysis of thermal heavy oil production

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ABSTRACT

Time-lapse seismic monitoring of a heavy oil reservoir undergoing steam injection is a critical step in the evaluation of production efficiency, where pressure, temperature and fluid changes in the reservoir can be monitored remotely over a large spatial area without drilling costly observation wells. Seismic amplitude data can be used to image changes in the reservoir, providing a qualitative view of production related effects and their spatial extent, however, the physical cause of the changes cannot be determined from amplitude data alone. The use of pre-stack simultaneous AVO inversion of 4D seismic data, in conjunction with rock physics analysis, 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 Athabasca Oil Sands bitumen reservoir. A holistic approach to interpretation was implemented, encompassing unconsolidated rock physics analysis, pre-stack 4D simultaneous AVO inversion to quantify elastic changes in the reservoir, and subsequent rock physics driven probabilistic lithology classification to separate our elastic changes into steam or gas, water, and mobile oil. Ultimately, the identification of various production related effects such as steam chamber development and mobile oil leads to improved reservoir optimization opportunities, allowing for an increase in bitumen production.

INTRODUCTION

Time-lapse (4D) monitoring of steam-assisted gravity drainage (SAGD) bitumen reservoirs is an important step to facilitate enhanced production over the life of a SAGD project. 4D seismic can be integrated with geological and engineering data and their interpretations to improve horizontal wellbore conformance, leading to improvements in cumulative steam to oil ratio (CSOR; the cumulative ratio of steam injected to oil produced over the life of a project), bitumen production, and ultimately enhanced cost efficiency and profit margins.

The traditional approach to seismic reservoir surveillance is partial to the qualitative analysis of 4D events on the basis of relative amplitude changes, observed on stacked seismic data. In an effort to maximize the value of 4D seismic, a transition from qualitative to quantitative interpretation is required, facilitated through pre-stack inversion to estimate elastic properties from seismic amplitudes and rock physics modeling to understand the relationship between elastic and reservoir parameters. The resulting observations and interpretations lead to enhancements in understanding both the locations of events, as well as the respective changes in reservoir parameters. Quantitative interpretation using insights from rock physics analysis provides insight into changes in actual reservoir parameters and conditions, as a function of deviations of in-situ pressures and temperatures due to steam injection.

The project is located in the Athabasca Oil Sands of Northeastern Alberta, Canada. The target of interest is the bitumen saturated sands of the McMurray Formation, a shallow unconsolidated reservoir at a depth of ~300 m below surface (Gingras and Rokosh, 2004). In the following, we discuss the various components of the project, including unconsolidated rock physics modeling, seismic pre-conditioning, 4D low-frequency model building and AVO inversion and probabilistic facies classification of the results to identify the petro-physical cause of the observed changes in the reservoir as a result of steam injection.

ROCK PHYSICS MODELING

A rock physics model was created to investigate the elastic response of the reservoir upon heating through steam injection, forming the basis for the interpretation of changes in elastic properties estimated through 4D AVO inversion. The rock physics model used for the 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, mineral fractions, mineral moduli and effective fluid moduli. The rock physics model is given by

$$\frac{1}{M+M_0} = \sum(1-\varphi)\frac{v_i}{M_i+M_0} + \frac{\varphi}{M_{fluid}+M_0}, \quad (1)$$

where M is an elastic (bulk or shear) modulus, φ is porosity, v_i is the volumetric fraction of the ith mineral, M_i is the elastic (bulk or shear) modulus of the ith mineral, M_{fluid} is the elastic modulus of the fluid, and M_0 is a regression parameter capturing local trends such as pressure or temperature affecting mineral moduli. Since bitumen has a finite shear modulus, we considered the bitumen as a third mineral phase in addition to sand and shale. A re-normalization of the in-situ volume of shale, porosity and water saturation was performed to yield volume fractions corresponding to a three mineral mix of bitumen, sand and shale. The resulting porosity then equals the space that was originally occupied by water with a water saturation of one. Subsequently, Bachrach's (2008) method was applied to predict the volume fraction of non-slip contacts to correct for the anomalously high Vp/Vs values observed in the logs caused by the unconsolidated mechanics of the reservoir. The newly derived effective sand parameters were used to derive a calibrated in-situ rock physics model with mineral end member moduli shown in Table 1.

Table 1: Elastic moduli and densities of mineral end members

Mineral	Bulk Modulus (GPa)	Shear Modulus (GPa)	Density (g/cc)
Sand	37	44	2.650
Unconsolidated Sand	37	22.2	2.650
Shale	21.8	2.7	2.600
Bitumen	4.5	0.4	1.024

To investigate the effect of pressure, temperature and fluid changes to the reservoir, we apply 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. Figure 1 shows the 4D rock physics model. For a more complete description of the workflow applied to the rock physics modeling, please refer to the accompanied paper titled "Rock physics modeling of a bitumen saturated reservoir with unconsolidated sands".

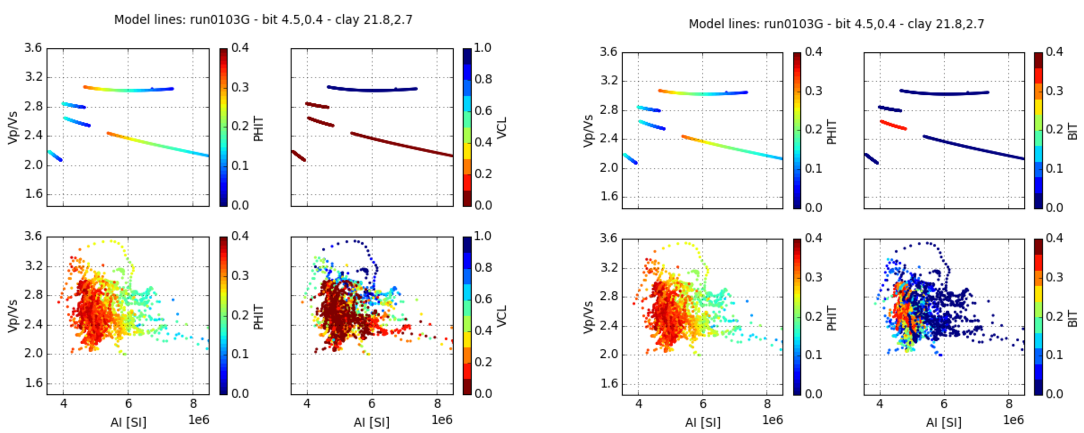

FIG 1: 4D rock physics model showing sand, clay, bitumen, steam and heated oil trend lines and observed data color coded by a) porosity and volume of clay and b) porosity and volume of bitumen. Fluid substitution points are shown as shorter trend lines.

SURVEY INFORMATION

This project was initiated with the intention of continuous monitoring of the survey area using permanently installed buried geophones to enhance ground coupling and allow for year-round acquisition. The baseline survey used for this study was acquired in 2006 prior to the buried geophone installation using traditional surface geophones. The monitor survey was acquired in 2015 using the permanent buried geophone arrays after approximately 6 months of continuous injection. At the time of the monitor survey, little-no production had taken place.

Because of the differences in acquisition between the baseline and monitor surveys, it is expected that the repeatability between the two surveys will be affected. As such, considerable effort must be spent to precondition the seismic data with the ultimate goal being to better match the two surveys by minimizing the differences in areas not affected by production.

4D AVO INVERSION WORKFLOW

Conventional 4D seismic data interpretation involves the analysis of travel time and amplitude changes between vintages to delineate the location and geometries of steam injection induced events. While amplitude and velocity changes can be linked to changes in reservoir temperature and pressure, interpretations are often qualitative in nature, and are subjected to noise and other repeatability issues. Extending the time-lapse workflow to include 4D AVO inversion, combined with rock physics analysis, can allow for a quantitative interpretation of changes in reservoir parameters. Ultimately, the objective is to: 1) improve delineation of regions undergoing steam injection through optimized seismic pre-conditioning, and 2) use rock physics-based data classification to highlight spatial variations in time-lapse character, allowing discrimination between events associated with steam and mobile heated oil.

Seismic Preconditioning

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 to eliminate high frequency noise outside the bandwidth of the 4D anomalies, 2) exponential gain correction to account for time related differences in amplitude levels, 3) spectral matching to stabilize the wavelet across the two vintages and 4) 3D seismic warping (e.g. Hale, 2013) to account for travel time and/or imaging differences as a result of velocity changes in the reservoir due to steam injection.

This last step is of particular importance as it allows for a direct comparison of amplitude changes between vintages and angle-stacks. 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. To compensate for any possible polarity reversals between angle-stacks, the Hilbert transform is used to compare the energy envelope. 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 alignment for each vintage was performed according to the order shown in Figure 2.

$$0^{\circ}\text{-}13^{\circ} \longrightarrow 13^{\circ}\text{-}20^{\circ} \longrightarrow fullBaseline$$

$$\longleftarrow 20^{\circ}\text{-}26^{\circ} \longleftarrow 26^{\circ}\text{-}31^{\circ} \longleftarrow 31^{\circ}\text{-}36^{\circ} \longleftarrow 36^{\circ}\text{-}41^{\circ} \longleftarrow 41^{\circ}\text{-}45^{\circ}$$

FIG 2: Ordering of warping alignment.

The time and in-line cross-line shifts between baseline and monitor vintages are computed on the full-stacks to limit bias. In this study, the full-stacks contain data from 5-31 degrees. Figure 3 shows the in-line (a), cross-line (b) and time (c) displacements between the baseline and monitor full-stacks extracted at the reservoir interval. The displacements are localized to the area of the horizontal well pairs and provide an indication of the areal extent of steam injection related anomalies. Figure 4 shows the difference of the baseline and monitor full-stacks before (a) and after (b) data pre-conditioning.

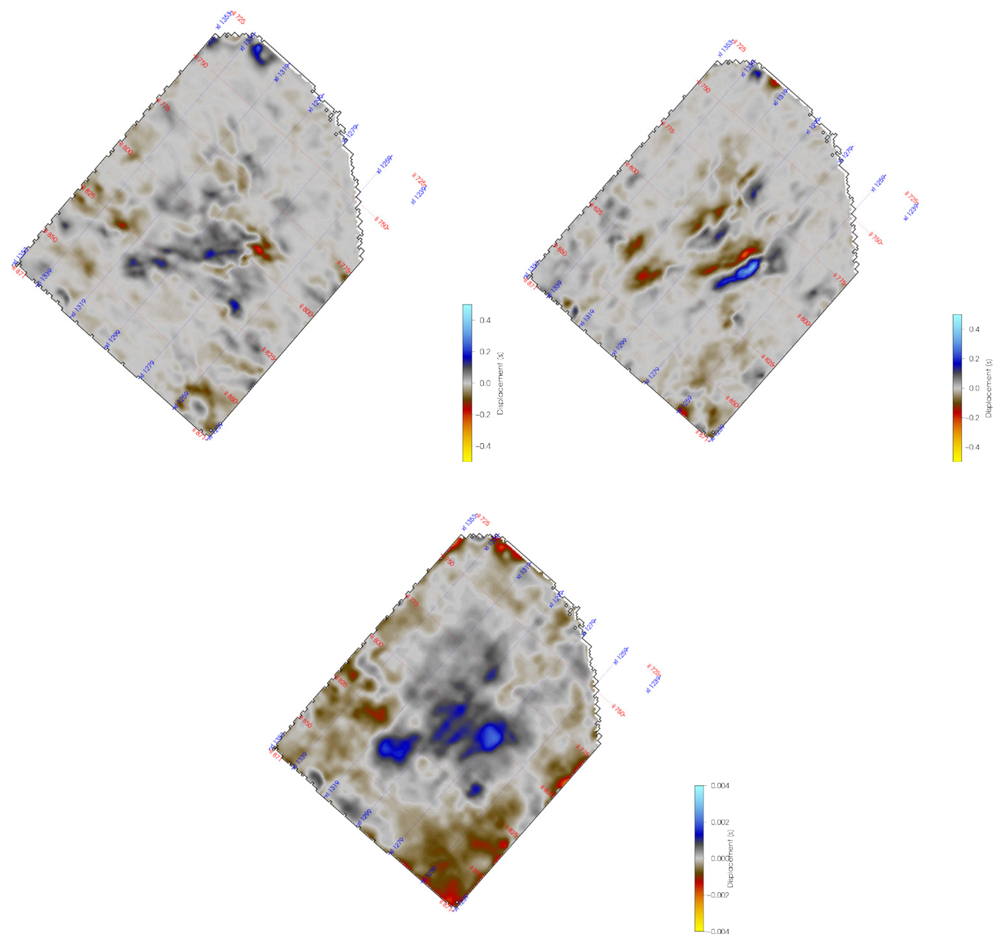

FIG 3: Horizon slices through the reservoir zone showing a) in-line displacement b) cross-line displacement and c) 4D time shifts.

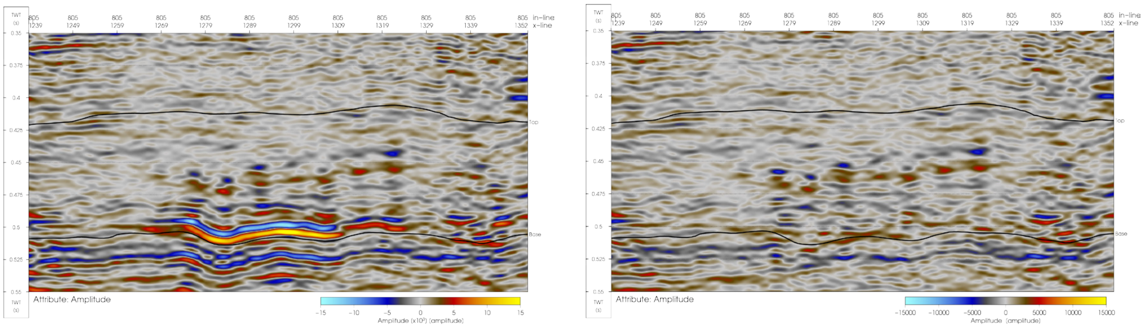

FIG 4: In-line cross-sections across all well bores a) before pre-conditioning b) after pre-conditioning.

Relative 4D AVO Inversion Results and Wedge Modeling

Pre-conditioned angle-stacks for both vintages were inverted simultaneously using an Aki-Richards inversion kernel parameterized in terms of changes in acoustic impedance, Vp/Vs ratio and density. The 4D inversion algorithm inverts simultaneously and symmetrically for 4D changes to limit bias towards any particular survey. Figure 5 shows a section of the 4D changes represented as a ratio of the monitor and baseline surveys for acoustic impedance (a) and Vp/Vs ratio (b) along the trajectory of one of the well pairs. Decreases in acoustic impedance and Vp/Vs ratio are visible as blue features within the reservoir zone, and are bounded by apparent increases in acoustic impedance and Vp/Vs ratio. Decreases in both acoustic impedance and Vp/Vs ratio correspond to the effects of steam injection and are consistent with the expected results as indicated by the rock physics modeling, whereas an increase in AI is not a result that is supported by our rock physics model. A simple wedge modeling exercise was performed to gain insight into the observed changes.

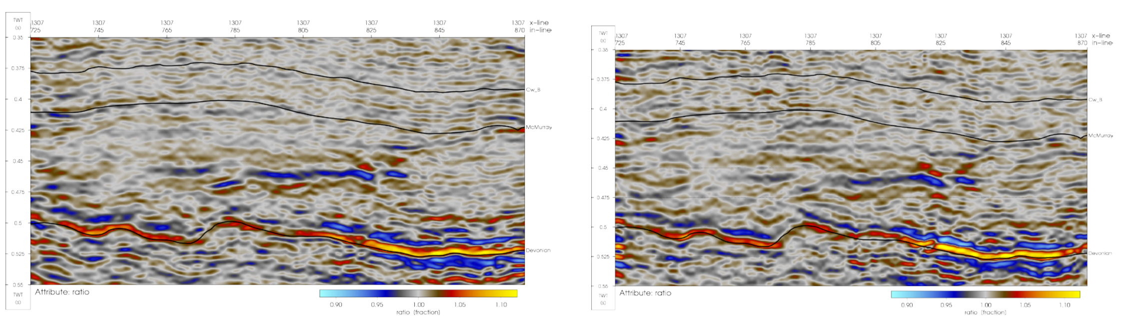

FIG 5: Cross-section of the ratio of monitor to baseline along a well-bore of a) acoustic impedance and b) Vp/Vs ratio.

To understand the nature of the relative 4D AVO inversion response, inversion tests were performed on a series of synthetic wedge models. The objective of this exercise was to investigate the band-limited nature of the input seismic data, and in particular, the missing low frequencies outside the seismic bandwidth. Here, we perform the modeling for acoustic impedance, where two separate models representing the reservoir properties at the time of the baseline and monitor were inverted. Subsequently, the ratio of the inversions was computed to investigate the response of the inverted 4D changes.

Figures 6a-6c show the input model of the baseline, monitor and their ratio respectively, which represents the expected result in the case of zero noise and infinite bandwidth (i.e. a perfect inversion). Figures 6d-6f show the results of the band-limited inversion, where synthetic seismograms are generated by convolving a wavelet with the model reflectivities and subsequently inverted using the same initial model for both the baseline and monitor wedges. In this band-limited case, the wedges are not perfectly resolved and exhibit strong side lobe energy above and below the 4D changes within the wedge that is consistent with the observations in our real data as shown in Figure 5. The increases in AI are therefore interpreted as the result of missing low frequencies in our seismic data and highlight the need to obtain 4D low-frequency models in order to obtain an improved inversion result.

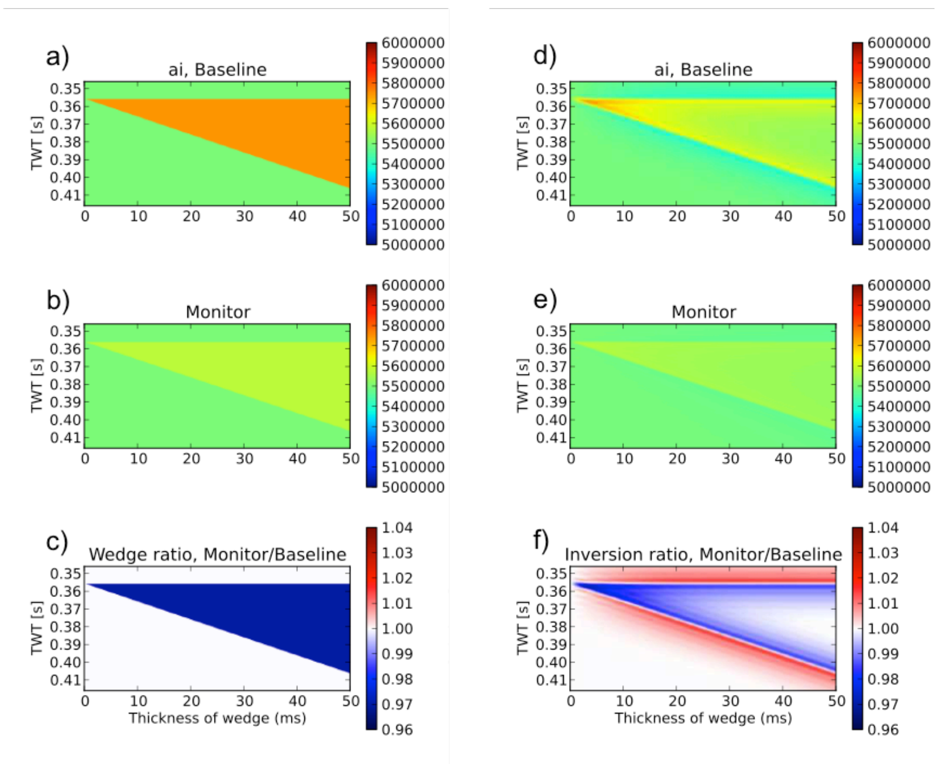

FIG 6: Wedge modeling of acoustic impedance showing perfect, full bandwidth inversion result on the left and band-limited result on the right.

4D low-frequency modeling

Understanding the frequency limitations of our 4D inversion results is an essential step to proper interpretation of our 4D results. In a 3D simultaneous 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 to guide structure with the possible inclusion of seismic velocities as a guide if the velocity model is accurate. In a 4D sense, we do not typically have access to 4D log data or accurate 4D seismic velocities to use as an input. As such, to minimize the band-limited effects on our inversion results, a low-frequency model must be derived from other means. Gray et al. (2016), Nasser et al. (2016) and Zhang et al. (2016) describe ways of building a 4D acoustic impedance low-frequency model using the 4D time-shifts that were calculated between vintages during the seismic warping under the assumption of a non-compacting reservoir. For this study, this assumption is assumed to be valid, but it should be noted that in an unconsolidated reservoir such as the McMurray formation, where porosities are near critical porosity, it is possible that either compaction or void creation could occur during steaming and production. A cross-section view of the computed 4D acoustic velocity change is shown in Figure 7.

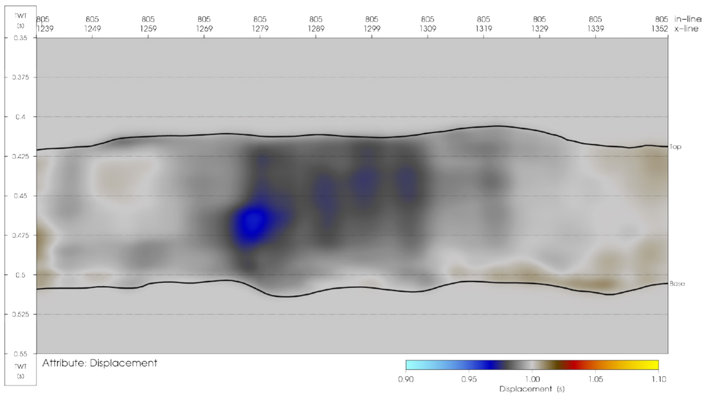

FIG 7: Acoustic velocity change computed from differentiating 4D time-shifts.

In a similar way, if three component data were available, a 4D Vp/Vs ratio low-frequency model can be calculated using 4D time-shifts of both the PP and PS data. Ziegler (2013), Gray et al. (2016) and Zhang et al. (2016) among others describe this process and the need for a 4D Vp/Vs low-frequency model to properly delineate areas with mobile heated oil. Unfortunately, in this study only PP seismic data were available requiring the 4D low-frequency Vp/Vs model be derived by other means.

Mesdag et al. (2015) describe a method of obtaining a 4D Vp/Vs model by linearly interpolating values between the identified top and bottom of interpreted chamber horizons. This method can be effective if changes are smoothly varying and uniform through a given zone, but is heavily reliant on interpretation of relative events and can lead to anomalous results if there is for instance remaining unmoved mobile bitumen within a steam chamber or other fluid separations from the top to bottom of the interpreted chambers.

Nasser et al. (2016) describe a different method using smoothly varying cross-correlations calculated between 4D acoustic velocity change and relative 4D shear impedance change. This method makes use of some basic rock physics theory. In the case of their study, a replacement of fluid from water to oil implies a change in acoustic velocity, but little-no change in shear impedance, while a change in effective stress implies a change in both acoustic velocity and shear impedance. A similar technique was applied to this dataset using a probabilistic facies classification on relative 4D inversion results. As can be seen in our rock physics modeling, if we assume no compaction due to steaming, our expected changes for both AI and SI should 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 can make use of this knowledge by applying a simple probabilistic facies classification to separate our relative 4D inversion results into steam, oil, noise and lobe effects. In a similar way to the cross-correlation method, we can use these facies volumes in conjunction with our 4D acoustic velocity change volume to create a Vp/Vs low-frequency model.

Figure 8 shows the probability density functions (PDFs) for oil, steam, oil lobe, steam lobe and noise in dSI vs. dAI space. The changes here are expressed as the ratio of the monitor divided by the baseline. Note that the oil and steam PDFs are separated approximately by a 1:1 line trending across dSI vs. dAI space. This simplistic interpretation comes from our rock physics analysis wherein if there is a larger decrease in AI than SI, we get a decrease in Vp/Vs, and are likely observing a steam effect. In contrast, if there is a larger decrease in SI than AI, we get an increase in Vp/Vs and are likely observing a change of state from bitumen to heated oil.

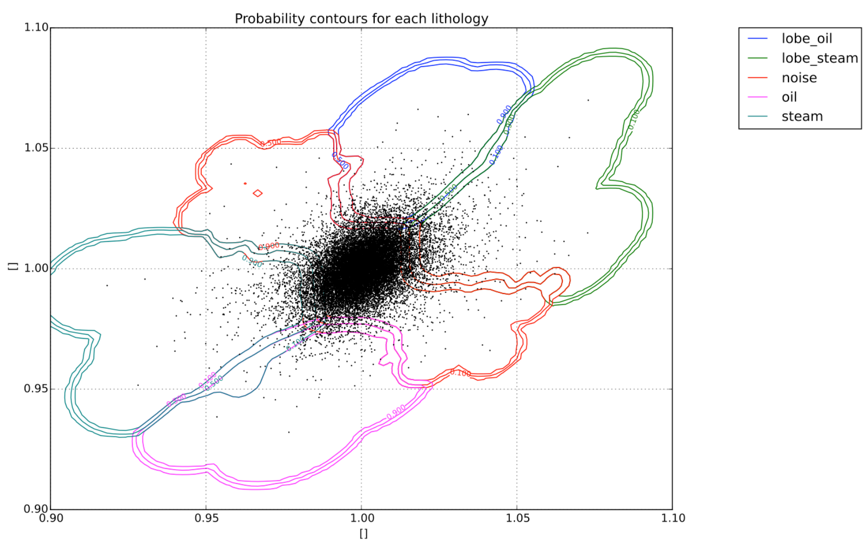

FIG 8: Probability density functions mapping steam, oil, noise, steam lobe and oil lobe facies. The y-axis is the ratio of shear impedance change and the x-axis is the ratio of acoustic impedance change.

We can then use these classifications in conjunction with our 4D acoustic velocity model to create a Vp/Vs model that has a relative increase in Vp/Vs in areas classified as either oil or oil lobe and a relative decrease in areas classified as either steam or steam lobe. Figure 9 shows the oil and steam facies classification results through an inline section of the survey along with the resulting 4D Vp/Vs low-frequency model that will be used as an input to an absolute 4D AVO inversion.

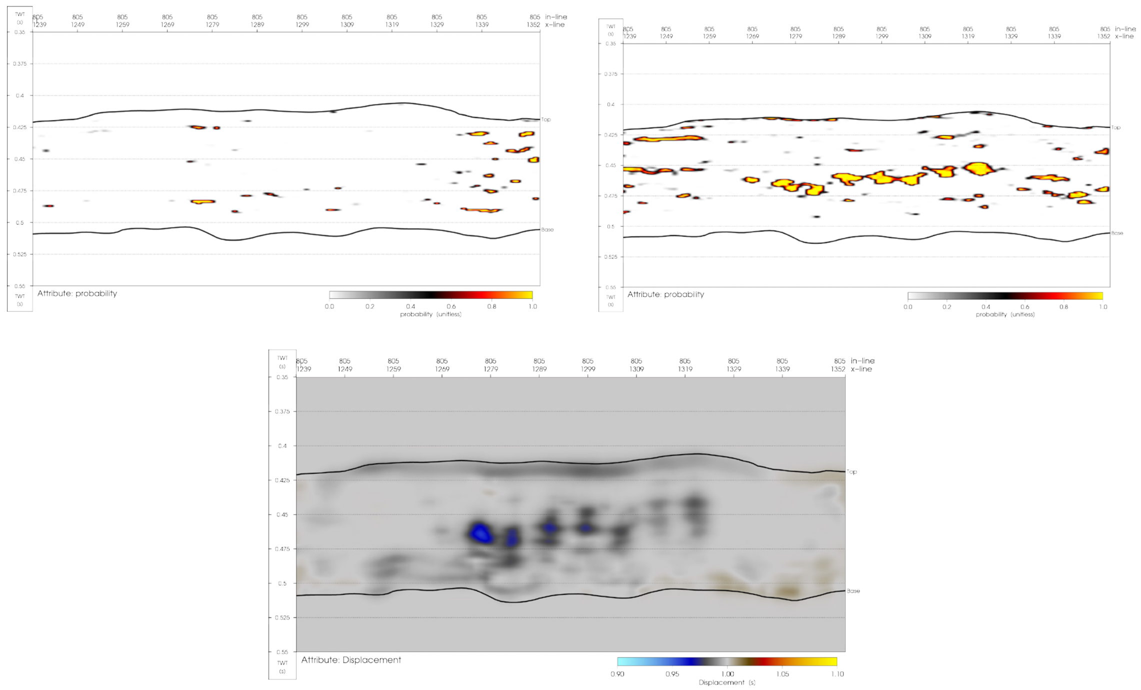

FIG 9: a) Heated oil probability, b) steam probability and c) 4D Vp/Vs low-frequency model.

RESULTS

Pre-conditioned angle-stacks for both vintages were inverted simultaneously for changes in acoustic impedance, Vp/Vs ratio and density using the 4D low-frequency models described in the previous section. Cross-sections of the 4D changes represented as a ratio of the monitor and baseline surveys for acoustic impedance and Vp/Vs ratio along the trajectory of one of the well pairs are shown in Figure 10. Notice that the side-lobes observed in the relative inversion results are largely removed, leading to an improvement in the resolution and interpretability of the results.

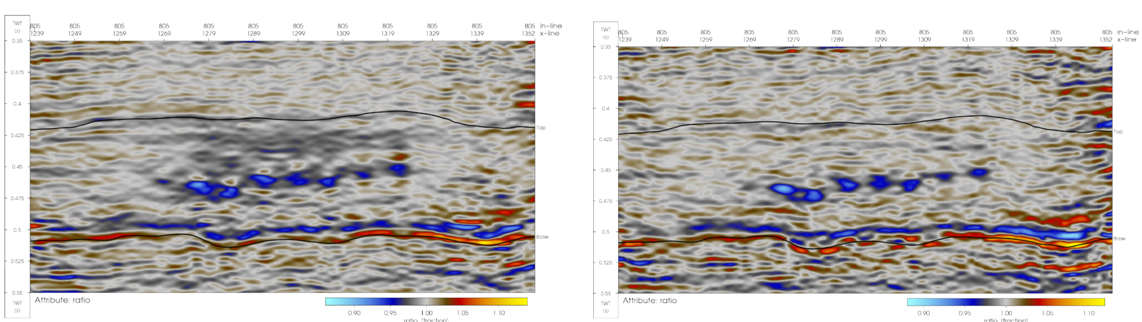

FIG 10: Acoustic impedance (left) and Vp/Vs (right) monitor to baseline ratios.

Figure 11 shows horizon slices through the reservoir zone of the minimum dAI and dVp/vs and maximum dVp/Vs absolute 4D inversion results. Although not shown, we note that in the absolute 4D results, the acoustic impedance maximum maps are still partially contaminated with side-lobe energy as demonstrated by and apparent increase in AI along some well bores. With improved frequency coverage in our seismic it is possible that this effect could be further minimized, but currently these lobes remain an on-going source of noise in our results. Nonetheless, the 4D low-frequency models still provide a significant improvement in the inversion results.

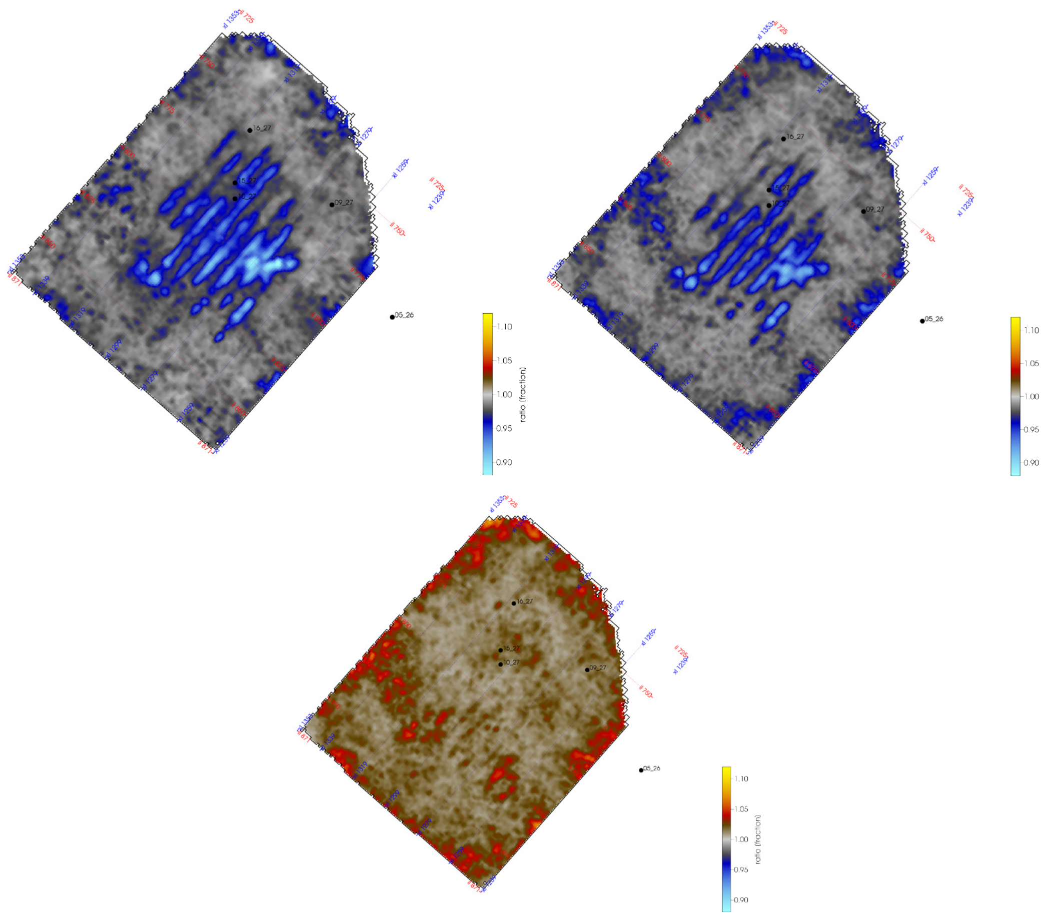

FIG 11: Horizon slices of elastic property changes through the reservoir zone. From top left to bottom: minimum dAI, minimum dVp/Vs, maximum dVp/Vs.

Interestingly, in spite of how early this survey was taken with respect to the life span of an oil-sands project, we can already clearly see all eight well bores delineated with decreases in both AI and Vp/Vs ratio corresponding to the steam response. Additionally, there are also possible indications that we are beginning to see bitumen changing phase to heated oil as evidenced by the remaining increases in Vp/Vs ratio. The fact that we are able to easily detect these anomalies only six months into steaming reinforces the utility of using time-lapse seismic to monitor thermal heavy oil production.

UNCERTAINTY AND FUTURE WORK

The elastic inversion workflow for this project is largely completed, but ultimately the goal of this study is to use our rock physics model to complete a 4D rock physics inversion wherein changes in fluid, and ideally temperature and pressure are quantified. The coupling of fluid effects with temperature and pressure effects is an on-going source of uncertainty in our rock physics modeling and by extension, any rock physics inversion. This problem is compounded by the fact that we only have two parameters (dAI and dVp/Vs) that we can estimate with any kind of certainty. Trying to use only two parameters to estimate potentially upwards of four parameters (eg: heated oil, steam, temperature and pressure) is by definition an underdetermined problem. As such, subsequent rock physics inversion studies on this dataset will be limited to estimating the most significant of these effects. However, without any available 4D calibration points for elastic properties of the reservoir with heated oil or steam etc. the results of any such rock physics inversion study will be very difficult to validate. Nonetheless, as an exercise in demonstrating the possibilities of 4D seismic inversion technology on thermal heavy oil reservoirs, the study could be valuable. Ultimately, to limit bias and validate any 4D inversion project it is required that there be 4D calibration points in the form of observation wells re-logged during operation, or cumulative injection or production or temperature or pressure logs.

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