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Fluid Characterization using 4D Simultaneous AVO and Rock Physics Inversion

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Summary

Time lapse (4D) seismic is a well-established technology used to monitor production in oil and gas fields. Specifically, in oil-sands SAGD operations the outcomes of injecting steam in conjunction with bitumen production are fluid replacement, temperature and pressure changes, and geomechanical effects within the reservoir. Together these changes create time-lapse responses which are possible to detect on 4D seismic.

Time lapse seismic has multiple roles during the life cycle of SAGD operations. First, at the early stages of steam injection, the proper steam distribution along the horizontal section is highly important for efficient steam chamber development and proper balance of steam-oil ratio (SOR). Time-lapse seismic data is particularly effective in tracking thermal changes due to steam migration and the heterogeneity of the reservoir by way of 2D maps or 3D geo-bodies for a qualitative interpretation. However, advancing with quantitative methods is required for a better understanding of swept or stranded heated bitumen zones as the steam chambers grow to reach a mature state. Maturity is reached when most of the steam has conformance entirely along the horizontal section of the well path, has communicated with neighboring wells, and has reached the top of the reservoir. Quantitative 4D seismic interpretation and rock physics analysis are essential to decouple the often-competing effects embedded in a 4D signal.

This paper outlines a case study of a quantitative workflow using 4D simultaneous AVO and 4D rock physics inversion to detect changes in the spatial distribution of the steam chamber and heated bitumen in the subsurface. A 4D McMurray oil-sands dataset is analysed, with 7 years between start of steaming and production, and acquisition of the monitor survey.

This workflow entails performing AVO-preserving seismic preconditioning on the baseline and monitor seismic data to both minimize 4D noise, and account for 4D velocity changes from baseline to monitor. A 3D absolute AVO inversion is first performed on the baseline to optimize this preconditioning, as well as wavelet and inversion parameter selection. A simultaneous 4D AVO inversion is then performed on the baseline and monitor surveys, to invert for 4D changes in Acoustic Impedance and V_p/V_s ratio. A baseline 3D rock physics inversion for mineral fractions, porosity and fluid saturations is performed to optimize parameters and to use as a constraint for the 4D rock physics inversion. This 4D rock physics inversion is then run with the primary goal of estimating changes in gas saturation (steam) and water saturation (heated bitumen).

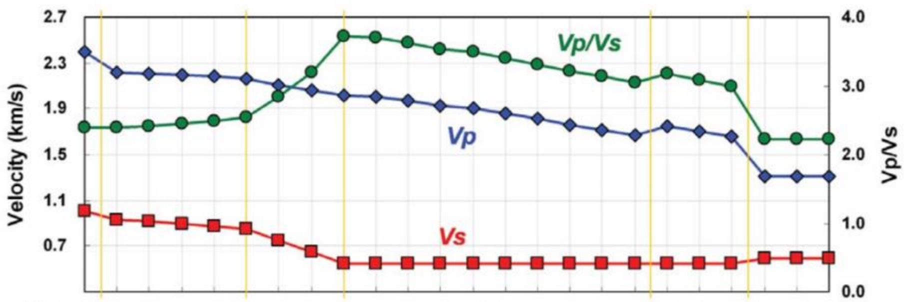
A key additional insight through this work is the observations from steam core measurements of elastic logs during production. The resulting changes in elastic properties differ significantly from expected responses and demonstrate the fundamental need to properly collect these monitor data for correct inversion interpretation.

Theory

This section provides a brief, high-level description of AVO inversion and rock physics inversion. An inverse problem involves calculating a model from a set of observations. In AVO inversion, we calculate the elastic model of the subsurface that produced the angle-dependent reflection amplitudes observed in seismic data. An Aki-Richards (1980) inversion kernel, a linearized version of the Zoeppritz equations, was used to compute the angle-dependent reflectivities. In this case, pre-stack partial angle-stacks for each vintage were inverted simultaneously for changes in acoustic impedance, V_p/V_s and density. Angle-dependent wavelets and pre-conditioning of the input seismic data were rigorously tested through to inversion to determine the optimum inversion settings for any given dataset. It is of utmost importance that we achieve the most accurate and robust elastic inversion result possible in order to ensure any subsequent interpretation and rock physics inversion is also accurate.

The 4D rock physics inversion operates similarly to the 3D, but the 4D elastic inversion results are used as input to this inversion to invert for changes in gas (steam) and oil (heated bitumen) saturations. The process of the 4D rock physics inversion produces quantifiable results that can easily be communicated across disciplines and is a robust tool to simplify the interpretation of 4D data. Additionally, 4D data signals that are not explained by the rock physics framework are effectively filtered, or isolated for further analysis.

The inverted 4D elastic changes can be classified into fluid responses to build prior models for the 4D rock physics inversion. Kato et al. (2008) performed experimental lab simulations of steam injection on core to measure how P and S-wave velocities change with changes in reservoir pressure and temperature. The figure below shows the results of this study, with the key finding showing that as temperature increases, V_s decreases more rapidly than V_p, leading to V_p/V_s increasing sharply as the reservoir and bitumen are heated. The interpretation of this observation is that the bitumen is so viscous that at in-situ conditions it actually behaves as a quasi-solid phase with a finite shear modulus. As the temperature increases and the viscosity decreases, the shear modulus collapses to zero resulting in a characteristic sharp decrease in V_s.



Step	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Pp (psi)	300	300	400	500	600	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700
T (°C)	10	10	10	10	10	10	15	20	25	30	50	70	80	100	120	140	160	180	200	220	240	260	280	300
Sw (%)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	80	80	80	80	80	80

Figure 1: Reservoir simulation results showing sequential changes in P- and S- wave velocities and V_p/V_s ratio induced by steam injection. From Kato (2008).

These theoretical changes in V_p and V_p/V_s were initially used to classify fluid changes from 4D elastic inversion results. The V_p/V_s is key to decoupling different production effects as an increase in V_p/V_s indicates heated bitumen, while a decrease indicates steam is causing a gas effect in the reservoir. Any increase in V_p or acoustic impedance are defined as noise in a 4D sense, as velocity increases aren't expected to occur with steam injection. Importantly, this expected increase in V_p/V_s in bitumen saturated zones was not in fact observed in the steam core data acquired in this study.

Method, Workflow, and Observations

Preconditioning

While the scope is large and workflow complex in a 4D rock physics inversion for fluid classification, the initial step is to perform a relatively simple AVO and rock physics inversion on the baseline seismic survey. By doing so, the geophysicist may calibrate and optimize many aspects of the inversion (such as preconditioning, wavelets, parameters, prior models) which are applied throughout the 3D and 4D inversions. These results are also useful for building initial reservoir geomodels and understanding virgin reservoir conditions.

For this project, preconditioning on the baseline angle gathers included filtering to remove low and high frequency noise (4, 8, 140, 165 Hz corner frequencies), and radon de-multiple to remove multiples contaminating the McMurray interval. After stacking into angle-stacks ranging from 0-57°, a Cadzow FXY deconvolution is applied to remove remaining random noise in the seismic. Additionally, to correct for minor spectral differences between vintages, the monitor is spectrally matched to the baseline survey.

Alignment of seismic events in the angle stack domain is important for properly capturing the true AVO response of each seismic event, and the associated lithology. For 4D studies, proper alignment of events between vintages is extremely important for accurately capturing 4D elastic and petrophysical changes

Simultaneous 3D AVO Inversion, and rock physics inversion

Prior to moving forward with the 4D inversion, 3D elastic and rock physics inversions are performed on the baseline survey. This is done to calibrate the inversion and seismic parameters, and to estimate reservoir properties prior to steaming and production. The preconditioning and wavelets used for the baseline inversion are the same as will be used in the 4D inversion. A facies-driven low-frequency model is generated from the relative inversion results and well-logs. The well logs are filtered using elastic and petrophysical log cut-offs to produce trends typical of a sand and shale in this reservoir, which are broadcast across the volume to produce sand and shale low frequency models. The relative inversion results are then classified into sand and shale responses. Using log cut-offs to define sand and shale responses, we generate probability density functions for sand and shale which are applied to these volumes, producing lithology probability volumes. The lithology trend low-frequency models are applied per the lithology probability volumes, generating facies-driven low frequency models. An absolute inversion is then performed, generating inverted acoustic impedance, V_p/V_s, and density volumes for the baseline survey.

These elastic volumes are used as input into a rock physics inversion. A calibrated rock physics model has been produced based on the client's well logs and petrophysics, tying the elastic properties to petrophysical properties. Using the rock physics model and the inverted elastic volumes, we can invert for any reservoir property that included in the model, such as porosity, mineral fractions, and fluid saturations. In this study, we invert for porosity, volume of shale, and water saturation. While these results aren't the final goal of the overall study, they can be very useful for reservoir modelling. Correlations of inverted properties to well log values were between 75-80%, and these are essential for updating the geological model. The rock physics inversion achieves an average correlation of 60%, with several wells exceeding 80% correlation to logs.

Simultaneous 4D AVO Inversion

Both vintages are inverted simultaneously for changes in acoustic impedance, V_p/V_s, and density. The first step is to run a relative inversion, using constant background models for each property that assumes no change. The relative inversion results are used for classifying steam and heated oil as part of 4D low-frequency model building. We are able to build 4D low-frequency models for AI and V_p/V_s using the 4D relative inversion results and the displacement field resulting from the 4D alignment. Differentiating the 4D warp displacement field provides an analogue to the limits of steam chambers and production effects in the seismic volume. Initial fluid classifications can be applied on the 4D relative inversion results. Figure 2 shows the definition of these fluid classification probability density functions. These classifications are based on theoretical expectations from Kato (2008) and the results in Figure 1 where increases in V_p/V_s indicate the presence of heated oil and decreases indicate steam. 4D Increases in AI are generally considered noise, however pressure or saturation changes can in some cases cause this increase. For this study, the threshold for 4D changes is set to a maximum AI 4D ratio of 1.

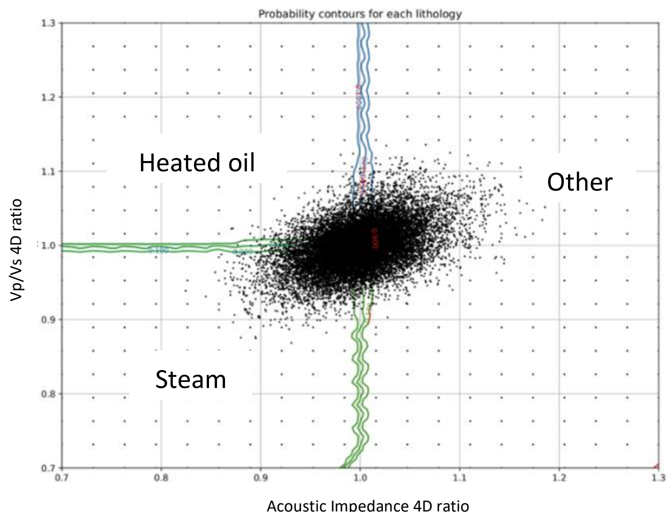


Figure 2: Probability density functions for fluid classification on relative 4D inversion results.

The 4D V_p/V_s low-frequency model is built by combining the differentiated warp displacements with the steam and heated oil probabilities. Where there is probability of steam in the classification, we expect both the V_p/V_s and the V_p to decrease, therefore we simply scale the differentiated displacement field by the 4D relative V_p/V_s change. Where there is probability of heated oil, we expect V_p to decrease, but the V_p/V_s to increase, therefore we flip the polarity of the differentiated displacement field and then scale by the 4D relative V_p/V_s change. Ideally, the 4D V_p/V_s low-frequency model would be built using the 4D displacements field resulting from the alignment of converted wave data, however this is very costly and difficult to acquire and process, thus isn't often available as was the case for this study. The workflow applied here requires an extra step of interpretation, and is therefore less certain, but demonstrates that 4D V_p/V_s low-frequency models can be created using only PP data.

4D Rock physics inversion

The primary goal of the 4D rock physics inversion is to invert the 4D elastic property changes for changes in fluid saturations. The 3D baseline rock physics inversion results serve as prior models for the 4D inversion. With the fluid properties of steam, heated oil, and bitumen, we can invert for changes in gas saturation (steam), and changes in water saturation (heated oil). We are able to resolve the shape and distribution of steam chambers, as well as distribution of heated oil (mobile bitumen) around the steam chambers (Figure 3). These fluid saturation changes correlate well to temperature logs, providing validation of these results.

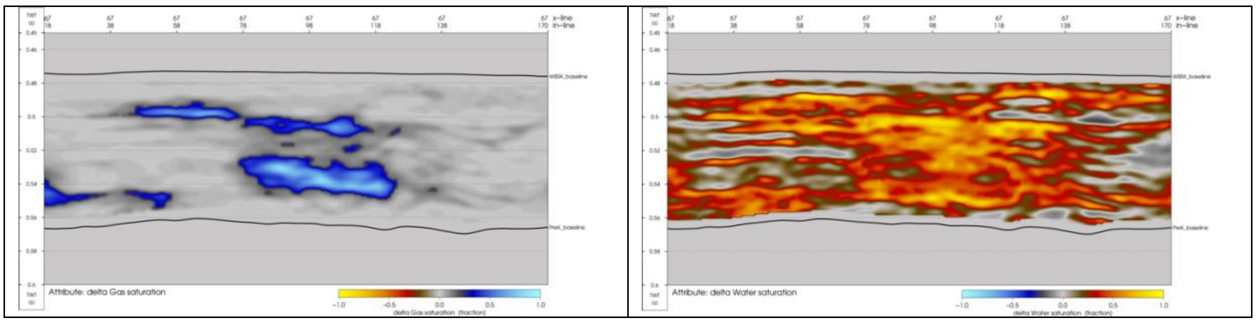


Figure 3: 4D rock physics inversion results for change in steam saturation (left) and change in heated oil saturation (right).

Results, Observations, Conclusions

An extremely valuable data point in this study was steam core logs, providing a validation point for the 4D elastic inversion and direct measurements for 4D interpretation and rock physics modelling. Some key differences from Kato (2008) were discovered when exploring the steam core data: V_p decrease with temperature was consistent between the lab measurements and the steam core. However, rather than observing the expected decrease in V_s, the steam core showed an increase in V_s with increasing temperature. This leads to an overall decrease in V_p/V_s with increasing temperature, for both steam and heated oil. These data are shown in Figure 4, colored by temperature log data. Applying the pdf's shown in figure 2 to this data would produce erroneous fluid classifications, both in general and for use in low-frequency models. This data supports the conclusion that for this area, the bitumen does not in fact have a finite shear modulus and that the rock physics behaves in general more similar to a standard fluid. We do not currently have an explanation for why the V_s would increase with increasing temperature, but this behavior was observed consistently in all three steam core wells that were acquired.

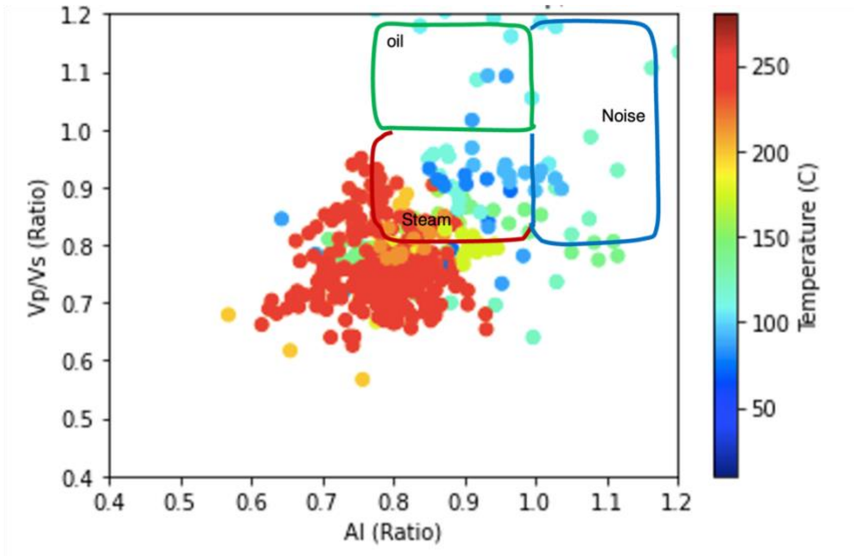


Figure 4: Steam core Vp/Vs vs AI, colored by Temperature. Steam core data shows an overall decrease in Vp/Vs with temperature, counter to the results from Kato (2008). PDF's from figure 4 are overlain, demonstrating invalidity for this dataset.

Due to the disagreement between these steam core results and our previous classification, reassessing the fluid classification was necessary. New PDF's for steam, heated oil, and noise were calibrated to these results (Figure 5), and applied to the inversion results and low-frequency models. The 4D absolute and rock physics inversions were repeated with these new models. Fluid classifications for steam and heated oil are much more well defined with the steam core calibrated PDF's (Figure 6). Steam chamber development and extent now correlates more clearly to injector/producer well pair locations.

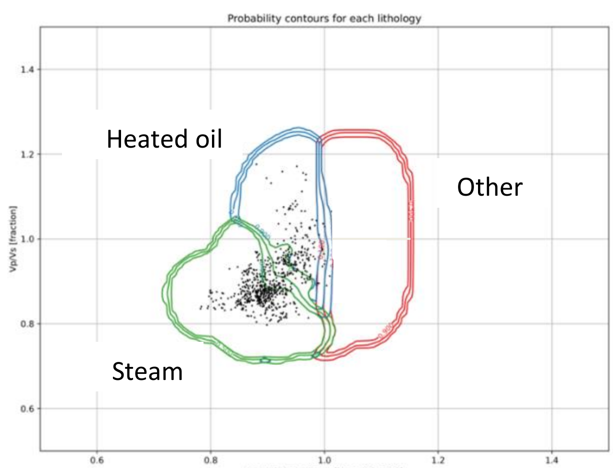


Figure 5: Updated fluid classifications on relative inversion results, based on steam core and temperature data.

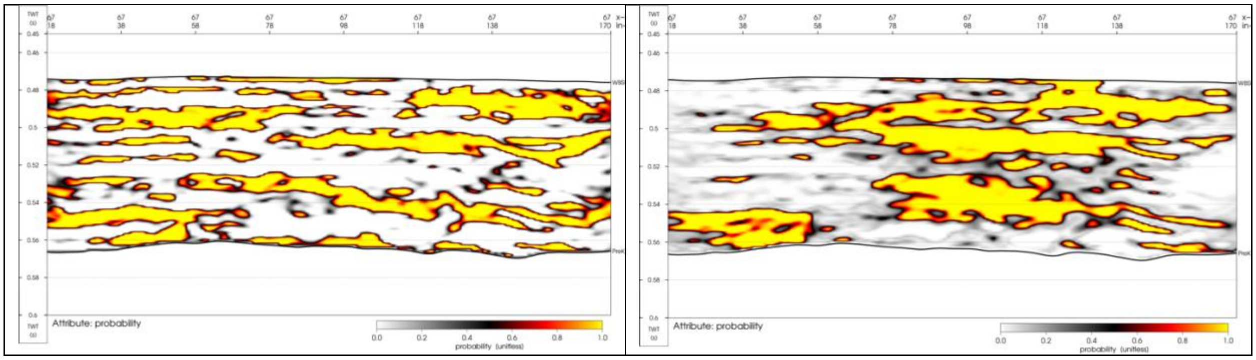


Figure 6: Difference in fluid classifications for steam probability when using theoretical/lab cutoffs (left), and calibrating to steam core data (right)

Conclusions

The 4D inversion workflow presented produced results which match the elastic and temperature logs very well. These outcomes of validated fluid saturations changes, steam core calibrated fluid classifications, and high correlation porosity and volume of shale inversions provide useful products for further reservoir development. This includes geomodel updates, economics estimates, steam injection guidance, and infill well drilling decisions. Steam core measurements as validation led to refining fluid classifications on 4D elastic inversion results, generating uplift over using theoretical/lab measured responses.

Once the workflow has been developed, and parameters fleshed out for a particular area or client, repeated inversions for new monitor surveys or for new 4D studies nearby are simplified.

Acknowledgements

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