

# Forecasting bitumen state and production from 3C-4D seismic

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## Summary

Assessing the liquid state of bitumen and its production is now possible from 4D seismic. From conventional 4D seismic data, steam chamber volume can be determined. From 3C-4D (3-component, 4-dimensional) PS (P-wave down, converted S-wave up) seismic data, the liquid state of the bitumen, immediately produceable bitumen, and future produceable bitumen can be forecast. This presentation shows how we have done this. During steam assisted gravity drainage (SAGD) processing of an oil sands reservoir, two marked phase changes occur. First, bitumen changes from a quasi-solid state to a produceable liquid state when heated. Changes in the  $V_p/V_s$  ratio determined from 3C-4D seismic data in oil sands reservoirs indicate the presence of bitumen heated to its liquid, and therefore mobile and produceable state. Second, a steam chamber develops as the liquid bitumen is displaced with gas and steam during production. Therefore, the size of the steam chamber is used to quantify all these measurements by comparing it to how much bitumen has been produced by the time of the 4D seismic acquisition. From this calibration, and well measurements, it is possible to quantify the other effects. The use of 3C-4D seismic data is critical to assess where the heated bitumen resides in the reservoir because it exists around the steam chamber, and can be detected best by low-frequency changes in the  $V_p/V_s$  ratio. The 3C-4D differences allow the visualization of these low-frequency high  $V_p/V_s$  ratio zones outside the steam chamber.

The 3C-4D suggest a much broader expanse of mobile oil above and around the steam chamber than might be suggested by Butler (1991) theory. In addition, it appears that a lot of mobile bitumen sits below the producers and therefore will be difficult to produce with a gravity method. This has important implications for the type and placement of infill and extension wells in and around existing SAGD well pairs, as well as for workovers.

## Introduction

Zeigler (2013) demonstrated that significant changes in  $V_p/V_s$  ratios are associated with the change from quasi-solid bitumen (Han et al, 2007) to its liquid form. When quasi-solid bitumen is heated to its liquid state, its shear modulus, and therefore shear velocity ( $V_s$ ), go to zero, which is one definition of a liquid. Meanwhile, the bitumen's P-wave velocity ( $V_p$ ) gradually decreases as the bitumen warms. The significant drop in  $V_s$ , combined with a slight decrease in  $V_p$ , cause a large increase (>30%) in the  $V_p/V_s$  ratio of the sands containing heated, liquid, and therefore, mobile bitumen. This increase in the  $V_p/V_s$  ratio is significantly larger than the decrease in P-wave impedance commonly used to identify the steam chamber in an oil sands reservoir. Therefore, the  $V_p/V_s$  ratio change associated with heated bitumen should be quite prominent and observable in 3C-4D differences, even with the lower resolution of PS data. The  $V_p/V_s$  ratio undergoes a substantial increase only during its liquid state and the  $V_p/V_s$  ratio is approximately equal to or

lower than the  $V_p/V_s$  of virgin reservoir when steam replaces the bitumen. Due to the thickness (0-50m) of the steam chambers and the heated bitumen surrounding them in Athabasca oil sands reservoirs, these  $V_p/V_s$  anomalies will often be so thick as to be below the period of the conventional P-wave seismic wave. Therefore, conventional seismic can only see their top and base, but not the full chamber (Pro4D Guide, 2007). Time-lapse interpretation of the differences in the deepening velocities, ideally from PSDM (pre-stack depth migration), through the heated zones or differences in the time horizons (Zeigler, 2013) in the 3C seismic monitor survey below the heated zones, identify thick zones of liquid, mobile bitumen on the edges of the steam chambers and around the producing wells. Reversing these observations, large, thick, increases in  $V_p/V_s$  ratio imply the presence of substantial volumes of heated, mobile bitumen. Through the use of pre-stack, joint inversion (Hampson et al., 2005) and multiattribute transforms (Hampson et al., 2001), we create volumes of gas, temperature, and saturation, which allow us to evaluate the 3C-4D anomalies by comparing them to well logs from observation wells in and around the steam chamber. The conventional 4D difference can be related to the amount of bitumen that has already been produced (Zhang et al 2017). The 3D differences in  $V_p/V_s$  ratios produced by the 3C-4D method allow us to interpret where bitumen has been heated to the point where it is mobile and therefore produceable. This will have a significant impact on our ability to optimally place infill wells and adapting operating strategies for production optimization in the existing SAGD well pairs.

## Method

The method for applying a 3C-4D inversion to oil sands data is described in Gray et al (2016). Critically, the inversion of the PS-wave 3C-4D seismic monitor needs a low-frequency adjustment to its background model to account for the significant drop in S-wave velocities through the mobilized bitumen zone. Due to the thickness of the steam chamber in this Athabasca reservoir, this drop in S-wave velocities is below the period of the P-wave and the PS seismic data. Therefore, the critical step in this process is to determine where low-frequency changes in  $V_s$  can be identified. Large decreases in  $V_s$  combined with a slight decrease in  $V_p$  is where the bulk of the mobile bitumen sits. Ideally low-frequency velocities can be estimated by PS-PSDM velocity analysis on the baseline and monitor PS data. Alternatively, the time shift between the PS baseline and the PS monitor through the reservoir can be used Gray et al (2016). This time shift can then be converted to an adjustment to the low-frequency background model for the joint inversion of the monitor, similar to what is described for adjustment of the P-wave monitor in the Pro4D Guide (2007), except that the velocity is P-wave down and S-wave up. The difficulty with the latter method is determining where in depth the low-frequency velocity anomaly sits. In our example we assumed that it went from the top of the steam chamber to the bottom of the reservoir.

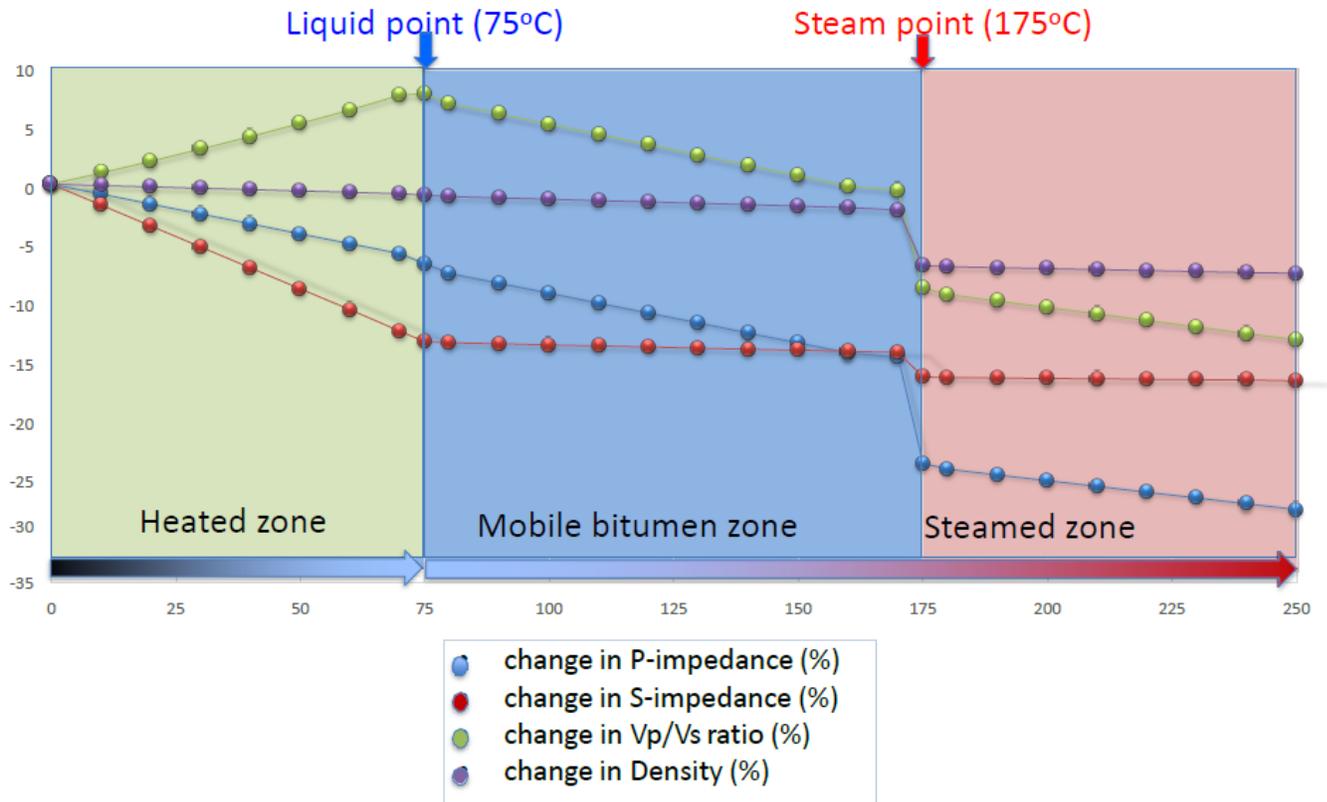


Figure 1: Percent changes in elastic properties, Vp, Vs, density, and Vp/Vs with temperature, saturation and pressure. Indicated are where quasi-solid bitumen is being heated (green, with decreasing S-Impedance), the mobile bitumen zone (blue, with flat S-Impedance), and the steamed zone (red) where all elastic properties drop at steam temperature. (After Todorovic-Marinic, 2017).

The shear-wave velocities ( $V_s$ ) start to drop rapidly as soon as the bitumen starts to heat up (Figure 1), which means that this low frequency adjustment must extend beyond the steam chamber because there is heat beyond the steam chamber. Furthermore, our observations indicate that the  $V_s$  adjustment is required for some distance away from the steam chamber, e.g. Figure 2 where the mobile bitumen anomaly extends at least 200m away. Therefore, the low-frequency adjustment to the shear-wave velocity should not be estimated from the P-wave ( $V_p$ ), low-frequency adjustment. The shear-waves are delayed traveling through the liquid bitumen sands relative to the cold, quasi-solid bitumen sands because of the reduction of the shear-wave velocity in the liquid. This creates a time delay that we use to identify how much and where the shear-wave velocity should be modified in the low-frequency  $V_s$  model used in the pre-stack inversion of the 4D monitor survey. The background density model is left unchanged because only small changes in density are expected (Figure 1). Once the above low-frequency corrections to the background models for  $V_p$  and  $V_s$  are made, the 3C-4D monitor is pre-stack, jointly (PP and PS simultaneously) inverted using the same parameters as the baseline.

The rapid decrease in the shear-wave velocity causes a rapid increase in the  $V_p/V_s$  ratio, but as the bitumen is replaced by steam or gas  $V_p$  drops substantially, which causes the  $V_p/V_s$  ratio in the steam chamber to drop to values much closer to virgin reservoir  $V_p/V_s$  values, or slightly below (Figure 1). Therefore, there should be a zone of high  $V_p/V_s$  ratios around the steam

chamber that should correspond to heated, liquid, and therefore mobile, bitumen, and a zone of lower Vp/Vs ratios and lower P-impedance associated with the steam chamber. This is what we observe (Figures 2 & 3) and what we use to distinguish the various liquid states (Zhang et al, 2017). The area of mobile bitumen outside of the steam chamber appears to be quite significant (e.g. Figures 2 and 4, and Figure 6.5 in Zeigler, 2013). This anomalous zone of high Vp/Vs ratios related to mobile bitumen also appears to be at least as thick as the steam chambers (e.g. Figure 2). Therefore, the anomalous zone will often be thicker than the seismic bandwidth covers. Therefore, a means of seeing this low-frequency trend is required. The only way that we are aware of to get this low-frequency trend is to use some form of shear-wave seismic. Ideally this will be done by depth migrating both the PS monitor and baseline. In this example, we accomplished this by interpreting the monitor – baseline 4D time-difference in the shear-wave reflector interpretations above and below the reservoir, similar to the method described in the Pro4D Guide (2007) for conventional 4D. The low-frequency adjustment required for the pre-stack joint inversion done here is estimated using the time delay from our 3C-4D seismic data, as described in Equation 1. As can be seen from the equation, the PS data is critical for this adjustment.

$$Ps(mon) = \frac{Tps(mon)}{Tps(bas)} [Ps(bas) + Pp(bas)] - Pp(mon) \quad (1)$$

Where:

$P$  is slowness in s/m

$T$  is two-way travel-time in s

The subscripts  $s$ ,  $ps$  and  $p$  represent the SS, PS and the PP waves, respectively.

The terms in the brackets ( $bas$  and  $mon$ ) represent the baseline and monitor, respectively.

## Examples

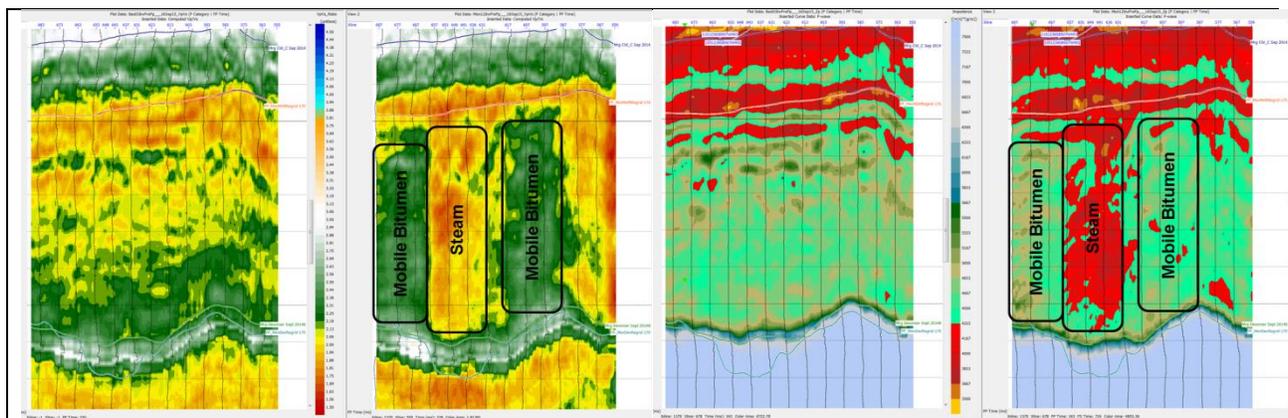


Figure 2: On the left is the Vp/Vs ratio from the baseline. On the right are the Vp/Vs responses of the 3C-4D monitor with interpretations of the states of the fluids from the combination of the conventional PP-4D (Figure 3) and 3C-4D Vp/Vs differences in the boxes. Range is 1.5 – 4.5.

Figure 3: On the left is the P-impedance from the baseline from the conventional PP-4D. On the right the P-impedance response of the monitor with interpretations of the states of the fluids from the combination of the conventional and 3C-4D differences. Range is 3000-7000 m/s\*g/cc.

The results of the pre-stack inversions are shown in Figures 2-4. Figure 2 is the key result because it shows that substantially higher  $V_p/V_s$  ratio values of 2.8-2.9 lie where we would expect them to be associated with heated, mobile bitumen just outside of the steam chambers that have been interpreted from the conventional PP-4D in Figure 3. The  $V_p/V_s$  ratios in the interpreted steam chamber are slightly lower than the background  $V_p/V_s$  ratios in the baseline (left side of Figure 2). The increase in the  $V_p/V_s$  ratios in the interpreted mobile bitumen zones is greater than 30% (2.1-2.2 to 2.8-2.9), as expected from Zeigler's (2013) theory. Gray et al (2016), Zhang and Larson (2016), Zhang et al (2017), and Todorovic-Marinic et al (2017) establish that the 3C-4D results appear to represent mobile bitumen and heated quasi-solid bitumen as shown in Figure 4. Figure 4 shows the results of the classification methods described in Zhang et al (2017) used to interpret the various states of the liquids in the producing reservoir: the steam chamber (red), mobile bitumen (blue), and heated quasi-solid bitumen (green). The locations of all these fluid states make sense, with the steam chamber on the inside, the heated quasi-solid bitumen on the outside and the mobile bitumen between. Zhang and Larson (2016) show that the size of the steam chamber is related to total production to date. This allows Zhang et al (2017) and Todorovic-Marinic (2017) to quantify the 4D response to production based on the 2014 4D anomaly and production to the date of the 4D acquisition, and it allows them to predict future production by using the 2014 3C-4D anomalies as follows. The mobile bitumen gives an idea of how much oil can be produced immediately, and therefore is useful for planning workovers and infill wells. The heated quasi-solid bitumen gives an idea of how much production is available in the near future, and therefore is useful in planning infill wells. In this presentation we will show that it realistically predicts production in 2016, two years out from the 2014 4D acquisition. The 2014 prediction has a correlation coefficient of 77% and has an error of 14% compared to the actual production. The 2016 prediction has a correlation of 92% and an error of 10% compared to the production through 2016.

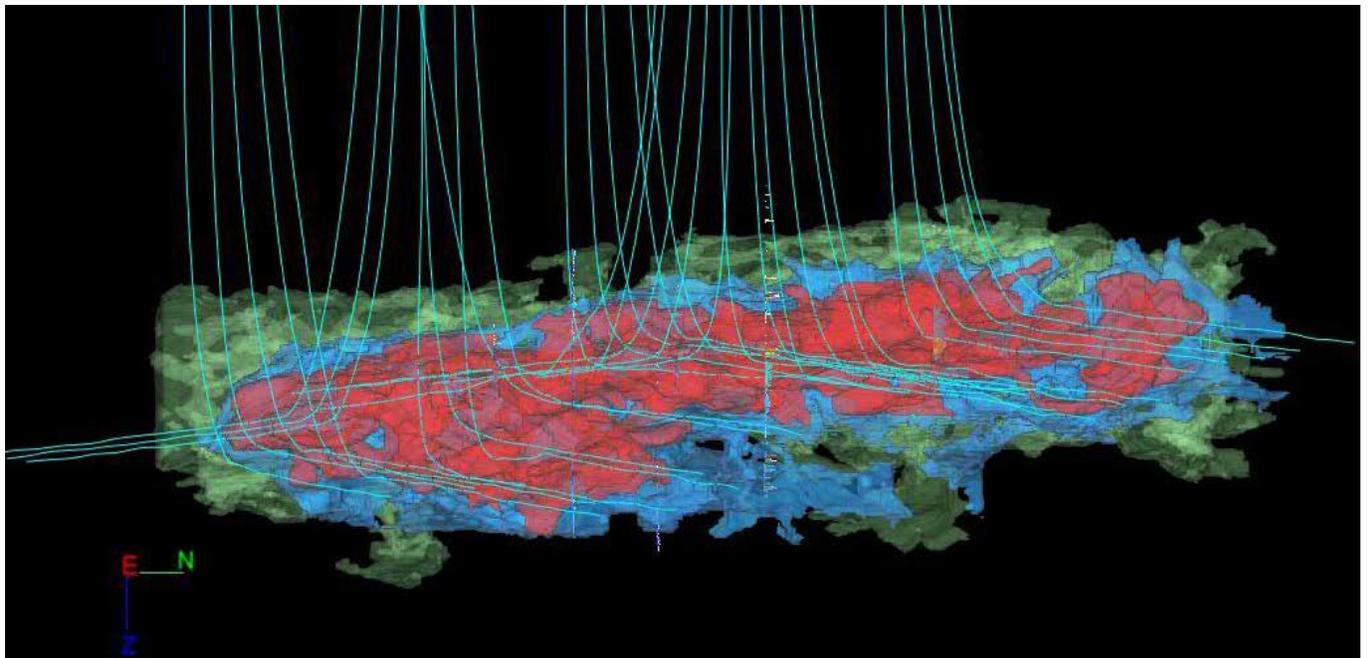


Figure 4: Quantitative interpretation of the steam chamber (red), mobile bitumen (blue), and heated quasi-solid bitumen (green) (after Todorovic-Marinic, 2017).

## Conclusions

Mobile, heated bitumen seems to be indicated by significant increases of 30% or more in the Vp/Vs ratio between baseline and 4D monitor surveys. Vp/Vs changes can be determined from differences in prestack inversion of 3C-4D seismic data. Furthermore, the Vp/Vs anomalies occur where mobile, heated bitumen is expected: below the bottom of, and on the edges of, the steam chamber. The Vp/Vs anomalies on the edge of the steam chamber are larger than expected. The combined 3C-4D anomalies can be used to estimate liquid states of bitumen in the reservoir. In addition, the current-day steam chamber can be correlated to total production and the resulting 3C-4D anomalies have been used to predict future production with good correlation to the actual production. Therefore 3C-4D analysis creates value by assisting in the identification of infill and extension well opportunities and providing guidance for adapting operating strategies for production optimization in the existing SAGD pairs .

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