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3C-4D locates mobile bitumen in oil sands reservoirs

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Summary

Vp/Vs ratio changes determined from 3C-4D (3-component, 4-dimensional, i.e. time-lapse) seismic data in oil sands reservoirs appear to indicate the presence of bitumen heated to its liquid, and therefore mobile state. This may turn out to be the most important use of 3C seismic data since its use to image through gas clouds. When quasi-solid bitumen is heated to its liquid state, its shear modulus, and therefore shear velocity (Vs), go to zero (which is one definition of liquid). Meanwhile, the bitumen's P-wave velocity gradually decreases, causing a large increase (>30%) in the Vp/Vs ratio of the sands containing heated, liquid, and therefore, mobile bitumen. This increase in the Vp/Vs ratio is at least as large as the decrease in P-wave velocity commonly used to identify the steam chamber in an oil sands reservoir. Therefore, the Vp/Vs ratio change associated with heated bitumen should be quite prominent in 3C-4D seismic data. However, due to the thickness (0-50m) of the steam chambers and the heated bitumen surrounding them in Athabasca oil sands reservoirs, these Vp/Vs anomalies will often be so thick as to be below the period of the seismic wave. Therefore, the seismic can only see their top and base, but not the full chamber. Time-lapse interpretation of the differences in the time horizons in the 3C seismic monitor survey below the heated zones identify the locations of thick zones of liquid, mobile bitumen (Zeigler, 2013). We extend this time-lapse interpretation to include pre-stack, joint inversion of the 3C-4D data to produce 3D volumes of the differences in the Vp/Vs ratios related to the heated bitumen. The 3C-4D horizon differences allow us to estimate the low-frequency variations that are required to do the inversion properly. The inversion volumes suggest a much broader expanse of mobile oil around the steam chamber than might be suggested by Butler (1991) theory. This has important implications for the placement of infill and extension wells in and around existing SAGD well pairs.

Introduction

Zeigler (2013) demonstrated that significant changes in Vp/Vs ratios are associated with the change from quasi-solid bitumen (Han et al, 2007) to its liquid form. The Vp/Vs ratio undergoes a substantial increase only during its liquid state and the Vp/Vs ratio is approximately equal to the virgin reservoir value when steam replaces the bitumen. In Kato et al's (2008) laboratory study of bitumen sands from a nearby reservoir, it appears that there is ~50% change in the Vp/Vs ratio when quasi-solid bitumen at ~10^{o}C changes to its liquid form at ~25^{o}C in the Athabasca oil sands (Figure 1). Zeigler (2013) shows a map (Zeigler, 2013, Figure 6.5) where average Vp/Vs ratio changes of greater than 35% are seen around (but, for the most part, not in) steam chambers interpreted from conventional PP-4D seismic differences. Reversing these observations, large changes in Vp/Vs ratio imply the presence of heated, mobile bitumen. Through the use of pre-stack, joint inversion (Hampson et al, 2005), we extend the method from the 2D Vp/Vs ratio difference maps of Zeigler to 3D volumes, which allow us to evaluate the Vp/Vs differences by comparing them to well logs from observation wells in and around the steam chamber. The 3D differences in Vp/Vs ratios 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 pairs.

Method

We have extended Zeigler's 3C-4D method to allow for 3D visualization of mobile bitumen through the use of pre-stack, joint PP & PS inversion techniques, applied to both the baseline and monitor surveys. The baseline is pre-stack, joint inverted for estimates of P-impedance, the Vp/Vs ratio and density using the method of Hampson et al (2005). The inversion of the P-wave 4D seismic monitor needs a low-frequency adjustment to its background model to account for the signficant drop in P-wave velocities through a thick steam chamber (Pro4D Guide, 2008). Due to the thickness of the steam chamber in a typical Athabasca reservoir, this drop in P-wave velocities is below the period of the seismic wave. Therefore, a correction to the inversion of the 4D seismic monitor is required for oil sands reservoirs.

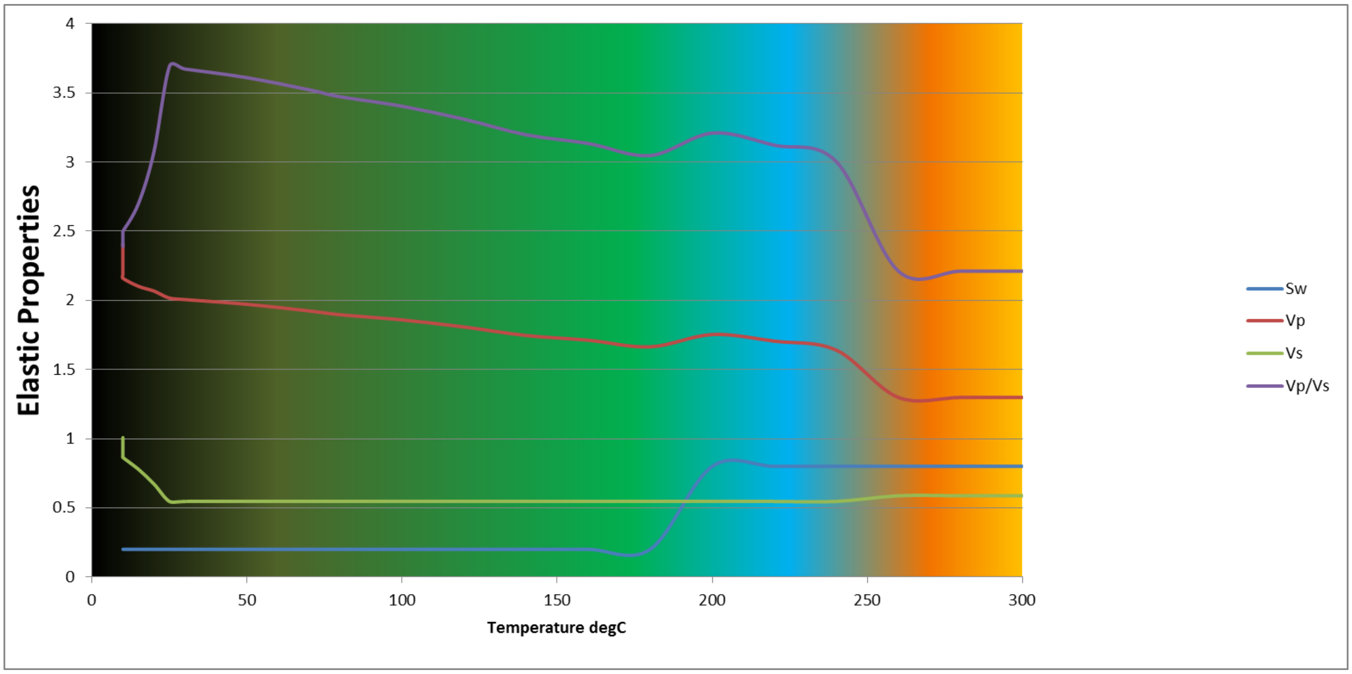

Figure 1: Changes in elastic properties, Vp, Vs and Vp/Vs with temperature, saturation and pressure (after Kato et al, 2008). The background colour represents the fluid in the reservoir: black is bitumen, green is mobile bitumen (determined using the lowest Vs values), blue is water and orange is steam.

Fortunately, the software we use allows us to adjust the low-frequency, background, P-wave velocity model based on the time-shifts observed in the reflectors below the reservoir. However, for pre-stack inversion, the shear-wave velocity model is also required. It requires a similar low-frequency adjustment. However, shear-wave velocities (Vs) 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. Furthermore, our observations indicate that the Vs adjustment is required for some distance away from the steam chamber, e.g. Figure 2 Therefore, the low-frequency adjustment to the shear-wave velocity should not be estimated from the P-wave (Vp), low-frequency adjustment. The seismic shear-waves are delayed traveling through the liquid bitumen sands relative to the cold, quasi-solid bitumen sands because of the drop 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 Vs 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. Once the above low-frequency corrections to the background models for Vp and Vs are made, the 4D monitor is pre-stack inverted using the same parameters as the baseline.

The rapid decrease in the shear-wave velocity causes a rapid increase in the Vp/Vs ratio, but as the bitumen is replaced by steam or gas Vp drops substantially, which causes the Vp/Vs ratio in the steam chamber to drop to values much closer to virgin reservoir Vp/Vs values (Figure 1). Therefore, there should be a zone of high Vp/Vs ratios around the steam chamber that should correspond to heated, liquid, and therefore mobile, bitumen. The area of mobile bitumen outside of the steam chamber appears to be quite significant (e.g. Figure 2 and Figure 6.5 in Zeigler, 2013). This anomalous zone of high Vp/Vs ratios related to mobile bitumen also appears to be as thick as the steam chambers (e.g. Figure 2). Therefore, the anomalous zone often thicker than the seismic can see (i.e. it is below the seismic bandwidth). 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. This is done by interpreting the monitor – baseline 4D time-difference in the shear-wave reflectors below the reservoir. 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. Fortunately, for this project, we have 3C-4D seismic data from which we can make this low-frequency Vs adjustment.

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

Where:

P is slowness in s/m

T is two-way travel-time in s

The subscripts s and p represent the PS seismic data and the PP seismic data, respectively

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

Examples

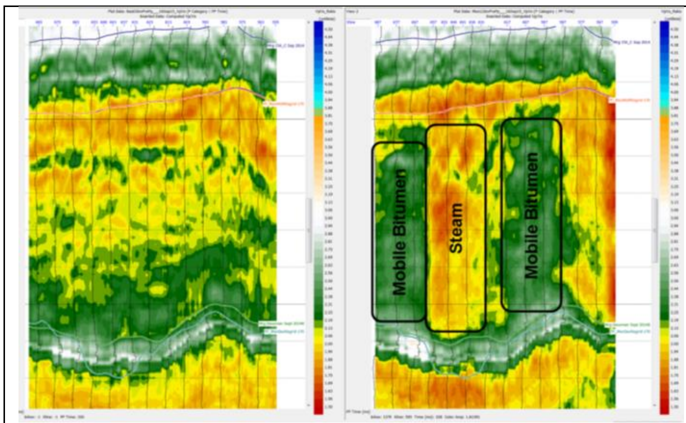

Figure 2: On the left is the Vp/Vs ratio from the baseline. On the right are the Vp/Vs responses of the 3C-4D monitor with interpretations of the states of the fluids from the combination of the conventional PP-4D (Figure 3) and 3C-4D Vp/Vs differences in the boxes.

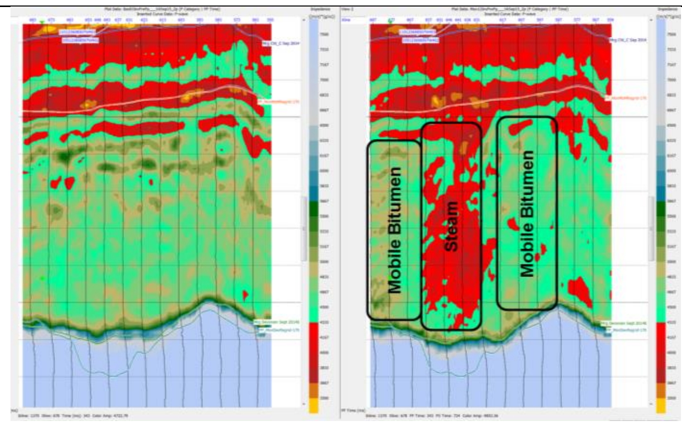

Figure 3: On the left is the P-impedance from the baseline from the conventional PP-4D. On the right the P-impedance response of the monitor with interpretations of the states of the fluids from the combination of the conventional and 3C-4D differences.

The results of the pre-stack inversions are shown in Figures 2-5. Figure 2 is the key result because it shows that substantially higher Vp/Vs 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 Vp/Vs ratios in the interpreted steam chamber are slightly lower than the background Vp/Vs ratios in the baseline (left side of Figure 2). The increase in the Vp/Vs 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 theory. Figure 4 shows that both the Vp/Vs ratio and P-impedance changes are consistent with the temperature and post-steam saturation logs taken around the same time. Large drops in P-impedance (pink) are associated with steam (>200^{o}C) in the log and large increases in the Vp/Vs ratio are associated with lower temperatures and higher oil saturations. Figure 5, using opacity in 3D, shows how the Vp/Vs ratio changes (green) interpreted from the 3C-4D seismic wrap around the area interpreted from conventional PP-4D changes to be the steam chamber (pink). The Vp/Vs anomalies in Figures 4 and 5 also appear where we would expect them to be: at the base of the steam chamber, where the mobile bitumen pools before being evacuated by the producing well, and around the boundaries at the top and edges of the steam chamber. However, the green, high Vp/Vs zone, representing our interpretation of mobile bitumen, extends much further than we would have anticipated from Butler's (1991) theory of steam chamber development. The green zones, interpreted to be mobile bitumen, if corroborated as in Figure 4, may provide valuable information to guide infill and extension well opportunities. For example, the large green zone in Figure 4 between the two northernmost pads suggests a possible infill opportunity.

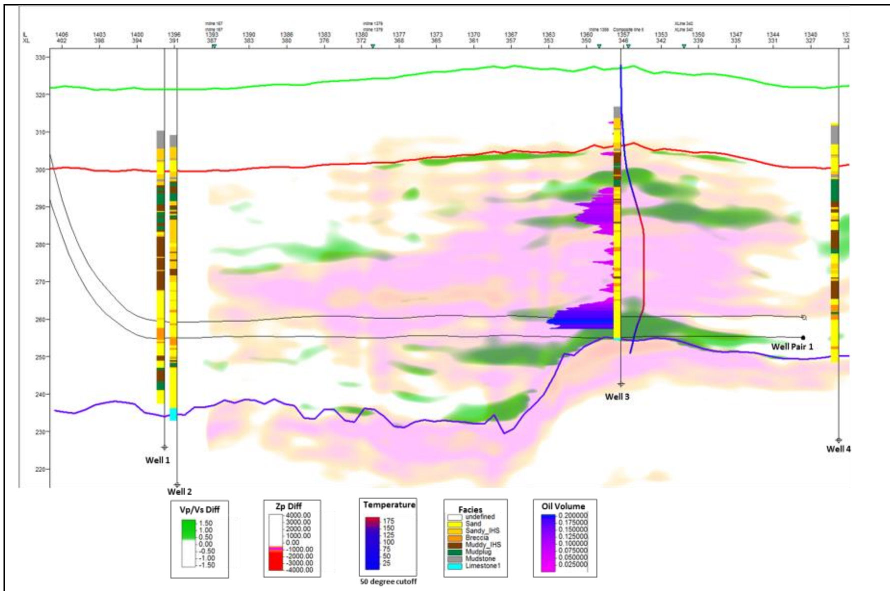

Figure 4: Pink shows the steam chamber, interpreted from conventional PP-4D. Green shows the mobile bitumen, interpreted using Vp/Vs differences from the 3C-4D. These data are compared to an observation well with temperature on the right (red is steam and the curve is cut off below 50^{o}C), post-steam oil saturation on the left and facies in the middle track.

Figure 5: Green is where we interpret mobile bitumen from Vp/Vs increases in the 3C-4D monitor survey. Pink is where we interpret the steam chamber from the conventional PP-4D monitor survey.

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 3C-4D seismic data that seem to correlate with well logs from observation wells in and around the steam chamber. 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 and therefore create value by assisting in the identification of infill and extension well opportunities and adapting operating strategies for production optimization in the existing SAGD pairs .

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