Multicomponent Time-Lapse Monitoring of Bitumen Recovery and Geomechanical Implications*

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Abstract

In-situ recovery of bitumen resources in Northwestern Canada occurs in the near surface (deeper than 75m and typically less than 600m). The recovery method patented and used by Petrobank is known as Toe-to-Heel-Air-Injection (THAI®), which is an in-situ combustion process that is used for the recovery of bitumen and heavy oil. It combines a horizontal production well with a vertical air injection well placed at the toe. This is an in-situ combustion process, which burns the heavy end asphaltenes of the bitumen to mobilize and upgrade oil in-situ, while recovering up to 65% of the bitumen. Because of the shallow depth of operation in combination with the properties of bitumen, where the oil is part of the formations matrix, this process produces large changes in the reservoir and in how the formation carries and distributes a load (Wikel, 2012). Therefore, this affects how the reservoir and overburden distribute regional and local stresses. This requires monitoring of the reservoir during combustion and for stress changes in the formation of interest. In addition to this, the overburden must be monitored and studied to ensure cap rock integrity through time. This will help us avoid well damage or surface venting of pressure. Time-lapse multi-component studies are well suited for this purpose.

Data from the Conklin THAI pilot show that the combustion front is moving toward the heels of the wells in a non-uniform pattern (Kendall and Wikel, 2011) and that PS1/PS2 anomalies in the overburden are caused by changes in the stress state through time (Wikel et al., 2012). In addition to this, new data has shown that front movement has changed with time and operational improvements. In addition, stress directions and magnitudes in the reservoir and overburden have changed as the front has progressed from 2008-2011. Well deformation in the area can be directly attributed to stress changes in the overburden. These changes have implications for how the pilot is managed in the future. Examples from past and new data sets will be shown along with drilling and operational data from the pilot facility.

Introduction

Toe-to-Heel-Air-Injection (THAI) is an in-situ controlled-combustion process that cracks, upgrades, and mobilizes heavy oil (Figure 1a). Compressed air is injected in to the reservoir after a pre-injection-heating-cycle (steam) brings the reservoir up to an appropriate temperature for combustion to occur. The bitumen is then cracked leaving a coke zone that becomes the fuel for the process. In front of the coke zone is a

mobilized and upgraded oil zone that is then produced by a horizontal well through gravity drainage. The THAI process does not require gas or water as in SAGD except in the pre-ignition start-up phase. Lab results indicate that THAI will provide an upgrade of about 10 API.

4D-3C seismic has been chosen as the method to monitor the advancement of the combustion front in addition to assessing the cap rock integrity through time. This will allow us to not only monitor how the combustion front grows through time with production but to also monitor areas that deviate from regional stress. This is important to operate our facility in the most efficient and safest manner possible. Stress changes are expected to be heterogeneous, anisotropic, and not readily predictable due to reservoir and overburden complexity.

Theory and Method

Seismic velocities (P and S wave) are highly dependent on temperatures, as shown by Han et. al., 2006 ([Figure 1b](#)). This figure shows the dramatic decrease in P wave velocities from 0-200°C and the associated decrease in shear velocities. In fact, shear wave velocities in the lab are noted as going to zero as the bitumen moves from being a solid, to quasi-solid, to liquid. In-situ, this is most likely not the case as there is still sand and coke left behind in the reservoir. This is known from direct experience at the Conklin pilot. The velocity decrease through time is what will drive the time-lapse response. In addition to this, the process will strip bitumen from the matrix of the formation in addition to changing the pore pressure, causing stress changes in both the reservoir and overburden. This change will be monitored using converted wave splitting through time.

Azimuthal anisotropy can be caused by a combination of several factors including regional (and local) variations in the horizontal stress, vertical cracks or fractures, and lithology (Olofsson et. al., 2003). When the converted wave (down going P upcoming S) is rotated out of the radial and transverse into the fast and slow shear directions, the PS1 direction has been shown to travel in the direction of maximum horizontal stress in the absence of fracturing or faulting ([Figure 2](#)). In the very near surface of the earth in Northern Alberta, a significant amount of shear wave splitting has been observed (Whale et. al., 2009 and Cary et. al., 2010) that is attributed to large differences in horizontal stress magnitudes. This phenomenon occurs at such a shallow depth in rocks that are relatively free from fracturing. This is ascertained from large coring programs within the Alberta oil sands to delineate bitumen thickness. The absence of fracturing and faulting and presence of meandering estuarine channels means that significant shear wave splitting in the near surface is likely due to horizontal stress anisotropy (Wikel et al, 2012). This difference in horizontal stress anisotropy could be caused by localized geologic features or structure. Since regional stress in the area is thought to be in a reverse/thrust fault regime, this deviation could cause a change to a strike-slip regime. The implication of this is that fracturing could go from growing in the horizontal plane to growing vertically and compromising the caprock. When vertical fracturing occurs, a breach of the caprock is much more likely and can cause operational setbacks, or in the worst case, venting of pressure to surface.

Five seismic volumes will be used in the following discussion:

- The 2003 coarsely sampled (15X20m bins) p-wave data (west 3D);
- The 2005 coarsely sampled (15X20m bins) p-wave data (east 3D);
- The 2008 true baseline high resolution (5X5m bins) multicomponent data; and,
- The 2009, 2010 and 2011 monitor surveys that have identical acquisition parameters to the 2008 data.

The 2003 and 2005 data were merged, processed and interpreted for regional mapping purposes. The merged volume was then interpolated and regularized in the area that overlaps with the 2008 data. Following a scheme similar to Trad et. al. (2008), new shots and receivers were built using a five-dimensional (offset, azimuth, inline, crossline and frequency) interpolator based on Fourier reconstruction. By taking advantage of the multidimensional aspect of the process, information from different dimensions can be used simultaneously to infill missing data. Interpolating simultaneously in the four spatial dimensions of offset, azimuth, inline, and crossline instead of just the latter two fully exploits the redundancy of the 3D data, significantly improving the spatial sampling. These interpolated data, while obviously not ideal, were used as the

The following excerpt from Wikel et. al., (2012) outlines just how these changes correlate to subsurface stress changes:

> "Changes in the PS1/PS2 time lag between 2008 and 2009 correlate to overburden stress changes that have direct impact on wellbores in the area (Figure 3). Shear wave-splitting increases (from zero in 2008 to 5-8ms of PS1/PS2 splitting in 2009) in the area around well 15-12, where tubing and borehole deformation occurred shortly after the 2009 seismic shoot. The increase in splitting is interpreted to be the result of higher horizontal stresses occurring due to overburden stress changes during bitumen extraction. There is no indication in this analysis that this stress change has affected caprock integrity; it does show, however, that stresses within the overburden do change over time as in-situ bitumen recovery progresses. In addition, horizontal producer well P3B developed a minor surface casing vent flow that could be the result of overburden stress changes (splitting decreased from 8-9ms in 2008 to almost 0 in 2009). This shows a direct correlation between a deviation in shear wave anisotropy and change in PS1 direction through time and physical borehole deformation."

Conclusions

In near surface (<600m depth) recovery of bitumen, a full understanding of the overburden and the reservoir is necessary to safely and economically extract the resource. Time-lapse multicomponent seismic is well suited for this task, as it allows us to not only monitor the main THAI front movement through time, but also what our activities in the reservoir do to the overburden. As an industry, we tend to test and constrain cap rock integrity at the outset and assume it mostly changes linearly through time with depletion and production. However, we know that with changing pore pressure, and in our case matrix re-organization as bitumen is stripped away, that the stress load will be constantly changing in ways we cannot possibly predict through modeling. We have shown that 4D-3C seismic can not only locate and monitor these changes, but also tie to well data and optimize our operations.

Acknowledgements

Selected References

Cary, P., X. Li, G. Popov, and C. Zhang, 2010, Shear wave splitting in compliant rocks, *in* S. Chopra and R.R. Stewart, eds., Multicomponent seismic: The Leading Edge, v. 29/10, p. 1278-1285.

Han, D., J. Liu, and M. Batzle, 2006, Acoustic Properties of Heavy Oil Measured Data: 76th Annual International Meeting, SEG, Expanded Abstracts, p. 1903-1907.

Kendall, R., and K. Wikel, 2011, Utilizing 4D-3C Seismic to Monitor the THAI Production Process: 73rd EAGE Conference & Technical Exhibition, Expanded Abstracts, p. G025.

Olofsson, B., Probert, T., Kommedal, J.H., and Barkved, O.I., 2003, Azimuthal anisotropy from the Valhall 4C 3D survey, *in* J. Simmons and M. Backus, eds., Multicomponent: The Leading Edge, v. 22/12, p. 1228-1235.

Whale, R., R. Bale, K. Poplavskii, K. Douglas, X. Li, and C. Slind, 2009, Estimating and compensating for anisotropy observed in PS data for a heavy oil reservoir: SEG Expanded Abstracts, v. 28, p. 1212-1216.

Wikel, K., R. Kendall, R. Bale, J. Grossman, and K. DeMeersman, 2012, 4D-3C Geomechanical Study of In-Situ Bitumen Recovery Utilizing Toe to Heel Air Injection: First Break, v. 30/2, p. 55-65.
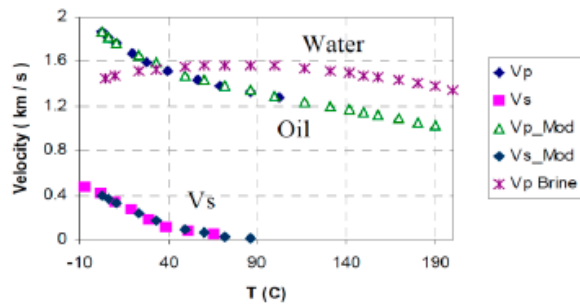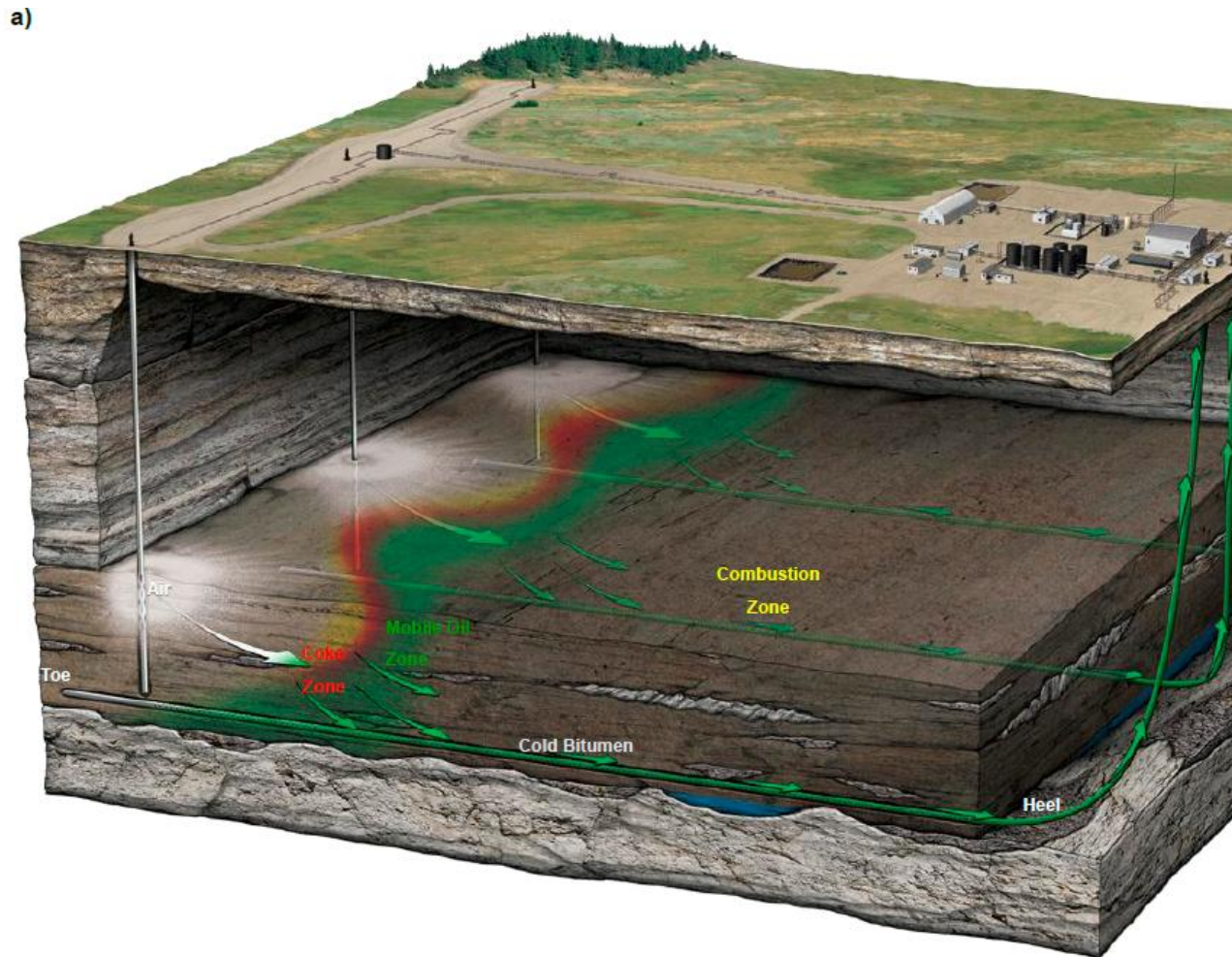
Figure 1. a) Shows a schematic of the Conklin THAI pilot facility showing the combustion zone, coke zone, mobile oil zone, and the horizontal well; b) shows velocity data from Han et al. (2006).
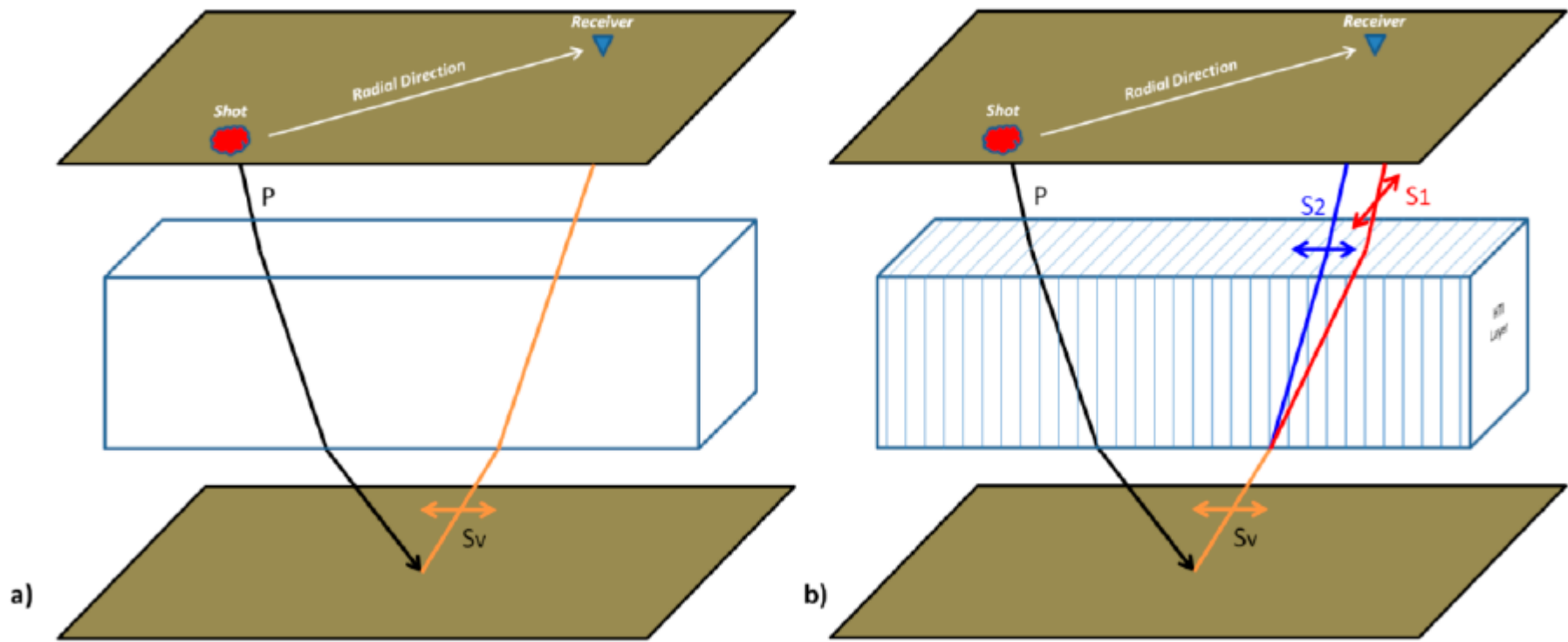
Figure 2. Shows the concept of converted wave splitting in HTI media. Without HTI anisotropy, the wave propagates without splitting (a). With HTI anisotropy, the converted wave splits into two modes, labeled S1 and S2 (b). The layering can be thought of as vertical fracturing or regional direction of maximum horizontal stress in the absence of fractures (Wikel et al., 2012).
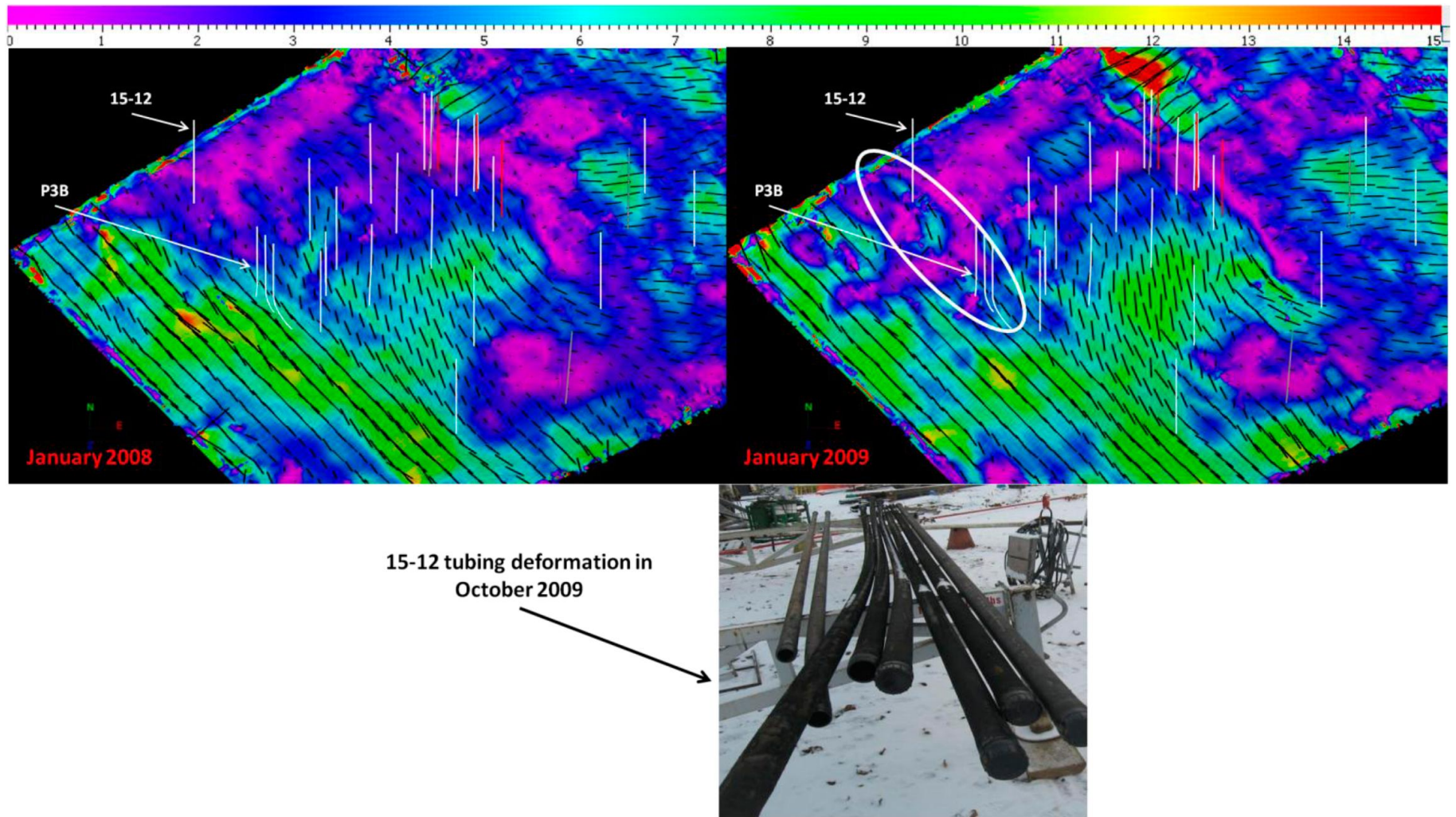
Figure 3. Changes in the PS1/PS2 time lag between 2008 and 2009 correlate to overburden stress changes that have direct impact on wellbores in the area.