4D-3C geomechanical study of in-situ bitumen recovery in NW Canada using Toe-to-Heel Air Injection

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Abstract
Recent observations of shear-wave splitting in the near surface have been interpreted as a consequence of the stress state rather than the presence of fractures. The analysis of such shallow anisotropy measurements from shear-wave splitting on converted-wave data allows us to evaluate caprock integrity and detect areas where the stress in the caprock may deviate from the regional faulting regime. This information is vital in discerning whether the caprock is able to withstand recovery of shallow in-situ bitumen and heavy oil. Moreover, using time-lapse multi-component data, we can use the changes in splitting azimuth and time delay to monitor overburden and reservoir changes occurring during production. Here we show that converted-wave splitting changes, observed at the Conklin Demonstration Project between 2008 and 2009, can be directly correlated to changes occurring in the overburden. Additionally, we show that the stress state of the overburden, and in particular the transition from one stress regime to another with depth, is considerably more complex than has generally been assumed.

Introduction
In north-western Canada, recovery of bitumen resources is performed in situ, as opposed to surface mining, at depths greater than 75 m and typically less than 500 m. Toe-to-Heel Air Injection (THAI) is an in-situ combustion based method for recovery of bitumen and heavy oil patented and used by Petrobank. The method combines a horizontal production well with a vertical air-injection well placed at the toe of the production well: this causes burning of the heavy-end asphaltenes (coke) in the bitumen to simultaneously mobilize and crack/upgrade the oil in the reservoir, recovering 65% of the bitumen. Because of the shallow depth of operation, and the fact that the bitumen is effectively part of the formation matrix, the overburden is influenced by the bitumen recovery. In common with other enhanced bitumen recovery methods, therefore, THAI affects the local stresses within the supported overburden, as well as the reservoir itself. These changes should be monitored to ensure caprock integrity is maintained, as well as to avoid well damage.

In the past, 3D converted-wave (PS) data have been used both to detect fractures and differential stress. Typically, the emphasis has been on fractures in consolidated formations, rather than stress changes within compliant near-surface rocks, which lack large-scale fracturing. However, shear-wave splitting observations in the near surface have recently been analysed (Bale et al., 2009; Whale et al., 2009; Cary et al., 2010). The highly variable fast (PS1) direction and PS1–PS2 time-lags are understood to relate to changes in stress regime rather than fracturing, in these near-surface environments. The analysis of such shallow anisotropy measurements from shear-wave splitting in converted-wave data allows us to evaluate caprock integrity and detect areas where the caprock may deviate from the regional faulting regime. This information is vital in discerning whether the caprock is able to withstand shallow in-situ bitumen and heavy oil recovery.

Moreover, using time-lapse multi-component data, we can use the changes in the splitting characteristics, i.e., azimuth and time delay, to monitor overburden and reservoir changes occurring during production. In this paper we show that converted-wave splitting changes, observed at the Conklin Demonstration Project between 2008 and 2009, can be directly correlated to changes occurring in the overburden. Additionally, we show that the stress state of the overburden, and in particular the transition from one stress regime to another with depth, is considerably more complex than has generally been assumed.

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Conklin Demonstration Project regional geology
The geology of the Fort McMurray region is dominated by clastic sedimentary packages that overlie Devonian carbonates (Figure 1). The near surface of Petrobank’s operating area near Conklin is characterized by glacial till and varying degrees of down-cutting by glacial channels, which are prevalent in the region. Beneath the till lies the Mannville Group of Cretaceous age, which comprises three major formations: the lowermost McMurray Formation, the Clearwater Formation, and the uppermost Grand Rapids Formation (Andriashek...
and Atkinson, 2007). The McMurray Formation is composed of a series of fluvial anastomosing channel complexes with thick, porous, basal channel sands interspersed with abandoned channel deposits and rip-up clasts. The bitumen within the McMurray has an API of ~8° and is actually part of the supporting matrix within the formation: sand grains are supported by a bitumen matrix. The McMurray Formation is the target formation for THAI production at the Conklin Demonstration Project facility. The overlying Clearwater shale, including the uppermost Wabiskaw shales, is the caprock needed to ensure containment of the process (Figure 2).

### THAI oil recovery

Oil sands are mixtures of sand, clay, water, and bitumen (Figure 3a). To remove the bitumen from the sand, several in-situ methods are employed. The most widely used methods involve steam, such as cyclic steam stimulation (CSS) and steam-assisted gravity drainage (SAGD), the latter of which uses parallel multi-lateral horizontals to heat the bitumen with steam and produce liquids through gravity drainage. SAGD is the most widely used method of bitumen recovery in Canada at this time, and is a high-pressure recovery method. Other methods include cold mechanical removal of the bitumen via the wellbore (CHOPS), solvent-based methods (VAPEX), and/or in-situ combustion methods.

THAI is an in-situ controlled-combustion process that cracks, upgrades, and mobilizes heavy oil (Figure 3b). Compressed air is injected into the reservoir after a pre-ignition heating cycle has raised the reservoir temperature sufficiently 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, mobilized, upgraded oil is produced by a horizontal well through gravity drainage and pressure drawdown from the injector to producer. The THAI process does not require gas or water, as in SAGD, except at start-up. Laboratory results indicate that THAI will provide an upgrade of about 8–10° API and actual production from the Conklin Demonstration Project shows an upgrading of ~4° API. The difference between laboratory and actual API is due to mixing of native mobilized bitumen with THAI oil (Kendall, 2009).

### Geomechanics

In the very near surface (50–500 m) in north-eastern Alberta, the minimum principal stress is vertical (Figure 4a). This stress state is known as a thrust-faulting regime. When fractures are initiated, whether natural or man-made, in this regime they propagate horizontally (Figure 4b, right). At some depth, the weight of the overburden exceeds the minimum horizontal stress, and the stress state shifts to a strike-slip regime in which any tensile fractures initiated will be vertical (Figure 4b, left). Due to the variability of the geology within the overburden in the area, this transition zone from horizontal to vertical fracturing is highly variable where fluvial glacial channels are present and cut deeper into the strata of the Mannville Group. An example of this variability and depth of glacial channel cutting is shown in Figure 5.

The lack of density estimates in the very near-surface strata mean that the variation of the overburden gradient in north-eastern Alberta is poorly understood, yet understanding this variability in the overburden geology and gradient is critical.
The left has no clear transition zone below the data provided, which start at 240 m. These logs highlight the variability in the depth of this transition zone, although it should be noted that the well locations and testing procedures are not provided.

The sketch in Figure 7 shows how glacial channels control the transition from horizontal to vertical fracturing. In areas where Quaternary channels cut deep into underlying formations, the transition from horizontal to vertical fracturing varies with depth and the formation where it occurs. A real-world example from Statoil’s Leismer property shows this varying transition zone by comparing the overburden gradient to the well-tested mini-fracture breakdown pressure in Figure 6. The log on the right has a clear transition zone from 270–390 m, while the log on the left has no clear transition zone below the data provided, which start at 240 m. These logs highlight the variability in the depth of this transition zone, although it should be noted that the well locations and testing procedures are not provided.

The sketch in Figure 7 shows how glacial channels control the transition from horizontal to vertical fracturing. In areas where Quaternary channels cut deep into underlying formations.
formations, the transition into a strike-slip stress regime is shallower. This is because glacial till is slightly denser than the surrounding formations, so its weight in the channels raises the overburden stress above the minimum horizontal stress at a shallower depth. Glacial till at Conklin has an average density ~2300–2400 kg m\(^{-3}\), while the underlying Mannville Formation has an average density ~2100–2200 kg m\(^{-3}\) (Figure 8). The current wellbore stress testing methodology for measuring fracture pressure makes crude assumptions about the overburden. Without further analysis of the overburden
geology, geophysics, and density logs to depths as shallow as possible, a complete understanding of the stress state is not possible. In addition, changes in stress state over time are currently not accounted for in commercially operating schemes.

The release of steam to the surface during the Total Joslyn Creek SAGD project provides an example of why the stress regime in the overburden is important (Figure 9). The interpretation of this incident by the Alberta government’s Energy Resources Conservation Board found that it was caused by a combination of shear failure, operating above the maximum operating pressure (MOP), and poor caprock integrity. No one was injured in this incident; however, the safety issues raised since its occurrence in 2006 are still very pertinent today, and the Alberta government continues to refine the way we measure and monitor caprock integrity. In the next sections we will show that time-lapse multi-component seismic surveying in conjunction with well data is well suited for this purpose.

Figure 8 Density log comparison within the Conklin Demonstration Project area. Well 15-12 contains thick glacial till whereas well OB4 contains a thinner glacial till channel. These logs show the accuracy of the seismic interpretation and also the relatively high density of the glacial till compared with the underlying Mannville formations.

Figure 9 Left: the result of the Joslyn Creek SAGD steam release in northern Alberta in 2006. Right: simplified diagram from the Alberta government report on the mechanism of the blowout, where shear failure caused the steam chamber to compromise the overburden. The Alberta government and Total noted that thermal effects could also have played a role in the failure. From ERCB Staff Review and Analysis (2010).
Seismic data
Petrobank has acquired a high-resolution multi-component time-lapse dataset over the Conklin Demonstration Project area to monitor the movement of the THAI front and caprock integrity through time. The dataset consists of a pseudo-baseline 2003 survey from a larger regional data set, and monitor surveys purposely acquired in 2008, 2009, 2010, and 2011 (Figure 10). The monitor surveys were designed for high-resolution monitoring of the THAI front, and have a bin size of 11 × 11 m².

PS azimuthal anisotropy and processing
The polarization of S-waves is a particularly useful property to both detect and quantify azimuthal anisotropy. In the case of layered isotropic media, the PS reflected energy is polarized such that it has a horizontal component which is radial or parallel to the shot–receiver azimuth. In this case, the transverse component records no PS signal.

Azimuthal anisotropy, which is associated with either fracturing or differential stress, leads to the phenomenon of shear-wave splitting in converted wave reflections. Unlike P-wave
velocity or amplitude variation with azimuth, shear-wave splitting results from the presence of two distinct shear-wave modes with orthogonal polarizations in the horizontal plane. The polarizations are generally aligned with the direction of fracture strike, or maximum stress, for the fast S1 shear wave, and fracture normal, or minimum stress, for the slow S2 wave (Figure 11). Consequently, in contrast to the isotropic case, the polarization of the PS data for azimuthal anisotropy is partly determined by the orientation of the anisotropy, not just the shot–receiver geometry. It therefore carries valuable information. It is also important to realize that uncorrected shear-wave splitting can have a deleterious effect on the PS image, since these two modes interfere. Therefore, shear-wave splitting analysis has two roles: estimating the direction and strength of the anisotropy, and eliminating S1–S2 interference to improve the resolution of the PS image.

Shear-wave splitting can be detected and analysed using multi-azimuth data after initial rotation into the radial and transverse orientations. The fast and slow shear waves, S1 or S2, are not in general aligned with an arbitrary shot-receiver azimuth. As a result they contain signal which appears on both radial and transverse data. The exception is for shot-receiver directions which happen to be aligned with either the S1 or the S2 direction. It is well known (e.g., Bale et al., 2005) that these azimuths are also associated with polarity changes on the transverse component. The location of these polarity flips can be determined either by visual inspection or by an appropriate automated method. Figure 12 shows horizontal component data from one common conversion point (CCP) location, averaged over a superbin of 11–by–11 bins, from the Conklin survey data. Figure 12a shows the original radial and transverse data before correction. The arrows indicate approximate positions associated with polarity changes on the transverse. By comparing these locations with arrival times on the radial, we can distinguish between S1 (blue) and S2 (red), directions.

The automated method used to determine the orientations of S1 and S2 is a least-squares analysis of the transverse component amplitudes (Bale et al., 2005). The method can be used either on azimuthally stacked data (Figure 12), or directly on pre-stack gathers. The analysis shown here was done directly on the pre-stack data without sectoring and used the data window 650–800 ms TWT. The choice of analysis window determines the depth to which S-wave anisotropy is measured and later corrected for. In this example, we performed an overburden correction for anisotropy up to 800 ms TWT. The correction consisted of a rotation to the S1–S2 coordinate system, followed by a weighted optimal stacking method to generate S1 and S2 traces. These traces are correlated to determine the total time delay between S1 and S2 signals. Then a time-variant shift, linearly interpolated between the surface and the centre of the analysis windows, was applied to the S2 shear-wave to align it with the S1. This realignment compensates for the splitting effect and allows recombination of the split waves into new radial and transverse datasets, which we refer to as radial prime and transverse prime, respectively.

In the ideal case, the result would be that all of the signal on the transverse component would be reassigned to the radial prime data, leaving only noise on the transverse prime component up to 800 ms TWT in this case. After this step, it is possible to analyse and correct for deeper azimuthal anisotropy below 800 ms TWT. The new radial prime data can then be used for an improved PS image (Figure 13). Figure 12b shows the radial prime and transverse prime data for the data shown in Figure 12a after correcting for shallow azimuthal anisotropy.

Figure 12 Azimuthal sector gathers showing the effects of shear-wave splitting and its compensation. Each gather has 36 traces, each representing a stack of data within a 10° azimuth sector, ranging through 360°. The upper gathers are the radial data and the lower gathers transverse data. Data at one location (a) before correction, and (b) after correction. The arrows indicate approximate azimuths where a polarity change is observed on the transverse data in (a), associated with fast (blue) and slow (red) orientations, as inferred from the radial data. After correction, the transverse gathers have reduced signal and the radial gathers have improved alignment of the radial, especially for the events around 650–800 ms TWT. After the analysis described in the text, the estimated S1 azimuth was 50° clockwise from north, the time delay was estimated as 21 ms and the S1–S2 correlation coefficient was 0.45.
Only. Note the improved alignment of the radial and removal of signal from the transverse for shallow events above 800 ms. Deeper events (900–1000 ms TWT) are also corrected for the effects of shallow anisotropy, but may still suffer the effect of azimuthal anisotropy within the reservoir. Splitting related to the reservoir could potentially be corrected for by repeating the above analysis using the radial and transverse prime data that was obtained after overburden correction.

The effect of extracting, rotating, and aligning transverse shear-wave energy onto the radial component (i.e., layer stripping) is demonstrated by the migrated CCP stacks in Figure 13. The migrated radial CCP stack of Figure 13a is uncorrected, while the one shown in Figure 13b has been corrected for anisotropy in the overburden. The time-delay map is also displayed for reference, and the inline/crossline slices were selected so that they intersect at a local peak in the time-delay. Events in Figure 7b are generally imaged more coherently and with higher resolution. Moreover, events which were disconnected or misaligned in Figure 13a are successfully healed as can be seen in the first and second encircled regions in Figure 13b.

Of more immediate interest for the current study are the actual values of the S1 orientation and S1–S2 time delays which are estimated during the analysis. These attributes are shown as spatial maps in Figure 14. An indication of the quality of anisotropy estimation is the similarity between S1 and S2 records after correction, which is measured by the value of the cross-correlation peak. This attribute map is shown in Figure 14c. Generally in this dataset, the correlation coefficient was found to be in the region of 0.6, which is reasonable but not high. However, it is quite uniform, indicating good consistency across the survey in terms of

Figure 13 The effect of rotating transverse shear-wave energy onto the radial component is demonstrated by the migrated radial CCP stacks (a) prior to layer-stripping, and (b) after layer-stripping. The time-delay map is displayed at time zero for reference, and the inline/crossline slices intersect at a peak in the time-delay. Events in (b) are generally imaged more coherently and with higher resolution. Moreover, fragmented events in (a) have become more continuous in (b), as can be seen in the regions highlighted with black circles.
quality of the anisotropy estimation. The azimuth plot in Figure 14a indicates a clear transition from S1 azimuths trending NW–SE (blue colours) in the north-east part of the survey, to more E–W oriented azimuths (yellow colours) in the south-western part of the survey (azimuths are measured clockwise from north) However, it is always important to take into account the time delay in Figure 14a when assessing the significance of these orientations, as small time delays indicate a very weak anisotropy which makes orientations less certain. The view in Figure 15 shows a combined S1 azimuth/S1–S2 time delay map, which has this comparison naturally incorporated. The strength of anisotropy (i.e., the time delays) is coded into the size of the ‘plates’ here, while plate orientation shows the S1 direction. This display reveals areas of weaker anisotropy near the transition from NW–SE orientation to E–W orientation.

PS1/PS2 time lag and PS1 direction through time at Conklin

A significant amount of shear-wave splitting has been observed in the very near surface in northern Alberta (Bale et al., 2009; Whale et al., 2009; Cary et al. 2010) attributed to large differences in horizontal stress magnitudes. This phenomenon occurs at a shallow depth in rocks that are relatively free from fracturing, which is known from large coring programmes within the Alberta oil sands to delineate bitumen thickness. The absence of fracturing and faulting and presence of meandering estuarine and Quaternary glacial till channels means that significant shear-wave splitting in the near surface is probably due to lithology and horizontal stress anisotropy.

Changes in the PS1/PS2 time lag between 2008 and 2009 correlate with overburden stress changes that directly impacted wellbores in the area (Figure 16). Shear-wave splitting increases (from zero in 2008 to 5–8 ms of PS1/PS2 splitting in 2009) in the area around well 15-12, where tubing and borehole deformation occurred shortly after the 2008 and 2009 monitor surveys. 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.

Figure 14 Shear-wave splitting attribute maps from analysis centred on a horizon at approximately 0.725 s: (a) S1 azimuth from 0–180° from north; (b) time delay between S1 and S2 from 0–20 ms; and (c) quality control attribute from 0–1. A clear global change in orientation is observed between the north-east and south-west parts of the survey, with some further smaller scale variations.

Figure 15 Perspective plate-based view of combined S1 orientation and S1–S2 time delay attributes from Figure 14. The plate lengths are proportional to the time delay (also shown as colour background) and the plates are oriented according to the S1 azimuth. This type of display naturally suppresses S1 orientations which are associated with small amounts of splitting, and gives a more intuitive sense of the anisotropy.
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 8–9 ms to almost zero). This shows a direct correlation between a deviation in shear-wave anisotropy and change in PS1 direction through time and physical borehole deformation.

Conclusions
Geomechanical characterization of the reservoir and near surface is of the utmost importance during the in-situ recovery of bitumen and heavy oils. Knowledge of stress fields pre-drill is extremely useful for wellbore stability studies to assist in drilling and also well integrity design over time. Due to the high pressures used, local deviations from regional stress can cause fractures to propagate vertically, as opposed to horizontally, and breached the caprock leading to operational problems and, in the worst case, surface venting of high pressures. In addition, shear failure of the caprock is possible through time with heave of the overburden from high pressure operations. Areas that may deviate from regional stress can be constrained pre-drill by using 3D-3C seismic data to denote areas where the PS1 direction deviates from the regional trend and PS1/PS2 time lags increase spatially. When analyzed with the near-surface geology, geophysics, and well logs, an accurate near-surface model will allow better placement of geomechanical test wells to constrain the reservoir and caprock fracture pressure. In addition, time-lapse changes in PS1/PS2 time lag and PS1 direction are indicative of stress variations as recovery progresses.

As an industry, we tend to assume that the overburden is homogenous and isotropically stressed as recovery of bitumen progresses through time. Our data and examples show that the overburden is not only much more geomechanically complex, but also that it changes through time, which is critical when monitoring caprock integrity.

References


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