SPE-206127-MS

Aplicability of an Innovative and Light Seismic Approach to Monitor SAGD Operations in Surmont: A Blind Test

Victoria Brun and Elodie Morgan, SpotLight; Brad Gerl and Luis Cardozo, ConocoPhillips; Jeremie Batias, Total

This paper was prepared for presentation at the 2021 SPE Annual Technical Conference and Exhibition held in Dubai, UAE, 21 - 23 September 2021.

Abstract

Surmont is a heavy oil field located in northeast Alberta which is currently being developed by a joint venture between ConocoPhillips and Total using Steam Assisted Gravity Drainage (SAGD). To monitor the enhanced oil recovery process and caprock integrity, highly repeatable 4D seismic surveys using dynamite have been completed over the years. In order to maximize the value of information while controlling costs, a novel light seismic monitoring approach has been "blind-tested" on existing 4D data.

The concept requires the use of only one source and one receiver couple, optimally placed in the field to monitor one or several subsurface spots, using time redundancy to detect 4D changes in these zones of interest. Three spot locations have been defined by the client on a well pad for which the history was not provided. For each of these spots, specific series of seismic processing steps have enabled the identification of the optimum source/receiver locations. Then, these optimum raw seismic traces extracted from different 4D campaigns have been analysed to detect potential time shift changes in the selected horizon induced by the growth of the steam chamber.

Time-shift changes were plotted for all 3 spots. An increase was observed for one of the spots (Spot 3) from the first 4D monitor in 2010 up to the last monitor in 2015. An increase was also plotted between March 2013 and September 2013 for another spot (Spot 1), changes attributed to the dynamics of the steam chamber. On the contrary, spot 1 did not see any effect of the steam. These time-shift changes were then successfully cross-checked with temperature data from observation wells, confirming the qualitative variations attributed to the effects of the steam chamber evolution.

It demonstrated the viability of this innovative seismic and focused monitoring approach to monitor the evolution of the steam chamber in Surmont. This also paves the way for a simpler and yet reliable and cost-effective way of monitoring the evolution of the steam chamber to further optimize production and increase rentability.

Introduction

Surmont is a heavy oil field located in northeast Albert, Canada. A pilot project started in 1997 using Steam Assisted Gravity Drainage (SAGD) as improved oil recovery method to develop the field. This technique utilizes a pattern of horizontal well pairs that continually inject steam into the reservoir to mobilize the heavy oil so it can be produced (Byerley et al., 2009). To monitor the enhanced oil recovery process, highly repeatable 4D seismic surveys have been completed over the years which have helped optimize well operating strategy and reservoir models, allowing respectively better economic performances and more accurate prediction. Indeed, the presence of steam in the reservoir was expected to lead to significant changes in seismic impedances (Forgues et al., 2015) which could help track the development of the steam chamber.

To maximize the value of information while controlling costs, a novel light seismic monitoring approach has been "blind-tested" on existing well and 4D data. The concept requires the use of only one source and one receiver optimally placed in the field to monitor a "spot" in the subsurface and using repeated shots over time to detect 4D changes in the zone of interest. Subsurface changes linked to variations of constraints, temperature, pressure, or saturation can be tracked in the non-migrated domain by comparing seismic traces successively acquired between several time intervals by each source/receiver couple.

The objective of this blind test was to assess this light monitoring approach and see if it could complement or help space out over time 4D campaigns in specific locations where the uncertainty remains high while controlling costs. In a world chasing lower environmental and CO_2 footprint, such solution could represent for O&G operators an affordable alternative to conventional monitoring techniques.

Material and Methods

The *Surmont Phase 1* 4D program consists of 3 different survey areas covering individual SAGD drainage patterns of approximately 1.6km^2 each. The results discussed in this paper utilized the 4D design made of permanent single-component analogue geophones buried 6 meters below the surface and 125g dynamite charges loaded in cased shot holes at 6-meter depth. Such a design ensures that each 4D monitor survey re-occupies the exact same shot and receiver station locations that were used for the 4D baseline survey, providing maximum repeatability (Byerley et al., 2009). The dataset used in this paper focuses on Pad 101N, where a 4D baseline was acquired in 2010 and followed by 7 monitors every 6 months from March 2012 until March 2015.

For this blind test, three spots' locations have been defined by the client on a well pad for which the reservoir history and behaviour were not provided. The goal was to see how a light monitoring approach focusing on spots, rather than a full area, could help track the steam chamber dynamics and confirm the findings of 4D legacy data or/and observation wells acquired from 2010 to 2015. The three spots' locations to blind test the monitoring of the steam chamber evolution in different areas of the field are presented in Figure 1. Two of the spots (1 & 3) were deliberately placed on observation wells to allow for a reliable correlation between what is observed at each spot and the collected data in these wells over the monitored period.

Figure 1—Blind-test scenario on PAD101 North. Spots' locations have been defined over observation wells in order to correlate the detections of the steam chamber variations. Reservoir depth is 450m.

Firstly, a survey design was completed to find the optimum source/receiver locations to monitor the selected spots. It was performed using the migrated 3D seismic baseline from 2010 and a RMS velocity model to retrieve the most contributory sources/receivers couples having participated in the illumination of the spot. A Common Spot Gather (CSG) was extracted from the raw field data of the 2010 baseline (Figure 2) using an optimized ray tracing algorithm (Morgan et al., 2019).

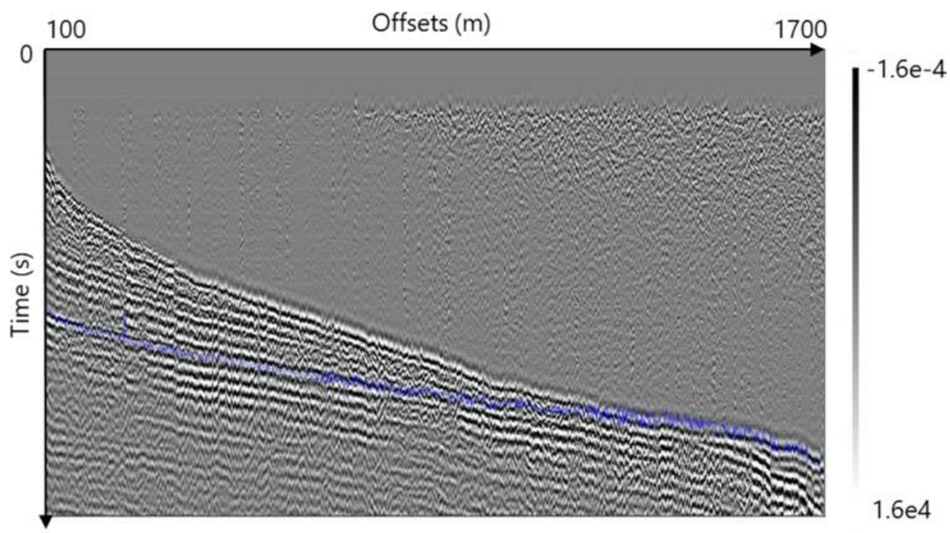

Figure 2—Common Spot Gather example for Spot 1 (displayed with a 40-80 Hz band-pass filter). TWT of the reservoir computed by the ray tracing algorithm is highlighted in blue.

Secondly, an optimum criteria selection linked to the signal-to-noise ratio (SNR) over these seismic traces was performed to detect the most repeatable traces of the dataset. This selection is critical and includes signal-to-noise ratio analysis to avoid noisy areas such as ground roll, surface noises or refractions. The two-way time (TWT) of the reservoir on these raw traces is also computed and shown on Figure 2.

The most contributory traces of the spot are kept for a subsequent detection process and correspond to the most reliable traces of the CSG (Figure 3): they display the highest signal-to-noise ratio and are the most repeatable through time, outside of the reservoir window. A NRMS value of less than 10% was computed above the reservoir area, proving a high repeatability of the operational model implemented in the Surmont field.

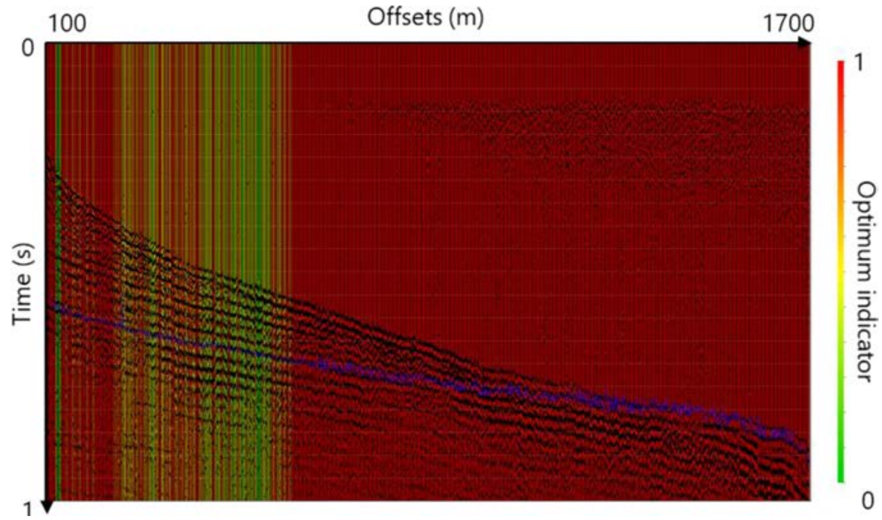

Figure 3—Common Spot Gather example for Spot 1 overlayed by an optimum indicator showing the most contributory traces in green.

Optimum traces were sorted according to their azimuth value (Figure 4). Traces between 0 and 90 degrees display a higher signal to noise ratio, especially at reservoir level, compared to traces between 90 and 180 degrees. They will be preferred when performing the optimum selection.

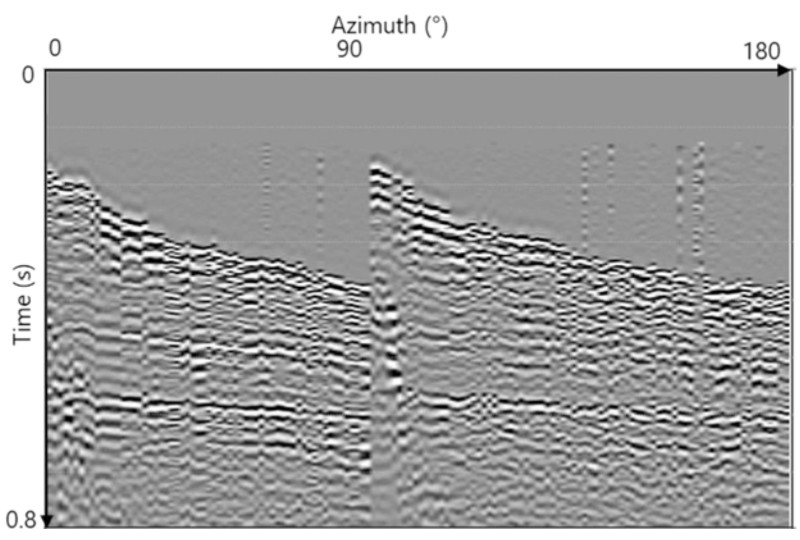

Figure 4—Azimuthal Common Spot Gather example for Spot 1. The left panel (azimuth 0-90) shows a much better signal to noise ratio than the right panel. Optimums will be selected as part of this panel. Traces have been separated in two azimuths classes, between 0-90° and 90-180°, to help visualise the data quality discrepancy explained earlier.

The optimum traces selection process also considers non-geophysical parameters, such as surface obstructions for example: when comparing optimal positions, a source located next to a road will be preferred over one located in the middle of the bush, for accessibility reasons; conversely, receivers located far away from any roads or production infrastructures are generally preferred, to avoid surrounding noise as much as possible. Finally, in the cases where a detection is performed using several spots close to one another, the mutualisation of two or more source points for different spots can be considered (Figure 5).

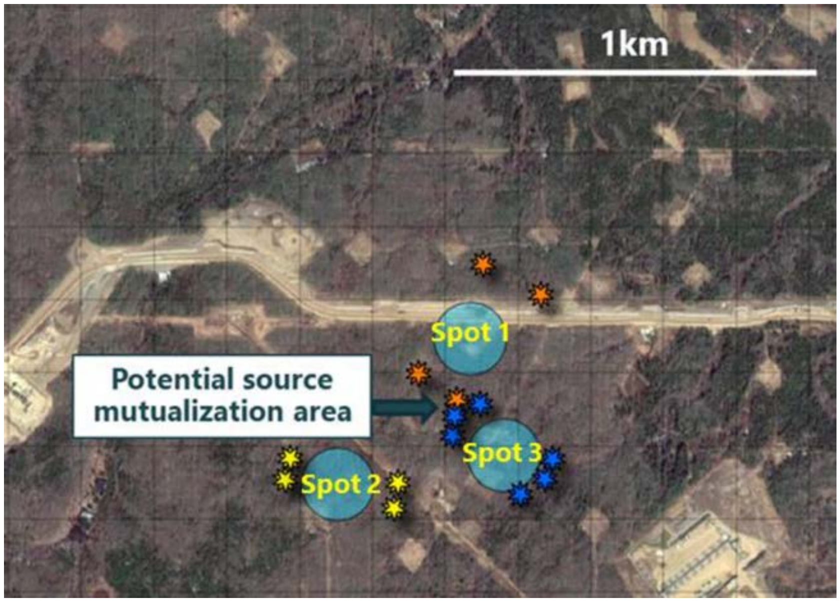

Figure 5—Surface obstructions are considered to ease the acquisition phase. For example, the northernmost orange stars will be preferred as source points as they are closer to the road. However, a potential source mutualization could be set up between Spot 1's southernmost position & Spot 3's north-east one.

Results: Post-mortem analysis

The most stable trace of the CSG is selected *via* the optimum criteria presented above to perform a time-shift study over the 8 traces (corresponding to the base and the 7 subsequently acquired monitors) for each spot.

The seismic trace can be influenced by many different effects such as the weather or water table variations (affecting the whole trace) and the 4D effects happening in the reservoir (and affecting the trace at and under the reservoir). To separate the reservoir and overburden effects from each other, a reference horizon above the reservoir is used to correct the dataset using time-shift compensation over time. This reference horizon is picked over the original shot-point coming from the baseline of 2010 which includes the optimum trace used for the detection (Figure 6). Once the overburden variation is corrected, the only remaining 4D effect should be the one happening at reservoir level: the detection can now be performed.

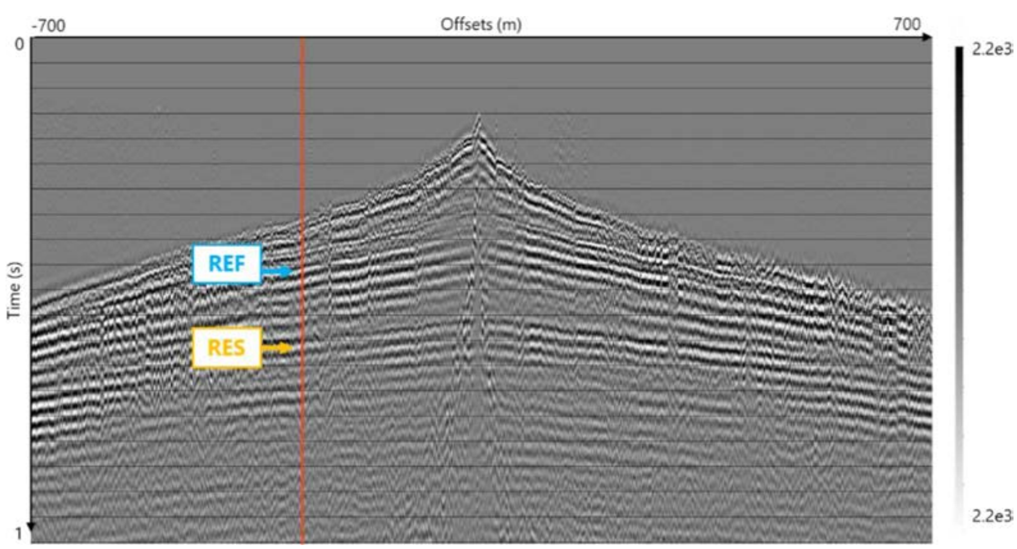

Figure 6—Associated shot-point of an optimal trace (in red), with chosen reference horizon (REF) and reservoir (RES) TWT highlighted.

The time-shift plot for Spot 1 (Figure 7), which is directly linked to the steam chamber dynamics, shows that variations remain under the noise level: time-shift values do not exceed 1 millisecond, suggesting no visible 4D effect.

Figure 7—Time-shift curve for Spot 1. Each dot corresponds to a 4D dataset.

The time-shift plot for Spot 2 (Figure 8) shows a consistent positive change between March and September 2013 and an effect building over time starting in March 2013: indeed, a steep time-shift change from 0 to 4 milliseconds is observed.

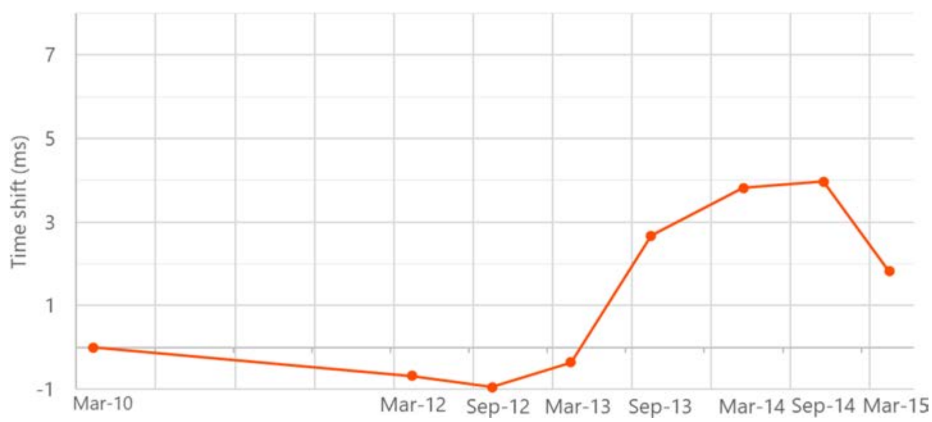

Figure 8—Time-shift plot for Spot 2. Each dot corresponds to a 4D dataset.

Finally, the time-shift plot for Spot 3 (Figure 9) shows a continuous increase from the 2010 baseline to the last monitor acquired in 2015: a variation of up to 7 milliseconds is observed, suggesting the building of a 4D effect that may have started as early as 2010.

Figure 9—Time-shift plot of Spot 3 and associated uncertainties. Each dot corresponds to a 4D dataset.

As mentioned, the baseline was acquired 2 years before the first monitor, a factor that can affect the repeatability. The error ($\mathcal{E}$) in time-shift measurement between seismic traces depends on the signal to noise ratio (*S/N*), the frequency bandwidth (B_f) and the number (n) of independent frequency samples being used to calculate the time-shift. It can be estimated by the following formula (Mari et al., 1999):

$$\varepsilon = \frac{\sqrt{3}}{\pi\sqrt{2}} \cdot \frac{1}{\sqrt{(n-1)n(n+1)}} \cdot \frac{1}{\left(\frac{S}{N}\right)Bf}$$

The signal to noise ratio has been estimated using a singular value decomposition approach to separate the signal from the noise on each trace that has been corrected from any changes in the subsurface. The frequency bandwidth can be estimated more simply as the width at half-height of the modulus of the power density spectrum. The number n of independent frequencies is a function of the smoothing introduced by the weighting function (Tukey function). For a Tukey function the smoothing equivalent to the weighting is performed over three points and only n=2 independent points can be counted (Dumont et al., 2001).

This error in time-shift can explained the last time-shift variation of Spot2. With n=2, B_f =40 Hz and *S/N* =6.5, the error $\mathcal{E}$ is equal to 0.6 ms when considering the base that was acquired in 2010. With n=2, B_f =20 Hz and *S/N* =3.9, the error $\mathcal{E}$ is equal to 2.7 ms for March 2015. As a result, the error on Δt is twice $\mathcal{E}$ and estimated at 1.2ms for the base and 5.4ms for the last monitor.

Also, a correlation coefficient was computed for each of the traces compared to the base. A mean correlation value of 96% was observed for each monitor compared to the base, except for the last that displays a coefficient of 86%, proving once again the poor repeatability of the last monitor, thus a less reliable detection for this monitor.

Intermediate conclusions

After the presentation of these results, temperature data from observation wells was provided by the client to compare these hypotheses to field observations and cross-check this new detection approach. The comparison is shown in Figure 10.

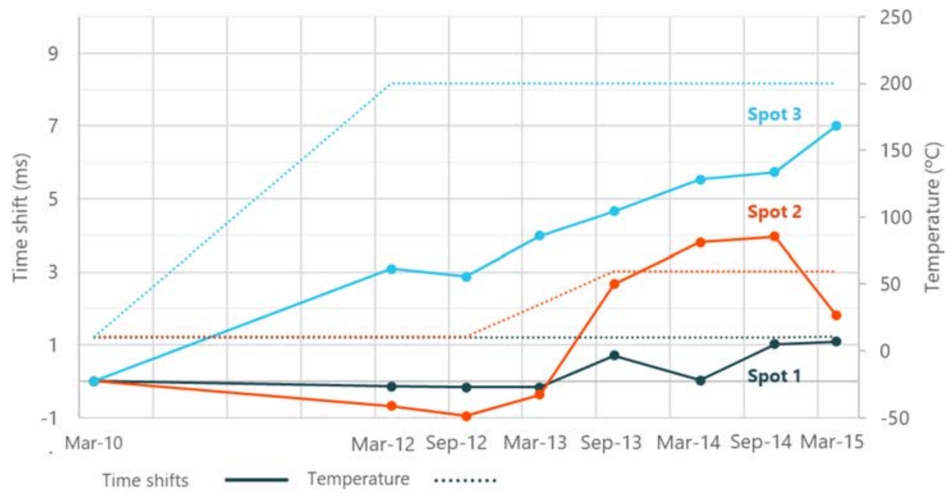

Figure 10—Time-shift plots (solid lines) for each spot & corresponding temperature data (dotted lines) from the observation wells in the vicinity of each spot.

Figure 10 tends to show that the evolution of temperature and time-shifts follows similar trends for each spot (note that the temperatures are represented as constant values but could potentially reach a higher level as they were given as a low scale value):

Spot 1: the temperature curve remains low and flat from 2010 to 2015, showing that no steam front (or its associated impact) has reached this observation well. It corroborates the absence of significative time-shift detection over the same period of time.

Spot 2: No temperature or time-shift changes were observed between 2010 and March 2013. Starting from March 2013, the temperature estimation (no well measurements available at this location) indicates an increase while the time-shift picks up between March and September 2013. It confirms SpotLight's hypothesis that the steam chamber is affecting the reservoir properties in this zone around these dates.

Spot 3: The observation well indicates an increase in temperature between March 2010 and March 2012 with a temperature of at least 200°C from this time onward. Similarly, the time-shift also increases from 2010 to 2015, which confirms the trend seen at the well.

From the comparative observation made for Spot 3 between the evolution of temperature and time-shifts, we highlight once again that the process of steam injection leads to many modifications, at reservoir level and above, associated with temperature, saturation, pore pressure and constraints changes. For instance, the injected steam increases the temperature within and adjacent to the steam chamber and thus introduces thermal expansion effects (Chalaturnyk & Polikar, 2004). The evolution of those physical parameters impacts the seismic velocities and reflectivities (Lerat et al., 2009). Positive time shifts observed here are coherent with expected and measured 4D responses in a SAGD case.

The objective behind this study is to provide a qualitative information of 4D evolution over the area of interest. However, with further development of the technology, it could be possible to estimate the variations of physical parameters in a quantitative way.

Refraction

In addition to these promising results, a detection using refraction has also been conducted. Refraction seismic surveillance methods have previously been suggested by Tatanova et al. (2007) and LandrØ et al. (2004) for high velocity carbonates acting as the refracting layer.

The proposed method works by measuring time-shifts on first arrival head-waves from the high velocity Devonian formation situated immediately beneath the McMurray reservoir. These first arrivals are essentially free of interference with surface waves and multiples, the most severe forms of seismic noise in the area. The method assumes that the dominant time-lapse effects are confined to the reservoir. Travel time changes between a baseline and monitor survey then reflects changes in the reservoir at the locations where the head-wave intercepts the reservoir layer, as illustrated in Figure 11 (Hansteen et al., 2010).

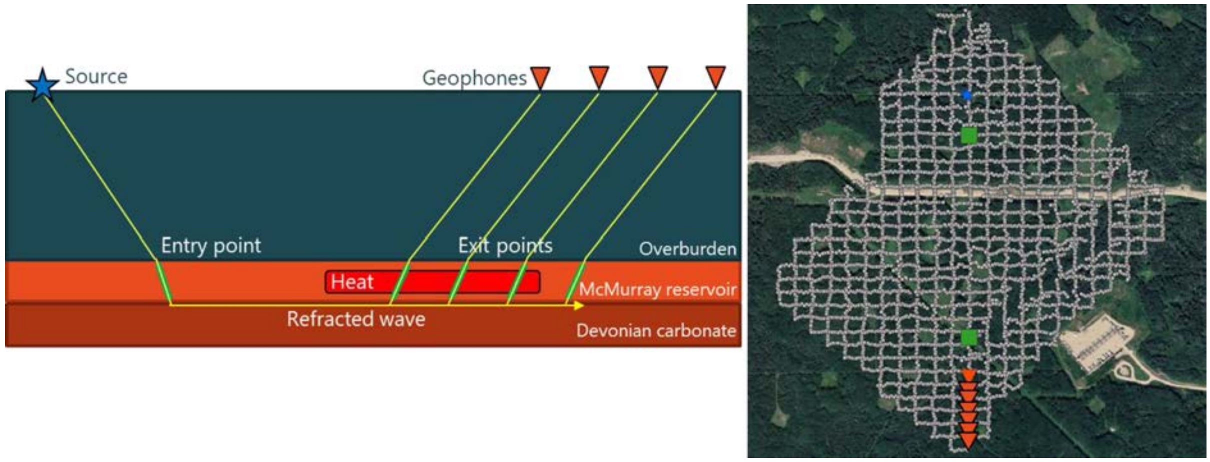

Figure 11—The time-lapse refraction method (from Hansteen et al., 2010). A seismic wave is incident at the Devonian carbonate at the critical angle and refracts along this high velocity layer. The locations where the down-going and up-going waves intersect the reservoir are labelled entry and exit points, respectively (left image). These locations, the source and geophones are also displayed on the acquisition design of Pad101 North (right image).

After identifying an area where the entry point is not subject to change (using 4D seismic maps), a comparison of the first break arrivals time between March and September 2013 show variations of a few milliseconds (Figure 12), with an average of 2.96 ms for all receivers. These results are consistent with the 4D data available in the area showing a significant change of the steam chamber between these two surveys at all of the exit points.

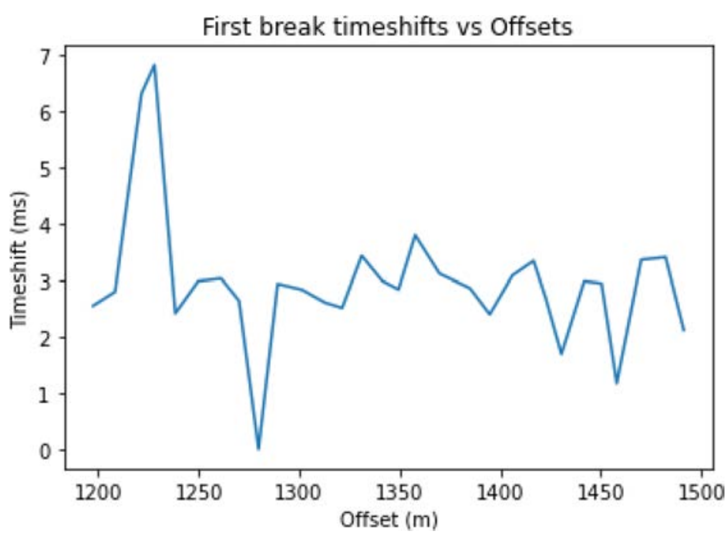

Figure 12—First arrivals time shifts between March and September 2013 versus offsets.

Having an entry point located outside the steamed area would be the best-case scenario for a future detection using refraction.

Conclusion

In this paper, a novel light and focused seismic detection approach has been successfully tested to monitor the SAGD process in a pad of the Surmont heavy oilfield. The technique consists in monitoring 4D changes in subsurface spots with just 1 source/receiver couple optimally placed on the surface (or the shallow subsurface). This non-migrated 4D seismic detection technique offers an agile & cost-effective alternative to conventional seismic in certain cases.

Using a series of 4D monitors acquired from 2010 to 2015, 3 spots were targeted on a pad to test the approach. After a survey design consisting in retrieving the most contributory seismic traces to the spot's illumination and the corresponding source/receiver couples, the time-shift evolution was computed for the 2010-2015 period.

Time-shift changes were plotted for all 3 spots and an increase was observed for 2 spots out of 3 (spots number 2 & 3), changes that can directly be correlated to the dynamics of the steam chamber. Indeed, these positive time-shift increases were successfully cross-checked with temperature data from observation wells, provided by the client after presentation of our results to avoid any bias when interpreting the data.

Therefore, this blind test has successfully demonstrated the ability of this focused seismic monitoring approach to detect 4D changes in precise subsurface locations a.k.a. spots, along with its reliability. With just one seismic source/receiver couple, it was possible to monitor the evolution of the steam chamber at reasonable cost and therefore space out in time the 4D campaigns so that they can be triggered only when needed. This tool could also be useful to (semi-) permanently monitor cap rock integrity for the whole duration of the process.

Given the range and complexity of factors that could affect the evolution of seismic attributes during SAGD, further development of this approach is required to extract more quantitative results and better understand how SAGD affects the reservoir properties in specific locations.

Uncertainties analysis showed that some data was not repeatable enough to be used as reliable monitors. This could be overcome in future field measurement by using temporal redundancy: several shots per monitor at the same shot location (Morgan & al. 2019)

Thanks to these results, a field measurement with this new approach is scheduled for 2021 to monitor the development of the steam chamber in another pad of the Surmont field.

Acknowledgements

We would like to acknowledge ConocoPhillips and Total for allowing us to publish this work. A warm thank you to Brad Gerl and Luis Cardozo from ConocoPhillips for allowing us to work on the Surmont dataset and for an excellent collaboration that has led to a successful use case. Thank you to Jeremie Batias for having introduced us to ConocoPhillips. Thanks to the SpotLighters who worked on the project: Geoffroy Bonnefous, Elodie Morgan, Julia Costa De Sousa, Jean-Luc Mari, Antoine Thomas and Habib Al-Khatib.

References

Byerley, G., Barham, G., Tomberlin, T., & Vandal, B. [2009]. 4D seimic monitoring applied to SAGD operations at Surmont, Alberta, Canada. SEG 2009 International Exposition and Annual Meeting, Houston.

Chalaturnyk, R., Polikar, M., [2004]. Issues With Reservoir Geomechanical Simulations of the SAGD Process. *Journal of Canadian Petroleum Technology*, volume **43**, n°5, pp 30–40, May.

Dumont, M-H., Fayemendy, C., Mari, J-L., Huguet, F. [2001]. Underground gas storage: estimating gas column height and saturation with time lapse seismic. *Petroleum Geoscience*. **7**, 155–162.

Forgues, E., Meunier, J., Hubans, C. [2015]. Steam injection seismic experiment in Northern Alberta. *CSPG/CSEG 2006 GeoConvention*, Calgary.

Hansteen, F., Wills, P., Hornman, K., Jin, L. [2010]. Time-lapse Refraction Seismic Monitoring. SEG Denver 2010 Annual Meeting.

LandrØ, M., Nguyen, A. K., & H., Mehdizadeh. [2004]. Time lapse réfraction seismic – a tool for monitoring carbonate fields. 74th Annual Meeting, SEG Expanded Abstracts 23, 2295.

Lerat, O., Adjemian, A., Auvinet, A., Baroni, A., Bemer, E., Eschard, R., Etienne, G., Renard, G., Servant, G., Michel, L., Rodriguez, S., Aubin, F., Euzen, T. [2009]. Modelling of 4D seismic data for the monitoring of the steam chamber growth during SAGD process. *CIPC*, Calgary.

Morgan, E., Garden, M., Egreteau, A., Boubaker, Y., Gestin, K., Mari, J.L. [2019]. Focused and continuous ultra-light seismic monitoring : a gas storage example. 82nd EAGE Conference, Amsterdam.

Tatanova, M., Bakulin, A., Kashtan, B. M., & Korneev, V. [2007]. Head-wave monitoring with virtual sources. 77th Annual International Meeting, SEG, Expanded Abstracts 26, 2994.