Feasibility study of time-lapse seismic monitoring for SAGD heavy oil reservoir production – A rock physics study

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Abstract

We present a feasibility study for monitoring of SAGD enhanced oil recovery with seismic methods in Western Canada. We determine the change in the elastic properties of the reservoir after steam injection based on well logs, a realistic but simplified steam chamber model, and the assumption that Gassmann's equation is applicable. Our calculations indicate that the seismic properties of the reservoir do not change substantially in this particular case without additional geotechnical effects, and therefore seismic monitoring of SAGD processes in certain thin and deep reservoirs will be a challenging process.

Introduction

Heavy oil reservoirs are found all over the world with the largest deposits being located in Western Canada and the Orinoco River reservoir in Venezuela. Heavy oil reservoirs in Western Canadian Sedimentary Basin are large and to an extent easily found. As such, seismic methods were never much used to actually explore for such resources. A different situation exists today when producing these fields. The very high viscosity of the oil requires expensive and technically complicated thermal recovery methods to mobilize the crude. The heavy oil reservoirs in the Western Canadian Sedimentary basin are often produced using an enhanced oil recovery method such as Steam Assisted Gravity Drainage (SAGD, Butler, 1991). This method is relatively expensive and remotely monitoring of the steam chamber in the reservoir is an important tool in engineering decision processes. By-passed sections of the reservoir are an example for problems that may occur due to the complexity of the geology or completion problems of the horizontal wellbores. For these reasons, the focus of applied seismic is shifting towards monitoring of changes in the reservoir with time and estimating in-situ properties and conditions. However, injecting steam into a heavy oil reservoir causes relatively complicated changes of the seismic properties.

The feasibility of monitoring heated reservoirs with seismic methods is based on the dramatic decrease of the P-velocity with temperature (see, for example, Wang and Nur, 1988 and Eastwood, 1993). The measurements in the mega hertz range indicate that the P-velocity of an oil-saturated sand decreases by about 20 %, when the sample is heated to approximately 120 ºC. However, these studies did not consider a fluid replacement steam for oil. Nur et al. (1984) described that injected steam as a carrier for heat causes only a small change of the seismic properties. Further the amount of heated oil in a SAGD process may not be that large as in current engineering models there are large temperature gradients between the steam zone and the unheated reservoir.

To test the feasibility of seismic monitoring we carry out an extensive analysis of well logs from different reservoirs in the Western Canadian Sedimentary basin. From the well logs we identify the reservoir and determine the elastic properties of the composite material. To simulate a SAGD process we replace the oil in the pore space by a mixture of steam, water, and oil. Then we create modified well logs, and based on those we compute synthetic seismic traces. We will extract two seismic attributes from the synthetic seismic and compare them to those determined from the original well logs.

Method

a) Determination of the elastic properties

To determine the elastic properties of the porous material we assume that the Gassmann (1951) equation can be applied. In Gassmann's equation all parameters except the frame properties are either easy to measure (e.g. porosity ϕ) or available in tables (such as the bulk modulus of the solid material, K_s, or the fluid bulk modulus, K_f). A value of the frame bulk modulus, K_d, that is consistent with the well log, can be found by solving Gassmann's equation for K_d:

$$K_d = \frac{1 + K_{eff}\left(\frac{\phi}{K_s} - \frac{1}{K_s} - \frac{\phi}{K_f}\right)}{\frac{1 - \frac{K_{eff}}{K_s} + \phi}{K_s} - \frac{\phi}{K_f}}. \qquad (1)$$

In this equation, K_{eff} is the effective bulk modulus of the effective medium. We can determine its value from the well log as well:

$$K_{eff} = \rho\left(v_p^2 - \tfrac{4}{3}V_s^2\right) \qquad (2)$$

The shear frame modulus, μ_d, can be determined in a similar way from the density and S-sonic log.

As we do not know the elastic properties of the oil (and indeed there may be additional complications introduced by the oil viscosity), we determine the bulk frame modulus from the effective properties in the water layer. We assume that this value does not change in the oil layer. We can test the validity of this assumption by comparing the shear frame modulus in both parts of the reservoir. If the shear frame modulus does not change substantially, the bulk frame modulus remains most likely the same as well. The modulus of the saturating water was determined based on the ambient temperature, pressure, and salinity data using the formulas by Batzle and Wang (1992).

b) Fluid substitution

In a SAGD, process high quality steam is injected into the reservoir. This means that the steam consists of at least 70 % water in the vapor phase and the remainder in the liquid phase. Usually up to 80 % of the original oil can be produced. If some of the steam immediately condenses after injection, we can obtain the following model for the steam chamber. Within the steam chamber, the pore space is filled with a mixture of 65 % steam vapor, 15 % water, and 20 % oil. The temperature will be about 270 ºC, whereas the pore pressure does not change. Outside the steam chamber, we will have the original pore fluid and the original pore pressure and temperature.

The co-existence of steam and liquid water requires the temperature and pressure to be close to the saturation condition. The density and bulk moduli of steam and water under those conditions are widely available in steam tables (e.g. Keenan et al., 1969, and Irvine and Hartnett, 1976).

To calculate the properties of the pore fluid after steam injection we assume that the three components are uniformly distributed in the steam chamber. Then we can use a volume averaging equation to calculate the effective density and a Reuss averaging method to determine the effective bulk modulus of the fluid.

c) Synthetic seismograms

We calculate the synthetic seismograms by a simple convolution method. From the density and P-sonic log, we first calculate the impedance. Then this log is converted to a time series and finally convolved with a Ricker wavelet of different center frequencies to obtain a seismic trace. From this trace, we extract two seismic attributes that can be used to estimate the in-situ changes in the reservoir. First, we analyze the travel time lag of the reflection from the bottom of the reservoir in the modified well log as compared to the original well log. The second attribute is the change in the reflection strength at the top of the reservoir. We will test the feasibility to monitor SAGD processes by comparing these two attributes at two different times in the injection history.

Examples

We apply this method to a well log recorded in Western Saskatchewan. Steam has been injected into a heavy oil reservoir since 1998 and seismic surveys have been repeatedly recorded since 1999 by the University of Alberta. However, we were not able to detect significant changes in the seismic signature of the reservoir. This is somewhat surprising given the amount of steam that has been injected into to the reservoir.

The reservoir sandstone is about 20 m thick, of which approximately 8 m are saturated with water. In figure 1, we show the part of the log at the reservoir depth. The oil-bearing reservoirs in this area are easily identified by the coal and shale layers above and the carbonates below. The resistivity log helps us to distinguish between the oil sand and the water saturated sand. Additional information such as porosity and density of the solid material as well as saturation of oil and water in the reservoir are available from a core analysis for a well close by. Therefore, an extensive amount of information is available for this area.

All logs beside the resistivity log show that the reservoir layer is fairly uniform. This suggests that the petrophysical properties, especially the elastic moduli of the frame, do not change considerably within the reservoir layer. In a first step, we determine the elastic properties of the frame as described above. For the water layer, we determine a frame bulk modulus of 8.7 GPa, and the shear frame modulus is 4.5 GPa. The shear frame modulus decreases

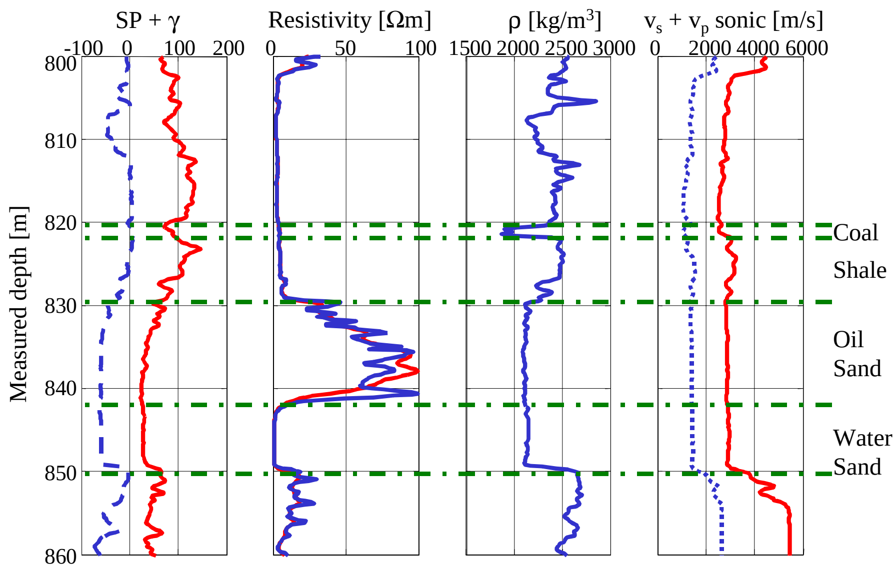

Figure 1 In the well log the reservoir can be clearly distinguished from the coal and shale layer above and the carbonates below.

Table 1 The seismic properties of the effective medium and the pore fluid before and after the steam injection, respectively. All values before fluid substitution have been determined from the well logs, whereas the data after steam injection were calculate using effective medium theories.

	Before	After	Change
ρ_{eff} [kg/m^3]	2120	1870	- 11.8 %
K_f [GPa]	2.38	9.6×10^{-3}	- 99.6 %
K_{eff} [GPa]	11.8	8.7	- 30.4 %
V_p [m/s]	2864	2767	- 3.4 %
V_s [m/s]	1403	1498	+ 6.8 %

Table 2 The properties of the rock matrix and the heavy oil before and after fluid substitution for the Athabasca reservoir. The parameters for the solid and liquid constituent were taken from published data, whereas the effective properties were calculated using Gassmann's equation

	Before	After	Change
K_d [GPa]	0.667		---
μ_d [GPa]	0.308		---
K_f [GPa]	2.77	1.5×10^{-3}	- 99.5 %
ρ_{eff} [kg/m^3]	2122	1898	- 10.6 %
K_{eff} [GPa]	7.86	0.672	- 91.5 %
V_p [m/s]	1974	755	- 61.8 %
V_s [m/s]	381	402	+ 5.5 %

only negligibly to 4.3 GPa, which also supports our assumption that the reservoir is homogeneous. Applying the steam chamber model describe previously, we calculate the effective seismic properties in the reservoir after steam injection. The effective bulk modulus of the fluid is calculated by applying a Reuss average, the effective density results from a volume average method, and the effective bulk modulus is based on Gassmann's equation. The results of our calculations are summarized in table 1. Generally, we observe a considerable decrease of the bulk modulus of the fluid, the effective density, and the effective bulk modulus of the composite material. However, the P-velocity decreases only marginally by 3.4 %.

The synthetic seismograms were calculated for a 75 Hz Ricker wavelet. The traces for the conditions before and after steam injection are plotted in figure 2 along with the reflectivity time series. The difference between the two traces is only very small in this case and it will be very difficult to detect changes in the reservoir with seismic methods under the current set of assumptions. The travel time to the bottom of the reservoir changes only by 1 ms, and the change in the strength of the reflected amplitude is small ($\leq$ 10%).

For a second example, we used published rock physical data for a reservoir of the Athabasca complex in Northern Alberta. With about 150 m depth this deposit is much shallower then the previous reservoir. Chalaturnyk (1996) carried out an extensive geomechanical study for an Athabasca reservoir. The values for the elastic frame properties and the porosity measured for this reservoir a provided in table 2. With a frame bulk modulus of approximately 670 MPa the rock matrix is considerably weaker consolidated when compared to the previous example. However, exact in-situ properties of the crude are not available. We therefore estimated the bulk modulus and density of the fluid using the empirical equations by Batzle and Wang (1992). The results of our calculations are summarized in table 2. The P-velocities decrease substantially by more than 60% after the fluid replacement. Therefore, seismic monitoring of the SAGD process is more likely to be feasible, as the measurements reported by Schmitt (1999) show. Unfortunately, we do not have well log data available to create synthetic seismograms.

Conclusions

Based on detailed well logs and realistic assumptions of a SAGD process we determined the change in the elastic properties of the reservoir zone after steam injection. We do not observe a substantial change of the seismic velocity after the fluid substitution. The difference in the two seismic attributes travel time lag and reflection strength before and after steam injection seem not to be large enough to be recordable with seismic methods. This explains probably our problems in detecting differences in the time-lapse seismic images.

The reasons for this are most likely the relative stiff frame in the reservoir layer and the thin reservoir. In our first example, the stiffness of the frame makes up about 75 % of the bulk modulus of the effective medium. As the frame properties are assumed to not change after the fluid replacement only a small amount of the total stiffness is affected. Therefore, the stiff frame of the reservoir makes it rather insensitive to fluid replacement, and the thin reservoir, along with the small velocity change, does not allow to cause a significant travel time lag. In this example, the variations in the bulk density contribute more to any changes in the reflectivity. The synthetic seismogram, on the other hand, show that the change in the reflected amplitude is difficult to resolve with frequencies in the seismic band. The strong reflection

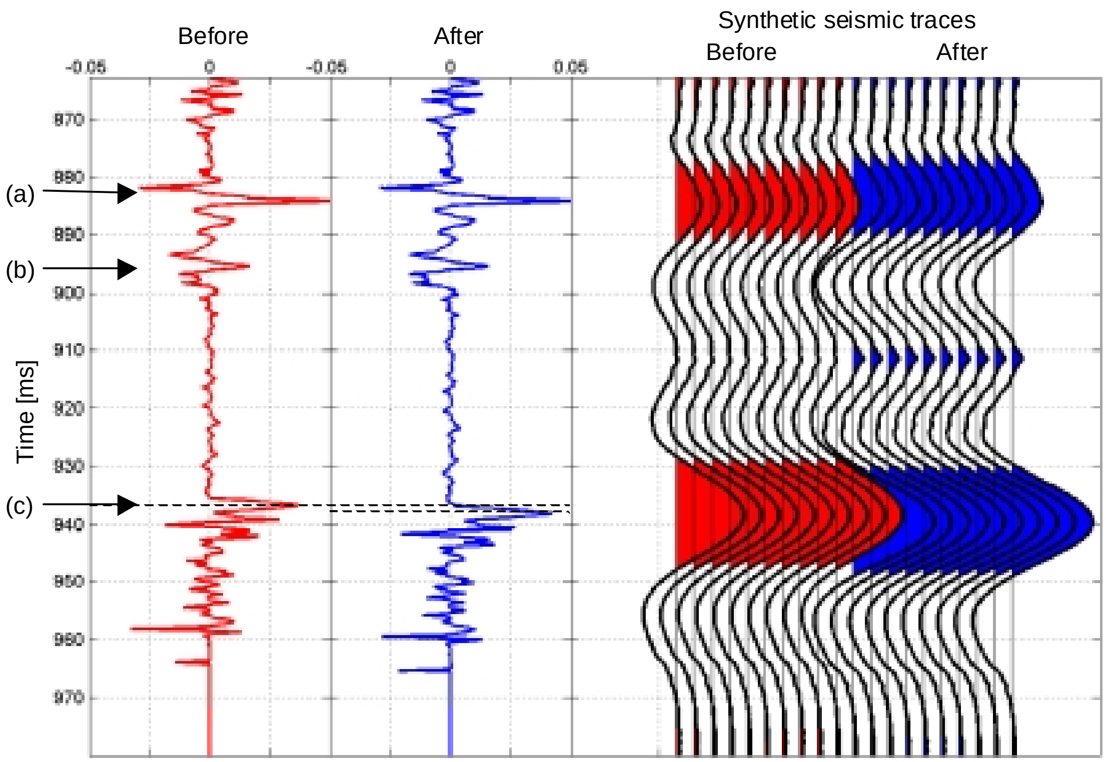

Figure 2 The synthetic traces are plotted against travel time along with the reflectivity time series for the reservoir conditions before and after steam injection. Three reflections of the coal-shale (a), shale-top of sand (b), and thesand-carbonate © interface are indicated by the arrows. The two dashed lines in the two panels to the left show the small increase in travel time to the bottom reflection of the reservoir.

from the coal-shale interface dominates the overall seismic signal in the interesting time window. Therefore, the small changes in the reflection from the top of the reservoir sand are difficult to observe.

The second example in this study is significantly less consolidated. In this case, the frame bulk modulus contributes only 8.5 % to the total bulk modulus of the effective medium. A substantial change of the bulk modulus of the pore fluid therefore results in a significant change of the overall properties of the effective medium. For reservoirs with a weak rock frame, seismic monitoring is much more likely to be feasible.

Based on these results it seems that for seismic monitoring of SAGD enhanced oil recovery processes to be feasibility it is important not only to consider the fluid properties before and after steam injection. If the contribution of the frame to the total stiffness of the effective medium is large then the fluid effect is small and monitoring the steam zones within the reservoir with seismic methods is difficult. The results by Schmitt (1999), however, show that under different conditions in shallower reservoirs seismic monitoring of SAGD processes is possible.

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